The assessment of degradation state in Ecological Infrastructure and prioritisation for rehabilitation and drought mitigation in the Tsitsa River Catchment

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Abstract

Ecosystem degradation is a serious concern globally, including in South Africa, because of the potential adverse impacts on food security, livelihoods, climate change, biodiversity, and ecosystem services. Ecosystem degradation can result in flow alteration in the landscape through changes in the hydrological regime. The study adopts the South African National Biodiversity Institute (SANBI) Framework of Investing in Ecological Infrastructure (EI) to prioritise the restoration of degraded ecosystems and maintain ecosystem structures and functions. This study aims to assess how EI (specifically wetlands, grassland, abandoned cultivated fields, and riparian zone) can facilitate drought mitigation: to assess land degradation status and identify priority EI areas that can be restored to improve the drought mitigation capacity.

Two assessment methods were used in this study. Firstly, the Trends.Earth tool was used to assess degradation and land cover change from the year 2000-2015 in Tsitsa catchment, through assessment of Sustainable Development Goal degradation indicator (SDG15.3.1) at a resolution of 300 m. The degradation indicator uses information from three sub-indicators: Productivity, Landcover and Soil Organic Carbon to compute degraded areas. The degraded areas need to be restored and rehabilitated to maintain the flow of essential ecosystems services provided by EI. The second assessment used the Analytical Hierarchy Process (AHP), which integrates stakeholder inputs into a multi-criteria decision analysis (MCDA). The AHP is a useful decision support system that considers a range of quantitative and qualitative alternatives in making a final decision to solve complex problems. As part of the AHP analysis, participatory mapping using Participatory Geographic Information System was conducted to obtain stakeholder inputs for prioritising restoration of the key EI categories (wetlands, grassland, abandoned cultivated fields, and riparian zone) in the catchment. During the participatory mapping, communities prioritised the key EI based on three criteria: (1) ecosystem health, (2) water provisioning and (3) social benefits. The AHP method was used in ArcGIS to prioritise suitable key EI restoration areas with high potential to increase water recharge and storage, contribute to drought mitigation and ecosystem services for the catchment. The prioritisation of EI for community livelihoods in the AHP analysis included all three main criteria. In comparison, the prioritisation of suitable key EI restoration areas for flow regulations was based on two criteria: ecosystem health and water provisioning.

The land degradation indicator showed that approximately 54% of the catchment is stable, 41% is degraded land, and 5% of the area has improved over the assessment period (15 years). The degradation status in the EI suggests that more than half (>50%) of each EI category is stable, but there are areas showing signs of degradation, including 43% of grasslands degraded and 39% of wetlands, cultivated lands, and riparian zones also degraded. Degradation is dominant in the upper (T35B and T3C) and lower (T35K, T35L and T35M) parts of the catchments. The three criteria used by the stakeholders in the prioritisation process of the key EI were assigned 12 spatial attributes (the catchment characteristics about the study area in relation to the criteria) to indicate relevant information needed for selecting suitable restoration areas to enhance flow regulation.

The AHP analysis results identified approximately 63% (17,703 ha) of wetlands, 88% (235,829 ha) of grasslands, 78% (13,608 ha) of abandoned cultivated fields and 93% (3,791 ha) of the riparian zones as suitable areas for restoration to mitigate drought impact through flow regulation. Also, the suitability results showed 63% (17,703 ha) of wetlands, 58% (2,203 ha) of riparian zones, 68% (11,745 ha) of abandoned cultivated fields and 46% (122,285 ha) of grasslands as suitable restoration areas for improving ecosystem services for community livelihoods. The AHP analysis identified more than 39-43% (of the degraded EI indicated by the Trends.Earth analysis) areas that are suitable for restoration, because key EI plays a significant role in flow regulation and people’s livelihoods, especially when they are managed, maintained, and restored to good health conditions. Therefore, the prioritized EI areas should be either maintained, managed, rehabilitated or restored. The major distinct causes of land degradation are woody encroachment in grasslands, invasion of alien plants on abandoned cultivated fields and soil erosion in the catchment.

The most suitable EI areas recommended for restoration are those natural resources near local communities, which provide essential ecosystem services to sustain their livelihood. Therefore, degraded EI in the T35 catchments should be restored and maintained to improve livelihood and mitigate drought impacts. The study pointed out how the key selected ecological infrastructure can help mitigate the impacts of droughts and improve human livelihood. The study contributes towards the important concept of investing in ecological infrastructure to improve the social, environmental, and economic benefits.

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List of abbreviations

AHP	Analytic Hierarchical Process
CCI-LC	Climate Change Initiative-Land Cover
CLOs	Community Liaison Officers
CHIRPS	Climate Hazards Group Infrared Precipitation with Stations
DEA	Department of Environmental Affairs
DEFF	Department of Environment Forestry and Fisheries
DWAF	Department of Water Affairs & Forestry
DWS	Department of Water and Sanitation
EI	Ecological Infrastructure
EVI	Enhanced Vegetation Index
ESA-CCI	European Space Agency Climate Change Initiative
FAO	Food and Agriculture Organisation of the United Nations
IAP	Invasive Alien Plants
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ISRDP	Integrated Sustainable Rural Development Programme
LDN	Land Degradation Neutrality
MAR	Mean Annual Runoff
MCDA	Multi-Criteria Decision Analysis
MEA	Millennium Ecosystem Assessment
NBA	National Biodiversity Assessment

NBS	Nature-Based Solutions
NDP	National Development Plan
NDVI	Normalised Difference Vegetation Index
NLC	National Land Cover
NPP	Net Primary Productivity
NWRS2	National Water Resource Strategy 2
PGIS	Participatory Geographic Information System
QGIS	Quantum Geographic Information System
RESTREND	Residual Trend Analysis
RUE	Rain Use Efficiency
SDG	Sustainable Development Goal
SLM	Sustainable Land Management
SANBI	South African National Biodiversity Institute
Stats SA	Statistics South Africa
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNESCO	United Nations Educational, Scientific and Cultural Organization
WUE	Ecosystem Water-use Efficiency

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Dedication

This thesis is dedicated to all the Mahlaba clans, Sodidi, Shengele.

Chapter 1: General introduction

1.1 Background

In the mid-2010s, it was estimated that about 1.9 billion people were living in areas with a high potential for severe water scarcity, with approximately 1.8 million people affected by land degradation through drought or desertification (UN-Water, 2018). Drought and water scarcity are recognised as major challenges in arid to semi-arid countries, affecting over 2 billion people globally (IPCC, 2014).

A semi-arid region like South Africa is a water-stressed country with an average annual rainfall of about 450 mm (DEA, 2018) compared to the global average annual rainfall of 990 mm (Lamb et al., 2020). South Africa faces several water crises and concerns, including the security of future water supply, environmental degradation and resource pollution (Kotze, 2013). Water quantity and quality failure issues are a concern since they result in a shortage of water supply. Factors like climate change and human activities cause ecosystem degradation and accelerate the country's water crisis issues (Mander et al., 2017; DEA, 2018). The projected effects of climate change (reduction of rainfall in some areas, increased evapotranspiration, increase in temperature, frequent extreme events such as droughts) are expected to worsen water scarcity in South Africa (DEA, 2013; DEA, 2014).

Consequently, the pressure on water supply security is expected to increase, and there is a high demand for water and increased uncertainty in water use planning and management (Kotze, 2013; Gonzales & Ajami, 2017). The water shortage and increase in water-related problems (water yield, storage and quality) have been accelerated by the environmental challenge of land degradation that many countries face (Vinet & Zhedanov, 2010; DEA, 2012). Land degradation is an environmental challenge that South Africa is currently facing (Wessels et al., 2007a), affecting South Africa's rich biodiversity, a wide range of habitats and biomes, and people's survival (Vinet & Zhedanov, 2010). In South Africa, about 38% of the population live in ecologically degraded areas (Anderson et al., 2017; Sigwela et al., 2017), and an estimated loss of ecosystem services of about US$ 65 billion, which is approximately R 97 billion due to land cover and environmental degradation was experienced between 1990 and 2014 (Anderson et al., 2017). Land degradation in South Africa is caused by human and climate factors (Wessels et al., 2007a). Factors such as poor land-use practices and land cover changes affect natural resources, result in shifts in function and structure of ecosystems (productive potential of land and water resources) (DEA, 2012).

The loss and degradation of natural ecosystems negatively increase water-related risks in the catchment, like the decline of water quantity in surface water bodies (DEA, 2012). The degradation of natural ecosystems such as wetlands, riparian areas and grasslands results in alteration of water movements and flow regulation within the landscape due to changes in the hydrological processes such as infiltration, evapotranspiration and overland flows (SANBI, 2013a; Le Maitre et al., 2014). For example, degraded wetlands lose the capacity to store and release water to the surface during drought or recharge groundwater (Vinet & Zhedanov, 2010; DWS, 2014a). The term flow regulation refers to the ability of a healthy natural vegetation cover that helps to regulate surface and groundwater by capturing and storing water from precipitation to reduce surface run-off and releasing water slowly to sustain flows during the dry season (DEA, 2014; Le Maitre et al., 2014).

Changes in the natural land cover (e.g. due to invasion of alien plants) affect water flows by increasing surface water flow, causing flooding, and reducing infiltration baseflow (Le Maitre et al., 2014). Further, changes in the hydrological processes can hinder water availability; consequently, water-related problems, worsened by global climate change, are mostly felt in rural areas where drinking water is scarce (SANBI, 2014).

The impacts of drought and land degradation on water flow increase people's vulnerability to water scarcity, especially the rural communities that do not have reliable water supply or potable water (DEA, 2014). There is an urgent need for ecological restoration to conserve and sustain these ecological infrastructure and ecosystem services that the communities benefit from. To combat environmental degradation, the South African government has prioritised natural ecosystems protection by developing several environmental policies. These policies include, for example, the National Environmental Management Act (No. 107 of 1998), the Biodiversity Act (No. 10 of 2004), the Protected Areas Act (No. 57 of 2004), and the Forest Fire Act (No. 101 of 1998). All the above-listed policies are designed for conservation and resource protection (Bennett & Kruger, 2015) and investment in ecological infrastructure (SANBI, 2014).

The South African government adopted the concept of investing in ecological infrastructure (EI) to maintain the natural functioning of EI and rehabilitate degraded areas to enhance the benefits, as indicated in the National Infrastructure Plan announced in 2012 (Vinet & Zhedanov, 2010; Kotze, 2013). The rehabilitation and maintenance of ecological infrastructure sustain rural communities livelihoods through direct and indirect benefits and regulating and provisioning ecosystem services (Sigwela et al., 2017). For instance, grasslands and wetlands provide regulating services such as attenuating floods, trapping sediments (leading to better water quality) and providing drinking water from rivers (Huchzermeyer et al., 2018a). Monitoring, maintenance, and restoration of degraded lands contribute towards achieving clean water and sustainable livelihoods for the people, consistent with the United Nations Sustainable Development Goals (SDGs) on water security, SDG6 (https://sdgs.un.org/goals). Other relevant SDGs are SDG13 that targets actions to combat climate change and its impacts, and SDG15 that relates to land management. The SDGs are linked to the South African National Development Plan (NDP) for 2030, aiming to address poverty and inequalities (Claassen & Hill, 2017; Cumming et al., 2017).

Human activities influence water flow (storage, reduction in water recharge sources, e.g., low precipitation inputs and abstraction for water use), so they can cause drought (Van Loon et al., 2016). For instance, human activities such as land use and land cover changes are causing modification in ecological infrastructure such as wetlands, rivers and vegetation. These modifications will influence water flow processes like causing a reduction in infiltration and soil moisture, reducing groundwater recharge and streamflow, which can lead to drought (Van Loon & Laaha, 2015; Van Loon et al., 2016; Kim & Jehanzaib, 2020). Also, the unsustainable water abstraction in both surface and ground water reduces the available water, enhancing drought impacts (Van Loon et al., 2016; Kim & Jehanzaib, 2020). Therefore, drought, land degradation, and human activities negatively water security, causing water shortage, affecting the ecology and socio-economic conditions. These water shortage drivers are serious issues that need to be attended to, to avoid adverse impacts on water resources. So, this study prioritised four key Ecological Infrastructure (EI) (wetland, grassland, riparian zones and abandoned cultivated fields) for restoration to increase streamflow and mitigate drought impacts, employing the South Africa National Biodiversity Institute's (2014) Framework for Investing in EI. The justification for these EI is provided below. This research seeks to support the concept of investing in EI as an option for increasing catchment water security by enhancing water storage through catchment management. The study selects the key areas of natural resources which when maintained, restored, and rehabilitated can improve water storage and flow regulation, especially during water shortages.

1.2 The rationale of the study

The increase in climate change associated with human impacts threatens natural resources such as water resources affecting water security and ecosystem service (UN-Water, 2018)**,** consequently impacting people's livelihood within the catchment. Restoration and maintenance of natural resources can restore natural catchment behaviours (structure, e.g., physical characteristics and function), improve ecosystem services and landscape resilience, and reduce drought impacts (Stoelzle et al., 2014)**.** Investing in EI is crucial for maintaining ecosystems' natural functions to sustain important ecosystem services, which benefit people and the environment. The importance of protecting natural resources, restoring and rehabilitating degraded areas for water services is recognised in the literature (Le Maitre et al., 2014, 2016; Mander et al., 2017), where researchers advocate for land rehabilitation to improve subsurface and surface water sources. However, implementation methods (resource protection) to protect and maintain natural resources for improving ecosystem service is a challenge (Gichuki et al., 2019). This study focuses on how ecological infrastructure can mitigate the impacts of drought by increasing and maintaining streamflow during dry seasons. The study output will provide valuable information towards the rehabilitation plan for degraded areas, which may positively impact the proposed two dams (Ntabelanga and Laleni) within the study catchment. This research contributes to the emerging concept of investing in ecological infrastructure to deal with land degradation, climate change adaptation, and achieving the SDGs. The study also indicates that protection and management of ecological infrastructure to good health conditions can be used to solve water-related issues while simultaneously contributing to the improvement of rural living conditions. It is critical for this study to explore the values and benefits of managing EI.

1.3 Aims and objectives.

This study aims to assess how ecological infrastructure facilitates drought mitigation and EI degradation status for the prioritisation plan for rehabilitation to mitigate drought in the Tsitsa River Catchment.

The following objectives were used to achieve the overall aim of the study:

i. To identify key target ecological infrastructure in the catchment.
ii. To assess the state and changes in target EI over the past 15 years.
iii. To develop a prioritisation plan for the rehabilitation of degraded EI.

1.4 Background of the study area

The study area is situated in the Tsitsa River catchment, a tributary of the Mzimvubu River in the Eastern Cape Province, South Africa. The Tsitsa River catchment is in the former Transkei between Maclear and Qumbu towns and surrounded by small rural communities (Figure 1.1). The study area covers quaternary catchments from T35A to T35M, with an area of 4,924 km^2 and falls within the Strategic Water Source Area in the Drakensberg region. The catchment falls within three local municipalities: the Elundini, Mhlontlo and Nyandeni local municipalities (Figure 1.1).

The climate of the catchment is highly variable and fluctuates between droughts and floods (Van der Waal et al., 2017). The area has a sub-tropical climate, with the Mean Annual Precipitation ranging from 786 mm to 1000 mm (Schulze, 1997), and the highest rainfall is experienced between November and February (DWS, 2014a). The mean annual temperatures range between 6.6 °C in winter and 20.3 °C in summer, with the highest temperature occurring in January and the lowest 0°C in the winter months (DWS, 2014a).

The catchment is characterised by the Beaufort group of rocks, which is dominated by sandstone combined with shales and mudstone (Le Roux et al., 2015). Loamy soils predominate, with duplex soils that are highly unstable and erosive. The soils are characterised by highly erodible clay content, soil properties that result in the extensive gully and deep fine sediments deposited around into the Tsitsa River (ERS, 2011; Le Roux et al., 2015).

The study catchment is dominated by the Grassland biome, which constitutes 61% of the vegetation. The remaining land cover comprises 15% of cultivated lands and 8% plantations, with the remaining 16% distributed among other land covers: indigenous bush/forest, wetlands, bare ground, and villages (Figure 1.1) (GEOTERRAIMAGE, 2019a). Invasive alien plants severely infest the catchment, most commonly the *Acacia mearnsii* (Black wattle) and *Acacia dealbata* (Silver wattle)(ERS, 2011; Huchzermeyer, Schlegel and Van der Waal, 2018).

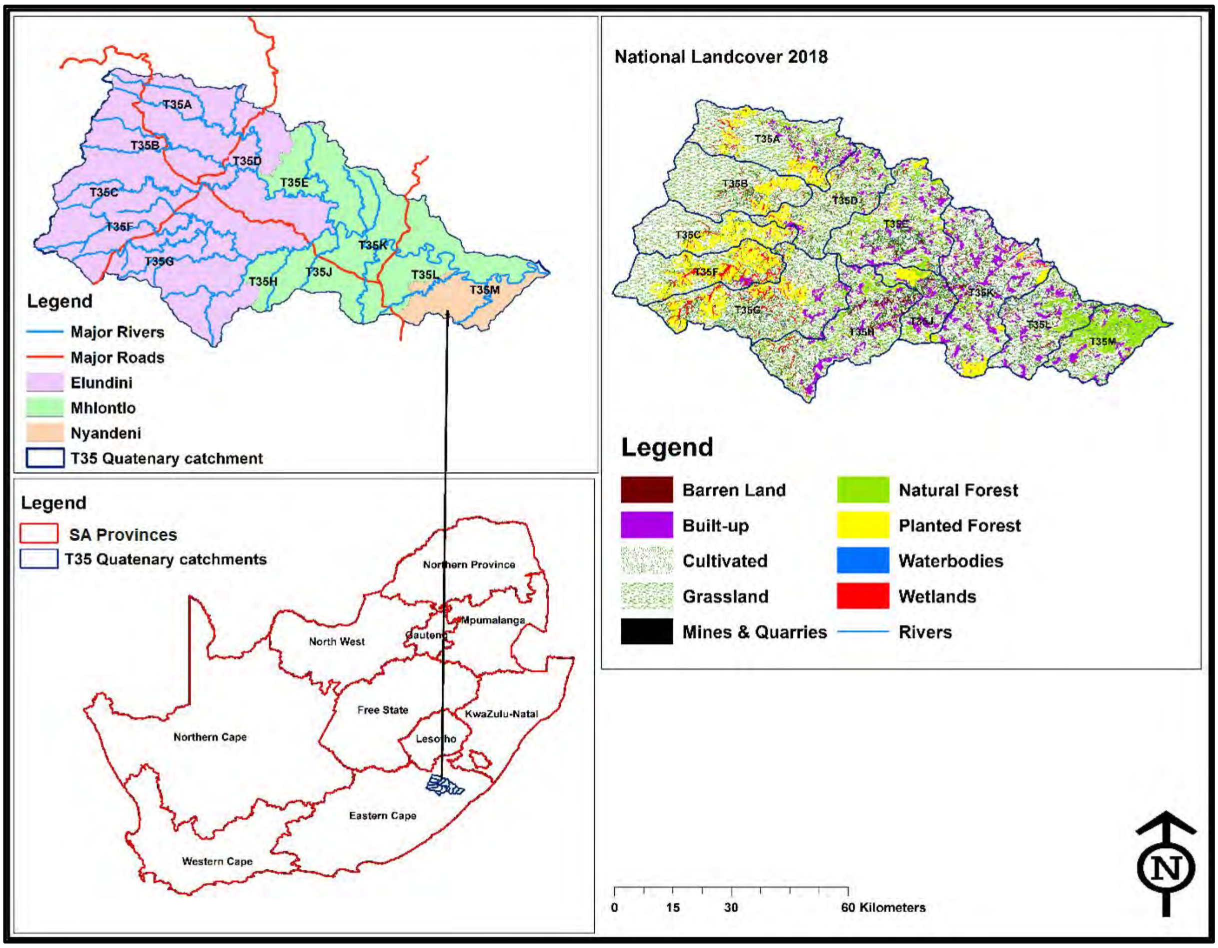


Figure 1.1: Location of the study area, the Tsitsa River catchments (T35) in the Eastern Cape province of South Africa with present local municipalities. Based on the National Landcover 2018 (GEOTERRAIMAGE, 2019a), the land cover distribution within the catchments and dominant rivers in the catchment are presented.

The dominant land uses in the catchment are communal and private lands supporting commercial farms and plantations and subsistence farming. Land use in the privately-owned areas includes forestry and commercial agriculture, whereas the communal areas mostly consist of rural subsistence farming (Le Roux et al., 2015; Bannatyne et al., 2017; Cockburn et al., 2018).

The study area falls within the top of the list of poorest and less developed regions of South Africa (DWS, 2014b). The people living in the area still face financial and social difficulties as a result of apartheid: which separated the Transkei homeland from the Republic of South Africa. Resulting in limited Government services and forced removal of black people from white areas into the Transkei increased population in the area adding more pressure on local resources (DWS, 2014b; Le Roux et al., 2015; Van der Waal et al., 2017). Most of the people living within the Tsitsa River catchment depend on various farming practices such as livestock farming, forestry, or crop cultivation. Communities living in the catchment depend primarily on natural resources to sustain their livelihoods (DWS, 2014b; Huchzermeyer et al., 2018b). The key natural resources include rivers, grasslands, cultivated fields, wetlands, and riparian vegetation. However, change in land-use practices in the catchment has led to degradation of the landscape. These changes result from human activities such as poor management of grazing, over-cultivation and social and political issues, which have led to the degradation of the land in the area (Cockburn et al., 2018). Poor infrastructure and poverty has led the youth to move to urban areas, leaving older people and young ones at home who are less able to do hard labour and look after the environment (Van der Waal et al., 2017). Communal lands are some of the most degraded areas in South Africa, particularly in areas like the former Ciskei, Transkei and KwaZulu (Hoffman & Todd, 2000b). Communal areas in former Transkei homelands have extensive land degradation; this includes the Tsitsa River catchment (study area). Lack of land ownership in the communal lands and with different local government systems reduces land control and natural resources management, leading to land degradation (Van der Waal et al., 2017). Degradation in the catchment has detrimental effects on the catchment’s ecological infrastructure (Huchzermeyer et al., 2018a).

Most of the EI degradation in the Tsitsa catchment is due to anthropogenic activities (Le Roux et al., 2015; Schlegel & Huchzermeyer, 2018), such as poor land management practices (e.g., poor management of grazing, uncontrolled fires), poor farming practices, and cultivated land abandonment. The degraded ecological infrastructures include wetlands, grasslands, soil, river water quality and rangelands (Le Roux et al., 2015; Schlegel & Huchzermeyer, 2018). The quality and the quantity of the ecosystem services that the ecological infrastructure provide affect communities’ livelihoods.

In the Tsitsa catchment, most wetlands are highly degraded, and others are vulnerable to further degradation (Schlegel & Huchzermeyer, 2018). The Tsitsa catchment is also prone to the abandonment of cultivated lands for social, economic and climatic reasons (Huchzermeyer et al., 2018b). These abandoned lands are a sediment source, which increases the erosion and sediment discharge into the rivers (Huchzermeyer et al., 2018b). Loads of sediments in rivers will affect the dams' durability and capacity, directly affecting livelihoods.

The extensive land degradation and multipurpose dams (Ntabelenga and the Laleni) in the Tsitsa River proposed by the South African Department of Environment, Forestry and Fisheries (DEFF) have stimulated the Tsitsa Project. This Project focuses on the restoration of degraded areas within the catchment to mitigate the siltation threat to the proposed dams in the area while also improving people’s livelihoods in the catchment (Van der Waal et al., 2017). The dams were proposed by the Department of Water and Sanitation (DWS) as part of the UMzimvubu Water Project to alleviate the severe poverty in the Tsitsa catchment area through job creation and water supply (DWS, 2014b). The Tsitsa Project is a 10-year (2015–2025) project funded by the National Department of Environment, Forestry and Fisheries to repair the catchment by restoring the landscape to prevent silting of planned dams and to ensure the sustainability of ecosystems that improve the livelihoods of the people who live in the catchment (Biggs et al., 2018). The Tsitsa Project collaborates with the Lima Rural Development Foundation to implement sustainable land use management interventions and plans in the catchment. Lima is a non-governmental, non-profit organisation engaged in a broad range of rural and urban development interventions throughout South Africa (Lima, 2017). To link and bridge the gap between the Tsitsa Project team and people living in the catchment, Tsitsa has established Community Liaison Officers (CLOs) whose role is to connect and exchange communication between communities, Lima and the Tsitsa Project.

Although the Tsitsa Project focuses on restoring natural resources within the catchment (Van der Waal et al., 2017), it is important to prioritise natural resources for management and rehabilitation to maintain and mitigate the impacts of drought in the area. There is a need to identify the key EI in the catchment that plays a significant role in increasing water availability, especially because of low precipitation during the dry season. It is also critical to identify current natural resources conditions and prioritise restoration and rehabilitation of degraded key natural resources to improve sustainable livelihoods in the catchment. This study focuses primarily on assessing the state of key targeted EI (wetlands, grasslands, riparian zones and abandoned cultivated lands) and prioritising EI for rehabilitation planning and mitigating the impact of drought to improve livelihoods Tsitsa River catchment.

For prioritisation of suitable EI for restoration, community mapping of the key natural resources using the Participatory Geographic Information System (PGIS) method was conducted in two selected villages in the upper catchment of Tsitsa (T35A) (Figure 1.2). Sigoga and Ntatyaneni villages were chosen because of the strong existing research relationship established by the ongoing catchment rehabilitation-related work under the Tsitsa Project of Rhodes University.

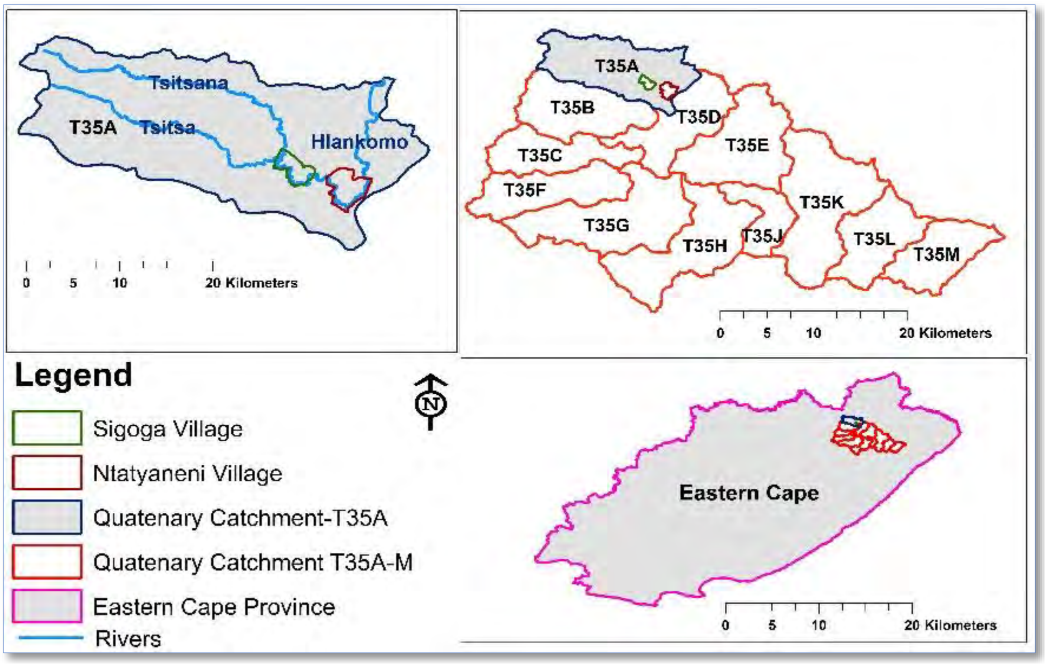


Figure 1.2: Location of Sigoga and Ntatyaneni villages in catchment T35A.

1.5 The key ecological infrastructure categories for assessment

The capacity of catchments to maintain surface water flows is influenced by land cover since land cover plays a significant role in controlling water partitioning in catchments (Le Maitre et al., 2014). The changes in vegetation cover impact hydrological flows in the catchments, influencing the amount of water infiltration, water repellence, baseflow and surface run-off (Le Maitre et al., 1999, 2000, 2014; Rebelo et al., 2015; Mander et al., 2017).

This study focuses on natural occurring EI in natural or semi-natural conditions that need to be managed and EIs that are degraded and need to be rehabilitated to enhance stream flow regulation and mitigate the impacts of drought on communities. The key ecological infrastructure refers to the important feature for delivering water-related services and contribution towards service delivery (Holness et al., 2016). The key ecological infrastructure in this study includes wetlands, grasslands, abandoned cultivated lands and riparian vegetation. The selected key EI categories were selected based on the important ecosystem services they provide to rural communities and their significant influence on streamflow (Kotze, 2013; SANBI, 2014; Alexander et al., 2016; Sigwela et al., 2017). In addition, the key EI were chosen based on their linkage to the South African National Biodiversity (SANBI) framework. The SANBI (2013) framework encourages restoration and maintenance of ecosystems like grasslands, wetlands, natural vegetation in the riparian zones and improvement of landscape management practices to sustain and maintain ecosystem service flows (SANBI, 2014).

Wetlands

Wetlands are transitional areas between terrestrial and aquatic ecosystems, covering various habitats such as freshwater marshes and peatland sand swamps (Belle et al., 2018). They are the smallest existing, highly productive ecosystems that provide important ecosystem services such as provisioning (food, water), regulating (water flow regulation), supporting (nutrients cycling) and cultural services (spiritual enrichment) to local communities (MEA, 2005; McCartney et al., 2010; Belle et al., 2018). In this study, wetlands were selected as key EI because they play an important role in the water cycle, such as maintaining stream flows during the dry season and contributing to groundwater and water purification (McCartney et al., 2010). Wetlands are considered natural hydraulic infrastructure because they play a vital role in protecting and supplying water resources to local communities (McCartney et al., 2010; Alexander & McInnes, 2012). The important ecosystem services provided by wetlands include flood attenuation, trapping sediments, and water purification and erosion control.

Despite the significant role of wetlands in providing valuable ecosystem services, they are degraded due to human activities (Alexander & McInnes, 2012; Rebelo et al., 2015; Pantshwa & Buschke, 2019). In South Africa, wetland ecosystems are the most threatened terrestrial ecosystems (Skowno et al., 2019). Human activities (such as wetland drainage, conversion into cultivated areas, overexploitation of wetland resources, and pollution) can threaten the wetland structure and function (Alexander & McInnes, 2012). These activities affect the natural functioning of wetlands and the flow of ecosystem services. So through rehabilitation and protection of wetlands, which are indicated as an investment approach in the ecological infrastructure SANBI framework (SANBI, 2014), their natural ecosystem functioning can recover (Alexander & McInnes, 2012). In the Tsitsa River catchment, wetlands play a significant role in trapping sediments that threaten the water quality in the area; however, most wetlands in the Tsitsa catchment are highly degraded (Schlegel & Huchzermeyer, 2018). Thus, investing in EI as proposed by the SANBI Framework can contribute to this important ecosystem's protection and rehabilitation.

Grasslands

Grasslands are important ecosystems with valuable biodiversity and diverse ecosystem services that underpin economic growth, social development, and human well-being (SANBI, 2013b). Grasslands play a significant role for people by providing natural resources that support many rural livelihoods, such as rangelands for grazing, which increases livestock production, raw materials for building houses, and cultural practices (Matsika, 2007; SANBI, 2013b; Sigwela et al., 2017). In this study, grasslands were selected because they are critically important for water production in catchments since they play a vital role in regulating streamflow (SANBI, 2013b; UN-Water, 2018). They influence water storage into the sub-surface and discharge into rivers that are vital baseflows during dry seasons, therefore maintaining water quantity (SANBI, 2013b). In addition, grasslands were selected because the study catchment’s land cover is dominated by grassland vegetation (Figure 1.3 &1.4).

Grassland ecosystems are the second-largest biome, covering approximately 30% of the South African land area (SANBI, 2013b). However, about 40% of South Africa’s grassland biomes are permanently modified, with nearly 60% of the areas threatened, putting grasslands biome as the second most threatened biome with less than 3% under formal protection (Matsika, 2007; SANBI, 2013b). The threat to the grassland biome is human-induced through land transformation activities such as agriculture and poor land management (Matsika, 2007; Blignaut et al., 2010; Zaloumis, 2013). The threat to grasslands is also caused by bush encroachment and invasion by exotic woody species.

Grasslands stabilise soils, enhance rainfall infiltration (Blignaut et al., 2010). Hence, the degradation of grasslands contributes to an increase in surface water run-off, which can cause soil erosion and lead to an increase in sediment loads in river systems and reduce infiltration, which reduces baseflow discharge into a stream (Le Maitre et al., 2019). In the study area, grasslands are threatened by the invasion of alien plants, soil erosion, gullies, fire and poor management of grazing (Schlegel & Huchzermeyer, 2018). Therefore, clearing invasive plants and better landscape management practices would significantly impact regulating water flows such as groundwater recharge and discharge into streamflow, particularly during the dry periods (Le Maitre et al., 1999, 2016; SANBI, 2013b).

Riparian zones

Riparian zones are the transition areas between land and river; for this study, riparian zones refer to land areas within the 150 m buffer of the streams in the area (Figure 1.3 & 1.4). The 150 m buffer was chosen to reduce over or under the selection of riparian areas in the catchment, and the 150 m buffer is within the 100 to 500 m range used in the Atlas for Water Production (Nel et al., 2011).

Riparian zones were selected as the key EI category because they play an important role in sustaining base flows in permanent rivers, especially during dry seasons and can maintain flood control function (SANBI, 2013b; Claassen & Hill, 2017). Also, riparian vegetation contributes to maintaining the water quality of the surrounding river systems by retaining sediment load and other run-off pollutants into the riparian areas(Sanz et al., 2017). Moreover, the riparian zones are important biodiversity areas; they provide valuable services such as habitat for many species, fuel, medicinal plants, water filtration and trapping sediments (Salemi et al., 2012).

Infestation of invasive alien plants causes vulnerability to the riparian area (SANBI, 2013b) and threatens the river ecosystems (Van Deventer et al., 2018). So, clearing invasive alien plants in riparian zones is an approach to restoring the ecological function of the riparian zone (SANBI, 2014) and increasing streamflow by reducing evapotranspiration (Salemi et al., 2012) and improving habitat availability and biodiversity.

Abandoned cultivated fields

Abandonment of cultivated fields is the result of the shift in economic (global market growth), social (rural population) and environmental (soil degradation) factors (Blair et al., 2018; Shackleton et al., 2019; Chaudhary et al., 2020). In this study, abandoned cultivated fields' refer to old terraced lands that are no longer ploughed (Huchzermeyer et al., 2018b). These areas have lost vegetation cover transformed by wind and water erosion into bare soils before recovery, increasing erosion and acting as a substantial sediment source (Van der Waal & Rowntree, 2018) and accelerating run-off in catchments (SANBI, 2013a). Also, the slow return of vegetation cover in abandoned cultivated fields causes some changes such as reducing soil erosion, sediment transportation and reducing water run-off at the catchment scale (Benayas et al., 2007).

Abandoned cultivated land also increases the potential for invasive alien plants (Scorer et al., 2019) through the return of vegetation, including non-native plants or exotic plants, which may cause an increase in evapotranspiration, reduce water yield and low flows (Benayas et al., 2007). Investing in EI through clearing invasive plants and better landscape management in the catchments can improve water provision and mitigate drought in catchments. The Tsitsa catchment is prone to the abandonment of cultivated lands, and these fields in the area are degraded due to invasive alien plants, gullies and erosion (Huchzermeyer et al., 2018b). So, abandoned cultivated fields need to be effectively managed to regulate water provisioning and soil erosion. Even though the number of cultivated lands increase in the catchment from 2014-2018 (Figures 1.3 and 1.4), it does not equate to the area of abandoned cultivated lands decreasing. The increase in cultivated lands from 2014 to 2018 is due to more commercial farming in the area rather than subsistence farming. This is particularly the case in the upper parts of the catchment that is mostly dominated by commercial plantations.The increase in commercial areas in the catchment is indicated by increase in plantation or planted forest, especially in the upper areas of the catchment (Van der Waal et al., 2017),which is also reflected in the South African National land cover data set for 2018 (GEOTERRAIMAGE, 2019a).

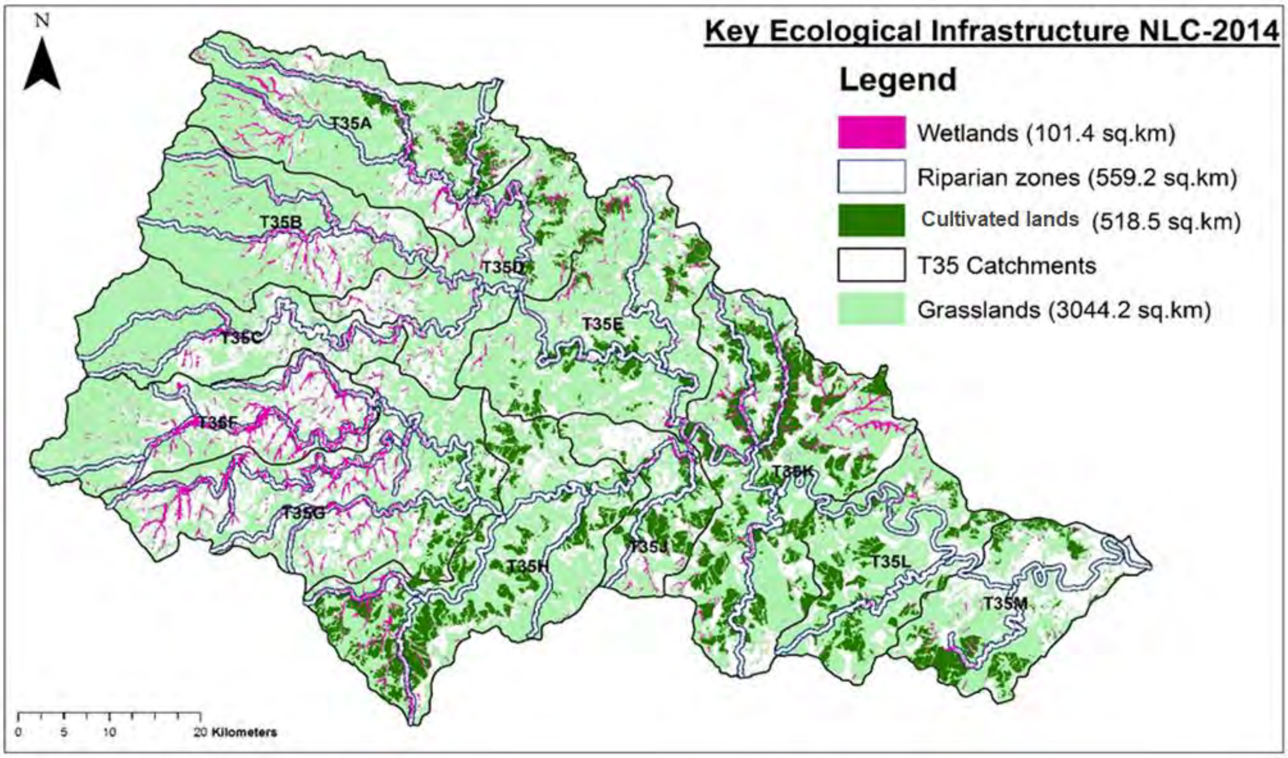


Figure 1.3: The distribution of the key ecological infrastructure using the National Landcover 2013/14

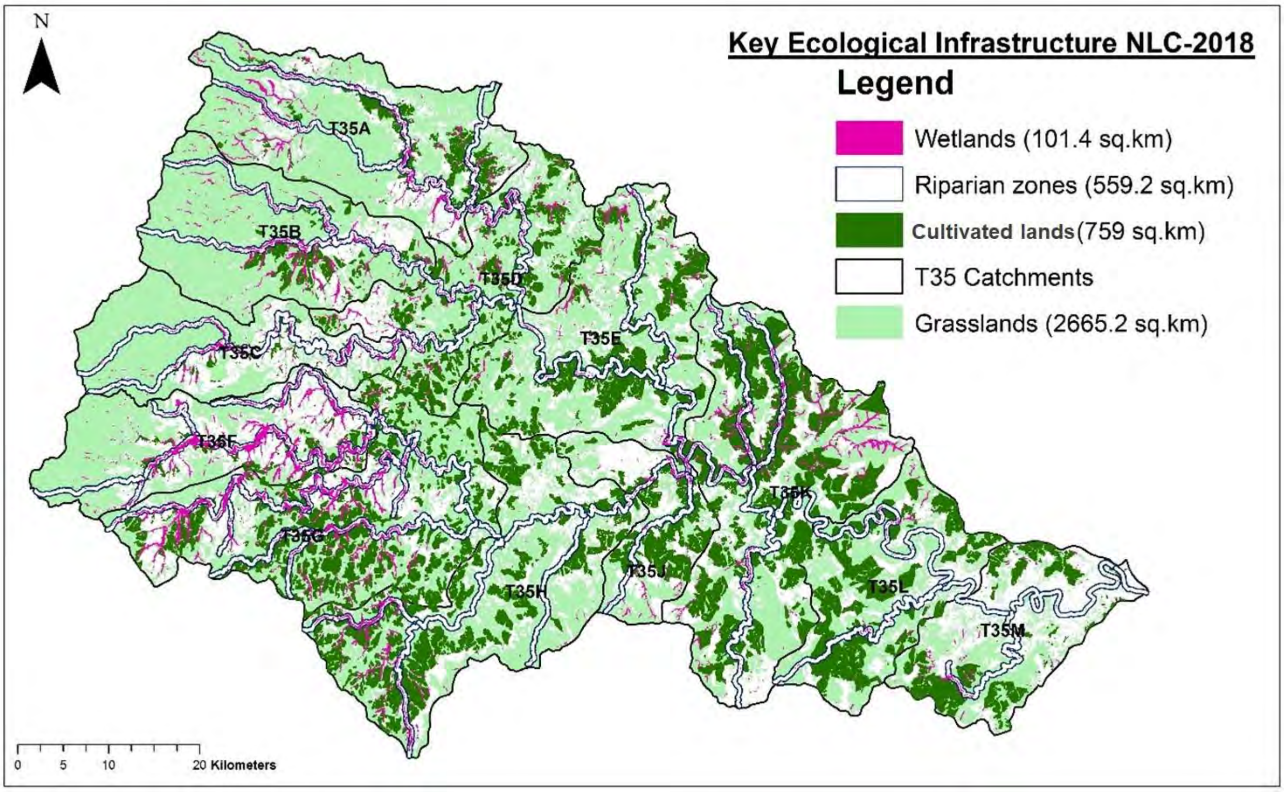


Figure 1.4: The distribution of the key ecological infrastructure using the National Landcover 2018.

1.6 Thesis structure

Chapter 1 provides a general introduction, background, significance, aim and objectives of the study. It also contains the characteristics of the study area and location. The chapter also identifies and describes the key ecological infrastructure areas.

Chapter 2 contains the literature review of the study.

Chapter 3 covers the degradation status in the focal ecological infrastructure and employed analysis methods.

Chapter 4 indicates suitable restoration areas of the catchment's ecological infrastructure, using the Multi-Criteria Decision Analysis.

Chapter 5 provides a synthesis, discussion of the key findings, conclusion, and recommendations.

Chapter 2: Literature review

2.1 Introduction

This chapter provides a literature review of water scarcity globally, focusing on arid to semi-arid areas like South Africa. The chapter describes common drivers and factors such as drought and catchment modification (land degradation) that have worsened water scarcity, especially in dry areas (UNCCD & FAO, 2020). This section also provides a description of drought and land degradation in South Africa and how land degradation and drought influence water flow in catchments. The chapter indicates how the concept of investing in Ecological Infrastructure (EI) is an environmental approach for mitigating water scarcity problems caused by drought and land degradation by indicating how investing in EI can mitigate drought impacts and contribute towards water security, especially during dry periods.

2.2 Water scarcity

Water scarcity is a global threat, particularly in dry parts of the world, such as South Africa (Hedden & Cilliers, 2014; Van Loon et al., 2016). Water scarcity refers to the long-term imbalance between water demand and water supply, where there is less water available than needed, leading to insufficient water supply than required to meet the social, environmental and economic needs (Van Loon et al., 2016). Factors such as unsustainable water use, poor water resource management and infrastructure (leakages in sewer systems, dam siltation), increase in water demand, and climate are some of the causes of water scarcity (Van Loon et al., 2016; Bwapwa, 2018). The increase in abstraction for economic growth (agricultural, industry and mining sectors) will impact water resources (Van Loon et al., 2016; Bwapwa, 2018; Donnenfeld et al., 2018).

The global estimate indicates that 70% of the water withdrawal is allocated for agriculture depending on the region, with 19% for industrial and 11% for municipal use (FAO, 2012), and the global water demand is estimated to increase by 20–30% by 2050 (Burek et al., 2016). The increase in water demand is driven by a combination of population growth, urbanisation, rising incomes, irrigation expansion, non-renewable electricity and growing manufacturing sectors (Donnenfeld et al., 2018).

Burek et al.'s (2016) research projected global hotspots of water scarcity for 2010 and highlighted changes in water scarcity class between 2010 and 2050, based on modelling scenarios (Figure 2.1). With the increase in the population, about 1.9 billion people globally live in potential severe water-scarce areas in the 2010s on an annual basis, and in 2050 the estimated number is about 2.7 to 3.2 billion people in the world (Burek et al., 2016). The predicted future increase in water demand and severe water scarcity by Burek et al. (2016) is similar to findings by (Hedden and Cilliers, 2014; IPCC, 2014; Gosling and Arnell, 2016; Donnenfeld, Crookes and Hedden, 2018). In South Africa, the climate trends from 1960-2010 indicated an annual increase in temperature and reduced rain days, particularly in autumn months (DEA, 2013). Gosling and Arnell (2016) also project an increase in water scarcity due to climate change in the eastern and western parts of South Africa by 2050 using modelling scenarios.

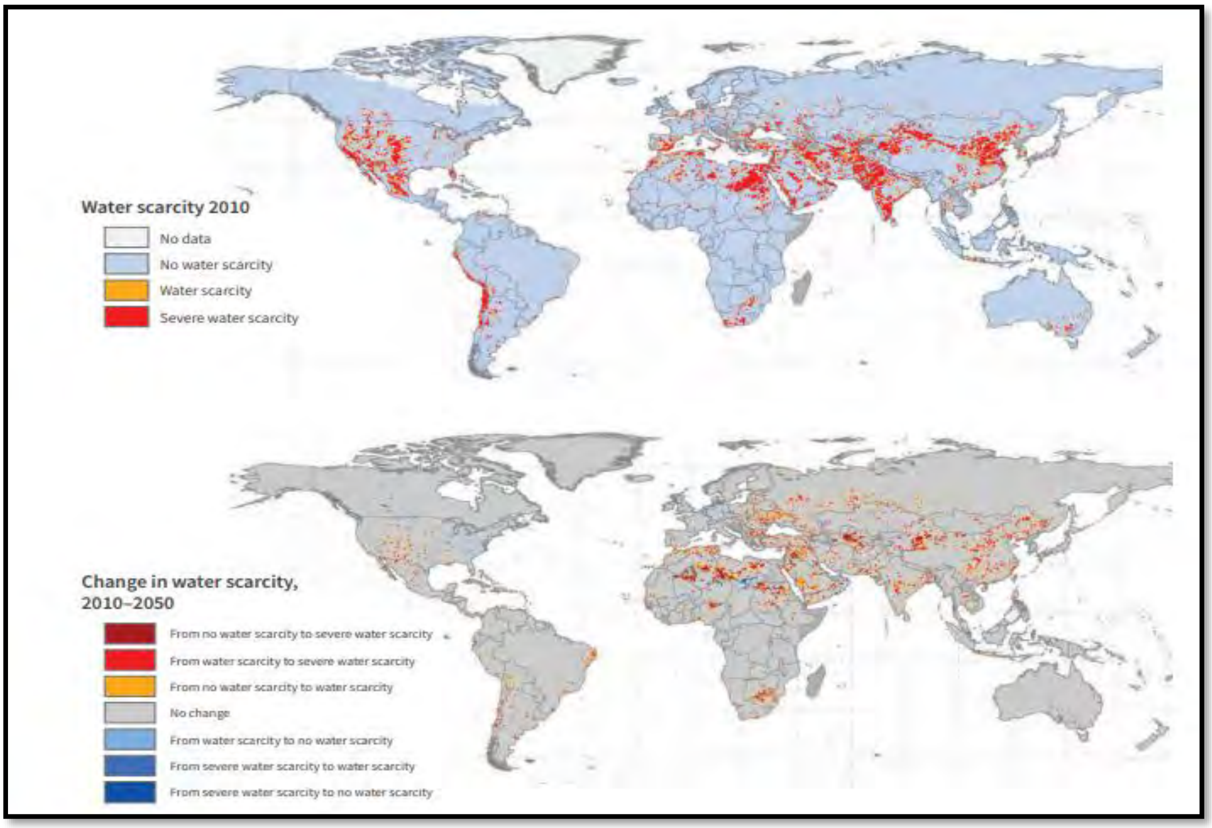


Figure 2.1: World water scarcity in 2010 (top) and 2010–2050 (bottom) [Based on Burek et al., 2016].

South Africa’s water resources are influenced and modified by anthropogenic (i.e. water abstraction) and natural (i.e. rainfall variability) factors, which further worsens the problem of water shortage (DEA, 2012; Bwapwa, 2018). The experience of water shortages in the country varies by socio-economic status groups; for instance, rural poor communities do not have access to potable water and mainly rely on rain and river water supply (DEA, 2014).

Therefore, there is a high potential for experiencing severe impacts of the dry season or drought, so actions are needed to deal with water problems.

The South African government has focused interest at a national scale on water security by developing and implementing the National Water Resource Strategy 2 (NWRS2, 2013). The NWRS2 is the second edition of NWRS that seeks to ensure that national water resources are managed to achieve development and socio-economic growth sustainably. The NWRS designed a plan for water resource management that aligns with the National Development Plan (NDP) targets, especially the target that focuses on improving water resource planning and management (Hedden & Cilliers, 2014). Also, the concept of EI was suggested as one of water resource management strategies (Mander et al., 2017; DEA, 2018); as a result, the South African government has used and invested in the concept of EI through environmental programmes such as the Natural Resource Management (NRM) programmes, for example, the Working for Water Programme. The investment is also indicated by the Strategic Integrated Project (SIP) programme, which was developed to invest in EI to improve the country’s water resources and other environmental goods and services. The SIP invests in EI through conservation, protection, restoration, rehabilitation, and key EI maintenance (DEA, 2014; SANBI, 2014), thereby enhancing water storage in the catchment. The clearing of alien invasive plants that consume large quantities of water compared to indigenous vegetation and revegetation (rehabilitation) of degraded areas in the catchment are examples of EI investment (Dzikiti et al., 2017; Mander et al., 2017).

2.3 Drought

Water scarcity is sometimes worsened and driven by droughts through water reduction, which has an adverse impact on ecological and community water needs (Clarke et al., 2012; Rockström et al., 2014). The aridity caused by drought adversely impacts economic growth, as well as social and ecosystem functioning (Clarke et al., 2012; Botai et al., 2020). Drought is generally defined as a temporal meteorological event caused by below-average precipitation received by an area, combined with high temperatures over a certain period (Eriyagama, Smakhtin and Gamage, 2009; Zhao and Dia, 2015). Drought is a naturally occurring phenomenon that is part of the climate cycle driven by various catchment characteristics (Dai, 2011, 2013), mainly due to decreased precipitation. Precipitation deficit leads to a shortage in surface and subsurface water. However, the intensity and duration of drought also depend on climatic and catchment attributes, such as the biophysical characteristics, which impact water storage (Dai, 2011, 2013; Van Loon et al., 2016). For instance, the reduction in precipitation and increase in evapotranspiration can cause a reduction in surface and subsurface water and catchment land-use changes can impact the area's ecosystem function, causing hydrological changes (McDowell et al., 2013; Le Maitre et al., 2014; Münch et al., 2017).

South Africa is a semi-arid region with an average rainfall of 450 mm, that is below the world average rainfall of 990 mm (Calow et al., 1997; Department of Environmental Affairs, 2017). Semi-arid environments such as South Africa are more likely to experience climate-driven water scarcity (Eriyagama et al., 2009), so drought is expected to be more frequent and intense in the future because of climate change, resulting from increased temperatures and erratic rainfall patterns (DEA, 2017). Over the past three decades, the country has suffered three major droughts: 1991-1992, 2002-2003, 2015, 2018 to currently (DEA, 2017; Botai et al., 2019).

The increase in demand for and exploitation of water resources and climate change can exacerbate drought severity, thereby intensifying water security concerns. A study by Botai et al. (2019), who used the Standardised Precipitation Index (SPI) and Standardized Streamflow Index (SSI) to assess the propagation patterns of drought characteristics in the South African water cycle, demonstrated that all the South African water management areas experience drought, affecting the country's water storage and increase the intensity and impact of drought. The study also indicated that droughts in South Africa are commonly characterised by climate and catchment characteristics (Botai et al., 2019). Therefore, it is important to understand the catchment characteristics and how they can impact droughts.

Drought and climate change can alter the water cycle components depending on the duration and severity of drought (Eriyagama et al., 2009). Increasing the strain on water resources, affecting water-related ecosystem services such as water quality and streamflow regulation (Hughes et al., 2018). For example, low precipitation and high temperatures cause high evaporation rates, which will affect processes like water recharge, soil moisture, water storage, and streamflow. Thus, water shortage may negatively impact livelihoods, biodiversity and vital ecosystem services and functions (Zhao & Dia, 2015).

Drought as a natural disaster can cause a reduction in available water resources leading to water insecurity, which can negatively impact agricultural productivity (both commercial and subsistence farms), resulting in food insecurity which can significantly threaten the livelihood of many South Africans (Clarke et al., 2012). As a result, many people in the country have suffered from the consequences of drought, particularly in poor and vulnerable communities, mainly in the country's rural areas (DEA, 2014). Rural communities are most affected by drought impacts due to reduced land productivity. The effects of drought in rural areas worsen the rural communities livelihoods, which already suffer from socio-economic factors like poverty, poor infrastructure, and high unemployment rates (Wang et al., 2016).

Since drought is not an unusual event in South Africa (DEA, 2012), it can occur throughout the year, and severe droughts associated with adverse socio-economic impacts have occurred across the Eastern Cape Province in recent years (2015-2016) (Graw et al., 2017), causing issues of water shortage and food insecurity (Botai et al., 2020). The Eastern Cape Province receives variable rainfall across the province, with annual rainfall ranging from 100-520 mm per annum (Botai et al., 2020). Consequently, the south and south-eastern parts of the Eastern Cape are prone to prolonged and frequent drought episodes (Botai et al., 2020). Thus, drought affects land productivity, reduction in grazing capacity, livestock, and the loss of other valuable natural resources that most rural communities in the area highly depended on for their livelihood. The study area within the Eastern Cape Province has experienced drought in 2015-2016, associated with delayed wet seasons (Van der Waal et al., 2017). Results of drought-affected planting season and crop growth and food production can lead to adverse impacts on rural communities livelihood (Van der Waal et al., 2017), and these impacts are expected to be more severe when the land is degraded. The impacts of drought are serious problems that need to be addressed because it is estimated that about 46 million South African lives in rural areas and are highly dependent on natural resources for livelihood (DEA, 2012).

2.4 Land Degradation

There is no standardised definition of land degradation, and it is defined differently based on the context and interest in which the term is used (de Jong et al., 2011; Dubovyk, 2017). The relevant definitions of land degradation in the South African context are from the Millennium Ecosystem Assessment, which defines land degradation as the reduction in the capacity of the land to function and produce ecosystem goods and services that support society (MEA, 2005). The South African Department of Environmental Affairs and Tourism (2004) refers to land degradation as reducing biological or economic productivity of agricultural lands, forests, and woodlands due to human impacts (Department of Environmental Affairs and Tourism, 2004).

South Africa has a long history of research dealing with land degradation (Hoffman and Todd, 2000b; DEA, 2012), with studies starting in the early 1920s (DEA, 2012). The South African government has taken measures to respond to land degradation, following global, national, and local programmes. Firstly, In 1995, South Africa participated in the United Nations Convention to Combat Desertification (UNCCD), intended to address poverty in the arid, semi-arid, and dry sub-humid parts of the world (DEA, 2012). Secondly, the country produced the National Action Programme (Hoffman & Todd, 2000a; Department of Environmental Affairs and Tourism, 2004), which combats land degradation to reduce poverty in rural areas. In addition, the country has also committed to provide reports on the environmental conditions in terms of soil and vegetation and to review the 'country's land degradation database' (Hoffman & Todd, 2000a). Thirdly, South Africa has agreed to be a part of the Sub-Regional Action Programme to combat desertification, which provides a collective response to land degradation problems within Southern Africa (DEA, 2012). Within the country, several programmes (the Comprehensive Agricultural Support Programme, the Integrated Sustainable Rural Development Programme (ISRDP) and Land Care) have been implemented to deal with the issue of land degradation (DEA, 2012).

2.4.1 Assessment of land degradation in South Africa

A national review of land degradation in South Africa was conducted by Hoffman and Todd (2000) and was based on assessing soil and vegetation degradation in the 367 magisterial districts of South Africa between 1997 and 1998, using a series of participatory workshops. The national review was built on the perceptions of agricultural officers and resource conservation technicians from the Department of Agriculture members present in the workshop. The study on the nature and extent of land degradation in South Africa (Hoffman and Todd, 2000) produced results based on assessing the potential impact of various factors on land degradation used.

The severely degraded areas were found in six provinces, with KwaZulu Natal, the Eastern Cape, Limpopo, and North-West Province perceived as having severe degraded communal land, and the Northern Cape and Western Cape Province emerging as severely degraded (Hoffman & Todd, 2000a). The study by Meadows and Hoffman (2003) compared the predicted monthly precipitation data from Hewitson's (1999) study to simulate rainfall change scenarios and investigated how these precipitation changes could impact future South African land degradation changes. The study indicated that areas identified in the national review as severely degraded are likely to experience further degradation under predicted climate change. The communal and some commercially farmed areas are more likely to be further degraded under predicted climate change scenarios (Meadows & Hoffman, 2003). The probability of degradation in the former rural homelands of South Africa was also identified in a study by Bai et al. (2008), who assessed the decline in ecosystem function and land productivity using a satellite-based normalised difference vegetation index product. The results indicated a decline in rain-use efficiency-adjusted NDVI and indicated about 24% of the global degradation shown by the decline in net primary productivity.

Almost ten years later, the national land degradation survey in South Africa was conducted in 2008 by the Department of Agriculture. The assessment of land degradation was based on the Land Degradation Assessment in Drylands (LADA) project (Department of Agriculture, 2009), and it aimed to provide a progress report on the country's distribution and characteristics (extent, status, causes and impacts) of land degradation (Department of Agriculture, 2009). A recent review on South Africa's land degradation was conducted by Von Maltitz et al. (2019). The study provided a critical review of the country's land degradation experience, using different perceptions of land degradation (Von Maltitz et al., 2019) and the results of progress towards land degradation neutrality in South Africa. The study points out the constraints of using global indicators in reporting land degradation neutrality and recommends developing a local monitoring tool that fits the South African context for better monitoring and setting up targets of the country's land degradation neutrality. In addition, Von Maltitz et al. (2019) suggested an assessment of land degradation in South Africa at a biome scale for a better understanding and monitoring of land degradation in the country. The described above studies indicate the degradation state in the country. However, land degradation is a complex phenomenon that establishes at different spatial and temporal scales and ecosystem types, with different local and specific problems that underpin land degradation (Dubovyk, 2017).

2.4.2 The assessment of common drivers of land degradation

Assessment of land degradation includes measuring the biophysical indicators (land use or land cover change, land productivity, changes in soil) and biodiversity (Orr et al., 2017). In South Africa, land degradation is commonly assessed by identifying and assessing its causes (Pelser & Khorehloa, 2000; DEA, 2012; Blair et al., 2018). These causes include alien plant invasion, wood encroachment, overgrazing (DEA, 2012), cropland abandonment and soil degradation (Dlamini et al., 2014; Von Maltitz et al., 2019).

Land degradation of grasslands is caused by different factors, with various consequences, depending on the area's specific context (SANBI, 2013b). The common factors of land degradation include climatic variation and human-induced degradation (Dubovyk, 2017; Liniger et al., 2019). Extreme climate events such as drought or flooding are the drivers of land degradation (DEA, 2012; Dubovyk, 2017). The dominant human-driven factors of land degradation in grasslands are commonly caused by poor land management practices such as incorrect application of fire, poor management of grazing, and overuse of grassland resources, the transition of grassland areas into cultivated or artificial land areas, causing soil erosion (DEA, 2012; SANBI, 2013b; Von Maltitz et al., 2019). Additionally, invasive alien plants and woody encroachment contribute to land degradation in grassland areas (DEA, 2012; SANBI, 2013b).

Land degradation can be assessed qualitatively or quantitatively based on the drivers of land degradation using different methods at different spatial and temporal scales, depending on the study's aims and objectives (Bai et al., 2008; de Jong et al., 2011; Dubovyk, 2017). The common methods used for assessing land degradation include the use of experts knowledge assessment, field measurements, Geographic Information System (GIS), remote sensing and modelling approaches used at local, national and international scale (Department of Agriculture, 2009; de Jong et al., 2011; Dubovyk, 2017). Several studies have been conducted to assess degradation in grasslands based on the drivers or cause of degradation and the extent and impacts of grassland degradation (Shackleton and Gambiza, 2008; Rowntree et al., 2004; Thompson et al., 2008). The common assessed drivers of land degradation in grasslands include invasive alien plants, bush encroachment, abandoned cultivated fields and other drivers.

Alien plant invasion, one of South Africa's most critical environmental issues (Richardson & Van Wilgen, 2004), is an important contributor to land degradation through the loss of grassland vegetation, leading to decrease land productivity and water resources (DEA, 2012). The impact of invasive plants on the landscape is highlighted by several studies conducted in the country assessing the impact of alien plants in the environment. Richardson and Van Wilgen (2004) conducted a national review of the impact of alien invasive plants in natural ecosystems, which highlighted how a reduction in native species density and diversity causes changes in soil characteristics (e.g., nutrient reduction) and changes in water flows (reduced streamflow). Alien plants have significant impacts on the surface water resources of South Africa and groundwater (Le Maitre et al., 2000), as shown by studies, such as Le Maitre et al. (2000) assessment on the impact of alien plants on water use of surface water resources of South Africa. The study estimated approximately 3300 cubic meters per year of water use by alien invasive in South Africa, with a possibility of a significant increase in water use causing more water loss in certain catchments (Le Maitre et al., 2000). Alien plants affect water quality by increased evaporation rates, reduced streamflow as water use by plants increases, and reduced dilution capacity, which results in poor water quality (Chamier et al., 2012). Invasive alien plants are among the most critical environmental issues, and they contribute the most to vegetation degradation and reduction in land productivity (DEA, 2012).

Abandoned cultivated lands have been identified as causes of land degradation. South Africa has a long history of the abandonment of cultivated land due to socio-economic shifts, demonstrated by several research studies (Vogels et al., 2017; Blair et al., 2018; Shackleton et al., 2019). The social-economic shift post-1994 includes freedom of movement, meaning people were allowed to move to other places causing rural migration, which can lead to a shortage of rural labour, which can help lead to the abandonment of cultivated areas (FAO, 2016; Van der Waal et al., 2017). Theft of livestock and materials are a major problem in communal and commercial areas, which is also the cause of cropland abandonment. Also, cropland abandonment can be caused by financial constraints for farming. Climate change and climate variabilities such as rainfall variability, droughts and floods can also cause abandonment of croplands and lead to degradation (FAO, 2016; Blair et al., 2018).

The abandonment of cropland disturbs the provisioning of ecosystem services, hydrological regime, soil fertility and ecosystem biodiversity of an area (Blair et al., 2018). Abandoned cultivated landscapes are commonly linked with bush encroachment, as the land turns into bush, increasing woody vegetation cover at the expense of grass cover (Blair et al., 2018). Also, abandoned cultivated areas are vulnerable to invasive alien plants contributing to land degradation due to changes in habitats and ecosystem functioning (DEA, 2012; Scorer et al., 2019).

Bush encroachment is also the cause of land degradation, and it is defined as "the process whereby the cover of indigenous woody plants increases in a grassy ecosystem savanna or grassland" (Turpie et al., 2019). Overgrazing decreases herbaceous plants leading to reduction in grassland production which can result in increased tree recruitment and bush encroachment (SANBI, 2013b; Mpati, 2015). The increase of woody vegetation in the natural grassland area is seen as a problem because of the loss of ecosystem services provided by natural grassy ecosystems (trapping sediments, native species, rangelands) (Hoffman, 2014). Stafford et al. (2017) conducted a study to assess the extent of bush encroachment in South Africa using the South African National land cover data for the year 2010 and estimated that about 6.5% of the land area is South Africa (especially the North West, Mpumalanga, northern parts of KwaZulu Natal and Eastern Cape province) is encroached (Stafford et al., 2017).

The impacts of land degradation and drought are often pronounced for rural communities since they primarily depend on natural resources for their socio-economic well-being (Shackleton et al., 2007; Sigwela et al., 2017). Therefore, there is a need for effective solutions which deal with the impacts of land degradation and drought to maintain the ecosystem function and provisioning of ecosystem goods and services.

Nevertheless, there is wide evidence indicating the recognition of the issues of ecosystem degradation in the country. The recognition has been shown by increasing interest and effort in restoring and managing drainage basin (Shackleton et al., 2017). There is an increase in recognition of the importance of the natural ecosystem that supports biodiversity and provides services to people to improve and reduce poverty while increasing development (Shackleton et al., 2017).

2.5 Nature-based solution

Water shortages have a significant impact on ecosystems, people's livelihoods, and the socio-economic development of a country. The effects of drought in the environment are accelerated by human activities, such as water overuse and increased water demand as populations expand (Rey et al., 2017). Ecosystem degradation also accelerates the impacts of drought and water shortages, causing a change in water resources strategies (UN-Water, 2018). There is a need for effective measures of dealing with drought to reduce, mitigate and prepare for future drought-related impacts (Botai et al., 2020). However, there is growing interest in an effort directed towards water security and ecosystem management, including the concept of Nature-based Solutions (NBS). The nature-based solution focuses on sustainable management and restoration of modified ecosystems, which also deals with social-environmental challenges (UN-Water, 2018). The NBS aims at dealing with issues like land degradation, water scarcity, and sustainable resource management; the NBS for water is a natural process that contributes to improving water management using ecosystem services (UN-Water, 2018). The NBS is an integrated water resource management strategy for mitigating drought and land degradation by improving ecosystem services (UNCCD, 2016). In addition, the NBS is conceptualised to alleviating social-ecological challenges like climate change, food security or address natural disasters.

The NBS for water involves the conservation of natural resources and rehabilitation of modified ecosystems, and it uses nature-based actions to achieve water security while contributing to the concept of SDGs (UN-Water, 2018). The NBS for water is directly linked to the Sustainable Development Goals (SDG), particular the SDG6 (ensure availability and support the achievement of water and sanitation for all) (United Nations, 2015) and contributes towards sustainable management of terrestrial ecosystems for the SDG15 (Stavi & Lal, 2015). The SDG6, particularly target 6.6, aims to protect and restore water-related ecosystems, such as mountains, forests, wetlands, and rivers; this also relates to the concept of Ecological Infrastructure (EI). Ecological Infrastructure includes healthy mountain catchments, rivers, wetlands, streams, estuaries and dunes (DEA, 2014; SANBI, 2014). The Ecological Infrastructure for water security aims to improve water resources and other environmental goods and services through the conservation, protection, rehabilitation and maintenance of the ecological Infrastructure that underpins water-related ecosystem service (DEA, 2014; UN-Water, 2018).

2.6 The concept of ecological Infrastructure

In 1984 during the Man and Biosphere Programme (MAB) (UNESCO, 1984) about urban planning, scientists from different countries proposed the term “ecological infrastructure” (EI). In the MAB meeting, EI referred to the natural landscape and natural areas and defined ecologically sustainable growth that supports civilisation (Da Silva & Wheeler, 2017; Hengl et al., 2017). Since ecosystems provide goods and services to humanity, it was proposed that these systems be regarded as a type of Infrastructure as they perform the same roles as any other infrastructure (Da Silva & Wheeler, 2017). The concept of EI arose to support the well-studied concept of ecosystem provisioning or the benefits of ecosystem services to people and the environment (Cumming et al., 2017).

The term Ecological Infrastructure (EI) is described as naturally functioning ecosystems that generate, produce and deliver significant services to people (De Klerk, 2016; SANBI, 2013). The concept of EI is very similar to the term Green Infrastructure (GI), which refers to “naturally functioning ecosystems and cultural landscapes that deliver valuable services to people” (Shackleton et al., 2017). Both GI and EI solutions work with the energy present in the environment rather than against it (using the ecosystem-based approach for water security) (UN-Water, 2018). The term “Green Infrastructure” is broadly used, and in some cases, it includes the built Infrastructure (SANBI, 2014), whereas EI separates natural ecosystems from other “green infrastructure” (Cumming et al., 2017).

The term ‘ecological infrastructure’ is variously defined in the literature because EI is defined based on the context of using the term (Da Silva and Wheeler, 2017); thus, the concept of ecological Infrastructure has been understood differently. For example, it has been described in relation to the context, discipline or goal in which it is applied (e.g., green or blue Infrastructure, which incorporates both natural and engineered infrastructure) (O’Farrell et al., 2019; Pasquini & Enqvist, 2019). The DEA (2014) defines EI as the network of natural functioning lands and other spaces that are the foundation of growth for life-supporting and enhancing ecosystem services that people depend on for survival. Ecological Infrastructure also refers to “naturally functioning ecosystems that deliver valuable services to people, such as freshwater, climate regulation, soil formation and disaster risk reduction" (DEA, 2014; SANBI, 2014).

Within the South African context, ecological Infrastructure is defined by the South African National Biodiversity Institute (SANBI) (2014) as natural functioning ecosystems that provides valuable ecosystem services to people, which include healthy mountain catchments, wetlands, rivers and coastal dunes and nodes(SANBI, 2014). Therefore, EI can be natural land cover types that provide different valuable ecosystem services (Cohen-Shacham et al., 2016; Shackleton et al., 2017). The SANBI concept of investing in EI is a strategy for accumulating various benefits to society, including water and food security. Such investment can be in the form of maintaining the natural functioning of natural resources and the restoration and rehabilitation of degraded natural areas.

2.7 SANBI framework on ecological infrastructure

To ensure the well-being of the future generation, investment in Infrastructure is necessary (SANBI, 2014). The SANBI framework of investing in ecological Infrastructure through ecosystem management supports the concept of nature-based solutions. The SANBI framework promotes using a range of approaches for investing in EI, including clearing invasive alien plants from the catchment and riparian zones, restoring natural vegetation along with riparian areas, rehabilitating wetlands and improving the use of rangeland. Removing alien invasive plants is important for investing in ecological Infrastructure, especially removing invasive alien plants in the mountain and riparian areas will improve downstream water quality and quantity (SANBI, 2014; UN-Water, 2018). Water quality improves when the establishment of natural vegetation can reduce runoff and soil erosion in the mountainous areas, and filtration of sediments by riparian zone improves stream water flow (DEA, 2014; UN-Water, 2018). Invasive alien plants such as wattle and gum trees are estimated to remove about 7% of South Africa's total annual runoff (SANBI, 2014). Therefore, clearing these invasive trees will increase catchment water runoff and have the potential to increase stream flows during dry periods (SANBI, 2014). Wetlands play a crucial role in delivering different ecosystem services such as water purification, flood regulation and drought mitigation, but more than 60% of the South Africa wetlands are identified as threatened (DEA, 2014). Therefore, rehabilitation of wetlands will improve water quality through filtration, increase water yield, maintain surface water flows during the dry season by storing water during wet periods (DEA, 2014; SANBI, 2014; UN-Water, 2018). These approaches promote the catchment’s health to enhance water-related ecosystem services, increase water storage and water yield in the catchment, and mitigate drought impacts.

The SANBI concept of investing in EI was established to emphasise the significance of maintaining and restoring natural ecosystems and focuses on social, environmental, and economic benefits provided by natural resources. The SANBI (2014) framework of investing in EI is linked to the South African National Development plan for 2030, particularly Action 7 focusing on the investment in infrastructure for water that considers disaster risk reduction and protection of freshwater ecosystem and Action 8 that covers the maintenance and restoration for ensuring environmental sustainability and resilience to future changes (Cumming et al., 2017). The SANBI framework is also related to the NBS framework because EI is an application of NBS, namely for water security. The SANBI framework is mostly related to climate impact reduction and improving water security in the South African context. For this reason, the framework relates to water security and is employed as the theoretical base of this study. The present study focuses on investing in existing natural resources (EI) such as wetlands, grassland, cultivated areas and riparian vegetation, and for this research, the term EI is defined as functioning ecosystems that produce and deliver valuable services to people. Natural functioning resources include mountain catchments, rivers, wetlands, and interconnected structural elements in the landscape and seascape (SANBI, 2014). In this study, the term “ecological infrastructure” is centered on the conservation, restoration, management and investment in natural functioning systems (SANBI, 2014).

2.7.1 Investing in ecological infrastructure in South Africa

There is a growing global recognition of EI's role in improving, sustaining, and supporting built Infrastructure (UN-Water, 2018). In South Africa, there is an increasing need to understand EI’s role and investment towards building infrastructure that supports the country’s growth and development (SANBI, 2014). There is also an emerging interest in EI investment in the country, as indicated by several programmes and research projects related to maintaining and restoring ecosystems to provide the ecosystem services that support the country’s socio-economic development (SANBI, 2014). These programmes are the natural resource management through the “Working For …” programmes and include Working for Wetlands, Working for Land, Working for Water, Working for Fire, which are aimed at restoring ecosystems functioning and providing ecosystem services (DEA, 2014).

Ecological infrastructure investment may include rehabilitation of degraded places or protecting EI from the increasing pressure of ecosystem service needs and land-use changes. Investing in EI through rehabilitation, maintenance and enhancement of existing infrastructures provides benefits to society, the economy and the environment (SANBI, 2013b, 2014). EI supports rural development and supports people's livelihoods in rural areas through jobs generated during restoration (SANBI, 2013a). For example, communities receive jobs and training during the wetland rehabilitation or restoration process, contributing to their income and skills.

A functioning EI provides ecosystem services that contribute to poverty alleviation, health, and well-being. Investing in EI should reduce, mitigate, and prevent risks, such as water crises and disasters (SANBI, 2014). For example, a catchment in a good ecological state can significantly impact reducing flood damage through increased infiltration by vegetation cover and reduced surface runoff. There are many benefits associated with EI and investing in EI, but the degradation of natural resources reduces them. Environmental infrastructure needs to be maintained and managed, and in some cases, restored (SANBI, 2014).

Ecological Infrastructure plays a significant role in ecosystem services. These ecosystem services include provisioning services (food, medicine), regulating services (erosion control and flood prevention), cultural services (spiritual and recreational) and supporting services (nutrient cycling and soil formation) (MEA, 2005; TEEB, 2010; SANBI, 2014; Da Silva & Wheeler, 2017). The ecosystem services listed above can be strengthened and obtained through investing in EI, as indicated by Figure 2.2, which illustrates the benefits of investing in EI. The ecosystem services listed above fulfil human livelihood needs, especially for rural people who mainly depend on these ecosystem services for their survival. Because most rural communities are often located in remote areas, ecological Infrastructure frequently substitutes built Infrastructure to support local livelihoods (Schlegel & Huchzermeyer, 2018). Therefore, a clear need to invest in ecological infrastructure to sustain the flow of ecosystem services.

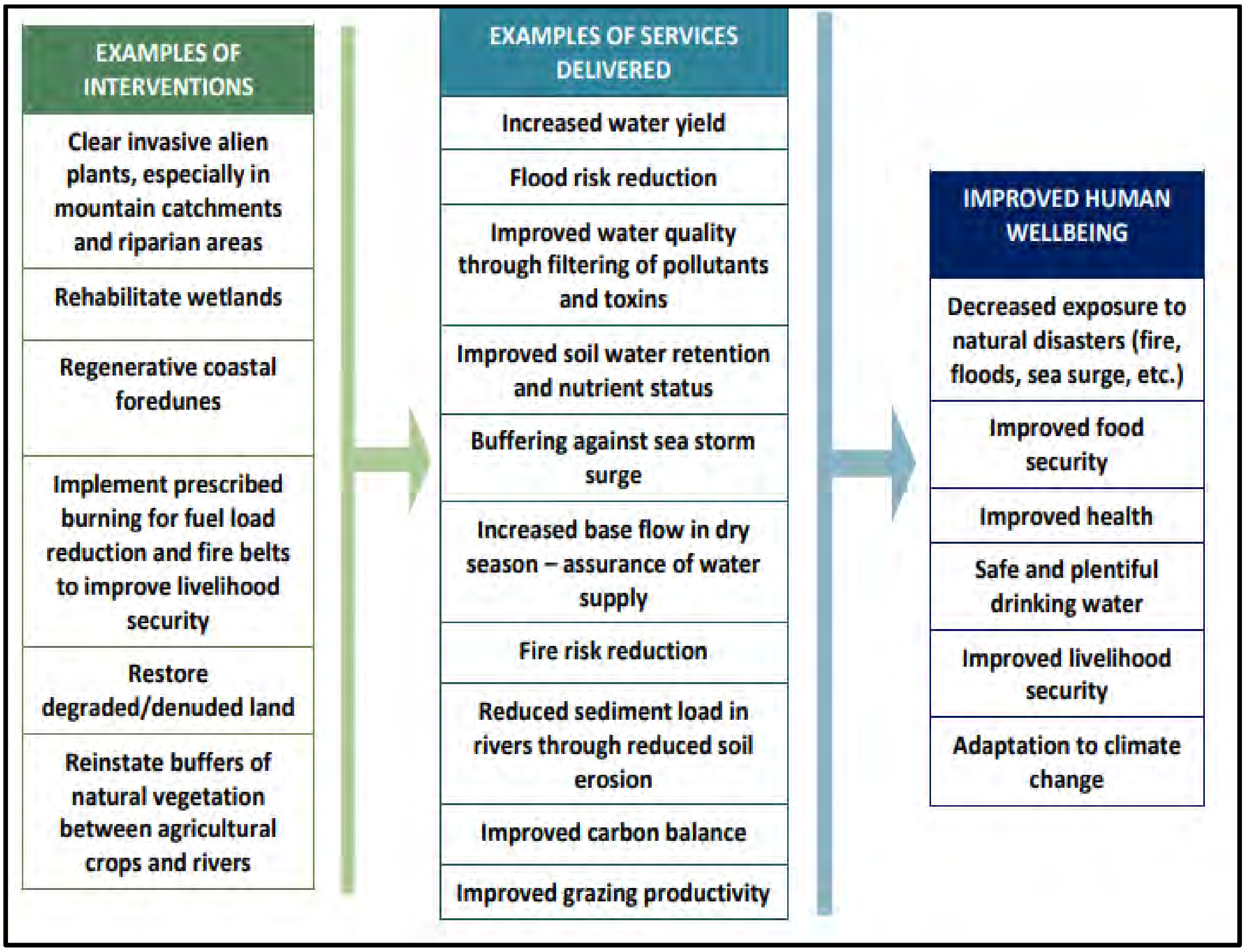


Figure 2.2: Examples of the benefit (goods and services) delivered to society from applying different approaches for investing in ecological Infrastructure (SANBI, 2014).

Management of EI, such as riparian plants, wetland, grassland, natural forest, and crops, can enhance water quality and quantity while improving other ecosystem services. Also, natural resources (grassland, wetland, native plants, and soils) provide water-related ecosystem services. For example, plant roots generally enhance the soil structure, water or water storage availability, and water infiltration. So, EI plays an important role in regulating hydrological flows (UN-Water, 2018). Rehabilitation of landscape effectively improves water quality and quantity, providing different benefits for both humans and the environment while improving environmental or land resilience, sustainability, and productivity of an area (UN-Water, 2018). However, the resilience of a system to respond to stresses and return to the original state after experiencing stress depends on robust structural and functional elements, which can help catchment resilience, particularly during drought and flood events (Sanz et al., 2017).

Thus, the management of EI can be an effective way of improving water supply and water quality. Understanding the connection between vegetation degradation or change in land cover and the hydrological process under drought conditions can be a lens to quantifying the impacts of drought and human activities on watershed ecosystems. Determining the importance and impact of land use and cover on streamflow can help develop sustainable water resource management strategies.

2.7.2 Investing in ecological infrastructure for water security

Climate factors, environmental characteristics of an area, land use or land cover changes, and other anthropogenic activities affect the quantity and quality of water on land (Kaushal et al., 2017). These factors change the hydrology and water movement through the ecosystem and water storage. For instance, clearing vegetation can decrease water storage and water retention. Also, factors like the geological setting, influence water movement, infiltration rates have a strong impact on water availability and water quality. Consequently, the South African freshwater resources are deteriorating in terms of water quality and quantity due to anthropogenic (land-use changes) impacts and climate events (drought and floods)(Van Deventer et al., 2018). Commonly poor land management (which can result in overgrazing and land cover changes) leads to the degradation of natural ecosystems in catchments (Li et al., 2017). The catchment land cover influences rainfall partitioning into the surface and subsurface water (Le Maitre et al., 2014). Appropriate catchment management practices can be used to mitigate droughts and floods by enhancing catchment storage (Van Loon & Laaha, 2015). Since land cover influences the capacity of a catchment to sustain water flows through impact on infiltration.

Degradation of the ecosystem and vegetation cover influences hydrological processes such as interception, infiltration, evapotranspiration, and runoff generation. Vegetation cover plays a significant role in the terrestrial water cycle by influencing the amount of water absorbed per area. A decline in vegetation cover increases surface runoff, either negatively or positively, depending on the land cover dynamics (Kaushal et al., 2017). These factors have contributed to a global water crisis linked to the resiliency of catchment water to climate change (Kaushal et al., 2017).

Le Maitre, Kotzee and O’Farrell (2014) demonstrated how a degraded catchment could change the water cycle process within an area compared to a well-managed (near-natural) catchment. The study showed how a well-managed and landscape degraded by land use and land cover change could impact flow regulation within the catchment. Even if the two catchments receive the same amount of rain, the hydrological processes can differ (Le Maitre et al., 2014). When land is degraded, the vegetation and soil characteristics are disrupted. The natural function (flow regulation) of the landscape is interrupted, causing less infiltration, percolation, interflow, and water retention; consequently, surface water runoff, quick-flow and soil evaporation increase (Figure 2.3). The changes in streamflow due to land cover changes and land use have significant implications for vulnerability in the surrounding communities (Le Maitre et al., 2014), and especially in rural areas.

The study by Mander et al. (2017) provides evidence of the benefits of investing in EI and how such investment can facilitate drought resilience and improve ecosystem services. The study results from two catchments (Umngeni and Baviaanskloof) indicated that if the EI in the catchment could be rehabilitated, maintained, and protected, the baseflow could increase by 1.6 million m^3 per year and streamflow by 7 million m^3 per year at the Umngeni catchment. In the Baviaanskloof, the results showed that the base flow could increase to 42 million m^3 per year, with a streamflow increase of 11 million m^3 per year. These results illustrate that investment in EI provides significant gains in terms of ecological benefits and highlights that EI investments can maximise water supply and water quality and reduce the pressure of water shortages during dry seasons or drought.

Therefore, "Investment in ecological Infrastructure should be considered a fundamental component of societal responses to drought" (Mander et al., 2017) in areas like South Africa to sustain provisioning and availability of water in catchments. Such investments are needed to increase human well-being, which results from a positive interaction of humans, nature and society (Anderson et al., 2017). Since management of natural resources generally improves ecosystem function and process, improving water-related ecosystem services, which enhances ecosystem services to people, provides better survival opportunities to communities that largely depend on natural resources for their daily needs. In addition, investment in ecological Infrastructure will enable South Africa to be more resilient to the increasing predicted drought intensity while meeting the country's water needs for people and the economy (Vinet & Zhedanov, 2010: 2).

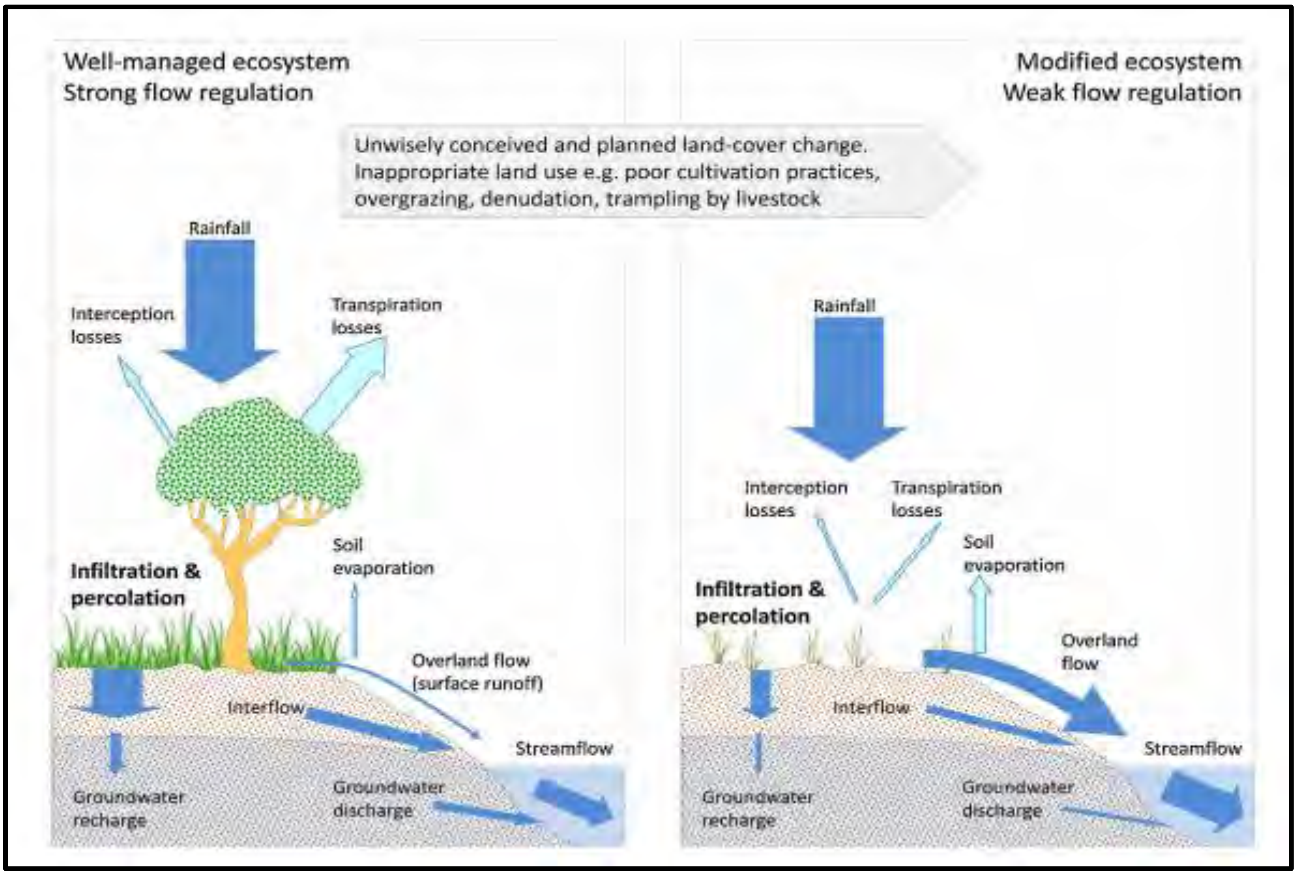


Figure 2.3: Elements of the flow regulation service, processes that link them and effects of the land cover change and unsustainable land use in a natural or well-managed landscape compared to degraded, modified landscape sourced from (Le Maitre et al., 2014: 33).

Chapter 3: Assessment of land degradation status in the Tsitsa catchment

3.1 Introduction

Land degradation is one of the major environmental concerns worldwide (Wunder et al., 2018) because it threatens the future sustainability of life on Earth, with the potential of severe impact on food security, livelihoods, climate change, biodiversity, and ecosystem services (IUCN, 2015). The phenomenon of land degradation is complex, driven by many factors, with consequences that differ depending on the scale, space, and context of an area, causing assessment of degradation to be an intricate task (Initiative ELD & UNEP, 2015). As a result, land degradation is mainly evaluated by assessing the drivers or causes of land degradation (Initiative ELD & UNEP, 2015). The drivers and processes of land degradation are assessed based on the influence of degradation on soil, vegetation, biodiversity, and water resources (Pelser & Khorehloa, 2000; DEA, 2012). These drivers and processes are influenced by climate variability, climate change (Initiative ELD & UNEP, 2015), and human drivers, such as land-use practices (deforestation, poor management of grazing, poor agricultural management) (Department of Agriculture, 2009).

As a result of the complexity of land degradation, different methods are used to assess degradation levels in South Africa, and common methods include the use of remote sensing data, satellite imagery, modelling software, biophysical assessment and stakeholder inputs at a national and local scale (Department of Agriculture, 2009). The use of various methods is because none of the methods is better than the other since each method has its limitations(FAO, 2003). For example, Bai et al. (2008) used the satellite-based Normalised Difference Vegetation Index product to assess land degradation indicated by the decline in land productivity using the Net Primary Productivity as an indicator at a national scale. The limitation of satellite-based data is that they do not account for other biophysical factors (soil nutrients, plants, and animals), which are part of the environmental function (Gibbs and & Salmon, 2015). The stakeholder inputs method was used in the national assessment of land degradation in South Africa in 1999 using agricultural land status and agricultural expert opinions (Hoffman & Todd, 2000a). However, the limitations of using biophysical and stakeholder methods in assessing degradation at a local scale only considers a single aspect or does not account for the complexity of degradation (FAO, 2003). The biophysical assessment focuses on the description and quantification of the biophysical processes and their direct effects (on soil, water and vegetation) but does not account for the drivers and impacts of land degradation (FAO, 2016). Therefore, it is important to consider different factors and indicators in assessing land degradation for reporting and monitoring land degradation, supporting land degradation neutrality (Gonzalez-Roglich et al., 2019; Liniger et al., 2019).

Land degradation neutrality is an initiative to stop and reverse land degradation and restore degraded land (Dubovyk, 2017), under the United Nations Convention to Combat Desertification (UNCCD) from 1994, aiming to reduce land degradation and desertification in all affected countries. The United Nations Conference on Sustainable Development (UNCSD) has set a goal to reach land degradation neutrality by the year 2030 (Stavi & Lal, 2015; IAEG-SDGs, 2016). Land degradation neutrality describes a state in which the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase (World Meteorological Organization, 2005; IUCN, 2015). The goal to reach land degradation neutrality was established to encourage measures to avoid, reduce and reverse degradation in areas that are already experiencing degradation (Orr et al., 2017).

Land degradation neutrality forms part of the Sustainable Development Goals (SDGs), specifically SDG 15, which promotes life on land. The SDG 15.3 aims to combat desertification, restore degraded lands and soil, and strive to achieve land degradation neutrality by the year 2030 (IUCN, n.d; Orr et al., 2017). Sustainable Development Goal 15.3.1, an indicator for measuring the progress towards the SDG15.3 target, is a measure of land degradation, measuring “the proportion of land that is degraded over the total land area” (Sims et al., 2017; Wunder et al., 2018). The SDG 15.3.1 indicator uses three sub-indicators for monitoring land productivity, land cover change, and soil organic carbon (United Nations, 2015).

The first sub-indicator is the land productivity indicator, which refers to the biologically productive capacity of the land and is the source of all food, fibre, and fuel that sustains humans (Clark et al., 2001; UNSC, 2015). This sub-indicator detects changes in the health and productive capacity of the land and reflects the net effects of changes in the ecosystem functioning in terms of plant and biomass growth (Sims et al., 2017). Therefore the loss of vegetation in productive lands can result from land degradation (Bennett et al., 2012; Graw et al., 2017). Land cover change is the second sub-indicator, which is observed as the physical cover of the Earth’s surface, which indicate distribution of vegetation types, water bodies, human-made infrastructure; land cover change indicator also includes the use of natural resources (Sims et al., 2017; UNCCD, 2018). Change in land cover can indicate signs of degradation, especially when there is a reduction in productivity of ecosystem services that are desirable for people and the environment in the area (UNCCD, 2018). The third sub-indicator is Soil Organic Carbon (SOC), which refers to the amount of carbon stored in soil and is the main component of soil organic matter (Sims et al., 2017). Soil organic carbon can be used to assess ecosystem health (UNCCD, 2018) since SOC has a significant influence on the soil's physical, chemical, and biological properties. Therefore, the loss of SOC due to land degradation can cause a reduction in soil quality and fertility (Stavi & Lal, 2015) and impact other functions such as the ability of soil to retain water, soil erosion, and crop productivity. For assessing and monitoring land degradation in SDG 15.3.1, the three sub-indicators described above are combined to identify degraded areas.

This study assessed the proportion of land degradation from the year 2000-2015 in the study area using Trends.Earth tool. This study assessed land degradation up to the year 2015, because during this study period, the Trends.Earth plugin provided an assessment period from the year 2000 to the year 2015, so, this study assessed land degradation and land cover change from 2000-2015.However, now the tool has been upgraded and cover the assessment period from year 2000 to the year 2020. Trends.Earth plugin is a recently released tool by Global Environmental Facility (GEF) to assess and monitor land degradation status using global data sources at different scales using a common methodology (Conservation International, 2019). Trends.Earth tool combines the three sub-indicators (land productivity, soil organic carbon, and land cover transitions) for monitoring degradation.

The Trends.Earth tool has been employed in several research studies on land productivity and degradation, such as studies conducted in Kenya, Uganda, Senegal and Tanzania (Olsson et al., 2018). The tool has been used globally by Gonzalez-Roglich et al. (2019) in assessing global land degradation neutrality (Olsson et al., 2018) Trends.Earth is used to identify areas of significant vegetation changes, as well as to perform residual trend analysis (RESTREND) using the Normalised Difference Vegetation Index (NDVI), which is a measure of vegetation health (Olsson et al., 2018). The RESTREND method is used commonly for distinguishing between natural variability and degradation processes in water-restricted ecosystems (Wessels et al., 2012; Liu et al., 2019). However, one of the limitations of RESTREND is that it can be an unreliable measure in land degradation assessments in situations when degradation occurs in the middle of the assessment period, which results in a weaker linear relationship (Wessels et al., 2012). Therefore, a Rain Use Efficiency (RUE) method for correcting climate effects is important for better assessing land degradation because the RUE method is not affected by short-term changes in the environment and is calculated yearly (Symeonakis & Drake, 2004). The Rain Use Efficiency is mostly used in areas with a semi-arid climate, and RUE assesses the relationship between precipitation and land productivity (Wessels et al., 2007a; Chang et al., 2018).

Von Maltitz et al. (2019) used Trends.Earth to assess land productivity dynamics in South Africa, and the tool used to map out the country's land productivity status in terms of decline and increase. The study indicated the common limitation of the tool of false-positive results, which is also acknowledged in the use of trends literature (Gilbey, (n.d.); Sims et al., 2017, 2019; Cowie et al., 2018; UNCCD, 2018). The false positive in the Von Maltitz et al. (2019) study showed an increase in productivity in areas known to be mostly degraded, possibly due to climate effect or the presence of alien plants, which created an impression of increased productivity. However, Cowie et al. (2018) recommended using local data sets and expert opinion (stakeholder inputs) to identify the false-positive results from land degradation assessment. In addition, the Trends.Earth tool has also been used to assess land degradation and vegetation productivity in drylands in South African (Hoffman et al., 2018). The Hoffman et al. study used the Trends.Earth to assess vegetation changes in the Karoo from 1982-2015 productivity trends. The results indicated that the Karoo dry land area is mostly stable (90%) and less degraded than in the mid-twentieth century (Hoffman et al., 2018).

In this study, the Trends.Earth tool was employed to assess land degradation status in the Tsitsa River catchment and identify the proportion of degraded areas. The study also assessed the state and changes in the targeted ecological infrastructure (grasslands, wetlands, abandoned cultivated lands, and riparian zones) over the past 15 years in the Tsitsa River catchment. The degradation results from Trends.Earth were compared with a local land cover change dataset from 1990-2018 to determine the accuracy of the results.

3.2 Methods for calculating SDG15.3.1 degradation indicator: The proportion of degraded land.

The Trends.Earth tool is the land degradation monitoring tool developed by Conservation International (Conservation International, 2019). The tool was developed to provide a consistent and effective way to monitor land change and track the achievement of the Sustainable Development Goals (Conservation International, 2019). This study used Trends.Earth plugin tool in QGIS (Conservation International, 2019) to assess the land degradation status under SDG15.3.1 land degradation indicator for 15 years (from 2000–2015) in the Tsitsa River catchment (T35) in the Eastern Cape Province, South Africa. Trends.Earth plugin is free, open-access software that uses various Python scripts that run analyses on the Google Earth Engine platform (Conservation International, 2019). The Trends.Earth tool was installed in QGIS version 2.18.15 and was used to perform the SDG15.3.1 degradation analysis. The results include a plot of time series, land cover maps, and tables, which indicate the land degradation status of the Tsitsa catchment (T35). Various datasets were used to calculate the sub-indicators for the SDG15.3.1 degradation indicator, and these datasets are described in the sub-sections below (Table 3.1).

Table 3.1: Dataset and data sources used in the study to assess land degradation indicators.

Dataset and data source	**Period**	**Spatial resolution**	**Measured index**	**Reference for dataset**
MOD13Q1	2001–2016	250 m	Productivity	(LP-DAAC-USGS, 2017)
ESA-CCI-LC	1992–2015	300 m	Land cover change	(ESA-CCI, 2015)
SOILGRIDS250	2000–2015	250 m	SOC	(ISRIC-World Soil Information, 2017)
CHIRPS	1981–2016	0.05°	RUE (Precipitation)	(Climate Hazards Center, 2020)

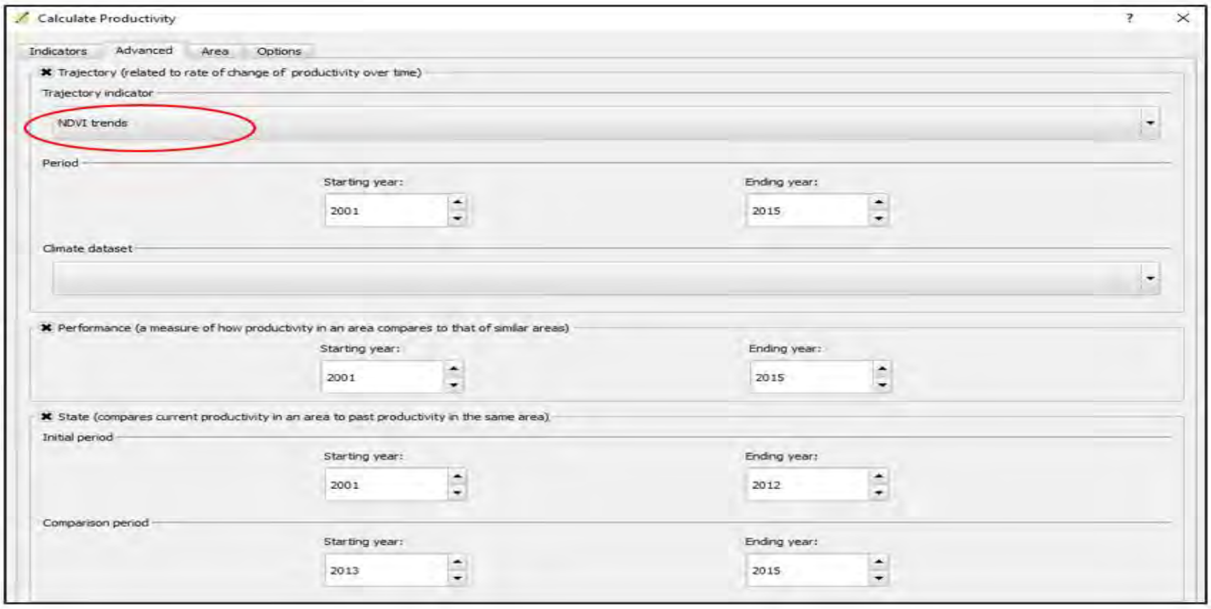
1) The Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) data set uses vegetation indices (https://lpdaac.usgs.gov/products/mod13q1v006/).
2) European Space Agency (ESA) Climate Change Initiative (CCI) Land Cover (https://www.esa-landcover-cci.org/).
3) SoilGrids- Global Gridded Soil Information (https://www.isric.org/explore/soilgrids).

4) Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a quasi-global spanning at 50°S-50°N with spatial resolution 0.05° precipitation dataset (https://www.chc.ucsb.edu/data/chirps).

All three SDG 15.3.1 sub-indicators were calculated and combined to generate the SDG 15.3.1 indicator in this study. The plugin was set up for calculating the SDG15.3.1 indicator from the baseline period of the year 2000 to the final (target) year 2015. Calculations for each sub-indicator and data source used in the study area are described below.

3.2.1 Sub-indicator 1: Land Productivity

Land productivity for the study area was calculated using the three productivity sub-indicators (trajectory, performance, and state productivity). Land productivity sub-indicators were calculated using 250 m MODIS Normalised Difference Vegetation Index (NDVI) time series product (MOD13Q1) from the year 2000 to the year 2015. The Normalised Difference Vegetation Index (NDVI) is a numerical indicator that uses visible light and near-infrared light bands of the electromagnetic spectrum reflected by the plant to measure vegetation health or greenness of an area (Pettorelli et al., 2005), and it is commonly used as a surrogate for land productivity (Sims et al., 2017; UNCCD, 2018). Land productivity performance and trajectory were calculated based on the NDVI analysis in the land cover classes for the assessment period. The land productivity state compared changes in the primary productivity of the area from 2001–2012 (baseline) and primary productivity for 2013–2015 (current period) (Figure 3.1). Since primary productivity is affected by climate, the second analysis of land productivity using climate effect correction was conducted using the Rain Use Efficiency (RUE) method with Climate Hazards Group Infrared Precipitation with Station (CHIRPS) precipitation (0.05°) data (Climate Hazards Center, 2020) (Figure 3.2). The CHIRPS data is measured using local rainfall station data and satellite data from the quasi-global spanning at 50°S-50°N at a finer resolution of 5 km (Conservation International, 2019; Climate Hazards Center, 2020). The RUE method was used for climate correction because it is preferred for water-limited areas, and land productivity in semi-arid regions is influenced by rainfall variability (Wessels et al., 2007b; Fensholt & Rasmussen, 2011). In dry areas, there is a positive relationship between rainfall and Net Primary Productivity (Wessels et al., 2007b), the Net Primary Productivity (NPP) is defined as the remaining amount of carbon estimated after photosynthesis and autotrophic respiration over a given time (Clark et al., 2001). The RUE index was used to adjust the climate factor and eliminate the bias caused by rainfall variability to identify human-induced driving factors of land degradation (Conservation International, 2019; Sims et al., 2019).


Calculate Productivity

☒ Trajectory (related to rate of change of productivity over time)

Trajectory indicator

NDVI trends

Period

Starting year: 2001

Ending year: 2015

Climate dataset

☒ Performance (a measure of how productivity in an area compares to that of similar areas)

Starting year: 2001

Ending year: 2015

☒ State (compares current productivity in an area to past productivity in the same area)

Initial period

Starting year: 2001

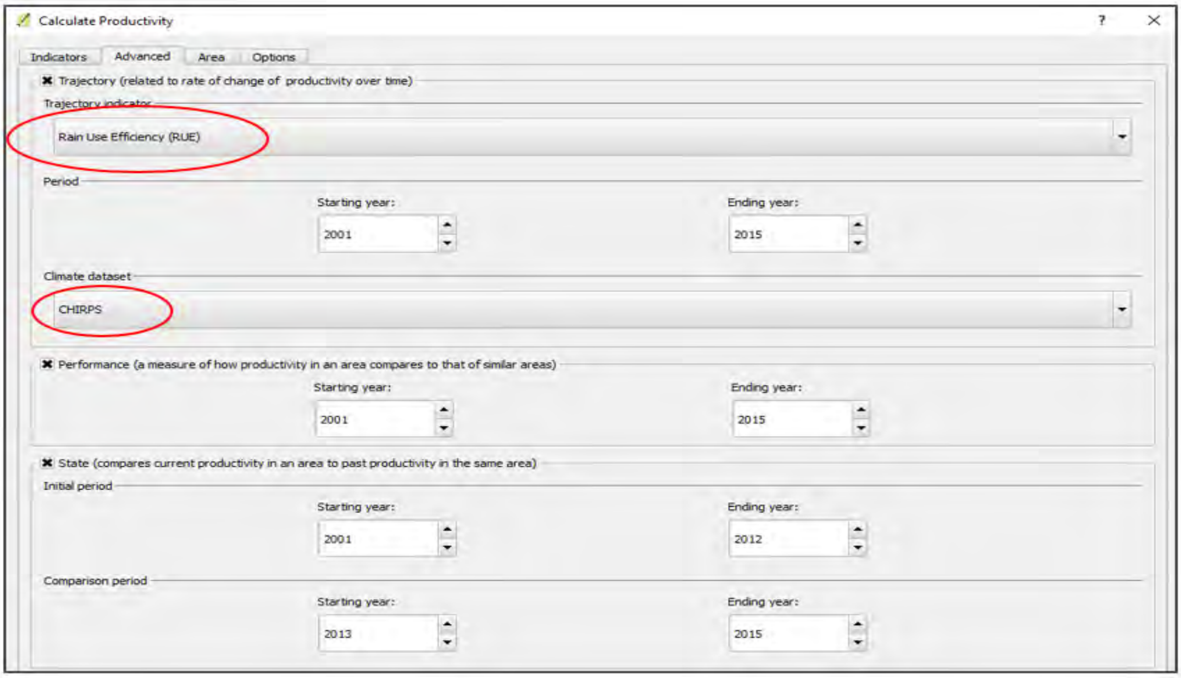
Ending year: 2012

Comparison period

Starting year: 2013

Ending year: 2015

Figure 3.1: Data used in Trends.Earth calculating sub-indicator one on land productivity for catchment T35 without climate correction.


Calculate Productivity

☒ Trajectory (related to rate of change of productivity over time)

Trajectory indicator

Rain Use Efficiency (RUE)

Period

Starting year: 2001

Ending year: 2015

Climate dataset

CHIRPS

☒ Performance (a measure of how productivity in an area compares to that of similar areas)

Starting year: 2001

Ending year: 2015

☒ State (compares current productivity in an area to past productivity in the same area)

Initial period

Starting year: 2001

Ending year: 2012

Comparison period

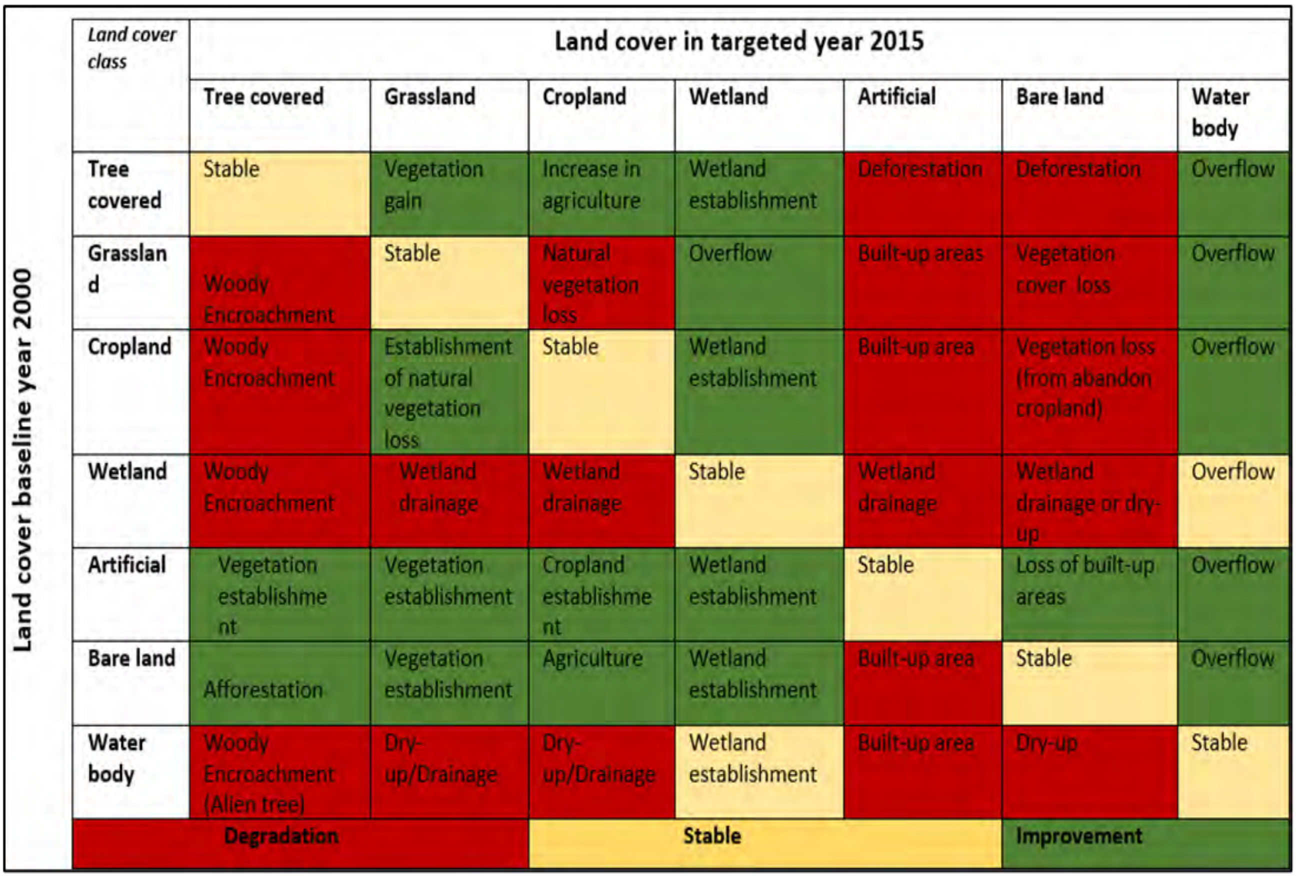
Starting year: 2013

Ending year: 2015

Figure 3.2: Data used in Trends.Earth tool to calculating land productivity of the catchment T35 with climate correction.

3.2.2 Sub-indicator 2: Land cover change

The land cover change was calculated using land cover data from the European Space Agency Climate Change Initiative (ESA CCI-LC) at 300 m resolution from the initial year (2000) to the target year (2015). Each land cover transition was defined based on the understanding of changes (positive or negative change) in the catchment and the use of available literature (Figure 3.3). However, positive change or improvement in land cover does not necessarily indicate a suitable change for the environment. For example, a land cover transition of tree-covered areas into cropland shows agricultural growth, which can disrupt the ecosystem structure and function through deforestation, clearing, and cultivation, impacting the environment (Matsika, 2007; FAO, 2011). In this study, adverse changes in grassland areas were determined based on loss or reduction of ecosystem services, biodiversity, and land productive capacity. For example, changes in cropland to grassland are defined as a positive change because the change from a cultivated area into grassland indicates regeneration of grassland vegetation (Matsika, 2007). A transition in grassland into tree-covered areas is considered negative since it is generally bush encroachment, contributing the most to degradation in grassland biome due to the disturbed natural ecosystem function (Matsika, 2007; Luvuno et al., 2018). Also, changes in cultivated land, especially abandoned croplands, are identified as negative changes because abandoned cultivated lands are vulnerable to invasive alien plants, disrupting ecosystem functioning (Matsika, 2007; Blair et al., 2018; Scorer et al., 2019). Any changes from natural land cover into artificial or bare land areas are considered a negative change because of the natural resources' loss in natural ecosystem services. The transition of wetlands into tree-covered areas, grasslands, or cropland is considered a negative change because the loss of wetlands into trees is associated with alien vegetation, and the change in wetlands into croplands is related to the cultivation of the flood plains wetlands (Dini & Bahadur, 2016). Transformation in wetlands is defined as negative because of the loss of valuable, diverse ecosystem goods and services provided by wetlands.

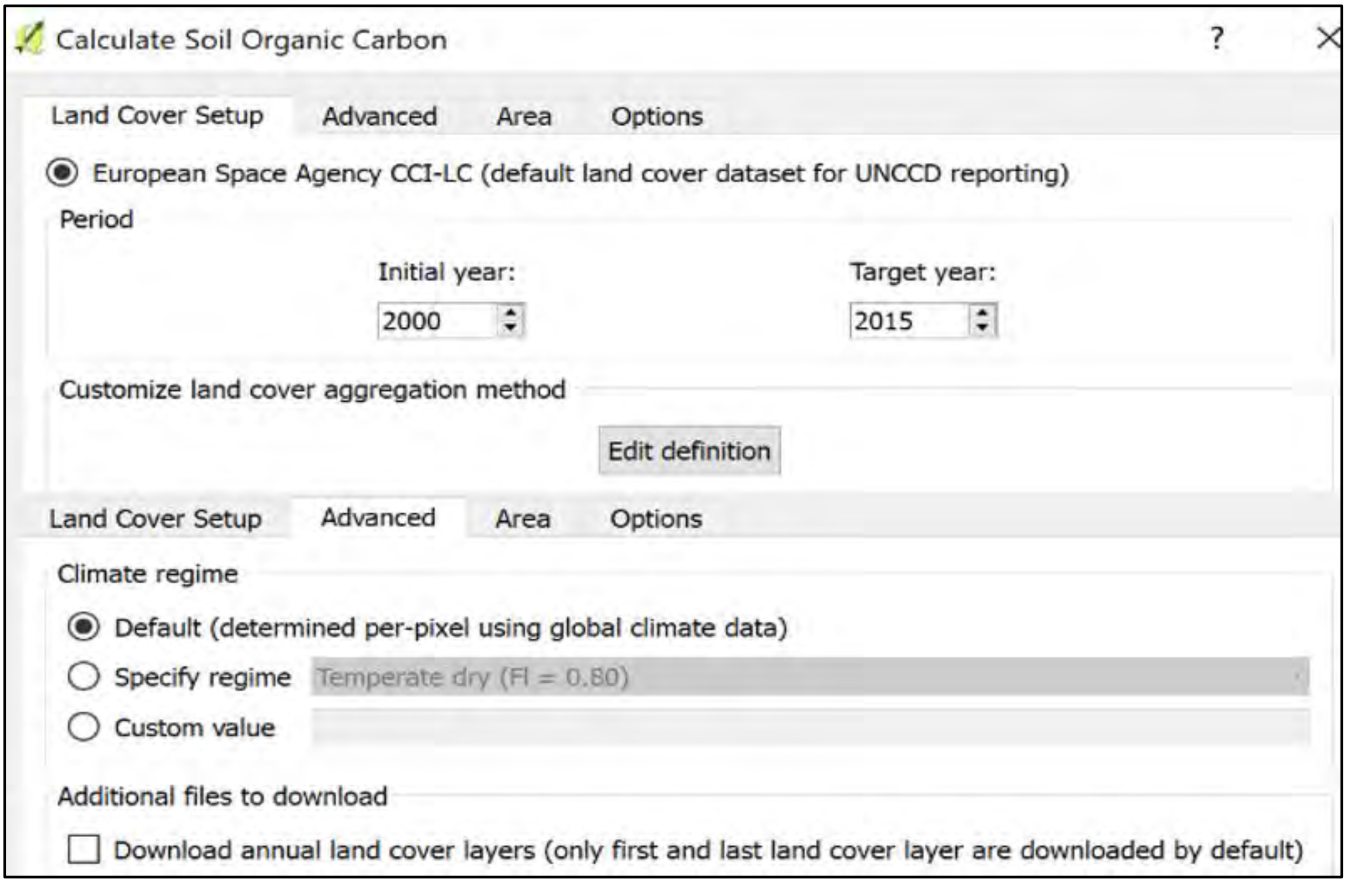


	Land cover class	**Land cover in targeted year 2015**						
		Tree covered	**Grassland**	**Cropland**	**Wetland**	**Artificial**	**Bare land**	**Water body**
Land cover baseline year 2000	**Tree covered**	Stable	Vegetation gain	Increase in agriculture	Wetland establishment	Deforestation	Deforestation	Overflow
	Grassland	Woody Encroachment	Stable	Natural vegetation loss	Overflow	Built-up areas	Vegetation cover loss	Overflow
	Cropland	Woody Encroachment	Establishment of natural vegetation loss	Stable	Wetland establishment	Built-up area	Vegetation loss (from abandon cropland)	Overflow
	Wetland	Woody Encroachment	Wetland drainage	Wetland drainage	Stable	Wetland drainage	Wetland drainage or dry-up	Overflow
	Artificial	Vegetation establishment	Vegetation establishment	Cropland establishment	Wetland establishment	Stable	Loss of built-up areas	Overflow
	Bare land	Afforestation	Vegetation establishment	Agriculture	Wetland establishment	Built-up area	Stable	Overflow
	Water body	Woody Encroachment (Alien tree)	Dry-up/Drainage	Dry-up/Drainage	Wetland establishment	Built-up area	Dry-up	Stable
	Degradation			**Stable**			**Improvement**	

Figure 3.3: Defined land cover transition process used to assess land degradation in the catchment T35. The possible major land cover transition; represented in Red (degradation), Green (improvement), and Gold (stable).

3.2.3 Sub-indicator 3: Soil Organic Carbon (SOC)

Soil Organic Carbon is calculated as soil carbon stocks, using soil data and land changes in land cover and the changes in SOC are assessed based on combined impacts of climate and land cover change (Hengl et al., 2017; Conservation International, 2019). So, the degradation in SOC for the T35 catchment was calculated in the Trends.Earth tool using the default land cover dataset from the ESA-CCI-LC (2000–2015) (Figure 3.4) and climate regime default data determined per pixel using the global climate data. In this study, SOC was calculated using SOC data derived from the 250 m SoilGrids project by International Soil Reference and Information Centre (ISRIC), which uses the topsoil (upper 30 cm) to calculate SOC through computer modelling. In the results of the assessment, land use areas experiencing a loss of 10% or more SOC are considered potentially degraded, and areas experiencing a gain of 10% or more as potentially improved (Conservation International, 2019). However, an increase in SOC may not indeed indicate improvement in the landscape or the assessed area because of the possibility of false positives (Sims et al., 2017; Cowie et al., 2018; Gonzalez-Roglich et al., 2019). For example, the transition in grasslands to plantations will cause an increase in SOC; this does not indicate improving conditions but can show degradation because of adverse impacts associated with the transition process.



Calculate Soil Organic Carbon

● European Space Agency CCI-LC (default land cover dataset for UNCCD reporting)

Period

Initial year: 2000

Target year: 2015

Customize land cover aggregation method

Climate regime

● Default (determined per-pixel using global climate data)

○ Specify regime Temperate dry (FI = 0.80)

○ Custom value

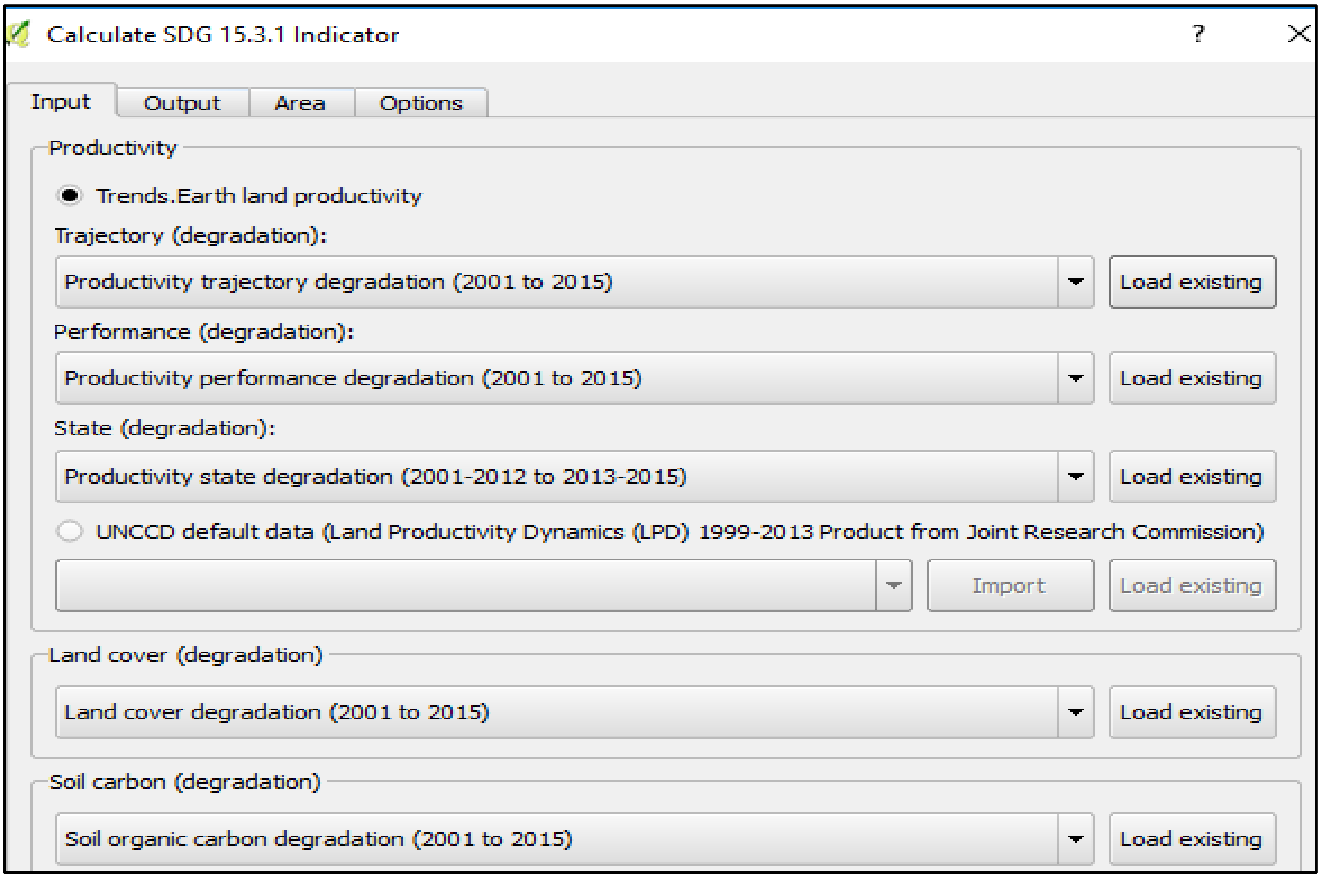
Additional files to download

☐ Download annual land cover layers (only first and last land cover layer are downloaded by default)

Figure 3.4: Data selected in Trends.Earth to calculate sub-indicator 3 on Soil Organic Carbon for catchment T35.

3.2.4 Calculating SDG15.3.1 Degradation indicator

In the final SDG15.3.1 land degradation indicator calculation, the plugin combines the three sub-indicators, using the “one-out all-out rule” to generate three potential states: improvement, degradation or stable (Figure 3.5). The one-out all-out rule specifies that if one of the sub-indicators is identified as degraded, then the area is classified as degraded for the SDG 15.3.1 indicator (Figure 3.6). Therefore, the area is considered potentially degraded in reporting land degradation. Improvement can be attained when all three sub-indicators improve, or one or two sub-indicators are stable during the assessment period. The third outcome for SDG 15.3.1 indicator of ‘stable’ state can only be achieved when all three sub-indicators are stable (Conservation International, 2019). The SDG15.3.1 degradation indicator for the catchment area was also calculated using land productivity data to correct climate effects. A series of maps, results and tables were produced, as shown in the results section 3.3 of the thesis. The supplementary information on calculating SDG 15.3.1 indicator using Trends.Earth tool, describing how the Trends.Earth tool calculates each sub-indicators, and the available climate correction in the plug in is described in appendix 1.



Productivity

● Trends.Earth land productivity

Trajectory (degradation): Productivity trajectory degradation (2001 to 2015)

Performance (degradation): Productivity performance degradation (2001 to 2015)

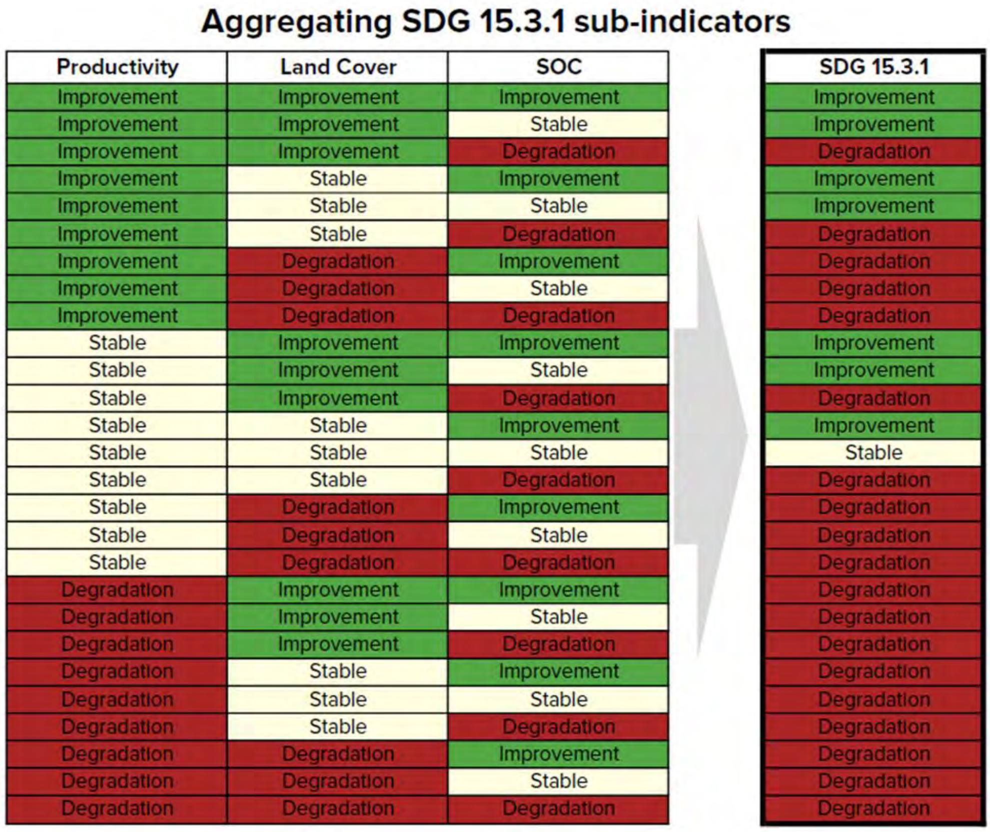
State (degradation): Productivity state degradation (2001-2012 to 2013-2015)

○ UNCCD default data (Land Productivity Dynamics (LPD) 1999-2013 Product from Joint Research Commission)

Land cover (degradation): Land cover degradation (2001 to 2015)

Soil carbon (degradation): Soil organic carbon degradation (2001 to 2015)

Figure 3.5: Data selected in Trends.Earth to calculate the final SDG15.3.1 indicator for catchment T35.



Aggregating SDG 15.3.1 sub-indicators

Productivity	Land Cover	SOC	SDG 15.3.1
Improvement	Improvement	Improvement	Improvement
Improvement	Improvement	Stable	Improvement
Improvement	Improvement	Degradation	Degradation
Improvement	Stable	Improvement	Improvement
Improvement	Stable	Stable	Improvement
Improvement	Stable	Degradation	Degradation
Improvement	Degradation	Improvement	Degradation
Improvement	Degradation	Stable	Degradation
Improvement	Degradation	Degradation	Degradation
Stable	Improvement	Improvement	Improvement
Stable	Improvement	Stable	Improvement
Stable	Improvement	Degradation	Degradation
Stable	Stable	Improvement	Improvement
Stable	Stable	Stable	Stable
Stable	Stable	Degradation	Degradation
Stable	Degradation	Improvement	Degradation
Stable	Degradation	Stable	Degradation
Stable	Degradation	Degradation	Degradation
Degradation	Improvement	Improvement	Degradation
Degradation	Improvement	Stable	Degradation
Degradation	Improvement	Degradation	Degradation
Degradation	Stable	Improvement	Degradation
Degradation	Stable	Stable	Degradation
Degradation	Stable	Degradation	Degradation
Degradation	Degradation	Improvement	Degradation
Degradation	Degradation	Stable	Degradation
Degradation	Degradation	Degradation	Degradation

Figure 3.6: Image from the Trends.Earth document (2019) showing the integration of the three sub-indicators (productivity, land cover, and soil organic carbon) of the SDG15.3.1 degradation indicator done following the one-out all-out rule.

3.2.5 Assessment of land degradation of the targeted key EI

The study assessed degradation status in the key targeted ecological infrastructure (wetlands, croplands, riparian vegetation, and grasslands). To determine the degradation state of the targeted EI, ArcGIS tool version 10.6 was used to run the analysis for degradation status in the key EI. The outputs of the degradation assessment in terms of SDG15.3.1 indicator for the Tsitsa River catchment was clipped into the South Africa National Land Cover (SANLC) dataset for 2014 to produce shapefiles of the key EI (grasslands, wetlands and abandoned cultivated lands). The SANLC (2014) datasets were generated from a 20 m multi-seasonal Sentinel two imager (GEOTERRAIMAGE, 2019b). A 150 m river buffer was applied to the 2010 national river network dataset from the Department of Water Affairs using the ArcGIS tool to identify riparian vegetation. The 150 m river buffer was clipped with the SDG15.3.1 land degradation indicator results to indicate degradation status in the riparian vegetation.

3.2.6 Comparison of land degradation results from Trends.Earth with the local datasets

This study compared land degradation results estimated by the Trends.Earth with two local datasets, National Biodiversity Assessment (NBA) 2018 and South Africa National Land Cover Change Assessment 1990–2018.

The NBA is the primary tool for monitoring and reporting on the state of biodiversity in South Africa and is linked to international reporting, such as the United Nations Convention on Biological Diversity (CBD) and the Convention to Combat Desertification (UNCCD), as well as the Sustainable Development Goals (SDGs). The NBA data supports South African international reporting requirements linked to the UNCCD by assessing long-term changes in the ecosystem and assessing the rates of terrestrial habitat loss (Skowno et al., 2019). This analysis examines the correlation between the NBA category for ecosystem threat status and ecological conditions of natural resources and the land degradation results in the catchment. Ecosystem threat status indicates the degree to which ecosystems are still intact or are losing vital aspects of their structure and functional composition. The Ecosystem threat status is categorised as Critically Endangered (CR), Endangered (EN), Vulnerable (VU), or Least Concern (LC), based on quantitative criteria and thresholds linked to ecosystem extent and condition (Skowno et al., 2019). The ecological condition in the terrestrial ecosystem is estimated using mainly land cover change data, details of habitat loss, fragmentation, degradation, and overutilisation of natural resources. Ecological conditions in the ecosystem categories are: natural (A), near-natural (B), moderately modified (C), and heavily to critically modified (D/F) (Skowno et al., 2019).

Based on the SDG15.3.1 degradation results, wetland degradation status was compared using the NBA Inland wetland conditions and Ecosystem Threat Status (ETS) indicators in the NBA 2018 dataset. Wetlands found in the catchment based on the SANLC dataset were clipped with the SDG15.3.1 degradation indicator results. The layer produced with wetland degradation status (SDG15.3.1 indicator) was compared to the NBA 2018 wetland ecological condition and ecosystem threat status. The relationship between the NBA data layer and wetland degradation layer was observed and is discussed in section 3.3.3 below.

The SANLC Change Assessments dataset was used to compare land degradation results because it provides long-term assessment changes in land cover, and it is a nationally accepted dataset. The data also offer recent updated national land cover categories and changes from 1990 to 2018; these data indicated trends in land cover changes. The SANLC Change Assessment data is a 30 m spatial resolution, created using land cover change estimates based on the 1990–2018 NLC datasets (GEOTERRAIMAGE, 2019a). The results of the land degradation indicator in the catchment area are at a much coarser resolution (300 m), and the SANLC Change Assessment data is at finer spatial resolution (30 m), making it more suitable for comparing the degradation identified by the Trends.Earth tool. The finer resolution data was used to compare the Trends.Earth degradation results in the catchment were used because the degradation results are assessed at course resolution, so the higher resolution images were suitable for comparison. Also, the SANLC Change Assessment data is validated local data, making it more suitable for assessing the accuracy of the Trends.Earth results assessed using global datasets as recommended in the Good Practise Guidance (Sims et al., 2017).

The SANLC assessment data was compared with land degradation in grasslands, abandoned cultivated lands and riparian zones categories. The land cover change class from land cover change assessment 1990–2018 data set was categorised into seven land cover classes, defined by the UNCCD. These land cover classes were used to calculate land cover and land degradation indicators in the catchment (Table 3.2). The land cover change assessment table, representing areas with change and areas with no change, which are redefined and group the 20-land cover classes. The transition assessed from 1990 to 2013/2014 and from 2013/14 to 2018 data into the seven land cover classes used in the assessment. The aggregation of the seven-land cover class was done using the land cover categories from NLC-Change Assessment 1990–2018 (Table 3.2). Each land cover transition from the South Africa National land cover change assessment dataset (2018) was redefined as stable, degraded, or improved using the same land cover definition used in Figure 3.3. section 3.2.2 reporting land degradation indicator in the study catchment (Table 3.2). The land cover transition layer from SANLC-Change Assessment was open in ArcGIS and clipped into the T35 (study areas catchment) and a new attribute column was added to redefine the transition process and edit. Each transition state was defined using the three conditions for reporting land degradation state (stable, degraded and improvement), and the results were displayed in ArcGIS. The layer produced from the ArcGIS of defined land cover degradation status was compared to the SDG15.3.1 land degradation indicator for the Tsitsa River catchment.

Table 3.2: The South Africa National Land Cover Change Assessment 2018 land classes correspond to the aggregated seven land cover classes from the UNCCD. The numbers in the SANLC change assessment represent the class code from 1990 and 2013/2014 land cover data sets.

UNCCD code	**UNCCD Class**	**Land cover categories from NLC-Change Assessment 1990–2018**
1	**Tree-covered areas**	Indigenous Forest (1)
		Thicket / Dense Bush (2)
		Natural Wooded Land (3,4, 42, 43)
		Planted Forest (5,6,7)
		Shrubland (8,9,10,11,46)
2	**Grassland**	Grasslands (12,13, 44)
3	**Cropland**	Cultivated Commercial Permanent Orchards (32, 35)
		Cultivated Commercial Permanent Vines (33)
		Commercial Annuals Pivot Irrigated (34, 38)
		Commercial Annuals Non-Pivot (36, 37, 39, 40)
		Cultivated Subsistence (41)
4	**Wetland**	Wetlands (22,23,24, 73)
5	**Artificial Land**	Built-up Residential All (47 - 56, 61 - 64)
		Built-up Smallholdings (57 - 60)
		Built-up Commercial (65)
		Built-up Industrial (66)
6	**Other lands**	Barren Land (25,26,28,29,30,31,45)
		Eroded Lands (27)
7	**Water bodies**	Waterbodies (14 – 21)

Table 3.3: Landcover transition from the Tsitsa River catchment based on the National Land Cover Change Assessment from the SANBI 2018. The colours represent the following: areas with no change (yellow), areas of improvement (light green) and areas of land degradation (dark red).

Land cover change assessment 2018	**Tree-cover**	**Grassland**	**Wetlands**	**Water bodies**	**Barren Land**	**Cultivated areas**	**Built-up areas**
Tree-cover	63	64	65	66	67	68	69
Grasslands	125	126	127	128	129	130	131
Wetland	166	167	168	169	170	171	172
Water bodies	144	145	146	147	158	159	150
Barren land	196	197	198	199	200	201	202
Cultivated areas	268	269	270	271	272	273	274
Built-up areas	372	373	374	375	376	377	378

3.3 Results of calculated sub-indicators for SDG15.3.1 degradation indicator

3.3.1 Sub-indicator 1: Productivity

Land productivity results in T35 catchment without climate correction suggested that the catchment was experiencing 41.10% productivity degradation, while 44.73% of the total land area has stable productivity and 14.15% of the area has improved land productivity (Figure 3.7). Land areas of degraded productivity or the early signs of decline in productivity are in the upper catchment and include the quaternary catchments T35B, T3C, T35D and T35F. In the middle part of the catchment, from T35E to T35J, the area is mostly stable or shows improved land productivity. The lower parts of the catchment (T35K, T35L and T35M) show early signs of decline in productivity caused by the stable but stressed land in the area, and there are signs of decline in productivity in these lower areas (Figure 3.7). The results of land productivity with climate correction (using the RUE method) show that areas that were classified as declining in land productivity without climate correction (Figure 3.6) are classified as having early signs of decline in the results with climate correction (Figure 3.8). Land productivity in the catchment for the years 2000–2015 with climate effect shows areas of improved (4.73%), stable (55.03%) and degraded (40.22%). Land productivity with climate correction indicates that a large portion of the land area in the catchment showed early signs of decline, while some parts of the catchment showed stable land productivity (Figure 3.8).

Summary of change in Land Productivity		
	Area (sq km)	Percent of total land area
Total land area:	4924.7	100%
Land area improved:	697.0	14.15%
Land area stable:	2202.7	44.73%
Land area degraded:	2023.9	41.10%
Land area with no data:	1.1	0.02%

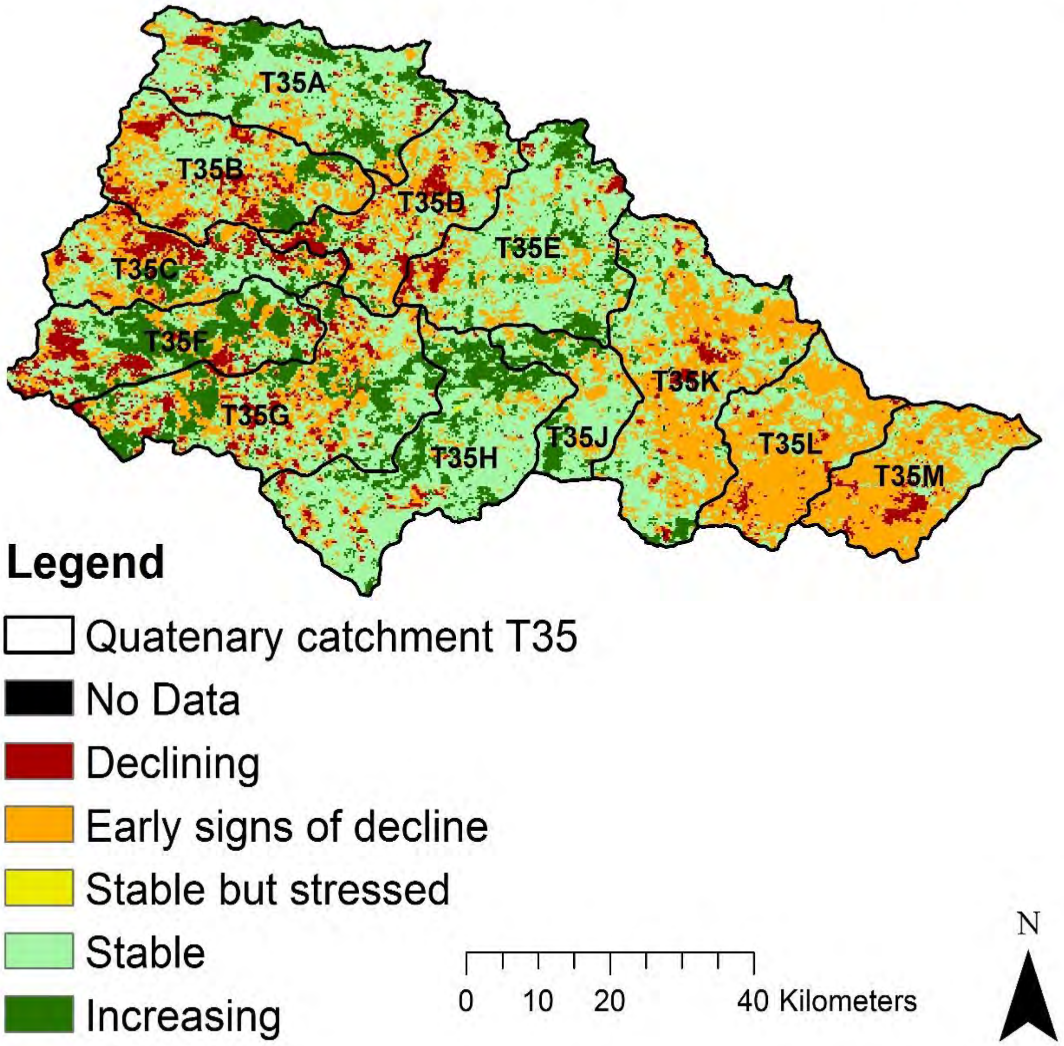
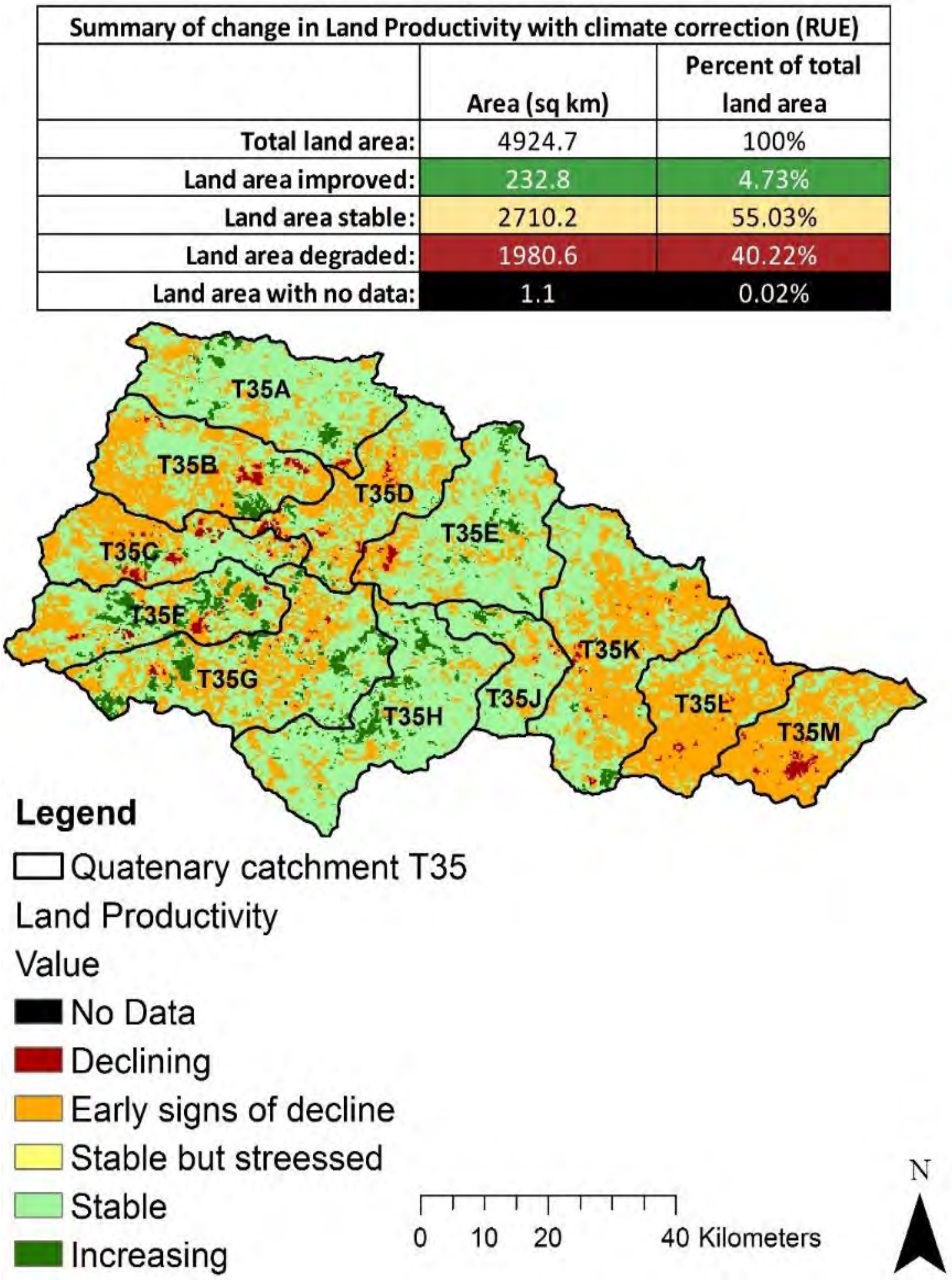


Figure 3.7: Map of land productivity distribution and a summary table of land productivity in the Tsitsa River catchment from the year 2000 to 2015 without climate correction.

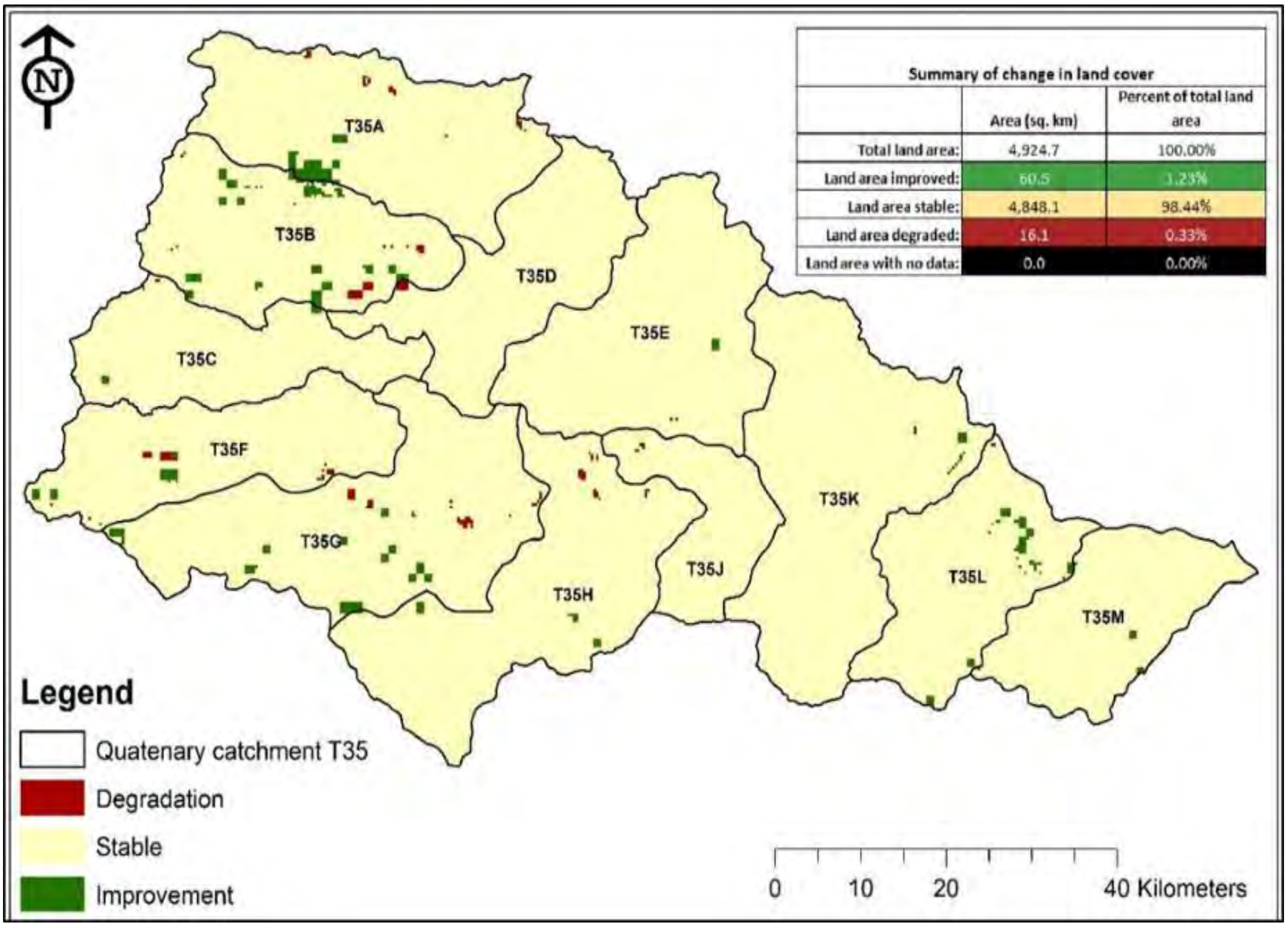


Summary of change in Land Productivity with climate correction (RUE)		
	Area (sq km)	Percent of total land area
Total land area:	4924.7	100%
Land area improved:	232.8	4.73%
Land area stable:	2710.2	55.03%
Land area degraded:	1980.6	40.22%
Land area with no data:	1.1	0.02%

Figure 3.8: Map of productivity distribution status and a summary table of land productivity with climate correction in the Tsitsa River catchment from the year 2000 to 2015.

3.3.2 Sub-indicator 2: Land cover change

Results indicated that 98.44% of land cover was stable between 2000–2015, with an improved land cover of approximately 1.23% of the area. Only 0.33% of the upper catchment was degraded over this period (T35A, T35B, T35F, T35G and T35H) (Figure 3.8). The major land cover transition in the catchment was the loss of tree-covered areas (6.13 % loss) in the upper catchment (T35A, T35B, T35F, T35G) (Figure 3.9 and Table 3.4). The results show more changes (gains) in the artificial areas (19.43% gain), wetlands (an increase of 4.36%), grasslands (an increase of 1.03%) and croplands (0.64% increase). However, the transition indicated degradation, improvement, and stable land cover. The gain in the artificial area is caused by the high loss of grasslands and tree-covered areas and transition (Figure 3.9) into artificial land and this transition is defined as degradation (Table 3.5). The transition of grasslands and tree-covered areas into wetlands leads to gain in wetlands and the transition is defined as improvement (Table 3.5). The changes from the tree-covered area into grasslands caused an increase in grassland area, indicating improvement in land cover (Table 3.5). Also, the loss of tree-covered areas (Figure 3.10) into cropland areas caused a gain in cropland and this transition is defined as land cover improvement (Table 3.5). No change was observed in land cover categories 'other lands' and 'water bodies' (Table 3.4 & 3.5).



Summary of change in land cover

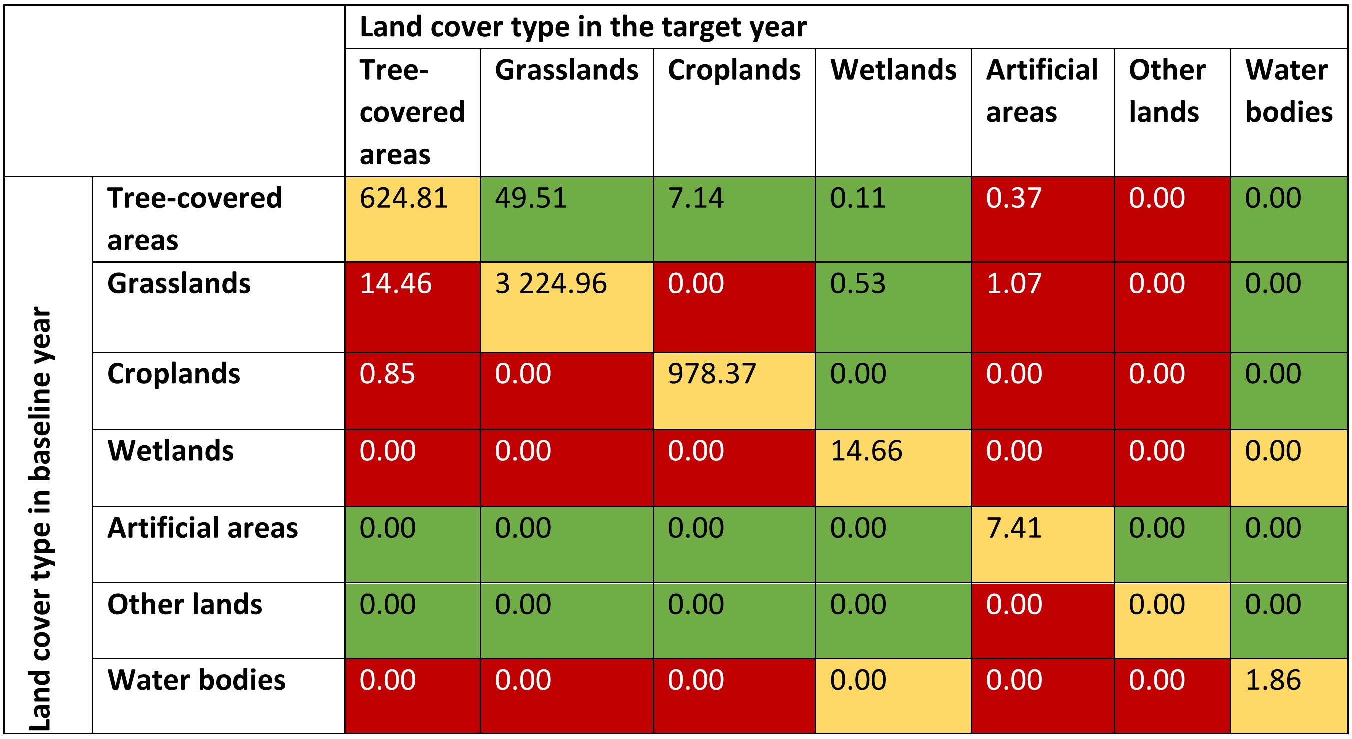
	Area (sq. km)	Percent of total land area
Total land area:	4,924.7	100.00%
Land area improved:	60.5	1.23%
Land area stable:	4,848.1	98.44%
Land area degraded:	16.1	0.33%
Land area with no data:	0.0	0.00%

Figure 3.9: Land cover degradation status and summary of land cover change between 2000–2015 in the Tsitsa River Catchment.

Table 3.4:Land cover change by cover class from baseline (2000) land area year to the target year (2015) in Tsitsa catchment (T35).

Land cover class	**Baseline land area (sq. km) year 2000**	**Target land area (sq. km) year 2015**	**Change in the area (sq. km)**	**Change in the area (%)**	**Type of change in the area: Gains (+)/Losses (-) No change (0)**
Tree-covered areas	681.93	640.12	-41.81	-6.13	-
Grasslands	3,241.02	3,274.46	33.45	1.03	+
Croplands	979.22	985.51	6.29	0.64	+
Wetlands	14.66	15.30	0.64	4.36	+
Artificial areas	7.41	8.85	1.44	19.43	+
Other lands	0.00	0.00	0.00	0.00	0
Water bodies	1.86	1.86	0.00	0.00	0
Total:	*4,926.10*	*4,926.10*	*0.00*		

Table 3.5: Land area by type of land cover transition (sq. km) for Tsitsa River catchment from the baseline year 2000 to the targeted year 2015. The colour represents the land cover change definition; Red (degradation), Green (improvement), and Gold (stable).



		Land cover type in the target year						
		Tree-covered areas	**Grasslands**	**Croplands**	**Wetlands**	**Artificial areas**	**Other lands**	**Water bodies**
Land cover type in baseline year	**Tree-covered areas**	🟨 624.81	🟩 49.51	🟩 7.14	🟩 0.11	🟥 0.37	🟥 0.00	🟩 0.00
	Grasslands	🟥 14.46	🟨 3 224.96	🟥 0.00	🟩 0.53	🟥 1.07	🟥 0.00	🟩 0.00
	Croplands	🟥 0.85	🟥 0.00	🟨 978.37	🟩 0.00	🟥 0.00	🟥 0.00	🟩 0.00
	Wetlands	🟥 0.00	🟥 0.00	🟥 0.00	🟨 14.66	🟥 0.00	🟥 0.00	🟨 0.00
	Artificial areas	🟩 0.00	🟩 0.00	🟩 0.00	🟩 0.00	🟨 7.41	🟩 0.00	🟩 0.00
	Other lands	🟩 0.00	🟩 0.00	🟩 0.00	🟩 0.00	🟥 0.00	🟨 0.00	🟩 0.00
	Water bodies	🟥 0.00	🟥 0.00	🟥 0.00	🟨 0.00	🟥 0.00	🟥 0.00	🟨 1.86

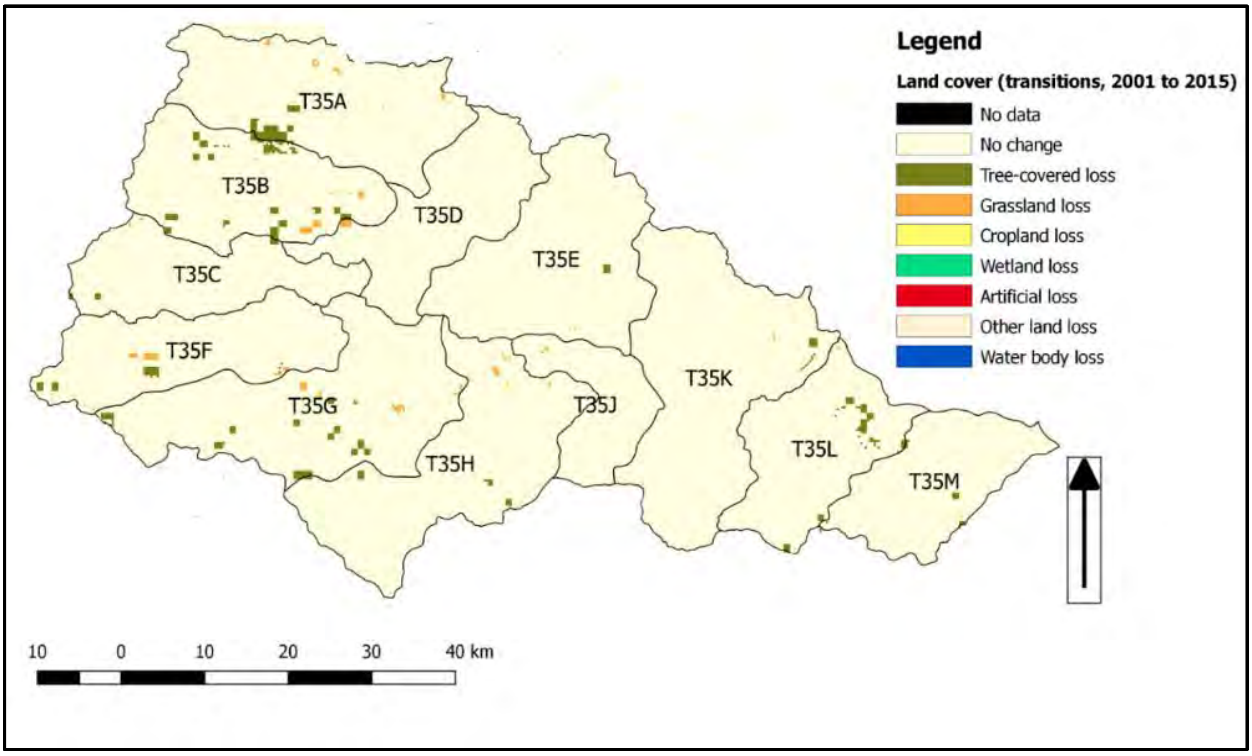


Figure 3.10: Land cover change (land cover loss) for seven land cover classes in the Tsitsa River catchment between 2001 and 2015.

3.3.3 Sub-indicator 3: Soil Organic Carbon (SOC)

The results of soil organic carbon indicate that 99.87% of the land area was stable, with small areas of improvement (0.01%) and a small amount of degradation (0.10) SOC in the catchment (Table 3.6). These results suggest that all the land cover classes showed less than 10% average net reduction or increased SOC stocks between the baseline (2000) and the target year observations (2015). The results also showed a positive correlation between land cover transition with SOC, when land cover class is gained or lost, together with the gain or loss in SOC. Major changes were in gain (grassland 1.03%, cropland 0.64%, wetland 4.36% and artificial 9.43%) and loss in SOC (tree-covered -6.22%) (Table 3.7). Since SOC in Trends.Earth is calculated based on the annual change in land cover transitions; the results of SO analysis showed a loss in SOC (-0.38%) with changes in the tree-covered area to grassland. Changes in the tree-covered area to cropland showed loss (-5.36%) in SOC (Table 3.8). Major loss in SOC from the baseline to the targeted year was indicated where grassland area changes to artificial land showed a loss in SOC (-17.14%) and gained during the transition change from cropland to the tree-covered area (7.43%) (Table 3.8).

Table 3.6: Summary of change in soil organic carbon (SOC) from 2000 baseline to the observed targeted year 2015 in the Tsitsa River Catchment.

Summary of change in Soil Organic Carbon		
	Area (sq. km)	**Percentage of total land area**
Total land area:	4924.2	100.00%
Improved soil organic carbon:	0.5	0.01%
Stable soil organic carbon:	4917.8	99.87%
Degraded soil organic carbon:	4.9	0.10%
No data for soil organic carbon:	1.0	0.02%

Table 3.7: Summary of change in soil organic carbon (SOC) from each land cover class in the Tsitsa River Catchment.

	Baseline area (sq. km)	Target area (sq. km)	Change in the area (sq. km)	Change in the area (percentage)
Tree-covered areas	681.93	640.12	-40.81	-6.22%
Grasslands	3241.02	3274.46	33.26	1.03%
Croplands	979.22	985.51	6.26	0.64%
Wetlands	14.66	15.30	0.64	4.36%
Artificial areas	7.41	8.85	1.44	19.43%
Other lands	0.00	0.00	0.00	0.00%

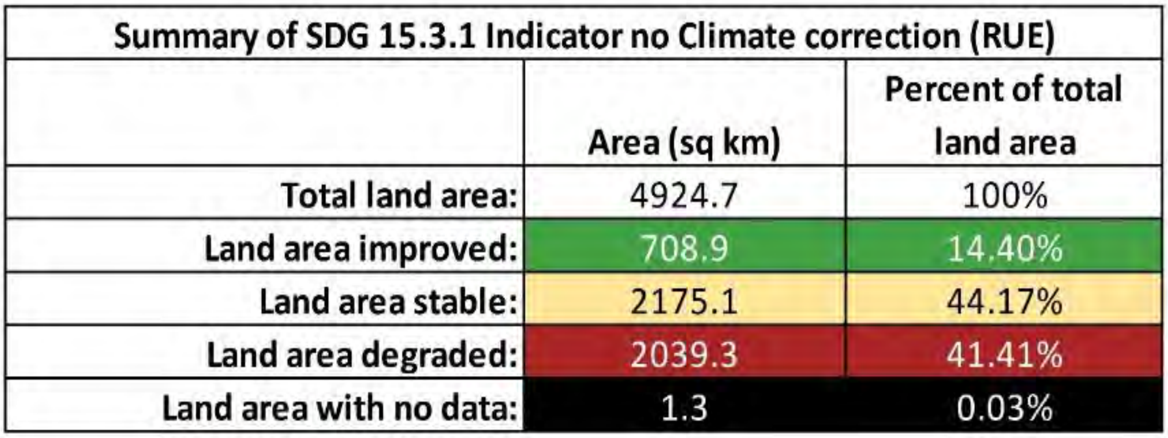
Table 3.8: Soil organic carbon change from baseline (2000) to target (2015) by type of land cover transition (as a percentage of initial stock).

	Land cover type in the target year						
		Tree-covered areas	**Grasslands**	**Croplands**	**Wetlands**	**Artificial areas**	**Other lands**
Land cover type in the baseline year	**Tree-covered areas**	-0.01%	-0.38%	-5.63%	0,00%	0.00%	0%
	Grasslands	0.00%	0.00%	0%	0.00%	-17.14%	0%
	Croplands	7.43%	0%	0.00%	0%	0%	0%
	Wetlands	0%	0%	0%	0.00%	0%	0%
	Artificial areas	0%	0%	0%	0%	-0.51%	0%
	Other lands	0%	0%	0%	0%	0%	0%

3.3.4 SDG15.3.1 degradation indicator

Trends.Earth results for SDG15.3.1 degradation indicator without climate correction showed that approximately 41.43% of the land area in Tsitsa is degraded, but some areas in the catchment (14.40%) showed improvement or recovery over the assessment period of 2000 to 2015, and almost half of the catchment land is stable (44.17%) (Figure 3.11). The upper sections (T35A, T35B, T35C, T35D, T35F and T35G) of the catchment and the lower parts of the catchment (T35K, T35L and T35M) are highly degraded compared to the middle catchment, according to the SDG 15.3.1 degradation indicator. The results from Trends.Earth land degradation indicates a high level (nearly half of the catchment) of degradation in terms of the SDG15.3.1 if climate correction is not included.

The results for the SDG15.3.1 degradation indicator with climate correction showed that about 54.29% of the catchment is stable, 40.52% degraded, and 5.15% of the land area improved (Figure 3.13). Degradation is more widespread in the upper and lower parts of the catchment than in the middle part of the catchment, which is stable. The SDG15.3.1 indicator results for the Tsitsa River catchment with climate correction (Figure 3.12) showed a 9.25% decrease in improved areas, a 10% increase in stable areas and a 0.89% decrease in degraded areas in the catchment compared to SDG15.3.1 degradation results without climate correction.



Summary of SDG 15.3.1 Indicator no Climate correction (RUE)		
	Area (sq km)	Percent of total land area
Total land area:	4924.7	100%
Land area improved:	708.9	14.40%
Land area stable:	2175.1	44.17%
Land area degraded:	2039.3	41.41%
Land area with no data:	1.3	0.03%

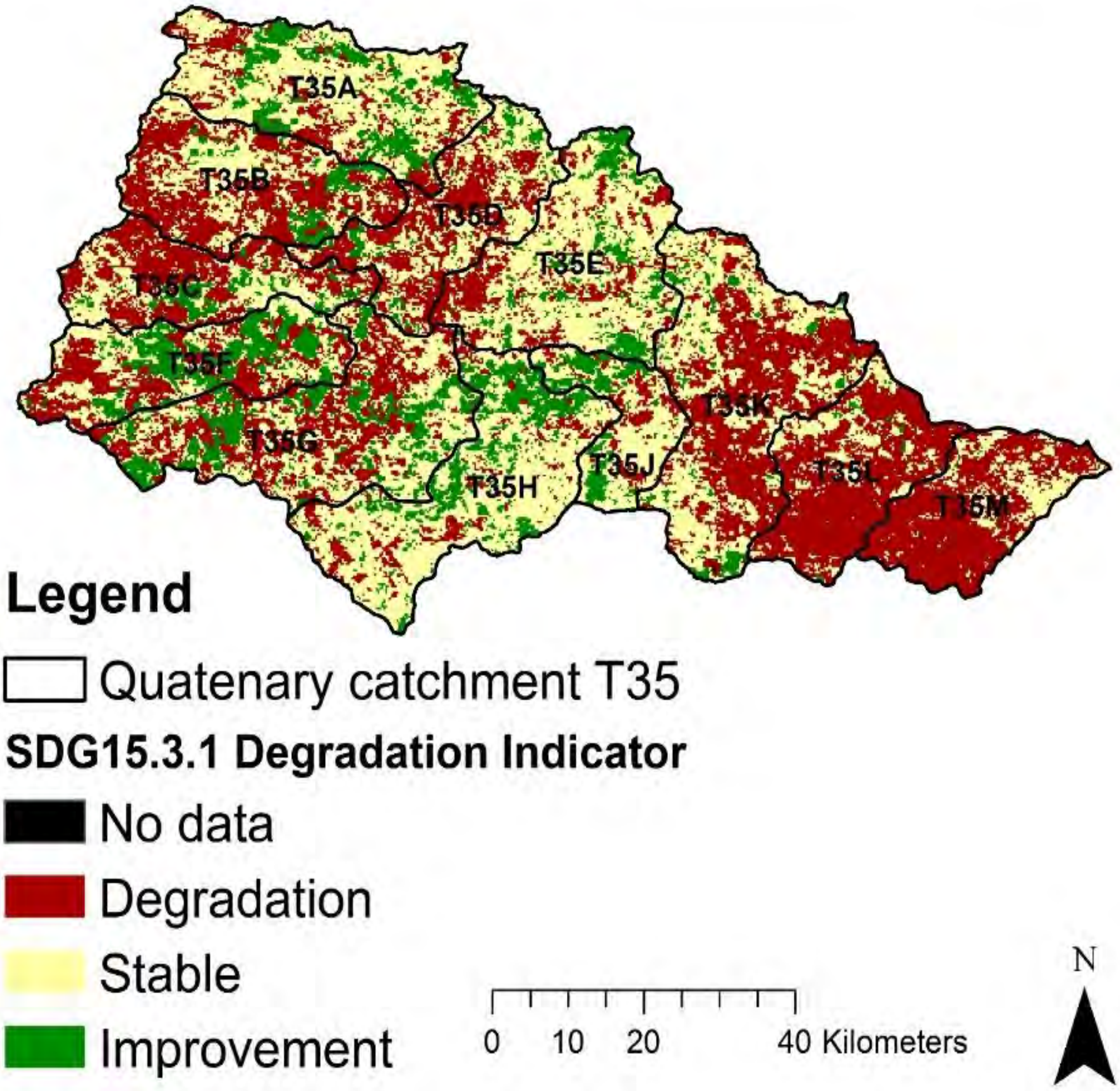


Figure 3.11: The final SDG 15.3.1 degradation indicator without climate correction for Tsitsa River catchment from the year 2000 to 2015.

Summary of SDG 15.3.1 Indicator with Climate correction (RUE)		
	Area (sq km)	**Percent of total land area**
Total land area:	4924.7	100%
Land area improved:	253.8	5.15%
Land area stable:	2673.8	54.29%
Land area degraded:	1995.7	40.52%
Land area with no data:	1.3	0.03%

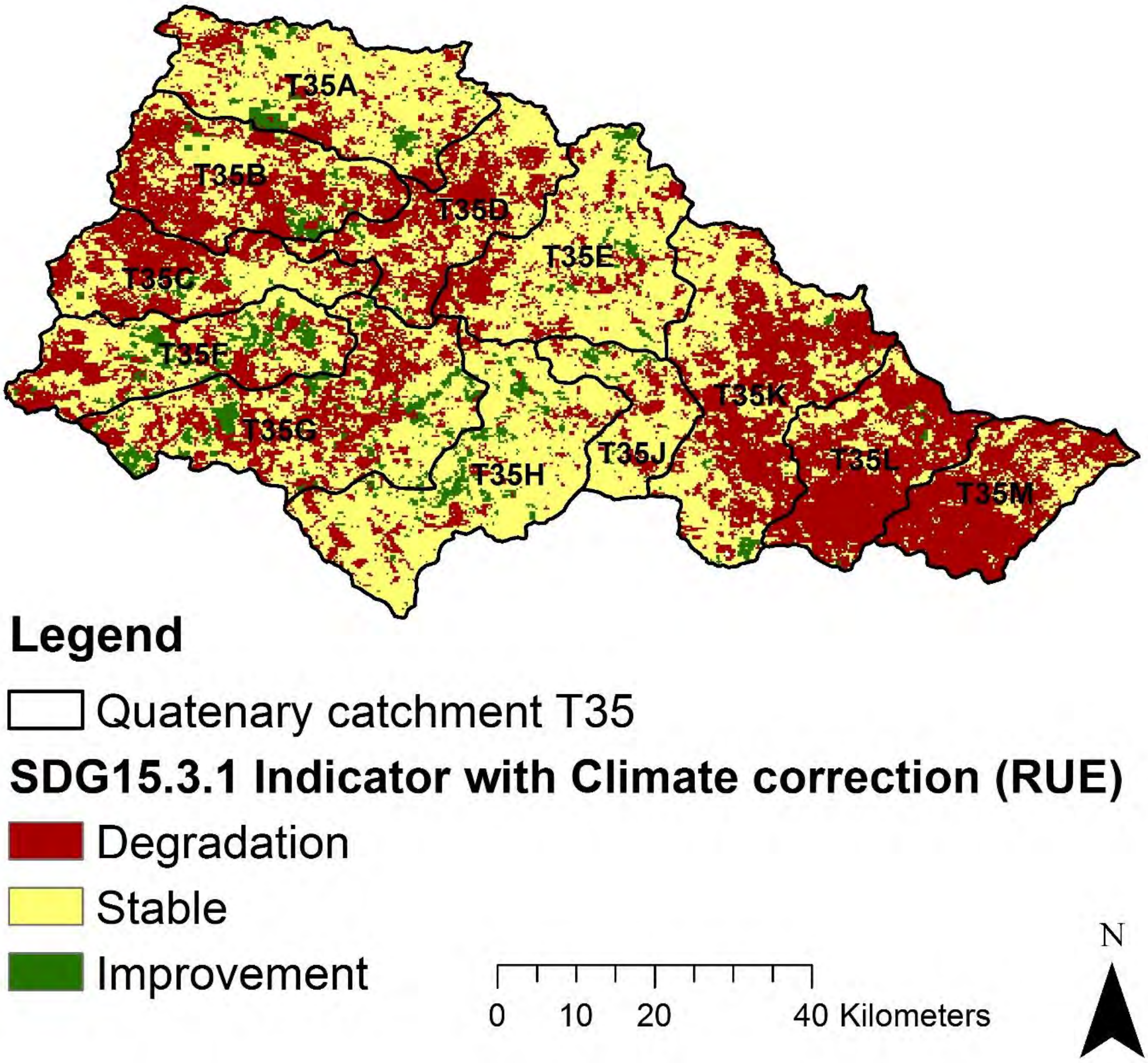


Figure 3.12: The final SDG 15.3.1 degradation indicator with climate correction for Tsitsa.

3.3.5 Land degradation in the targeted key EI

Results of land degradation in the targeted EI in the study catchment suggest that more than half of each EI category is stable. Half of the grassland category is stable (54% covering 1916.82 sq. km), mostly in the catchments T35A, T35E, T35H and T35J, with few areas showing improvement (3% covering 132.28 sq. km). Grasslands in the quaternary catchment T35K, T35L, and T35M are mostly degraded (43% of 1516.82 sq. km) (Figure 3.13).

In the cultivated land cover category, approximately 57% (887.49 sq. km) is stable, with the most degraded (39% of 606.87 sq. km) areas in the lower parts of the catchment and the upper catchment (Figure 3.13). Improved areas in cultivated land show a small proportion of about 4% (59.22 sq. km). Wetlands in the catchment are predominantly found in the upper section of the catchment from quaternary catchment T35A to T35G and are partially distributed in the lower parts of the catchment T35K and T35M (Figure 3.14). For wetlands are mostly stable (56% covering 95.31 sq. km), with improvement (5% covering 8.91 sq. km) and degraded areas (39% covering 67.05 sq. km). All quaternary catchments in the study area showed partial degradation of wetlands, with more degradation in T35K and T35M (Figure 3.14). In all the quaternary catchments, riparian vegetation was degraded (39% covering 357 sq. km), although more than half of the area is stable (55% of 501 sq. km), particularly in quaternary catchments T35A, T35E, T35H and T35G.

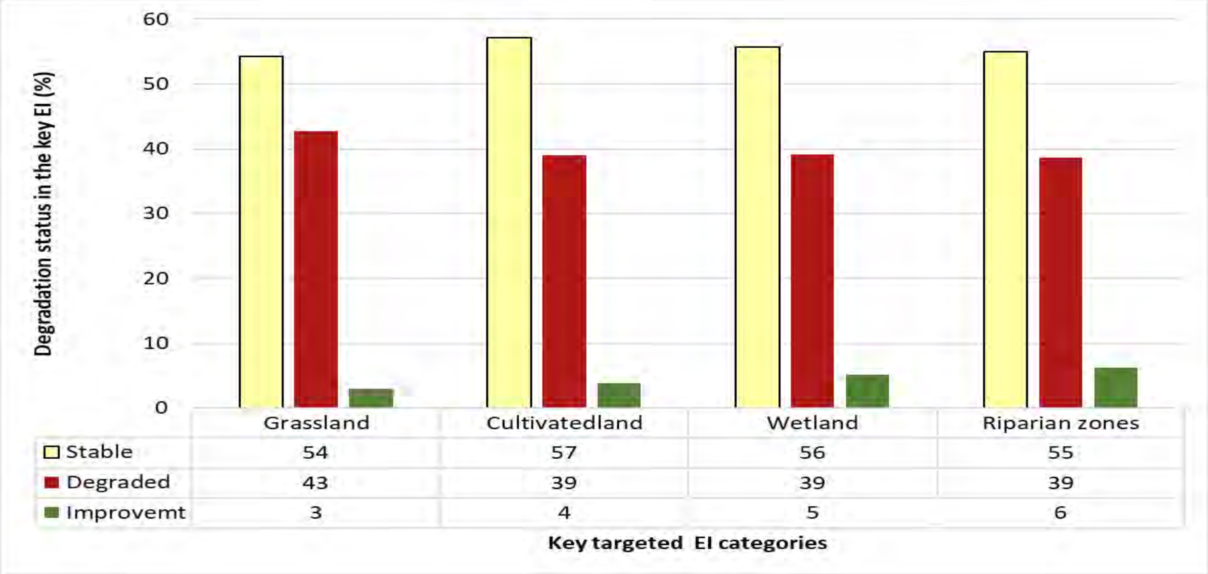


Figure 3.13: Land degradation status in the key targeted ecological infrastructure in the Tsitsa River catchment based on the number of pixels per EI polygon.

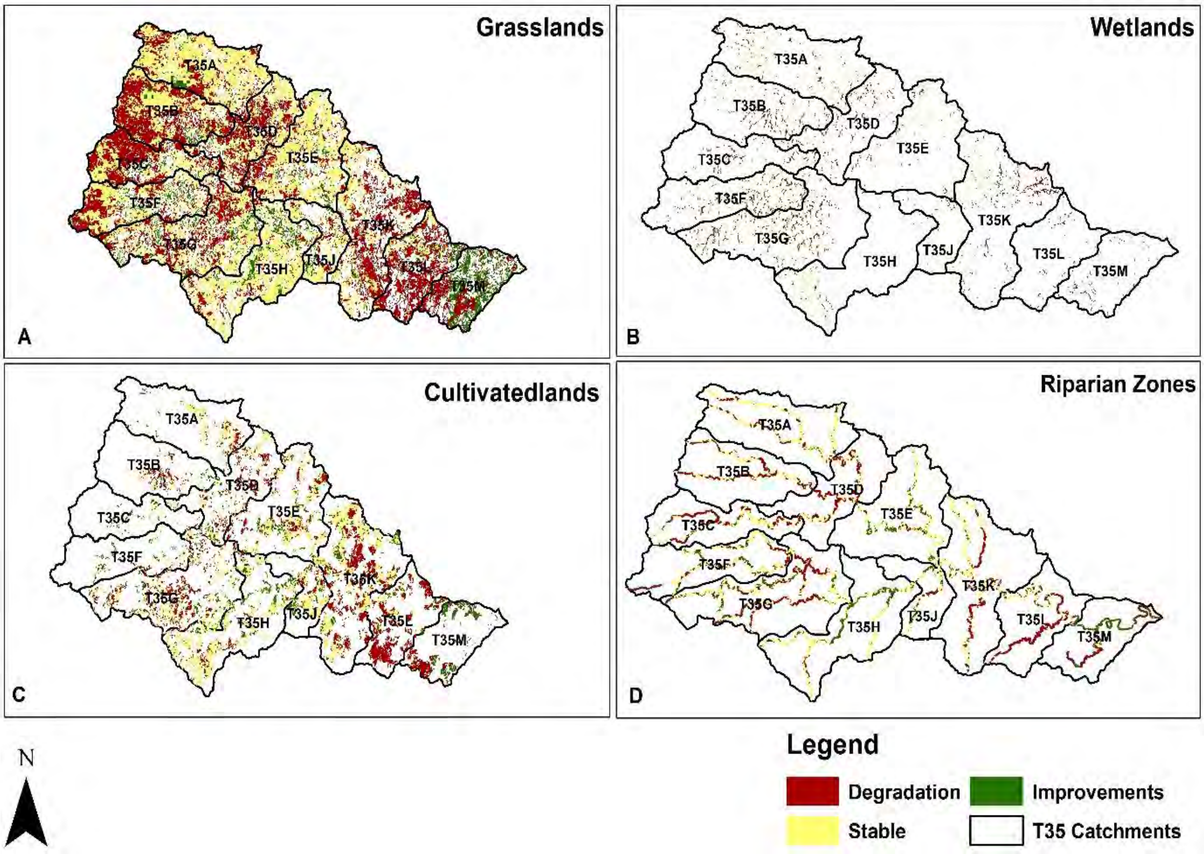


Figure 3.14: Image A represents land degradation distribution in grasslands; B shows the distribution of degradation status in cultivated land; C is wetlands land degradation distribution; D shows land degradation status in the riparian vegetation with a 150 m river buffer in the Tsitsa River catchment.

3.3.6 Comparison results from Trends.Earth with local land cover datasets

The degradation in wetlands identified by Trends.Earth tool correlated with the NBA dataset and showed that degraded wetlands based on land degradation indicator (90%) were identified as critically endangered, losing structure and functional composition (Figure 3.15). Wetlands that are moderately modified and heavily critically modified were presented as degraded by the Trends.Earth tool means that heavily modified wetland has lost its natural conditions and been modified in adverse ways; in short, they are degraded.

Comparing degraded areas from the land degradation indicator with the National Land Cover change assessments results were correlated. The Trends.Earth tool indicated less changes in the land cover indicator, with some changes occurring mostly in the upper catchments, which are identified by the land degradation indicator as degraded were also identified as degraded by the NLC change assessment, indicating a land cover transition. In the upper catchment, especially in the T35A, T35B, T35C, T35D, T35F and T35G catchments, more land cover transition has resulted in the loss of significant natural resources. The land degradation indicator showed that the middle part of the catchment is mostly stable, and the NLCA2018 also indicated that little transition in the land cover has occurred in the middle, which is mostly stable with no observed land cover change (Figure 3.16).

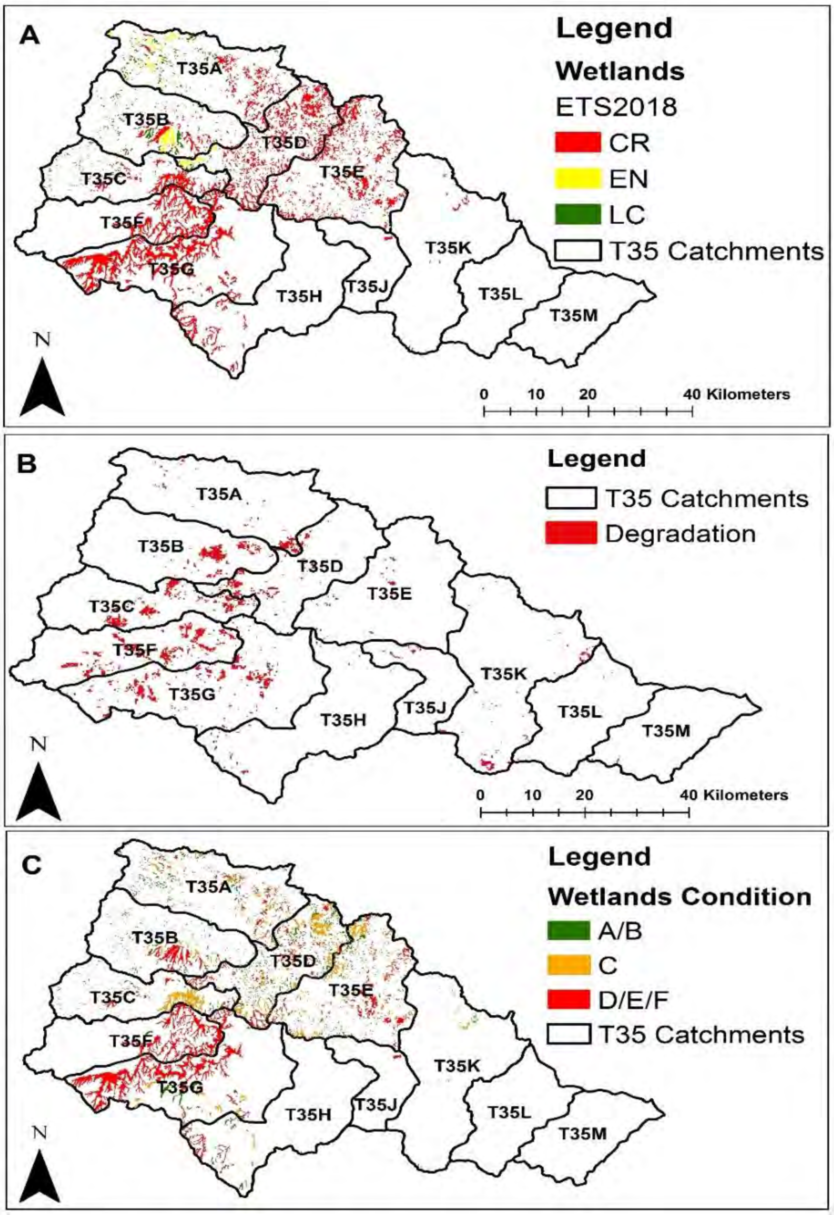


Figure 3.15: Map A: wetland presence Ecosystem Threat Status (ETS), critically endangered (CR), endangered (EN), and least concern (LC) based on NBA 2018 data. Map B: wetland degradation status based on the SDG15.3.1 indicator. Map C: wetland condition (AB)natural to near natural, moderately modified (C), and serious to critically modified (DEF) based on the NBA 2018.

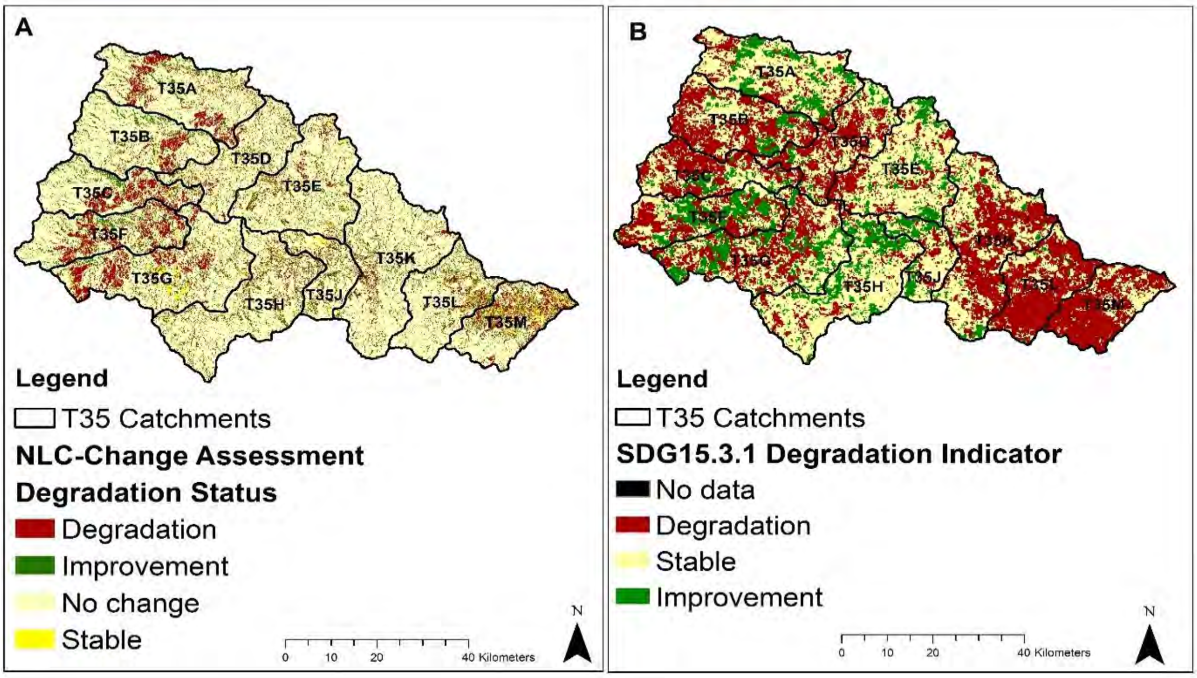


Figure 3.16: Map A: land cover degradation status using NLC-Change Assessment (based on the land cover change from 1990-2018); Map B: land degradation in the catchment based on the Trends.Earth tool.

3.4 Discussion

Land degradation is one of the major threats to terrestrial ecosystems, reducing their productivity and ecosystem services rendered to humans (FAO, 2016). Land degradation can be driven by a natural process but is accelerated by human activities (FAO, 2011, 2016). The natural drivers include changes in seasonal rainfall (rainfall variability), causing an increase in rainfall to cause floods or reduction in precipitation leading to drought and wildfire, triggering soil, vegetation and water degradation (Department of Agriculture, 2009; DEA, 2012; FAO, 2016; Cowie et al., 2018). Transformation in EI can lead to a loss in the natural capacity of EI to provide various ecosystem services, depending on the degree of change (SANBI, 2013a); therefore, it is essential to monitor environmental degradation as a way of reporting and informing decision making. This study assessed land degradation status using the SDG15.3.1 indicator (land degradation indicator) in the Tsitsa River catchment based on land productivity, land cover change, and soil organic carbon using the one-out all-out rule as explained in the methodology section.

The Trends.Earth tool assesses land productivity using the NDVI trend analysis, looking at Net Primary Productivity (NPP) (Conservation International, 2019).The land productivity findings with climate correction indicated that more than half (55.03%) of the area have stable land productivity. Thus results may mean that approximately half of the catchment is not experiencing further degradation, but neither is improving or recovering (UNCCD, 2017, 2018). The results indicated almost half (40.22%) of the catchment had degraded land productivity, making the land productivity indicator the major contributor (compared to land cover and soil organic) to the overall catchment degradation status. The 40.22% of area degradation in land productivity with climate correction may indicate human-induced changes in plant productivity in the catchment (Sims et al., 2019).

The decline in NPP in the catchment may indicate degradation in the catchment because generally, the loss in primary productivity or NPP is associated with land degradation (IUCN, 2015; Gonzalez-Roglich et al., 2019). However, not all changes in NPP indicate land degradation or improvement (Bai et al., 2008a) because it depends on the degradation type. For instance, bush encroachment and increase in invasive species in grasslands will cause an increase in primary productivity, leading to an increase in the NDVI during the assessment period, and this degradation type can threaten people's livelihoods in the areas (Graw et al., 2017; Cowie et al., 2018; Gonzalez-Roglich et al., 2019). Hance, the good practice guide of the Trends.Earth document suggested the validation of land degradation neutrality using the local datasets (Sims et al., 2017) and the use of local stakeholders to verify degradation on the ground and identify false-positive results (Cowie et al., 2018). Thus, in this study, degradation results are compared with South Africa's National Land Cover Change Assessment datasets to identify the false-positive results.

In this study, areas with increased land productivity were found mostly in the upper catchments in commercial land areas with plantations or planted forest and in some communal areas, as indicated in Figure 3.8 (Van der Waal et al., 2017; GEOTERRAIMAGE, 2019a). The improvement in land productivity in the upper catchment may be caused by the increased soil nutrient stock from plantations and areas invaded by invasive plants (McLeod et al., 2016) and the changes in grassland areas into cropland or plantation is defined as degradation (Table 3.3). The study by Graw et al. (2017) indicated an increase in vegetation productivity in the Eastern parts of the Eastern Cape Province (where this study is found). The increase in vegetation productivity can relate to bush encroachment, which is identified as a problem because encroachment is an indicator of land degradation (Graw et al., 2017). The other cause of an increase in vegetation productivity identified by Graw et al. (2017) was the high rainfall in the Eastern side of the Eastern Cape. Since vegetation growth can be influenced by precipitation variability (Bai et al., 2008b), climate variability is an important factor when assessing productivity and removing the impact of climate variability that impact the productivity state (Symeonakis & Drake, 2004). Therefore, in this study, the climate factor was removed to assess land productivity and degradation in the catchment. The study results suggest that catchment decline in land productivity is associated with areas with grasslands loss, particularly in the lower catchments (GEOTERRAIMAGE, 2019b). The reduction in land productivity could indicate ecosystem changes in vegetation (de Jong et al., 2011).

Additionally, degraded soils can cause a decline in land productivity (Obalum et al., 2012), so reducing the catchment land productivity may be associated with soil degradation due to soil erosion. The study area is characterised by erosive duplex soils, with widespread deep gully erosion, especially in the middle and lower parts of the catchment (Le Roux et al., 2015; Van der Waal & Rowntree, 2018). Although land productivity can indicate degradation, using the indicator alone to assess degradation tends to overlook other forms of degradation (Gibbs &

Salmon, 2015). Hence, the use of land productivity alone as an indicator for degradation is not recommended.

Thus, land degradation was assessed using land productivity indicators and two other indicators (land cover change and soil organic carbon) in this study. The results of land cover change and land cover status in the catchment showed that 98.44% of the catchment is stable, with a minimal transition on land cover, with some areas showing transition in the upper catchments. The low degree of land cover transition in the area may be because the catchment is less developed in terms of built infrastructure (Le Roux et al., 2015) and is mostly rural. Furthermore, a small proportion (1.23%) of land cover in the study area was improving; these areas are located mostly in the upper catchment, where most wetland and cultivated lands are widely distributed (Huchzermeyer et al., 2018b; GEOTERRAIMAGE, 2019b). The NLC change assessment for 2018 also indicated a positive change in land cover classes in the upper parts of the catchment. In addition, this study identified an area of less than 1% of land cover change being degraded due to tree-cover loss as the main change in land cover in the catchment, particularly in the upper sections. The catchment T35, is dominated by extensively planted forestry, about 7.5% (GEOTERRAIMAGE, 2019b). Therefore, tree cover changes could result from deforestation (as indicated by the high transition of tree-cover losses in the upper sections of the catchment) during the harvesting period in plantations. The decline in tree-covered areas in the catchment may also be because the forest in the catchment is used as a source of different materials, such as firewood and building materials. It is possible that signs of degradation in the upper catchments may be caused by natural factors, such as erosion of unstable soil caused by wind and water (Bai et al., 2008a), especially in high elevation areas. In this study, the catchment is characterised by steep slopes with shallow soils and gullies with a high risk of erosion (Van der Waal et al., 2017), which may be the reason for degradation in land cover in the upper catchments.

The results of soil organic carbon showed that the changes in SOC were influenced by the changes in land cover and land use in the areas. Trends.Earth analysis results indicated that the SOC in the catchment is mostly stable (99.87%), possibly because the area is dominated by a grasslands, which host large quantities of SOC (DEA, 2015). The changes in SOC are also influenced by changes in land cover and land use; thus, the impact of land cover on SOC is indicted by reduction or loss in SOC; loss (0.10% of degraded SOC) was associated with losses in tree cover and grassland. Grassland coverage influences soil nutrients and storage (DEA, 2015; Sims et al., 2019); therefore, loss of SOC can indicate soil degradation (loss of soil fertility and soil erosion) (FAO and ITPS, 2017) because low fertility enhances the risks of poor vegetation cover, causing more soil erosion (Van der Waal et al., 2017). In addition, the grassland area in the Tsitsa catchment contained planted trees that add more carbon stock to the soil (DEA, 2015), so tree cover loss may impact SOC storage in the catchment. The areas that show an increase of 0.01% in SOC may be the gain in wetlands in the areas because wetlands store a significant amount of nutrients. Nevertheless, SOC has a significant influence on the soil's physical, chemical, and biological properties and is critical for improving soil fertility and quality, water retention, reducing soil erosion, and enhancing crop productivity (UNCCD, 2018). Thus, the level of SOC can be used as a proxy for the ecosystem and soil health (UNCCD, 2018).

The SDG15.3.1 sub-indicator results indicated that approximately 41% of the total land area in the Tsitsa River catchment is degraded, with most degradation occurring in the upper catchments and lower sections of the catchment. The findings of this study of land degradation are consistent with the SANBI (2013a) results in assessing ecological infrastructure within the study area; the SANBI assessment indicated that about 36% of land in the catchment had been transformed (SANBI, 2013a). The degradation in the Tsitsa River catchment is due to loss of vegetation cover and soil erosion (Van der Waal et al., 2017) caused by various issues (overgrazing, soil erosion, increase of old cultivated land, unsustainable crop farming, and wood encroachment) (Sigwela et al., 2017; Huchzermeyer et al., 2018). For instance, the presence of abandoned cultivated lands in the catchment is one of the leading causes of land degradation (Huchzermeyer et al., 2018b) because abandoned cultivated fields are associated with bare land (Rowntree et al., 2004). The bare land in the abandoned cultivated areas is commonly encroached by woody vegetation (shrubs) and alien invasive plants, making about 10% of coverage (SANBI, 2013a). Alien plant invasion and woody encroachment are major drivers of degradation (van Wilgen et al., 2008; DEA, 2012; Luvuno et al., 2018; Yapi et al., 2018). As a result, encroachment of woody vegetation is a problem in the Eastern Cape, causing land degradation (Van der Waal et al., 2017).

The abandoned cultivated fields are degraded, as indicated by the presence of large gullies (Le Roux et al., 2015; SANBI, 2013). Degradation in the high terrain in the Tsitsa River catchment is also evident in the shallow soils in the upper catchment (Van der Waal et al., 2017). Because the catchment is dominated by communal land, mostly located in steeper slopes, these areas are generally subjected to higher levels of degradation (Hoffman & Todd, 2000a; Meadows & Hoffman, 2003). The Tsitsa River catchment is characterised by communal areas which are associated with poor grazing and farming practices (Meadows & Hoffman, 2003; Von Maltitz et al., 2019); an issue that has been identified in other studies (Bai et al., 2008b; Blair et al., 2018) as a cause of degradation in communal lands and croplands. The results of this study indicate that the drivers of degradation in the catchment are anthropogenic.

3.5 Limitations

Although the plug-in tool determined the extent of degradation within the catchment, there are limitations associated with the use of global data. Trends.Earth default data in the tool is at a coarse resolution of 300 m (UNCCD, 2018), which can be used to assess and monitor land degradation at multiple scales. However, the default dataset on Trends.Earth tool will not be relevant at all scales and geographies depending on the catchment scale (Conservation International, 2019; Gonzalez-Roglich et al., 2019). In this study, the land degradation analysis was assessed at the catchment scale, and there is the possibility of inconsistency between the trends data and the actual ground observed situation. Moreover, the land cover classes in Trends.Earth were integrated from 210 classes into seven, meaning that the possible generalisation and land cover class is determined by dominant detected per image, meaning that small-sized land cover classes, like wetlands, were identified less often. Although the plugin allows users to use local land cover data sets, in this study, it was not feasible to use the available South Africa National Land Cover Change Assessment because it covers different baselines of change from 1990–2018, while this study covered a baseline from 2000–2015. Hence, the SANLC assessment data is used for substantiation degradation results from Trends.Earth.

Although SOC is an important indicator for assessing land degradation, there are limitations associated with using the SOC indicator. These limitations include data accuracy; data availability; the high spatial heterogeneity of soil properties, combined with relatively slow rates of change over time; the high cost of monitoring changes in soil properties (Sims et al., 2019). Assessment of carbon stock in the soil below the ground can be costly, and little data are available (IUCN, 2015). These limitations associated with SOC may cause an error and inaccurate data outputs for reporting land degradation in the area; this may affect planning and decision-making to deal with land degradation.

3.6 Conclusion

Trends.Earth tool used in Quantum Geographic Information System (QGIS) used the combined land cover, land productivity, and SOC indicators using the one-in, all-out rule to calculate the SDG15.3 indicator in the catchment. Generally, the Tsitsa River catchment is ‘mostly stable’ with ‘moderately degraded’ in other parts of the catchment, driven by the physical characteristics of the catchment as indicated in the study's outcomes. However, some areas within the catchment show an improvement or recovery from degradation to better conditions. Although more than half of the catchment is stable, there is room for improvement to restore and rehabilitate degraded land areas to keep the catchment in good, near-natural conditions. Overall, Trends.Earth tool is a valuable method that can be used at a different scale, although it provides better results when employed at a large scale and uses the available approved local dataset.

Chapter 4: Prioritisation of suitable restoration areas for streamflow regulation using stakeholder and spatial data in multi-criteria decision analysis (AHP method)

4.1. Introduction

There is a global effort to deal with ecosystem degradation, including implementing policies, strategies, and actions. Actions dealing with degradation have resulted in the idea of restoring natural capacity to increase the sustainable flow of ecosystem services to people, an aspect that has increasingly been considered in making decisions (Alexander, Aronson, Whaley & Lamb, 2016). Hence, ecological restoration of degraded ecosystems has become a global priority (IRP, 2019; Alexander et al., 2016). “Restoration" is defined as "Any intentional activity that initiates or accelerates the recovery of an ecosystem from a degraded state" (IPBES, 2018, p.30). Restoration aims to protect vital ecosystem services, which have the potential to provide the following benefits: biodiversity, climate regulation, water retention, food and materials (IRP, 2019), especially during dry periods. Thus, ecological restoration can be seen as a long-term solution to mitigate the impact of drought (DEAT, 2004).

In South Africa, ecological restoration is facilitated by existing restoration programmes, such as Sustainable Land Management (SLM), and the SLM programmes can be used to achieve land degradation neutrality (Lötter et al., 2009). Sustainable Land Management actions can also improve ecosystem health and productivity (Orr et al., 2017) through practices that avoid, reduce, restore, and rehabilitate degraded land (Cowie et al., 2018). Land management practices can help achieve Sustainable Development Goals (SDGs) and improve South Africa's development status. For instance, rehabilitation of degraded lands in the catchment can advance ecosystem health and well-being, improve livelihoods, mitigate climate impacts, and enhance biodiversity. By maintaining and enhancing the ecosystem, soil fertility increased, crop production and yield are enhanced, high quality and food and water and medicinal plants are produced sustainably, and biodiversity is protected (SANBI, 2014; Mander et al., 2017). Landscape restoration can contribute towards SDGs 1 (reduce poverty), 2 (hunger), 3 (good health and human-wellbeing) and 15 (life on land) (Gichuki et al., 2019; IRP). Therefore, Ecological Infrastructure needs to be maintained, managed, and in some cases, restored (SANBI, 2013a, 2014).

There is extensive evidence of positive ecosystem restoration results, but there are limitations to restoration effectiveness. These limitations include limited funds from public and private sectors, limited resource capacity, lack of effective monitoring, and poor decision-making about selecting areas for restoration and planning to restore the degraded ecosystems (DEAT, 2004; Alexander et al., 2016; Skowno et al., 2019). Moreover, the management of natural resources is usually complex; a method that considers different decision-making factors and includes stakeholders is necessary. In planning and decision-making for restoration, it is crucial to consider stakeholders and interested and affected parties' voices to make better decisions (Balzan et al., 2018).

Methods like the multi-criteria decision analysis (MCDA) that consider different decision-making aspects are useful in the process of making decisions for better possible solutions. The MCDA is a method that is commonly used to make decisions about complex issues, such as natural resource management (Mutikanga & Sharma, 2011). The method has been widely used in various fields of study, but Huang et al. (2011) have indicated the value of a broad application of the MCDA assessment in the environmental science field (Huang et al., 2011). The MCDA method has been commonly used in resource management studies (Mutikanga and Sharma, 2011; Forsyth et al., 2012; Martin & Poff, 2016; Rojas & Loubier, 2017) and was used by Favretto et al. (2016) to assess the value of ecosystem services provided by dry grassland in land use and land management in the Kgalagadi District in Botswana. The results indicated that community grazing lands provide multiple ecosystem services in the areas (Favretto et al., 2016)

Many approaches exist under the umbrella of the MCDA (Huang, Keisler & Linkov, 2011) and include the following methods: Analytic Network Process (ANP); preference ranking organisation method for enrichment evaluation (PROM-ETHEE); the elimination and choice translating reality (ELECTRE); the technique for order preference by similarity to ideal solutions (TOPSIS); multi-attribute utility theory (MAUT) and the Analytic Hierarchy Process (AHP) (Daim et al., 2013). All of the above MCDA methods are effective in planning and decision-making and have been applied in solving various real-world problems (Daim et al., 2013), but this study focuses only on the AHP analysis to select suitable restoration areas for streamflow. The AHP is the most frequently used methodology of all the MCDA methods in environmental studies because it explores different opportunities and evaluates options by different stakeholders of multiple aspects, both qualitative and quantitative (Daim et al., 2013).

Saaty (1980) developed the AHP, commonly used in natural resource decision-making, as a method for solving complex problems effectively (Klutho, 2013). The AHP is a good decision support system that uses a range of quantitative and qualitative alternatives (Mutikanga & Sharma, 2011) and includes stakeholder inputs in the analysis (Lade et al., 2012). Thus, it may help the decision-maker set priorities, make the best decisions (Saaty, 1980) and reduce bias in decision-making by using a pair-wise comparison matrix that considers other factors and alternatives (Thungngern, Sriburi & Wijitkosum, 2017).

The AHP method is mostly used in Environmental Impact Assessment (EIA), environmental strategies, and Geographic Information System (GIS) assessments (Huang et al., 2011) and has been applied to the analysis of water-related problems, particularly in water policy evaluation, strategic planning, water resources management, and infrastructure selection (Hajkowicz & Collins, 2007; Mutikanga & Sharma, 2011). Thungngern et al. (2017) conducted an MCDA study in water-related issues using the AHP for water resources management, and the outcomes indicated that an AHP method could be useful in water management by incorporating stakeholder participation in making decisions. In South Africa, Forsyth et al. (2012) used the MCDA framework through the AHP method incorporating stakeholder inputs to prioritise areas for control of invasive alien plants in the Western Cape Province.

The AHP method can also be integrated with other techniques, like the Geographic Information System (GIS), in which the AHP and GIS methods are commonly used in solving complex problems with multiple objectives (Rojas & Loubier, 2017). Hence, in this study, the MCDA (AHP) analysis with GIS is used to identify the location of naturally occurring ecosystems that can increase or maintain stream flow when they are restored or maintained in a natural to near-natural condition. The AHP approach and GIS are used to identify suitable restoration areas in wetlands, grasslands, riparian zones and abandoned cultivated fields that could play a significant role in flow regulation and mitigate droughts impacts in the study catchment. The key natural resources were selected based on the potential to influence hydrological flows in the catchment and the important ecosystem services such as water, food, and raw materials provided to rural communities by those natural resources.

As part of the AHP analysis, the Participatory Geographic Information System (PGIS) method was employed to involve stakeholder views in decision-making. A PGIS is commonly used in land use planning and management (Brown & Kyttä, 2014) and combines different geospatial information management tools and approaches, such as maps and satellite images. This method was used for the participatory planning processes in rural areas to demonstrate people's knowledge visually (Brown & Kyttä, 2014) and to include the stakeholder inputs within the AHP process. So, in this research study, the PGIS method was used for community engagement which enhanced understanding of the importance and benefits of natural resources to people and accounted for stakeholder views in selecting suitable restoration EI areas for drought mitigation. Also, the PGIS method was used to identify, locate, and prioritise the key ecological resources of the community; to provide input into a prioritisation plan for restoring resources; to gain community-based participation to get insights into how the key EI changed in terms of degradation, and to prioritise important EI for restoration.

During restoration or rehabilitation, it is important to ensure suitable sites regarding environmental costs, benefits, and resilience (Cowie et al., 2018) because restoring and maintaining ecological infrastructure can increase dry season flows and improve water quality (SANBI, 2014). So, the study's objective was to develop a prioritisation plan for the rehabilitation of degraded ecological infrastructure to improve drought mitigation and benefit local communities in the catchment. Selecting site stakeholder engagement in community mapping was used to provide community input for the rehabilitation plan. The study employed the AHP method in GIS to select the suitable areas for restoration in the ecological infrastructure to mitigate drought impacts. The results output can benefit the restoration and Sustainable Land Management planning for the catchments that supply water to the proposed dams in the study catchment, and the outcomes of the study are indicated in section 4.3 of the thesis.

4.2. Methodology

4.2.1. Stakeholder engagement in community mapping using the workshop approach

In the participatory workshop, Google Earth and printed maps of the area were used to locate the community's targeted natural resources. Landmark features helped the participants locate their area on the maps and point out the ecological infrastructure important for their livelihoods and environment and the priority areas were digitised using the Google Earth platform. The CLOs working with the Tsitsa Project team invited the community from both villages to the workshop and the invited participants were residents who had lived in the area for a minimum of 10 years and were older than 18 years. Forty participants attended the workshop, including the local sub-headman, three CLOs, a representative from Lima and the Tsitsa Project, and members from the Rhodes Research team (three master's students from the Institute for Water Research, Rhodes University). The following agenda was used to govern both the workshop structure and to include the community's voice in the process.

a. Welcome and introductions: The workshop, facilitated by the Rhodes research team and the Tsitsa facilitators, opened with prayer and participants were welcomed. An icebreaker used for introductions created a sense of welcome and equality.
b. Introductions from organisations present: Facilitators introduced the purpose of the workshop and read the consent document (**Appendix 3**) in English and translated it into IsiXhosa. Attendees were assured that the study had been ethically approved by the Rhodes University Research Office and had been granted ethical clearance **(Ethics Clearance letter: Appendix 2).**
c. Participatory mapping process: The first workshop took place on 19 November 2019 at Ntatyaneni Primary school, and the second workshop was conducted in Sigoga village on 22 November 2019. The workshop facilitators divided the communities into three randomly selected groups (Figure 4.1), each assigned a CLO and a member of the Rhodes University team as facilitators. The workshops were facilitated in both English and isiXhosa.

Figure 4.1: Workshop groups in Sigoga and Ntatyaneni villages.

d. **Community mapping and presentations:** As a first step of the exercise, each group was asked to sketch (i.e., map out) the catchment, describing the village and focusing on pointing out the areas where the key targeted natural resources are located (Figure 4.2). Each group was given 40 minutes for drawing and 20 minutes for presentation to the rest of the group (Figure 4.2).

e. **Natural resource prioritisation:** During this session, the direct-to-digital Participatory Geographic Information System (D2D-PGIS) tool was used to map out the location of key natural resources and identify priority areas for rehabilitation and project the image onto the wall where everyone could see it. The D2D mapping uses Google Earth to directly map information from the community (Weyer et al., 2019). At the end of the mapping exercise, all the groups were combined. Three people from the workshop pointed out the location of targeted natural resources on the displayed Google Earth image and selected the priority resources for rehabilitation identified by the groups. Based on community needs, key natural resources for rehabilitation were prioritised for three targeted natural resources (springs/wetlands, abandoned cultivated land, and grassland/rangelands), excluding riparian vegetation. During this process, everyone was welcome to make suggestions and correct each other (Figure 4.2).

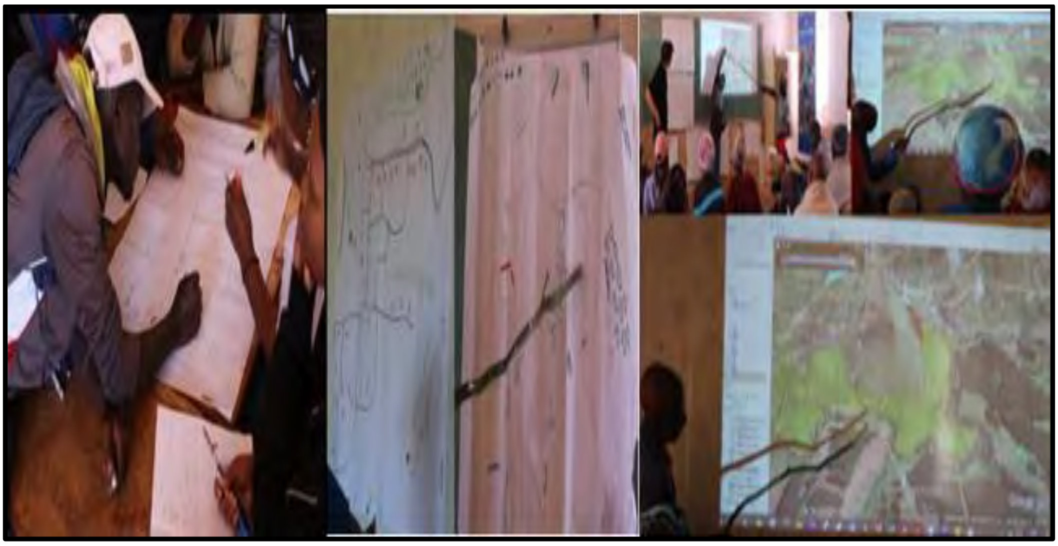


Figure 4.2: Images of the workshop processes during the prioritisation of natural resources.

For the riparian zone, an informal discussion was used rather than the methods described above. Participants were asked if they had noticed any changes in riverbanks in the past 20 years. Discussion points were noted and are reflected in the results section. At the end of the workshop, four community members were asked to accompany the Rhodes University Research team to observe nearby prioritised resources mentioned during the sessions.

4.2.2. Assessment of suitable restoration priority areas of EI using the AHP method

The Analytical Hierarchy Process method consists of six steps: (1) define the main goal; (2) determine attributes and criteria; (3) create a pair-wise comparison matrix; (4) perform the judgement of the pair-wise matrix; (5) determine weights, and (6) check for matrix consistency (Saaty, 2000). In this study, the three main criteria: Ecosystem Health (criterion 1), Water Provisioning (criterion 2) and Social Benefits (criterion 3), were derived based on community mapping workshops in the two villages within the study area (Section 1.4). The spatial dataset used in the study analysis is shown in Table 4.1. The 12 attributes (spatial datasets) used for each criterion to achieve the main goal were determined by the Research Members of the Water Research Commission Project (K5/2928). The attributes were approved by the project reference members and experts on ecological restoration, resource and catchment management, and the attributes were selected based on literature and available datasets related to the goal. The details of the justification of using the 12 attributes are described in section 4.2.2.1 below.

Table 4.1: Spatial attributes dataset used for the criteria, with descriptions and spatial resolution.

Main criteria	Datasets	Description	Resolution
Ecosystem health	Land degradation indicator (Chapter 3)	Raster layer showing degradation states for key EI	250 m
	2018 Ecosystem protection level (Van Deventer et al., 2018; Skowno et al., 2019)	Raster file showing ecosystem protection level of terrestrial ecosystems excluding aquatic ecosystems	30 m
	Recently cleared areas (ESA-CCI, 2015)	Raster layer showing the transformation of tree-covered areas area to other land cover classes covering the period 1990-2015.	300 m
	Stream order (DWAF, 2006)	Vector layer with 1-7 stream order levels as line features	1: 500 000
	Present ecological status (Van Deventer et al., 2018)	NBA layer for inland aquatic ecological conditions	1: 500 000
Water provisioning	Estimated flow reduction by IAPs (Le Maitre et al., 2016)	Raster layer of % annual reduction factor by alien plants	250 m
	Groundwater recharge (Bailey & Pitman, 2015)	Raster map showing annual average aquifer recharge	1 km
	Surface water runoff (Bailey & Pitman, 2015)	Raster map showing water source areas by mean annual runoff	1arc minute
	National Wetlands Map (Van Deventer et al., 2018)	NBA vector layer of ecological condition, hydrogeomorphic type and protection level. Wetland size is also included as area (ha)	1: 5 000
Social benefits	Proximity	The distance from EI to the homesteads based on RSA sub-areas vector layer	1:250 000
	Population density (Stats SA, 2011)	Vector layer showing population density per km^2 (per square kilometre)	1: 250 000

4.2.2.1 Defining the spatial attributes and distribution in the catchment and their restoration importance for drought mitigation used in the AHP analysis

Attributes used in Criterion 1: Ecosystem health

1. Present Ecological Status (PES): The PES in the river and inland wetland ecosystem focuses on the degree of degradation (Skowno et al., 2018), with the PES attribute derived from the 2018 NBA inland aquatic database, which provides a range of river and wetland conditions from A (natural) through to F (severe modification) (Van Deventer et al., 2018). The assessment considers underlying indicators such as flow modification, physio-chemical characteristics and habitat condition (Skowno et al., 2018). Most rivers in the study catchment are moderately modified, while a small proportion exhibit natural to near-natural conditions. Most wetlands in the T35 catchments are seriously to critically modified, with a small portion of the wetlands in the upper catchment area are in natural to near natural conditions (Figure 4.3). The PES was selected to increase streamflow because it indicates changes in aquatic ecosystems (pollution and habitat degradation)**.** Moderately modified wetlands were given a higher-ranking score because they can be reasonably restored at a lower cost to improve their current condition to prevent further degradation. Natural wetlands were ranked lower than seriously critically modified wetlands and were given an average ranking score because natural or near wetlands may not need to be restored.

2. Ecosystem protection level (EPL): The ecosystem protection level is an indicator that demonstrates how well an ecosystem type is formally protected by law (Skowno et al., 2018). Protected areas are large areas of EI that can provide services, such as clean water, and can mitigate droughts and floods (Skowno et al., 2018). There are four categories for EPL: Well Protected (WP), where 100% of the ecosystem is protected; Moderately Protected (MP), where about where 50–99% of the ecosystem is protected; Poorly Protected (PP), where the extent protected is between 5% and 49%; and Not Protected (NP) where the extent protected is less than 5% of the target (Skowno et al., 2018). Protected ecosystems are less exposed to degradation (Hoffman et al., 2018), and therefore, a well-protected ecosystem is ranked high because it can maintain natural stream water flow in the catchment. Areas that are not protected by law are considered as being of low importance to increasing streamflow. The river ecosystem in the upper catchments is well to moderately protected. The main river systems are not protected and those in the headwater of the catchments are moderately protected, as is the case for wetlands in the upper areas; most wetlands in the catchment are not protected (Figure 4.3).

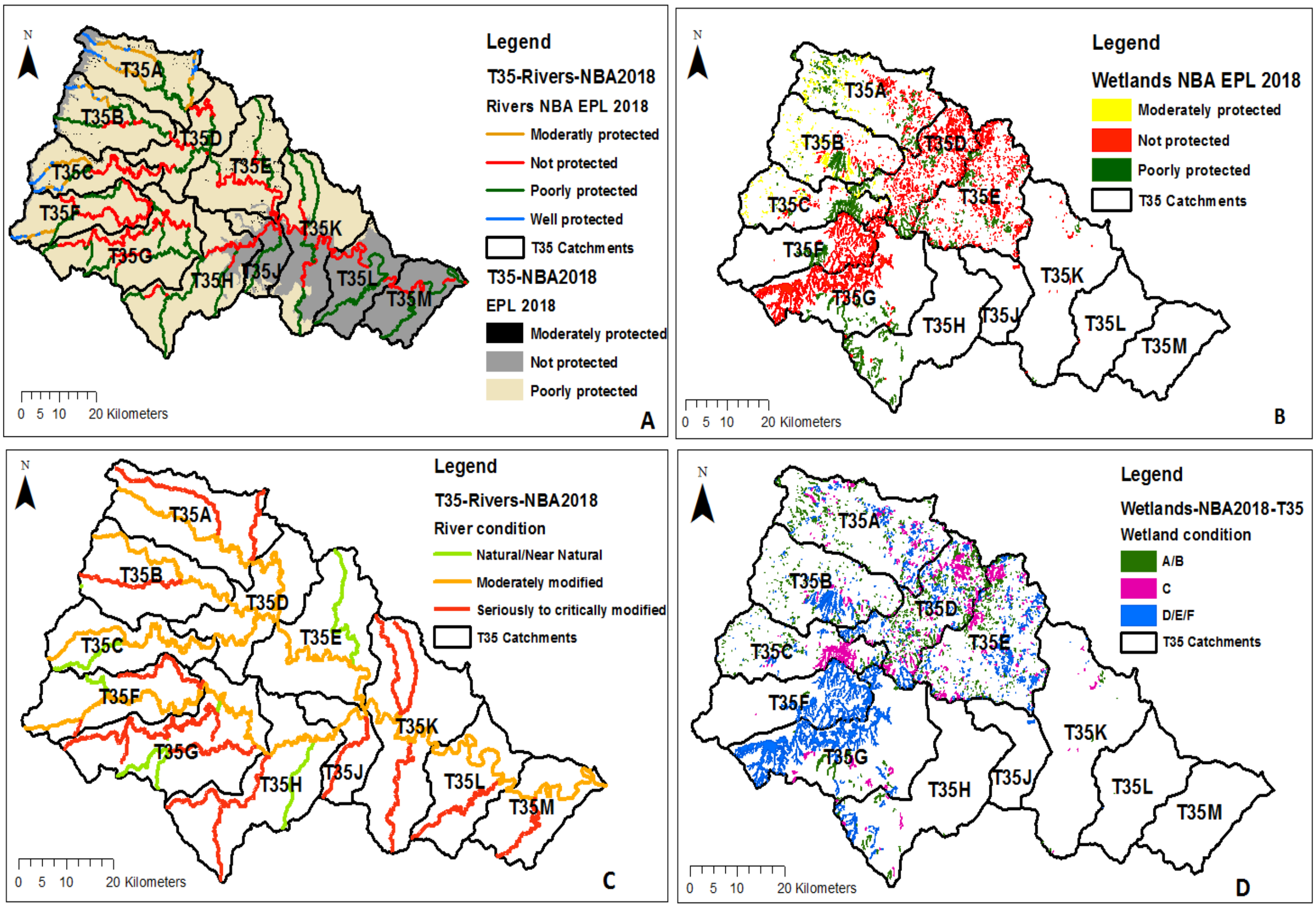


Figure 4.3: Distribution of the five ecosystem health attributes in the T35 catchments (National Biodiversity Assessment,2018).

3. Land degradation indicator: A land degradation indicator measures the proportion of degraded land over the total of a specific area (Sims et al., 2017). The final assessed SDG15.3.1 land degradation indicator was calculated using the integration of the three sub-indicators: Productivity, Landcover and Soil Organic Carbon, discussed in detail in Chapter 3. Land degradation indicator is reported using the three categories: stable, degraded and improving conditions, were derived from (Conservation International, 2019). Land degradation increases surface water runoff and generates quick flow (Le Maitre, Kotzee & O'Farrell, 2014). Changes in vegetation cover can also change catchment storage discharge dynamics, especially groundwater storage and groundwater discharge dynamics (Cheng et al., 2017). So, the land degradation indicator shows potential areas that can reduce water recharge in the catchment and reduce stream flow, mostly during the dry season. Therefore, degraded areas are given high priority for restoration to increase streamflow because degradation is widely spread within the catchment (Figure 4.4).

4. Recently cleared areas: The recently cleared areas are derived from tree-cover loss to other land cover categories. The data set observed from 2000 to 2015 (from the European Space Agency Land Cover Change) was at 300 m resolution. Grasslands dominate the catchment, with large areas invaded by alien plants, so the tree-cover loss was viewed as a catchment restoration method. Recently cleared areas were ranked higher than areas with no transition, assuming that the land cover might return to its natural condition after trees were removed. The areas with no change were ranked least important. Recently cleared areas are dominant in the upper parts of the catchment because plantations predominate in these areas (Figure 4.4).

5. Stream order: Tributaries are generally less heavily impacted than mainstem rivers (Skowno et al., 2018), but the existence of alien plants reduces streamflow (Le Maitre et al., 2000). So, clearing invaded areas in the lower stream orders (high tributaries) through programmes such as Working for Water would increase ecosystem services, such as water provision, by increasing water recharge into the rivers. In this study, the headwater streams (the first and second order streams) were ranked high, and main rivers (high order streams) were ranked as low importance for achieving the goal of increasing stream flow. The catchment has up to fourth-order streams with first-order streams dominating the catchment (Figure 4.4).

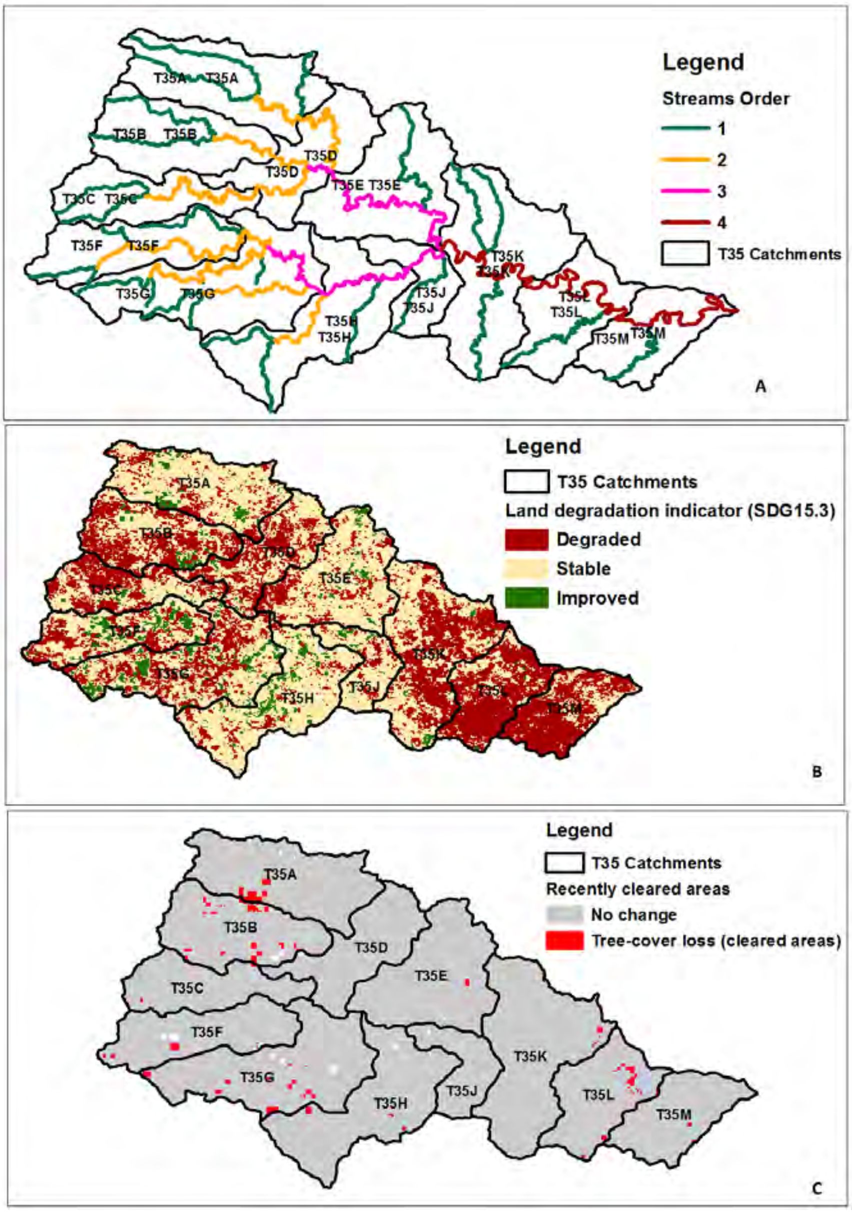


Figure 4.4: Distribution of the ecosystem health attributes, stream order (A) (DWS,2006), land degradation (B) (Trends.Earth Conservation International) and cleared area in the T35 catchments (C) (ESA-CCI, 2015).

Attributes used in Criterion 2: Water provisioning

1. Groundwater recharge to streamflow: Although river flow water originates from precipitation (Stoelzle et al., 2014; Anandhi et al., 2018), in dry seasons, groundwater discharge dominates river systems (Le Maitre & Colvin, 2008). This study uses baseflow recharge data from the Second National Groundwater Recharge Assessment from the South African Water Resources database (Bailey & Pitman, 2016) as a representation of available groundwater contribution to streamflow through baseflow. Areas with high groundwater recharge of more than 150 mm/a were ranked as high priority areas, and areas with low groundwater recharge (less than 36 mm/a) scored less critical. Groundwater recharge is mostly high in the upper catchments, but recharge varies within the catchments (Figure 4.5).

2. Estimated flow reduction due to invasive alien plants (IAPs): Invasive alien plants are a significant threat to freshwater in South African catchments (Yapi et al., 2018; Le Maitre et al., 2016) because alien plants growing away from the channel banks take up soil water and near-surface groundwater, leading to a reduction in surface flows in the channel. In this study, the estimated flow reduction by Le Maitre et al. (2016) was used to represent the percentage of reduction in surface water yield due to alien plant impacts. The estimated reduction of flow caused by alien plants in the catchment is 6% to 30%, and in the upper parts of the catchment, the flow reduction is 40% to 100% (Figure 4.5).

3. Surface-water yield (mm/a): Mean annual surface runoff is used to define the Strategic Water Source areas (Nel et al., 2013; Le Maitre et al., 2018)and is calculated by including all water flowing in rivers and receiving groundwater or interflow contribution. The surface water yield includes water source areas, high water production areas with an average annual surface runoff that exceeds 135 mm which supports downstream areas (Nel et al., 2013; Le Maitre et al., 2018) Strategic water source areas occupy a small surface area (8%) of South Africa's total area but contribute over 50% of the water supply, making them important freshwater source areas (Nel et al., 2017)**.** The areas with a mean annual runoff yield of more than 180 mm/a were ranked high because water is more likely to be stored from the system, increase the area's annual water yield, and be more likely to have dry season flow, which is vital to river water in rural areas/communities. The T35 catchments are dominated by moderate surface water runoff, which is less than or equal to 170 mm/a (Figure 4.5).

4. Wetland Size (Ha): Catchment T35 is dominated by large wetlands in the catchment's upper sections (Figure 4.6). The size of a wetland influences its potential to contribute to the surface water; more extensive wetlands have a higher possibility of contributing to surface water flow than smaller wetlands (Rebelo et al., 2015). Thus, bigger wetlands were ranked higher for achieving the goal, and smaller wetlands between zero and five hectares were ranked as least important. The wetland size data were derived from the fifth national wetland assessment dataset (Van Deventer et al., 2018).

5. Wetland Type: The National Wetland Map version five (NWM5) dataset provides wetland hydro-geomorphic units (Van Deventer et al., 2020) because wetlands provide different ecosystem services (Kotze et al., 2009). For instance, floodplain wetlands contribute more effectively to flood attenuation than do unchanneled valley bottom wetlands, which are more effective in trapping sediments (Kotze et al., 2009). Floodplains and valley-bottom wetlands in South Africa are in the worst ecological condition, with less than 5% of their extent in a natural/near-natural state (Skowno et al., 2019). Thus, in this study, valley-bottom (both channelled and unchanneled) and seepage wetland types were given a higher rating for their significant contribution to streamflow regulation, while the low-gradient wetland types were given a lower rating. The T35 catchment is dominated by seeps, floodplains, and channelled valley-bottom wetlands (Figure 4.6).

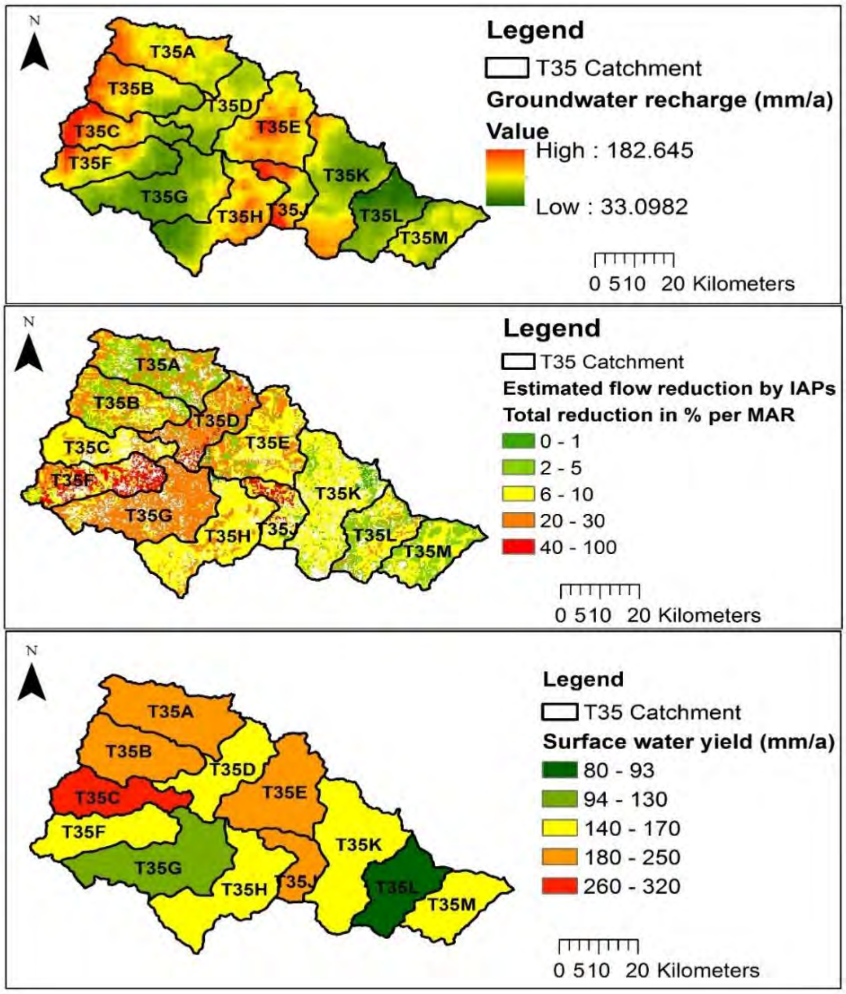


Figure 4.5: The distribution of the Ground Water, Estimated flow reduction due to IAPs recharge and Surface Water Yield.

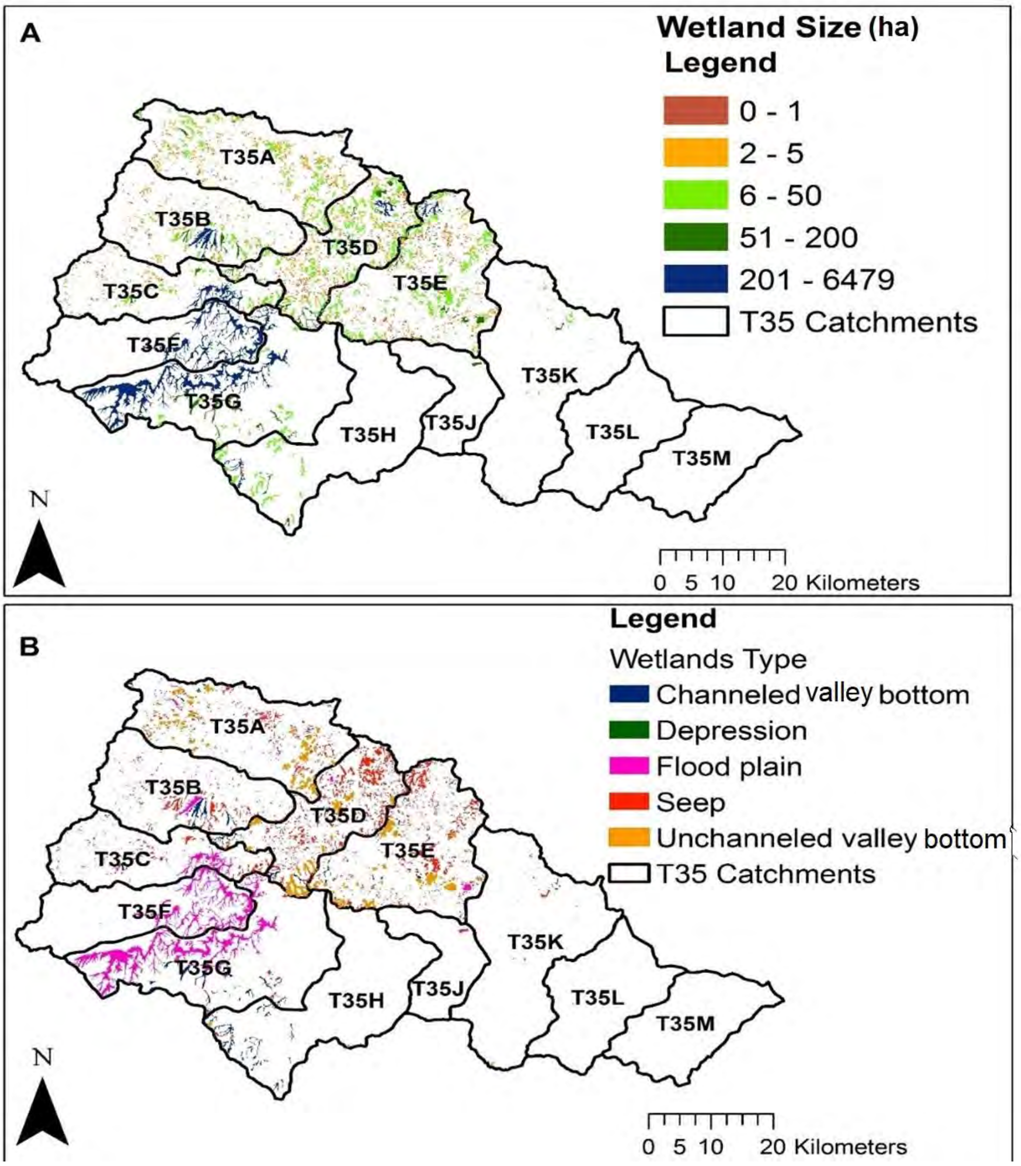


Figure 4.6: Distribution of wetlands, A wetland size (ha) and B wetland type in the T35 catchments.

Attributes used in Criterion 3: Social benefits

1. Distance from villages: The proximity attribute was derived from the community mapping of natural resources outputs, where communities indicated the importance of having easy access to natural resources. Moreover, the proximity of natural resources is an important attribute for selecting suitable restoration sites because restoration of the degraded ecosystem provides valuable ecosystem service to communities. A Multiple Ring Buffer tool, which is an ArcGIS tool that can create specific distance zones around a feature (ESRI, 2014), was used to create a buffer of 4 km around the villages to indicate the proximity of natural resources to people The 4 km maximum buffer was selected because it is with the accessible areas with significant natural resource. The closest areas to villages were given a higher score, and natural resources at more than 4 km were ranked as a low priority (Figure 4.7).

Population density: To a large extent, rural communities depend on natural resources to sustain their livelihood (Sigwela et al., 2017). The population density attribute was derived from the 2011 census dataset (Stats SA, 2011), which indicates population per area. The population density attribute was used to demonstrate the potential number of people who can benefit from ecological restoration and depend on the surrounding resources. The catchment is covered by a low to moderate population (0–983 people per sq. km). Areas with a higher population were given higher scores, and less densely populated areas were assigned a lower score (Figure 4.7).

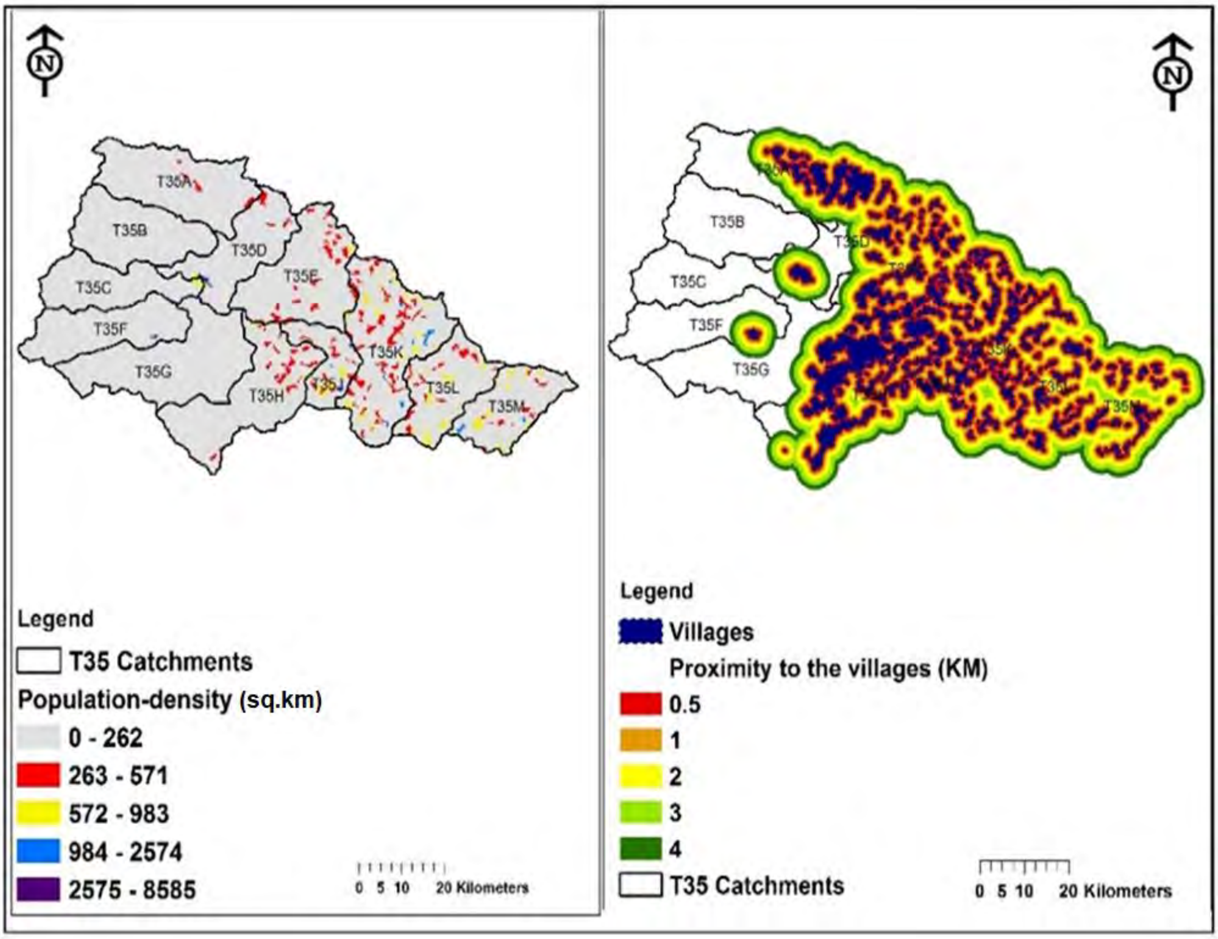


Figure 4.7: Population density (people per sq.km) and proximity (km) of natural resources to villages in T35.The AHP was used to assess suitable restoration areas to enhance flow regulation in the study catchment.

The study's objective was broken down into a hierarchical structure with possibilities for making changes, and the stakeholder input from the workshops was used to prioritise suitable areas within the AHP analysis. The flow diagram in Figure 4.8 was used in the study analysis. All the attribute data were converted into a raster, projected into Albers Africa equal projection, and the pixel size was resampled to 30 m by 30 m per pixel size. The attribute weights were taken from the ranking of attributes by experts in ecological restoration and resource management. For Criteria 1 (Ecosystem Health) and 2 (water provisioning), five attributes were weighted based on the assigned weights from the experts. For Criterion 3, the two attributes were automatically weighted equally. All attributes were weighted and overlaid based on their weighted values in ArcGIS, using the weighted overlay tool, which is a modelling suitability method used in ArcGIS; it multiplies the layer reclassification raster cell's suitability value by its layer weight and totals the values to derive a suitability value (ESRI, 2014). Criteria outputs from weighting and overlay of the attributes were clipped into EI categories; Criteria 1 and 2 were weighted and overlaid equally to identify suitable zones for restoration. The outputs from the weighted overlay of these two criteria were weighted and overlaid with Criterion 3. A series of maps and tables were produced and are shown in the results Section 4.3 below. Calculations of the attribute weights and consistency ratio checks were done on an Excel spreadsheet (Appendix D section 4.7).

4.2.2.2. Step 1 of the AHP: Defining the goal

The study goal was to identify suitable restoration areas of key EI categories that could mitigate the impact of drought through streamflow regulation and benefit local communities in the catchment.

4.2.2.3. Step 2: Identification of the criteria

The criteria for restoration were derived from community engagement through the community mapping process. Villagers in the two villages identified in the section above provided three main criteria. Criterion 1, ecosystem health, was derived from the community’s prioritisation of grassland or rangelands with good grass cover for livestock grazing; wetlands were also deemed vital because they provide healthy, good grass cover for good livestock grazing, especially in winter. For criterion 2, water provisioning wetlands were considered an important EI category for getting water and providing good grass for the livestock. Springs were identified as essential EI, especially the perennial ones (those that provide water throughout the year). Criterion 3, social benefits, was identified when the communities prioritised EI based on proximity to the homesteads. The natural resources close to villages were more critical for accessibility and safety reasons expressed in the community mapping. Overall, 12 spatial datasets were used in the assessment. Criteria 1 and 2 had five attributes, and criterion 3 was assigned two attributes.

Reclassification

The attributes contained different content, measurement units and details, so a reclassification process using a scale from 5 to 1 was used to standardise attributes to a common scale, based on their relative importance to the aim. Reclassification was done using the reclassification tool in ArcGIS. Each attribute category was assigned scores based on the importance of their contribution to the criteria, so all attributes for each criterion were reclassified and assigned score values based on their capacity to influence the criteria. The following values were used to rank the attributes: 1 and 2 indicate low importance; 3 moderately important; 4 and 5, highly important for the criteria (Table 4.2).

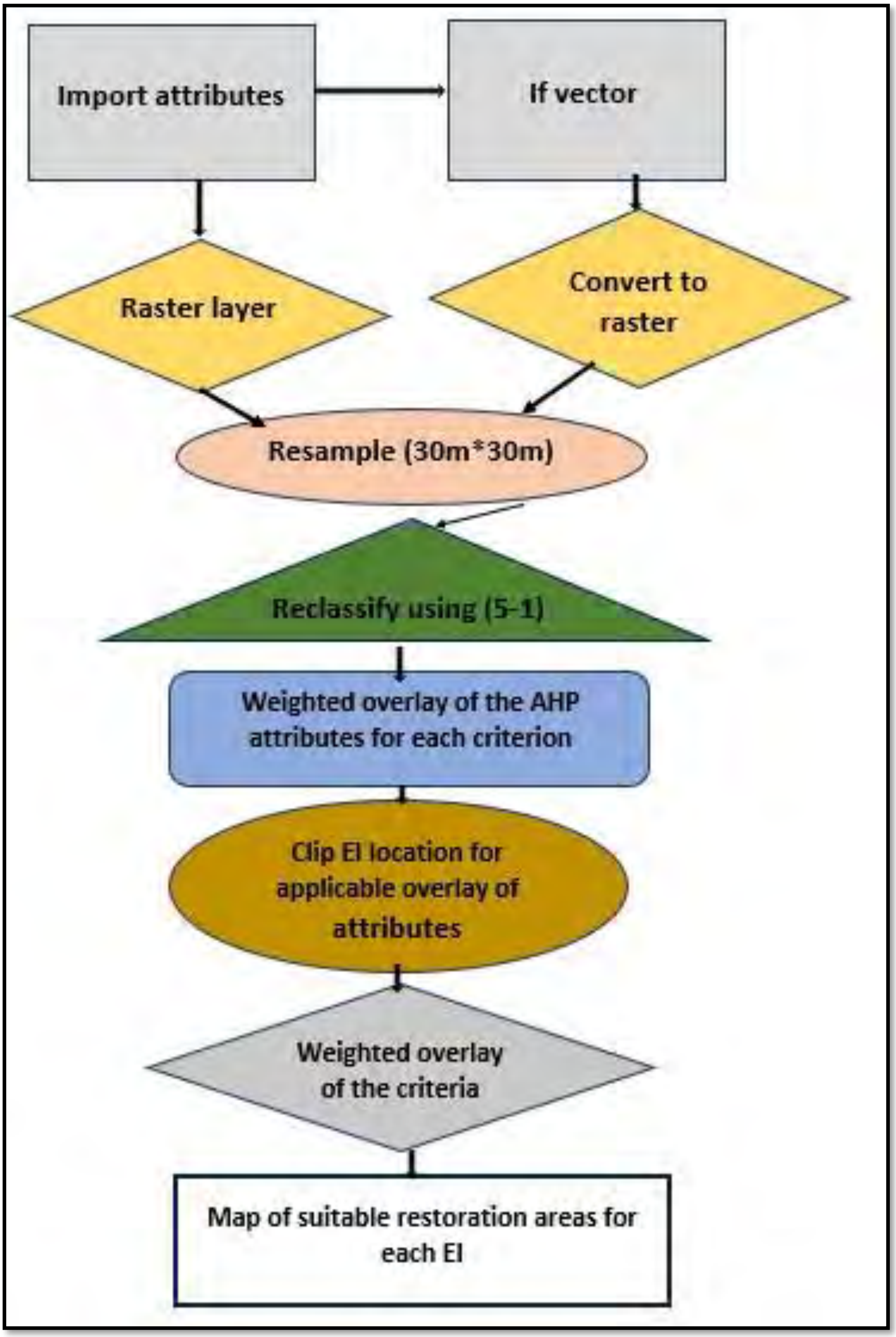


Figure 4.8: Flow diagram showing the steps followed for the MCDA process using ArcGIS tools.

Reclassification of the three criteria

Criterion 1: Ecosystem Health: Reclassification of the five attributes used for Criterion 1 (ecosystem health) showed different levels of importance (Table 4.2). The improving and stable areas were categorised as moderately important (ranked with a score of three) for ecosystem health and degraded land areas are reflected as ‘highly significant’ for the ecosystem, therefore, land degradation was scored between four and five (Table 4.2). Land areas that present the ecological status of natural/near-natural and moderately modified conditions were given a ‘highly significant’ focus for ecosystem health and these areas were ranked score either four or five. Also, areas that are critically to seriously modified were classified as ‘low significant’ for ecosystem health and were ranked a score of one to two (Table 4.2). Poorly protected areas were reclassified as ‘moderately important’, and moderately protected areas are reclassed as highly significant for restoration to improve ecosystem health. A moderate proportion of the catchment consisted of unprotected areas and was classified as ‘low priority’ for ecosystem health and were scored a value of one to two (Table 4.2). The first and second-order streams were reclassified as highly significant, and the third-order and fourth-order streams were classified as moderately important for ecosystem health and the stream orders that are above the fourth-order were classified as ‘low significant’ for restoration to improve ecosystem health.

Criterion 2: Water provisioning: Areas with groundwater recharge of more than 100 mm/a were reclassified as ‘highly significant’, and those with 65 to 100 mm/year reclassified as ‘moderately important’; areas with less than 65 mm/a were categorised as ‘very low importance’ for water provision in the catchment. Regions where IAP estimated flow reduction was greater than 15% were identified as high; areas with estimated flow reduction due to IAPs ranging from 10–15% were categorised as ‘moderately important’, and areas where estimated flow reduction was less than 10%, were considered as ‘less significant’ for water provisioning. Surface water yield areas greater than 135 mm/a were considered a very important priority, while areas with surface water yield between 60 and 135mm/a were reclassified as moderately significant for water provisioning. Also, areas with surface water yield that is less than 60 mm/a were classified as low importance for improving surface water yield. In the catchment area, bigger wetlands (>50 ha) were reclassified as highly important wetlands for water provisioning, and wetlands smaller than 1 ha were categorised as the least important for water provision (Table 4.2).

Criterion 3: Social Benefits: Areas that are approximately 2km or less away from villages were categorised as 'highly important', as they are accessible to people; areas of more than 4 km away from villages were 'less important' for social benefits. Sections with population density per km^2 of more than 900 people per village were reclassified as 'high priority' and those with fewer than 300 people were reclassified as 'less important' for social benefits (Table 4.2).

Table 4.2: The applicable attributes with the ranked scores based on the importance of the attribute class to the criteria, where numbers 1-2 (low), 3 (moderate) and 4-5 (highly) are significant. The area marked with X in the table indicates that the attribute ranked score value is not applicable.

Attributes	**Ranked score value for attributes classes**				
	1	**2**	**3**	**4**	**5**
Criterion 1: Ecosystem Health					
Land degradation indicator	X	X	Improved and Stable	Degraded	
Present Ecological Status	Critically modified	Seriously modified	Largely modified	Moderately modified	Natural/near-natural
Recently cleared areas (ha)	No change	X	X	X	Tree cover loss
Ecosystem protection level	X	Not protected	Poorly protected	Moderate protection	Well Protected
Stream order	6	5	3-4	2	1
Criterion 2: Water Provisioning					
Estimated flow reduction (%)	<1	5-10	10-15	15-25	>25
Surface water yield (mm/a)	<25	25-60	60-135	135-220	>220
Groundwater recharge (mm/a)	<35	35-65	65-100	100-150	>150
Wetland size (ha)	<1	1-5	5-50	50-200	>200
Wetland type	Depression	Flat and Floodplain	Seepage	Channelled valley bottom	Unchanneled valley bottom
Criterion 3: Social Benefits					

Distance from villages (km)	>4	04-3	03-2	02-1	<1
Population density per km^2	<300	300-600	600-900	900-1200	>1200

4.2.2.4. Step 3: Establishment of attributes weights through pair-wise comparison matrix

To calculate the weight for each criterion, the AHP created a pair-wise comparison matrix that compares each alternative against each other alternative, using a numerical scale of 1–9 created by Saaty (1980; 2000). The pair-wise comparison is used to determine how much element A is more important than element B (Kaushal, Gold & Mayer, 2017)**.** For this study, a pair-wise comparison matrix was used to compare two attributes to determine which attribute was more important for the goal; each attribute value was assigned to each criterion to determine the importance of the criteria towards the goal.

The WRC research members conducted an online AHP survey to formulate the relative weight of attributes. Online questionnaires were sent out to experts, researchers, and students with experience in catchment and resource management of the study area. The Google drive questionnaire contains a word document that explained each attribute's details and how it influences the main goal.

A link available at https://forms.gle/7reZUbh8uc2kGhKX8 (Appendix 4) on the Google form questionnaire was shared using email. Participants (experts) were asked for their consent and directed to complete the form by ranking the attributes for Criteria 1 and 2, based on their relevance for selecting suitable restoration priority areas in the EI categories to mitigate drought. Forty-eight experts were asked to participate in the analysis and were given 16 days to respond. Only, 22 participants responded to the questionnaire. The matrix was computed using the mode value from the comparison results of the attributes and the AHP rule for calculating weights; for example, if Attribute A was four times more important than B, attribute B would be one over four (¼, i.e., a quarter) of the importance of A.

4.2.2.5. Step 4: Perform the judgment of the pair wise matrix

Once the pair-wise matrix was built, matrix values were normalised by dividing each attribute value in a cell by the sum of the attribute value in a column. The sum of normalised matrix values for each attribute must be equal to 1 (Saaty, 1980; Ramanathan, 2001; Brunelli, 2015).

4.2.2.6. Step 5: Determine weights

The mathematical procedure for calculating the overall score and weights is complex (Saaty, 1980), so in this study, Excel was used to derive the final weights, which were derived by taking an average of the pair-wise matrix's normalised values (detailed steps are shown in Appendix C).

4.2.2.7. Step 6: Consistency ratio check

The final priorities values make sense if they are derived from the consistency matrix, so it is important to calculate the matrices' consistency (Philippe, 2012). There is a possibility of inconsistency in the results, so the AHP permits a margin of up to 10% of inconsistency (Philippe, 2012). The consistency check is calculated to confirm there were no contradictions in the matrix comparison and determine the result's validity. In calculating the consistency ratio, the following values need to be calculated: consistency index and a random index (Klutho, 2013; Philippe, 2012; Saaty, 1980).

The consistency index (CI) is the value calculated through lambda-max value minus the total number of attributes divided by the number of attributes minus one. The consistency index is calculated to assess how far off the criteria values are from consistent values. The random index (RI) is determined from the RI values provided by Saaty (2000), based on the number of criteria. Random index values, which are available in the literature (Saaty, 2000), are constant values calculated by a computer, and the values are based on the number of attributes used in the pair-wise comparison. For this study, RI = 1.12. Finally, the consistency ratio is calculated using the consistency index value divided by the consistency ratio. All the calculation steps and equations for the AHP analysis in this study are shown in Appendix 5.

4.3 Results

4.3.1 Stakeholder engagement outputs from the community mapping

In workshop sessions conducted in the two villages, the communities were introduced to the concept of Ecological Infrastructure (EI) and the importance of EI. Participants described EI as the natural resources that they used (springs, wetlands, grasslands, forests, rivers, plantations), and these resources were identified as core natural resources that provide essential ecosystem services important for their livelihoods. At Ntatyaneni village, the locations of 11 springs, three abandoned cultivated lands and one rangeland area were identified and mapped as vital natural resources in the area (Figure 4.9). In Sigoga village, mapped natural resources in the area include 12 springs, and four areas of abandoned cultivated land and three rangelands (Figure 4.10). The community prioritised natural resources based on the community needs, with each resource unit classified as 'most important' based on the quantity and quality of the ecosystem services it could provide using the ranking criteria for prioritisation (Table 4.3).

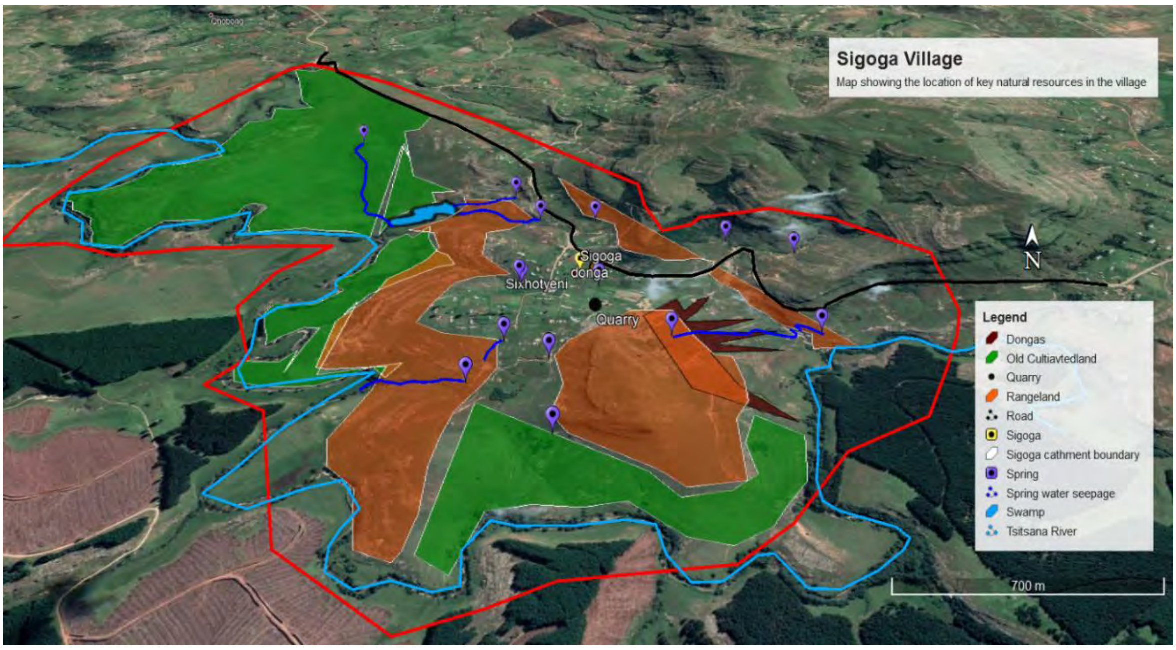


Figure 4.9: Google Earth image showing locations of mapped key natural resources at Sigoga village.

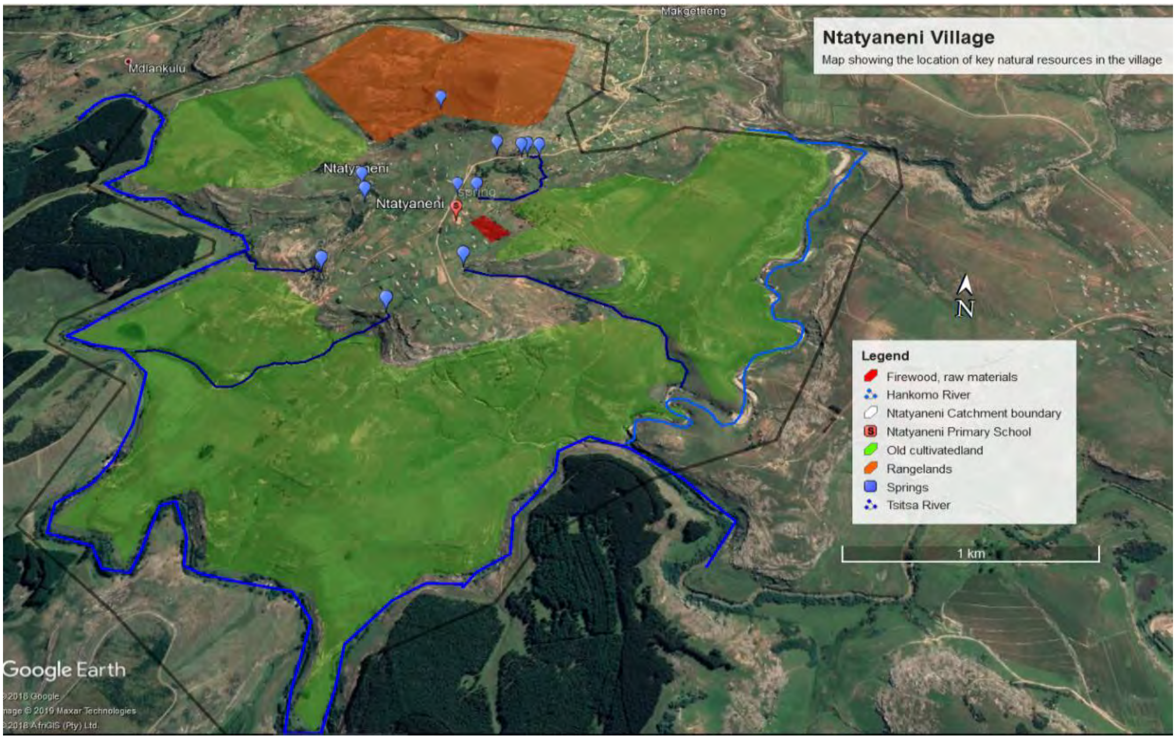


Figure 4.10: Google Earth image showing the location of mapped key natural resources at Ntatyaneni Village.

Table 4.3: Prioritisation criteria for each key natural resource based on community preference.

Key resource	**Criteria for prioritisation**
Springs/Wetland	Prioritised springs are those with good water quality, used as a source of drinking water; springs that flow throughout the year or yield plentiful water; springs accessible and within a reasonable distance from homesteads. Wetlands with water and good vegetation around them for livestock grazing.
Abandoned cultivated lands	Important abandoned croplands were those that were slightly degraded or not degraded (abandoned cropland with recovered vegetation) with good grass cover for livestock grazing.
Rangelands	Rangeland priority was based on grass cover present in the field and those close to the homesteads and water sources.

Mapped springs and wetlands

Springs are the community's primary water source because there are no taps in the area; therefore, all springs in the area provide significant services to communities. At Ntatyaneni village, five springs were ranked as ‘most important’ to the community, and in Sigoga village, six springs were identified as ‘most important’ to the community. Wetlands are formed as the result of constant water flowing from the springs in the upper sections and were prioritised for animal use, such as pigs and livestock who obtain water and grass for grazing, especially in winter. During site visits at Ntatyaneni village, it was observed that most seeps and springs were connected to gullies/dongas (Figure 4.11).

Figure 4.11: Examples of springs that flow throughout the year, and seeps or wetlands below the springs, as identified by the community at Ntatyaneni village.

Mapped abandoned cultivated land and Rangelands

Abandoned cultivated land in both villages is used for different purposes, such as livestock grazing areas and cultural practices. At Ntatyaneni village, one abandoned cropland area was ‘more important’ to the community grazing and cultural practices (Figure 4.12). In Sigoga village, two abandoned croplands were identified to be more critical to the community than other cultivated land in the area (Figure 4.13B). Abandoned cultivated land was identified as ‘most important’ because it was less degraded and had good grass cover for livestock grazing. Rangelands provide food for livestock, and for this reason, rangelands in both villages are highly important. In Ntatyaneni village, the mapped rangeland area was ranked as ‘significant’ (Figure 4.12), and in Sigoga village, two rangelands were identified as ‘more important’ (Figure 4.13A) than the other rangelands mapped in the area.

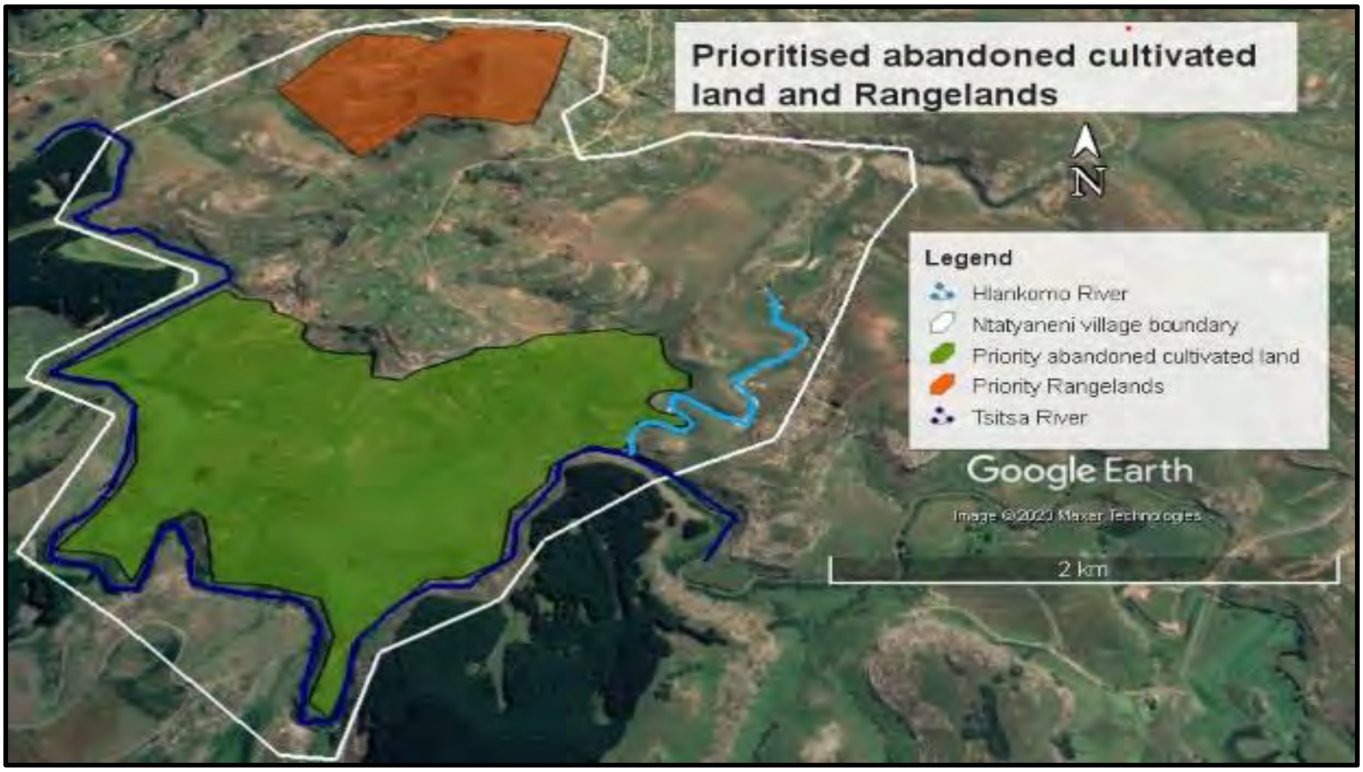
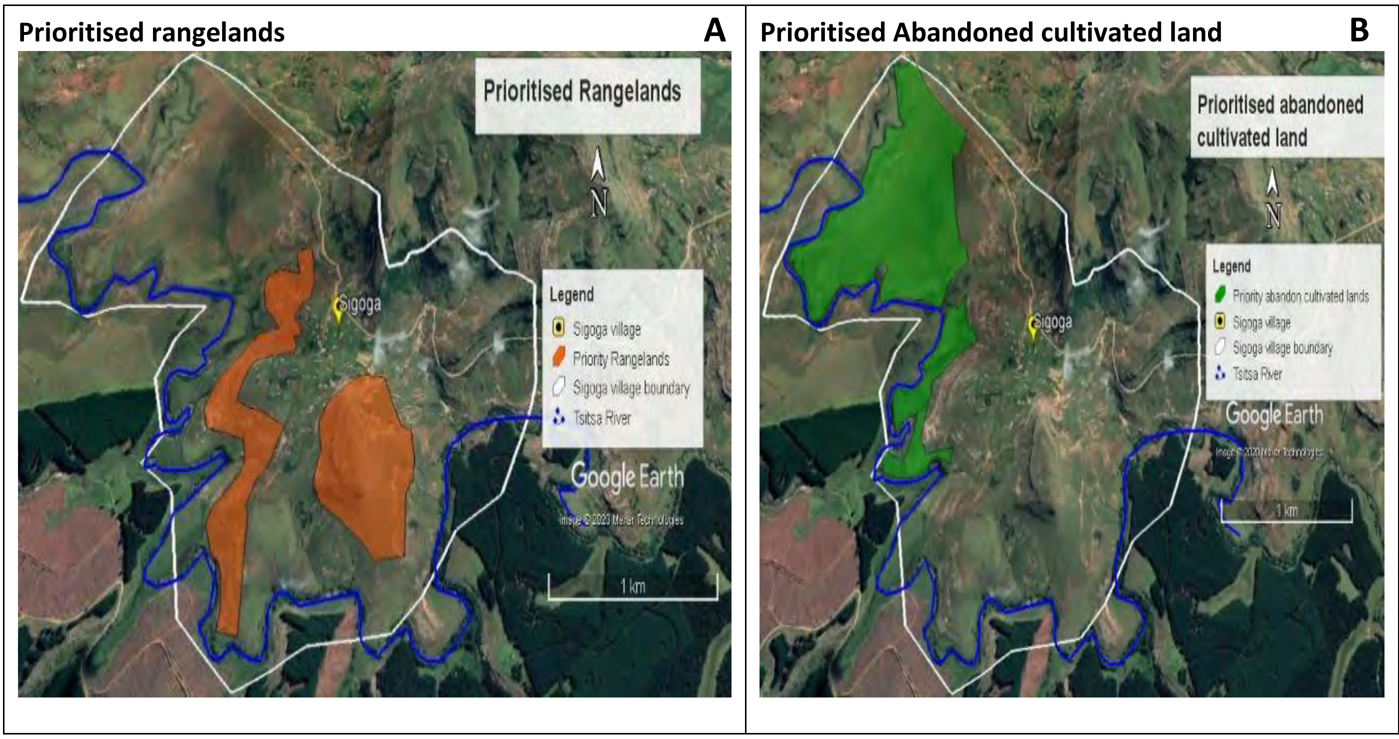


Figure 4.12: Prioritised rangelands and abandoned cultivated land at Ntatyaneni village.



Prioritised rangelands A

Prioritised Abandoned cultivated land B

Figure 4.13: Prioritised abandoned cultivated land (A) and rangelands (B) at Sigoga village.

Riparian vegetation

Participants were asked the following question: Have you noticed any changes in the size or plant types found by the riverbanks over the past 20 years?

Summary of the answers: The community indicated that they had noticed a change within the riparian zone: the alien *Acacia mearnsii* (Black wattle) and *Acacia dealbata* (Silver wattle) was more widespread and denser than it was before. The wattle present in the riparian zones is important for the community since they use the present trees for firewood, building material and other things.

4.3.2. Results from the AHP survey

Thirteen of the surveyed respondents (59%) out of 22 surveyed had a moderate restoration management experience, five respondents (23%) had a minimum level of experience, three (14%) indicated extensive restoration management experience and only one (4%) of respondents indicated no experience in restoration management. Overall responses to Criterion 1 (Ecosystem Health) indicated that more than 96% (21 out of 22) of the experts agreed that the five attributes selected influenced their selection of the restoration priority (Figure 4.14). For Criterion 2 (Water Provisioning), the response results reflect that all (100%) the participant experts agree with the use of the five attributes and that these attributes had an influence on selecting priority restoration areas to mitigate drought in the catchments (Figure 4.15).

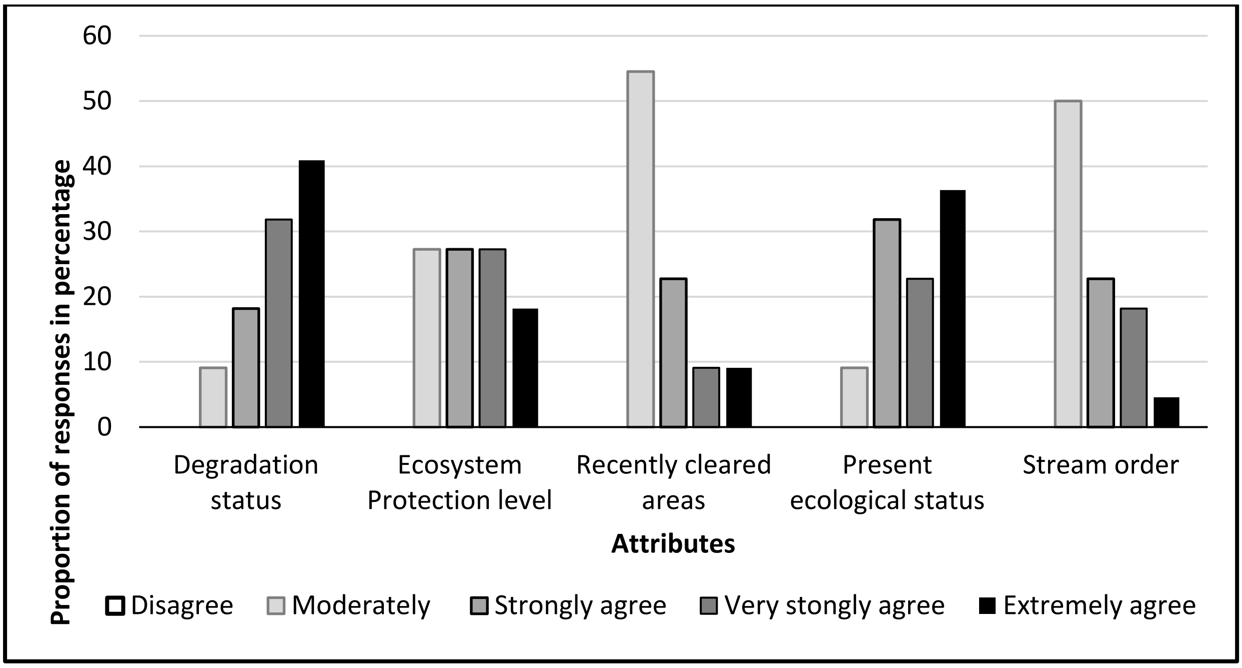


Figure 4.14: Approval of the five attributes used for ecosystem health that influence selecting priority restoration areas to improve drought mitigation.

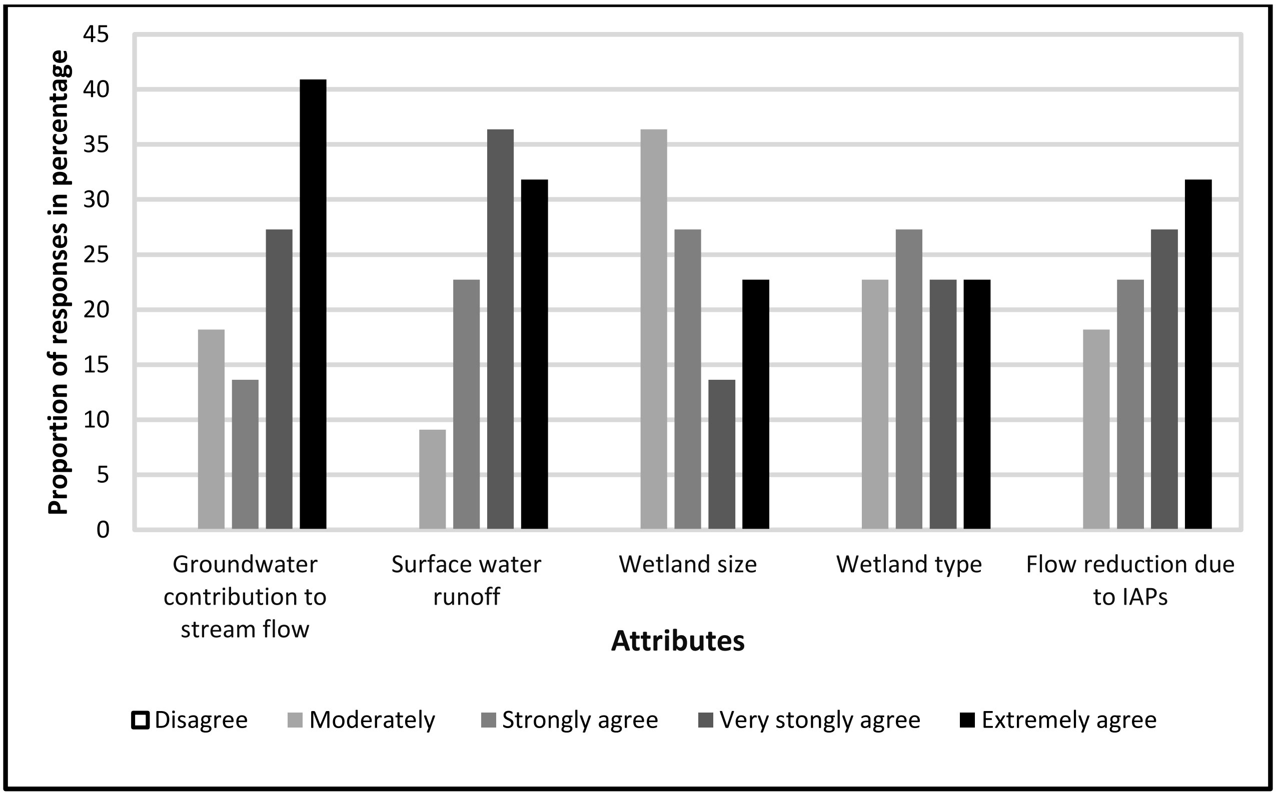


Figure 4.15: Approval of the five attributes used for water provisioning that influence selecting priority restoration areas to improve drought mitigation.

Calculation of attribute weights using the AHP process.

The results of the pair-wise comparison of the attributes indicate that, in selecting suitable restoration areas, land degradation, ecosystem protection level and present ecological status are equally important but more highly important than the recently cleared areas and stream order. The pair-wise comparison of Criterion 2's attribute indicated that surface water runoff, groundwater recharge, and flow reduction due to IAPs were highly important for selecting restoration to increase streamflow. Wetland size and wetland types were less important for selecting suitable areas for restoration. The weighting scores of the attributes from the most important to the least important for the goal are as follows: the present ecological status (31%), ecosystem health protection (29%), degradation indicator (26%), with stream order (8%) and recently cleared areas (being the least important with 6%). According to the experts, surface water runoff (27%) is more important for water provisioning than the other attributes, followed by groundwater contribution to streamflow (25%) and runoff reduction due to IAPs (20%); wetland size and wetland type (14%) were least important (Table 4.4).

Calculating the consistency ratio

The consistency value was calculated to check if the assigned weight values from the experts (Table 4.5) were correct or not. The lambda max was computed for both criteria and a value calculated of 5.09 (Criterion 1), 5.12 (Criterion 2), which suggests that the lambda max values are correct since they are close enough to the number of independent variables (five attributes). The consistency index and random index values were calculated to determine the consistency ratio for the two criteria. The weights calculated for the criteria were consistent: ecosystem health had a consistency value of 2%, and water provisioning a consistency ratio of 3% (Table 4.5). These results indicate that the AHP matrix used for the analysis was consistent and acceptable to use in the AHP process because the values were less than 10%, which means that each attribute has a constant scale.

Table 4.4: Averaged normalised criteria weights from the pair-wise comparison matrix and final assigned weights for the three criteria (all 12 attributes) used in ArcGIS analysis.

Criteria	**Attributes**	**Weighted criteria values for attributes**	**Weighted criteria for attributes in %**
Ecosystem health	Degradation indicator (LD)	0.26	26
	Ecosystem protection level (EPL)	0.29	29
	Recently cleared	0.06	6
	Present ecological status (PES)	0.31	31
	Stream order	0.08	8
Water provisioning	Groundwater recharge (GWR)	0.25	25
	Surface water runoff (SWR)	0.27	27
	Wetland size (WS)	0.14	14
	Wetland type (WT)	0.14	14
	Flow reduction due to IAPs (FR)	0.2	20
Social benefit	Population density	0.5	50
	Proximity	0.5	50

Table 4.5: Consistency index values calculated using the random index, lambda max.

Criteria1: Ecosystem Health	
Λmax	5.09
Consistency index (CI)	0.02
Random index (RI)	1.12
Consistency ratio (CR)	0.02
CR in percentage	2.08
Criteria2: Water Provisioning	
Λmax	5.12
Consistency index (CI)	0.03
Random index (RI)	1.12
Consistency ratio (CR)	0.03
CR in percentage	2.70

4.3.3. Suitable restoration areas for drought mitigation

Suitable restoration priority areas for wetlands and riparian zones

The study identified 62% (17,703.24 ha) of wetlands suitable for restoration to mitigate drought in the Tsitsa River catchment. About 88% (15,720.21 ha) of wetlands was identified as moderately suitable, and around 11% (1,980.81 ha) was categorised as highly suitable for restoration. A very small proportion of 0.01% (2.34 ha) was categorised as 'low suitability'. The most suitable wetlands for restoration in the catchment were found in the upper regions of the area (Figure 4.16). Approximately 93% (3,791 ha) of the riparian zones in the catchment were identified as suitable restoration areas to increase streamflow. The analysis indicated that 56.3% (2,135.34 ha) of the riparian zones in T35 was highly suitable for restoration and 43.6% (1,653.12 ha) was moderately suitable for restoration. A very small portion, less than 1% (0.06%) of the riparian zone covering 2.34 ha, identified 'low suitability' for restoration (Figure 4.16). Riparian zones in the upper landscape areas were categorised as highly suitable areas for restoration to increase streamflow.

Suitable restoration priority areas for abandoned cultivated fields and grasslands

Results for abandoned cultivated fields show about 78% (13,607.64 ha) were identified as suitable areas for restoration for drought mitigation, and over 95% of abandoned cultivated fields in the catchment were identified as a high priority for restoration 12 998.88 ha in the catchment. About 5% (608.76 ha) of abandoned cultivated fields was regarded as moderately suitable for restoration to increase streamflow and mitigate drought (Figure 4.17). The AHP results for restoration in grassland in T35 catchments indicated 88% (235,828.8 ha), with 78.30% (18,465.24 ha) of moderately suitable areas for restoration. Only 21.36% (504.29 ha) of grasslands were highly suitable for restoration to mitigate droughts impacts in the catchment. Approximately 0.32% of 765.27 ha were identified as areas with low suitability for restoration by the MCDA analysis. A small portion of less than 1% (0.368 ha) of grassland was highly suitable for restoration to increase streamflow in the catchment, especially in the dry season. Grasslands in the upper areas of the catchment were categorised as a high priority to achieving the goal (Figure 4.17).

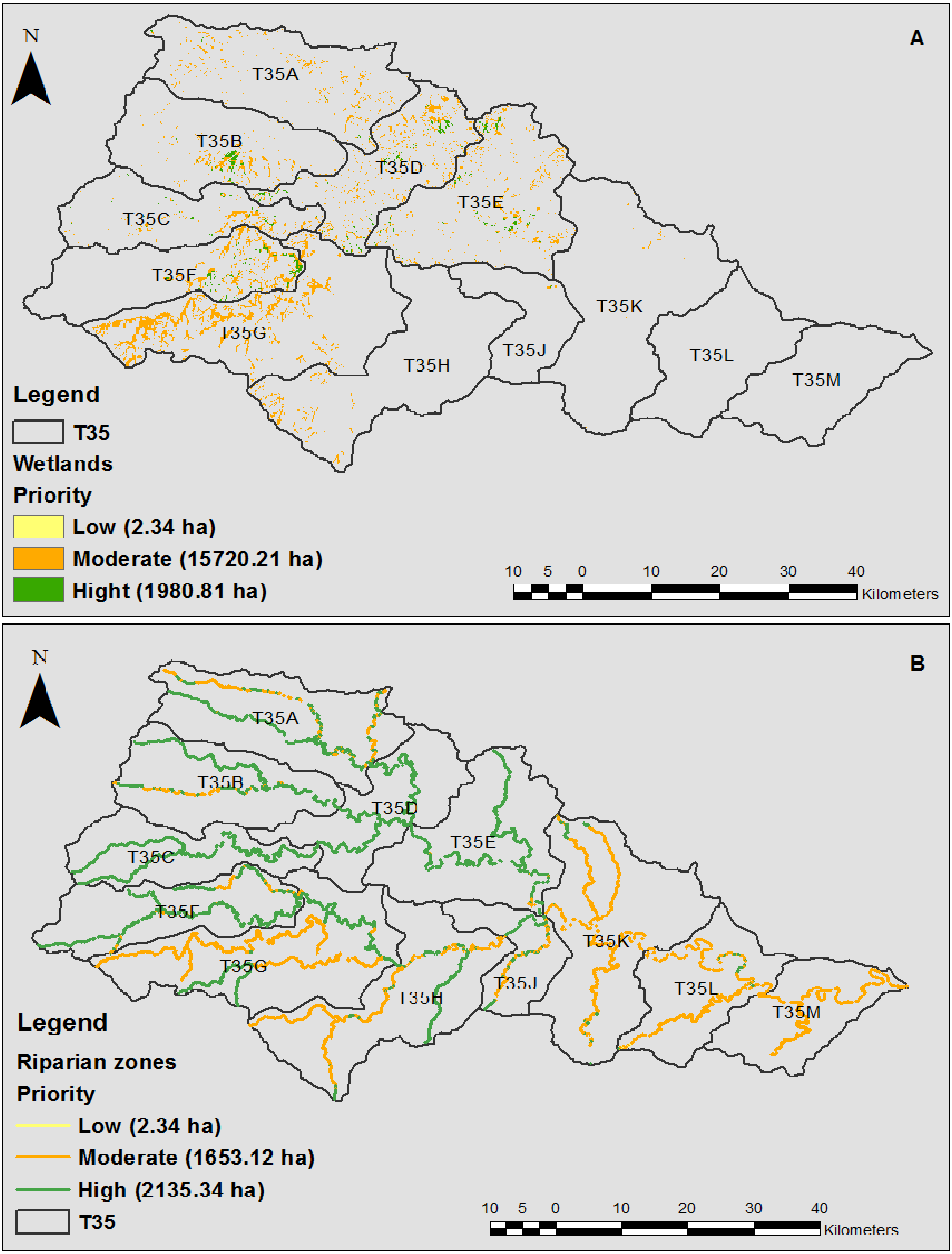


Figure 4.16: Suitable wetlands (A) and suitable riparian zones areas (B) for restoration to improve the flow regulation function, focusing on ecosystem health and water provisioning the T35 catchments.

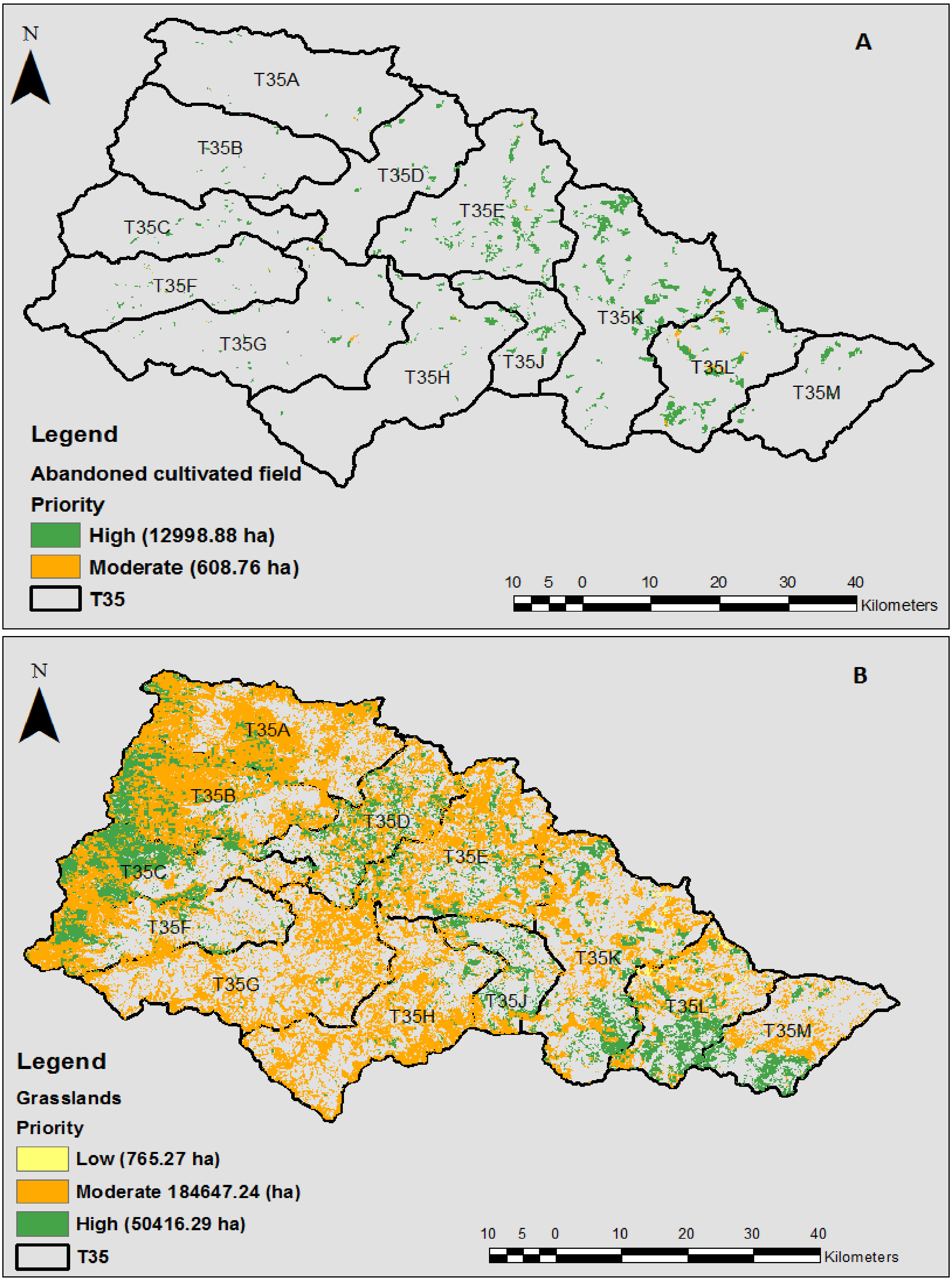


Figure 4.17: Suitable grasslands (A) and abandoned cultivated areas (B) for restoration to improve the flow regulation function, focusing on ecosystem health and water provisioning the T35 catchments.

4.3.4. Suitable restoration areas for improving drought mitigation and ecosystem services for the catchment living.

The weighting and overlay of the three criteria show suitable restoration areas for the four EI categories to improve local communities' ecosystem services. Suitable areas were ranked using a priority level scale (low, moderate, and high) based on the possibility of influencing the water recharge zone and increasing groundwater recharge storage while benefiting rural livelihoods in the catchment. The overall results include suitable restoration areas identified by the AHP model and the areas mapped during the community mapping process explained above.

Suitable restoration priority areas for wetlands and riparian zones

The AHP analysis identified 63% (17,703 out of 28,317 ha) of wetlands as suitable for restoration, but about 37% of wetlands were not suitable restoration areas (Figure 4.18). Of the 17,703 ha of suitable sections in the catchment to increase streamflow, more than 88% (15,720.21 ha) of wetlands were identified as moderately suitable areas, 11% (1,980.81 ha) were highly suitable, and about 0.001% (1.98 ha) were of low suitability. Communities also selected roughly 24.5 ha (0.1%) of suitable wetlands for restoration, and the AHP analysis identified these wetlands as highly or moderately suitable areas for restoration. The high priority areas for wetland restoration are mostly found in the upper catchments (T35B, T35C, T35D, T35E) and T35F (Figure 4.18). Of the riparian zones,58% (2,202.48) ha was identified as suitable areas for restoration. Almost 46% covering 1016.28 ha was identified as highly suitable, and 54% covering 1,183.86 ha moderately suitable, and 0.01% (3.34 ha) were low suitability zones in the riparian margins (Figure 4.18). The headwaters or the first-order streams were categorised as a high priority area. Rivers allocated in the upper areas of the catchment were also categorised as a high priority, and rivers in lower parts of the catchment (T35K, T35L, and T35M) were classified as moderate priority areas for restoration to improve services capacity in the catchment and benefit the communities.

Suitable restoration priority areas for abandoned cultivated fields and grasslands

The AHP results demonstrate that 92.94% (10,932.93 ha) of the abandoned cultivated areas are categorised as highly suitable for restoration. Moderately suitable areas in the catchment only covered 7 % (814.14 ha) and less than 1%, were rated as a low priority covering 0.06% (7.11 ha) of abandoned cultivated fields suitable for restoration. The AHP outputs categorised the abandoned cultivated fields prioritised by communities as highly suitable areas for restoration, covering 479.83 ha; abandoned cultivated fields associated with settlement areas are widely distributed in the catchment T35. Overall, the abandoned cultivated fields in the Tsitsa River catchment are mostly prioritised as high priority areas for restoration (Figure 4.19).

Approximately 15.71% (19,229.49 ha) of grasslands were suitable for restoration and categorised as a high priority. The results show that a large proportion of about 78.66% (96,195.69 ha) of grasslands areas was a moderate priority. About 5.61% (6,860.16 ha) of grasslands in the catchments was categorised as a 'low suitability' area covering about 5.61% (6,860.16 ha). Furthermore, the AHP analysis identified grasslands (rangelands) covering 116.84 ha and prioritised by the community in the Tsitsa River catchment as highly to moderately suitable restoration areas. Based on the MCDA model approach results, the upper grasslands have a low priority level and grasslands around villages were classified as moderate to high priority levels, especially the grassland areas in the lower parts of the catchment (Figure 4.19).

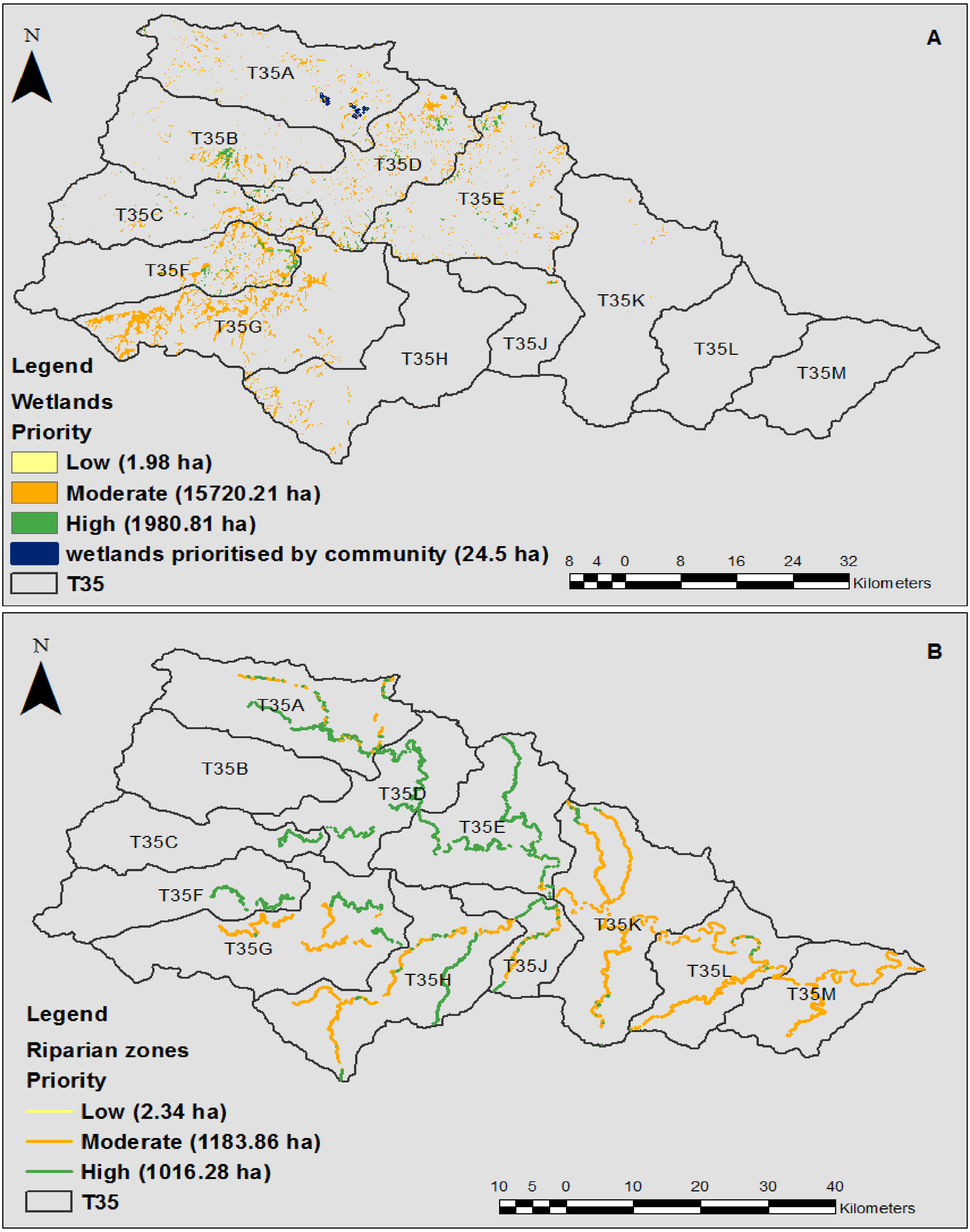


Figure 4.18: Suitable wetland restoration priority areas, with their area size coverage (A) and suitable riparian areas (B) in the catchment in hectares, identified to improve flow regulation function.

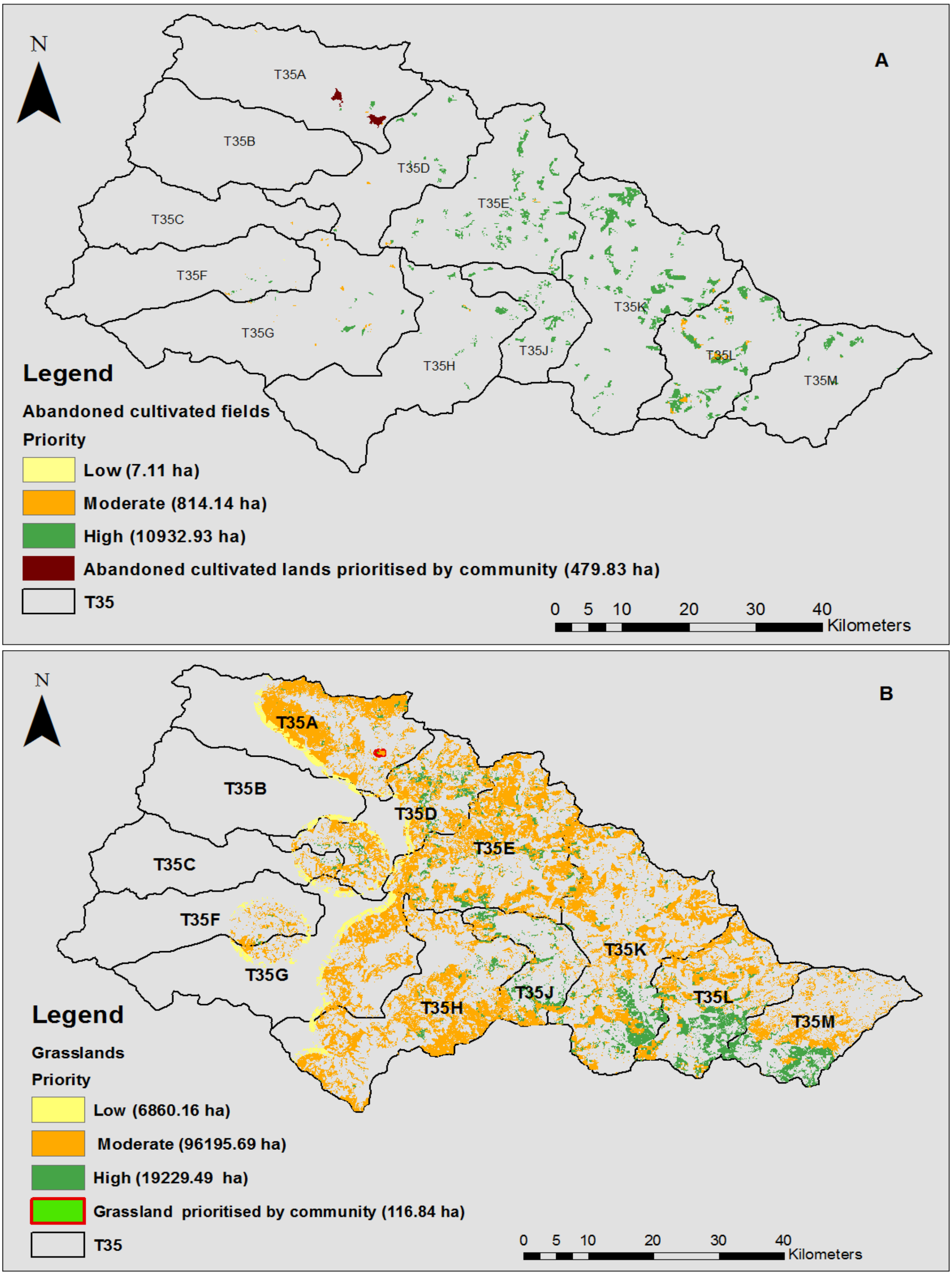


Figure 4.19: Suitable abandoned cultivated fields for restoration areas by MCDA model and communities for restoration (A) and suitable grasslands for restoration (B) in the Tsitsa River catchment.

4.4. Discussion

Land restoration practices increase the flow of critical ecosystem services such as water, crops, and firewood (Hartel et al., 2014) and support natural resources' sustainable use. Good land management practices also enhance biodiversity, achieve biodiversity protection (Alexander et al., 2016), and mitigate climate and drought impacts by enhancing natural vegetation cover (Gichuki et al., 2019; IRP 2019; Groot 2015). Nevertheless, there are issues (budget constraints, prioritising site selection, monitoring) that hinder effective restoration. In planning for land restoration, one should consider various contributing factors that affect the process of achieving effective restoration. Hence, the process of selecting sites for restoration should consider different attributes, as demonstrated in this study using the MCDA method of the AHP to consider various aspects in selecting suitable restoration areas for flow regulation.

This study used the AHP methodology to prioritise restoration areas to improve streamflow, especially in dry seasons. The AHP analysis combined community engagement, expert knowledge, and the 12 spatial data attributes to identify possible catchment areas suitable for restoration. Local communities identified the key mapped natural resources in the catchment as essential because they provide essential goods and services. However, the importance of natural resources to people depends on the benefits, needs, choices and values of the people and depending on the context (Balzan et al., 2018). Hence, the communities indicated that they valued the importance of natural resources mostly for the provisioning of ecosystem services. As a result, natural resources (wetland, grassland and abandoned cultivated fields) that provide direct ecosystem services to people (generally crucial for their well-being) were those most often deemed important.

The results from the AHP analysis pair-wise comparison of the attributes in criterion 1 (ecosystem health) suggest that the ecosystem protection level and the present ecological status of the natural resources in the catchment were important for selecting areas for restoration to increase streamflow. These two attributes were identified as necessary for streamflow because of the significance of their influence on ecosystems. For, instance protection of the upper areas of the catchments will influence the surrounding river, especially downstream (Kotze, 2019). The pair-wise comparison for criterion 2 (water provisioning) suggested that surface water runoff and groundwater recharge are important for water provisioning. Therefore they should be considered in selecting regions to restore to contribute to water provisioning in the catchment areas since groundwater is a significant water source that can recharge the terrestrial ecosystems (inland wetlands and rivers) (Kotze, 2019).

4.4.1. Stakeholder engagement and prioritised suitable restoration areas for improving drought mitigation and ecosystem services.

Wetland ecosystems provide a range of ecological and social services that benefit people, society and the economy at large (Working for Wetlands Programme, 2018). The effective functioning of wetlands has been frequently mentioned in available literature (Rebelo 2018; Thorslund et al., 2017; Kotze et al., 2009; MEA 2005). These authors have indicated that a wetland's goods and services improve human well-being (through clean water provision) (Lamsal et al., 2020).

The process of community mapping and presentations to locate the key natural resources around the village area seemed to be more effective in stimulating interaction and participation. For the reason that during the mapping process, community members seemed to be more involved in the discussion and highly active in the mapping process. The community members were working as a group helping each other in the process. This process was most effective in stimulation interaction because the mapping exercise process was easier for them to understand. The outcome of stakeholder engagement was that wetlands and springs were more critical for livestock grazing, especially during the dry season (Rebelo et al., 2009; Rebelo et al., 2015). The suitability analysis results from the AHP also identified wetlands around homesteads as highly suitable for restoration. Wetlands that were highly prioritised for restoration were mostly wetlands that are poorly or not protected and are severely to moderately modified. Skowno et al. (2018) indicated that inland wetlands have the least protection (about 60% not protected), causing wetlands to be vulnerable to modification. As wetlands are not protected or poorly protected, the floodplains and valley-bottom wetlands are in the worst ecological condition (Skowno et al., 2018). The flood plains and valley-bottom wetlands play a huge role in flood attenuation (IRP 2019; Rebelo et al., 2015; Kotze et al., 2009; Hajkowicz & Collins 2007); however, they have been degrading mainly as a result of drought, fire and poor grazing practices (Belle et al., 2018). Prioritising these wetlands for restoration will improve natural functioning and enhance ecosystem services that benefit people and the streamflow. Sigwela et al. (2017) in Tsitsa found that communities in the surrounding areas indicated that abandoned cultivated lands with grass cover are important for livelihoods because they provide ecosystem services such as fodder for livestock and habitat for species (Sigwela et al., 2017). The abandoned cultivated fields were identified as a high priority to increase streamflow and benefit people. The abandoned cultivated fields are prioritised based on the presence of water and good grass cover for livestock grazing by the community during workshops, because good grass cover in abandoned fields could improve local communities' livelihoods through improved livestock grazing.

The community expressed different reasons for not cropping the area anymore: fields are degraded with massive gullies and increased temperatures and changes in rainfall patterns. These reasons are similar to those stated by Shackleton et al. (2018) for a study conducted in KwaZulu Natal and Transkei. Shackleton et al. (2019) highlighted issues associated with abandoned cultivated lands, particularly in the South African context, pointing out that the consequences of cropland abandonment are social, environmental and economical and include land degradation, woody encroachment, soil erosion, loss of soil nutrients, decrease in food production and increase in poverty (Blair et al., 2018; Shackleton et al., 2019).

Grasslands that were selected as necessary for rehabilitation were those that were located near water sources and could provide feed for livestock. Prioritised rangeland in both villages was located close to local homes. The reason for selecting natural resources surrounding villages was for safety and proximity to the homestead. Grasslands provide several important ecosystem services to people and the environment by mostly maintaining biodiversity and diverse ecosystem processes (SANBI, 2013b) and providing food to livestock (Shackleton & Gambiza, 2008) and raw materials for rural communities. The prioritised grasslands and abandoned cultivated land in this study are similar to the prioritised land cover classes that provide essential ecosystem services to rural communities in the Tsitsa River catchment (Sigwela et al., 2017). The communities pointed out that poor grass condition is unwanted as they are dry and less productive, cannot provide food for animals, and are subject to soil erosion that creates problems for food production (Sigwela et al., 2017). Restoring the key natural resources in the catchment identified in the study will enhance rural livelihoods.

Therefore, restoration of degraded EI is essential to keep and improve the benefits of natural resources.

4.4.2. Suitable areas for restoration in the key EI categories to improve streamflow

Not all wetlands sustain streamflow in dry periods, especially those associated with large amounts of water loss due to evapotranspiration, resulting in less water released from the wetland (Kotze, 2019). However, some wetlands can sustain groundwater and deep interflow (Kotze, 2019). Most wetlands in the Tsitsa catchment are moderately suitable for restoration to increase streamflow. The highly and moderately suitable wetlands were generally valley-bottom and seep wetlands, and these wetlands can play a significant role in streamflow regulation because they can store and transmit water during dry seasons (Kotze et al., 2009). As wetlands are saturated, they help replenish underground water (Alexander & McInnes, 2012).

Moreover, wetlands are crucial ecosystems that have a significant role in the environment. The study selected the upper wetlands as a high priority for restoration; this is important because restoration of wetlands upstream of the dam can increase water quality and life span of downstream dams by enhancing their ability to purify the water flowing into the dam (Dini & Bahadur, 2016). In the context of our study area, restoration of degraded wetlands in the upper catchments will have positive impacts on the large dam proposed in the lower part of the study area.

Results show that grasslands in the headwaters (mountainous areas) in catchments are high to moderately suitable for restoration to increase water recharge and maintain streamflow, especially during dry seasons, because an increase in vegetation cover also improves the hydrological cycle (Groot, 2015). Mountainous grassland is essential for maintaining, regulation of the quality flow of water (De Groot et al., 2013; Blignaut et al., 2010) because natural grasslands form an effective system for water recharge. An increase in grassland cover increases soil protection against erosion, reduces surface water runoff, and the result is increased water retention, infiltration, and increased water availability (Sanz et al., 2017). An increase in soil capacity to allow, return and transmit water in the catchment will increase water storage and benefit streamflow. The available studies indicate that there are essential benefits of grasslands restoration, including enhancing soil quality, reducing soil loss, and improving biodiversity, productivity, and production (Sanz et al., 2017: Lötter, Stronkhorst &

Smith, 2009). The study conducted by Blignaut et al. (2010) in a simulation of ecosystem restoration benefits indicates how natural or near-natural grasslands can contribute to streamflow. The study indicated that restoration of degraded grasslands reduces soil erosion and storm runoff and increases winter stream flow through baseflow recharge in dry seasons (Blignaut et al., 2010). So, sustainable land management and restoration of key EIs in the upper catchments can significantly influence downstream hydrological responses (Blignaut et al., 2010). Therefore, catchment restoration of the upper catchments of T35 can benefit downstream through an increase in water availability for the proposed dam. Restoration improves water availability to rural communities, for whom direct abstraction of river water is a primary water source, especially during dry seasons (Blignaut et al., 2010). The restoration of grasslands to increase streamflow can increase water availability for communities in T35, particularly during dry periods.

Riparian zones and abandoned cultivated fields are identified as highly to moderately suitable for restoration. The results indicated that the headwaters' riparian zones are crucial for restoration because such restoration will benefit the downstream users by increasing water storage in the recharge zones. Furthermore, restoring the upper streams by clearing IAPs (especially in the upper catchments) and in the riparian zones, which use a significant amount of water, will increase groundwater availability and improve streamflow. The riparian zones that are invaded by the IAPs reduce stream flow (water flowing into the river) through increased evaporation of groundwater stored in aquifers accessed through plant roots (Le Maitre et al., 2000, 2014, 2016, 2018); therefore, the present IAPs in these areas need to be cleared. For this reason, groundwater plays a significant role in extending the period of flows in a river system through groundwater discharge from base flow (Le Maitre & Colvin, 2008). However, the clearing process of the IAPs should be done strategically because riparian ecosystems are sometimes the primary source of valuable ecosystem services (fuelwood, medicinal plants) to support life in rural areas (IRP, 2019).

4.5. Limitations

4.5.1. The limitations of spatial datasets

Although the attributes used in the study based on literature show the considerable influence of streamflow regulation and drought mitigation, this study acknowledges some limitations with the spatial data sets used in the AHP process in ArcGIS. The study by Le Maitre et al.

(2016) identified several limitations in computing the estimated flow reduction due to invasive alien plants and potential surface water recharge zones. The first limitation is the possibility of underestimating the invaded area because the alien plant distribution data set generated by Kotze et al. (2010) does not include South Africa's arid inland (Kotzé et al., 2010). Le Maitre et al. (2016) also considered even the revised estimate of flow reduction in 2016 to be underestimated, mainly because the extent and impact of riparian invasions had been underestimated.

Another limitation of the Le Maitre et al. (2016) dataset of estimated flow reduction is that the estimated flow reduction based on the mapped proportion of major invasive taxa was low (4–6%). However, the proportion of invasive taxa in the riparian zones may be much higher, resulting in the surface water runoff estimates underestimated in the catchments due to invasive alien plants (Le Maitre et al., 2016). Other issues associated with datasets relate to recently cleared areas that are at coarse resolution (300 m). The recent cleared areas dataset does not specify the type of tree-cover loss (native species or invasive alien plants), but the study assumed that tree cover loss was due to clearing invasive trees.

4.5.2. The limitations of the AHP method

Although the AHP method seems a good method for decision making, it does not provide an absolute answer to the problem of selecting suitable restoration areas, although it does provide possible solutions (Oguztimur, 2015; Karthikevan et al., 2016). Thus, results from the AHP analysis cannot guarantee the findings and decision for selecting suitable restoration areas as definitely true (Oguztimur, 2015), but this study does identify the possible suitable restoration areas that can increase streamflow and essential ecosystem services. The AHP uses qualitative values to indicate the importance of the criteria and attributes, which is sometimes a problem because qualitative data cannot be evaluated for absolute values (Kaushal et al., 2017). The response of the pair-wise comparison from the experts may be based on the expert's preference because the weighting of criteria or preference of attributes can be based on personal views (Karthikevan et al., 2016). Consequently, the weight assigned to the attributes may be based on a personal preference (Karthikevan et al., 2016), impacting the AHP final weighting.

This study acknowledges that there might be a low representation of stakeholders in the prioritisation process because the workshops were conducted in one quaternary catchment to represent 12 quaternary catchments. If the community mapping had been conducted in all the quaternary catchments, there might have been more than three criteria selected. Better inclusion of a wider range stakeholders is necessary to reduce the weighting and criteria uncertainties, which have a major influence on the final decisions. The other general limitation of using the AHP method in decision-making is that comparing different criteria may lead to difficulty for the decision-maker, resulting in inconsistent AHP results (Olson, 1988). In this study, the pair-wise comparison results were consistent (less than 10%) because all the participant experts in the study have some experience in land restoration and share a common goal.

4.6. Conclusion

Based on the study results, it is evident that natural resources provide different goods and services to rural people, and the level of importance varies depending on the context. The study identified and delineated the suitable priority areas that could be improved to increase streamflow in catchment T35 and mapped the appropriate areas to restore and increase streamflow. The findings were based on importance from the three levels: low, moderate, and high priority areas. The participatory mapping and geographic information systems can be used as part of integrated assessments to develop sustainable rural land management decision-making. Also, the AHP method is a valuable tool to use in dealing with complex resources management decisions. Restoring degraded natural resources is essential to improve and sustain the important ecosystem goods and services provided by the ecological infrastructure. The overall objective was accomplished at the end of the analysis: possible areas that can increase streamflow in the catchment were mapped.

Chapter 5: Synthesis, conclusion, and recommendations

5.1 Introduction

Approximately 36% of the population in the world is living in water-scarce areas, with an estimated increase of water shortages to affect approximately 5 billion people by 2050 (UN-Water, 2018). Environmental problems such as drought and land degradation can enhance water scarcity (UNCCD and FAO, 2020) because healthy landscapes such as wetlands, grassland, and riparian zones have a natural capacity to influence hydrological function; they influence storage and infiltration of water (UNCCD and FAO, 2020). However, the natural capacity of land cover to maintain water flows is lost due to degradation, which adversely impacts on water security. The underlying drivers of land degradation include soil erosion, IAPs, woody encroachment, and land-use change, which causes a decline in the provision of terrestrial ecosystem services (Gichuki et al., 2019), affecting nearly 3.2 billion peoples' well-being (IPBES, 2018b).

Therefore, dealing with drought and achieving water security is necessary to manage and preserve landscape and water resources (UNCCD and FAO, 2020). Also, combating land degradation by restoring degraded land is an urgent priority to protect important ecosystem services that are important for the life and well-being of humans (IPBES, 2018b). As a result, restoration of degraded lands is a global priority for achieving SDG15.3 while reducing the impacts of climate change through improved environmental and societal resilience and enhanced quality of the flow of ecosystem goods and services that are a benefit to people (De Groot et al., 2013; Alexander et al., 2016).

This study assessed land degradation status in the Tsitsa River catchment and prioritised restoration of the degraded areas to increase stream flow and benefit local communities in the catchment. This chapter summarizes the study's key findings and provides the research contribution of the results. The first part of the chapter summarizes the main findings and contributions towards the overall aim of the study. The chapter ends by concluding and providing recommendations for future studies.

5.2 How restoration of the key ecological infrastructure mitigates drought

Vegetation cover plays a significant role in the terrestrial water cycle (precipitation, infiltration, and evapotranspiration) (Le Maitre et al., 2014; Li et al., 2018). Healthy natural vegetation regulates water flows on both surface and groundwater in catchments during dry and wet seasons (DEA, 2014). Complete vegetation cover can also help reduce soil erosion through filtration, increased infiltration, reduced runoff, and increased groundwater recharge, which play an important role in streamflow recharge in dry periods (Rebelo et al., 2015; Van der Waal & Rowntree, 2018). Therefore, healthy vegetation enhances streamflow regulation and mitigate drought impacts.

Land restoration through improving land vegetation cover can improve the water flows in catchments, causing an increase in infiltration, enhancing groundwater, and reducing surface water runoff (De Groot et al., 2013; Groot, 2015). Restoration and rehabilitation of natural resources contribute to drought mitigation by enhancing water security flow in catchments (Van Loon & Laaha, 2015). The enhanced flows contribute towards water security and promote catchment resilience to climate extremes such as drought and floods (UNCCD & FAO, 2020). Therefore, restoration of the prioritised key EI, wetlands, grassland, riparian zones and abandoned cultivated lands will contribute towards water supply regulation in the catchment and contribute to drought mitigation (UN-Water, 2018). Clearing of IAPs (in the mountain catchments) and in riparian zones will decrease the water use by IAPs and increase water yield (DEA, 2014), which can be a positive benefit for streamflow recharge in dry seasons. For grassland restoration and management, enhanced infiltration reduces soil erosion and encourages better flow regulation by improving infiltration (DEA, 2014; Mander et al., 2017; Hughes et al., 2018). Land management using an ecosystem-based and a community-based approach that focuses on soil erosion control, soil fertility management, and improved vegetation can enhance physical water retention and water availability (Sanz et al., 2017). So, restoration of grasslands, wetland, and riparian zones can mitigate flooding and increase water security (IPBES, 2018a) and restoring degraded lands in the Tsitsa River catchment can be an effective solution for climate adaptation and mitigation.

5.3 Indication of how the restoration of the key EI contributes to the SDGs

Effective restoration of the prioritised EI can effectively mitigate drought impacts while also providing a wide range of benefits to the United Nations Sustainable Development Goals (IRP, 2019). In this study, restoration, rehabilitation, and management of the EI categories in the Tsitsa River catchment can contribute to achieving SDG 1,2,3,6 and 15. Restoration of degraded lands can contribute towards achieving SDG 1, “no poverty”, through the restoration process that provides job opportunities to add to the income for people to buy food and sustain their livelihoods in the catchment. In addition, restored land can improve ecosystem services such as soil structure and water supply, causing increased productivity leading to more food for people (Cumming et al., 2017; IRP, 2019). The land restoration approach that focuses on soil erosion control, soil protection, nutrients cycling, and water management can enhance land productivity, increasing food production, thus contributing towards the SDG2 “Zero hunger.”(Alexander et al., 2016; Cumming et al., 2017; IRP, 2019). The benefits of restoration of degraded EI can positively contribute towards health and well-being and thus contribute towards achieving the SDG 3 “health and well-being.” Restoration of wetland and riparian zones can improve water quality by filtration of sediments, nutrients, and pollutants and enhancing water availability by increasing water storage contributing to the SDG 6 “clean water and sanitation” (IPBES, 2018a, 2018b; UN-Water, 2018; IRP, 2019).

Restored wetlands, riparian zones, grasslands, and abandoned cultivated lands can increase food and water security and reduce natural disasters such as floods and drought. Restoration of degraded lands contributes towards achieving land degradation neutrality (SDG15.3.1) while supporting the achievement of other SDGs (UNCCD & FAO, 2020). Land degradation neutrality promotes the use of measures to avoid, reduce and reverse degradation (UNCCD and FAO, 2020) and can be achieved through Sustainable Land Management approaches (Orr et al., 2017; UNCCD, 2017) and achieving land degradation neutrality plays a significant role in the achievement of multiple SDGs.

5.4 Summary of the key findings

CHAPTER 3 of the study was developed to assess the changes in target EI over the past 15 years. The Trends.Earth tool computes land degradation indicator (the SDG 15.3.1 indicator) by combining land productivity, land cover, and soil organic carbon sub-indicators using the one-out all-out statistical rule. The land degradation results indicated that land cover and soil organic carbon indicators are mostly stable. The results also showed that land productivity indicators mostly contributed to land degradation in the catchment. The SDG 15.3.1 degradation indicator suggests that more than half (54.29%) of the catchment is stable, with one third (40.52) of degraded which is mostly found in the upper (T35A, T35B, T35C, T35D, and T35G) and lower (T35K, T35L, and T35M) parts of the catchment. Small areas (5.15%) showed improvement which was due to the re-growth of good grasslands cover and wetlands formation. Land degradation in the catchment includes the loss of vegetation cover, soil erosion, loss of productive lands due to woody encroachment, degradation driven by poor grazing and fire management approaches, large areas of bare soil on abandoned cultivated fields. The degradation poses a serious threat to sustainable livelihood in the catchment (Van der Waal et al., 2017). In addition, in the Tsitsa catchment, land degradation is linked to increased sediment connectivity due to gullies and cut river channels (van der Waal and Rowntree, 2018).

Chapter 4 outlines the prioritised suitable EI areas for restoration to mitigate drought using the AHP method in ArcGIS incorporated the community stakeholders' views and ecosystem restoration experts' opinions on suitability selection. The key ecological infrastructure suitability analysis included wetlands, grasslands, abandoned cultivated lands, and riparian zones. The EI categories were selected based on their importance in influencing the hydrological flows and providing services that benefit local communities. The stakeholder engagement prioritised natural resources based on the provisioning of ecosystem goods and services, e.g., grasslands, wetlands, and abandoned cultivated lands were prioritised based on the good healthy grass-cover accessible and close to water sources for livestock grazing. The prioritisation findings indicated that about 11% of wetlands, 56% of riparian zones, 21% of grasslands, and 95% of abandoned cultivated lands were highly suitable for restoration to enhance flow regulation and mitigates drought impacts in the catchment. The AHP analysis also identified 11% of wetlands, 46% of riparian zones,92% of abandoned cultivated lands, and 15% of grasslands identified as suitable for restoration to enhance ecosystem services to local communities, improve livelihoods and contribute to drought mitigation.

5.5 Research contributions

The study contributes to an interest in the socio-ecological and socio-economic outcomes of investing in ecological infrastructure, focusing on the benefits of investment in EI to people living in areas targeted for investment. The concept of investing in EI in South Africa has increased, indicating a high representation of studies on ecological infrastructure investment (Rasmussen et al., 2021). So, this study firstly contributes towards the concept of investing in EI by indicating the role and benefits of investing in ecological infrastructure to rural communities in the study area, especially during dry seasons. Secondly, this study is an addition to previous studies focusing on demonstrating the benefits of investing in EI by restoring or managing and maintaining the natural landscape using the SANBI framework for investing in EI. Studies such as Mander et al. (2017) indicated how EI investment could facilitate drought impacts through enhanced baseflow and streamflow and enhance ecosystem service in greater uMngeni catchment. In addition, this study contributes to the emerging concept of investing in ecological infrastructure to deal with land degradation, climate change adaptation, and achieving the SDGs. The study also indicates that protection and management of ecological infrastructure to good health conditions can contribute to the improvement of rural living conditions. Therefore, this research also contributes to the SANBI framework of investing in ecological infrastructure and the South African Strategic Integrated Project (SIP) 19, which focus on improving SA water resources through investing in ecological infrastructure. Lastly, the prioritisation plan for restoration areas in the catchment can be used in the integrated planning for SLM and restoration in the catchment to improve water for the proposed dams (Ntabelanga and Laleni) and benefit local people. Also, the prioritised areas can be used to implement SLM and Natural Resource Management approach for restoration in the catchment.

5.6 Conclusion and recommendations

This study has indicated the degradation status of the Tsitsa river catchment and identified suitable restoration areas that can improve flow regulation and benefit rural communities using the global, local data sets and stakeholder's views. The study successfully identified the degradation state in the catchment using the Trends.Earth tool and identified the common drivers of degradation in the areas. The AHP in the GIS tool method was successfully used to prioritize suitable restoration areas and priority areas accessible to people and play a major role in maintaining livelihood in the catchment. The study identified the role of ecological infrastructure in rural areas by highlighting the benefits of investing in ecological infrastructure to enhance water security, contribute to drought mitigation, and improve rural community livelihood. This research has indicated the potential of the wide range of benefits gained through ecological infrastructure investments and indicated how investing in EI can contribute to improving social, environmental, and economic status. Even though the results of the study contribute and indicate the significance of investing in EI, there is a still a need for verification of the results.

Recommendations for further research

- The study recommends the Trends.Earth tool for future assessment of land degradation in catchments. It is recommended to use the local land cover dataset, field observation or Ground-Truthing and stakeholder participation to validate the land degradation results from Trends.Earth tool for better understanding of the complexity of degradation in the catchment.
- The study recommends a wide representation of stakeholders in the prioritisation process, including a large number of different interested and affected parties in decision making for the prioritisation of restoration areas.
- This study also recommends use of high-resolution, local, and available data to assess land degradation and use of historical remote sensing images to demonstrate the degradation state in the catchment.
- Further research studies need to assess land degradation neutrality for reporting at a biome level while considering the common drivers of degradation in the assessed biome.

References

Alexander S, Aronson J, Whaley O, Lamb D. 2016. The relationship between ecological restoration and the ecosystem services concept. *Ecology and Society* 21. DOI: 10.5751/ES-08288-210134

Alexander S, McInnes R. 2012. The benefits of wetland restoration. *Ramsar Scientific and Technical Briefing* 20. DOI: 10.13140/RG.2.1.3024.1124

Anandhi A, Crandall C, Bentley C. 2018. Hydrologic characteristics of streamflow in the Southeast Atlantic and Gulf coast hydrologic region during 1939-2016 and conceptual map of potential impacts. *Hydrology* 5(3). DOI: 10.3390/hydrology5030042

Anderson SJ, Ankor BL, Sutton PC. 2017. Ecosystem service valuations of South Africa using a variety of land cover data sources and resolutions. *Ecosystem Services* 27: 173–178. DOI: 10.1016/j.ecoser.2017.06.001

Bai Z, Dent DL, Olsson L, Schaepman ME. 2008a. *Global assessment of land degradation and improvement 1: identification by remote sensing*. *Report 2008/01, FAO/ISRIC-Rome/Wageningen*. DOI: report 2008/01

Bai ZG, Dent D, Olsson L, Schaepman ME. 2008b. Proxy global assessment of land degradation. *Soil use and management* 24: 223–234. DOI: 10.1111/j.1475-2743.2008.00169.x

Bailey AK, Pitman WV. 2015. *WR2012 Study User's Guide Version 1. Water Resources of South Africa 2012 Study (WR2012).Report K5/2143/1.* Pretoria, South Africa

Bailey AK, Pitman WV. 2016. *Book of Maps. WRC Report Number TT 382/08*. Water Resources South Africa

Balzan M V, Caruana J, Zammit A. 2018. Assessing the capacity and flow of ecosystem services in multifunctional landscapes: Evidence of a rural-urban gradient in a Mediterranean small island state. *Land Use Policy* 75: 711–725. DOI: 10.1016/j.landusepol.2017.08.025

Bannatyne LJ, Rowntree KM, Van Der Waal BW, Nyamela N. 2017. Design and implementation of a citizen technician–based suspended sediment monitoring network: Lessons from the Tsitsa River catchment. *Water SA* 43: 365–377. DOI: 10.4314/wsa.v43i3.01

Belle JA, Collins N, Jordaan A. 2018. Managing wetlands for disaster risk reduction: Managing wetlands for disaster risk reduction: A case study of the eastern Free State, South Africa. *Jàmbá: Journal of Disaster Risk Studies*, *10*(1) DOI: 10.4102/Jamba.v10i1.400

Benayas MR, Martins A, Nicolau M, Schulz JJ. 2007. Abandonment of agricultural land: an overview of drivers and consequences. *CAB Reviews: Perspectives in agriculture, veterinary science, nutrition and natural resources*, *2*(57). DOI: 10.1079/PAVSNNR20072057

Bennett B, Kruger F. 2015. *Forestry and water conservation in South Africa*. ANU Press.

Bennett JE, Palmer AR, Blackett MA. 2012. Range degradation and land tenure change: Insights from a “released” communal area of Eastern Cape Province, South Africa. *Land Degradation and Development* 23: 557–568. DOI: 10.1002/ldr.2178

Bhandari J, Pan X, Bijaya GCD. 2015. Spatial and seasonal variation in rain use efficiency in semiarid grasslands of Inner Mongolia. *Advances in Meteorology*, *2015*: 1–8

Blair D, Shackleton CM, Mograbi PJ. 2018. Cropland abandonment in South African smallholder communal lands: Land cover change (1950–2010) and farmer perceptions of contributing factors. *Land* 7: 121. DOI: 10.3390/land7040121

Blignaut J, Mander M, Schulze R, Horan M, Dickens C, Pringle C, Mavundla K, Mahlangu I, Wilson A, Mckenzie M, Mckean S. 2010. Restoring and managing natural capital towards fostering economic development : Evidence from the Drakensberg, South Africa. *Ecological Economics* 69: 1313–1323. DOI: 10.1016/j.ecolecon.2010.01.007

Blignaut J, Wit M De, Milton S, Esler K, Maitre D, Mitchell S, Crookes D. 2013. *Determining the economic risk/ return parameters for developing a market for ecosystem goods and services: following the restoration of natural capital: A system dynamics approach, volume 1 : Main Report*. Pretoria, South Africa

Botai CM, Botai JO, Adeola AM, Wit JP De, Ncongwane KP, Zwane NN. 2020. Drought risk analysis in the Eastern Cape Province of South Africa : The Copula Lens. *Water* 12: 1–20. DOI: 10.3390/w12071938

Botai J., Botai MC, Wit J., Muthoni M, Adeola A. 2019. Analysis of Drought progression physiognomies in South Africa. *Water* 11: 1–21. DOI: 10.3390/w11020299

Brown G, Kyttä M. 2014. Key issues and research priorities for public participation GIS (PPGIS): A synthesis based on empirical research. *Applied Geography* 46: 122–136. DOI: 10.1016/j.apgeog.2013.11.004

Brunelli M. 2015. Introduction to the Analytic Hierarchy Process. *Springer.*

Burek P, Satoh Y, Fischer G, Kahil MT, Scherzer A, Tramberend S, Nava LF, Wada Y, Eisner S, Flörke M, Hanasaki N, Magnuszewski P, Cosgrove B, Wiberg D. 2016. *Final Report*. *Water Futures and Solution*

Burrell AL, Evans JP, Liu Y. 2017. Remote sensing of environment detecting dryland degradation using Time Series Segmentation and Residual Trend analysis (TSS-RESTREND). *Remote Sensing of Environment* 197: 43–57. DOI: 10.1016/j.rse.2017.05.018

Bwapwa JK. 2018. Review on main issues causing deterioration of water quality and water scarcity : a case study of South Africa. *Macrothonk Institute* 7: 14–34. DOI: 10.5296/emsd.v7i3.13156

Calow RC, Robins NS, Macdonald AM, Macdonald DMJ, Gibbs BR, Orpen WRG, Mtembezeka P, Andrews AJ, Appiah SO. 1997. Groundwater management in drought-prone areas of Africa. *International Journal of Water Resources Development* 13: 241–262. DOI: 10.1080/07900629749863

Chamier J, Schachtschneider K, Maitre DC, Ashton PJ, Wilgen BW Van. 2012. Impacts of invasive alien plants on water quality, with particular emphasis on South Africa. *Water SA* 38: 345–356. DOI: 10.4314/wsa.v38i2.19

Chang J, Tian J, Zhang Z, Chen X, Chen Y, Chen S, Duan Z. 2018. Changes in grassland rain use efficiency and NDVI in northwestern China from 1982 to 2013 and its response to climate change. *Water (Switzerland)* 10: 1–20. DOI: 10.3390/w10111689

Chaudhary S, Wang Y, Dixit AM, Khanal NR. 2020. A synopsis of farmland abandonment and its driving factors in Nepal. *Land* 9: 2–22

Cheng L, Zhang L, Chiew F, Canadell JG, Zhao F, Wang Y-P, Hu X, Lin and K. 2017. Quantifying the impacts of vegetation changes on catchment storage-discharge dynamics using paired-catchment data. *Water Resour* 53: 5963–5979. DOI: 10.1002/2017WR020600.Received

Claassen M, Hill L. 2017. Protecting the environment for development – Linking ecosystem function and development outcomes. 27–29

Clark D, Brow S, Kicklighter D, Chambers J, Thomlinson J, Ni J. 2001. Measuring net primary production in forests: concepts and field methods. *Ecological Applications* 11: 356–370

Clarke CL, Shackleton SE, Powell M. 2012. Climate change perceptions, drought responses and views on carbon farming amongst commercial livestock and game farmers in the semiarid Great Fish River Valley, Eastern Cape province, South Africa. *African Journal of Range and Forage Science* 29: 13–23. DOI: 10.2989/10220119.2012.687041

Climate Hazards Center. 2020. *CHIRPS: Rainfall estimates from rain gauge and satellite observations*. *University of California Santa Barbara*, 1

Cockburn J, Palmer C (Tally) G, Biggs H, Rosenberg E. 2018. Navigating multiple tensions for engaged praxis in a complex social-ecological system. *Land* 7: 1–24. DOI: 10.3390/land7040129

Cohen-Shacham E, Walters G, Janzen C, Maginnis S. 2016. *Nature-based solutions to address global societal challenges*. *Nature-based solutions to address global societal challenges*. DOI: 10.2305/iucn.ch.2016.13.en

Conservation International. 2019. *Trends.Earth Documentation*. *Release 1.0.7. Available: https://trends.earth/docs/en/pdfs/Trends.Earth.pdf [30 July 2019]*

Cowie A, Orr B., Sanchez V, Chasek P, Crossman N, Erlewein A, Louwagie G, Maron M, Metternicht G, Minelli S, Tengberg A, Walter S, Welton S. 2018. The scientific conceptual framework for Land Degradation Neutrality. *Environmental Science and Policy.Elsevier.* 79: 25–35. DOI: 10.1016/j.envsci.2017.10.011

Cumming TL, Shackleton RT, Förster J, Dini J, Khan A, Gumula M, Kubiszewski I. 2017. Achieving the national development agenda and the Sustainable Development Goals (SDGs) through investment in ecological infrastructure: A case study of South Africa. *Ecosystem Services* 27: 253–260. DOI: 10.1016/j.ecoser.2017.05.005

Da Silva JMC, Wheeler E. 2017. Ecosystems as infrastructure. *Perspectives in Ecology and Conservation* 15: 32–35. DOI: 10.1016/j.pecon.2016.11.005

Dai A. 2011. Drought under global warming: A review. *Wiley Interdisciplinary Reviews: Climate Change* 2: 45–65. DOI: 10.1002/wcc.81

Dai A. 2013. Increasing drought under global warming in observations and models. *Nature Climate Change* 3: 52–58. DOI: 10.1038/nclimate1633

Daim T, Oliver T, Kim J. 2013. Research and Technology Management in the Electricity Industry: Methods, Tools and Case Studies. *Springer* 8: 17–31. DOI: 10.1007/978-1-4471-5097-8

Dardel C, Kergoat L, Hiernaux P, Grippa M, Mougin E, Ciais, P 2 and Cam-Chi Nguyen C. 2014. Rain-use-efficiency: What it tells us about the conflicting Sahel greening and Sahelian paradox. *Remote sensing* 6: 3446–3474. DOI: 10.3390/rs6043446

De Groot RS, Blignaut J, Van Der Ploeg S, Aronson J, Elmqvist T, Farley J. 2013. Benefits of Investing in Ecosystem Restoration. *Conservation Biology* 27: 1286–1293. DOI: 10.1111/cobi.12158

de Jong R De, Bruin S De, Schaepman M, Dent D. 2011. Quantitative mapping of global land degradation using Earth observations. *International Journal of Remote Sensing ISSN:* 32: 6823–6853. DOI: 10.1080/01431161.2010.512946

De Klerk A. 2016. Research into ecological infrastructure steps up a gear. *Water Wheel* 15: 24–27

DEA (Department of Environmental Affairs). 2012. 2nd South Africa Environment Outlook. A report on the state of the environment. Executive Summary. Department of Environmental Affairs, Pretoria. DOI: 10.1520/MNL10373M.

DEA (Department of Environmental Affairs). 2013. *Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Climate trends and scenarios for South Africa*. Pretoria, South Africa.

DEA (Department of Environmental Affairs). 2014. *Ecological Infrastructure for Water Security', Revision 6.1: Final draft for submission to the Presidential Infrastructure Coordinating Commission*. Pretoria, South Africa.

DEA (Department of Environmental Affairs). 2015. *Synopsis Report: National Terrestrial Carbon Sink Assessment*. *Department of Environmental Affairs*. Pretoria, South Africa

DEA (Department of Environmental Affairs). 2017. *South Africa 2an annual climate change report*. Pretoria, South Africa. Available: https://www.environment.gov.za/sites/default/files/reports/southafrica_secondnational_climatechnage_report2017.pdf [7 November 2020]

DEA (Department of Environmental Affairs). 2018. *Ecosystem-Based Adaptation (Eba) in South Arica*. *Department of Environmental Affairs, Pretoria, South Africa*.

Department of Agriculture. 2009. *Mapping land degradation and conservation in South Africa Table of contents*. Pretoria, SouthAfrica

Department of Environmental Affairs and Tourism. 2004. *National action programme combating land degradation to alleviate rural poverty*. South Africa Pretoria

Dini J, Bahadur U. 2016. South Africa's national wetland rehabilitation programme: Working for wetlands. In: Finlayson, CM, Everard, M., Irvine, K., McInnes, R., Middleton, B., van Dam, A. D (ed) *The Wetland Book*, 1–7. DOI: 10.1007/978-94-007-6172-8

Dlamini P, Chivenge P, Manson A, Chaplot V. 2014. Geoderma Land degradation impact on soil organic carbon and nitrogen stocks of sub-tropical humid grasslands in South Africa. *Geoderma* 235–236: 372–381. DOI: 10.1016/j.geoderma.2014.07.016

Donnenfeld Z, Crookes C, Hedden S. 2018. *A delicate balance Water scarcity in South Africa*. *Institute for Security Studies*

Dubovyk O. 2017. The role of Remote Sensing in land degradation assessments: opportunities and challenges. *European Journal of Remote Sensing* 50: 601–613. DOI: 10.1080/22797254.2017.1378926

DWAF. 2006. *The construction of a hydrologically correct, annotated 1: 500 000 spatial datasets of the rivers of South Africa and contiguous basins. Report number N/000/00/REH/0701, DWAF: Resource Quality Services, Pretoria, South Africa*

DWS (Department of Water and Sanitation). 2014a. SIP 19 : Ecological Infrastructure for Water Security. 1–100. Available: https://www.environment.gov.za/sites/default/files/docs/sip19_ecologicalinfrastructure_watersecurity.pdf [7 November 2019]

DWS (Department of Water and Sanitation). 2014b. *Feasibility Study for the Mzimvubu Water Project Main Report Volume 1: Report*. Pretoria, South Africa

Dzikiti S, Ntshidi Z, Le Maitre DC, Bugan RDH, Mazvimavi D, Schachtschneider K, Jovanovic NZ, Pienaar HH. 2017. Assessing water use by Prosopis invasions and Vachellia karroo trees: Implications for groundwater recovery following alien plant removal in an arid catchment in South Africa. *Forest Ecology and Management* 398: 153–163. DOI: 10.1016/j.foreco.2017.05.009

Eriyagama N, Smakhtin V, Gamage N. 2009. *Mapping drought patterns and impacts: a global perspective* (Vol. 133)

ERS. 2011. *Umzimvubu Catchment Overview*. Available: https://umzimvubu.files.wordpress.com/2014/09/umzimvubu-summary-report-dec-2011.pdf [7 November 2019]

ESA-CCI. 2015. *Global land cover series map 1992-2015*. *European Space Agency*. Available: https://www.esa-landcover-cci.org/?q=node/197 [3 July 2020]

ESRI. 2014. *Understanding weighted overlay*. *Environmental Systems Research Institute*, 1–2. Available: https://www.esri.com/about/newsroom/wp-content/uploads/2019/05/understanding-weighted-overlay.pdf [22 October 2020].

FAO. 2003. *Data sets, indicators, and methods to assess land degradation in drylands*. *World Soil Resources Reports*

FAO. 2011. *Land Degradation Assessment in Drylands (LADA) project*. Rome

FAO. 2012. *AQUASTAT - FAO's Global Information System on Water and Agriculture*.

FAO. 2016. *Land degradation assessment Indrylands land degradation*. Rome, Italy

FAO and ITPS. 2017. Global soil organic carbon map - GSOCmap version 1.0. *Food and Agriculture Organization of the United Nation* 1–5

Favretto N, Stringer LC, Dougill AJ, Dallimer M, Perkins JS, Reed MS, Atlhopheng JR, Mulale K. 2016. Multi-Criteria Decision Analysis to identify dryland ecosystem service trade-offs under different rangeland land uses. *Ecosystem Services* 17: 142–151. DOI: 10.1016/j.ecoser.2015.12.005

Fensholt R, Rasmussen K. 2011. Analysis of trends in the Sahelian 'rain-use efficiency using GIMMS NDVI, RFE and GPCP rainfall data. *Remote Sensing of Environment* 115: 438–451. DOI: 10.1016/j.rse.2010.09.014

Forsyth GG, Le Maitre DC, O'Farrell PJ, van Wilgen BW. 2012. The prioritisation of invasive alien plant control projects using a multi-criteria decision model informed by stakeholder input and spatial data. *Journal of Environmental Management* 103: 51–57. DOI: 10.1016/j.jenvman.2012.01.034

Gamoun M. 2015. Rain use efficiency, primary production and rainfall relationships in desert rangelands of Tunisia. *Land Degradation & Development* 27: 738–747. DOI: 10.1002/ldr.2418

GEOTERRAIMAGE. 2019a. *South African national land cover 2018 report & accuracy assessment*. Pretoria

GEOTERRAIMAGE. 2019b. *South African National Land-Cover Change Assessments 2018*. Available:https://www.environment.gov.za/projectsprogrammes/egis_landcover_datasets [7 November 2020]

GEOTERRAIMAGE. 2019c. *South African National Land-Cover 2018 Report & Accuracy Assessment*. South Africa Pretoria

Gibbs HK, Salmon JM. 2015. Mapping the world's degraded lands. *Applied Geography* 57: 12–21. DOI: 10.1016/J.APGEOG.2014.11.024

Gichuki L, Brouwer R, Davies J, Vidal A, Kuzee M, Magero C, Walter S, Lara P, Oragbade C, Gilbey B. 2019. *Reviving land and restoring landscapes: policy convergence between forest landscape restoration and land degradation neutrality*. *Reviving land and restoring landscapes: policy convergence between forest landscape restoration and land degradation neutrality*. Gland, Switzerland: IUCN. DOI: 10.2305/iucn.ch.2019.11.en

Gilbey B. (n.d.). *A review of the Land Degradation Neutrality Process*. Nairobi, Kenya

Gonzales P, Ajami N. 2017. Social and Structural Patterns of Drought-Related Water Conservation and Rebound. *Water Resources Research* 53: 10619–10634. DOI: 10.1002/2017WR021852

Gonzalez-Roglich M, Zvoleff A, Noon M, Liniger H, Fleiner R, Harari N, Garcia C. 2019. Synergizing global tools to monitor progress towards land degradation neutrality: Trends.Earth and the World Overview of Conservation Approaches and Technologies sustainable land management database. *Environmental Science and Policy* 93: 34–42.

DOI: 10.1016/j.envsci.2018.12.019

Gosling SN, Arnell NW. 2016. A global assessment of the impact of climate change on water scarcity. *Climatic Change* 134: 371–385. DOI: 10.1007/s10584-013-0853-x

Graw V, Ghazaryan G, Dall K, Gómez AD, Abdel-Hamid A, Jordaan A, Piroska R, Post J, Szarzynski J, Walz Y, Dubovyk O. 2017. Drought dynamics and vegetation productivity in different land management systems of Eastern Cape, South Africa-A remote sensing perspective. *Sustainability (Switzerland)* 9: 1–19. DOI: 10.3390/su9101728

Groot D. 2015. Benefits of landscape restoration, with a focus on African dryland biomes. *Just diggit* 2: 1–6

Guo L, Sun F, Liu W, Zhang Y, Wang H. 2019. Response of ecosystem water-use efficiency to drought over China during 1982–2015: spatiotemporal variability and resilience. *Forests*, *10*(7): 598

Hajkowicz S, Collins K. 2007. A Review of Multiple Criteria Analysis for Water Resource Planning and Management. *Water Resour Manag* 21: 1553–1566. DOI: 10.1007/s11269-006-9112-5

Hartel T, Fischer C, Câmpeanu A, Milcu J, Hanspach and IF. 2014. The importance of ecosystem services for rural inhabitants in a changing cultural landscape in Romania. *Ecology and Society* 19

Hedden S, Cilliers J. 2014. Parched prospects-the emerging water crisis in South Africa. *Institute for Security Studies Papers*, *2014*(11)

Hengl T, De Jesus JM, Heuvelink GBM, Gonzalez MR, Kilibarda M, Blagotić A, Shangguan W, Wright MN, Geng X, Bauer-Marschallinger B, Guevara MA, Vargas R, MacMillan RA, Batjes NH, Leenaars JGB, Ribeiro E, Wheeler I, Mantel S, Kempen B. 2017. *SoilGrids250m: Global gridded soil information based on machine learning*. *PLoS ONE*. DOI: 10.1371/journal.pone.0169748

Hoffman MT. 2014. Changing Patterns of Rural Land Use and Land Cover in South Africa and their Implications for Land Reform. *Southern African Studies* 40: 707–725. DOI: 10.1080/03057070.2014.943525

Hoffman MT, Todd S. 2000a. A National Review of Land Degradation in South Africa : The Influence of Biophysical and Socio-economic Factors. *South African Studies* 26: 742–758. DOI: 10.1080/713683611

Hoffman T, Skowno A, Wesley B, Mashele S. 2018. Long-term changes in land use, land cover and vegetation in the Karoo drylands of South Africa: implications for degradation monitoring§. *African Journal of Range and Forage Science* 35: 209–221. DOI: 10.2989/10220119.2018.1516237

Hoffman TM, Todd S. 2000b. A National Review of Land Degradation in South Africa: The influence of Biophysical and Socio-economic Factors. *Journal of Southern African Studies* 26: 743–758. DOI: 10.1080/713683611

Holness SD, Dini JA, De Klerk A, Oberholster P. 2016. *High risk wetlands atlas: Reference guide to the Mpumalanga mining decision support tool*. Water Research Commission:

Pretoria, South Africa

Huang IB, Keisler J, Linkov I. 2011. Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Science of the Total Environment* 409: 3578–3594. DOI: 10.1016/j.scitotenv.2011.06.022

Huchzermeyer N, Schlegel P, van der Waal B. 2018a. *Managing alien invasive plants in the upper Tsitsa River catchment, catchment T35 A-E Management Plan TSITSA*. Grahamstown

Huchzermeyer N, Sibiya S, Schlegel P, Van der Waal B. 2018b. *Cultivated lands in the Upper Tsitsa river catchment T35 A-E*. *Tsitsa project*. Grahamstown, South Africa

Hughes CJ, De Winnaar G, Schulze RE, Mander M, Jewitt GPW. 2018. Mapping of water-related ecosystem services in the uMngeni catchment using a daily time-step hydrological model for prioritisation of ecological infrastructure investment – Part 2: Outputs. *Water SA* 44: 590. DOI: 10.4314/wsa.v44i4.08

IAEG-SDGs. 2016. The final list of proposed Sustainable Development Goal indicators*. Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators (E/CN. 3/2016/2/Rev. 1)*

Initiative ELD, UNEP. 2015. *The Economics of Land Degradation in Africa: Benefits of Action Outweigh the Costs. Economics of Land Degradation Initiative, Bonn, Germany.*

IPBES. 2018a. Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.* Bonn, Germany

IPBES. 2018b. *Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science*. Bonn, Germany.

IPCC. 2014. *Climate Change 2014-Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects: Volume 1, Global and Sectoral Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report*. *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Cambridge University Press: Cambridge, UK and New York, USA

IRP. 2019. *Land Restoration for Achieving the Sustainable Development Goals: An international resource panel think piece.* Nairobi, Kenya Copyright

ISRIC-World Soil Information. 2017. *SoilGrids—global gridded soil information*. Available: https://www.isric.org/explore/soilgrids [18 September 19]

IUCN 2015. Land Degradation Neutrality: implications and opportunities for conservation, Technical Brief 2nd Edition, November 2015. Nairobi: IUCN. 19p. *Land Degradation Neutrality : implications and opportunities for conservation*, Nairobi

Karthikevan R, Venkatesan KG., Chandrasekar A. 2016. A Comparison of Strengths and Weaknesses for Analytical Hierarchy Process. *Chemical and Pharmaceutical Sciences* 9: 11–15

Kaushal SS, Gold AJ, Mayer PM. 2017. Land use, climate, and water resources-global stages of interaction. *Water (Switzerland)* 9: 815. DOI: 10.3390/w9100815

Kim TW, Jehanzaib M. 2020. Drought risk analysis, forecasting and assessment under climate change. *Water (Switzerland)* 12: 1–7. DOI: 10.3390/W12071862

Klutho S. 2013. *Mathematical decision making: : An Overview of the Analytic Hierarchy Process Contents*. Washington: Whitman College

Kotze D, Marneweck G, Allan B, Lindley D and, Collins N. 2009. *A technique for rapidly assessing ecosystem services supplied by wetlands*. Gezina

Kotze DC. 2019. *Chapter 2: The ecosystem services provided by the Inland Aquatic Realm in South Africa, in Van Deventer et al*. Pretoria, South Africa

Kotzé I, Beukes H, Berg EVD, Newby T. 2010. *National Invasive Alien Plant Survey. Report Number: GW/A/2010/21*. Pretoria, South Africa. DOI: Report Number: GW/A/2010/21

Kotze P. 2013. Investing in Ecological Infrastructure for future water security. *The Water Wheel* 23–27

Lade O, Oloke D, Chinyio E, Fullen M. 2012. Use of multi-criteria decision analysis methods for water supply problems: A framework for improved rainwater harvesting. *Journal of Environmental Science and Engineering. A*, *1*(7A): 909–917

Lamb HH, Smith PJ, Loewe FP, Enfield DB, Waggoner PE, Wells NC, Bluestein HB, Gentilli J, Hayden BP, Arnfield AJ, Cenedese C, Davies R, Pielke RA, Mason BJ, and Krishnamurti T. 2020. “Climate” World distribution of precipitation. Available: *https://www.britannica.com/science/climate-meteorology/Amounts-and-variability*

Lamsal, P., K. P. Pant, L. Kumar and KA. 2020. Sustainable livelihoods through conservation of wetland resources : a case of economic benefits from Ghodaghodi Lake, western Nepal. *Ecology and Society* 20: 12

Le Houerou HN, Bingham RL, Skerbeki W. 1988. Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. 1–18. DOI: 10.1016/S0140-1963(18)31001-2

Le Maitre D, Chapman D, Versfeld R. 2000. The impact of invading alien plants on surface water resources in South Africa : A preliminary assessment. *Water SA* 26: 12

Le Maitre D, Görgens A, Howard G, Walker N. 2019. Impacts of alien plant invasions on water resources and yields from the Western Cape water supply system (WCWSS). *Water SA* 45: 568–579. DOI: 10.17159/wsa/2019.v45.i4.7538

Le Maitre DC, Colvin CA. 2008. Assessment of the contribution of groundwater discharges to rivers using monthly flow statistics and flow seasonality. *Water SA* 34: 549–564. DOI: 10.4314/wsa.v34i5.180652

Le Maitre DC, Forsyth GG, Dzikiti S, Gush MB. 2016. Estimates of the impacts of invasive alien plants on water flow in South Africa. *Water SA* 42: 659–672. DOI: 10.4314/wsa.v42i4.17

Le Maitre DC, Kotzee IM, O’Farrell PJ. 2014. Impacts of land-cover change on the water flow regulation ecosystem service: Invasive alien plants, fire and their policy implications. *Land Use Policy* 36: 171–181. DOI: 10.1016/j.landusepol.2013.07.007

Le Maitre DC, Scott DF, Colvin C. 1999. A review of information on interactions between vegetation and groundwater. *Water SA* 25: 137–152

Le Maitre DC, Seyler H, Holland M, Smith-Adao L, Nel JL, Maherry A, Witthüser K. 2018a. *Identification, Delineation and Importance of the Strategic Water Source Areas of South Africa, Lesotho and Swaziland for Surface Water and Groundwater*. *Journal of Visual Languages & Computing*. Water Research Commission, Pretoria. DOI: Report No. TT 743/1/18

Le Maitre DC, Seyler H, Holland M, Smith-Adao L, Nel JL, Maherry A, Witthüser K. 2018b. *Delineation and importance of the Strategic Water Source Areas of South Africa, Lesotho and Swaziland for surface water and groundwater*. *Water Research Commission*. Water Research Commission, Pretoria

Le Roux J, Barker C, Weepener H, Berg E Van den, Pretorius S. 2015. *Sediment yield in the Mzimvubu River catchment*.

Li F, Liu X, Zhang X, Zhao D, Liu H, Zhou C, Wang R. 2017. Urban ecological infrastructure: an integrated network for ecosystem services and sustainable urban systems. *Journal of Cleaner Production* 163: S12–S18. DOI: 10.1016/j.jclepro.2016.02.079

Li S, Yang H, Lacayo M, Liu J, Lei G. 2018. Impacts of land-use and land-cover changes on water yield: A case study in Jing-Jin-Ji, China. *Sustainability (Switzerland)* 10: 1–16. DOI: 10.3390/su10040960

Lima. 2017. *Lima rural development foundation-organisation profile*. Available: https://lima.org.za/about-us/organisational-profile/ [7 November 2019]

Liniger H, Harari N, van Lynden G, Fleiner R, de Leeuw J, Bai Z, Critchley W. 2019. Achieving land degradation neutrality: The role of SLM knowledge in evidence-based decision-making. *Environmental Science & Policy* 94: 123–134. DOI: 10.1016/J.ENVSCI.2019.01.001

Liu C, Melack J, Tian Y, Huang H, Jiang J, Fu X, Zhang Z. 2019. Detecting land degradation in eastern China grasslands with time series segmentation and residual trend analysis (TSS-RESTREND) and GIMMS NDVI3g data. *Remote sensing* 11: 1014

Lötter L, Stronkhorst LD, Smith HJ. 2009. *Report : Sustainable Land Management Practices of South Africa Report Number :* Pretoria, SouthAfrica

Luvuno L, Biggs R, Stevens N, Esler K. 2018. Woody encroachment as a social-ecological regime shift. *Sustainability (Switzerland)* 10: 2221. DOI: 10.3390/su10072221

Mander M, Jewitt G, Dini J, Glenday J, Blignaut J, Hughes C, Marais C, Maze K, van der Waal B, Mills A. 2017. Modelling potential hydrological returns from investing in ecological infrastructure: Case studies from the Baviaanskloof-Tsitsikamma and uMngeni catchments, South Africa. *Ecosystem Services* 27: 261–271. DOI: 10.1016/j.ecoser.2017.03.003

Martin D and, Poff N. 2016. An objective method to prioritize socio-environmental water management tradeoffs using multi-criteria decision analysis. *River Research and Applications*, *33*(4):1–12. DOI: 10.1002/rra.3103

Matsika R. 2007. *Land-cover change: Threats to the grassland biome of South Africa* (Doctoral dissertation, University of the Witwatersrand).

McCartney M, Rebelo L., Sellamuttu S., de Silva S. 2010. *Wetlands, agriculture and poverty reduction* (Vol. 137). *International Water Management Institute*. DOI: 10.5337/2010.230

McDowell NG, Fisher RA, Xu C, Domec JC, Hölttä T, Mackay DS, Sperry JS, Boutz A, Dickman L, Gehres N, Limousin JM, Macalady A, Martínez-Vilalta J, Mencuccini M, Plaut JA, Ogée J, Pangle RE, Rasse DP, Ryan MG, Sevanto S, Waring RH, Williams AP, Yepez EA, Pockman WT. 2013. Evaluating theories of drought-induced vegetation mortality using a multimodel-experiment framework. *New Phytologist* 200: 304–321. DOI: 10.1111/nph.12465

McLeod M, Cleveland C, Lekkberg Y, J M, Phillipot L, Bru D, and Callaway R. 2016. Exotic invasive plants increase productivity, the abundance of ammonia-oxidizing bacteria and nitrogen availability in intermountain grasslands. *Journal of ecology* 104: 994–1002. DOI: 10.1111/1365-2745.12584

MEA (Millennium Ecosystem Assessment). 2005. *Ecosystems and human well-being - Synthesis of the Millennium Ecosystem Assessment*. *Island Press*. DOI: 10.1196/annals.1439.003

Meadows ME, Hoffman TM. 2003. Land degradation and climate change in South Africa. *The geographical* 169: 168–177

Mpati TM. 2015. *Satellite-based long-term evaluation of bush encroachment on sourish-mixed veld at the Towoomba Research Station in Bela Bela, Limpopo Province* (Doctoral dissertation).

Münch Z, Okoye PI, Gibson L, Mantel S, Palmer A. 2017. Characterizing degradation gradients through land cover change analysis in rural Eastern Cape, South Africa. *Geosciences*, *7*(1): 1–22. DOI: 10.3390/geosciences7010007

Mutikanga HE, Sharma SK. 2011. Multi-criteria decision analysis: a strategic planning tool for water loss management. *Water resources management*, *25*(14): 1–12. DOI: 10.1007/s11269-011-9896-9

Nel J, Colvin C, Le Maitre D, Smith J, Haines I. 2013. *South Africa's Strategic Water Source Areas. CSIR Report No: CSIR/NRE/ECOS/ER/2013/0031/A*. Stellenbosch

Nel J, Driver A, Strydom W, Maherry A, Petersen C, Hill L, Roux D, Nienaber S, Van Deventer H, Swartz E, Smith-Adao L. 2011. *Atlas of freshwater ecosystem priority areas in South Africa: Maps to support the sustainable development of water resources.* Water Research Commission: Pretoria, South Africa

Nel JL, Le Maitre DC, Roux DJ, Colvin C, Smith JS, Smith-Adao LB, Maherry A, Sitas N. 2017. Strategic water source areas for urban water security: Making the connection between protecting ecosystems and benefiting from their services. *Ecosystem Services* 28: 251–259. DOI: 10.1016/j.ecoser.2017.07.013

Niu S, Zhang Z, Xia J, Zhou X. 2011. Water-use efficiency in response to climate change: from leaf to ecosystem in a temperate steppe. *Global Change Biology* 17: 1073–1082. DOI:

10.1111/j.1365-2486.2010.02280.x

NWRS2 (National Water Resource Strategy2). 2013. *Water for an equitable future and sustainable future*. Available: https://cer.org.za/wp-content/uploads/1999/12/NWRS2-2013.pdf [18 September 19]

O'Farrell P, Anderson P, Culwick C, Currie P, Kavonic J, McClure A, Ngenda G, Sinnott E, Sitas N, Washbourne C-L, Audouin M, Blanchard R, Egoh B, Goodness J, Kotzee I, Sanya T, Stafford W, Wong G. 2019. Towards resilient African cities: Shared challenges and opportunities towards the retention and maintenance of ecological infrastructure. *Global Sustainability* 2. DOI: 10.1017/sus.2019.16

Obalum SE, Buri MM, Nwite JC, Hermansah, Watanabe Y, Igwe CA, Wakatsuki T. 2012. Soil degradation-induced decline in productivity of sub-Saharan African soils: the prospects of looking downwards the lowlands with the Sawah ecotechnology. *Applied and Environmental Soil Science*, *2012*.: 1–10. DOI: 10.1155/2012/673926

Oguztimur S. 2015. *Why fuzzy analytic hierarchy process approach for transport*. *Research gate*. Beşiktaş/İstanbul - Turkey

Olson L. 1988. Topics in the theory of the analytic hierarchy process: Opportunities and limitations of AHP in multiobjective programming. *Mathematical and Computer Modelling: An International Journal*, *11*: 206–209

Olsson L, Yengoh GT, Gonzalez-Roglich M, Tengberg AE, Zvoleff A, Noon M. 2018. Disentangling the effects of climate and land use on land degradation: A synthesis of field observations and theoretical foundation. *GEF-Land Degradation Monitoring Project Disentangling Report.* . United States

Orr B., Cowie VM, S.P C, Chasek N., Crossman A, Erlewein G, Louwagie M, Maron GI, Metternicht S, Minelli AE, Tengberg S, Walter and SW. 2017. *Scientific conceptual framework for land degradation neutrality. In A report of the science-policy interface.United Nations Convention to Combat Desertification (UNCCD)*. Bonn, Germany

Pantshwa OA, Buschke FT. 2019. Ecosystem services and the ecological degradation of communal wetlands in a South African biodiversity hotspot. *Royal Society open science*, *6*(6): 181770. DOI: 10.1098/rsos.181770

Pasquini L, Enqvist JP. 2019. *Green infrastructure in South African cities report for cities support programme undertaken by African Centre for Cities*.

Pelser A., Khorehloa T. 2000. Some causes and strategies pertaining to land degradation in South Africa. *South African journal agriculture* 29: 24–46

Pettorelli N, Vik JO, Mysterud A, Gaillard J-M, Tucker CJ, Stenseth NC. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution* 20: 503–510. DOI: 10.1016/J.TREE.2005.05.011

Philippe N. 2012. *Multicriteria Decision Analysis*. John Wiley & Sons, Ltd: West Sussex. DOI: 10.4135/9781412972093.n246

Ramanathan R. 2001. A note on the use of the analytic hierarchy process for environmental impact assessment. 27–35. DOI: 10.1006/jema.2001.0455

Ramsar Convention Secretariat. 2012. What are wetlands? *Ramsar information* 2. Paper no1. Available: https://www.ramsar.org/sites/default/files/documents/library/info2007-01-e.pdf[18 September 2020]

Rasmussen LV, Fold N, Olesen RS, Shackleton S. 2021. Socio-economic outcomes of ecological infrastructure investments. *Ecosystem Services* 47: 101242. DOI: 10.1016/j.ecoser.2020.101242

Rebelo AJ. 2018. *Ecosystem services of Palmiet wetlands: The role of ecosystem composition and function* (Doctoral dissertation, Stellenbosch: Stellenbosch University).

Rebelo AJ, Le Maitre DC, Esler KJ, Cowling RM. 2015. Hydrological responses of a valley-bottom wetland to land-use/land-cover change in a South African catchment: Making a case for wetland restoration. *Restoration Ecology* 23: 829–841. DOI: 10.1111/rec.12251

Rey D, Holman IP, Knox JW. 2017. Developing drought resilience in irrigated agriculture in the face of increasing water scarcity. *Regional Environmental Change* 17: 1527–1540. DOI: 10.1007/s10113-017-1116-6

Richardson DM, Van Wilgen BW. 2004. Invasive alien plants in South Africa: how well do we understand the ecological impacts?: working for water. *South African Journal of Science*, *100*(1): 9

Rockström J, Falkenmark M, Allan T, Folke C, Gordon L, Jägerskog A, Kummu M, Lannerstad M, Meybeck M, Molden D, Postel S, Savenije HHG, Svedin U, Turton A, Varis O. 2014. The unfolding water drama in the Anthropocene: Towards a resilience-based perspective on water for global sustainability. *Ecohydrology* 7: 1249–1261. DOI: 10.1002/eco.1562

Rojas D, Loubier JC. 2017. Analytical hierarchy process coupled with GIS for land management purposes. In *Proceedings of the 22nd International Congress on MODSIM, 2017* (No. CONFERENCE). 03-08 December 2017.

Rowntree K, Duma M, Kakembo V, Thornes J. 2004. Debunking the myth of overgrazing and soil erosion. *Land degradation & development*, *15*(3): 203–214. DOI: 10.1002/ldr.609

Saaty T. 1980. The analytic hierarchy process: planning, priority setting, resource allocation.

Saaty T. 2000. Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process. 5: 1–35

Salemi LF, Groppo JD, Trevisan R, Marcos de Moraes J, de Paula Lima W, Martinelli LA. 2012. Riparian vegetation and water yield: A synthesis. *Journal of Hydrology* 454–455: 195–202. DOI: 10.1016/j.jhydrol.2012.05.061

SANBI (South African National Biodiversity Assessment). 2013a. *Assessment of Ecological Infrastructure for Three Potential Dams in the Umzimvubu*. Pretoria, South Africa

SANBI (South African National Biodiversity Assessment). 2013b. *Grasslands Ecosystem Guidelines: landscape interpretation for planners and managers. Compiled*. Pretoria, South Africa

SANBI (South African National Biodiversity Assessment). 2014. A Framework for Investing in Ecological Infrastructure in South Africa. 1–22

Sanz M., de Vente J-L, Chotte M, Bernoux G, Kust I, Ruiz M, Almagro J-A, Alloza R, Vallejo V, Castillo A, Hebel, and Akhtar-Schuster M 2017. 2017. *Sustainable Land Management contribution to successful land-based climate change adaptation and mitigation: A Report of the science-policy interface*. Bonn, Germany

Schlegel P, Huchzermeyer N. 2018. *Biophysical Monitoring Plan, Tsitsa River T35 A-E methodological outline Report.* Grahamstown, South Africa. Available: https://www.ru.ac.za/media/rhodesuniversity/content/tsitsaproject/digitalpublications/documents/biophysical_monitoring_plan_methodological_report_2018.08.14_v5.pdf [18 September 2019]

Schulze RE. 1997. *South African Atlas of Agrohydrology and Climatology Water Research Commission*. Pretoria, South Africa

Scorer C, Mantel SK, Palmer AR. 2019. Do abandoned farmlands promote the spread of invasive alien plants? Change detection analysis of black wattle in montane grasslands of the Eastern Cape. *South African Geographical Journal*, *101*(1): 36–50. DOI: 10.1080/03736245.2018.1541018

Shackleton CM, Gambiza J. 2008. Social and ecological trade-offs in combating land degradation: the case of invasion by a woody shrub (Euryops floribunda) at Macubeni, South Africa. *Land Degradation & Development*, *19*(4): 454–464. DOI: 10.1002/ldr.849

Shackleton CM, McGarry D, Fourie S, Gambiza J, Shackleton SE, Fabricius C. 2007. Assessing the effects of invasive alien species on rural livelihoods: Case examples and a framework from South Africa. *Human ecology* 35: 113–127. DOI: 10.1007/s10745-006-9095-0

Shackleton CM, Mograbi PJ, Drimie S, Fay D, Hebinck P, Hoffman MT, Maciejewski K, Twine W. 2019. Deactivation of field cultivation in communal areas of South Africa: Patterns, drivers and socio-economic and ecological consequences. *Land Use Policy* 82: 686–699. DOI: 10.1016/J.LANDUSEPOL.2019.01.009

Shackleton RT, Angelstam P, van der Waal B, Elbakidze M. 2017. Progress made in managing and valuing ecosystem services: a horizon scan of gaps in research, management and governance. *Ecosystem Services* 27: 232–241. DOI: 10.1016/j.ecoser.2016.11.020

Sigwela A, Elbakidze M, Powell M, Angelstam P. 2017. Defining core areas of ecological infrastructure to secure rural livelihoods in South Africa. *Ecosystem Services* 27: 272–280. DOI: 10.1016/j.ecoser.2017.07.010

Sims NC, England JR, Newnham GJ, Alexander S, Green C, Minelli S, Held A. 2019. Developing good practice guidance for estimating land degradation in the context of the United Nations Sustainable Development Goals. *Environmental Science and Policy* 92: 349–355. DOI: 10.1016/j.envsci.2018.10.014

Sims NC, Green C, Newnham GJ, England JR, Held A, Wulder MA, Herold M, Cox SJD, Huete AR, Kumar L, Viscarra-Rossel RA, Roxburgh SH, McKenzie NJ. 2017. *Good practice* *guidance. SDG indicator 15.3. 1: proportion of land that is degraded over total land area. In United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany.*

Skowno A, Poole C., Raimondo D., Sink K., Deventer V, Van Niekerk L, Harris L., SmithAdao L., Tolley K., Zengeya T., Foden W., Midgley G., Driver A. 2018. *National Biodiversity Assessment 2018: The status of South Africa's ecosystems and biodiversity.* Pretoria.

Skowno AL, Raimondo DC, Poole CJ, Fizziotti B, Slingsby JA. 2019. *South African national biodiversity assessment 2018 Technical Report Volume 1: Terrestrial Realm*. *South African National Biodiversity Institute*. Pretoria, South Africa

Stafford W, Birch C, Etter H, Blanchard R, Mudavanhu S, Blignaut J, Ferreira L, Marais C. 2017. The economics of landscape restoration: Benefits of controlling bush encroachment and invasive plant species in South Africa and Namibia. *Ecosystem Services* 27: 193–202. DOI: 10.1016/j.ecoser.2016.11.021

Stats SA. 2011. *Census 2011:Improving lives through data ecosystem*. *Department of Statistics South Africa. Available: http://www.statssa.gov.za/?page_id=3836 [7 November 2020]*

Stavi I, Lal R. 2015. Achieving zero net land degradation: Challenges and opportunities. *Journal of Arid Environments* 112: 44–51. DOI: 10.1016/J.JARIDENV.2014.01.016

Stoelzle M, Stahl K, Morhard A, Weiler M. 2014. Streamflow sensitivity to drought scenarios in catchments with different geology. *Geophysical Research Letters* 41: 6174–6183. DOI: 10.1002/2014GL061344.

Symeonakis E, Drake N. 2004. Monitoring desertification and land degradation over sub-Saharan Africa. *International Journal of remote sensing*, *25*(3): 573–592. DOI: 10.1080/0143116031000095998

Tang X, Ma M, Ding Z, Xu X, Yao L, Huang X, Qing G, Song L. 2017. Remotely monitoring ecosystem water use efficiency of grassland and cropland in China's arid and semi-arid regions with MODIS data. *Remote Sensing*, *9*(6)*:* 1–17. DOI: 10.3390/rs9060616

TEEB. 2010. *Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB*.

Thompson M, Vlok J, Rouget M, Hoffman MT, Balmford A, Cowling RM. 2009. Mapping grazing-induced degradation in a semi-arid environment: a rapid and cost-effective approach for assessment and monitoring. *Environmental Management*, *43*(4). *Springer* 43: 585–596. DOI: 10.1007/s00267-008-9228-x

Thorslund J, Jarsjo J, Jaramillo F, Jawitz JW, Manzoni S, Basu NB, Chalov SR, Cohen MJ, Creed IF, Goldenberg R, Hylin A, Kalantari Z, Koussis AD, Lyon SW, Mazi K, Mard J, Persson K, Pietro J, Prieto C, Quin A, Van Meter K, Destouni G. 2017. Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management. *Ecological Engineering*, 108: 489–497. DOI: 10.1016/J.ECOLENG.2017.07.012

Thungngern J, Sriburi T, Wijitkosum S. 2017. Analytic hierarchy process for stakeholder participation in integrated water resources management. *Engineering Journal* 21: 86–

103. DOI: 10.4186/ej.2017.21.7.87

Turpie J, Botha P, Coldrey K, Forsythe K, Knowles T. 2019. *Towards a policy on indigenous bush encroachment in South Africa*. Department of Environmental Affairs, Pretoria, South Africa

UN-Water/WWAP (United Nations World Water Assessment Programme). 2018. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. Paris

UNCCD (United Nations Convention to Combat Desertification). 2016. *The Ripple Effect: A fresh approach to reducing drought impacts and building resilience*. Bonn, Germany. DOI: DOI: 10.1097/00006247-200202000-00015

UNCCD (United Nations Convention to Combat Desertification). 2017. *Land degradation neutrality fund: An innovative fund project dedicated to sustainable land use*. *Mirova Responsible Investing*. Paris

UNCCD (United Nations Convention to Combat Desertification). 2018. Performance review and assessment of implementation system seventh reporting process: *Reporting manual for the 2017-2018 UNCCD reporting process*. Available: https://prais.unccd.int/sites/default/files/helper_documents/2-Manual_EN_1.pdf [10 November 2020]

UNCCD (United Nations Convention to Combat Desertification) & FAO (Food and Agriculture Organization). 2020. Land Degradation Neutrality for Water Security and Combatting Drought. Bonn, Germany

UNESCO (United Nations Educational Scientific and Cultural Organization). 1984. *Final Report, Programme on Man and the Biosphere (MAP).International Experts Meeting on Ecological Approaches to Urban Planning.MAB Report Series 57*.

United Nations. 2015. *Transforming our world: The 2030 Agenda for Sustainable Development. United Nations sustainable knowledge platform*. *Sustainable Development Goals*. New York, USA

UNSC (United Nations Statistical Commission). 2015. *Statistical Commission*. United Nations, New York

Van der Waal B, Rowntree K. 2018. L Landscape connectivity in the upper Mzimvubu river catchment: an assessment of anthropogenic influences on sediment connectivity. *Land degradation & development*, *29*(3): 713–723. DOI: 10.1002/ldr.2766

Van der Waal B, Rowntree K, Roux J, Buckle J, Biggs H, Braack M, Kawa M, Wolff M, Palmer T, Sisitka L, Powell M, Clark R, Ntshudu M, Mtati N, Tol J Van, Zijl G Van. 2017. *THE TSITSA PROJECT Restoration and Sustainable Land Management Plan Infrastructure for Improved Livelihoods and Futures T35A-E (Phase 1 of TP)*. Grahamstown, South Africa

Van Deventer H, Smith-Adao L, Mbona N, Petersen C, Skowno A, Collins NB, Grenfell M, Job N, Lötter M, Ollis D, Scherman P, Sieben E, Snaddon K. 2018. *National Biodiversity Assessment 2018: Technical Report. Volume 2a: South African Inventory of Inland Aquatic Ecosystems (SAIIAE). South African Inventory of Inland Aquatic Ecosystems.* Pretoria, South Africa

Van Deventer H, Van Niekerk L, Adams J, Dinala M., Gangat R, Lamberth S., Lötter M, Mbona N, MacKay F, Nel J, Ramjukadh C. 2020. National Wetland Map 5: An improved spatial extent and representation of inland aquatic and estuarine ecosystems in South Africa. *Water SA*, *46*(1) 66–79. DOI: 10.17159/wsa/2020.v46.i1.7887

Van Loon AF, Laaha G. 2015. Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology* 526: 3–14. DOI: 10.1016/j.jhydrol.2014.10.059

Van Loon AF, Stahl K, Di Baldassarre G, Clark J, Rangecroft S, Wanders N, Gleeson T, Van Dijk AIJM, Tallaksen LM, Hannaford J, Uijlenhoet R, Teuling AJ, Hannah DM, Sheffield J, Svoboda M, Verbeiren B, Wagener T, Van Lanen HAJ. 2016. Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches. *Hydrology and Earth System Sciences* 20: 3631–3650. DOI: 10.5194/hess-20-3631-2016

van Wilgen BW, Reyers B, Le Maitre DC, Richardson DM, Schonegevel L. 2008. A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. *Journal of Environmental Management* 89: 336–349. DOI: 10.1016/j.jenvman.2007.06.015

Vinet L, Zhedanov A. 2010. A “missing” family of classical orthogonal polynomials. *Journal of Physics A: Mathematical and Theoretical*, *44*(8): 1–403. DOI: 10.1088/1751-8113/44/8/085201

Vogels MFA, de Jong SM, Sterk G, Addink EA. 2017. Agricultural cropland mapping using black-and-white aerial photography, object-based image analysis and random forests. *International Journal of Applied Earth Observation and Geoinformation* 54: 114–123. DOI: 10.1016/j.jag.2016.09.003

Von Maltitz PG, Gambiza J, Kellner K, Rambau T, Lindeque L, Kgope B. 2019. Experiences from the South African land degradation neutrality target setting process. *Environmental Science and Policy* 101: 54–62. DOI: 10.1016/j.envsci.2019.07.003

Wang KB, Ren ZP, Deng L, Zhou ZC, Shangguan ZP, Shi WY, Chen YP. 2016. Profile distributions and controls of soil inorganic carbon along a 150-year natural vegetation restoration chronosequence. *Soil Science Society of America Journal* 80: 193–202. DOI: 10.2136/sssaj2015.08.0296

Wessels KJ, Prince SD, Malherbe J, Small J, Frost PE, VanZyl D. 2007a. Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa. *Journal of Arid Environments* 68: 271–297. DOI: 10.1016/j.jaridenv.2006.05.015

Wessels KJ, Prince SD, Zambatis N, Macfadyen S, Frost PE. 2007b. Relationship between herbaceous biomass and 1-km2 Advanced Very High-Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South Africa. *International Journal of Remote Sensing*, *27*(05): 951-973. DOI: 10.1080/01431160500169098

Wessels KJ, van den Bergh F, Scholes RJ. 2012. Limits to detectability of land degradation by trend analysis of vegetation index data. *Remote Sensing of Environment* 125: 10–22. DOI: 10.1016/j.rse.2012.06.022

Working for Wetland Programme. 2018. *Rehabilitation Plan for the Gatberg Wetland Project, Eastern Cape: Planning Year 2017/2018. Prepared by Jenny Youthed, Aurecon South Africa (Pty) Ltd as part of the planning phase for the Working for Wetlands Rehabilitation Programme. Report No. 113223/11682a.*

World Meteorological Organization. 2005. *Climate and Land Degradation*. Switzerland. Available: https://www.droughtmanagement.info [22 August 2020]

Wunder S, Kaphengst T, Larsen AF, McFraland K, Albercht S. 2018. Implementing SDG target 15.3 on "Land Degradation Neutrality." *Ecologic Institut, Berlin*. 60

Yapi TS, O'farrell PJ, Dziba LE, Esler KJ, Aronson J. 2018. Alien tree invasion into a South African montane grassland ecosystem: Impact of Acacia species on rangeland condition and livestock carrying capacity. *International Journal of Biodiversity Science* 14: 105–116. DOI: 10.1080/21513732.2018.1450291

Zaloumis NP. 2013. South African grassland ecology and its restoration. University of Cape Town, South Africa

Zhao T, Dia A. 2015. The magnitude and causes of global drought changes in the twenty-first century under a low – moderate emissions scenario. *Journal of Climate* 28: 4490–4512. DOI: 10.1175/JCLI-D-14-00363.1

Appendices

Appendix 1: Supplementary background on calculating SDG 15.3.1 indicator using Trends.Earth tool

Appendix 1.1 Calculating SDG 15.3.1 sub-indicators

The assessment for the SDG15.3.1 degradation indicator uses information from three sub-indicators; Productivity, Land cover and Soil Organic Carbon (Conservation International, 2019), which are described below. The final assessed SDG15.3.1 indicator is reported based on the following three categories: stable, degraded, or improving.

Sub-indicator 1: Land productivity

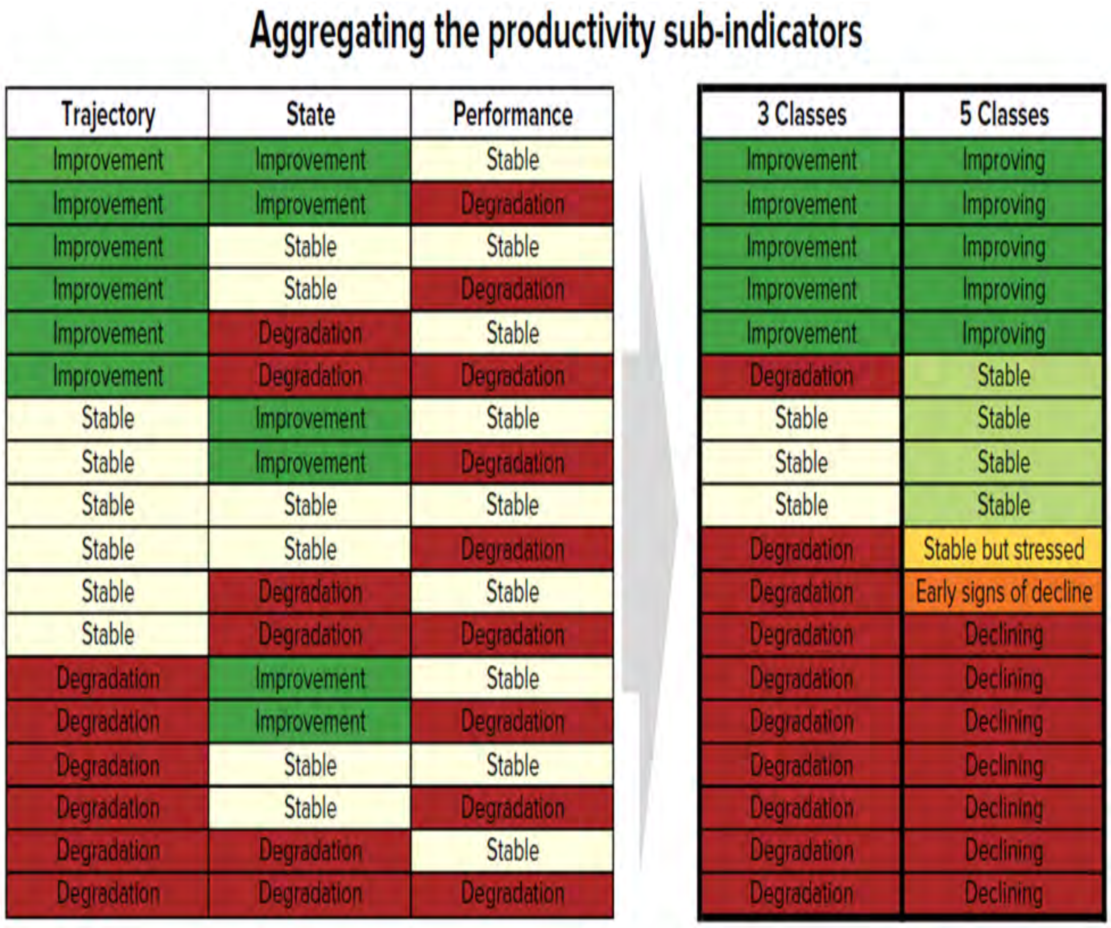
Land productivity can be measured using Net Primary Productivity (NPP), which is defined as the remaining amount of carbon estimated after photosynthesis and autotrophic respiration over a given time (Clark et al., 2001). Various vegetation indices can be calculated and used as a substitution for land productivity, such as the Normalised Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) (UNCCD, 2018).

Land productivity in the Trends.Earth plugin was measured using the NDVI time-series data from three calculated productivity sub-indicators, including the productivity *Trajectory*, *Performance,* and *State* (Conservation International, 2019). The productivity *trajectory* measures the rate of change in primary productivity over time. The productivity *performance* measures the local productivity relative to other similar vegetation types in similar land cover types or bioclimatic regions throughout a given study area. Productivity *performance* also analyses how a region performs relative to other regions with similar productivity potential (Sims et al., 2017). The productivity *state* measures the mean NDVI productivity of a feature or recent pixel changes (average productivity from the last three years 2013–2015) in primary productivity compared to the productivity of the observed baseline period (long-term period 2001–2012) of the spatial unit (Sims et al., 2017).

The three sub-indicators of productivity are combined into five classes of reporting the land productivity dynamics: improving; stable; stable but stressed; early signs of decline. Land productivity dynamics indicate the overall direction, relative change intensity and persistence of NPP (UNCCD, 2018). The five classes identify areas with persistent and active declines in NPP, pointing to potential ongoing land degradation. Also, the classification points out areas that have already experienced degradation processes and have reached a new equilibrium; they have not degraded further within the observation period (UNCCD, 2018; Conservation International, 2019). The aggregation processes and interpretation of the five classes are shown in Figure A1 and Table A1 presented below.

Table A1: Guidelines for interpretation of the direction of land productivity based on the five classes (UNCCD, 2018, p. 15).

Land productivity Dynamics class	**Guidelines for interpretation**
Declining	Indicates a high probability of recently active land degradation processes.
Early signs of decline	Indicates a high probability of recently active land degradation processes.
Stable but stressed	Often represents persistent strong inter-annual variations in land productivity, which indicate the beginning of instability in the land conditions.
Stable	Indicates a low probability of active land degradation and therefore a satisfactory or acceptable situation. However, it does not exclude the possibility that the land has already undergone degradation processes and has reached a new equilibrium (i.e., it is not further degrading, but neither is it recovering).
Increasing/Improving	Indicates a satisfactory or improving situation from a degraded state, but in some cases, it may also indicate unfavourable processes such as shrub encroachment in grasslands, or land abandonment.



Aggregating the productivity sub-indicators

Trajectory	State	Performance	3 Classes	5 Classes
Improvement	Improvement	Stable	Improvement	Improving
Improvement	Improvement	Degradation	Improvement	Improving
Improvement	Stable	Stable	Improvement	Improving
Improvement	Stable	Degradation	Improvement	Improving
Improvement	Degradation	Stable	Improvement	Improving
Improvement	Degradation	Degradation	Degradation	Stable
Stable	Improvement	Stable	Stable	Stable
Stable	Improvement	Degradation	Stable	Stable
Stable	Stable	Stable	Stable	Stable
Stable	Stable	Degradation	Degradation	Stable but stressed
Stable	Degradation	Stable	Degradation	Early signs of decline
Stable	Degradation	Degradation	Degradation	Declining
Degradation	Improvement	Stable	Degradation	Declining
Degradation	Improvement	Degradation	Degradation	Declining
Degradation	Stable	Stable	Degradation	Declining
Degradation	Stable	Degradation	Degradation	Declining
Degradation	Degradation	Stable	Degradation	Declining
Degradation	Degradation	Degradation	Degradation	Declining

Figure A1: Process of aggregating three sub-indicators (trajectory, state and performance) of land productivity into five classes of reporting land productivity state (Conservation International, 2019: 27).

Sub-indicator 2: Landcover

Trends.Earth tool assesses the land cover change in an area over a given period, from the baseline year 2000 to the target year 2015 (although shorter periods can be selected). Trends.Earth uses seven land cover classes aggregated from the 22 land cover classes used by the UNCCD Land Degradation Neutrality (LDN) (Sims et al., 2017: 21). Land cover classes are computed using an imagery product provided by the European Space Agency: Climate Change Initiative (CCI) at 300 m resolution to calculate land cover degradation and land cover transition. Changes in the seven land cover classes (Table A2) are measured at the pixel level (300 m), and they are classified into one of three classes: stable, improved, or degraded. Land cover class changes might be described according to major land cover change processes. These land cover processes include changes in land cover and land use, including processes such as deforestation, urban expansion (built-up areas), loss of natural vegetation, flooding/water overflow, wood encroachment, wetland drainage, water drainage, the establishment of vegetation, cropland wetland, agricultural practice (Sims et al., 2017, 2019; UNCCD, 2018). These land cover change processes affect the ecosystem either through improvement or deprivation of ecosystem services.

Sub-indicator 3: Soil Organic Carbon (SOC)

Trends.Earth compares SOC for the baseline and targeted years in each spatial feature (Conservation International, 2019). Soil organic carbon in the plugin is calculated as carbon stock in the soil using the default data, determined per pixel, using ISRI Soil Grids global climate data from 2001-2015 (Conservation International, 2019). The data for SOC was derived from the 250 m SoilGrids project by ISRIC, which uses the topsoil (upper 30 cm) to calculate SOC through computer modelling. The plugin uses changes in land cover to calculate the relevant differences in baseline (2001) soil organic carbon to the targeted year (2015).

Table A2:The 22 land cover classes from the ESA-CCI aggregated into seven classes from the UNCCD-land cover classification system.

Input land cover class from ESA CCI- LC (22 classes)	**Output land cover class (7 classes)**
• Tree cover, broadleaved, evergreen, closed to open (>15%) • Tree cover, broadleaved, deciduous, closed to open (>15%) • Tree cover, needle-leaved, evergreen, closed to open (>15%) • Tree cover, needle-leaved, deciduous, closed to open (>15%) • Tree cover, mixed leaf type, closed to open (>15%) • Mosaic tree and shrub (>50%)/herbaceous cover (<50%)	• ***Tree-covered***
• Mosaic herbaceous cover (>50%)/ tree, shrub, (<50%), scrubland, scrubland evergreen, scrubland deciduous, • Scrubland • Grassland • Lichens and mosses • Sparse vegetation, tree, shrub, herbaceous cover (<15%)	• ***Grassland***
• Cropland rainfed, herbaceous cover, tree, or shrub cover • Cropland irrigated or post-flooding. • Mosaic cropland (>50%)/natural vegetation, tree, shrub, herbaceous cover (<50%) • Mosaic herbaceous cover (>50%)/tree and shrub (<50%)	• ***Cropland***
• Tree cover, flooded, saline water. • Tree cover, flooded, fresh or brackish water. • Shrub or herbaceous cover, flooded, fresh/saline/brackish water	• ***Wetlands***
• Urban areas	• ***Artificial***
• Bare areas consolidated bare areas, unconsolidated bare areas. • Permanent snow and ice	• ***Bare land***
• Water bodies	• ***Water bodies***

Appendix 1.2: Correcting the effect of climate on land productivity

Reduction in vegetation cover alone in a given area does not necessarily mean the area is degraded because vegetation cover is influenced by factors such as phenology, that is, natural, seasonal variations in rainfall (Symeonakis & Drake, 2004). The changes in Sub-indicator 1 on land productivity may be influenced by many factors such as climate variation, geographic location and human activities (Bai et al., 2008b), and it is important to consider these factors in the process of assessing land productivity. Reducing the influence of climate factors in measuring an area's productivity is important to identify significant human-induced driving factors of land degradation (Conservation International, 2019; Sims et al., 2019). Trends.Earth plugin offers three climate correction methods (rain use efficiency, residual trend analysis, and ecosystem water use efficiency) that can be used to adjust the NDVI trajectory values using precipitation data.

Rain Use Efficiency (RUE) is defined as the ratio of annual NPP to annual precipitation (Le Houerou et al., 1988). Rain Use Efficiency is a key indicator for measuring the relationship between plant productivity and rainfall (Bhandari et al., 2015). In arid and semi-arid land, primary productivity is closely linked to rainfall amount and distribution, and NPP in these areas is strongly affected by rainfall. Thus, there is a positive relationship between rainfall and NPP (Symeonakis & Drake, 2004; Bhandari et al., 2015).

Even though there is a clear relationship between plant growth and rainfall distribution in arid and semi-arid areas, this does not entirely mean that increased rainfall will result in an increase of vegetation and NNP because there are other limiting factors such as soil fertility, texture, and increase in temperature (Gamoun, 2015). A limitation of using the RUE method lies in the method used, RUE values, the data used, and ecological interpretations of results (Dardel et al., 2014). The RUE method works well in regions where rainfall is a main driver of productivity, especially in dry and semi-dry areas, but it does not perform well in wet areas (tropical) and sparsely vegetated regions (Wessels et al., 2007b)

Residual Trend Analysis (RESTREND) is a pixel-based approach, which calculates the relationship between the NPP of vegetation and precipitation (Wessels et al., 2012)**.** The RESTREND method is used for correcting climate influence in an NDVI trend by calculating a linear regression between annual maximum NDVI values (Wessels et al., 2012; Liu et al., 2019). This method has been used to detect dryland degradation based on climatic data and vegetation indices in the grassland in eastern China (Liu et al., 2019)**,** where it was observed that the RESTREND method might underestimate the greening trend in the grassland (Liu et al., 2019). The RESTREND method underestimates degradation when the relationship between vegetation and precipitation is non-linear (Wessels et al., 2012; Burrell et al., 2017; Liu et al., 2019). Nevertheless, RESTREND performs well for detecting extreme and rapid land degradation (Wessels et al., 2012).

Ecosystem Water Use Efficiency is the ratio of net primary productivity to evapotranspiration (ET). Evapotranspiration is defined as precipitation minus the water lost to surface runoff, recharge to groundwater and changes to soil water storage. The Water Use Efficiency method accounts for the interception of water before usage by plants under the assumption that productivity and precipitation are linear. This method works on the assumption that Water Use Efficiency increases during dry conditions. The limitation of using this method for climate calibration is the accuracy of the evapotranspiration data. The Water Use Efficiency method is vulnerable to climate change because factors such as wind, temperature, and precipitation can influence plant transpiration, soil evaporation and affect ecosystem productivity (Niu et al., 2011; Tang et al., 2017; Guo et al., 2019).

Appendix 2: Ethical approval letter from Rhodes University.

RHODES UNIVERSITY
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Human Ethics subcommittee
Rhodes University Ethical Standards Committee
PO Box 94, Grahamstown, 6140, South Africa
t: +27 (0) 46 603 8055
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e: ethics-committee@ru.ac.za

www.ru.ac.za/research/research/ethics
NHREC Registration no. REC-241114-045

27 November 2019

Bawinile Mahlaba

Review Reference: 2019-0663-929

Email: g18m1959@campus.ru.ac.za

Dear Bawinile Mahlaba

Re: Assessment of ecological infrastructure in Tsitsa River catchment

Principal Investigator: Dr. Sukhmani Mantel

Collaborators: Ms. Bawinile Mahlaba

This letter confirms that the above research proposal has been reviewed and **APPROVED** by the Rhodes University Ethical Standards Committee (RUESC) – Human Ethics (HE) sub-committee.

Approval has been granted for 1 year. An annual progress report will be required in order to renew approval for an additional period. You will receive an email notifying when the annual report is due.

Please ensure that the ethical standards committee is notified should any substantive change(s) be made, for whatever reason, during the research process. This includes changes in investigators. Please also ensure that a brief report is submitted to the ethics committee on the completion of the research. The purpose of this report is to indicate whether the research was conducted successfully, if any aspects could not be completed, or if any problems arose that the ethical standards committee should be aware of. If a thesis or dissertation arising from this research is submitted to the library's electronic theses and dissertations (ETD) repository, please notify the committee of the date of submission and/or any reference or cataloging number allocated. Sincerely

J Dames

Prof Joanna Dames

Chair: Human Ethics sub-committee, RUESC- HE

Appendix 3: Consent letter used in community Mapping at Sigoga and Ntatyaneni.

RHODES UNIVERSITY
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Grahamstown ● 6140 ● South Africa

IWR

Institute for Water Research
Tel: +27-(0)46-603-8311; website: www.ru.ac.za

My name is Bawinile Mahlaba and I am a postgraduate student of the Institute for Water Research at Rhodes University, Grahamstown. I am working on a project about the mapping of Ecological Infrastructure, these are natural resources that provides goods and services. The aim of the project is to provide an assessment of how ecological infrastructure helps with reducing drought frequency and strength, and the evaluation of ecological infrastructure presence, current state, and prioritisation for rehabilitation in the Tsitsa catchment. The project is funded by the Water Research Commission (WRC), National Research Foundation (NRF) and Department of Environmental Affairs (DEA).

As part of this project I will be working in your village (Upper Tsitsana and Hlankomo). The headman (Mr Mdletye) has agreed that I can work in your village. The project has received ethicalclearance by Rhodes University I will be having one workshop, with approximately 35 stakeholders in each village. The workshop will be in the form of group discussion and the discussion topics will be guided by 3 questions that will be asked during the workshop. The workshop will be approximately 3 hours long and participation in the workshop is voluntary. If you decide not to participate there will not be any negative consequences.

There are no right and wrong answers. I am here to learn from you about your ideas, knowledge, and practices in this village. You can answer freely, openly and you are free to decline to answer any specific questions. Just say so and we will simply move on to the next one. I will record your answers to the questions, but I will not record your name or where you live. Therefore, there will be no way any other person can identify you from the questionnaire sheets. Thus, your answers will be anonymous.

I will not hand over the data collected to any other person other than my academic supervisor. The data will be entered into a computer of which only myself and my supervisor will have access. Thus, your answers will be confidential. I do not anticipate any physical or economic risks or discomfort to you from participating in this study other than those encountered in day-to-day life. You will not receive any direct benefit or monetary compensation for participation in this project. However, your input can help us propose solutions for restoring the landscapes in the area

Once the project is complete I will first write up a thesis for my degree. But I will also provide feedback to the village by coming back to the village around June 2020 to give feedback. Summary feedback will be given to the Tsitsa Project, the WRC, and other interested departments. The main research findings may also be provided to relevant people such as nongovernment organizations or government so that they can learn from this research and the information may help them to better understand communities like yours and so hopefully design better strategies. The results may also be published in an academic article so that other researchers and students can also learn about the subject.

If you have any questions about the project, you can ask me now. Otherwise, if you think of questions later you can ask me at the end of the interview, or even later you can call or message me on my cellphone 076 5896 251. If you have any concerns you can call my supervisor, Dr. Sukhmani Mantel on 046-603-7695.
Based on what I have just shared with you, are you willing to participate? If you say yes, I would like you or a representative to sign here that you have been informed about the project and have agreed to participate, or I will tick this box to indicate that I have read this information to you, and that you understand and that you are willing to take part.

Your proceeding to sit in for this workshop will be taken as consent to be part of this study.

Signature.....................

Date................

☐ Verbal consent given

Appendix 4: Questionnaire

1. Section A: Information for Participants

Please refer to the attached document in the email for the information sheet and informed consent.

I have read the attached information / confirm that the above information has been explained to me in a language that I understand, and I am aware of this document's contents. I have asked all questions that I wished to ask, and these have been answered to my satisfaction. I fully understand what is expected of me during the research. I have not been pressured in any way, and I voluntarily agree to participate in the project as mentioned above.

- ○ I am giving my consent to participate in the research.

How would you rate your experience/knowledge of degradation/restoration in South Africa (select one)?

- ○ Extensive
- ○ Moderate
- ○ Minimum

Section B-1: Establishing a hierarchical structure for prioritising key areas for rehabilitation with respect to ecosystem health.

Goal: To prioritise EI for rehabilitation for drought mitigation

Catchment health-related attributes:

i. Land degradation indicator: The proportion of land degraded over the total area, calculated over 15 years.

ii. Ecosystem protection level: This attribute is being used to reflect the potential of catchment management interventions to take effect to reduce the degradation threat to each ecosystem type due to ecosystem protection and management, which may lead to increased flow regulation capacity of catchments.

iii. Recently cleared areas: The previously cleared areas show tree-covered areas transformed into other land cover classes.

iv. Present ecological status: The assessment of the present ecological state considers a range of factors, including physio-chemical conditions, flow, and habitat quality. This indicator is used to reflect the present and future desired aquatic conditions, which is crucial for identifying the ideal rehabilitation sites based on cost-to-benefit.

v. Stream order: Management interventions such as the Working for water programme give a higher priority to headwaters to avoid reinvasion downstream.

1. Regarding ecosystem health, how much do you agree that the attributes in the left column influence selecting priority rehabilitation areas to improve the drought mitigation capacity of catchments?

	Disagree (1)	Disagree (1)	Disagree (1)	Disagree (1)	Disagree (1)	Disagree (1)
Degradation status	○	○	○	○	○	○

Ecosystem protection level	○	○	○	○	○	○
Cleared areas	○	○	○	○	○	○
Present ecological status	○	○	○	○	○	○
Stream order	○	○	○	○	○	○

2. Using the scale of 1-9 compare the relative importance of the two attributes listed (1 denoting degradation status as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting ecosystem protection as EXTREMELY important). Please rank the relative importance of the two attributes.

Degradation status	1	2	3	4	5	6	7	8	9	Ecosystem protection.
	○	○	○	○	○	○	○	○	○	

3. Compare the two listed attributes using a scale of 1-9 (1 denoting degradation status as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting cleared areas as EXTREMELY important). Please rank the relative importance of the two attributes.

Degradation status	1	2	3	4	5	6	7	8	9	Cleared areas
	○	○	○	○	○	○	○	○	○	

4. Compare the two listed attributes using a scale of 1-9 (1 denoting degradation status as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Degradation status	1	2	3	4	5	6	7	8	9	Present Ecological status
	○	○	○	○	○	○	○	○	○	

5. Compare the two listed attributes using a scale of 1-9 (1 denoting degradation status as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting stream order as EXTREMELY important). Please rank the relative importance of the two attributes.

Degradation status	1	2	3	4	5	6	7	8	9	Stream order
	○	○	○	○	○	○	○	○	○	

6. Using the scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting recently cleared areas as EXTREMELY important), please rank the relative importance of the two attributes.

Ecosystem protection	1	2	3	4	5	6	7	8	9	Cleared areas
	O	O	O	O	O	O	O	O	O	

7. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Ecosystem protection	1	2	3	4	5	6	7	8	9	Present ecological status
	O	O	O	O	O	O	O	O	O	

8. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Ecosystem protection	1	2	3	4	5	6	7	8	9	Stream order
	O	O	O	O	O	O	O	O	O	

9. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important), please rank the relative importance of the two attributes.

Cleared areas	1	2	3	4	5	6	7	8	9	Present ecological status
	O	O	O	O	O	O	O	O	O	

10. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important), please rank the relative importance of the two attributes.

Cleared areas	1	2	3	4	5	6	7	8	9	Stream order
	O	O	O	O	O	O	O	O	O	

11. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Present ecological status	1	2	3	4	5	6	7	8	9	Stream order
	O	O	O	O	O	O	O	O	O	

Section B-2: Establishing a hierarchical structure for prioritising key areas for rehabilitation with respect to hydrological functioning

Goal: To prioritise EI for rehabilitation for drought mitigation

Attributes relating to hydrological functioning:

i. Estimated flow reduction due to invasive alien plants: Proportion of surface runoff being taken up by alien invasive plants in the quaternary catchment.

ii. Surface water runoff: This attribute is an essential indicator for the partitioning of flows (e.g., overland, interflow etc.), which is essential because land-use change modifies the proportion of surface runoff to infiltration which affects the responsiveness of a catchment to rainfall.

iii. Groundwater contribution to streamflow: Although precipitation is the primary source of catchment water recharge, groundwater becomes the primary source of water recharge in catchments through base flow during dry periods.

iv. Wetland size: For the wetland EI category, the inclusion of wetland size is important because larger wetlands play a more important role in flow regulation than smaller wetlands.

v. Wetland type: Wetland type is an important indicator for the hydrological influence of wetlands to surface water depending on the hydro-geomorphology of wetlands.

1. Regarding the hydrological function of catchments, how much do you agree that the attributes in the left column influence selecting priority rehabilitation areas to improve the drought mitigation capacity of catchments?

	Disagree (1)	Disagree (1)	Disagree (1)	Disagree (1)	Disagree (1)	Disagree (1)
Groundwater contribution to streamflow	○	○	○	○	○	○
Surface runoff	○	○	○	○	○	○
Wetland size	○	○	○	○	○	○
Flow reduction (due to IAPs)	○	○	○	○	○	○
Wetland type	○	○	○	○	○	○

2. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting

present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Groundwater contribution to streamflow

Surface runoff

1 2 3 4 5 6 7 8 9

○ ○ ○ ○ ○ ○ ○ ○ ○

3. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Groundwater contribution to streamflow

Wetland size

1 2 3 4 5 6 7 8 9

○ ○ ○ ○ ○ ○ ○ ○ ○

4. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Groundwater contribution to streamflow

Wetland type

1 2 3 4 5 6 7 8 9

○ ○ ○ ○ ○ ○ ○ ○ ○

5. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Groundwater contribution to streamflow

Flow reduction (due to IAPs)

1 2 3 4 5 6 7 8 9

○ ○ ○ ○ ○ ○ ○ ○ ○

6. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Surface water runoff	1	2	3	4	5	6	7	8	9	Flow reduction (due to IAPs)
	O	O	O	O	O	O	O	O	O	

7. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Surface water runoff	1	2	3	4	5	6	7	8	9	Wetland type
	O	O	O	O	O	O	O	O	O	

8. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Flow reduction due to APs	1	2	3	4	5	6	7	8	9	Wetland size
	O	O	O	O	O	O	O	O	O	

9. Compare the two listed attributes using a scale of 1-9 (1 denoting ecosystem protection as EXTREMELY important, 5 denoting EQUAL importance and 9 denoting present ecological status as EXTREMELY important). Please rank the relative importance of the two attributes.

Wetland size	1	2	3	4	5	6	7	8	9	Wetland type
	O	O	O	O	O	O	O	O	O	

Appendix 5: AHP calculation steps

Table A3: Step1: A pair-comparison using the median value from the response.

Criteria1: Ecosystem Health					
	LD	**EPL**	**Cleared**	**PES**	**Stream order**
LD	1	1	5	1	2
EPL	1	1	5	1	4
Cleared areas	0.2	0.2	1	0.2	1
PES	1	1	5	1	5
Stream order	0.5	0.25	1	0.2	1
sum	***3.7***	***3.45***	***17***	***3.4***	***13***
Criteria2: Water provisioning					
	GWR	**SR**	**WS**	**WT**	**FR**
GWR	1	1	2	2	1
SR	1	1	3	2	1
WS	0.5	0.33	1	1	1
WT	0.5	0.50	1	1	1
FR	1	1	1	1	1
SUM	***4***	***3.83***	***8***	***7***	***5***

Step 2: Normalize pair-wise matrix

A normalized pair-wise comparison matrix is calculated using the value in the matrix for each attribute divided by the sum value in the attribute column ($\frac{1}{3,7}$ = 0.27). Criteria weight was calculated using the average of elements in a row, as the sum of values in a row divided by the number of the attribute (see example below)

$$\frac{0,27+0,29+0,29+0,29+0,15}{5} = 0,26$$

Table A4: The normalised pair-wise comparison matrix in the AHP process.

Criteria1: Ecosystem Health						
	LD	**EPL**	**Cleared areas**	**PES**	**Stream order**	**Criteria weight**
LD	0,27	0,29	0,29	0,29	0,15	**0,26**
EPL	0,27	0,29	0,29	0,29	0,31	**0,29**
Cleared areas	0,05	0,06	0,06	0,06	0,08	**0,06**
PES	0,27	0,29	0,29	0,29	0,38	**0,31**
Stream order	0,14	0,07	0,06	0,06	0,08	**0,08**
Criteria2: Water Provisioning						
	GWR	**SR**	**WS**	**WT**	**FR**	**Criteria weight**
GWR	0,25	0,26	0,25	0,29	0,20	**0,25**
SR	0,25	0,26	0,38	0,29	0,20	**0,27**
WS	0,13	0,09	0,13	0,14	0,20	**0,14**
WT	0,13	0,13	0,13	0,14	0,20	**0,14**
FR	0,25	0,26	0,13	0,14	0,20	**0,20**

Step 3: Calculating the weighted sum

The weighted sum is calculated as not normalized pair-wise matrix values in step1 multiply by the value of criteria weight for each column. For example, LD value multiply by the LD criteria weight value (1*0.26=0.26), then the weighted sum value is calculated as the average of the values, e.g., a weighted sum for LD

$$LD = \frac{0{,}25+0{,}27+0{,}68+0{,}14+0{,}39}{5}=1.74$$

Table A5: The calculated weighted sum value for each attribute in the criterion.

Criteria1: Ecosystem Health						
	LD	**EPL**	**Cleared areas**	**PES**	**Stream order**	**Weighted sum value**
LD	0,25	0,27	0,68	0,14	0,39	1,74
EPL	0,25	0,27	0,68	0,14	0,78	2,13
Cleared areas	0,05	0,05	0,14	0,03	0,20	0,47
PES	0,25	0,27	0,68	0,14	0,98	2,33
Stream order	0,12	0,07	0,14	0,03	0,20	0,55
Criteria2: Water Provisioning						
	GWR	**SR**	**WS**	**WT**	**FR**	**Weighted sum value**
GWR	0,25	0,27	0,27	0,29	0,20	1,28
SR	0,25	0,27	0,41	0,29	0,20	1,42
WS	0,12	0,09	0,14	0,14	0,20	0,69
WT	0,12	0,14	0,14	0,14	0,20	0,74
FR	0,25	0,27	0,14	0,14	0,20	1,00

Step 4: Calculating the ratio

Ratio= weighted sum value/criteria weight value

Table A6: The calculating the ratio for each attribute in the criterion.

Ecosystem Health			
	Weighted sum value	**Criteria weight**	**Ratio (weighted sum/criteria weight)**
LD	1,74	0,25	6,68
EPL	2,13	0,27	7,32
Cleared areas	0,47	0,14	7,59
PES	2,33	0,14	7,59
Stream order	0,55	0,20	6,89
Water provisioning			
	Weighted sum value	**Criteria weight**	**Ratio (weighted sum/criteria weight)**
GWR	1,28	0,25	5,14
SR	1,42	0,27	5,16
WS	0,69	0,14	5,09
WT	0,74	0,14	5,10
FR	1,00	0,20	5,11

Step 5: Calculating Lambda max values

Lambda max is calculated as the average value of the ratios.

$\lambda_{max}\ for\ EH = \frac{6,68+7,32+7,59+7,59+6,89}{5}$ =5,093

$\lambda_{max}\, for\, WP = \frac{5{,}14+5{,}16+5{,}09+5{,}10+5.11}{5}$ *=5,121*

Step 6: Calculating Consistency index

$$\boldsymbol{CI\, for\, EH} = \frac{(\boldsymbol{\lambda_{max}-n})}{(\boldsymbol{n-1})} = \frac{(\mathbf{5{,}093-5})}{(\mathbf{5-1})} = 0{,}0232$$

$$\boldsymbol{CI\, for\, WP} = \frac{(\boldsymbol{\lambda_{max}} - \boldsymbol{n})}{(\boldsymbol{n} - \mathbf{1})} = \frac{(5{,}121 - 5)}{(5 - 1)} = 0{,}03025$$

Step 7: Calculating Consistency Ratio

$CR\, for\, EH = \frac{CI}{RI} = \frac{0{,}0232}{1.12}$ **100 = 2,07%*

$CR\, for\, EH = \frac{CI}{RI} = \frac{0{,}0325}{1.12}$ **100 = 2,90*