Watercourse Buffers in the Sugarcane Landscape: A Buffer Delineation Approach, Hydrological Simulation and Investigation of Costs and Benefits

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

The National Water Act (No. 36 of 1998) (NWA) sets out to ensure that a quantity and quality of water sufficient to satisfy basic human needs and to protect aquatic ecosystems is secured. As with alternative land-uses, sugarcane cultivation can modify the landscape in a way that affects the functional links and water flows between terrestrial and aquatic systems, as well as negatively affecting water quality and ecosystem health through pollution inputs. The South African Sugar Industry recognizes the need for responsible and sustainable sugarcane production and has developed a number of better management practices across various aspects of sugarcane cultivation.

Watercourse buffers, areas of native vegetation which separate the watercourse from the adjacent land-use, are one practice towards protecting freshwater ecosystem health in a productive landscape. Buffer areas, in various forms, have long been a feature of agricultural landscapes, primarily as a measure to mitigate the movement of diffuse pollution from agricultural land to surface waters. Watercourse buffers are increasingly recognised as part of a more holistic approach to landscape planning and management driven by widespread sustainability concerns. Watercourse buffers in agricultural landscapes aim to support continued land-use while simultaneously contributing to the maintenance of watercourse condition and function. Establishing watercourse buffers within existing sugarcane cultivation landscapes has outcomes for the sugarcane grower, broader society and the environment. These outcomes result in both local (on-farm) and broader (societal) costs and benefits. These costs and benefits are not evenly distributed, both between the current land user and society and between current and future generations. Generally, the costs of establishing watercourse buffers in existing sugarcane cultivation accrue at the local scale (to the land owner) and the benefits at a larger catchment scale (society). On the other hand, profit from sugarcane production is a private benefit, realized to an extent, at a cost to society of degraded watercourses and biodiversity loss.

The Terms of Reference for this study developed from an agreement between the Department of Water and Sanitation (DWS) and the Sugar Industry to work together towards the protection of watercourses in the sugarcane landscape. A cost-benefit study of watercourse buffer establishment was identified as a means of generating further information towards decisions regarding measures for the protection of watercourses within sugarcane cultivation.

The intention of the study was to develop a more nuanced and informed understanding of the biophysical outcomes and associated costs and benefits of establishing watercourse buffers

within sugarcane cultivation, highlighting important aspects for consideration in the decision-making process and key directions for future research. At a strategic level, cost-benefit analysis can be used as a tool for organizing disparate information and building a more reasoned understanding of the outcomes of a proposed action across stakeholders. This approach to cost-benefit analysis aims to establish a base for a discussion among stakeholders towards negotiation and decision-making by identifying key issues and affected stakeholder groups.

The general steps of a cost-benefit assessment (CBA) guided the tasks undertaken in this study. CBA involves the identification, measurement and valuation of the outcomes (e.g. water yield) of the alternatives being considered. This required first identifying an appropriate buffer (width) to be evaluated. There is no single 'best design' for watercourse buffers and, currently, in South Africa there are no recommended watercourse buffer zones for existing sugarcane production areas. From a water quantity and quality perspective, an important aspect affecting hydrological processes within a catchment is the interactive relationship between soils and water (hydropedology) which influences how water moves through the landscape (surface flows, sub-surface flows and groundwater flows). Hillslope characteristics can form an integral part of water resource management. While buffer zone guidelines are available (i.e. the 'Buffer Zone Guidelines for Rivers, Wetlands and Estuaries', Macfarlane and Bredin, 2017), they are intended for the assessment of a proposed new development, or land-use change, from the perspective of mitigating diffuse surface runoff. The guidelines do not consider sub-surface flow interactions in the determination of buffer width.

In this study, an approach to delineate watercourse buffers within sugarcane cultivation landscapes that takes into account hillslope characteristics was developed. The approach was applied to a case study catchment in the Midlands North sugarcane production area to assess the costs and benefits of establishing the guideline buffer widths. The study was conducted primarily as a desktop-based assessment supported by previous relevant research, the existing knowledge base, additional primary data collection and expert consultation.

In the proposed watercourse buffer delineation approach, the hillslope class is taken as the primary determinant of buffer width. Each hillslope class is associated with a specific buffer width: as the hillslope class changes (varies across the landscape), the recommended buffer width changes. The buffer width is, therefore, dynamic (variable), within a range, across the landscape in relation to the hillslope class. The proposed buffer width range was developed based on the best available science, drawing from established research on buffer function and buffer width determination, previous research in the case study area and recent progress in the understanding, conceptualisation and quantification of hydropedological processes. Practical application, ongoing research and changes in policy mean the proposed range may need to be revised over time.

Further to specifying the buffer width based on hillslope class, site-specific factors related to the adjacent land-use that pose (or reduce) the threat to the watercourse are an important consideration. This is taken into account in the proposed buffer delineation approach by introducing a site assessment to assess the threats to the watercourse. This provides an opportunity for a reduction in buffer width based on reduced threat to the watercourse which could be achieved through the adoption of additional suitable better management practices. In this way, the approach encourages on-site mitigation and management that could further reduce impacts to the watercourse and reduce the impact to the farmer of implementing a wide buffer. It provides an opportunity for the farmer to benefit from adopting, or existing, better management practices. For a reduction in buffer width, the farmer would need to demonstrate the reduced threat to the watercourse. This could be achieved through the development and implementation of a land-use (farm) plan and on-going use (and associated reporting) of the SUSFARMS® Progress Tracker.

The proposed buffer delineation approach sets out the conceptual thinking and broad steps as a guideline to determining appropriate watercourse buffers within sugarcane cultivation that takes into account hillslope characteristics of the landscape. The approach, and associated buffer range, can be applied (generalised) across the sugar production regions. A hydropedology assessment of the area under consideration is required to establish the hillslope classes as a basis for applying the proposed buffer widths. This requires specialist expertise. However, a national hillslope classification initiative is underway and the hillslope classes should become publically available in the near future (3 to 5 years).

There are farm-level distributional implications of adopting a dynamic width buffer approach. The proportion of sugarcane area converted to buffer area will vary by farm area based on the hillslope classes present and the extent of watercourse. However, distributional effects are not entirely avoided in applying a uniform (single) width approach, as the buffer area requirement still varies across farms with the extent of watercourse and the degree to which existing sugarcane is cultivated in the watercourse and buffer area. From a regulatory perspective, it may be simpler to administer a uniform buffer width approach; however an up-to-date land-use (farm) plan and regular use of the SUSFARMS® Progress Tracker (or similar record keeping) could facilitate compliance monitoring.

The buffer delineation approach was applied in a desktop-based case study assessment. Spatial analysis, hydrological modelling and monetary valuation were used to quantify and value a sub-set of costs (income forgone and buffer establishment and maintenance) and benefits (water supply and quality) associated with establishing watercourse buffers in the case study catchment. Several scenarios of varying buffer width were investigated. Hydrological modelling was adopted as a means to quantify the hydrological response of the system to buffer establishment as the basis for determining the downstream social benefits of watercourse buffer establishment. The following key points are noted from the case study assessment:

- The hydrological modelling results suggest that buffer width, as determined by hillslope class, influences water discharge and sediment and nutrient loads as measured at the outflow node of the study catchment. The hydrological model calibration results and a comparison to the findings of similar local studies indicate that the baseline results and scenario comparisons are robust.
- Discharge increases with increasing buffer width, but at a declining rate of additional gain.
- Sediment and nutrient loads are reduced with increasing buffer width, but at a declining additional gain.
- A loss of sugarcane cultivation area for the land owners and the associated income forgone (13, 19 and 23% of baseline production with the narrow, moderate and wide buffer options, respectively; 4% of baseline production occurs within the watercourse itself).
- Additional costs associated with the establishment (e.g. revegetation and rehabilitation) and annual maintenance costs of buffer areas. Depending on the size of the buffer and the level of rehabilitation required, establishment costs vary considerably, but can add significantly to the costs incurred by the grower particularly in the case of severely degraded areas.
- A gain in native vegetation across the catchment (1 to 6% of the study catchment). Native vegetation is associated with a number of ecosystem services and agricultural support services.
- Based on the sub-set of costs and benefits valued in the case study assessment, the financial costs of buffer establishment significantly exceed the financial value of the water supply and quality benefits. However, water supply benefits were valued using the tariff for raw water which is a cost measure and not a reflection of the real value of water.

- The greatest additional gain in discharge per area of sugarcane converted to buffer is achieved under the watercourse only scenario.
- The greatest additional gain in sediment and nutrient reduction per unit area of sugarcane converted to buffer is achieved under the narrow buffer option.

Evaluating watercourse buffers based on their influence on discharge, sediment and nutrient outputs is a starting point, but fails to fully articulate the value of watercourse buffers in supporting both aquatic and terrestrial biodiversity and the additional ecosystem services associated with healthy watercourses (e.g. streamflow regulation) and a gain in native vegetation in the landscape (e.g. pest regulation, recreation opportunities, cultural services, climate regulation). Quantifying and valuing (using a monetary metric) the full range of benefits is challenging, and in some cases, not possible; whereas it is relatively more straightforward to value the costs of buffer establishment, resulting in an 'unbalanced' cost-benefit assessment. To address this, future research should give attention to investigating the potential to realize the additional benefits associated with buffers, both from the perspective of the grower and society. An especially relevant potential benefit is the role of native vegetation in pest regulation; this is a key direction for future research in the context of sugarcane cultivation.

This study has developed a deeper understanding of the outcomes of establishing watercourse buffers within sugarcane cultivation and highlighted a number of aspects that require additional consideration. Overall, the project makes the following primary recommendations, additional suggestions and considerations are outlined in the report.

- Watercourse buffers should be viewed as part of a broader management strategy towards sustainable and responsible agriculture (including the maintenance of aquatic ecosystem health) based on local needs, pressures and landscape settings and considered in combination with other better management practices (e.g. soil and water conservation measures, nutrient reduction practices). Ideally, watercourse buffers should be considered at a farm scale as part of a farm / land-use planning process from which an appropriate set of better management practices can be identified. The SUSFARMS® manual and progress tracker provides a 'vehicle' for promoting implementation and tracking progress.
- The proposed buffer delineation approach, and associated buffer range, can be applied (generalised) across sugar production regions, based on the hillslope classes determined for each region. The buffer width range can be applied to identify a guideline width based on hillslope characteristics, which can then be modified given

site-specific objectives and threat factors. The proposed approach would be enhanced with further application, specifically through empirical studies of buffer establishment across landscape characteristics and management practices.

- For the case study area, the results of the application of the buffer delineation approach suggest that the options of removing sugarcane from the watercourse and applying the narrow buffer width option provide the largest additional gains in terms of water quality and supply benefits. These two options are also associated with a lower impact to the sugarcane grower. The case study results are representative of the Midlands North region and are not generalizable across sugar production regions.
- A phased approach to buffer implementation should be considered, developed through cross-sector engagement (including various government departments, the sugar industry, research institutes) to set objectives related to watercourse condition and ecological and sustainability goals, identify appropriate practices towards achieving objectives, and to agree on the basis and timeframe of the phased approach.
- A phased approach should include primary empirical studies (pilot cases) of watercourse buffer implementation across a variety of landscapes and management practices, involving monitoring and evaluation. Pilot cases could be used to address a number of implementation and research questions. Further, pilot cases, especially those involving local stakeholders (growers, extension specialists) and observed data could provide motivation for the uptake and implementation of watercourse buffers.
- Consideration should be given to the support available to growers in establishing watercourse buffers. For example, support in developing land-use plans and delineating buffers; support in establishing watercourse buffers (e.g. technical / financial support in undertaking rehabilitation activities) and guidance in managing buffer areas. This may require strengthening extension services to support growers in a transition to better management practices. Options to relieve some of the initial financial burden during a transition phase should be explored (e.g. support from the national Natural Resource Management programme).

These insights and recommendations are a point of departure for a broader dialogue on taking forward watercourse protection within sugarcane cultivation and agricultural landscapes in general.

The study highlighted a number of aspects for future research:

- Demonstration (targeted monitoring, observed outcomes) of the benefits of watercourse buffers across a broader range of ecosystem services and the influence of buffer width of the provision of these services. Particularly, an investigation of the associated potential benefits to land-owners / growers (e.g. pest regulation services, cultural values).

- Strategies for managing buffers to achieve multiple objectives, or to optimize specific functions (e.g. sediment and nutrient trapping efficiency).
- Monitoring / observed data on sediment and nutrient loads (to support hydrological mode calibration).
- Empirical plot level studies of the sediment and nutrient reduction efficiencies of buffer areas (and width variations) and the effect of buffer condition on these efficiencies. This knowledge would inform how buffer areas should be managed for optimal sediment and nutrient reduction.
- The influence of buffer placement in the landscape on watercourse protection (e.g. other than adjacent to the watercourse) and the performance of fragmented buffer areas relative to continuous / connected buffers.
- The hydrological model applied in the case study assessment can be considered an important preliminary foundation for conceptualising sub-surface flow and buffer interactions and simulating the hydrological response of the watercourse to the establishment of watercourse buffers. Primary empirical studies are needed to further develop and strengthen the hydrological (SWAT) model in effectively reflecting hillslope-buffer-watercourse interactions including further examination of above- and below surface buffer attenuation processes. In future work, the model could be applied to interrogate the hydrological response to a number of additional scenarios (e.g. across other land-uses, changes in crop type, adoption of additional / alternative BMPs).
- The influence of watercourse buffers on peak and base flows.
- A comparison of a range of better management practices and various combinations thereof towards achieving set objectives, for example through a cost-effectiveness analysis.

A sustainability perspective is progressively being adopted by citizens, states and private sectors. Producers and retailers are under increasing pressure to shift to responsible and sustainable production driven by regulatory and market forces (WBCSD, 2015). In the medium to long term it may not be possible to sell sugar (and other agricultural commodities) without first demonstrating it has been produced under responsible practices. This means that the question of *whether to adopt* better management practices is no longer the debate, but rather questions regarding ‘which practices’, ‘optimizing benefits’ and ‘how to transition’ are issues that need to be addressed.

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LIST OF ABBREVIATIONS

AW-IPM	Area Wide Integrated Pest Management
B-C	Benefit cost (ratio)
BMP	Better Management Practice
CBA	Cost-benefit Assessment
DARD	Department of Agriculture and Rural Development
DWS	Department of Water and Sanitation
GIS	Geographic Information System
HRU	Hydrological Resource Unit
IB	Internodes bored
KZN	KwaZulu-Natal
LSG	Large Scale Grower
NPV	Net Present Value
NRM	Natural Resource Management (programme)
NWA	National Water Act
RV	Recoverable Value
SACGA	South African Cane Growers Association
SASA	South African Sugar Association
SASRI	South African Sugar Research Institute
SFRA	Stream Flow Reduction Activity
SIT	Sterile Insect Technology
SUSFARMS®	South African Sustainable Sugarcane Farm Management System
SWAT	Soil and Water Assessment Tool
UMDM	uMgungundlovu District Municipality
WTW	Water Treatment Works
WRC	Water Research Commission

1. INTRODUCTION

Sugarcane cultivation, and similarly many agricultural activities and alternative land-uses, can negatively impact watercourses and aquatic ecosystems. Sugarcane cultivation can modify riparian areas and watercourses affecting the functional links and water flows between terrestrial and aquatic systems, as well as negatively affecting ecosystem condition through pollution inputs. To a degree, these impacts can be mitigated through better management / cultivation practices and the South African sugar industry has developed a number of such practices particularly related to soil and water conservation measures, but also towards reducing nutrient (fertilizer) loss, among others.

A watercourse buffer is an additional option or practice for protecting watercourses from adjacent land-uses. Watercourse buffers are increasingly recognised as part of a broader management approach towards sustainable agriculture (IFC, 2011; Gravious et al., 2017; SAI, 2018). A watercourse buffer is an area adjacent to the watercourse set aside from the terrestrial land-use (e.g. agriculture), composed in many cases of riparian habitat and upland plant communities, which separates adjacent land-uses from watercourses (Macfarlane et al., 2009), Figure 1. Naturally vegetated riparian areas conserve aquatic ecosystems, allowing them to carry out a variety of functions, and can buffer watercourses from the impacts of adjacent land-uses.

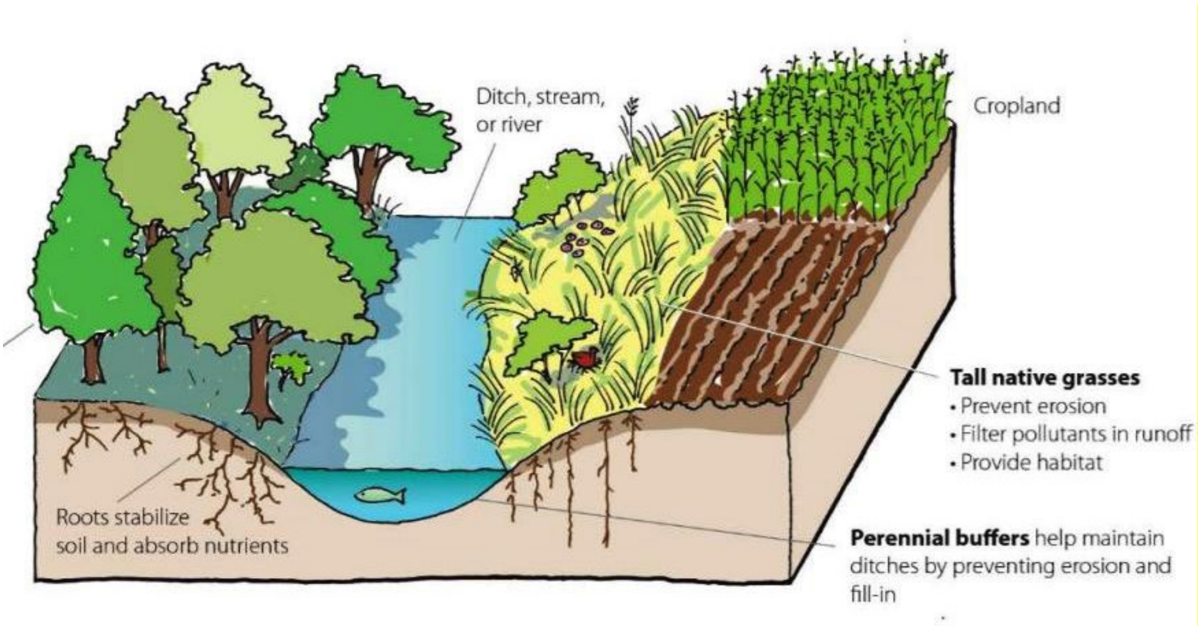

Figure 1: Schematic of a watercourse buffer in an agricultural landscape[1].

[1] Minnesota Board of Water and Soil Resources https://bwsr.state.mn.us/alternative-practices-introduction .

Buffers can provide a wide range of functions such as improving water quality, stabilizing stream banks, providing habitat for a range of wildlife species and maintaining downstream flows. These benefits are increasingly recognised by the agricultural sector, and farmers appear progressively more committed to applying sustainable practices as part of their ongoing land stewardship (Carvajal and Janmaat, 2016).

1.1. Rationale

This research project originated from an agreement between the Department of Water and Sanitation (DWS) and the Sugar Industry to work together towards improving the protection of watercourses within existing sugarcane cultivation. Watercourse buffers in agricultural landscapes aim to support continued land-use while simultaneously contributing to the maintenance of watercourse condition and function. Establishing watercourse buffers within existing sugarcane cultivation landscapes has outcomes for the sugarcane grower, broader society and the environment. These outcomes result in both local (on-farm) and broader (societal) costs and benefits. These costs and benefits are not evenly distributed, both between the current land user and society and between current and future generations. Through discussions between the Department (DWS) and the Sugar Industry, a cost-benefit study of watercourse buffer establishment was identified as a means of generating further information towards decisions regarding measures for the protection of watercourses within sugarcane cultivation.

1.2. Study objectives

The purpose of the study was to evaluate the establishment of buffer areas adjacent to watercourses within sugarcane cultivation as one practice for maintaining (and improving) the health of aquatic ecosystems within these landscapes. The intention of the study was to develop a more nuanced and informed understanding of the potential biophysical outcomes, particularly those related to water supply and quality, and associated costs and benefits of establishing watercourse buffers within existing sugarcane cultivation landscapes. At a strategic level, cost-benefit analysis can be used as a tool for organizing disparate information and building a more reasoned understanding of the outcomes of a proposed action across stakeholders and contexts (Naess, 2006; Laurans and Mermet, 2014). This approach to cost-benefit analysis aims to establish a base for a discussion among stakeholders towards negotiation and decision-making by identifying key issues and affected stakeholder groups.

Using the framework of cost-benefit assessment (CBA), the study aimed to:

- Generate information on the costs and benefits of establishing watercourse buffers in sugarcane cultivation;
- Highlight key aspects for consideration in the decision-making process;
- Suggest recommendations regarding watercourse buffer delineation (width) and aspects for future research.

CBA involves the identification, measurement and valuation of the outcomes (e.g. water yield) of the alternatives being considered. Several objectives were identified in this regard:

a) Determine the widths of the buffers to be evaluated by developing an approach for watercourse buffer delineation. Address an identified gap in the knowledge base by incorporating hydropedological characteristics into buffer width determination.
b) Modify and parameterize a hydrological model in order to measure (simulate) the water, sediment and nutrient fluxes resulting from several scenarios of buffer establishment as a means of measuring the water supply and quality benefits of watercourse buffers. Develop the spatial layers required to achieve this, integrating hydropedological information.
c) Apply the buffer delineation approach and hydrological model to a case study catchment to investigate and value (where possible) the costs and benefits associated with watercourse buffer establishment.

1.3. WRC project K5/2793 overview

In 2018, the Institute of Natural Resources (INR) and partners were awarded a research project through a Water Research Commission (WRC) solicited call to investigate the costs and benefits of establishing watercourse buffers within the sugarcane cultivation landscape. The overarching goal to which the study is intended to contribute is the improved protection of watercourses within sugarcane cultivation. The study was conducted primarily as a desktop-based assessment.

The scope of the project was agreed during the project inception phase (stakeholder inception workshop) and at subsequent reference group meetings. Adjustments from the proposed project terms of reference included:

- *Study area*: stakeholders highlighted the difference between rain-fed and irrigated sugarcane cultivation and noted the additional complexity of irrigated areas; it was agreed that the study would focus on rain-fed sugarcane cultivation. Stakeholders further highlighted that the various sugarcane production regions represent very diverse / complex landscapes that function very differently hydrologically.

- *Scale*: it was agreed that the scale of the modelling would be at a quaternary catchment scale, supported by reference data from the local catchment scale.
- *Study catchments*: Given the availability of existing data and previous studies, quaternary catchments U20G (Midlands, Noodsberg & Dalton Mills) was identified as the priority case study catchment.
- *Output*: the study would develop an approach for watercourse buffer delineation and apply the approach to quaternary catchment U20G (Midlands) in a case study assessment to quantify and value (where possible) the costs and benefits associated with watercourse buffer establishment in the quaternary catchment.
- *Focus areas*:
    - Large floodplain systems are particularly complex / unique systems and typically require management strategies and practices designed specifically for the floodplain in question (i.e. fine scale decision-making is required). It was agreed that no modelling would be undertaken for a catchment of a large floodplain planted with sugarcane. Potential management practices for floodplain systems were explored through a review of existing studies on floodplain management (see Appendix 5).
    - Potential pest (*Eldana saccharina Walker*) management benefits of watercourse buffers were highlighted by stakeholders. It was agreed that this potential benefit would be explored through consultation with relevant experts in the field and through a review of existing research (see Section 2.5.2 and Appendix 4).

The project contributed to capacity building through:

- The involvement of two university students (MSc level) in the research activities, which provided an opportunity for the students to further their skills in hydrological modelling as well as exposing the students to elements of project management, communication and stakeholder engagement;
- Bringing together stakeholders from the research, regulatory and practitioner spheres in an information sharing and discussion environment.

The project was innovative in:

- Incorporating hillslope response attributes and a hydropedological understanding into an approach for the delineation of watercourse buffers; and

- Modifying a SWAT hydrological model and developing the associated spatial layers that, together, can be used to simulate the hydrological response to the application of varying watercourse buffers.

2. CONTEXT AND REVIEW

The following sections set the context and highlight key insights from the literature review across a range of aspects. Additional information is provided in the appendices.

2.1. Sugarcane cultivation

Sugarcane accounts for approximately 80% of global sugar production. World market production for 2018/2019 was in the region of 198 million tons, with South Africa contributing 2.1 million tons to global sugar production (International Sugar Organization, 2018). Sugar crops (sugarcane and sugar beet) also offer additional products such as livestock feed, fibre and energy – particularly biofuels (sugar-based ethanol) and/or co-generation of electricity (cane bagasse). Sugarcane is regarded as a significant and efficient source of biomass for biofuel production (International Sugar Organization, 2018).

The South African sugar industry ranks as a cost competitive sugar producer, in the top 15 out of approximately 120 sugar producing countries worldwide, and produces an average of 2,3 million tons of sugar per season (SASA, 2017). The South African sugar industry is more than 150 years old and is a significant contributor to the South Africa economy, to direct employment in both sugarcane production and processing as well as indirect employment in support industries. The industry supports 85 000 direct jobs and an estimated 350 000 indirect jobs (SASA, 2017).The industry is however shrinking. Over the last 17 years, 2000/01-2016/17, the total area under cane in South Africa has decreased by nearly 67 thousand hectares or 15.6% (Govender, 2018). Sugar imports and the resultant inability to recover costs threaten the sustainability of the industry. For the period January 2017 to November 2017, more than 508 000 tons of sugar were imported into South Africa, which equates to more than 25% of South Africa's total sugar production (Govender, 2018).

Approximately 430 000 ha of terrestrial land is under sugarcane cultivation across the two provinces – KwaZulu-Natal and Mpumalanga – in which sugarcane is grown (SASA, 2017), of which approximately 60 % is rain-fed. These areas are sub-divided into agro-climatic production regions. Figure 2 shows the South African sugarcane production areas highlighting the broad agro-climatic production regions, sugar mills, and the rain-fed and irrigated areas.

There are 14 sugarcane mills situated across rural areas of the two provinces and a total number of 21 543 registered growers – 1 257 large-scale, 20 269 small-scale. In KZN, sugarcane represents approximately 50% of field crops in the province, and in Mpumalanga 19%. Sugarcane favours tropical and sub-tropical conditions with a minimum rainfall of 600 mm annually and a temperature range of 20-35˚C. A variety of soils can sustain sugarcane growth, however a porous, well-drained soil with a neutral pH and soils with a bulk density of (<1.6 g/cm^3) to allow water, nutrient and root penetration is preferred. As with other agricultural crops, sugarcane requires sufficient water and fertilizer inputs in order to maintain high yields (Martinelli and Filoso, 2008).

Sugarcane cultivation, as with other land-uses, can modify riparian areas and watercourses interfering with the functional linkages between them and the surrounding land, and negatively impacting freshwater ecosystem health and the provision of ecosystem services, Table 1. Many common agricultural practices result in sediment loss and in fertilizer, herbicide, fungicide, and pesticide runoff that degrades water quality (Qureshi and Harrison, 2001; Polintano and Pissara, 2005; Thorburn et al., 2011; Hess et al., 2016). Surface and groundwater pollution from sediment and nutrient loads emanating from agricultural catchments is a prominent environmental issue, with major consequences on water supply and aquatic ecosystem quality (Kollongei and Lorentz, 2014). The clearing of natural vegetation along watercourses can make riparian areas susceptible to erosion and bank destabilization leading to increased downstream sedimentation and flooding (Rein, 1999). Planting crops alongside and in watercourses can modify streamflow through greater water use relative to the native land-cover (Schulze & Schutte, 2015).

Land-uses, including sugarcane cultivation, modify the flow of water in the landscape. Water typically moves through the landscape along three pathways: surface flows, sub-surface flows (flows through the unsaturated zone, between the land surface and groundwater), and groundwater flows. Changes or disruptions in these pathways modify the flow of water to the watercourse. Many land-uses reduce water infiltration, converting what would be recharge of hillslopes and groundwater into surface flows (Job et al., 2019). As a result, water storage in hillslopes is reduced, and the slow release of the water from upland recharge soils to wetlands is reduced resulting in the progressive drying out of wetlands (Job et al., 2019).

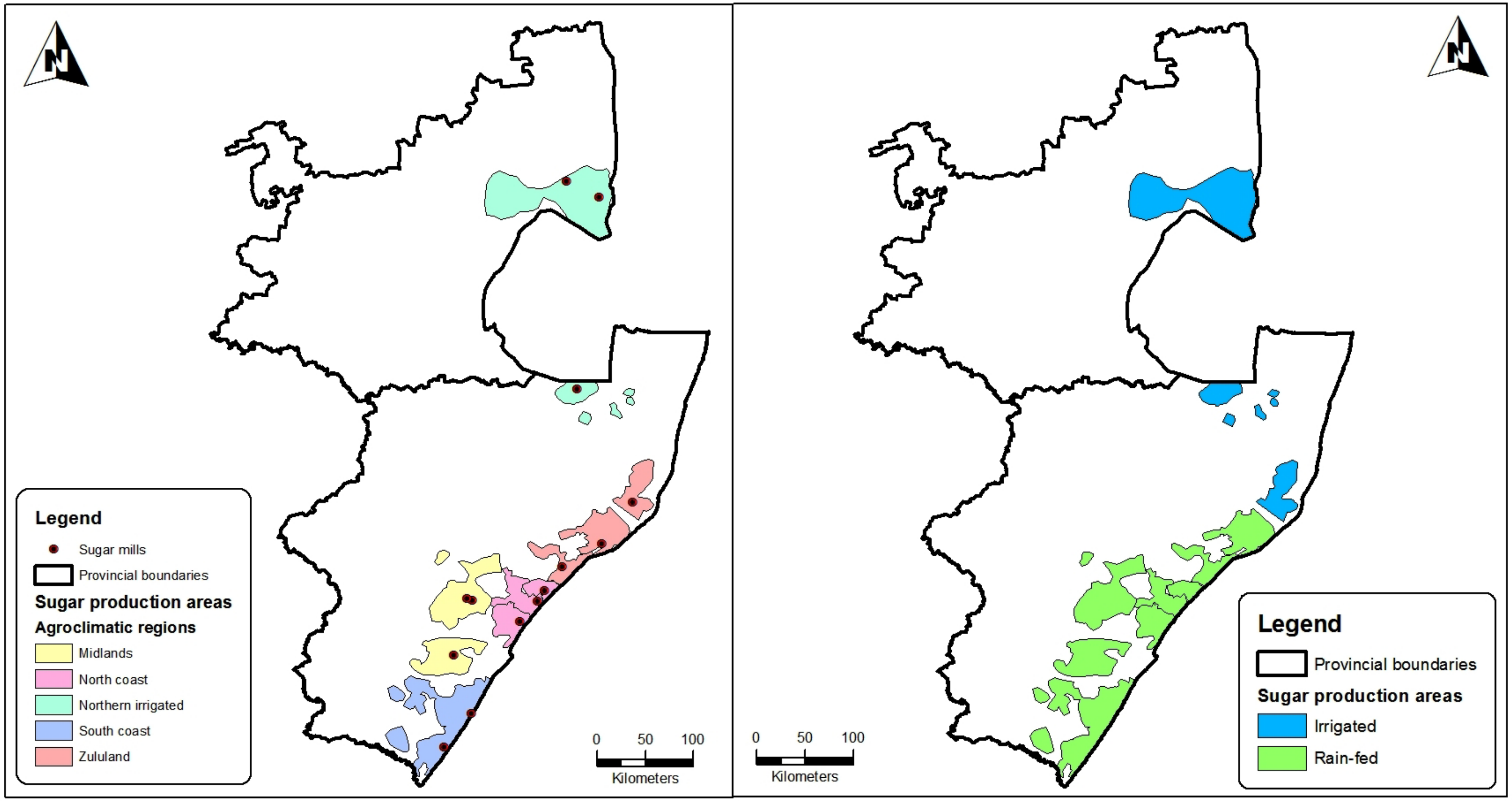

Figure 2: Overview of the South African sugarcane production areas (KZN and Mpumalanga provinces) highlighting the broad agro-climatic production regions and sugar mills (on left) and the rain-fed and irrigated areas (on right).

The primary impacts of sugarcane cultivation associated with riparian and freshwater environments are:

- Extensive vegetation clearing in riparian zones (of streams and in wetlands);
- Active draining of wetland systems;
- Soil erosion and stream sedimentation; and
- Contamination of watercourses with nutrients, pesticides and other discharges.

Riparian vegetation (type), and therefore land-use/cover, has a direct effect on streamflow through water use. Changes in riparian vegetation (e.g. from native vegetation to crop use) can influence downstream flows. The nature of the effect depends on the vegetation type and its water use relative to the vegetation it replaces (Schulze and Schutte, 2015).

In terms of crop water use, several South African studies have shown that the impact of sugarcane cultivation on streamflows varies, largely depending on the baseline land-cover it replaces: in some places sugarcane utilises more water than the natural vegetation it replaces while in others it uses less (Talanda et al. 2007; Schulze and Schutte, 2015). The extent, or relevance, of these impacts will depend on the local context in terms of both landscape attributes and the cultivation practices applied. The relationship between sugarcane cultivation and sub-surface flow modification is not well studied.

The South African sugar industry recognizes the need for better management practices (BMPs) to encourage responsible and sustainable sugarcane production (SASA, 2015). Better management practices across various aspects of sugarcane cultivation have been developed by the South African Sugar Research Institute to reduce the impacts of sugarcane cultivation. The South African Sustainable Sugarcane Farm Management System (SUSFARMS®) brings together legal requirements and BMPs towards sustainable agriculture and serves as a guide to track achievement of legal requirements and progress towards achieving better management practice (SASA, 2015).

Table 1: Potential impacts on watercourses and aquatic ecosystems associated with sugarcane cultivation

Modifier	Receptor and impact	Impact factors	Reference
Removal of 'natural' vegetation from riparian areas	Watercourse: riparian areas become susceptible to erosion and bank destabilization leading to increased downstream sedimentation and flooding.	Replacement land-cover	Rein (1999)
	Aquatic ecosystems: can raise temperatures in watercourse due to the absence of shade and root mass protection for stream banks. This may be undesirable for a number of species, and favourable for others.	Replacement land-cover	Carvajal and Janmaat (2016)
Water use (in cultivation)	Surface water: streamflow Can reduce, have a modest or even a positive impact of streamflow	Baseline land-cover, Alternative land-use Season (growing, harvest)	Hess et al. (2016) Schulze & Schutte (2015) Talanda et al. (2007)
Application of fertilizers, herbicides and pesticides	Surface water: water quality – nutrients, salinity Groundwater: water quality – nutrients, salinity	Loads/concentrations Runoff (slope, rainfall) Management system	Hess et al. (2016)
Soil erosion	Aquatic ecosystems: water quality – dissolved and suspended solids	Rainfall, slope, management system	Polintano and Pissara (2005)
Burning	Soil: heat from pre-harvest burning makes the topsoil hydrophobic , decreases the soil hydraulic conductivity and promotes runoff	Timing of burn (e.g. cooler morning burns vs. afternoon hotter burns)	Hartemink (2008) Ribeiro (2008)
Fallow periods	Soil: soil erosion	Rainfall Slope Management system	Hess et al. (2016) Martinelli and Filoso, (2008), Fischer (2008)
Compaction (agricultural vehicles)	Soil: soil erosion		Naseri et al. (2007)
Withdrawal of water for irrigation	Surface water and streamflow: affect flow regimes and aquifers further afield → downstream water availability Concentration of production areas → modify local water balances and affect available water supplies for competing uses	Location of production within the catchment Local soil and topography Farm management practices Local climate conditions	Hess et al. (2016) citing Schmidt (1997), Warburton (2012)
	Groundwater: scarcity of groundwater at a range of spatial scales	Concentration of production areas	Hess et al. (2016)

2.2. The National Water Act

The South African National Water Act (Act 36 of 1998 – NWA) gives National Government the overall responsibility for, and authority over, water resource management, including the equitable allocation and beneficial use of water in the public interest. Within the NWA, the '**Reserve**' means: "the quantity and quality of water required -

a) to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Services Act, 1997 (Act No. 108 of 1997), for people who are now or who will, in the reasonably near future, be -
   (i) relying upon;
   (ii) taking water from; or
   (iii) being supplied from, the relevant water resource; and
b) to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource".

A '**Stream Flow Reduction Activity (SFRA)**' is any activity (including the cultivation of any particular crop or other vegetation) that is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users, and declared an SFRA by the Minister (Section 36 of the National Water Act, 1998). The NWA (Section 36) "allows the Minister, after public consultation, to regulate land-based activities which reduce stream flow, by declaring such activities to be stream flow reduction activities. Whether or not an activity is declared to be a stream flow reduction activity depends on various factors, such as the extent of stream flow reduction, its duration, and its impact on any relevant water resource and on other water users. The control of forestry for its impact on water resources, currently exercised in terms of the Forest Act, is now exercised under this Part". Dryland sugarcane was identified as a potential SFRA, but rather than declaring it as such, the DWS and the Sugar Industry have agreed to work together to improve the management of watercourses within sugarcane cultivation.

To support watercourse protection, the DWS has published procedures to guide the identification and delineation of wetlands and riparian areas (2005) which determine the edge of watercourses and wetlands. These guidelines are complimented by a tool which was developed through a Water Research Commission (WRC) study finalised in 2017 (Macfarlane and Bredin, 2017) for determining the appropriate buffer zones for wetlands in different sectors or land-uses (Buffer Zone Guidelines for Rivers, Wetlands and Estuaries). The tool was developed for the assessment of a proposed new development, or land-use change, at the site scale with a focus on the threats to the watercourse of surface water pollution from the adjacent land-use. The tool considers watercourse buffers from the perspective of surface water flows, and the associated pollution inputs and does not consider sub-surface flow interactions in the determination of buffer width.

2.3. Watercourse buffers

A watercourse buffer is an area adjacent to the watercourse set aside from the terrestrial land-use which generally encompasses the riparian zone. Naturally vegetated riparian areas conserve aquatic ecosystems, allowing them to carry out a variety of functions, and can buffer watercourses from the impacts of adjacent land-uses. Riparian zones are the transitional areas between aquatic and upland terrestrial habitats. They encompass the physical structure and associated vegetation of the areas associated with watercourses and can be described generally as areas of vegetation adjacent to streams, rivers, lakes, reservoirs, and other inland aquatic systems that affect or are affected by the presence of water (Fischer et al., 2000). Riparian zones connect aquatic and upland environments through subsurface and surface hydrologic flow paths (Vidon et al., 2010).

While riparian zones typically comprise a small percentage of the landscape, often less than one percent, they often perform a disparate number of ecological functions when compared to most upland habitats (Fischer et al., 2000). Riparian zones have been widely recognized as functionally unique and dynamic ecosystems (Fischer et al., 2000). In modified landscapes, riparian zones are often disturbed, degraded or lost completely. The establishment of vegetated riparian buffer areas within agricultural landscapes is increasingly recognised as a component of best or better management practices (e.g. Farm Sustainability Assessment guide (SAI), 2018; Gravious et al., 2017; SASA, 2015; BONSUCRO, 2016; IFC 2011).

The following key points are noted from a review of literature on watercourse buffers:

- The ecosystem functions of buffers are dependent on a range of landscape attributes such as soil type, vegetation structure and slope, and on-site factors. The ability of buffers to provide a specific function relates to their position within the catchment, their linear extent (length, connectivity), the composition and density of vegetation species, and their width and slope.
- Riparian buffers can influence downstream hydrological response (e.g. runoff and its components of stormflow and baseflow); the nature of the effect depends on the vegetation type.

- There is no single 'best design' for an ideal riparian buffer zone; the 'best' design depends on the desired functions and a range of site characteristics.
- Much of the focus on buffer design is on the required buffer width, largely because this factor is the most easily manipulated to help increase the level of functions and benefits provided.
- The literature identifies three generic approaches to buffer width determination; a fixed or uniform width approach (simple), a modified fixed width approach and a dynamic or variable width approach (technical).
- Recommended buffer zone widths range considerably depending on the desired functions, from as narrow as 10 m for microclimate control to hundreds of meters to maintain habitat for important species (see Appendix 2).
- Attention is also drawn in the literature to both the limitations of buffer zones in protecting watercourses, and to other management options for protecting watercourses (depending on the context).
- Riparian buffers are one of a range of approaches to watercourse protection and their establishment and design should be considered in relation to catchment and local conditions, objectives and existing and other management approaches (e.g. on farm soil and water management practices).

2.4. Benefits and costs of watercourse buffers in agricultural landscapes

Watercourse buffers aim to support continued land-use while simultaneously maintaining the health of freshwater ecosystems. Implementing watercourse buffers in the sugarcane landscape entails replacing sugarcane cultivation that has encroached into the watercourse and adjacent riparian zone with native vegetation, and potentially extending the area of native vegetation to further buffer the watercourse from the impacts of the land-use. Establishing watercourse buffers within sugarcane cultivation landscapes has outcomes for the sugarcane grower, broader society and the environment. These outcomes result in both local (on-farm) and broader (societal) costs and benefits.

The literature identifies a range of benefits and costs associated with watercourse buffers in agricultural landscapes and emphasises that these costs and benefits are not evenly distributed, both between the current land user and society and between current and future generations[2]. The costs and benefits also occur at different spatial scales, generally with the

[2] See for example Currie et al. (2009), Jenkins et al., 2010, Chang et al. (2011), Punttila (2014), Robertson et al. (2014), Carvaljal and Janmaat (2016), Fraser et al. (2016) and Deliverable 1 and 2 of this WRC project.

costs accruing at the local scale (to the land owner) and the benefits at a larger catchment scale. The following points emerged from the international literature:

- The implementation of riparian buffers in agricultural landscapes is largely focused on water quality protection / improvement, this is also evident in the literature relating specifically to sugarcane cultivation; the role of buffers (when designed appropriately) in biodiversity conservation is also highlighted.
- Consideration of water use / streamflow impacts was not evident in the studies considered, rather water conservation / reduction practices were more commonly associated with withdrawal of water for irrigation and to address the volume of water used along the value chain (e.g. processing).
- Riparian buffer zones are often viewed / evaluated as part of a broader management plan (towards sustainable agriculture and or watercourse protection/restoration).
- While many of the cost-benefit studies identified a range of potential benefits associated with riparian buffers, generally only a sub-set of these were quantified. Many of the benefits, particularly those related to ecosystem services, are difficult to quantify and, further, to express in monetary values.
- Producers and retailers are under increasing pressure to shift to responsible and sustainable production driven by market and regulatory forces (WBCSD, 2015).

From the **perspective of the sugarcane grower**, the main cost associated with establishing watercourse buffers is the income forgone from reduced sugarcane production. This cost is associated with the conversion of sugarcane cultivation area to buffer area (and / or back to unplanted watercourse). In addition, there are costs associated with the establishment and maintenance of buffer areas. Establishment activities include the removal of sugarcane from the buffer area and the planting of replacement vegetation. Maintenance activities include the management of biomass and alien plant encroachment within the buffer area and watercourse. On the other hand, there is a growing recognition that sustainable management practices within agriculture **can provide numerous 'on farm' benefits** such as erosion control and top soil retention (Rein, 1999) pest management and pest-load reduction benefits, and aesthetic and cultural benefits associated with well-functioning natural habitats (Robertson et al., 2014; Evidentiary, 2016). Further, rehabilitated watercourses (and especially wetlands) are associated with more water being retained, and for longer periods, in the adjacent hillslopes (Van Huyssteen, 2019), which is beneficial to growers as this water would be available to crops (a potentially significant benefit during dry periods).

From the perspective of society, buffers in agricultural landscapes are desirable for the protection of aquatic ecosystem health and the maintenance of ecological services and the associated benefits, for the contribution to maintaining the Reserve (water quantity and quality), and to support biodiversity maintenance. Key impacts associated with agricultural land-use include increased sediment and nutrient loads to the receiving watercourse and effects on water yield through crop water use (relative to the native land-cover) and changes to the flow of water through the landscape to the watercourse (surface and sub-surface flow paths). Establishing buffer areas adjacent to watercourses within sugarcane cultivation can reduce these impacts and improve and maintain freshwater ecosystem health.

Several South African studies have investigated sugarcane water use relative to other crops (especially timber) and native vegetation. These studies have shown that the influence of sugarcane cultivation on streamflow, based on water use, varies across sugarcane production zones – particularly in relation to the type of 'native' vegetation the sugarcane replaces (Smithers et al., 1997, Schmidt, 1998; Bezuidenhout et al., 2006; Talanda et al. 2007; Jewitt et al., 2009; Schulze and Schutte, 2015). Additional findings are noted:

- Significant differences in runoff appear negligible in wet seasons and more prominent in drier months (Smithers et al., 1997).
- A marked difference in streamflow reduction between irrigated and dryland land-uses (Creemers and Pott, 2002).
- Climate change futures are likely to influence sugarcane-hydrology relationships (Jones et al., 2013).

In a study of the economic-environmental trade-offs of agricultural non-point source pollution control measures, field- and catchment-scale biophysical simulation models were developed to predict agricultural non-point source pollution within sugarcane cultivation (Matthews et al. (2012). Various practices related to non-point source pollution management were explored during the course of developing the models, including fertiliser regime, the spatial distribution of fields and the use of controls in the form of riparian buffers and contours. Preliminary results indicated that the use of buffers assisted in nitrogen and phosphorus pollution abatement and that field contours were particularly effective.

2.5. A benefit inventory

The literature suggests that riparian buffers are able to provide a wide range of functions from improving water quality to providing stability to stream banks and providing habitat for a range of wildlife species. These functions are associated with a range of potential benefits, Table 2.

Drawing from the literature on the likely impacts of sugarcane cultivation on watercourses (Section 2.1), buffer functions (Section 2.3 and Table 2), and cost-benefit studies of buffer implementation (Section 2.4), an 'inventory' of potential watercourse buffer benefits was compiled (Table 3).The benefits were grouped as those accruing at the local (on-farm) scale and therefore to the sugarcane grower / land-owner and those occurring at a broader (societal) scale. The purpose of the inventory is to draw attention to the range of buffer functions and associated potential benefits, particularly as many of these benefits are challenging to quantify. The contribution of watercourse buffers to pest control within sugarcane cultivation is a key potential on-farm benefit and is discussed in greater detail in Section 2.5.2 and Appendix 4.

Table 2: Summary of riparian buffer functions and associated benefits

Buffer function	Potential benefit
Filtration of sediments, nutrients, and pollutants in runoff	Improved downstream water quality • Multiple benefits associated with improved water quality, depends on the intended use of the water. • Captured soil could be used for soil replacement (it would also be organically rich) in cases of high soil loss/erosion[3].
Influencing microclimate and water temperature When streamside canopy is removed, water temperatures can increase and sensitive aquatic biota may succumb to thermal stress, low dissolved oxygen concentrations, or other stresses such as diseases, increased parasitism, or altered life cycles (maturation rates). Maintaining habitat critical for semi-aquatic species Maintaining habitat critical for aquatic species Maintenance of general wildlife habitat Screening (wildlife) from adjacent disturbances Maintaining habitat connectivity	Biodiversity gain • Multiple benefits associated with biodiversity gain, specific benefits linked to buffers include: ○ Natural predators of pest species ○ Pollination services ○ Maintenance of food chains ○ The scenic qualities of natural beauty, wildness, and privacy are enhanced by native buffer vegetation. Riparian areas support a wide variety of plant and animal communities. These communities form an interconnected food web that ranges from tiny microorganisms to large mammals.

[3] Rein (1999).

Buffer function	Potential benefit
Contribute to channel stability and flood attenuation Sedimentation in river systems is generated from channel instability manifested through erosion of the stream bed and banks. Vegetated buffers can slow surface flows and promote infiltration.	Channel stability • Soil conservation • Support long term viability of adjacent land-uses (e.g. agriculture) • Limit/reduce downstream sedimentation. Flood attenuation • Retain water in the landscape • Promotes base flow • Reduce risk of downstream flood damage (e.g. to transport infrastructure, agricultural lands).
Influence downstream hydrological response (e.g. runoff and its components of stormflow and baseflow, or evapotranspiration). Riparian vegetation (type) can have a direct effect on streamflow through water use. Riparian evapotranspiration (ET) can influence stream hydrology at a catchment scale by influencing the net loss of water from the stream towards the riparian zone (i.e., stream hydrological retention) (Lupen et al., 2016). Changes in riparian vegetation (land-use) can therefore influence downstream flows. Groundwater recharge through increased infiltration associated with buffer vegetation.	Potential positive influence on downstream hydrological response. The nature of the effect depends on the vegetation type (water use / evapotranspiration) (Schulze and Schutte, 2015). Contribute to baseflow during low rainfall periods.
Providing aesthetic appeal and recreation opportunities	Recreational opportunities (e.g. for hiking, fishing, bird watching). Positive impact on the visual quality of some agricultural landscapes; • Landscape preferences can vary by stakeholder group • Tension between naturalized settings and 'neatness' • Buffers with a managed / neat edge are most acceptable to farmers, landowners, and other rural residents (Lovell and Sullivan, 2006).

Source: Adapted from Macfarlane et al. (2009).

Table 3: Potential benefits of watercourse buffers in sugarcane cultivation

	POTENTIAL BENEFITS
	Agricultural support services Pest regulation • Native riparian and wetland habitat contributes to the regulation of Eldana saccharina Walker in sugarcane (when used as part of a push-pull strategy) • Provision of habitat for natural enemies of sugarcane pests Soil health and moisture management • Retention of water in adjacent hillslopes • Erosion control contributing to top soil retention Avoided damage associated with stream bank erosion and collapse
	Productive use of buffer area • Hay (cut grass) for use as livestock fodder and /or green manure • Recreational activities
	Avoided damage associated with high sediment loads • Reduced sediment load to downstream farm dams • Avoided damage to irrigation equipment (lower levels of sediment in water)
	Enhanced aesthetic and cultural value(s) of land • Biodiversity gain • Sense of stewardship • Amenity and recreation
	Contribution to sustainability goals • Producers and retailers are under increasing pressure to shift to responsible and sustainable production driven by market and regulatory forces.
BROADER (SOCIETAL)	**Sediment retention** • Reduced sediment loads to downstream system, important for ecosystem and species health and can be a significant benefit in the case of dam storage • Reduced damage to irrigation equipment from lower levels of sediment
BROADER (SOCIETAL)	**Improved water quality** • Nutrient load reduction – reduced water treatment costs
BROADER (SOCIETAL)	**Increased streamflow – downstream water yield** • Maintain the Reserve (water supply, ecological requirements) • Dilution – water quality improvements
BROADER (SOCIETAL)	**Biodiversity gain and habitat conservation**
BROADER (SOCIETAL)	**Streamflow regulation** • Maintenance of baseflow during dry periods • Regulation of excessive flooding and erosion reducing downstream damages
BROADER (SOCIETAL)	**Climate regulation** • Grassland and wetland ecosystems can contribute to carbon sequestration

Note: This is an inventory of potential benefits identified in the literature. While an extensive body of evidence exists supporting several of these benefits (e.g. improved water quality), many others require further investigation / empirical observations (e.g, pest regulation) or are particularly site and context specific (e.g. productive use of the buffer).

2.5.1. Hydrological benefits

As freshwater moves across the landscape – through surface, sub-surface and groundwater flows – it interacts with different terrestrial ecosystems which directly influence the hydrologic attributes (quantity, quality, location and timing) of water and the resulting hydrologic services and associated benefits to people (Brauman et al., 2007). These hydrologic services and benefits can be grouped into five main categories: diverted water supply, in situ water supply, water damage mitigation, spiritual and aesthetic benefits, and supporting services, Figure 3.

Water available for downstream use (storage and abstraction) is a key benefit associated with aquatic ecosystems. The timing, velocity and quality of this 'water' are equally as important as the quantity. The flow regulation and water quality amelioration services of the natural landscape are fundamental in this regard. Water quantity and quality effects are relatively well studied and modelled, however, flow regulation, infiltration and the retention of water in the landscape (e.g. adjacent hillslopes) are more difficult to model and quantify.

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Ecohydrologic process (what the ecosystem does)		**Hydrologic attribute** (direct effect of the ecosystem)	**Hydrologic service** (what the beneficiary receives)
Local climate interactions Water use by plants	➔	Quantity (surface and ground water storage and flow)	**Diverted water supply:** Water for municipal, agricultural, commercial, industrial, thermoelectric power generation uses **In situ water supply:** Water for hydropower, recreation, transportation, supply of fish and other freshwater products **Water damage mitigation:** Reduction of flood damage, dryland salinization, saltwater intrusion, sedimentation **Spiritual and aesthetic:** Provision of religious, educational, tourism values **Supporting:** Water and nutrients to support vital estuaries and other habitats, preservation of options
Environmental filtration Soil stabilization Chemical and biological additions/subtractions	➔	Quality (pathogens, nutrients, salinity, sediment)	
Soil development Ground surface modification Surface flow path alteration River bank development	➔	Location (ground/surface, up/downstream, in/out of channel)	
Control of flow speed Short- and long-term water storage Seasonality of water use	➔	Timing (peak flows, base flows, velocity)	

Figure 3: Relationship of hydrologic ecosystem processes to hydrologic services (reproduced from Brauman et al., 2007).

Since terrestrial ecosystems affect the attributes of the water moving through the landscape, changes in ecosystems (conversion, degradation) may influence or change these attributes and therefore influence or change hydrologic services. While crop cultivation 'uses' water and influences water 'quantity', it also modifies the flow of water in the landscape, affecting the 'timing' and 'location' of water and impacts the 'quality' of water.

Many land-uses reduce water infiltration, converting what would be recharge of hillslopes and groundwater into surface flows (Job et al., 2019). As a result, water storage in hillslopes is reduced affecting the release of water over time, with potentially significant consequences for the maintenance of baseflows and watercourse health. The maintenance of baseflows is essential for sustaining the ecological functioning of the system and supporting water availability during dry periods for both human and aquatic ecosystem needs.

"Natural systems such as wetlands and rivers or ecosystems with deep permeable soils can **regulate flows through the landscape** by slowing flows by means of storage and vegetative resistance and facilitating infiltration into soils (Turpie et al., 2017:3).

Streamflow regulation can have a profound effect on the volume of water ultimately available to downstream ecosystems and users (Brauman et al., 2007). The transfer of surface water to groundwater by infiltration reduces flood peaks and sustains base flow (Brauman et al., 2007). Streamflow regulation is associated with the following benefits:

- Maintenance of base flow during dry periods which supports downstream ecological health and water supply for human use;
- Promotes water storage – unexpected high rainfall events can render much of the mean annual rainfall from a catchment unusable or even a hazard if the flow cannot be slowed and captured;
- Increased predictability of flows – contributes to assurance of water supply over a sustained period;
- Retention of water in adjacent hillslopes (especially from intact / rehabilitated wetlands) increases availability of water for crops;
- Reduced downstream flood risk / damage to infrastructure and economic / livelihood activities.

Watercourse buffers can influence the 'quantity' 'quality' 'location' and 'timing' attributes of water, mitigating some of the impacts of adjacent land-uses and supporting the ecological functions and processes of watercourses. The benefits of watercourse buffers depend on their influence on these hydrologic attributes and the associated benefits for people (e.g. through downstream water use and storage).

Vegetated areas, intact riparian areas and wetlands, can capture sediments, nutrients, and pollutants in runoff from sugarcane cultivation preventing them from entering streams and rivers. In this way, watercourse buffers can **contribute to improving water quality** and reducing the impacts of high sediment and nutrient loads on downstream areas. High sediment loads to downstream systems are associated with a number of negative impacts, most relevant in terms of water supply benefits are (i) the **sedimentation of water storage dams** and the resulting loss in storage capacity (shortened dam lifespan) or the costs of dredging; and (ii) **damage to water conveyance infrastructure** including irrigation systems. While some level of sedimentation of the system is expected under natural conditions, and essential for beach maintenance, poor land management (cultivation) practices elevate catchment erosion and exacerbate downstream sedimentation. This also presents a **cost to the grower** in the form of **top soil loss** which reduces the productivity of the land over time. High sediment loads also have negative ecological consequences, smothering benthic habitats, altering the bed profile, increasing turbidity and altering nutrient processing and primary productivity (affecting food webs).

Upland, riparian and in-stream ecosystems are filters, sinks, processors and exporters of nutrients (nitrogen, phosphorus and carbon). Nutrient control in watercourse buffer and riparian areas is achieved through:

- Filtering (deposition and erosion, infiltration, dilution and adsorption/ desorption);
- Nutrient (especially nitrogen and phosphorus) uptake, assimilation and removal; and
- Nutrient cycling and transformation (e.g. denitrification) in the soil (Hansen et al., 2010).

In this way, watercourse buffers and intact watercourses can contribute to reducing excess nutrients from agricultural runoff to the downstream system. Excessive nutrient inputs to watercourses can lead to the eutrophication of downstream systems and reduce the capacity of these systems to provide ecosystem services. Eutrophication is associated with a number of negative impacts, particularly a reduction in the quality of water for human (and animal) use. In the case of water abstraction for human use, higher quantities of treatment chemicals, drawn-out treatment processes and increasingly sophisticated treatment technologies are required to restore water to a suitable quality, leading to rising water treatment costs. Continued use of polluted water can result in serious consequences with attendant costs including adverse human-health and well-being effects, environmental effects and effects on economic activities.

Eutrophication refers to the enrichment of the water environment with plant nutrients and is associated with excessive growth of phytoplankton (free floating algae) and rooted macrophytes (Graham et al., 2012). This can lead to the emission of odours from eutrophic waters due to the organic matter and algae that proliferate. Some algal species produce substances toxic to humans, animals and aquatic life. Nutrient enriched water can enhance conditions that favour the growth of waterweeds and some bacteria that favour eutrophic waters may cause diseases in humans (Sikhakhane, 2001). In considering the consequences of eutrophication, it is also important to acknowledge several potential benefits of eutrophication, including (i) increased productivity of some fisheries, (ii) positive fertilization effects on farmland through the use of nutrient-enriched irrigation water, and (iii) improved sources of food for some wild birds (Pretty et al., 2003).

2.5.2. Gain in area of native vegetation

A gain in native vegetation within the sugarcane landscape is associated with the following potential benefits:

- Agricultural support services (on-farm & broad scale benefits);
- Biodiversity gain and habitat conservation (broad scale benefits);
- Recreational activities (on-farm benefits);
- Climate regulation (broad scale benefits).

These benefits, particularly those related to biodiversity gain / maintenance, can be compromised by the fragmented nature of implementing watercourse buffers across only a single land-use type (sugarcane cultivation in this case); although, there is still significant potential for ecological corridors given that sugarcane farms are generally grouped together.

Biodiversity plays a vital role in agriculture; a fact increasingly being recognised amongst commercial and communal farmers across the world; who are also accepting the responsibility to look after the biodiversity on their land. Not only is the inherent value of the diversity of life being seen, but the close links between biodiversity, land condition and profitability are being defended. It is however not just about profitability, and many farmers recognise the role their management plays in maintaining the regional ecology upon which many people rely; with the obvious example being regional water security. Many farmers also desire to see the biodiversity features of their land conserved for the benefit and pleasure of future generations, and they have a strong sense of the ‘rightness’ to manage their land in a responsible manner (Lechmere-Oertel, 2018:4).

Agricultural support

Native habitats support organisms that provide agricultural support services in the form of agricultural pest control and pollination. Healthy wetlands and riparian areas can play an important role in the suppression and control of populations of the common sugarcane pest, *Eldana saccharina* Walker (hereafter 'Eldana') when implemented through a push-pull approach as part of an integrated pest management strategy (Cockburn, 2013; Mulcahy, 2018, Conlong, 2019[4]).

> The stem borer *Eldana saccharina Walker* (Lepidoptera: Pyralidae) is a common pest of sugarcane in eastern and Southern Africa and is considered a major constraint to sugarcane production (Conlong, 1990; Kvedaras and Keeping, 2007). Rutherford (2015) estimated the total direct loss to sugarcane growers (across South Africa) as approximately R344 million per annum. In an effort to reduce Eldana damage, many growers harvest the sugarcane crop earlier than the preferred cycle, causing additional economic losses, estimated to be in the region of R400 million per annum (Rutherford, 2015).

Establishing watercourse buffers within sugarcane cultivation contributes to the improvement and maintenance of wetland condition thus supporting pest control. Further to supporting the health of wetlands, the buffer areas themselves could provide habitat for Eldana parasitoids and predators as well as for other sugarcane pests (e.g. yellow sugarcane aphid and sugarcane thrips). Improved pest control is a benefit to sugarcane growers in:

- Reducing the damage to sugarcane inflicted by the pests,
- Reducing the need to harvest sugarcane early to avoid damage from Eldana, and therefore, increasing yields,
- Reducing the need for chemical pesticides and the associated long-term savings in pesticide costs.

The relationship between buffer width (extent of native vegetation) and pest control effectiveness is an area requiring further investigation.

While not directly relevant to sugarcane cultivation, crop pollination by insects is an essential ecosystem service that increases both the yield and the quality of many other crops (Turpie et al., 2017). Sugarcane growers are increasingly diversifying into other crops, particularly avocados and macadamias, both of which are dependent on insect pollinators. By supporting habitat for wild pollinators, watercourse buffer areas can contribute to reducing the costs of active pollination (e.g. hiring of bee swarms or dusting).

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[4] Pers comm. Senior Entomologist at SASRI. See Appendix 4 for further detail.

Biodiversity gain and habitat conservation

Aquatic biodiversity is dependent on the provision of suitable in-stream habitat. Watercourse buffers contribute to maintaining habitat critical for aquatic species largely through the contribution of plant matter (fallen leaves/branches) into streams that supports the stream ecosystem. It has been recommended that riparian areas need to be at least 30 m wide to provide sufficient inputs to support in-stream habitat (Hansen et al., 2010).

Riparian areas are noted for their higher **terrestrial biodiversity** value than the surrounding landscape. Riparian areas support terrestrial biodiversity by:

- Providing refuge, foraging and breeding habitat, and corridors for the movement riparian obligate and generalist taxa
- Maintaining soil moisture and humidity (Hansen et al., 2010).

Through supporting biodiversity maintenance and habitat gain, watercourse buffers can **contribute to meeting provincial (and national) biodiversity targets**. Increased habitat also supports additional ecosystem services such as pollination. Many of these biodiversity benefits are closely related to the degree to which buffer areas are connected to one another as well as to other patches of native vegetation. Optimal buffer widths for biodiversity maintenance and habitat gain are site specific depending on the particular species and connectivity between buffer areas.

Recreational activities

Related to biodiversity gain and habitat conservation are increased opportunities for recreation and aesthetic benefits, such as fishing, birding and wildlife viewing. Again, these benefits are enhanced by the connectivity between areas of natural habitat. Continuous watercourse buffers provide an opportunity for enhancing connectivity within the landscape.

Climate regulation

Natural systems can make a significant contribution to global climate regulation through the sequestration and storage of carbon (Turpie et al., 2017; Lechmere-Oertel, 2018). By increasing the area of native vegetation, watercourse buffers can contribute to global climate regulation.

> When natural systems are degraded or cleared, the carbon they store is released into the atmosphere. On the other hand, when degraded systems are rehabilitated, their potential to sequester and store carbon increases (Turpie et al., 2017).

3. APPROACH AND METHODS

The study was conducted primarily as a desktop-based assessment supported by previous studies, current related / relevant studies and some additional primary data collection (local scale modelling, economic cost data), expert consultation and stakeholder engagement. The scope of the study was refined through stakeholder consultation in the inception phase of the project (see Section 1.3). The general steps of a cost-benefit assessment (CBA) guided the tasks undertaken in this study. CBA involves the identification, measurement and comparison (e.g. through economic valuation) of the outcomes (e.g. water yield) of the alternatives being considered (Brouwer and Georgiou, 2012) and relies on biophysical measurements of the response of the system to the action / intervention (e.g. buffer establishment) (Spangenberg and Settele, 2016). This required first identifying an appropriate buffer (width) to be evaluated. However, there is no single 'best design' for a watercourse buffer and a first objective of the study was to develop an approach to delineating the width of watercourse buffers. The approach was then applied to a case study catchment in the Midlands North sugarcane production area to assess the costs and benefits of establishing the guideline buffer widths. Hydrological modelling was adopted as a means to quantify the hydrological response of the system to buffer establishment as the basis for determining the benefits. This is an important step in establishing the downstream social benefits of watercourse buffer establishment.

The following tasks were undertaken:

d) An approach for delineating the widths of buffers adjacent to watercourses was developed.
e) The buffer delineation approach was applied to a case study catchment to simulate the hydrological response (water, sediment and nutrient fluxes) of the system to the guideline buffer widths. A SWAT hydrological model was modified and parameterised for this purpose and, specifically, to integrate hydropedological information to strengthen the model and simulation outputs.
f) The costs and benefits associated with watercourse buffer establishment within the sugarcane cultivation landscape were investigated through a review of the existing knowledge base and the case study application of the buffer delineation approach.

The CBA framework and associated tasks undertaken in this study are illustrated in Figure 4.

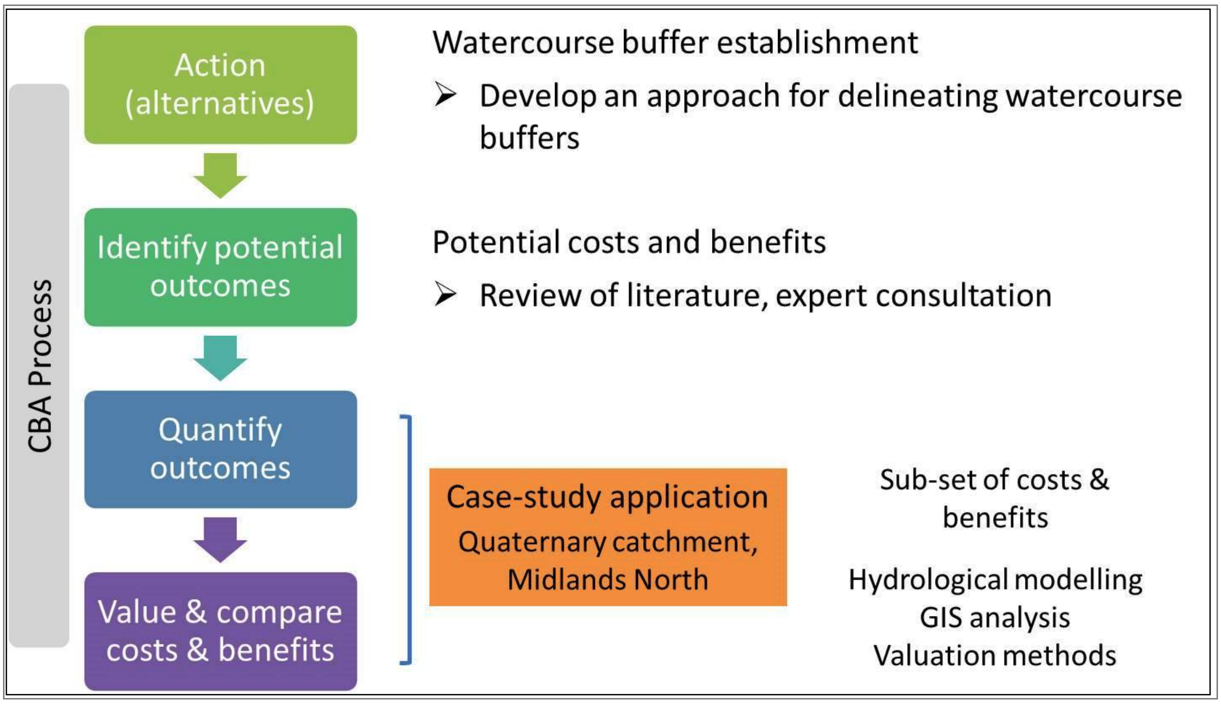

Figure 4: Schematic of the Cost-Benefit Assessment (CBA) process and the associated tasks undertaken in this study.

Stakeholders, including the Sugar Industry and the Department of Water and Sanitation (DWS), were consulted during the project. Two stakeholder workshops were held:

- Inception workshop – 15 June 2018 SASA, Mt Edgecombe – this workshop contributed to refining the scope of the study,
- Feedback & discussion workshop – 1 October 2019 SASA, Mount Edgecombe – this workshop focused on presenting the proposed buffer delineation approach, the subsequent discussion highlighted a number of opportunities and challenges for watercourse buffer implementation.

In addition, various members of the Sugar Industry were consulted on specific elements of the project, including:

- Midlands North Extension Specialist, SASA
- Senior Entomologist, SASRI
- Senior Manager, Midlands and South Coast, SA Canegrowers
- SUSFARMS® coordinator.

The approach and methods associated with each of the main tasks is detailed in the following sections

3.1. Development of the buffer delineation approach

The buffer delineation approach was developed drawing on established research on buffer function and buffer width determination (see Appendix 2 for an overview of studied / applied buffer widths), previous research (e.g. Lorentz et al., 2012) and existing tools (i.e. Macfarlane and Bredin, 2017) and significant recent progress in South Africa towards the understanding, conceptualisation and quantification of hydropedological processes (e.g. Le Roux et al., 20120; Van Tol et al., 2013; Van Tol and Lorentz, 2018).

In developing the buffer delineation approach, a number of factors were considered as 'inputs' to determining an appropriate width. However, the hillslope class was taken as the primary determinant of buffer width, which itself, takes into account a number of elements such as landscape topography. Including multiple factors in the determination of buffer width, while conceptually appealing, is practically challenging requiring extensive data inputs and spatial analysis.

The hillslope class was established based on the hydropedological classification system for South Africa (proposed as a means of classifying hillslope types). The basis of this classification is the hydropedological soil types, their spatial distribution and coverage along a slope (Van Tol, 2018). A hydropedological interpretation of regional soil information (land type data) was undertaken by Johan van Tol (University of the Free State) to characterise the hydropedological behaviour of dominant hillslopes in the case study catchment (U20G) and associated sugarcane production area (Midlands North). A similar assessment was also undertaken for the North Coast production area as a second potential case study area, see Appendix 1. The buffer delineation approach and further explanation is provided in Section 1.

3.2. Case study application and hydrological model development

Watercourse buffers are multifunctional and can provide a range of benefits. As a point of departure, the case study investigated the hydrological response resulting from various scenarios of watercourse protection within sugarcane growing regions, specifically the removal of sugarcane from watercourses and watercourse buffer establishment. Hydrological modelling was proposed as a means to investigate water, sediment and nutrient fluxes. The hydrological modelling was undertaken for a case study catchment (quaternary catchment U20G, Midlands North).

The catchment scale model was used to simulate the hydrological response of the system to the establishment of buffer zones along watercourses within sugarcane cultivation landscapes under various scenarios, at the quaternary catchment scale. The model developed for the UMDM project (SANBI/GEF; Scott-Shaw, 2018) was modified for this purpose[5]. This required several sets of new information and a number of model adjustments to meet the needs (research questions) of the study. Specifically, key parameters within the SWAT model were adjusted to take into account hydropedology classes / attributes. This is a novel development of the project. An extensive spatial analysis was undertaken to integrate, among others, land-use and watercourse extent, soils information, hillslope class classification and the associated buffer width and developed a number of layers to reflect different buffer width options. A small-scale modelling exercise, and in-field data, was used to inform and improve the lateral flow parameterisation of the catchment model. A number of iterations to calibrate and parameterise the model were undertaken. These are described in more detail in below.

3.2.1. Catchment selection

In selecting a case study site, both an analysis of spatial information and a review of existing research sites were undertaken and stakeholders were consulted. Discussions with stakeholders[6] highlighted that irrigated areas are complex and it was agreed, as a point of departure for this study, to focus on rain-fed production areas. Stakeholders also recommended the Midlands North production area as a priority to link with, and be able to draw on, other research efforts and related activities in the area[7].

A key factor influencing site selection was the availability of background data to improve the confidence of the desktop modelling exercises. Such information was available for the Mkabela River catchment within quaternary catchment U20G (Midlands North sugar production area) which had previously undergone instrumentation and monitoring for research purposes through an earlier WRC study. During the inception phase of the project several related research projects were identified, including a project modelling riparian clearing scenarios for the uMgungundlovu District Municipality (UMDM), KwaZulu-Natal (SANBI / GEF; Scott-Shaw, 2018). Through the UMDM modelling project, a SWAT hydrological model was set up for selected catchments of the Municipality, including quaternary catchment U20G (Midlands North), which presented an opportunity for this project to build on the UMDM SWAT model.

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[5] Permission was given by the SANBI team to build on the existing SWAT model set-up.
[6] Stakeholder workshop, 15 June 2018 SASA, Mt Edgecombe
[7] Research on integrated pest management (e.g. Cockburn, 2013), the development of land-use plans and engagement on the Sustainable Sugarcane Farm Management System.

Given the availability of background data, the opportunity to build on an existing hydrological model and the acceptance by stakeholders of the Midlands North area as a focus or starting point area, quaternary catchment U20G was selected as the site for developing the buffer delineation approach and simulating the hydrological response to various buffer scenarios.

3.2.2. Model description

The main advantages and input requirements of the SWAT model are summarized in Appendix 3. The spatial input data required by ArcSWAT are soils, elevation, which contributes to the derivation of flow paths and routes sub-basin flow, and land-use (Arnold and Fohrer, 2005). In attempts to improve model simulations, the total hillslope contribution to buffer zones, riparian areas and wetlands was quantified through a hydropedology study and utilized to add dimension to the current soils data (Van Tol, 2018). ArcSWAT groups the above-mentioned parameters and generates a series of Hydrologic Response Units (HRUs). An HRU is the smallest spatial unit of a model and is associated with unique characteristics based on soil, topography, slope and land-use (Kalcic et al., 2015). Input climate data has a significant influence on model outputs and it is essential that a long, representative record is used. ArcSWAT has the option to generate rainfall and temperate data if this is unavailable. Other meteorological data of importance to SWAT include; evaporation, relative humidity, solar radiation and wind speed. To improve simulations, it is recommended that data from more than one gauging station is used when generating climate records (SWAT can accommodate a maximum of 300).

Elevation: A 30 m (30 m x 30 m) Shuttle Radar Topography Mission (SRTM) global Digital Elevation Model (DEM) was used in the initial step of the modelling process. The DEM is used to divide the quaternary into smaller sub-basins, which is a function of the watershed delineation tool. This process also allows for the delineation of rivers and selection of outlet nodes.

Land-cover: The Ezemvelo KwaZulu-Natal 2008 land-cover layer (EKZNW, 2010) was used as a starting point and refined to accurately represent sugarcane within the catchment by validating against industry data (Scott-Shaw, 2018). This layer was derived from 2008 SPOT5 multispectral imagery and resampled to a 20 m pixel resolution. It is the finest resolution data available for the province. A water resources layer, delineated by Dr Richard Lechmere-Oertel (Biodiversity Planning and Management) was clipped into the land-cover layer. Thereafter, a range of buffer widths[8] was clipped into the land-cover to run the various scenarios. The buffer widths are based on three categories of implementation viz. narrow, moderate and wide, based on the risk to watercourses within the catchment (i.e. slope, management practises, etc.). In the modelling, the buffers were assumed to be natural grassland (sourveld) in good condition. The land-use definition tool clips the land-use to the study boundary and assigns the user a defined land-use code to each land-use (per HRU). The land-use codes are written as a text file which can be used to adjust scores/codes more efficiently compared to using the SWAT interface. The SWAT model was configured to include sugarcane cultivation as a land-use.

Soil: Emphasis was placed on improving model simulations through detailed soils analysis. The aim was to illustrate the contribution of subsurface flow down a hillslope to the buffer. SWAT soil and lateral flow parameters were adjusted to reflect the various zones delineated by the hydropedology study (Van Tol, 2018)[9]. When using a basic soil layer, SWAT takes into consideration soil structure, depth, number of layers and texture to define soil characteristics.

Slope: Five slope classes were calculated from the DEM, using the slope definition tool. Any number of classes can be defined, which has an influence on the number of HRUs that will be generated.

Climate data: Daily meteorological data from 5 South African Sugar Research Institute (SASRI) weather stations were used and patched/extrapolated with data (farm scale) from Fountain Hill Estate (a research catchment, Midlands, KZN). A text file for each station was generated containing information for all climate parameters (i.e. rainfall, temperature, wind speed and evaporation).

Flow data: Observed weir flow data were used to derive inflow discharges to the U20G quaternary and observed flow data at the outlet of the catchment (Nagle Dam) were used to guide the simulated runoff in U20G.

The model was set up and run for a 48 year simulation period (equivalent to the number of years' worth of climate data), where the first 3 years were used as a 'warm up' period. Once all input files are selected the model uses a series of tools to generate spatial outputs, that is

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[8] See section 1 for the buffer width determination process.
[9]A hydropedological interpretation of regional soil information (land type data) was undertaken by Johan van Tol (University of the Free State) as part of this study.

- Watershed delineation
- Sub-catchment and river reach delineation
- Land-use classification
- Hydrological soil classification
- Slope classification and
- HRU classification.

At the small scale, a catchment which had previously undergone instrumentation and monitoring for research purposes was selected within a sugar growing region – the Mkabela River Catchment near Wartburg in KwaZulu-Natal. This catchment was previously instrumented with field-scale runoff plots, and small catchment scale runoff flumes for the investigation of sediment and nutrient mobilisation dynamics and connectivity processes (Lorentz et. al., 2012). The Mkabela River forms a tributary of the uMngeni River within Quaternary catchment U20G, selected for the catchment scale modelling. The following activities were undertaken in relation to modelling at the small catchment scale within the upper Mkabela:

1. Background Data: Obtain relevant available data covering the catchment;
2. Transect Survey: Survey a transect of the Mkabela River to populate the HYDRUS model;
3. HYDRUS Model: Populate the HYDRUS model for investigation of the soil water (and ultimately nutrient) fluxes between the riparian zone, buffer zone and sugarcane fields.

The local scale simulation was useful in determining:

- Water fluxes arriving at the buffer strip;
- Nutrient fluxes arriving at and taken up in the buffer strip (HYDRUS is capable of simulating nutrient mass fluxes in the saturated and unsaturated zones);
- Reponses of water and nutrient fluxes to pull-back of sugarcane from the buffer area or in-field;
- Responses of water and nutrient fluxes to alternate buffer strip widths and vegetation types.

3.2.3. Model parameterisation

An existing SWAT hydrological model developed for a separate study in the same region was modified for use in the case study assessment. This required several sets of new information and a number of model adjustments to address the research questions of this study. A number of iterations were required to calibrate and parameterise the model. The SWAT model contains numerous parameters covering soil-water interaction and transport within the near surface to saturated zone that are relevant to site hydropedology and hillslope connectivity to riparian zones. A select subset of these parameters are typically left at default, but can be activated and/or adjusted if the level of detail and expertise is available and required (Neitsch *et al.,* 2009).

Table 4 summarizes the specific changes made to various parameters in the SWAT model. The interface sets these parameters to a default value initially, however, through investigation the user can alter these to provide a better reflection of the watershed. Changes were made to four major input files namely; basin, plant database, soil, management and HRU (hydrological resource unit).

Table 4: SWAT model parameter adjustments

Input File	SWAT Parameter	Grass Buffer	Sugarcane
.BSN	SURLAG	2	2
	ADJ_PKR	0.5	0.5
.crop-dat	USLE_C	0.15	0.1
.SOL	USLE_K	Default	Default
	SPCON	Default	Default
	SPEXP	Default	Default
	CH_EROD	Default	Default
	CH_COV	Default	Default
.MGT	USLE_P	0.5	0.8
	CN2	55	55
.HRU	ESCO	0.3	0.15
	EPCO	0.5	0.8

The basin input file defines general watershed attributes that govern physical processes e.g. water balance, surface runoff, nutrient cycling, etc. The surface runoff lag coefficient (SURLAG) which controls a portion of the total available water that will be allowed to enter the reach in a day was adjusted from 4.0 (default) to 2 across all land-uses. Note, as SURLAG decreases, more water is held in storage. ADJ_PKR, which is the peak rate adjustment factor for sediment routing in the sub-basin was adjusted to 0.5 (from 1.0 = default). This parameter is used later in the MUSCLE equation and therefore impacts the amount of sediment generated in the HRU's.

Attributes that control plant growth can be found in the plant database file. Here the USLE_C parameter was adjusted according to the values listed in the table. This parameter controls the degree (minimum value) to which a plant/land-use is susceptible to water erosion. Parameters controlling land and water management practises (e.g. planting, harvesting, tillage, etc.) are found in the management input file. Two variables were adjusted from default values namely; USLE_P (support practice factor) which is a ratio of the soil loss to management practice applied, and the CN2 (SCS runoff curve number for moisture condition) which is a function of the soils permeability, land-cover and antecedent soil moisture. The selection of values is recommended by a list given in the SWAT manual (depending on the management practise applied in the model).

The soil evaporation compensation factor (ESCO) and plant uptake compensation factor (EPCO), located in the HRU input file were adjusted accordingly. ESCO is a coefficient that allows the user to alter the depth to which soil evaporation can occur to meet demand. A decrease in the ESCO value allows for evaporation to occur at lower depths. EPCO is a function of transpiration and soil water availability. If the upper soil layer cannot provide sufficient moisture for plant uptake the user can adjust the EPCO parameter to allow the plant to engage moisture at a lower level (higher EPCO value e.g. = 1.0).

Since one objective of this study was to incorporate hydropedological information into the model, the near-surface and interflow parameters were adjusted according to the detail generated through the definition and distribution of hydropedological zones. Table 5 outlines key parameters within the SWAT model which were adjusted to take account of the four hydropedology classes of the study catchment. Further parameterization was informed by previous studies (Kienzle et al., 1995; Lorentz et al., 2012) and recently Otim et al. (2018) and guided by available literature (e.g. Beatrie et al., 2011; Bokan, 2015).

Table 5: SWAT model parameters adjusted to account for hydropedology classes

SWAT Parameter*		Hydropedology Class			
Input file	**Variable**	**1: Interflow**	**2: Shallow Responsive**	**3: Recharge (not connected)**	**4: Recharge to wetland**
.HRU	DEP_IMP		Set to 1.2 times the total soil depth		Set to 0.5 times the total soil depth
.HRU	SLSOIL	Set to 150 m			
.SOL	SOL_K	Set to 30 mm/h			
.HRU	HRU_SLP	Set to 0.02 m/m			
.HRU	LAT_TIME	Default			
.MGT	GDRAIN	Set to 0			
.HRU	LATQ	Default			

* *Neitsch et al., 2009.*

The following equations are applied to model the sediment (Neitsch et al., 2005) and nutrients (Neitsch et al., 2005, modified by Bereitschaft, 2007) trapped by buffer strips.

$$Sed_{out} = Sed_{in} - Sed_{in} 0.367 w^{0.2951}$$ ....Equation 1

Sed$_{out}$: sediment output

Sed$_{in}$: inflow sediment

W: strip width.

$$N_{out} = N_{in} - N_{in}(24.6 + 55.3\log(w) - 0.5Slope^2 - 14.4Veg)/100$$ ....Equation 2

N$_{out}$: nitrogen output

N$_{in}$: inflow nitrogen

W: strip width

Veg: empirical vegetation parameter

3.2.4. Model calibration

SWAT-CUP was used to calibrate the modelling using observed streamflow data from Department of Water and Sanitation (DWS) weir U2H005. Calibration is necessary to reduce the uncertainty associated with the models outputs. The base run was calibrated to provide practical input parameters which allows for input parameterization which was applied across the various scenarios. The results show an average correlation between the observed streamflow and the baseline scenario, Figure 5. SWAT successfully captured the timing of high and low peaks, but consistently over simulated throughout the modelling period. Two extreme flooding events (i.e. 1987 and 2009) were under-simulated.

Sediment could not be calibrated against observed data due to a lack of routine sediment monitoring (observed data). Sediment and nutrient input parameters were guided by infield studies conducted in the Mkabela catchment (this study) and previous studies (Kienzle et al.,1995; Lorentz et al., 2012), by large scale catchment studies (Kienzle et al.,1995) and by recent analyses of sugarcane catchment research (Otim et al., 2018).

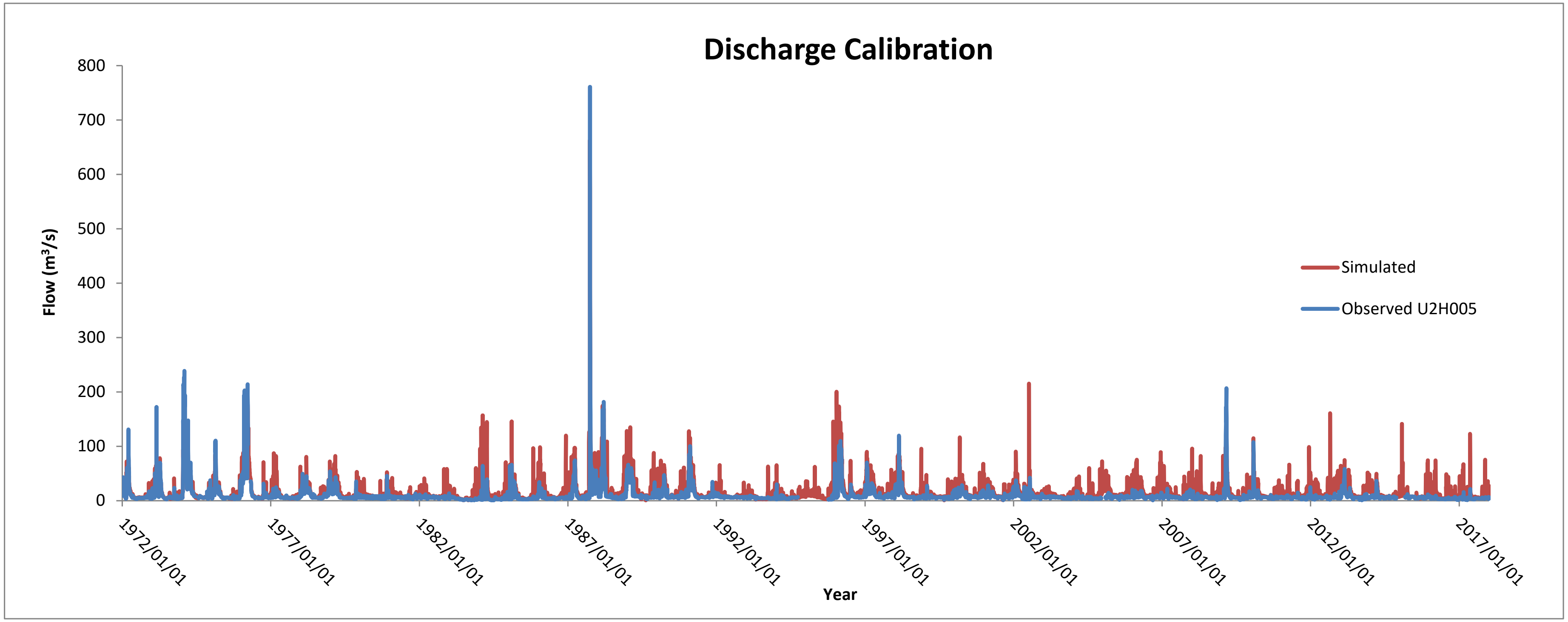


Figure 5: Observed vs simulated discharge, study catchment, 1971-2018.

3.3. Cost and benefit assessment

The potential costs and benefits of watercourse buffers are diverse and site specific, related to local conditions and objectives. Ideally, any cost-benefit assessment of a proposed intervention should consider all benefits and costs associated with the intervention relative to the case without the intervention. However, data and resource limitations often constrain the analyst's ability to measure and value many environmental benefits (Barbier et al.,1997) and generally only a sub-set of benefits are quantified (e.g. Campana, 2011; Rein; 1999; Qiu & Prato, 1998). An additional challenge in this context is the spatial and distributional 'mis-match' between the primary costs (local farm scale) and the primary benefits (catchment scale social benefits). The costs and benefits associated with watercourse buffers within sugarcane cultivation areas were investigated in two ways: (a) through a review of existing studies on buffer function and benefits to compile an inventory of potential benefits (Section 2.5); and (b) through a case study assessment of the establishment of watercourse buffers within sugarcane cultivation supported by spatial analysis, hydrological modelling and benefit / cost valuation.

a) The 'inventory' of potential benefits associated with watercourse buffers was compiled through a review of the literature on buffer functions, the potential impact of agricultural land-uses (with a focus on sugarcane cultivation) on riparian and freshwater environments and studies of the costs and benefits of buffer implementation in agricultural landscapes. The contribution of watercourse buffers to pest control within sugarcane cultivation was noted as a key potential on-farm benefit. A review of the literature, supported by expert consultation[10] was undertaken to explore the role of watercourse buffers and riparian and wetland habitat in the management of a common sugarcane pest – the stem borer Eldana saccharina Walker (Lepidoptera: Pyralidae). The purpose of the inventory is to draw attention to the range of functions of buffers and the associated potential benefits particularly as many of these benefits are challenging to quantify.

b) Assigning monetary values to the benefits of watercourse buffer establishment involves measuring how the quantity of each benefit (or underlying ecosystem service) would change as a result of the buffer, relative to the case without the buffer, and multiplying the difference by the marginal value of the benefit (e.g. the marginal value of a unit of water) (Pagiola et al., 2004). Given the challenge of quantifying the multiple

[10] Senior Entomologist at SASRI.

relationships between watercourse buffers, watercourse condition and the resulting ecosystem services and associated benefits, this study focused, as a point of departure, on quantifying the hydrological response – in terms of water, nutrient and sediment fluxes – of the catchment to the establishment of watercourse buffers in the sugarcane cultivation areas.

To do this, the buffer delineation approach was applied in a case study assessment. A hydrological model was used to simulate the hydrological response of the catchment to the implementation of the various scenarios compared to the baseline (current state) alternative. The results of the simulation were used to establish:

(i) The area (ha) of sugarcane that would be converted to buffer area under the different scenarios (using GIS analysis), and

(ii) The water, nutrient and sediment fluxes under each of the scenarios.

The area of sugarcane converted to buffer was used to estimate the costs of implementing the different buffer scenarios in terms of the income forgone from the permanent loss of cultivation area and the costs associated with establishing and maintaining the buffer areas. The cost estimates were informed by consultation with key stakeholders (e.g. SA Canegrowers regional economist) and available information (e.g. grassland rehabilitation cost estimates for the uMngeni catchment). The water, nutrient and sediment flux estimates were used as a basis for considering the hydrological benefits of watercourse buffer implementation. The benefit of additional discharge (water available in the downstream system), was valued based on the tariff for raw water for the case study area. The tariff does not reflect the value of water itself, but rather the costs associated with ensuring that water is available for human use and is an indicator of the 'costs saved' of an additional contribution to downstream water supply.

4. BUFFER DELINEATION APPROACH

There is no single 'best design' for watercourse buffers and, currently, in South Africa there are no recommended watercourse buffer zones for existing sugarcane production areas. From a water quantity and quality perspective, an important aspect affecting hydrological processes within a catchment is the interactive relationship between soils and water (hydropedology) which influences how water moves through the landscape (surface flows, sub-surface flows and groundwater flows). These 'hillslope' characteristics are an important determinant of an appropriate buffer intended to contribute to improved water quality and quantity.

While buffer zone guidelines are available (i.e. the 'Buffer Zone Guidelines for Rivers, Wetlands and Estuaries', Macfarlane and Bredin, 2017), they are intended for the assessment of a proposed new development, or land-use change, from the perspective of mitigating diffuse surface runoff. The guidelines do not consider sub-surface flow interactions in the determination of buffer width. However, hillslope characteristics determine the hydrological response of catchments (Sivapalan, 2003) and the hillslope is an important building block for understanding hydrological processes (Tromp-van Meerveld & Weiler, 2008). Hillslope characteristics can form an integral part of water resource management (Van Tol, 2018). In this study, an approach to delineate watercourse buffers within sugarcane cultivation landscapes that takes into account hillslope characteristics has been developed. Figure 6 summarizes the context behind the development of the proposed approach.

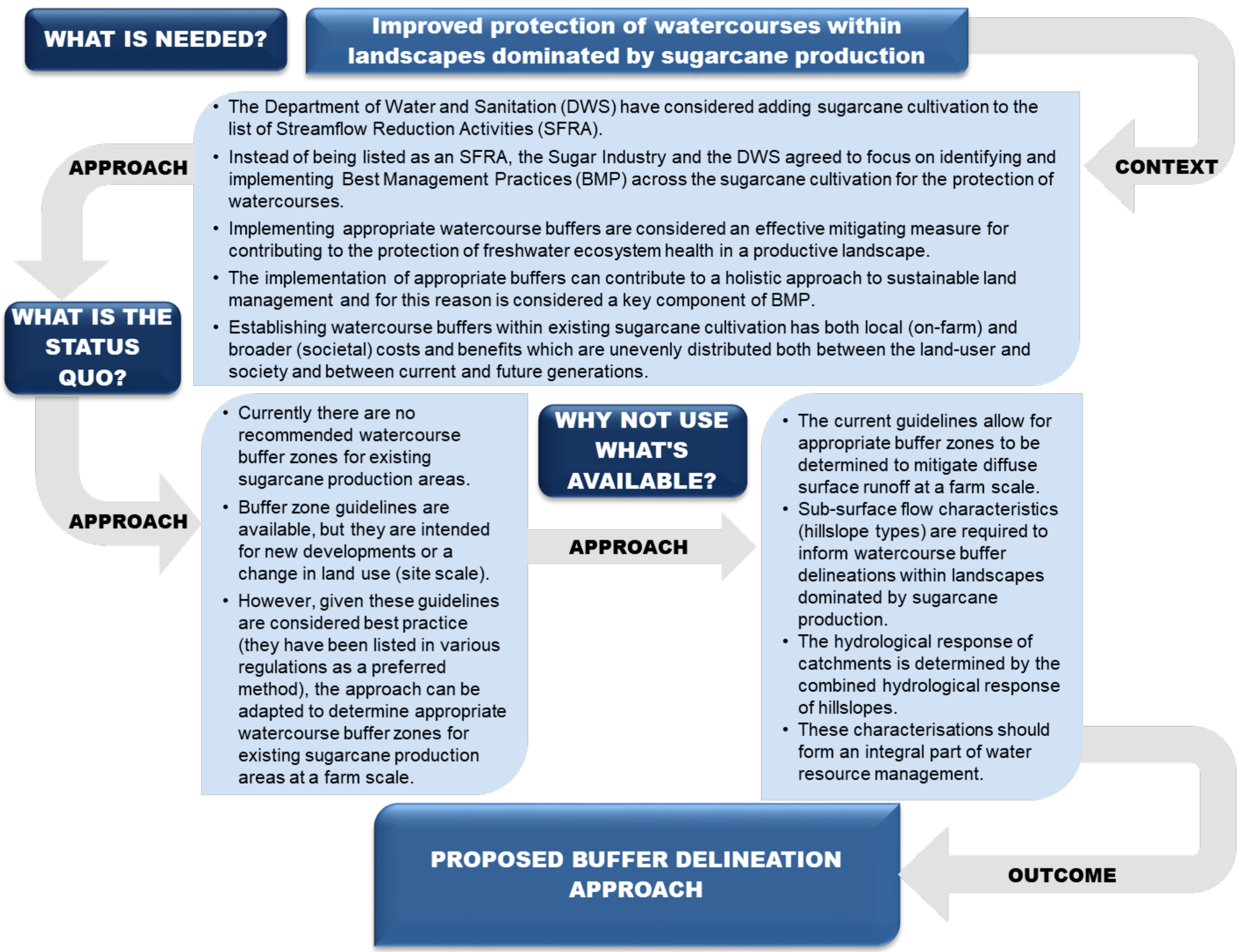


Figure 6: Context behind the proposed buffer delineation approach.

In the proposed watercourse buffer delineation approach, the hillslope class is the primary determinant of buffer width[11]. Hillslope classes have been identified for South Africa, following the hydropedological classification system of Van Tol et al. (2013)[12]. In the proposed approach, each hillslope class has been associated with a specific buffer width: as the hillslope class changes (varies across the landscape), the recommended buffer width changes, Table 6.

Table 6: Hillslope class and proposed buffer width for the for the delineation of watercourse buffers

Hillslope class	**Buffer width (m)**
Class	**Moderate**
Class 3 – Recharge to groundwater	15
Class 4 – Recharge to wetland	30
Class 1 – Interflow (soil / bedrock)	50
Class 2 – Shallow responsive	75

The buffer width is, therefore, dynamic (variable) across the landscape in relation to the hillslope class. For example, where a sugarcane cultivation area is dominated by hillslope class 4, a 30 m buffer width would apply; where the area is dominated by hillslope class 3, a 15 m buffer would apply. The approach should be applied separately to each bank of the watercourse as the hillslope characteristics may be different on opposite banks. This approach facilitates the optimization of buffer width against hillslope characteristics and is, therefore, conceptually more effective in protecting watercourses than a uniform[13] width which may be too narrow for effective watercourse protection in some instances and unnecessarily wide in others.

A comparison of the hydropedological hillslopes of the Midlands cultivation region and the North Coast region, Figure 7 (see also Section 5.1.2 and Appendix 1) highlights the variation in hillslope classes across production areas. In the Midlands region, Class 4 – Recharge to Wetland is the dominant hillslope class (52%, associated with a 30 m buffer); whereas Class

[11] At a regional scale, the hillslope class accounts for landscape topography (including slope).
[12] Hydropedological studies aim to characterise hydrological properties and processes, such as water flowpaths, residence times and groundwater/surface water interactions, based on the interpretation of soil properties and their spatial distribution (Van Tol, 2018). After conducting hydropedological studies on 52 hillslopes in South Africa, Van Tol et al. (2013) proposed a hydropedological classification system for the hillslopes of South Africa. The basis of this classification is the hydropedological soil types, their spatial distribution and coverage along a slope (Van Tol, 2018).
[13] With a uniform, or fixed width approach, as applied in the forestry sector in South Africa, a single uniform buffer width is set for entire the region or land-use.

2 – Shallow Responsive is the dominant hillslope class in the North Coast region (53%, associated with a 75 m buffer).

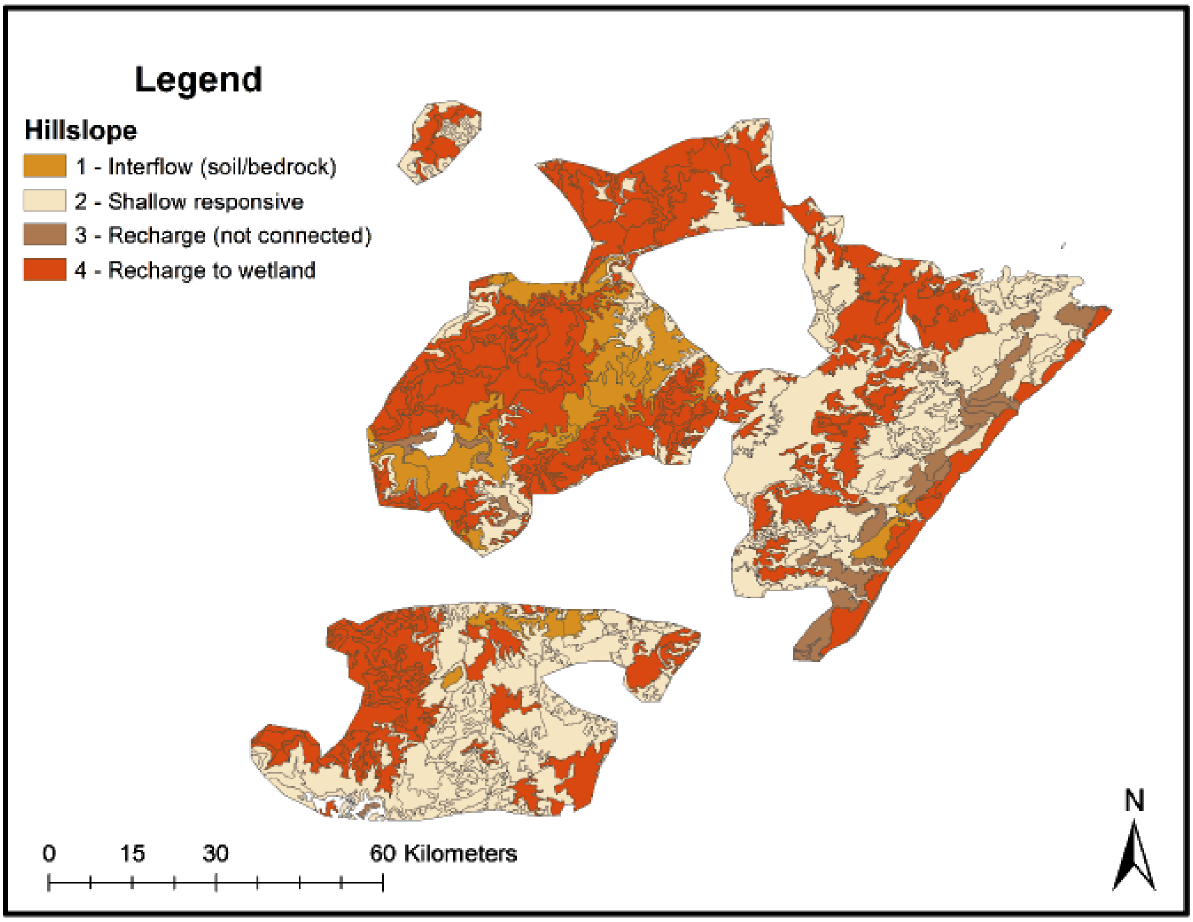


Figure 7: Hydropedological hillslopes of the Midlands and North Coast production areas.

The buffer width range was developed drawing on established research on buffer function and buffer width determination (see Appendix 2 for an overview of studied / applied buffer widths), previous research (e.g. Lorentz et al., 2012) and significant recent progress in South Africa towards the understanding, conceptualisation and quantification of hydropedological processes (e.g. Le Roux et al., 2012; Van Tol et al., 2013; Van Tol and Lorentz, 2018). The proposed buffer delineation approach, and associated range, can be applied (generalised) across the sugar production regions. A hydropedology assessment of the area under consideration is required to establish the hillslope classes as a basis for applying the proposed buffer widths. This requires specialist expertise. However, a national hillslope classification initiative is underway and the hillslope classes should become publically available in the near future (3 to 5 years).

Further to specifying the buffer width based on hillslope class, an important consideration are the site-specific factors related to the adjacent land-use that pose (or reduce) the threat to the watercourse. This is taken into account in the proposed buffer delineation approach by introducing a site assessment to assess the threats to watercourse and identify the better management practice (BMP) options (or those being applied) that address the identified threats. The desktop-tool associated with the Buffer Zone Guidelines for Rivers, Wetlands and Estuaries (Macfarlane and Bredin, 2017) can be used to guide the site assessment. Based on the site assessment, a case can be made as to whether the buffer width, as determined by the hillslope class, should be increased or reduced. In this way, each guideline buffer width, based on the hillslope class, is associated with a high threat to watercourse (wide buffer) and a reduced threat to watercourse (narrow buffer) option, Table 7. For example, where a sugarcane cultivation area is dominated by hillslope class 4 and a reduced threat to watercourse can be demonstrated; the 'moderate' 30 m buffer could be reduced to the narrow 15 m option. Conversely, should a site specific factor suggest a greater threat to the watercourse (e.g. a piggery / abattoir / feedlot / located near to the watercourse), the 'wide' 50 m option would apply.

Table 7: Hillslope class and buffer width range, for modifying the proposed buffer width based on higher or lower threat to the watercourse

Hillslope class	**Buffer width (m)**		
Class	**Narrow**	**Moderate**	**Wide**
Class 3 – Recharge (not connected)	10	15	30
Class 4 – Recharge to wetland	15	30	50
Class 1 – Interflow (soil / bedrock)	30	50	75
Class 2 – Shallow responsive	50	75	90

This option provides an opportunity for a reduction in buffer width based on reduced threat to the watercourse which could be achieved through the adoption of additional suitable BMPs. This approach opens the door to on-site mitigation and management that could reduce the impacts to the watercourse and reduce the impacts to the farmer of implementing a wide buffer width. It provides an opportunity for the farmer to benefit from adopting / existing BMPs. For a reduction in buffer width, the applicant (farmer) would need to demonstrate the reduced threat to the watercourse. This could be done through the development and implementation of a land-use (farm) plan and ongoing use (and associated reporting) of the SUSFARMS® Progress Tracker. Figure 8 summarizes the proposed buffer delineation approach schematically.

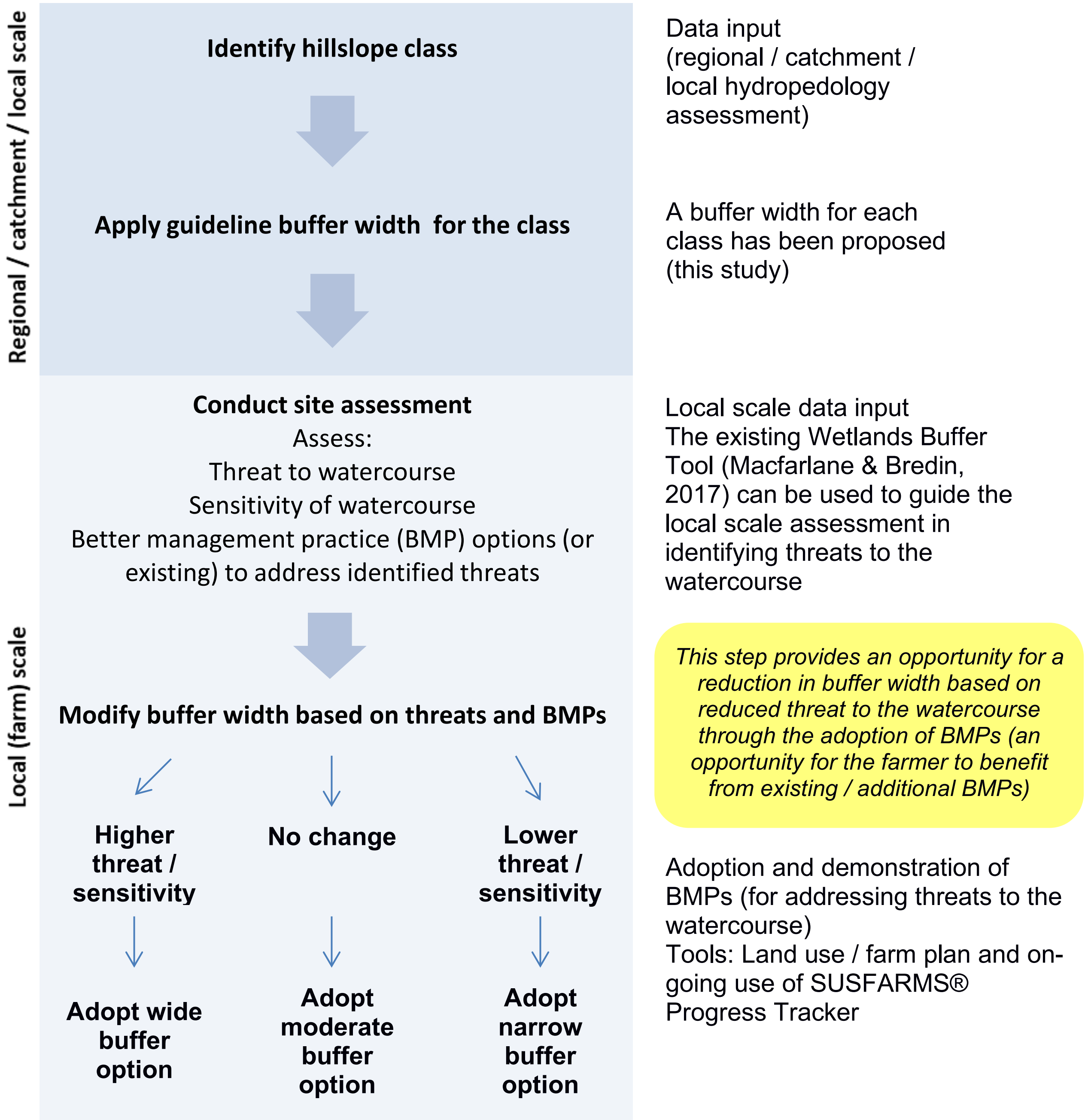
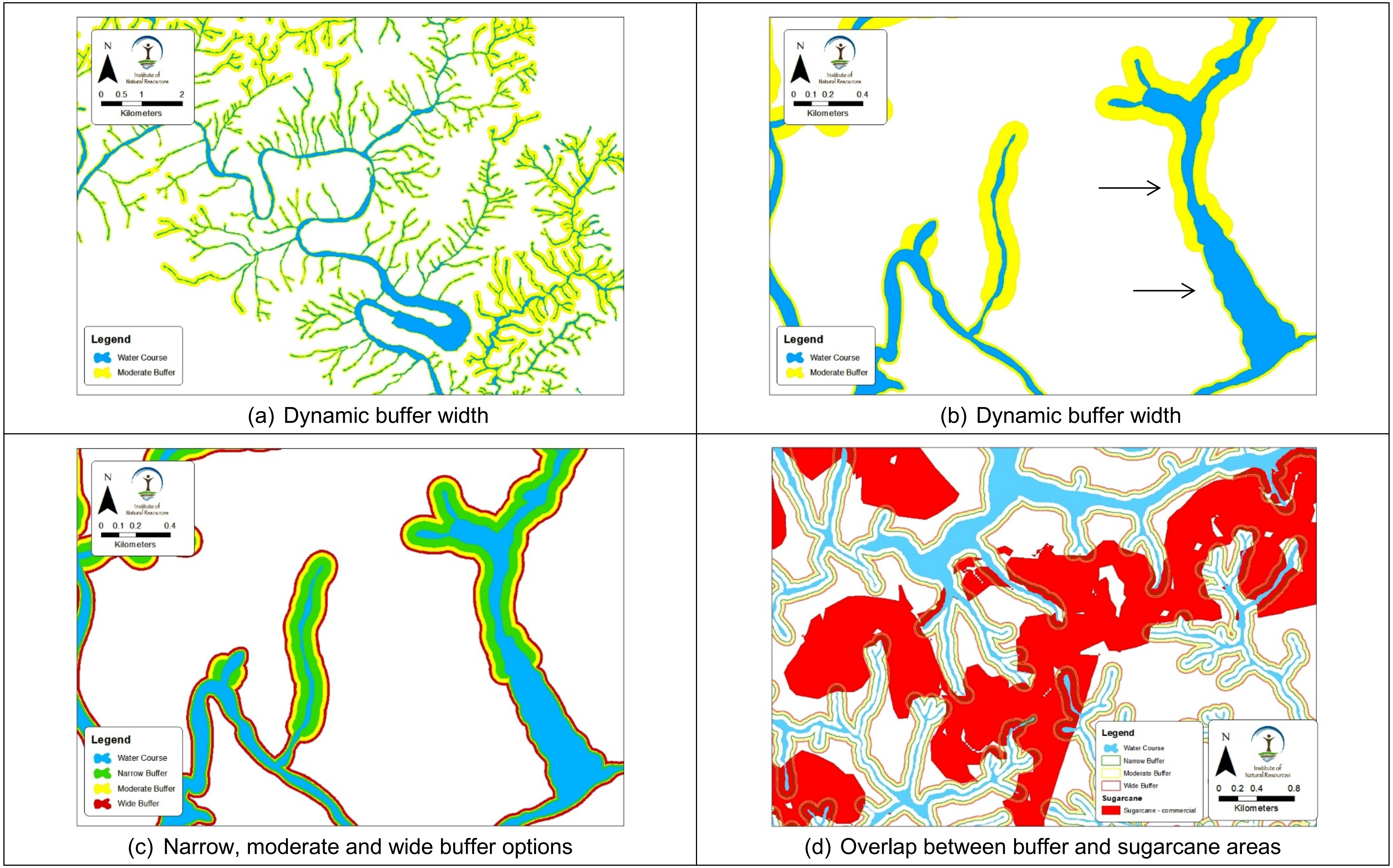


Figure 8: Schematic description of the proposed buffer delineation approach.

To illustrate the buffer delineation approach, Figure 9 shows, spatially, the application of the approach to quaternary catchment U20G (Midlands North). Maps (a) and (b) show the moderate buffer option and illustrate the dynamic nature of the buffer width. Map (c) illustrates the difference between the narrow, moderate and wide buffer options. Map (d) shows both the buffer areas and the sugarcane cultivation areas and illustrates the overlap between the two along some parts of the watercourse.



(a) Dynamic buffer width

(b) Dynamic buffer width

(c) Narrow, moderate and wide buffer options

(d) Overlap between buffer and sugarcane areas

Figure 9: Maps illustrating the buffer delineation approach (study catchment within U20G, Midlands North).

Additional considerations:
The proposed buffer delineation approach sets out the conceptual thinking and broad steps as a guideline to determining appropriate watercourse buffers within the sugarcane landscape that takes into account hillslope characteristics of the landscape. The approach is based on best available science and should be enhanced through further application and empirical studies of buffer implementation across landscape characteristics to refine the buffer range specified in the delineation approach; and 'test' the practicalities of the approach. Ongoing research, practical application and changes in policy mean the proposed approach may need to be revised over time.

While a dynamic buffer width approach has conceptual appeal in optimizing buffer width against landscape characteristics and land-use management practices, the approach poses some challenges in terms distributional effects and practical implementation.

- There are farm-level distributional implications of adopting a dynamic width buffer approach. The proportion of sugarcane area converted to buffer area will vary by farm area based on the hillslope classes present and the extent of watercourse. For example, those farms with a dominance of hillslope Class 2 – Shallow Responsive are subject to wider watercourse buffers than those farms with a dominance of hillslope Class 3 – Recharge to Groundwater. Some land owners will 'lose' a greater proportion of sugarcane cultivation area than others; overall, however, a dynamic approach facilitates the optimization of buffer width. Distributional effects are not entirely avoided in applying a fixed (uniform) width approach, as the buffer area requirement still varies across farms with the extent of watercourse and the degree to which existing sugarcane is cultivated in the watercourse and buffer area.
- From a regulatory perspective, it may be simpler to administer a uniform buffer width approach; however an up-to-date land-use (farm) plan and regular use of the SUSFARMS® Progress Tracker (or similar record keeping) could facilitate compliance monitoring.

For watercourse buffers to function effectively they must be well maintained. However, these areas are often vulnerable to alien invasive plant infestation, waste dumping and sand mining. Poorly maintained buffer areas may be more detrimental to the watercourse than well managed sugarcane cultivation. Buffer implementation and buffer width delineation should take into consideration these aspects at the local scale.

Narrow buffers are more vulnerable to edge effects. The narrower the watercourse buffer, the greater the perimeter to area ratio (Hansen et al., 2010). A larger buffer perimeter relative to buffer habitat area may introduce problems associated with edge effects. The most common being alien plant and weed invasion and their subsequent proliferation. While the width of the watercourse buffer is an important factor influencing its functioning and effectiveness, the continuity of the buffer along the watercourse is also important. Watercourse buffers that are heavily fragmented can compromise their overall effectiveness, particularly from the perspective of supporting / increasing biodiversity.

5. CASE STUDY APPLICATION

The proposed watercourse buffer delineation approach was applied to a case study catchment in the Midlands North sugarcane production area to investigate the costs and benefits of establishing the guideline buffer widths. Spatial analysis was used to establish the extent of sugarcane area that would be converted to buffer area with various scenarios of buffer implementation. Gross margin analysis was used to value the associated annual cost the grower. Buffer establishment and maintenance costs were also considered. Hydrological modelling and analysis was adopted as a means to quantify the hydrological response of the system to buffer establishment as the basis of the potential downstream social benefits. The differences between the scenarios relative to the baseline (and to each other) are of primary interest in evaluating the effects of changing buffer widths. This section reports the case study results. The findings are specific to the case study area as the buffer widths have been determined based on the hillslope characteristics of the case study area and the hydrological response of the system is specific to the physical characteristics of the case study area (e.g. type of native vegetation, soils).

5.1. Study area

5.1.1. Quaternary catchment U20G, Midlands North

Quaternary catchment U20G is located in the uMgungundlovu District Municipality (UMDM), KwaZulu-Natal within the Mvoti to Umzimkulu Water Management Area. The quaternary falls within the Midlands (North) sugarcane production area, near the Noodsberg and Dalton sugarcane mills, Figure 10.

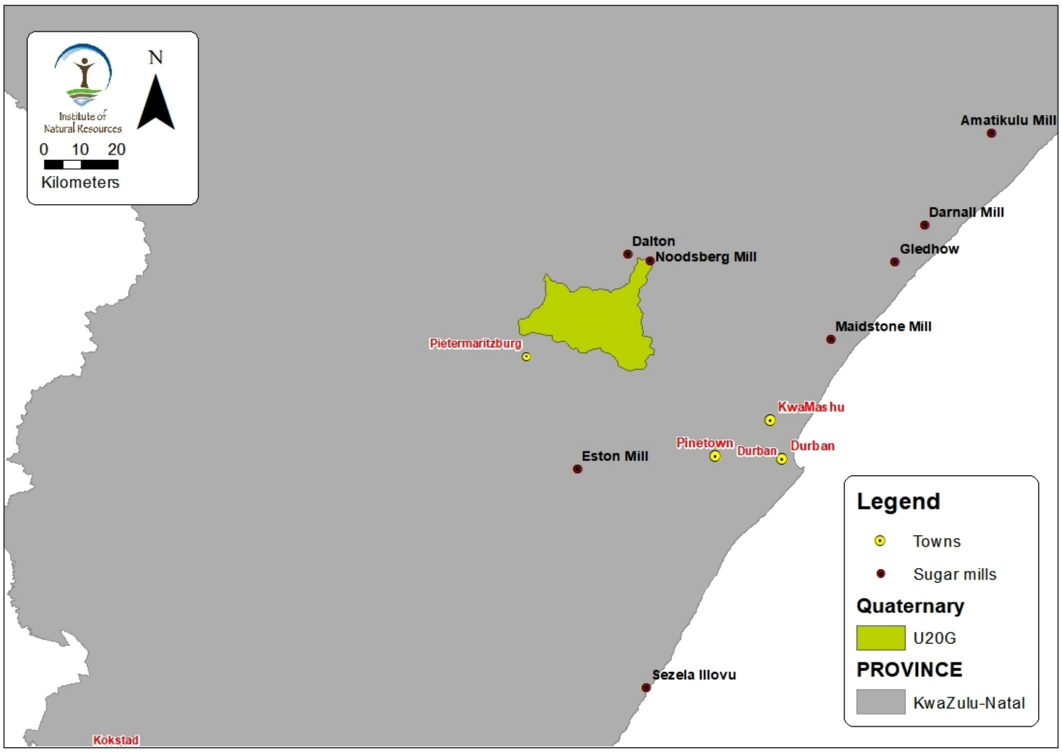


Figure 10: Location of quaternary catchment U20G, Midlands North.

Rainfall is highly variable across the quaternary, as a result of changing elevation. The average annual precipitation varies between 800-1000 mm (Schulze, 2007). The average annual evaporation is between 1600-1750 mm, which exceeds precipitation. This suggests that the region is a water scarce area. Temperature also varies temporally and spatially. Winter months are drier and colder with minimum figures of between 3-9°C, whilst summers are hot and humid with maximum temperatures reaching between 25-29°C. The underlying geology is made up of a number of different materials, i.e. shale, tillite, Natal Group arenite and Gneiss.

The broad land-uses within the quaternary are (not limited to); commercial sugarcane (approximately 25%) and commercial plantations (approximately 11%), other transformed areas make up another 25%, Table 8, Figure 11. The uMngeni River flows North West to South East through the catchment and is the main water supply for the activities in the area. The uMngeni River system is a key water resource in the KZN province, stretching 232 km from its source in the Drakensburg (a strategic water source area) to the Indian Ocean (Blue Lagoon – eThekwini). There are a number of water supply dams along the River which essentially services the greater Pietermaritzburg, eThekwini and surrounding areas. Albert Falls Dam, just upstream of U20G, is linked to Nagel Dam, which falls within U20G downstream of the sugarcane production areas, via the uMngeni River. Land-cover further downstream of U20G consists of large amounts of dense bushland, grassland and forest with built up and low density settlements. Rural subsistence agriculture is also common.

Table 8: Land types and percent cover of quaternary catchment U20G

Land type	% Cover (U20G)
Sugarcane (commercial)	24.64
Sugarcane (emerging)	0.00
Plantations	10.56
Natural	38.77
Rivers & Wetlands	0.55
Dams	0.88
Transformed (other)	24.59

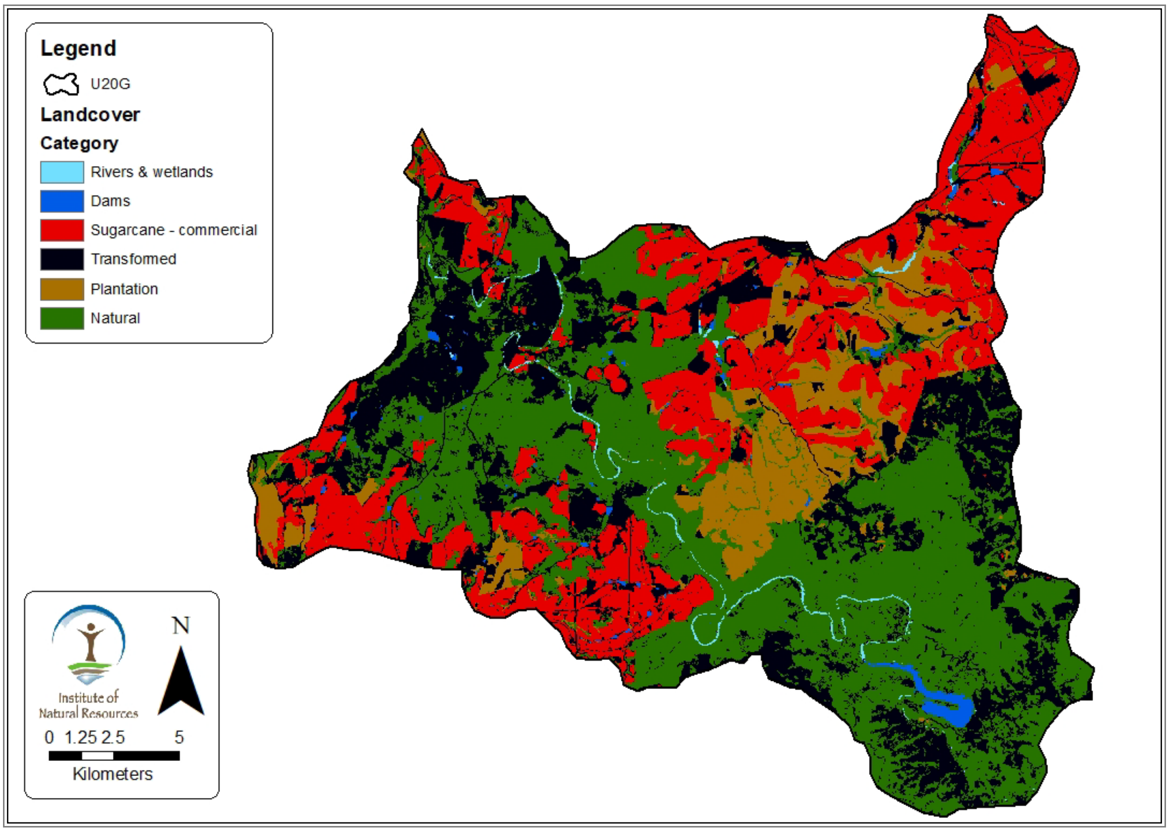


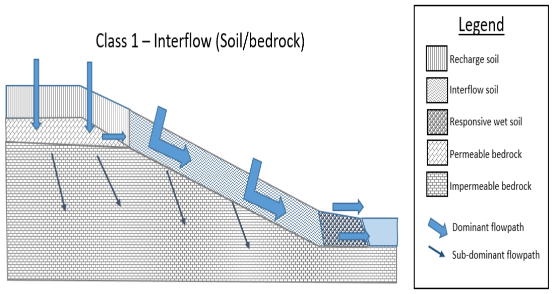
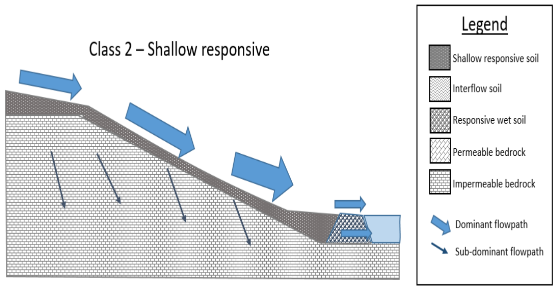
Figure 11: Land types of quaternary catchment U20G.

5.1.2. Hydropedology of quaternary catchment U20G

A hydropedological interpretation of regional soil information (land type data) was undertaken by Johan van Tol (University of the Free State) to characterise the hydropedological behaviour of dominant hillslopes in the study catchment (U20G) and associated sugarcane production area (Midlands North). Hydropedology is the relatively new, interdisciplinary research field that focuses on the interactive relationship between soils and water. Hydropedological studies aim to characterise hydrological properties and processes, such as water flowpaths, residence times and groundwater/surface water interactions, based on the interpretation of soil properties and their spatial distribution (Van Tol, 2018). These characterisations can form an integral part of water resource management, including watercourse protection and management.

Based on numerous years of data collection and analysis, four broad hydropedological soil types have been identified; recharge, interflow, responsive and stagnating soils (each category can then be broken down further based on depth, etc., Van Tol, 2018). These soil types have formed the basis of the hydropedological classification system for South Africa (Van Tol *et al.,* 2013). Hillslopes are fundamentally important in understanding and simulating hydrological processes and can be used to determine a catchment's hydrological response. Four hillslope response types were identified in quaternary catchment U20G, Table 9. The recharge to wetland (Class 4) is the dominant hillslope covering 59% of the area, sub-dominated by shallow responsive (Class 2) hillslopes covering 19% of the area, Figure 12. This pattern is the same for the greater Midlands sugar production area, Table 10.

Table 9: Hillslope response classes of quaternary catchment U20G (Van Tol, 2018)

Hillslope	Key Attributes	Hillslope section
Class 1: Interflow (soil/ bedrock)	• Dominance of interflow soils *above* saturated responsive soils (wetlands) • Relatively impermeable bedrock control redistribution of water	
Class 2: Shallow responsive	• Dominated by shallow responsive soils, which occupies more than 50% of the hillslope • Typical high peak (overland) flow due to small holding capacity • Small baseflow component	

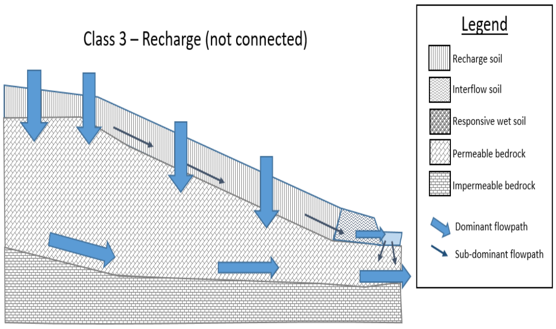
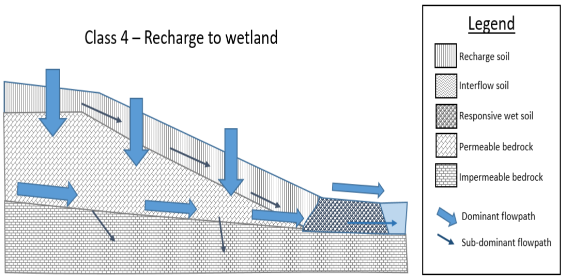
Hillslope	Key Attributes	Hillslope section
Class 3: Recharge (not connected)	• Bedrock permeable – dominant groundwater recharge • No contribution to streamflow (groundwater not connected) • Infiltration and vertical redistribution rate (on hillslope) is higher than precipitation rate	
Class 4: Recharge to wetland	• Recharge soils dominant (crest and wetland) • Contribution to stream via fractured bedrock • Waterlogged soils near stream limits further infiltration • Stable baseflow component	

Table 10: Areas and coverage of the various hillslope classes of quaternary catchment U20G and the Midlands sugarcane production area

	U20G		Midlands	
Hillslope Class	**Area (ha)**	**Coverage (%)**	**Area (ha)**	**Coverage (%)**
Class 1: Interflow	7 380	15	53 288	14
Class 2: Shallow responsive	9 227	19	130 768	33
Class 3: Recharge to groundwater	3 548	7	3 585	1
Class 4: Recharge to wetland	28 636	59	202 610	52

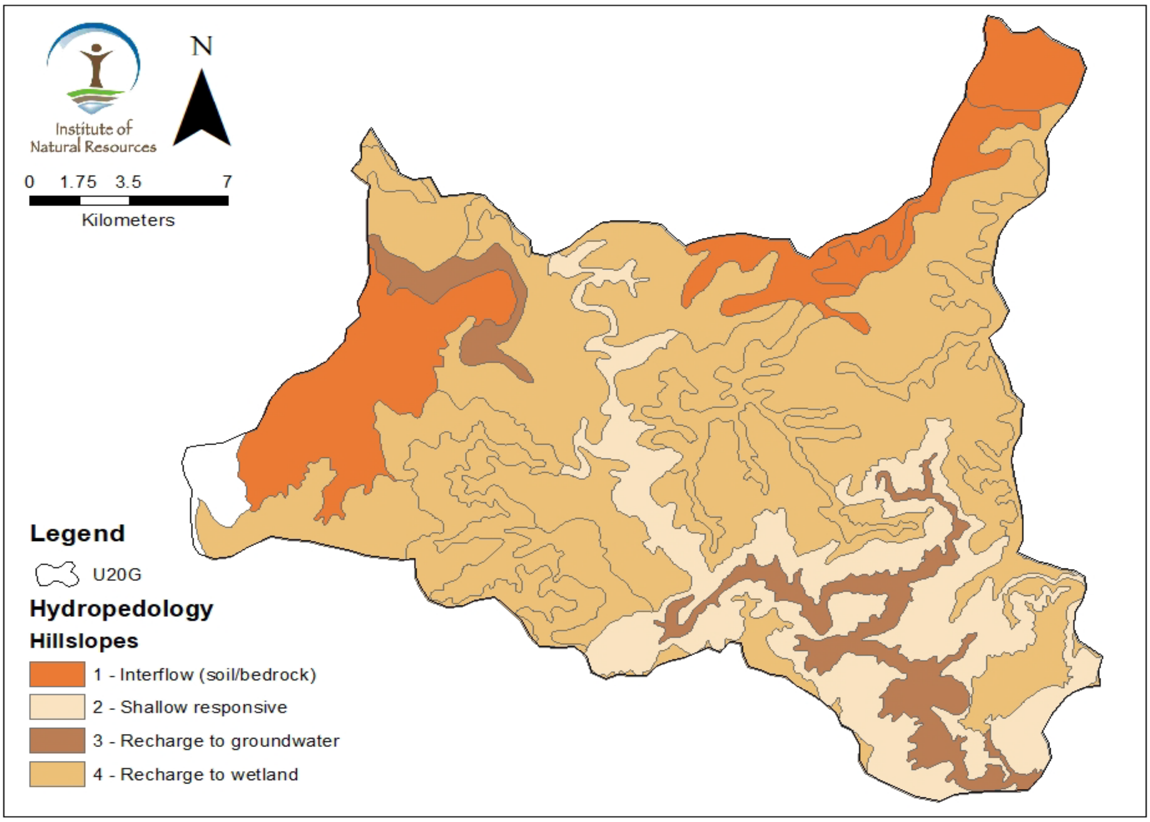


Figure 12: Hydropedological hillslopes of U20G (Van Tol, 2018).

5.1.3. Simulation boundary

Due to the location of various flow inputs to the catchment, and to exclude a large water supply dam (Nagle Dam) from the analysis, the case study catchment was modified from the quaternary catchment U20G (Midlands North), Figure 13 and Table 11. The results presented in this section relate specifically to the simulation catchment.

Table 11: Areas of the case study (simulation) catchment

Description	Areas
Area of simulation catchment (ha)	41 842
Area of sugarcane in simulation catchment (ha)	11 291
Proportion of simulation catchment under sugarcane (%)	27

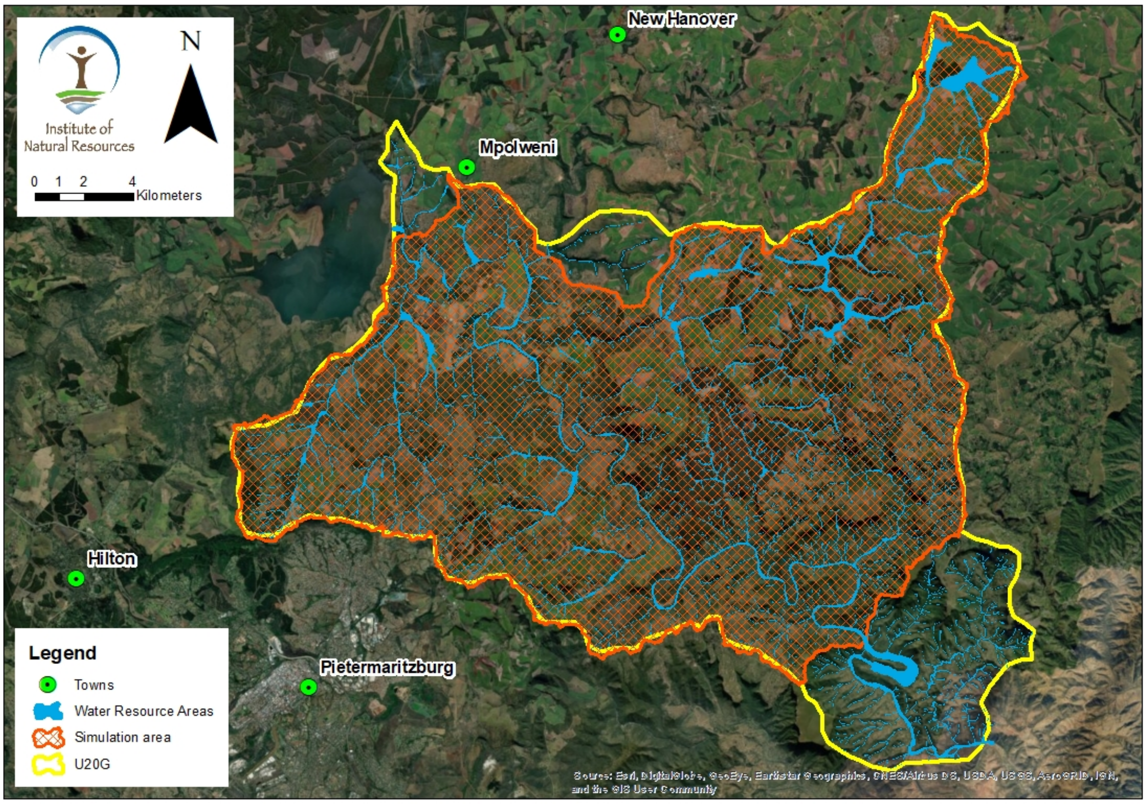


Figure 13: Map of the study area showing the simulation catchment and the boundary of quaternary catchment U20G (Midlands North).

5.2. Buffer delineation and scenarios

The buffer delineation approach was applied to the study catchment to delineate the buffers for evaluation, based on the hillslope classes present in the study catchment[14]. Given that the assessment was undertaken at a quaternary catchment scale (and not at the farm scale), the buffer widths were applied according to the hillslope class without any adjustment for the local scale threat context. However, the 'narrow' and 'wide' buffer options were explored through a scenario analysis.

Several scenarios were generated to investigate different buffer width options. The first scenario – the baseline – simulated the current state (no buffer establishment or removal of sugarcane from watercourse). The next four scenarios were related to watercourse protection measures, namely removal of sugarcane from the watercourse without any additional buffer establishment (scenario 2) and three scenarios of buffer establishment (scenarios 3-5),

[14] Given that the assessment was undertaken at a quaternary catchment scale (and not at the farm scale), the buffer widths were applied according to the hillslope class without any adjustment for local scale threat context. However, the 'narrow' and 'wide' buffer options were explored through a scenario analysis.

Table 12. Each watercourse protection scenario is cumulative (i.e. scenario 4 adds to scenario 2 and 3. Each scenario was applied to the sugarcane cultivation areas throughout the simulation boundary (i.e. the simulation reflects the establishment of watercourse buffers within the sugarcane cultivation areas of the study catchment only).

Table 12: Overview of case study scenarios

Scenario	Description
Scenario 1 **(BASE)**	**Baseline**: Current state
Scenario 2 **(INT)**	**Watercourse only:** Sugarcane removed from watercourse (wetland / riparian area), no buffer establishment
Scenario 3 **(LBW)**	**Narrow buffer:** Sugarcane removed from watercourse (wetland / riparian area), the narrow buffer width option for each hillslope class applied
Scenario 4 **(MWB)**	**Moderate buffer:** Sugarcane removed from watercourse (wetland / riparian area), moderate buffer width option for each hillslope class applied
Scenario 5 **(HWB)**	**Wide buffer:** Sugarcane removed from watercourse (wetland / riparian area), wide buffer width option for each hillslope class applied

A note on the buffer widths applied for each scenario

As per the proposed buffer delineation approach, the width of the buffer varies across the catchment in relation to the dominant hillslope class. Each hillslope class is associated with its own 'moderate buffer width' as well as a 'narrow' and a 'wide' buffer option. In simulating the different scenarios, the relevant buffer width (narrow, moderate, wide) was selected for each of the hillslope classes, meaning that the width of the buffer still varies across the catchment within each of the scenarios. For example, where hillslope class 4 occurs within the catchment, the width applied under the narrow scenario is 15 m; for hillslope class 2, the width applied under the narrow scenario is 50 m, and so on. Implementing the 'narrow' scenario means that the 'narrow' buffer width option for each hillslope class is selected where that hillslope class occurs. Implementing the moderate width buffer scenario means that the 'moderate' buffer width option for each hillslope class is selected and so on.

The *average* buffer widths across the study catchment under each scenario are reported in Table 13. The average buffer widths for this study catchment reflect the proportions of the various hillslopes types within the catchment.

Table 13: Average width of the buffers applied to the case study catchment under the various simulation scenarios and the resulting area of land-use change

	Width range (m)	Average width (m) for study catchment	Land-use change
Scenario	m	m	ha
1 – Baseline	0	0	
2 – Watercourse only	0	0	438
3 – Narrow buffer	10-50	20	1 518
4 – Moderate buffer	15-75	36	2 174
5 – Wide buffer	30-90	57	2 618

5.3. Discharge, sediment and nutrient fluxes

The discharge, sediment and nutrient levels at the outflow of the case study catchment under the various watercourse protection scenarios are summarized below. The baseline (BASE) scenario represents the current land-use in the study catchment. The scenarios represent the removal of sugarcane from the watercourse (for those areas where sugarcane is grown in the watercourse) and three scenarios of increasing buffer width. The simulation represents conditions for well-managed sugarcane cultivation and well-managed buffer areas.

Tables 14 to 17 and Figures 14 to 17 report the average annual outputs across all years of the simulation (1971-2018). 'Change from baseline' reflects the difference between the baseline level and the scenario level and 'Between scenarios' reflects the difference in level between each of the consecutive scenarios (e.g. between scenario 2 and 3, 3 and 4, etc.). The outputs are for the outflow node of the study catchment and reflect changes in discharge, sediments and nutrients as a result of 'converting' sugarcane to native vegetation under the different buffer scenarios. The proportion of the simulation catchment under sugarcane is 27%, and the scenarios reflect a 1 to 6% change in land-use across the catchment.

Table 14: Average annual discharge at the outflow node of the study catchment and increase in discharge under the various scenarios, 1971-2018

Scenario	Average annual discharge			
	Discharge Mm^3/year	Change from baseline Mm^3/year	Change from baseline %	Between scenarios Mm^3/year
1 – Baseline	197.03			
2 – Watercourse only	197.75	0.73	0.4%	0.73
3 – Narrow buffer	198.72	1.70	0.9%	0.97
4 – Moderate buffer	199.31	2.28	1.2%	0.59
5 – Wide buffer	199.71	2.68	1.4%	0.40

Note: Mm^3 is million m^3.

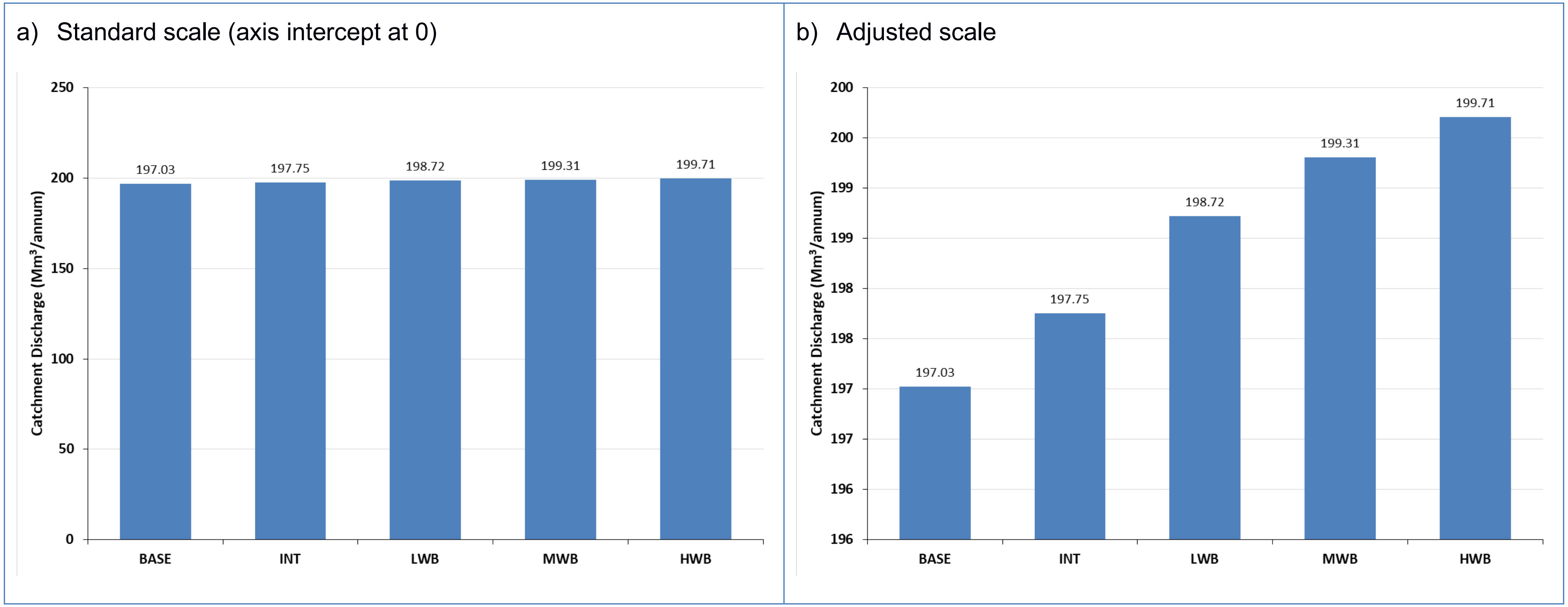


Figure 14: Average annual discharge at the outflow node of the study catchment, 1971-2018, all scenarios.

Note: Chart (a) standard axis and (b) adjusted axis.
BASE – current state; INT – sugarcane removed from watercourse; LWB – sugarcane removed from watercourse and narrow buffer width applied; MWB – sugarcane removed from watercourse and moderate buffer width applied; HWB – sugarcane removed from watercourse and wide buffer width applied.

Table 15: Average annual sediment load at the outflow node of the study catchment and increase in discharge under the various scenarios, 1971-2018

Scenario	Average annual sediment load						
	Load	Change from baseline				Between scenarios	
	Ton/year	Ton/year		%		Ton/year	
1 – Baseline	66 576						
2 – Watercourse only	62 815	-	3 761	-	5.6	-	3 761
3 – Narrow buffer	47 464	-	19 112	-	28.7	-	15 351
4 – Moderate buffer	45 003	-	21 573	-	32.4	-	2 461
5 – Wide buffer	44 753	-	21 823	-	32.8	-	250

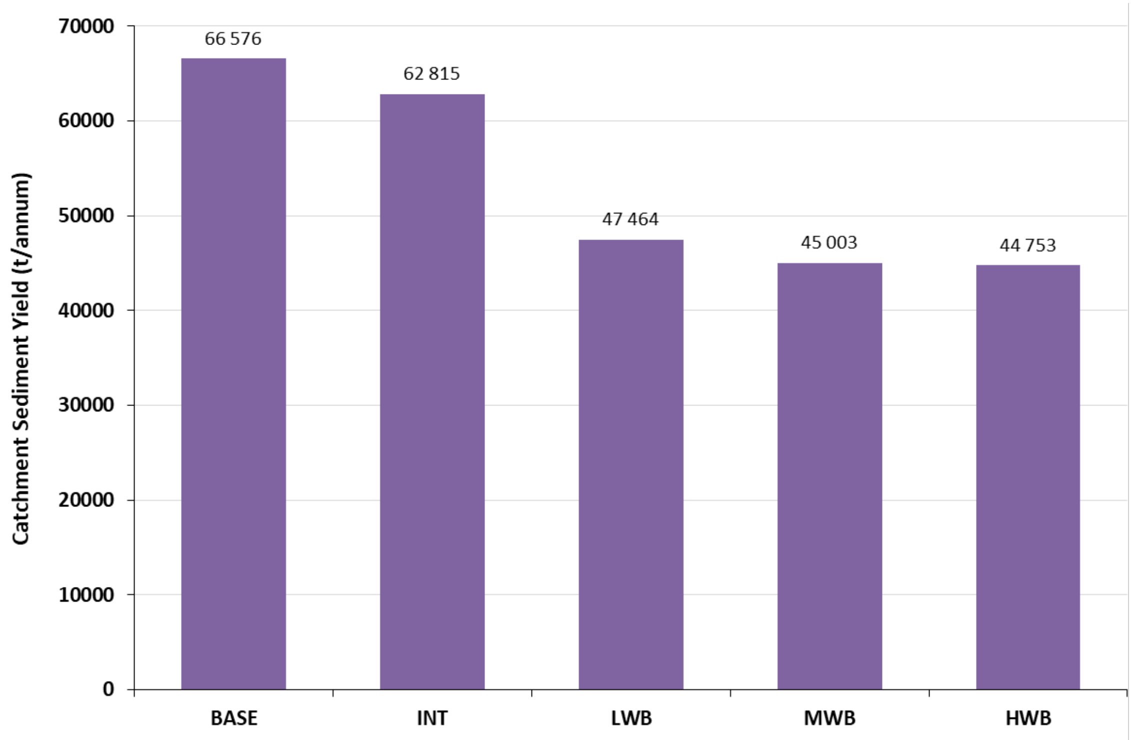


Figure 15: Average annual sediment load, outflow node of the study catchment, 1971-2018.

Note: BASE – current state; INT – sugarcane removed from watercourse; LWB – sugarcane removed from watercourse and narrow buffer width applied; MWB – sugarcane removed from watercourse and moderate buffer width applied; HWB – sugarcane removed from watercourse and wide buffer width applied.

Table 16: Average annual nitrate load at the outflow node of the study catchment and increase in discharge under the various scenarios, 1971-2018

Scenario	Average annual nitrate ($N0_3$) load			
	Load	**Change from baseline**		**Between scenarios**
	kg/year	kg/year	% baseline	kg/year
1 – Baseline	14 688	-		
2 – Watercourse only	13 778	- 910	- 6.2	- 910
3 – Narrow buffer	10 087	- 4 601	- 31.3	- 3 691
4 – Moderate buffer	9 854	- 4 834	- 32.9	- 233
5 – Wide buffer	9 802	- 4 886	- 33.3	- 51

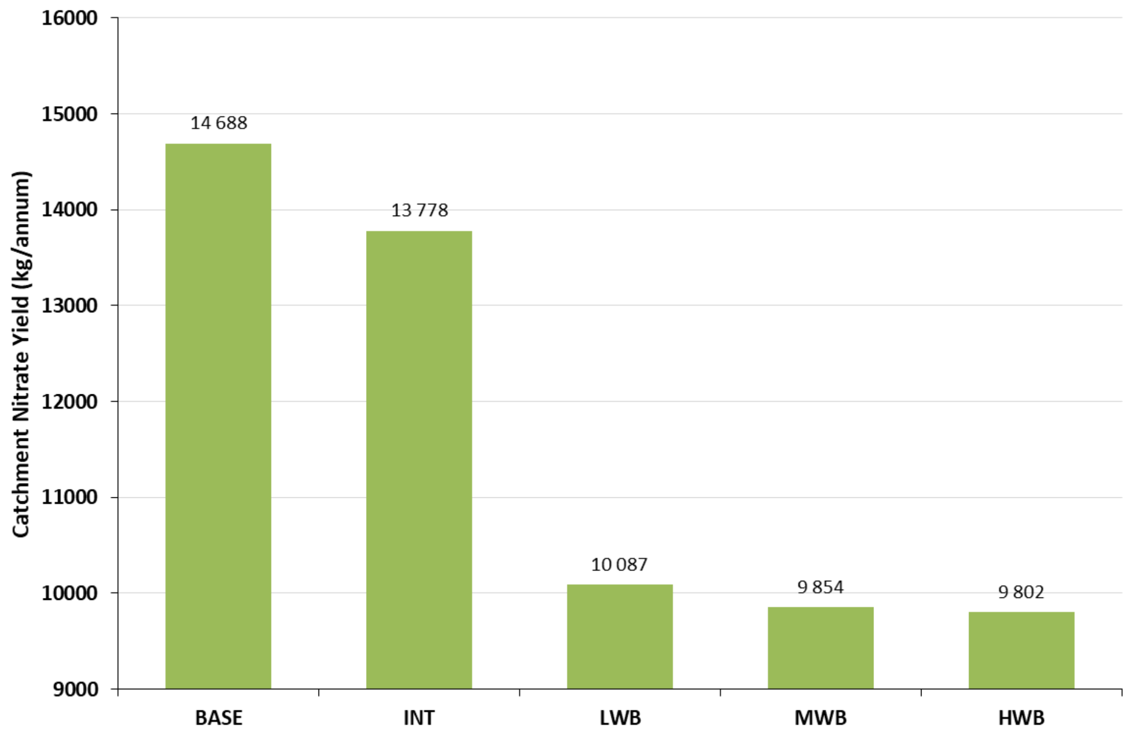


Figure 16: Average annual nitrate load, outflow node of the study catchment, 1971-2018.

Note: BASE – current state; INT – sugarcane removed from watercourse; LWB – sugarcane removed from watercourse and narrow buffer width applied; MWB – sugarcane removed from watercourse and moderate buffer width applied; HWB – sugarcane removed from watercourse and wide buffer width applied.

Table 17: Average annual phosphorous load at the outflow node of the study catchment and increase in discharge under the various scenarios, 1971-2018

Scenario	Average annual phosphorous (Total P) load			
	Load	Change from baseline		Between scenarios
	kg/year	kg/year	% baseline	kg/year
1 – Baseline	122 333			
2 – Watercourse only	114 754	- 7 579	- 6.2	- 7 579
3 – Narrow buffer	84 014	- 38 320	- 31.3	- 30 740
4 – Moderate buffer	82 069	- 40 264	- 32.9	- 1 944
5 – Wide buffer	81 641	- 40 693	- 33.3	- 429

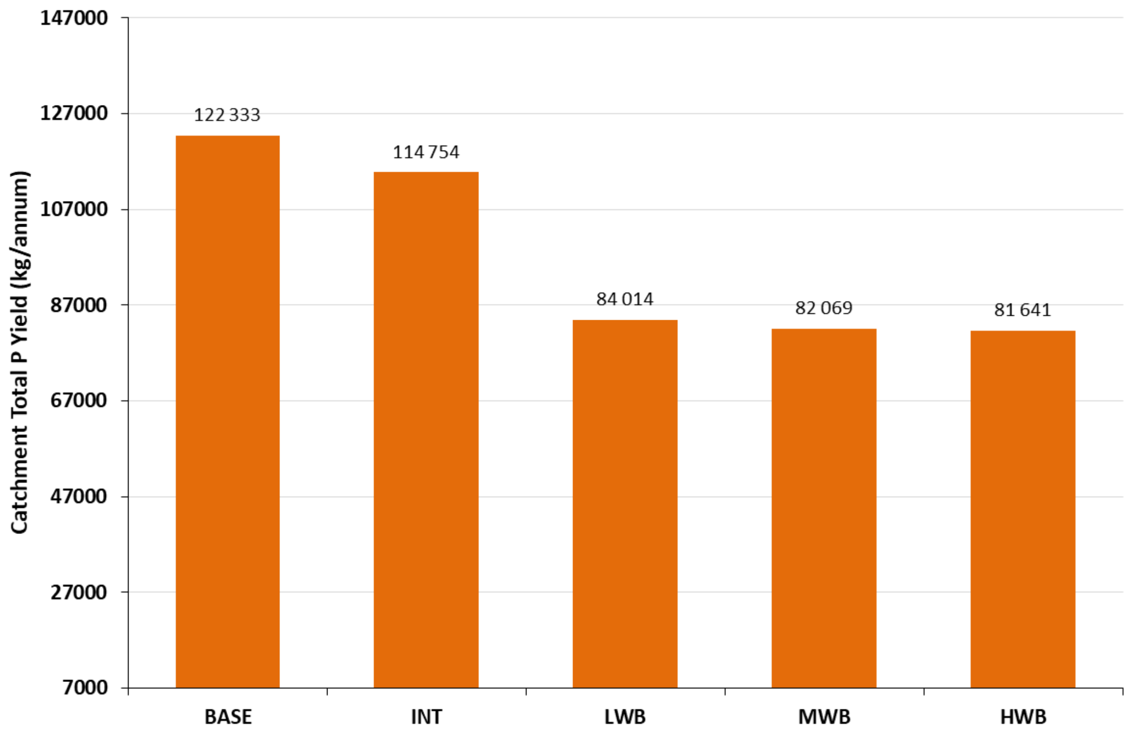


Figure 17: Average annual phosphorous load, outflow node of the study catchment, 1971-2018.

Note: BASE – current state; INT –sugarcane removed from watercourse; LWB – sugarcane removed from watercourse and narrow buffer width applied; MWB – sugarcane removed from watercourse and moderate buffer width applied; HWB – sugarcane removed from watercourse and wide buffer width applied.

The model simulation results indicate the following trends in discharge across the scenarios:

- The width of the buffer influences the discharge (water yield) at the outflow of the catchment. The change in discharge is relatively small, which is consistent with the relatively small change in land-use (1 to 6%).
- There is an overall trend of higher discharge with increasing buffer width.
- The largest *additional* gain in discharge occurs with the implementation of the narrow buffer option, which corresponds to the narrow buffer scenario having the largest *additional* area converted from sugarcane to buffer.
- As the buffer width increases, discharge continues to increase, but at a declining *additional* gain.

The model simulation results indicate the following trends in sediment and nutrient loads across the scenarios:

- The width of the buffer influences the sediment and nutrient loads to the downstream system.
- There is an overall trend of lower sediment and nutrient loads at the catchment outflow with increasing buffer width.
- The greatest *additional* reduction occurs with the implementation of the narrow buffer option, which corresponds to the narrow buffer scenario having the largest *additional* area converted from sugarcane to buffer.
- As the buffer width increases, sediment and nutrient loads are further reduced, but at a declining *additional* reduction.
- The results indicate a relatively small reduction in nutrient and sediment loads with removal of sugarcane from the watercourse (5.6 to 6.2%). This reduction increases significantly with implementation of a watercourse buffer (29 to 33%), but with comparatively small variations between the three buffer options.

The results of the catchment simulation indicate that the width of a watercourse buffer, as determined by hillslope characteristics, influences water, nutrient and sediment outputs. Previous local studies (e.g. Talanda et al. 2007; Schulze and Schutte, 2015), which have not explicitly considered hillslope characteristics, have shown that the impact of sugarcane cultivation on streamflows varies, largely depending on the baseline land-cover it replaces: where sugarcane replaces lower biomass grasslands discharge reductions are greater (Schulze and Schutte, 2015). In this catchment simulation, grassland replaces sugarcane (in the buffer area) and the results show that discharge increases from the baseline as the buffer width increases.

Trends in sediment and nutrient levels show a reduction in sediment and nutrient loads to the downstream system with increasing buffer width as a result of the trapping function of the buffer. Local studies investigating nutrient and sediment outputs under different management practices have demonstrated the ability of buffers to trap nutrients and sediments, and have shown that other in-field management practices (e.g. contours and fertilizer management) are also effective options (Kollongei et al., 2014; Lorentz et al., 2012). For poorly managed watercourse and buffer areas, the sediment and nutrient reduction efficiency of the buffer will be reduced.

Additional considerations

The hydrological model applied in the case study assessment can be considered an important preliminary foundation for conceptualising sub-surface flow and buffer interactions and simulating the hydrological response of the watercourse to the establishment of watercourse buffers. Primary empirical studies are needed to further develop and strengthen the hydrological (SWAT) model in effectively reflecting hillslope-buffer-watercourse interactions including further examination of above- and below surface buffer attenuation processes.

- In this study, a comprehensive sediment calibration was constrained by limited observed long-term sediment load data for both the study catchment and upstream against which to calibrate the model. The model would be enhanced by a comprehensive sediment calibration supported by primary data collection.
- In future work, the hydrological model for the study catchment could be further modified to refine the input parameters and buffer simulations, and then extended for use in comparing a range of land-uses and management practices under a wider variety of scenarios (e.g. those associated with climate change effects). Refinements would address:
    - Modifying the SWAT model parameters to better reflect local conditions and practices, including a comprehensive sediment calibration and further investigation of the model parameters related to the 'filter' functions;
    - Empirical plot level studies of the sediment and nutrient reduction efficiencies of buffer areas (and width variations) and the effect of buffer condition on these efficiencies.
- Additional directions for future research include:
    - Investigating stream-flow regulation effects – peak and baseflows under different buffer width scenarios;
    - Investigating BMPs for managing a buffer to optimize trapping efficiency;

- Investigating options for modelling a wider range of land-uses as well as different management practices and land-covers within the buffer area.

5.4. Costs and benefit assessment

The potential costs and benefits of watercourse buffers are diverse and site specific, related to local conditions and objectives. Identifying and measuring the value (monetary) of the associated costs and benefits relies on the quantification of the differences between alternatives measured in biophysical terms. As a point of departure, the case study focused on quantifying the hydrological response – in terms of water, nutrient and sediment fluxes – of the study catchment to the establishment of watercourse buffers in the sugarcane cultivation areas.

The proposed buffer delineation approach was applied to a study catchment (within quaternary catchment U20G, Midlands North). The results were used to establish:

(i) The area (ha) of sugarcane that would be converted to buffer area under the different scenarios and the corresponding gain in native vegetation, and

(ii) The discharge, sediment and nutrient levels at the outflow of the study catchment under each of the scenarios.

These results were used as the basis for considering the costs and benefits of establishing watercourse buffers within the study catchment. The area of sugarcane converted to buffer was used to estimate the costs of implementing the different buffer scenarios in terms of the income forgone from the permanent loss of cultivation area and the costs associated with establishing and maintaining the buffer areas, and as an indicator of the potential ecosystem services and benefits associated with a gain in native vegetation in the landscape. The discharge, nutrient and sediment flux estimates were used as a basis for considering the downstream social benefits of watercourse buffer establishment. The differences between the scenarios relative to the baseline (and to each other) are of primary interest in considering the effects of different buffer widths.

5.4.1. Sugarcane to buffer area conversion

Establishing watercourse buffers within sugarcane cultivation areas requires that those portions of sugarcane area that overlap with the watercourse and proposed buffer areas are converted to native (natural) vegetation. Table 18 summarises the change in sugarcane area across the study catchment associated with implementing the watercourse protection scenarios. 'Area converted' refers to the area of sugarcane converted to buffer area (natural vegetation) under each scenario (i.e. the difference in sugarcane area between the baseline and the scenario state). 'Between scenarios' refers to the additional area converted between each of the scenarios.

The results indicate that replacing sugarcane in the watercourse with native vegetation constitutes a 4% reduction in sugarcane area, while implementing the wide buffer option results in a 23% reduction in sugarcane area. The 'between scenarios' analysis shows that the largest additional area converted to buffer occurs with implementation of the narrow buffer option; the *additional* area converted to buffer then declines with increasing buffer width scenario (scenarios 3 to 5).

Table 18: Area of sugarcane under watercourse protection scenarios, study catchment, Midlands North

	Sugarcane Area				
Scenario	**Total**	**Area converted**		**Between scenarios**	
	Ha	Ha	% baseline	Ha	% baseline
1 – Baseline	11 291	-	-	-	-
2 – Watercourse only	10 853	438	4	438	4
3 – Narrow buffer	9 772	1 518	13	1 081	9
4 – Moderate buffer	9 116	2 174	19	656	6
5 – Wide buffer	8 672	2 618	23	444	4

Note: Area values are rounded to the nearest hectare.

Additional considerations:

- The area calculations are based on the available land-cover / land-use data, modified from the latest provincial EKZNW 2008 land-cover layer. The area changes are illustrative of the relative differences between scenarios based on the baseline land-cover information.
- Other land-uses within the catchment have not been considered as the objective was to isolate the effects of watercourse buffers in sugarcane cultivation area. However, it is recognized that many sugarcane growers have a mix of land-uses (e.g. sugarcane and timber), and in practice a watercourse buffer would ideally need to extend across different land-uses.

5.4.2. Watercourse buffer costs

There are two primary costs associated with the establishment of watercourse buffers: (a) the income forgone from the permanent loss of sugarcane area as a result of the conversion of cultivated areas into buffer area, and (b) the expense associated with the removal of sugarcane and the re-establishment of native vegetation. There is an additional annual cost associated with maintaining the buffer area. Under current governance arrangements, these costs are incurred by the sugarcane grower / land-owner.

a) Income forgone from the permanent loss of sugarcane area

As an indicator of the income forgone by growers from the conversion of sugarcane cultivation area to buffer area within the study catchment, the area of sugarcane converted to buffer, under each of the scenarios, was multiplied by the annualised gross margin of a hectare of sugarcane. The annualised gross margin per hectare of sugarcane grown in the Midlands North region was supplied by SACGA, and estimated based on averages for the Midlands area (e.g. yield and quality) and on certain assumptions (e.g. crop harvested at maturity). The estimated value of income forgone is an indication across the study catchment, actual values are farm specific.

Based on an annualised gross margin of R13 027.84 / ha, the annual income forgone across the study catchment, Table 19, ranges from R5.7 million per year (4% of baseline production value) for removing all sugarcane cultivation from the watercourse (no buffer area established) to R34.1 million (23% of baseline production value) under the wide buffer width scenario.

Table 19: Estimated sugarcane cultivation income forgone, under various scenarios of watercourse protection

Annualised gross margin: R13 027.84 / ha					
	Production value	**Area converted**	**Income forgone**		
Scenario			**By scenario**		**Between scenarios**
	R / year	Ha	R / year	% baseline	R / year
1 – Baseline	147 097 341	-	-	-	
2 – Watercourse only	141 397 140	438	5 700 201	4	5 700 201
3 – Narrow buffer	127 312 482	1 518	19 784 859	13	14 084 658
4 – Moderate buffer	118 762 311	2 174	28 335 031	19	8 550 171
5 – Wide buffer	112 974 432	2 618	34 122 909	23	5 787 878

Note: Minor discrepancies due to rounding.

The annual income forgone is distributed across approximately 73 sugarcane farms within the study catchment[15]; however, farm size and proportion of buffer area, and therefore income forgone per farm, varies. In contextualising the income forgone, it is useful to consider other costs of sugarcane cultivation. For example, based on Industry averages for sugarcane planting costs[16], fertiliser costs of R4462/ha equate to approximately R50 million for the study area. Fertiliser costs associated with ratoon management of R3307/ha, equate to approximately R37 million for the case study area.

Additional considerations:

- A constant gross margin per hectare of sugarcane across the catchment was assumed, however the gross margin was based on production data for the Midlands North area.
- The calculation takes into account that the variable costs associated with cultivating the converted area would no longer be incurred. There is no reduction in overhead costs (fixed costs) with the reduced sugarcane area and the grower would continue to pay rates on the total parcel of land.
- The value of the sugarcane roots has not been included in the calculation. For example for a 1st ratoon stage the value of sugarcane roots is R20 964 / ha, for a 2-4th ratoon stage it's R10 733 / ha, and for a 3-7th ratoon it's R5 496 / ha (SACGA, 2019).
- The income forgone estimates are based on the case where all sugarcane in the recommended buffer area is converted to native vegetation simultaneously. In practice, the conversion could be undertaken incrementally, for example, in line with a replanting programme, building up to the total area converted.
- Potential productive uses of the buffer area (e.g. recreation, livestock fodder, habitat for pest management and/or pollinators) have not been included at this stage, and require further investigation to determine their potential to benefit the grower. Current research, feedback from relevant experts and discussions with Industry stakeholders has highlighted both the costs associated with pest damage and pest management within the sector and the potential of increased native vegetation within the sugarcane landscape to contribute to pest regulation through an integrated pest management approach.

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[15] This figure was estimated from a spatial layer of sugarcane farm boundaries (SASA GIS Department, 2018) and is an indicator of the number of sugarcane farms in the catchment based on available data.
[16] SA Canegrowers Cane Planting Costs – Mechanical Land Prep, 2019/2020 season.

b) Buffer establishment and maintenance costs

It is often assumed that buffer areas will be established from ‘retiring’ land from agricultural activities (e.g. Balana et al., 2012). However, this is not always the case, and it is likely some ‘rehabilitation’ activities will be needed, for example to address drainage modifications and alien plant infestations. This study explored the potential costs of establishing and maintaining watercourse buffer areas.

The costs associated with establishing a watercourse buffer will vary across production areas in relation to the condition of the area and rehabilitation requirements (e.g. stabilising erosion, rehabilitating wetlands), the replacement vegetation required (e.g. grassland vs. forest) and access and terrain. Maintenance costs are largely related to biomass management and alien plant control activities, but may also include the maintenance of any structures (e.g. gabions) related to stream and wetland rehabilitation. Actual buffer establishment and maintenance costs will be specific to individual land parcels.

Original farm costs were sought as an indication of buffer establishment and maintenance costs within the sugarcane landscape. While farmers in the Midlands North region have been involved in buffer establishment and maintenance activities, inputs and costs associated with the activities are not generally recorded as separate cost items, and activities appear to be conducted as needed and when resources are available (Wilkinson, 2019).

As an indication of the potential costs associated with watercourse buffer establishment and maintenance, marginal cost estimates (R/ha) were sourced from similar studies. Grassland rehabilitation and maintenance costs were reported in a study of the uMngeni River Catchment (Jewitt et al., 2015), Table 20. Rehabilitation costs were reported for ‘severely’ and ‘moderately’ degraded grasslands: where

- Severely degraded refers to grassland and woodland with a substantial loss of basal cover and species diversity, with evidence of both gully and sheet erosion being prevalent;
- Moderately degraded refers to grasslands and woodlands, including old lands, which lack the species diversity of pristine land-cover types and a basal cover that is approaching the limits of acceptable change, but which have not degraded to the point of accelerated erosion being evident and invasive alien plant infestations are present but limited (Jewitt et al. 2015).

Maintenance costs were also reported, which reflect the annual maintenance following rehabilitation.

Given that the costs in Jewitt et al. (2015) were estimated for the uMngeni Catchment into which the case study catchment falls, these costs are a suitable indication of potential buffer establishment and management costs. Land preparation, weed control and planting costs for sugarcane cultivation provide a point of comparison for buffer establishment costs which require similar activities (depending on the scale of rehabilitation required), Table 20. The costs associated with the rehabilitation of severely degraded grasslands reported by Jewitt et al. (2015) are relatively similar to sugarcane planting costs, whereas the costs associated with moderately degraded are much less.

Table 20: Grassland rehabilitation cost estimates (uMngeni Catchment) and Sugarcane planting and management costs

Grassland rehabilitation costs[a] (2019 prices)	**R / ha**
Severely degraded	9 659
Moderately degraded	292
Untransformed management / maintenance	25
Restored management / maintenance	185
Sugarcane costs[b] (2018/19 prices)	**R / ha**
Sugarcane planting costs (minimum tillage)	10 333
Land preparation[c]	2 526
Planting	4 050
Weed control	3 757
Verge management	218

Note: [a] Source: Jewitt et al. (2015); [b] Source: SA Canegrowers planting and management cost – general rates 2018/19 season; [c] Includes ploughing, harrowing, and ridging contour structures.

Using these marginal cost estimates, three sets of buffer establishment and maintenance costs were estimated:

- Severe (lower estimate): using grassland rehabilitation cost estimates for severely degraded grasslands (Table 21);
- Severe (upper estimate): using sugarcane planting and maintenance costs as a point of comparison (Table 22);
- Moderate: using grassland rehabilitation cost estimates for moderately degraded grasslands (Table 23).

The estimated buffer establishment costs for the study catchment range from R127 762 (watercourse only scenario) to R764 599 (wide buffer scenario) based on costs to rehabilitate moderately degraded grasslands and R4.2 million (watercourse only scenario) to R25.3 million (wide buffer scenario) based on costs to rehabilitate severely degraded grassland). Maintenance costs range from R81 000 per year (watercourse only scenario) to R485 000 (wide buffer scenario).

Table 21: Estimated buffer establishment and maintenance costs, under various scenarios of watercourse protection, based on severely degraded grassland cost estimates

Severe (lower bound): Establishment cost R9 659/ha; Maintenance cost R185/ha/year			
	Area converted	**Establishment cost**	**Maintenance cost**
Scenario	Ha	R (once off)	R / year
1 – Baseline	-		
2 – Watercourse only	438	4 226 199	80 945
3 – Narrow buffer	1 518	14 663 521	280 852
4 – Moderate buffer	2 174	21 001 660	402 247
5 – Wide buffer	2 618	25 291 995	484 421

Table 22: Estimated buffer establishment and maintenance costs, under various scenarios of watercourse protection, based on sugarcane planting and management cost estimates

Severe (upper bound): Establishment cost R10 333/ha; Maintenance cost R218/ha/year			
	Area converted	**Establishment cost**	**Maintenance cost**
Scenario			
1 – Baseline	-	-	-
2 – Watercourse only	438	4 521 101	95 384
3 – Narrow buffer	1 518	15 686 734	330 950
4 – Moderate buffer	2 174	22 467 145	474 000
5 – Wide buffer	2 618	27 056 857	570 831

Table 23: Estimated buffer establishment and maintenance costs, under various scenarios of watercourse protection, based on moderately degraded grassland cost estimates

Moderate: Establishment cost R292/ha; Maintenance cost R185/ha/year			
	Area converted	**Establishment cost**	**Maintenance cost**
Scenario	Ha	R (once off)	R / year
1 – Baseline	-	-	-
2 – Watercourse only	438	127 762	80 945
3 – Narrow buffer	1 518	443 291	280 852
4 – Moderate buffer	2 174	634 899	402 247
5 – Wide buffer	2 618	764 599	484 421

Additional considerations:

- Under current governance arrangements buffer establishment and maintenance costs accrue largely to the landowner. However, the National Natural Resource Management (NRM) programme (Working for Water and Working for Wetlands) is committed to assisting landowners with the rehabilitation of wetlands[17] and the management of alien invasive plants and options in this regard should be explored.
- Establishment costs are a once-off cost associated with converting sugarcane cultivation to native vegetation and rehabilitating degraded areas. Maintenance costs are incurred annually and reflect the activities required to maintain the condition of the buffer area.
- The buffer establishment and maintenance costs were estimated based on the case where all sugarcane in the recommended buffer area is converted to native vegetation simultaneously. In practice, the conversion could be undertaken incrementally, in line with a replanting programme for example, and the costs of establishment spread over a number of years.
- Key to the ecological benefits of watercourse buffers is that they are well managed. Buffer areas are vulnerable to alien invasive plant infestations, dumping, and sand mining and need to be monitored and maintained.
- Costs associated with developing buffer management plans are not included.
- Potential productive uses of the buffer area (e.g. recreation, livestock fodder/green manure, habitat for pest management and/or pollinators) should be investigated further to determine their potential to benefit the grower.

5.4.3. Hydrological benefits

The results of the hydrological assessment were used to consider the difference in discharge and sediment and nutrient loads at the catchment outlet under the different buffer scenarios. The annual levels under baseline conditions were compared with what they were estimated to be under the different scenarios. This provides an indication of the influence of watercourse buffers (and of different widths) to streamflow and the sediment and nutrient loads entering the downstream system. In the case study, the downstream system is part of the Umgeni Water Supply System. The outflow node of the case study catchment lies just upstream of Nagel Dam on the uMngeni River. The percentage changes in discharge and sediment and nutrient loads can be construed as an estimation of the water supply and water quality amelioration benefits of watercourse buffers (at a quaternary catchment scale). These benefits

[17] The NRM programme has indicated a 50/50 sharing of wetland rehabilitation costs depending on available finances.

are specific to the case study area, as the buffer widths have been determined based on the hillslope characteristics of the case study area and the hydrological response of the system is specific to the physical characteristics of the case study area (e.g. type of native vegetation, soils).

Discharge

The hydrological model results for discharge fluxes are presented in Section 5.3. The results indicate that establishing watercourse buffers in the sugarcane areas of the case study catchment increase the discharge (water yield) to the downstream system. Larger buffer areas yield higher discharge, but with a declining *additional* gain.

For the case study catchment, increased discharge to the downstream system (uMngeni River) is associated with additional water available for human use. The value of this benefit can be illustrated based on the tariff for raw water. The tariff does not reflect the value of water itself, but rather the costs associated with ensuring that water is available for human use and is an indicator of the 'costs saved' of an additional contribution to downstream water supply. Using the raw water (untreated) tariff for the study area, (Umgeni Water – raw water cost), a relative comparison of the 'value' of changes in water discharge at the catchment outlet is shown in Table 24. 'Change from baseline' reflects the difference between the baseline level and the scenario level and 'Between scenarios' reflects the difference in level between each of the consecutive scenarios (e.g. between scenario 2 and 3, 3 and 4, etc.).

Table 24: Estimated 'value' of the discharge at the catchment outlet under various scenarios of watercourse protection

Tariff = R505/Ml	**'Value' of average annual discharge**			
Scenario	**Value** R/year	**Increase from baseline** R/year	 %	**Between scenarios** R/year
1 – Baseline	99 498 746			
2 – Watercourse only	99 866 202	367 456	0.4	367 456
3 – Narrow buffer	100 354 832	856 086	0.9	488 630
4 – Moderate buffer	100 651 657	1 152 911	1.2	296 825
5 – Wide buffer	100 853 786	1 355 040	1.4	202 129

Note: Slight discrepancies due to rounding; Ml is mega litre.

The estimates indicate:

- The benefit in terms of additional water available for human use in the downstream system of removing sugarcane from the watercourse and establishing buffers within sugarcane. The change in discharge is relatively small, which is consistent with the relatively small change in land-use (1 to 6%).
- The benefit increases with increasing buffer width, but at a declining rate, which corresponds with the declining additional area converted to sugarcane with each scenario.
- The largest benefit occurs under the wide buffer option, but the greatest additional gain occurs under the narrow buffer scenario which corresponds with the largest additional area of sugarcane converted to buffer under the narrow buffer option.

Sediments and nutrients

The hydrological model results for sediment and nutrient fluxes are presented in Section 5.3. The results indicate that establishing watercourse buffers in the sugarcane areas of the case study catchment reduces the load of sediment and nutrients to the downstream system. The widest buffer option results in the greatest reduction, however the variation between the three buffer scenarios is comparatively small.

Sediment loads to the downstream system are associated with the sedimentation of water storage dams and the resulting loss in storage capacity (shortened dam lifespan). The sedimentation of reservoirs is a key threat to reservoir management and the operational efficiency and effective lifetime of the reservoir (Basson and Rooseboom, 1999). While some level of sedimentation is expected and planned for, elevated catchment erosion shortens the lifespan of downstream dams and related infrastructure or incurs costs (e.g. dredging) to reduce these impacts. The percentage changes in sediment loads can be construed as an indication of the potential benefits of watercourse buffers in reducing these negative impacts (at the quaternary catchment scale).

The benefit of reduced sediment loads to the downstream system is commonly estimated either as the replacement cost of lost storage capacity (e.g. through constructing a substitute dam at a new site or raising the wall of the existing dam), or as the cost of dredging to remove the accumulated sediment. For this case study, an indicative value of sediment reduction was estimated based on generic dredging costs for large dams. This cost was obtained from a global study of water storage reservoirs (HydroCoop, 2013). Based on the sedimentation loads simulated through the hydrological modelling, potential sedimentation volumes and dredging costs were estimated, Table 25. The estimates are illustrative of the potential benefit of reduced sediment loads; in this case study context, the sedimentation of Nagle Dam is reduced through a sediment offtake (diversion) system upstream of the Dam. However, the need for the sediment diversion system does highlight the risk of dam sedimentation in the system.

Table 25: Estimated 'value' of sediment reduction to the downstream system under various scenarios of watercourse protection

Dredging = R29/m³	**'Value' of sediment reduction**			
Scenario	**Reduction** Ton/year	m³/year	**Value** R/year	**Between scenarios** R/year
2 – Watercourse only	3 761	2 786	80 800	80 800
3 – Narrow buffer	19 112	14 157	410 558	329 758
4 – Moderate buffer	21 573	15 980	463 425	52 867
5 – Wide buffer	21 823	16 165	468 791	5 366

Note: Dredging costs were based on the average cost of dredging (converted, USD 2/m³) estimated by HydroCoop (2013). The volume of sediment was estimated from mass using a density of 1.35 t/m³ (Turpie et al., 2017). 'Between scenarios' reflects the difference in level between each of the consecutive scenarios (e.g. between scenario 2 and 3, 3 and 4, etc.).

Excessive nutrient inputs to watercourses can lead to the eutrophication of downstream systems. The eutrophication of water supply dams can lead to an increase in water treatment costs in the form of higher quantities of treatment chemicals, drawn-out treatment processes and increasingly sophisticated treatment technologies. In an analysis of phosphorous loads in the uMngeni River and the cost of treating water abstracted from Nagle Dam (Durban Heights Water Treatment Works (WTW)), Turpie et al. (2017) found phosphorous loads (in the river) to be positively and significantly correlated with water treatment costs at Durban Heights WTW. The percentage changes in phosphorous loads simulated in this case study can be interpreted as an indication of the potential water quality amelioration benefit of watercourse buffers in terms of reduced water treatment costs.

The value of reduced nutrient loads to the downstream system can be estimated in terms of the avoided costs to the water treatment works associated with a reduction in nutrient loads (Turpie et al., 2010; Turpie et al., 2017). The water quality – water treatment cost model developed for the Nagle Dam system by Turpie et al. (2017) was used to estimate the value, in terms of water treatment costs avoided, of reduced phosphorous loads to the Nagle Dam system as a result of buffer establishment in the case study area[18]. The results are summarized in Table 26.

Table 26: Estimated 'value' of nutrient reduction to the downstream system under various scenarios of watercourse protection, based on reduced phosphorous loads

	'Value' of nutrient (Total P) reduction			
Scenario	**Reduction in Total P** kg/year	% baseline	R/year	**Between scenarios** R/year
2 – Watercourse only	7 579	6.2	56 336	56 336
3 – Narrow buffer	38 320	31.3	284 823	228 487
4 – Moderate buffer	40 264	32.9	299 274	14 451
5 – Wide buffer	40 693	-3.3	302 460	3 186

Note: 'Between scenarios' reflects the difference in level between each of the consecutive scenarios (e.g. between scenario 2 and 3, 3 and 4, etc.).

The value estimates for the sediment and nutrient reduction benefits suggest:

- A social benefit of watercourse buffers in terms of sediment reduction to the downstream water supply system, R80 800 to R468 791 per year.
- A social benefit of watercourse buffers in terms of nutrient reduction to the downstream water supply system, R56 366 to R302 460 per year.
- A combined water quality enhancement benefit of R137 166 to R771 251 per year.
- The sediment and nutrient reductions follow a similar trend across the scenarios, associated with an improved sediment and nutrient trapping function of a well-managed buffer area.
- Removal of sugarcane from the watercourse provides a sediment and nutrient reduction benefit; the benefit is significantly increased with the establishment of a watercourse buffer.
- The benefit increases with increasing buffer width, but at a declining rate, which corresponds with the declining additional area converted to sugarcane under each scenario.
- The largest relative benefit is achieved under the narrow buffer width option.

[18] Nitrate and phosphorous loads were highly correlated in the model; valuing and aggregating the reduction in both nitrate and phosphorous loads would be a 'double-counting' of the water quality enhancement benefit. The value of reduced phosphorous loads is representative of the nutrient reduction benefit.

Additional considerations:

- The modelled sediment and nutrient reduction estimates are based on assumed well-managed buffers and well-managed sugarcane cultivation, which does not necessarily reflect the conditions in practice.
- The value of the nutrient and sediment reduction benefits were estimated using accepted valuation approaches drawing on analyses and data from an existing local study (Turpie et al., 2017) in the case of nutrient reduction benefits, and generic cost information (Hydrocoop et al., 2013) in the case of the sediment reduction benefit.

5.4.4. Gain in area of native vegetation

A spatial analysis of the watercourse buffers under the various scenarios illustrates the gain in native vegetation with the removal of sugarcane from the watercourse itself and from the three buffer scenario areas, Table 27. 'Change from baseline' refers to the area of native vegetation gained under each scenario (i.e. the conversion of sugarcane cultivation to buffer area). The '% catchment' indicates the proportion of the gain in area of native vegetation relative to the area of the study catchment (41 841.64 ha). 'Between scenarios' refers to the additional area gained between each of the scenarios. The results indicate that replacing sugarcane in the watercourse with natural vegetation constitutes a 1% change in land-use within the catchment, while implementing the wide buffer option results in a 6% change in land-use within the catchment. The 'between scenarios' analysis shows that the *additional area* gained initially increases under the narrow buffer option (from the watercourse only scenario) and then declines with increasing buffer width scenario (scenarios 3 to 5).

Table 27: Gain in area of native vegetation with the establishment of watercourse protection measures

	Gain in area of native vegetation		
	Change from baseline		**Between scenarios**
Scenario	Ha	% catchment	Ha
1 – Baseline	-	-	-
2 – Watercourse only	438	1	438
3 – Narrow buffer	1 518	4	1 081
4 – Moderate buffer	2 174	5	656
5 – Wide buffer	2 618	6	444

A gain in native vegetation within the sugarcane landscape is associated with benefits related to biodiversity conservation and the provision of ecosystem services (such as pest regulation and pollination). The conversion of sugarcane to buffer area increases the percentage of native vegetation in the catchment, Table 27. The relationship between an increase in native vegetation and biodiversity and the provision of ecosystem services requires future investigation to determine the potential to realize the associated benefits (both to the grower and broader society). In the context of sugarcane cultivation, pest regulation services are a particularly relevant potential benefit requiring further research.

5.4.5. Evaluation

The catchment case study assessment is based a sub-set of benefits associated with watercourse buffers, specifically those related to water supply and water quality. However, watercourse buffers are multifunctional associated with a range of potential benefits. Quantifying and valuing (using a monetary metric) the full range of benefits is challenging, and in some cases, not possible; whereas it is relatively more straightforward to value the costs of buffer establishment, resulting in an 'unbalanced' cost-benefit assessment.

The percentage changes in measured indicators can be construed as an indication of the associated level of benefit or cost. The percentage changes from the baseline under each scenario for the measured indicators are summarized in Table 28. The summary highlights the increase in potential benefits with increasing buffer width and a concomitant increase in potential cost. The influence of watercourse buffers on sediment and nutrient reduction is relatively greater than the influence on water discharge.

Table 28: Summary of percentage changes in measured indicators with watercourse protection scenarios relative to baseline levels

	% change from baseline				
Scenario	Sugarcane area	Native vegetation	Discharge	Sediment	Nutrients
2 – Watercourse only	- 3.9	1.0	0.4	- 5.6	- 6.2
3 – Narrow buffer	- 13.5	3.6	0.9	- 28.7	- 31.3
4 – Moderate buffer	- 19.3	5.2	1.2	- 32.4	- 32.9
5 – Wide buffer	- 23.2	6.3	1.4	- 32.8	- 33.3

Note: Blue fill indicates a benefit; red fill indicates a cost. 'Watercourse only' represents the case where sugarcane is removed from watercourse and no additional buffer is applied.

A summary of the monetized sub-set of costs and benefits is provided in Table 29. These costs and benefits were compared in a Net Present Value Assessment and the resulting

Benefit-Cost (B-C) ratios are reported in Table 30. In addition to the B-C ratio, several additional appraisal indicators were calculated to reflect the gain in water and reduction in sediment and nutrient loads per unit area of sugarcane converted to buffer area, Table 30.

From the case study results and appraisal indicators, the following points are noted:

- Based on the sub-set of costs and benefits valued in the case study assessment, the financial costs of buffer establishment exceed the financial value of the water supply and quality benefits.
- The greatest additional gain in discharge per area of sugarcane converted to buffer is achieved under the watercourse only scenario.
- The greatest additional gain in sediment and nutrient reduction per unit area of sugarcane converted to buffer is achieved under the narrow buffer option.
- For the case study area, the results of the application of the buffer delineation approach suggest that the options of removing sugarcane from the watercourse and applying the narrow buffer width option provide the largest additional gains in terms of water quality and supply benefits. These two options are also associated with a lower impact to the sugarcane grower. The case study results are representative of the Midlands North region, but are not generalizable across sugar production regions.
- Additional gains in discharge and sediment reduction are progressively less with increases in buffer width to the moderate and high scenarios. This suggests that the buffer width range proposed in this study may be on the higher end of the effective spectrum from a water quantity and quality perspective (i.e. conservative). However, these results are not necessarily generalizable across all regions and additional case studies (pilot demonstrations), including plot level studies of pollution reduction efficiencies, are needed before refining the buffer range.

Evaluating watercourse buffers based on their influence on discharge, sediment and nutrient outputs is a starting point, but fails to fully articulate the value of watercourse buffers in supporting both aquatic and terrestrial biodiversity and the additional ecosystem services associated with healthy watercourses (e.g. streamflow regulation) and a gain in native vegetation in the landscape (e.g. pest regulation, recreation opportunities, cultural services, climate regulation). Future research is required in this regard. An especially relevant potential benefit that was not quantified in this assessment[19] is the role of native vegetation in pest regulation; this is a key direction for future research. Estimates for the Noodsberg (Midlands

[19] The role of native vegetation in pest regulation within sugarcane cultivation is a developing field of research and data is not yet available for quantifying and valuing these relationships.

North) area indicate losses due to Eldana damage of R641/ha[20] (Rutherford, 2015); equivalent to R7.2 million for the area of sugarcane cultivation in the case study catchment. The industry average is significantly higher at R1565/ha.

[20] From Rutherford (2015) adjusted for inflation.

Table 29: Summary of a sub-set of estimated costs and benefits associated with the implementation of watercourse protection scenarios existing sugarcane cultivation within the case study area (quaternary catchment U20G, Midlands North)

Scenario	Benefit-cost comparison						
	Income forgone R/year	Establishment severe R (once off)	Establishment moderate R (once off)	Maintenance R/year	Discharge gain R/year	Sediment reduction R/year	Nutrient (Total P) reduction R/year
2 – Watercourse only	5 700 201	4 521 101	127 762	80 945	367 456	80 800	56 336
3 – Narrow buffer	19 784 859	15 686 734	443 291	280 852	856 086	410 558	284 823
4 – Moderate buffer	28 335 031	22 467 145	634 899	402 247	1 152 911	463 425	299 274
5 – Wide buffer	34 122 909	27 056 857	764 599	484 421	1 355 040	468 791	302 460

Note: 'Watercourse only' represents the case where sugarcane is removed from watercourse and no additional buffer is applied. Buffer establishment costs are particularly variable, depending on the type and extent of rehabilitation required and both the estimates for severely degraded and moderately degraded cases are reported.

Table 30: Summary of appraisal indicators based on the sub-set of measured indicators

Indicator		Appraisal indicators			
		Watercourse only	Narrow buffer	Moderate buffer	Wide buffer
Discharge gain per area converted	l/ha/year	2	1.12	1.05	1.02
Sediment reduction per area converted	t/ha/year	8.60	12.59	9.92	8.33
Phosphorous reduction per area converted	kg/ha/year	17.32	25.24	18.52	15.54
B-C ratio (NPV analysis)	na	0.08	0.08	0.06	0.06

Note: The benefit-cost ratio was calculated in a Net Present Value Analysis based on the sub-set of costs and benefits reported Table 29. A 30 year timeframe and 8% discount rate were applied ((Mullins et al., 2014:69). The analysis was not sensitive to the discount rate (over a 0-8 % range). The colour scale reflects greater to lesser benefit (dark to light).

6. CONCLUSIONS AND RECOMMENDATIONS

This study investigated the establishment of buffers adjacent to watercourses within sugarcane cultivation areas as one practice towards protecting watercourses within these landscapes. Through the study:

a) An approach for delineating the widths of buffers adjacent to watercourses was developed. In the approach, buffer width is primarily determined by hillslope class. An option to modify the guideline width at the farm scale based on the local threat context is provided to further optimize buffer width against local management practice.
b) The costs and benefits associated with watercourse buffer establishment within the sugarcane cultivation landscape were investigated through a review of the existing knowledge base and the case study application of the buffer delineation approach. Spatial analysis, hydrological modelling and valuation (where possible) were used to quantify a sub-set of costs and benefits associated with establishing watercourse buffers within the case study area.

A review of the literature and cases of buffer implementation, and expert and stakeholder consultation, highlighted the following key aspects:

- Sugarcane in South Africa is cultivated across a range of landscapes under a variety of production practices.
- A number of better management practices have been developed towards sustainable sugarcane production; adoption of theses varies across growers and regions. A tool has been developed to track progress towards better management practices (the South African Sustainable Sugarcane Farm Management System – SUSFARMS®).
- Buffer areas are multi-functional, associated with a range of potential on-farm benefits (e.g. pest management) and social benefits, which creates opportunities to address a number of ecological, production and sustainability goals.
- The contribution of buffer areas to sugarcane pest regulation is an important on-farm benefit associated with a potential long-term reduction in pesticide use and the attendant costs. The relationship between buffer width (extent of native vegetation) and pest control effectiveness is an area requiring further investigation.
- Buffers are increasingly adopted within agricultural landscapes as a better management practice, this is being done through regulated standard buffer width approaches and through flexible approaches that allow for buffers to be modified or replaced with the implementation of other management practices.

- Buffer areas are vulnerable to dumping, sand mining and alien invasive plant infestation if not well managed. Poorly maintained buffer areas may be more detrimental to the watercourse than well managed sugarcane cultivation.
- Large floodplain systems are particularly complex, unique systems and require management strategies and practices designed specifically for the floodplain in question (i.e. fine scale decision-making is required).
- At present, the sugar industry in South Africa is shrinking and there are a number of policy changes affecting the industry, which have associated costs. Crop changes are taking place, particularly a shift from sugarcane to macadamia and avocado trees and bamboo plantations.

The proposed buffer delineation approach sets out the conceptual thinking and broad steps as a guideline to determining appropriate watercourse buffers within the sugarcane landscape that takes into account hillslope characteristics of the landscape. The proposed buffer delineation approach, and associated buffer range, can be applied (generalised) across the sugar production regions. The approach was developed based on the best available science, drawing from established research on buffer function and buffer width determination, previous research in the case study area and recent progress in the understanding, conceptualisation and quantification of hydropedological processes. The approach was applied in a desktop-based case study assessment. The results of the case study application suggest that the buffer width may be on the higher end of the effective spectrum from a water quantity and quality perspective (i.e. conservative). However, these results are not necessarily generalizable across all regions. Further application, particularly empirical studies of buffer implementation including plot level studies of pollution reduction efficiencies and further investigation of above- and below surface buffer attenuation processes, would strengthen and refine the approach.

The buffer delineation approach was applied in a desktop-based case study assessment. From the case study results and appraisal indicators, the following points are noted:

- The hydrological modelling results suggest that buffer width, as determined by hillslope class, influences water discharge and sediment and nutrient loads as measured at the outflow node of the study catchment. The hydrological model calibration results and a comparison to the findings of similar local studies indicate that the baseline results and scenario trends are robust.

- Discharge increases with increasing buffer width, but at a declining rate of additional gain. Sediment and nutrient loads are reduced with increasing buffer width, but at a declining additional gain.
- A loss of sugarcane cultivation area for the land owners and the associated income forgone (13, 19 and 23% of baseline production with the narrow, moderate and wide buffer options, respectively; 4% of baseline production occurs within the watercourse boundary).
- Additional costs associated with the establishment (e.g. revegetation and rehabilitation) and annual maintenance costs of buffer areas. Depending on the size of the buffer and the level of rehabilitation required, establishment costs vary considerably, but can add significantly to the costs incurred by the grower particularly in the case of severely degraded areas.
- A gain in native vegetation across the catchment (1 to 6% of the study catchment). Native vegetation is associated with a number of ecosystem services and agricultural support services.
- Based on the sub-set of costs and benefits valued in the case study assessment, the financial costs of buffer establishment exceed the financial value of the water supply and quality benefits. Water supply benefits were valued using the tariff for raw water which is a cost measure and not a reflection of the real value of water.
- The greatest additional gain in discharge per area of sugarcane converted to buffer is achieved under the watercourse only scenario.
- The greatest additional gain in sediment and nutrient reduction per unit area of sugarcane converted to buffer is achieved under the narrow buffer option.
- The proportion of sugarcane area converted to buffer varies by farm / land owner, based on the extent of watercourse and class of hillslopes present. As such, there are distributional implications associated with the implementation of watercourse buffers.
- The catchment case study assessment was based a sub-set of benefits associated with watercourse buffers, specifically those related to water supply and water quality. However, watercourse buffers are multifunctional associated with a range of potential benefits. Quantifying and valuing (using a monetary metric) the full range of benefits is challenging, and in some cases, not possible; whereas it is relatively more straightforward to value the costs of buffer establishment, resulting in an 'unbalanced' cost-benefit assessment.
- The current assessment does not include the long-term costs of continued, and further, degradation of watercourses – that is, the costs of 'no action'; a social cost accruing to current and future generations. Profit from sugarcane production is a private benefit,

realized to an extent, at a cost to society of degraded watercourses and biodiversity loss.

Evaluating watercourse buffers based on their influence on discharge, sediment and nutrient outputs is a starting point, but fails to fully articulate the value of watercourse buffers in supporting both aquatic and terrestrial biodiversity and the additional ecosystem services associated with healthy watercourses (e.g. streamflow regulation) and a gain in native vegetation in the landscape (e.g. pest regulation, recreation opportunities, cultural services, climate regulation). An especially relevant potential benefit is the role of native vegetation in pest regulation; this is a key direction for future research in the context of sugarcane cultivation.

The study highlighted a number of aspects for future research:

- Demonstration (targeted monitoring, observed outcomes) of the benefits of watercourse buffers across a broader range of ecosystem services and the influence of buffer width of the provision of these services. Particularly, an investigation of the associated potential benefits to land-owners / growers (e.g. pest regulation services, cultural values).
- Strategies for managing buffers to achieve multiple objectives, or to optimize specific functions (e.g. sediment and nutrient trapping efficiency).
- Monitoring / observed data on sediment and nutrient loads (to support hydrological mode calibration).
- Empirical plot level studies of the sediment and nutrient reduction efficiencies of buffer areas (and width variations) and the effect of buffer condition on these efficiencies. This knowledge would inform how buffer areas should be managed for optimal sediment and nutrient reduction.
- The influence of buffer placement in the landscape on watercourse protection (e.g. other than adjacent to the watercourse) and the performance of fragmented buffer areas relative to continuous / connected buffers.
- The hydrological model applied in the case study assessment can be considered an important preliminary foundation for conceptualising sub-surface flow and buffer interactions and simulating the hydrological response of the watercourse to the establishment of watercourse buffers. Primary empirical studies are needed to further develop and strengthen the hydrological (SWAT) model in effectively reflecting hillslope-buffer-watercourse interactions including further examination of above- and below surface buffer attenuation processes. In future work, the model could be applied

to interrogate the hydrological response to a number of additional scenarios (e.g. across other land-uses, changes in crop type, adoption of additional / alternative BMPs).

- The influence of watercourse buffers on peak and base flows.
- A comparison of a range of better management practices and various combinations thereof towards achieving set objectives, for example through a cost-effectiveness analysis.

Given these findings, the following recommendations are made.

- Watercourse buffers should be viewed as part of a broader management strategy towards sustainable and responsible agriculture (including the maintenance of aquatic ecosystem health) based on local needs, pressures and landscape settings and considered in combination with other better management practices (e.g. soil and water conservation measures, nutrient reduction practices). Ideally, watercourse buffers should be considered at a farm scale as part of a farm / land-use planning process from which an appropriate set of better management practices can be identified. The SUSFARMS® manual and progress tracker provides a 'vehicle' for promoting implementation and tracking progress.
- The proposed buffer width range should be applied to identify a guideline width, which can then be modified given site-specific objectives and threat factors. The approach, and associated buffer range, can be applied (generalised) across sugar production regions, based on the hillslope classes determined for each region. The proposed buffer delineation approach would be enhanced with further application, specifically through empirical studies of buffer establishment across landscape characteristics and management practices.
- For the case study area, the results of the application of the buffer delineation approach suggest that the options of removing sugarcane from the watercourse and applying the narrow buffer width option provide the largest additional gains in terms of water quality and supply benefits. These two options are also associated with a lower impact to the sugarcane grower. The case study results are representative of the Midlands North region, but are not generalizable across sugar production regions.
- A phased approach to implementation should be considered, developed through cross-sector engagement (including various government departments, the sugar industry, research institutes) to set objectives related to watercourse condition and ecological and sustainability goals, identify appropriate practices towards achieving objectives, and to agree on the basis and timeframe of the phased approach.

- A phased approach should include primary empirical studies (pilot cases) of watercourse buffer implementation across a variety of landscapes and management practices, involving monitoring and evaluation. Pilot cases could be used to address a number of implementation and research questions. Further, pilot cases, especially those involving local stakeholders (growers, extension specialists) and observed data could provide motivation for the uptake and implementation of watercourse buffers.
- Consideration should be given to supporting growers in implementing watercourse buffers, for example, support in developing land-use plans and delineating buffers; support in establishing watercourse buffers (technical / financial support in undertaking rehabilitation activities) and guidance in managing buffer areas. This may require strengthening extension services to support growers in a transition to better management practices. Options to relieve some of the initial financial burden during a transition phase should be explored (e.g. support from the national Natural Resource Management programme).

Additional considerations in taking watercourse protection forward in sugarcane landscapes are outlined below.

A phased approach could be based on:

- Beginning with a minimum initial step, such as, removing cultivation from the watercourse (or not re-planting in the watercourse); developing a land-use management plan for the farm which identifies ways (better practices) to reduce impacts to the watercourse with a concomitant commitment to, and tracking of, progress towards these.
- Location – targeting first degraded headwaters and then proceeding downstream; headwater systems are associated with a high opportunity for regulation of water quality and contribution to regional biodiversity (Hansen et al., 2010).
- Priority areas – criteria for prioritization would need to be agreed and could be related to priority catchments, or vulnerable catchments (e.g. zones of more vulnerable ecological function, areas of more intensive cultivation, areas characterized by poor management practices or relatively higher risks to the watercourse).
- Specific events – a change in crop (or other land-use change) offers an opportunity for implementation, or a change in land ownership.
- Regions / catchments with a more favourable enabling environment, for example where greater extension and / or department support is available, growers are more open to negotiate and collaborate – incentives for 'early' adopters could be considered

(e.g. support in establishing buffer areas, developing land-use and buffer management plans, etc.).

Maximising multiple benefits

Buffer areas in agricultural settings are commonly associated with addressing surface water pollution issues – their benefits in this regard are well-documented. However, buffer areas can perform a range of functions providing many additional benefits, many of these are less well studied particularly those related to agricultural support services (e.g. pest management, soil health and moisture management). The multi-functionality of buffers creates opportunities to address a number of ecological and production objectives – how to maximise these opportunities requires further investigation.

- Stakeholder deliberation and discussion is required to identify and prioritize goals.
- The policy framework with regard to supporting the achievement of multiple benefits and goals needs to be considered. Policies – related to agricultural production, water resource management, climate change and biodiversity for example – are often developed and applied independently. Policy formation and departmental collaboration to support dual goals is required.

Good management is essential to maintaining the functions of watercourse buffers

Buffer areas are vulnerable to dumping, sand mining and alien invasive plant infestation if not well managed. Poorly maintained buffer areas may be more detrimental to the watercourse than well managed sugarcane cultivation. Considerations in this regard, include:

- How to ensure that buffers are well managed (e.g. monitoring). Buffer management under changing land ownership also requires consideration.
- The DWS indicated a possible collaboration with the National Resource Management (NRM) programme (Working for Water and Working for Wetlands) in managing invasive alien plant infestations, to offset the costs of control. The NRM programme is willing to be involved on a 50/50 basis with landowners, depending on available budget.
- Options for the productive use of watercourse buffer areas, especially larger buffers which could consist of a range of vegetation species. Potential options include hay (cut grass) for use as livestock fodder and / or green manure and recreational activities.

Unique systems

Large floodplain systems are particularly complex, unique systems and require management strategies and practices designed specifically for the floodplain in question (i.e. fine scale decision-making is required). Existing evidence indicates that KZN’s floodplains have been significantly transformed, with each floodplain being influenced by different processes. While some initial guidelines for improved management of floodplains planted with sugarcane have been identified (Appendix 5), due to the uniqueness of the individual floodplains and the drivers of transformation, it is recommended that the management of floodplains be approached on a ‘system by system’ basis. Thus, allowing for specific management measures taking into account the uniqueness of each system, to be determined for the respective floodplains planted to sugarcane.

Uptake and motivators

- Cost-benefit analysis as a motivator of the adoption of innovations / new practices is questionable; particularly in the case of significant social and ecological benefits, as these types of benefits are often difficult to quantify and assign a monetary value and accrue at a much broader scale than the local costs associated with better management practices.
- Other drivers of adoption need to be explored, for example those related to culture and a sense of stewardship, education and empowerment, societal and peer pressure, and market-related forces (e.g. generating relative advantage in a changing culture of production).
- The benefits of buffers and better management practices need to be widely communicated. Knowledge sharing and awareness-raising can support uptake and reduce misinformation. Knowledge sharing by peers (other growers) is likely to be more influential.
- Involving stakeholders in pilot cases of buffer implementation and data collection could further support uptake.

A shifting context

At present, the sugar industry in South Africa is shrinking and there are a number of policy changes currently affecting the industry, which have associated costs. These pressures, along with climate change effects, are shifting the sugarcane cultivation landscape.

- Crop changes are taking place, particularly a shift from sugarcane to macadamia and avocado trees and bamboo plantations. Watercourse impacts across a range of crops require further investigation.
- Several regions are experiencing a conversion of sugarcane lands to development (particularly the coastal regions).
- Climate changes

- Growers have noted changes in rainfall intensity (e.g. from regular small events to less frequent high volume rainfalls) which increases soil runoff and sediments, which could influence buffer design.
- With changes in the climate, the suitability of land for various agricultural activities is also shifting.
- Climate change futures are likely to influence sugarcane-hydrology relationships.

These trends need to be considered in developing guidance and regulations for sustainable management practices within the sugarcane (and broader) landscape. Sustainable land-management strategies and practices should be aligned and compatible across land-use types.

Primary empirical studies

Primary empirical studies (pilot cases) could be used to:

- Investigate / demonstrate the provision of a wider range of ecosystem services and benefits, for example:
    - Pest management
    - Increased productivity of the adjacent lands over the long-term
    - Cultural values
    - Aesthetic value and recreation benefits
    - Carbon capture potential.
- Improve our understanding of hillslope-buffer-watercourse interactions.
- Generate farm-scale cost information on buffer establishment and maintenance.
- Develop guidance for farm-scale implementation and management of buffer areas (e.g. linked to land-use planning), identify and address data and expertise requirements.
- Explore how buffers could be designed (e.g. with regard to their placement within the catchment, vegetation types and arrangement, buffer length and connectivity) and implemented to achieve multiple objectives or to maximise specific benefits.
- Compare a range of better management practices and various combinations thereof towards achieving set objectives.
- Develop tools for the assessment and evaluation of the effectiveness of buffers (and other management practices), to:
    - Support the prioritization and optimization of buffers (benefits and design) and additional management practices,

    - Track progress towards goals (voluntary or compliance) – for example integration into the South African Sustainable Sugarcane Farm Management System (SUSFARMS®).
- Identify grower support needs (e.g. land-use planning, buffer delineation).

The knowledge generated through this research project has led to a deeper understanding of the outcomes of establishing watercourse buffers within sugarcane cultivation and highlighted a number of aspects that require additional consideration and directions for future research. These insights and recommendations are a point of departure for a broader dialogue on taking forward watercourse protection within agricultural landscapes in general.

A sustainability perspective is progressively being adopted by citizens, states and private sectors. Producers and retailers are under increasing pressure to shift to responsible and sustainable production driven by regulatory and market forces (WBCSD, 2015). In the medium to long term it may not be possible to sell sugar (and other agricultural commodities) without first demonstrating it has been produced under sustainable practices. This means that the question of whether to adopt sustainable production practices is no longer the debate, but rather questions regarding 'which practices', 'optimizing benefits' and 'how to transition' are issues that need to be addressed.

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8. APPENDICES

Appendix 1: Hydropedology assessment details

As part of the study, a hydropedological interpretation of regional soil information (land type data) was undertaken (Van Tol, 2018) to characterise the hydropedological behaviour of dominant hillslopes of two proposed case study catchments (U20G and U30B) and associated sugarcane production areas (Midlands and North Coast, respectively). The full report can be obtained from the WRC or the INR. The results pertaining to the Midlands region are reported in this final report (Case Study Application) the results of the North Coast assessment are outlined briefly below, Table A1-1. The hydropedological response interpreted from the broad land type categories shows that Class 2 hillslopes (shallow responsive) are the most prevalent class in the North Coast region (53%), with Class 4 hillslopes (recharge to wetland) being sub-dominant (35%).

Table A1-1: Areas and coverage of the various hillslope classes of the North Coast sugarcane production area

	North Coast	
Hillslope Class	**Area (ha)**	**Coverage (%)**
Class 1: Interflow	5 065	2
Class 2: Shallow responsive	138 967	53
Class 3: Recharge to groundwater	25 548	10
Class 4: Recharge to wetland	90 383	35

Appendix 2: A review of applied and recommended buffer widths

In the development of the Buffer Zone Guidelines for Rivers, Wetlands and Estuaries (Macfarlane and Bredin, 2017), a detailed literature review of buffer zone functions, and methodologies for determining buffer widths both locally and internationally was conducted (Macfarlane et al., 2009). Table A2-1 presents aquatic buffer widths and factors influencing buffer functionality for a range of buffer functions summarized from Macfarlane et al. (2009). The summary highlights that proposed buffer widths vary considerably and depend on the intended purpose of the buffer zone and the nature of multiple influencing factors. Cases or studies of buffer implementation related to watercourse protection, with a focus on the agricultural sector, were also consulted. Table A2-2 presents a brief overview of recommended buffer widths from these studies.

Table A2-1: Proposed widths of aquatic buffers associated with various buffer functions and factors influencing buffer functionality, summarized from Macfarlane et al. (2009)

Buffer width	Factors influencing buffer functionality
Sediment removal	
• Range: 1 m to > 100 m. Larger buffer widths typically advocated for steeper slopes or to ensure efficient removal of fine sediments	• Size of suspended particles • Flow rate – width, slope and soil permeability • Topography • Surface roughness of the buffer zone • Vegetation characteristics • Soil characteristics
Nutrient removal (nitrogen and phosphorus)	
• Range: 4.6 m to > 200 m. Larger buffer widths typically advocated for higher proportional removal of nutrients	• Slope • Type and amount of flow (surface vs. sub-surface flows) • Infiltration rate • Buffer width • Soil characteristics and drainage • Type, density, condition, and productivity of vegetation • Phosphorus specific – factors affecting sediment deposition • Nitrogen specific – seasonality, factors affecting denitrification (organic material supplied to the soil surface, soil chemistry – oxygen and carbon content, soil moisture).
Removal of toxics (bacteria, metals, pesticide)	
Range: 2 m for a moderate load reduction of pesticides to a conservative figure of 50 m	*Due to the rage of potential toxics, it not possible to generalize a set of influencing factors*

Buffer width	Factors influencing buffer functionality
Influencing microclimate and water temperature	
• 40 m in forested systems to maintain streamside temperatures and vegetation characteristics; significantly smaller in vegetation types of lower stature (e.g. grasslands)	• Amount of vegetation overhanging the stream • Channel width (< 5 m wide for shading effect) • Channel orientation relative to the sun • Vegetation characteristics – type, density
Maintaining habitat critical for semi-aquatic species	
Species dependent, examples include: • amphibians 30 to 1000 m • birds 15 to 2200 m Average for most species are between 100 and 300 m	Highly varied according to the needs of the species, include: • Habitat quality and suitability – vegetation characteristics (type and density) • Climate • Topography & slope • Size of habitat (of buffer and adjacent habitat)
Maintaining habitat critical for aquatic species	
Forested buffers – between 10.3 and 62 m; significantly smaller widths for vegetation of low average height such as those occurring in fynbos and grassland areas	*This function largely relates to the contribution of plant matter (fallen leaves/branches) into streams that supports the stream ecosystem.* • Slope • Vegetation height • Wind speed and direction
Maintenance of general wildlife habitat	
Range: 50 to 300 m	• Habitat quality – alien plants, fire management, grazing • Structural diversity and heterogeneity • Topography & slope • Size of habitat (of buffer and adjacent habitat) • Level of impact from adjacent land • Presence of rare, threatened or endangered species
Screening (wildlife) from adjacent disturbances	
Range: 14 to 100 m; widths between 15 m and 50 m more common	• Vegetation characteristics – height, density, quality • Permanence of screening – related to management practices (e.g. burning, mowing) • Buffer width • Surrounding land-use and related impacts
Maintaining habitat connectivity[21]	

[21] Connectivity is defined as 'the degree to which the landscape facilitates or impedes movement among resource patches' (Macfarlane et al., 2009).

Buffer width	Factors influencing buffer functionality
Range: 50 to 300 m	• Physical characteristics of the buffer zone – continuity of suitable habitat, extent or length of gaps between areas of suitable habitat, vegetation characteristics, buffer width • Species characteristics – such as mobility, habitat requirements, tolerance to disturbance, etc.
Channel Stability and Flood Attenuation	
Range: 6.3 to 225 m, narrow buffers more common, typically between 6.3 and 50 m	• Surrounding land-use • Vegetation type – riparian vegetation associated with improved resistance to erosion, Surface roughness of vegetation
Providing aesthetic appeal	
Not a primary determinant of buffer width	• Vegetation characteristics • Community preferences
Groundwater recharge	
No specific widths identified	• Factors affecting infiltration – slope, soil conductivity, vegetation and leaf litter

Table A2-2: Overview of cases and studies of buffers implementation for watercourse protection, with a focus on agricultural landscapes

Buffer width	Land-use	Buffer purpose	Buffer width approach	Reference
6-18 m	Sugarcane Field borders & filter strips along watercourses	Protect water quality	Dynamic widths, individual field assessment Widths based on slope. Width and vegetation composition modifications based on additional site factors (e.g. field erosion problem)	Sugarcane Environmental Best Management Practices. Louisiana, US (Gravious et al., 2017)
10-100 m	Agriculture Buffer strip along the watercourse	Protect water quality	Dynamic Widths based on risk to watercourse (nutrient leach & erosion) Buffer management plan required	Case study: Cost-benefit analysis of municipal water protection measures. Helsinki, Finland (Punttila, 2014)
Continuous buffer – at least 15 m average & 9 m minimum.	Agriculture	Protect water quality	Fixed minimum Option to adopt alternative riparian water quality practices providing equivalent protection in place of the buffer	Regulation: Minnesota Buffer Law Minnesota, US (Minnesota Legislature, 2019)
2 m, 8 m, 20 m Watercourse buffered by 20 m.	Agriculture	Phosphorus reduction	Fixed width, field buffers Three options compared in achieving various phosphorus load reductions Field-by-field targeting of buffer widths is more cost-effective	Integrating socio-economic and biophysical data in assessing post-effectiveness of buffer strip placement Lunan catchment, Scotland (Balana et al., 2012).
30 to 200 m	Multiple	Protect flowing waters and conserve biodiversity	Multiple	Review: Minimum width requirements for riparian zones Victoria, Australia (Hansen et al., 2010)

From a comprehensive review of the literature, Hansen et al. (2010), formulated a range of buffer width recommendations to address single function objectives related to protecting flowing waters and conserving biodiversity, for Victoria (Australia), Table A2-3. From their review, Hansen et al. (2010) noted the following as key points:

- International studies have clearly demonstrated that intact riparian zones of any width are better than none; riparian zones need to be restored to an appropriate width and reconnected to ensure they are fully ecologically and physically functional.
- Land-use intensity will govern the decision about which width is appropriate for a given location and management objective – in general terms, the greater the land-use intensity, the wider the buffer needs to be.
- Irrigation is associated with higher intensity, and generally distinctions are made between irrigated and non-irrigated land-use.
- Where best agricultural management practice is implemented (reducing impacts on the watercourse) the need for wider buffers is reduced.
- In order to maximise functional efficiency, riparian zones should be longitudinally continuous as well as sufficiently wide, targeting first degraded headwaters and then proceeding downstream.
- Based on a meta-analysis of >200 studies, riparian buffer widths of between 30 and 200 m are recommended, dependant on land-use intensity and management objective.
- Where land-use changes are proposed, riparian zones need to be adjusted to account for potential increases in disturbance impacts.

The land-use intensity, Table A2-3, was defined as follows (Hansen et al., 2010).

High:

- Dairy (high stocking rates >10 DSE/ha/annum 1,2)
- Irrigated dairy
- Dryland cropping (e.g. canola, wheat)
- High intensity grazing (high stocking rates – beef, horses, deer, etc.)
- Swine and poultry (CAFO)
- Market gardens (where crops are irrigated)
- High fertilizer application rates (>15 kg P/Ha/yr 3)
- Sealed roads within 30 m.

Moderate:

- Dairy (all other stocking rates ≤ 10 DSE/ha/annum)
- Grazing (medium stocking rates 5-15 DSE/ha/annum)
- Other forms of dryland cropping (e.g. lucerne) where irrigation is not used

- Orchards (including citrus)
- Other production crops including vines, hops, olives
- Medium-low fertilizer application rates (<15 kg P/Ha/yr)
- High-medium intensity sheep grazing
- Unsealed roads within 30 m.

Low:

- Grazing (low stocking rates <5 DSE/ha/annum all stock)
- Pasture cropping
- Timber plantations
- Forestry operations
- Pesticide application (e.g. Endosulfan-containing insecticides, glyphosate, organophosphates).

Table A2-3: Minimum width (m) recommendations for Victorian riparian zones (reproduced from Hansen et al., 2010)

Objective	Land-use Intensity High	Land-use Intensity Moderate	Land-use Intensity Low	Wetland/ lowland floodplain/ off-stream water bodies	Steep catchments/cleared hillslopes/ low order streams
Improve water quality	60	45	30	120	40
Moderate stream temperatures	95	65	35	40	35
Provide food and resources	95	65	35	40	35
Improve in-stream biodiversity	100	70	40	Variable	40
Improve terrestrial biodiversity	200	150	100	Variable	200

Note: Confidence (for application in Victoria): green=high, yellow=moderate, orange=low. Variable: variability in width is related to the lateral extent of hydrological connectivity and thus, any recommendation will be site specific.

Appendix 2 references

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Appendix 3: Hydrological model details

Box A3-1 provides a brief description of the models used in the hydrological study. Table A3-1 outlines the key benefits and input requirements of the SWAT model and Table A3-2 summarises the model input variables. Figure A3-1 illustrates how inputs are incorporated into SWAT to simulate water yield.

Box A3-1: Models used in the hydrological study

Catchment scale: SWAT – Soil and Water Assessment Tool

The Soil & Water Assessment Tool is a small watershed to river basin-scale model first developed in the early 1990s at Texas A&M University, which has evolved for use to simulate the quality and quantity of surface and ground water and predict the environmental impact of land-use, land management practices and climate change. SWAT is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds (https://swat.tamu.edu/).

Small scale: HYDRUS – Soil and Water Assessment Tool

HYDRUS is a software package for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media. The model is well applied to the investigation of water flow and solute transport within the unsaturated zone of soils (between the land surface and groundwater level) for applications in agriculture, industry and environment (https://www.pc-progress.com/en/Default.aspx?hydrus-3d).

Table A3-1: Summary of the SWAT model outputs, benefits and input requirements

Simulation	Benefits	Input Requirements			
Daily SCS driven water balance model: catchment runoff, baseflow, nutrients, sediments	Widely used, GIS linked, daily time step	Daily rain, PET	Slopes	Porosity, FC, WP, Hydropedology.	Uptake characteristics, rooting

Note: PET: potential evapotranspiration; FC: field capacity; WP: wilting point, SCS: Soil conservation service (model).

Table A3-2: Summary of key SWAT input variables (after Arnold et al., 2012)

File Name	Description
File.cio	Watershed file that names catchment levels for output parameters
.fig	Watershed configuration file
.pcp	Precipitation input file (up to 300 stations)
.tmp	Temperature file with daily minimum and maximum temperatures
Crop.dat	Land-cover / plant growth database file containing plant growth parameters
.hru	HRU level parameters
.sol	Soil input file

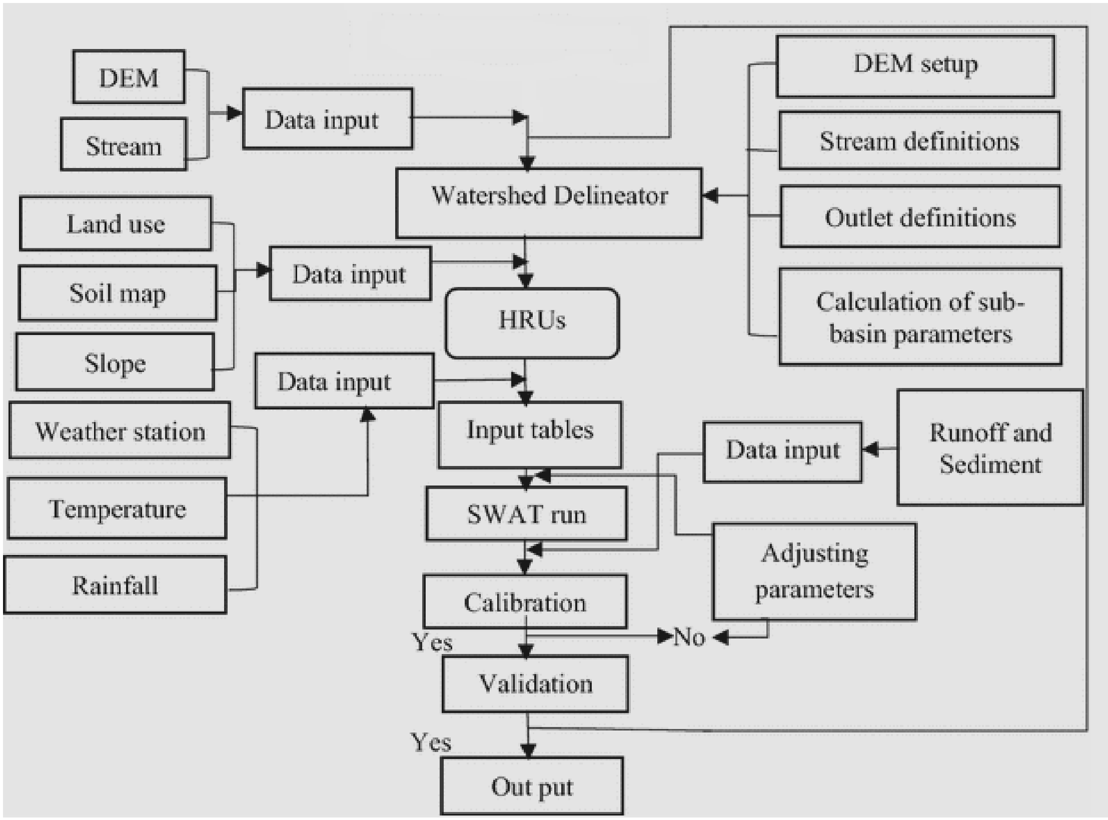

Figure A3-1: SWAT model process (Worku *et al.,* 2017).

Appendix 3 references

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Appendix 4: Eldana saccharina Walker (Lepidoptera: Pyralidae)

The stem borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae) is a common pest of sugarcane in eastern and Southern Africa and is considered a major constraint to sugarcane production (Conlong, 1990; Kvedaras and Keeping, 2007). *Eldana saccharina* is indigenous to parts of Sub-Saharan Africa and is found naturally in wetland sedges (Conlong and Hastings, 1984). The rapid expansion of sugarcane in the early 20th century led to the large scale destruction of wetlands through the conversion of wetlands to sugarcane fields. The removal of wetlands and the subsequent removal of Eldana's natural hosts led to Eldana moving into sugarcane fields (Cockburn, 2013). Eldana's natural enemies, particularly parasitoids, are not present in sugarcane and as a result, Eldana populations have increased rapidly in the absence of a biological control (Harraca *et al*., 2011). Eldana reaches higher population densities and causes greater tissue damage in sugarcane relative to its natural host. It has been hypothesized that this is due to the higher nutritional value of sugarcane and the absence of natural enemies and parasitoids to control populations (Conlong and Hastings, 1984).

Eldana saccharina completes the larval stage of its lifecycle inside sugarcane stalks where it is protected from its natural enemies. Here, Eldana larvae consume the inside of sugarcane stalks reducing sucrose levels, causing plant damage and leading to an overall reduction in cane yield and quality (Goebel and Way, 2003). Additionally, the plant tissue surrounding the borer becomes infected by the fungus Fusarium. Eldana together with Fusarium degrade the quality of sugarcane produced by reducing stalk sucrose content and increasing plant fibre (Kvedaras and Keeping, 2007; Conlong and Rutherford 2009).

Several Eldana outbreaks have been recorded in Southern Africa's sugarcane industry. For example, Eldana surveys conducted in Zimbabwe show that the borer is widespread throughout the industry. Estimated losses in recoverable sugarcane of 0.9% were recorded for 2000 and 2001 and 1% for 2002 (Mazodze and Conlong, 2003). Goebel and Way (2005) investigated the impact of two sugarcane stem borers (*Chilo sacchariphagus* and *Eldana saccharina*) in South Africa. Table A4-1 presents Eldana damage and the extent of infestation in Gingindlovu and Empangeni, KwaZulu-Natal prior to treatment implementation.

Table A4-1: Damage level and loss caused by *Chilo sacchariphagus* and *Eldana saccharina in Gingindlovu and Empangeni (Goebel and Way 2009)*

Season	Locality	% Internodes bored*	Loss in cane mass in t/ha (%)**	Loss in sucrose in t/ha (%)**
C. sacchariphagus: Réunion				
1995/96	Sainte-Marie	13.3	28.6 (25.9%)	4.3 (27.9%)
	Saint-Paul	27.2	40.0 (26%)	4.7 (24.2%)
1996/97	Sainte-Marie	10.6	31.0 (22.9%)	4.8 (26.8%)
	Saint-Paul	5.0	8.8 (5.8%)	0.0
1997/98	La Bretagne	20.7	28.3 (21.2%)	4.2 (24.3%)
E. saccharina: South Africa				
2001/02	Gingindlovu	18.4	12.2 (15%)	3.4 (28%)
	Empangeni	17.4	8.6 (9.9%)	2.6 (22%)
2002/03	Gingindlovu	31.3	8.4 (31 %)	1.7 (50%)
	Empangeni	8.6	7.9 (9.8%)	1.2 (17%)
2004/05	Gingindlovu	14.0	7.6 (17%)	1.2 (21.4%)

* *Level obtained from the most injured plots*
** *% Yield loss:Yield from protected plots (T3) – Yield from infested plots/ Yield from protected plots x 100*

Rutherford (2015) presents a more recent snapshot of the current impacts of Eldana damage on South Africa's sugar industry (Table A4-2). It has been shown that between 1 and 4% of recoverable value (RV) can be lost for every 1% of internodes bored (%IB). For illustrative purposes Rutherford (2015) used a figure of 1.5% RV loss for every 1% IB. For example, a crop with 16.5% IB at harvest will have a reduced RV yield by another quarter (16.5%×1.5= 25%). If the final yield with Eldana damage was 7.5 tRV/ha, then a yield of 10tRV/ha would have been attained (a loss of 2.5tRV/ha from 10tRV/ha is 25%). Using the 2014 RV price of R3300 t/RV the loss is equal to R8250/ha (Rutherford, 2015). With a harvested area of 271 000 ha/annum sustaining damage of approximately 3% internodes bored, the total direct loss to sugarcane growers across the country is approximately R344 000 000 per annum.

Table A4-2: Estimated mean loses per hectare harvested by P&D are area (%IB are means for the period 2002/03-2011/12) (loss Rands/ha = 0.015×%IB at harvest ×tRV/ha ×R3300)

PD&VCC area	Average yield tRV/ha (adjusted)	Average age at harvest (mo)	Average age at survey (mo)	Average % IB in surveys	#Estimated Average %IB at harvest	(loss) Rands/ ha harvested
Malelane/Komati	11.9	13.5	11.0	1.52	**2.0**	(1180)
Pongola	11.1	14.1	11.7	0.61	**1.0**	(550)
Umfolosi	10.4	12.6	10.5	0.28	**0.4**	(200)
Felixton	8.2	13.0	11.1	0.99	**1.5**	(610)
Amatikulu	7.7	14.0	11.4	2.30	**4.0**	(1520)
Entumeni	7.7	19.0	13.4	1.69	**3.3**	(1260)
Maidstone	7.6	15.0	13.5	3.74	**5.0**	(1880)
Gledhow	7.0	14.8	12.4	3.33	**5.0**	(1730)
Darnall	7.4	14.3	11.6	2.82	**5.0**	(1830)
Eston	11.1	25.0	16.2	1.64	**3.8**	(2090)
Noodsberg/UCL	10.4	23.5	19.0	0.64	**1.0**	(520)
Sezela	8.8	17.7	14.8	2.24	**3.8**	(1660)
Umzimkulu	9.0	19.1	14.1	1.80	**3.2**	(1430)
# %IB at harvest estimated based on a linear projected mean rate of increase for the interval between average age at survey and age at harvest.				Average	3.0	(1270)

Eldana prefer older sugarcane crops and as a result, farmers harvest cane earlier than the recommended 18-24 months to protect crops from Eldana infestations (Kvedaras and Keeping, 2007; Rutherford, 2015). Harvesting cane earlier than the recommended duration has severe economic implications and according to Rutherford (2015), indirect losses due to reduced cropping duration exceed direct losses caused by Eldana infestations. Rutherford (2015) estimates direct losses at R344 million per annum whilst indirect losses due to reduced cropping duration have been estimated at R400 million per annum. Together, direct and indirect economic losses as a result of Eldana are estimated at R744 million per annum (Rutherford, 2015). The studies reviewed above illustrate the economic impact Eldana infestations have on South Africa's sugar industry. Given the economic impacts of Eldana infestations, there is a need to control and suppress populations in sugarcane. Attempts to control Eldana populations include cultural, mechanical, chemical and biological controls (Webster *et al*., 2005; Barker *et al*., 2006). Globally, there is a move away from the reliance on agrochemicals towards more sustainable ecological solutions. Agroecological strategies therefore aim to reduce the dependence on agrochemicals and to improve agricultural sustainability. Cane growers have long relied on insecticides for the control of Eldana; however the use of insecticides for Eldana management is often not effective as insecticides cannot reach Eldana larvae once it bores into the stalk of the host plant (Barker *et al*., 2006). Chemical pesticides are often applied aerially thus require multiple applications to produce significant reductions in Eldana populations. Additionally, insecticide applications are expensive and may lead to resistance in pests. Insecticides are not considered a sustainable solution for the control of Eldana populations (Khan and Pickett, 2008). In an attempt to find a more sustainable approach for the control of Eldana populations in sugarcane, the South African Sugarcane Research Institute (SASRI) has developed an Area-Wide Integrated Pest Management plan (AW-IPM) (Rutherford and Conlong, 2010). The push-pull approach to controlling Eldana populations in sugarcane forms part of the AW-IPM.

Push-pull approach to pest management

Modern agriculture tends to focus on the mass production of a single crop creating a homogenous environment favorable for pests. Habitat management therefore aims to improve the biodiversity within the agricultural system creating a more heterogeneous landscape (Khan and Pickett, 2008). The push-pull strategy, a form of habitat management, manipulates the behavior or the sensory perception of a pest repelling it away from the resource one intends to protect towards a more attractive host/source removing the pest from the plant system and/or field one intends to protect (Cook *et al*., 2007). The use of the push-pull strategy for pest management has been widely adopted across Africa. One of the most successful push-pull adoption cases is the use of the strategy to control lepidopteran stem borers of maize (*Zea Mays* L. (Cyperales: Poaceae)). To date, 30 000 smallholder maize farmers in East Africa have implemented the approach and maize yields have increased from roughly 1 t ha^{-1} to approximately 3.5 t ha^{-1} (Khan *et al*., 2010). Plants emitting specific plant volatiles are strategically planted in and/or around a field to repel pests away from the crop one intends to protect whilst the "pull" plant draws the pest towards a more favorable host. The approach aims to increase biodiversity on farms to improve natural enemy populations. This strategy provides an ecologically based approach for the suppression and control of Eldana populations in sugarcane. The push-pull approach to Eldana management aims to prevent Eldana moths from laying eggs in sugarcane thus reducing larval infestation, damage to sugarcane and improving the quality of the sugarcane produced (Cockburn *et al*., 2014; Rutherford, 2015).

The push-pull approach to Eldana management involves planting "push" and "pull" plants which repel Eldana moths from sugarcane fields and draw them towards their natural hosts in wetlands (Figure A4-1). The push-pull approach manages the behavior of the female moth by drawing it towards its natural host in wetlands which in turn reduces the number of eggs laid in sugarcane reducing larval infestation and damage to sugarcane (Cockburn and Conlong, 2011). Wetlands sedges *Cyperus dives* and *Cyperus papyrus* are the natural hosts of the larval stage of Eldana (Conlong 1990; Webster *et al*., 2005). These sedges are indigenous to wetlands throughout the coast of KwaZulu-Natal and are used as a pull plant to draw Eldana out of sugarcane fields towards a more desirable host (Figure A4-1). The use of the push-pull approach for Eldana management involves planting wetlands sedges adjacent to sugarcane fields. A range of natural enemies are present in, and attack Eldana larvae, in indigenous host plants (Webster *et al*., 2005). For example, the parasitic wasp *Goniozus indicus Ashmead* (Hymenoptera: Bethylidae) has been found to attack Eldana in *Cyperus papyrus* however not in sugarcane (Smith *et al*., 2006). The presence of parasitoids and natural enemies in host plants aids to biologically control and suppress Eldana populations.

In addition to *Cyperus dives* and *Cyperus papyrus*, *Bacillus thuringiensis* (Bt) maize is also used as a pull plant to draw Eldana moths out of sugarcane fields (Figure A4-1) (Conlong and Rutherford, 2009; Rutherford, 2015). Although Eldana is not indigenous to maize, it has been found that when compared to sugarcane, egg laying Eldana moths are more attracted to Bt and non Bt maize. An added advantage of Bt maize is that the Cry1Ab toxin in Bt kills Eldana larvae within two days of consumption making it an ideal 'dead-end' crop to pull Eldana out of sugarcane fields (Cook *et al*., 2007). The efficacy of Bt Maize is however relatively short-lived as it must be replanted if it is to effectively attract Eldana over more than one moth peak (Cockburn, 2013).

Plant volatiles are an integral part of Eldana pest management. Molasses grass (*Melinis minutiflora* P. Beauv) produces volatiles which repel Eldana moths and is used as a push plant to repel Eldana from sugarcane (Barker *et al*., 2006). *Melinis minutiflora* produces plant volatiles which repel female moths from sugarcane fields stopping them from laying their eggs in sugarcane whilst simultaneously drawing Eldana parasitoids into sugarcane fields (Harraca *et al*., 2011). For example, *Xanthopimpla stemmator* (Thunberg) (Hymenoptera: Ichneumonidae) has been found to parasitize more Eldana pupae in the presence of molasses grass than in sugarcane alone (Conlong and Rutherford, 2009). Barker *et al*. (2006) showed that the presence of Molasses grass was able to reduce Eldana populations and damage by up to 50% and 57% respectively proving its ability to repel Eldana from sugarcane. Molasses grass can be planted along contours in sugarcane fields roughly 20 rows apart and about 20 rows from the wetland (Cockburn and Conlong, 2011). Molasses grass is not shade tolerant and does not pose the risk of becoming a weedy species that will encroach into cane fields (Rutherford, 2015, Mulcahy, 2018). Molasses grass grows best in well-drained soils in a sunny position. Prior to planting molasses, contours must be sprayed with glyphosphate herbicide to kill any weeds present reducing competition (Rutherford, 2015). An added advantage of using molasses grass as a repellent is that it may be used as cattle fodder.

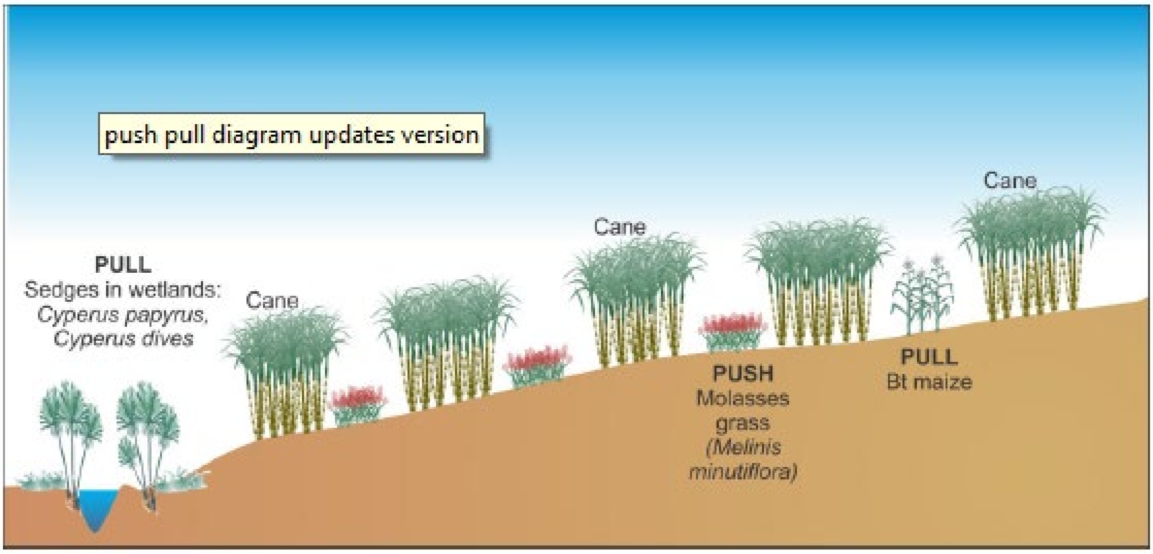

Figure A4-1: Push-pull approach recommended for management of Eldana *saccharina* Walker (Lepidoptera: Pyralidae) in sugarcane (Cockburn *et al*., 2014).

The use of wetlands for the control of *Eldana saccharina* in sugarcane

Wetlands play a critical role in the successful implementation of the push-pull approach to Eldana management as they provide a habitat for wetland sedges *Cyperus dives* and *Cyperus papyrus* which are the natural hosts of Eldana (Cockburn, 2013). The National Water Act (Act No. 36 of 1998) defines wetlands as “land which is transitional between a terrestrial and aquatic system where the water table is usually at or near the surface or the land is periodically covered with shallow water, and land which in normal conditions supports or would support vegetation adapted to life in saturated soil.” *Cyperus dives* is an obligate wetland plant which grows in marshy wetlands, drains and the margins of water bodies. Similarly, *Cyperus papyrus* is also an obligate wetland plant which grows in slow moving or standing water and marshy wetlands making *dives* and *papyrus* suitable for planting in wetlands (Rutherford 2015). By providing indigenous Eldana hosts and parasitoids adjacent to sugarcane fields, farmers are able to suppress pest infestations allowing them to extend growing periods. When compared to the use of insecticides and pesticides, rehabilitating and/or implementing riparian buffers provides a more sustainable option for the control of Eldana populations in sugarcane.

Cockburn (2013) investigated the efficacy of the push-pull strategy for the management of Eldana in the KwaZulu-Natal Midlands North region. The study was conducted in four model farms with each having a push-pull treatment, a control and a wetland. Maize and molasses grass were planted along contour banks. Surveys of Eldana damage and infestation were conducted on the control and treatment to determine whether the push-pull strategy was successfully drawing Eldana out of sugarcane. Here, sugarcane stalks were split along their length and the total number of internodes damaged was counted for every stalk. Cockburn (2013) found that the percentage internodes and stalks damaged over the sampling period were inconsistent. Higher stem borer damage levels were recorded in the treatment of two out of the four study sites. This was attributed to poor crop management (i.e. growing sugarcane beyond the recommended growing season and poor crop variety choice). The other two farms exhibited a two-thirds reduction in Eldana damage when the push-pull strategy was implemented. Lower damage levels were attributed to the presence of M. minutiflora. Cockburn (2013) illustrates that the push-pull approach to Eldana management; the push component in particular, can reduce Eldana damage in sugarcane. Poor crop management limited the ability of the push-pull approach to suppress Eldana damage thus it is important that the push-pull strategy is implemented as part of an integrated pest management strategy including crop husbandry. Model farms used for the push-pull trials were also used to study the ecology of stem borers in wetlands. *Cyperus dives* had the highest number of Eldana larvae proving its ability to successfully draw Eldana moths out of sugarcane fields.

Mulcahy (2018) investigated the efficacy of the push-pull approach to Eldana management on Eldana populations in two coastal sugarcane growing regions namely the north and south coast of KwaZulu-Natal. This study was conducted on five model farms where a push-pull treatment and a control were implemented on each farm with each including a wetland. Wetlands at each push-pull site were rehabilitated removing any invasive plants and sugarcane present as well as transplanting wetland sedges from neighboring farms to those without. Sugarcane stalks were randomly sampled from the control and treatment on each farm to determine Eldana populations and the extent of Eldana damage. The total number of internodes and internodes damaged per stalk were also recorded. Mulcahy (2018) recorded a significant decrease in the number of sugarcane stalks damaged on the push-pull sites in four of the five farms. On one of the treatments, a slight increase in the number of Eldana per 100 stalks as well as the number of stalks damaged was recorded. An overall reduction in the number of Eldana larvae found per 100 stalks was recorded in most of the push-pull sites. At the end of the study period, Eldana surveys were done on the rehabilitated wetlands to verify whether sedges were successfully attracting Eldana moths out of the sugarcane fields. Here, plant stalks, umbels and rhizomes were assessed for the presence of Eldana and the extent of Eldana damage. High Eldana populations and plant damage was recorded in the wetland sedges across all 5 farms with *Cyperus dives* having higher levels of damage and higher Eldana populations. Mulcahy (2018) shows that the push-pull approach to Eldana management effectively reduced the number of sugarcane stalks damaged on 80% of the model farms while simultaneously increasing Eldana populations in indigenous wetland sedges proving the approaches ability to control Eldana infestations in sugarcane.

Wetland health plays an important role in the successful implementation of the push-pull strategy. Wetland assessments conducted by Cockburn (2013) showed that the wetlands on the model farms were all in a modified condition and had invasive alien plants therefore could not maximize the potential habitat for sedges and stem borers. Thus by rehabilitating wetlands, farmers could increase the habitat available for Eldana which would provide a strong "pull" for egg-laying Eldana moths. Mulcahy (2018) rehabilitated wetlands on the model farms prior to implementing the push-pull strategy. From the studies reviewed above, it is clear that the Mulcahy (2018) study yielded better results indicating that the rehabilitation of wetlands plays an important role in the successful suppression and control of Eldana populations in sugarcane.

Farmer's perceptions on the use of the push-pull approach to Eldana management

A thorough understanding of grower's perceptions of pests and pest management is required for the successful implementation of knowledge intensive pest management approaches such as the push-pull strategy (Cockburn, 2013). Approximately 20% of sugarcane growers in the Midlands north region have adopted the push-pull strategy to Eldana management with roughly 5% choosing to implement both the pull and push components of the strategy (Cockburn, 2013). Cockburn (2013) assessed the adoption of the push-pull approach to Eldana management by large scale growers (LSG) in the Midlands north region. Fifty-three LSG were interviewed as part of the study and of the total number of farmers interviewed 36 had adopted the push-pull approach either partially of fully and 17 had not. The decision not to adopt the push-pull approach varied across famers with the "hassle" around implementing the push-pull approach and the cost of implementation being the greatest barriers to adoption. LSG's were often reluctant to implement the strategy as it requires additional resources such as labour. Another perception amongst some LSG's is that the planting of wetland sedges attracts Eldana to the farm as sedges provide a natural habitat for Eldana. LSG's are less likely to adopt the push-pull approach to Eldana management if they believe that healthy wetlands draw pests to their farms. A large majority of LSG's who had partially implemented the push-pull strategy did so by planting *Cyperus* in their watercourses. This was largely due to the fact that once planted, sedges require very little maintenance. The push plant *Melinis minutiflora* was deemed a "hassle" as it requires greater management.

Overall, Cockburn (2013) found that the majority of LSG's in the Midlands North were accepting of the push-pull approach to Eldana management. It also became apparent that the "hassle" around implementing the strategy is a barrier to implementation. Lastly, LSG'S who partially implemented the strategy preferred planting wetland sedges indicating that wetland rehabilitation is the most feasible approach to Eldana management. With this being said, when compared to planting molasses grass, farmers are more likely to adopt and implement the use of wetlands for the control of Eldana.

Expert consultation

A meeting with Dr. Desmond Conlong, Senior Entomologist, South African Sugarcane Research Institute[22], was conducted in April 2019. The information gathered from the interview supported the literature reviewed as part of this study. Dr. Conlong highlighted the importance of the push-pull approach for the successful control of Eldana populations. Farmer's perceptions and the acceptance of the push-pull approach was also discussed. Additional management time and resources (e.g. labour) are a primary concern in adopting a push-pull approach. Wetland rehabilitation ('pull') is generally considered more appealing, as it often reduces management requirements once the vegetation is established. Maize may be considered too much work as it requires additional management regarding timing. Generally, farmers preferred to plant wetland sedges as they are low maintenance once planted. Dr. Conlong emphasized, however, that a combination of both the 'push' and 'pull' components is most effective for Eldana control. The "pull" component of the strategy is most effective in areas where the sugarcane fields are close to/adjacent to wetlands. The ability of wetlands to "pull" Eldana out of sugarcane fields diminishes as one moves away from wetlands. With this being said, it is important that both the "push" and "pull" components of the strategy are implemented. The role of extension officers in the successful implementation of the push-pull strategy was discussed. Generally, one-on-one contact ensures that sugarcane growers follow through with the strategy at hand. Growers are more accepting of "hassle free" approaches and become increasingly reluctant the more complicated a strategy seems. Lastly, communication with extension staff and farmers reveals that there has been an improvement in the quality of water in "push-pull" fields.

Conclusion

The literature reviewed, together with input from the Senior Entomologist at the SASRI, suggest that healthy wetlands and riparian areas play an important role in the suppression and control of Eldana populations in sugarcane through the push-pull approach as part of an integrated pest management strategy. Based on the literature reviewed here, the push-pull approach appears to be an effective strategy, particularly as part of a broader integrated pest

[22] Des Conlong, Senior Entomologist, SASRI; Professor Extraordinary, Department of Conservation Ecology and Entomology, Stellenbosch University; Honorary Senior Lecturer, School of Biological and Conservation Sciences, UKZN.

management approach, for the control of Eldana in sugarcane. The successful implementation of the push-pull approach to Eldana management is dependent on sugarcane grower's acceptance and willingness to implement the strategy. From this review, it became apparent that sugarcane farmers prefer to partially implement the push-pull strategy by planting *Cyperus* in wetlands adjacent to sugarcane. Wetland rehabilitation and the planting of wetland sedges are more appealing to farmers than the planting of molasses grass and maize within fields which is associated with greater management requirements.

Wetlands and riparian areas that are in good condition and provide a habitat for Cyperus dives and Cyperus papyrus have been shown to contribute to the control of Eldana populations in sugarcane. Establishing watercourse buffers within sugarcane cultivation supports the improvement and maintenance of wetland condition[23]. However, the use of buffer zones for improved watercourse management has not been taken into consideration as part of the push-pull approach to controlling Eldana populations. The effectiveness of buffer zone implementation as part of the push-pull approach to managing Eldana populations in sugarcane requires further investigation.

Further to supporting the health of wetlands, the buffer areas themselves could provide habitat for Eldana parasitoids and predators. In this regard, senior entomologist at the South African Sugarcane Research suggested the following:

- Planting a mix of flowering forbs, grasslands, indigenous trees and shrubs in the buffer would increase the biodiversity of the buffer zone drawing Eldana parasitoids and predators to the sugarcane area.
- Trees, for example, are good roosts for bats which feed on Eldana moths. Shrubs, grasses and flowering plants could provide nectar and pollen for foraging fly and wasp parasitoids and predators.
- Apart from being a useful biocontrol for Eldana, increasing the biodiversity in the buffer zone can also act as a biocontrol for other sugarcane pests such as the yellow sugarcane aphid and sugarcane thrips.

The findings suggest that sugarcane farmers may be willing to implement buffer areas given the pest regulatory services they provide.

[23] Establishing watercourse buffers implies the removal of sugarcane from, and the rehabilitation of, the watercourse (wetlands and streams).

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Appendix 5: Improved management of floodplains planted with sugarcane

Large floodplain systems are particularly complex, and unique systems and typically require management strategies and practices designed specifically for the floodplain in question (i.e. fine scale decision-making is required). Considerations and options for the management of floodplain systems within sugarcane cultivation were explored through interrogating existing relevant research. Key aspects are highlighted in the following sections; see Deliverable 3, this project, for a detailed review.

Floodplains are defined as valley bottom areas with well-defined river channels characterized by floodplain features such as natural levees and oxbow lakes (Kotze *et al*., 2008). Floodplains are subject to inundation by lateral water flows from adjacent rivers, which results in alluvial material deposits and an accumulation of sediment. The continued deposition of nutrient-rich sediments has made floodplains amongst the most productive landscapes (Tockner and Stanford, 2002).

Given their high productivity, floodplains have been the focus of human habitation and development for centuries leading to the degradation of their ecological integrity (Brown *et al*., 2018). In KZN, the removal of riparian vegetation for sugarcane production has been a driver of floodplain transformation. For example, sugarcane has been grown on the Mfolozi floodplain since 1911, with the current sugarcane production area on the floodplain estimated at 10 000 ha (Searle, 2014). Sugarcane production in KZN is predominantly in the north and south coast as well as in the Midlands North region. However, floodplains planted to sugarcane are primarily located along the North Coast sugarcane production area (Figure A1-1).

This review[24] aims to highlight possible recommendations for the management of floodplains planted to sugarcane. However, given the level of transformation of floodplains within the sugarcane production areas (Figure A3-1), it is important to highlight some of the key drivers of floodplain transformation, and therefore some of the challenges with trying to develop guidelines for improved management of floodplains planted with sugarcane.

Apart from sugarcane production, KZN's floodplains have been severely transformed by other factors including reservoirs, river channelization, artificial levees and the draining of wetlands (Hupp et al., 2009; Van Heerden, 2011). The modification of river flows as a means of controlling and/or storing water alters the pattern and volume of river flows with the net result

[24] See Deliverable 3, this project for additional detail.

being a change in the timing, frequency and duration of floodplain inundation (Brown et al., 2018). Generally, floodplains along dam regulated rivers are flooded less frequently than those along non-regulated rivers (Hupp et al., 2009). For example, the construction of the Pongolapoort dam on the Pongola River has significantly altered the hydrological behavior and ecological response of the floodplain downstream (Deliverable 3, this project). In addition, developments upstream of existing reservoirs have a cumulative impact on controlled flow releases. For example, the construction of the Bivane dam upstream of the Pongolapoort dam has reduced flow into the dam. Reduced spills into the downstream reaches of the river have also occurred as a result of the Bivane dam (Brown et al., 2018).

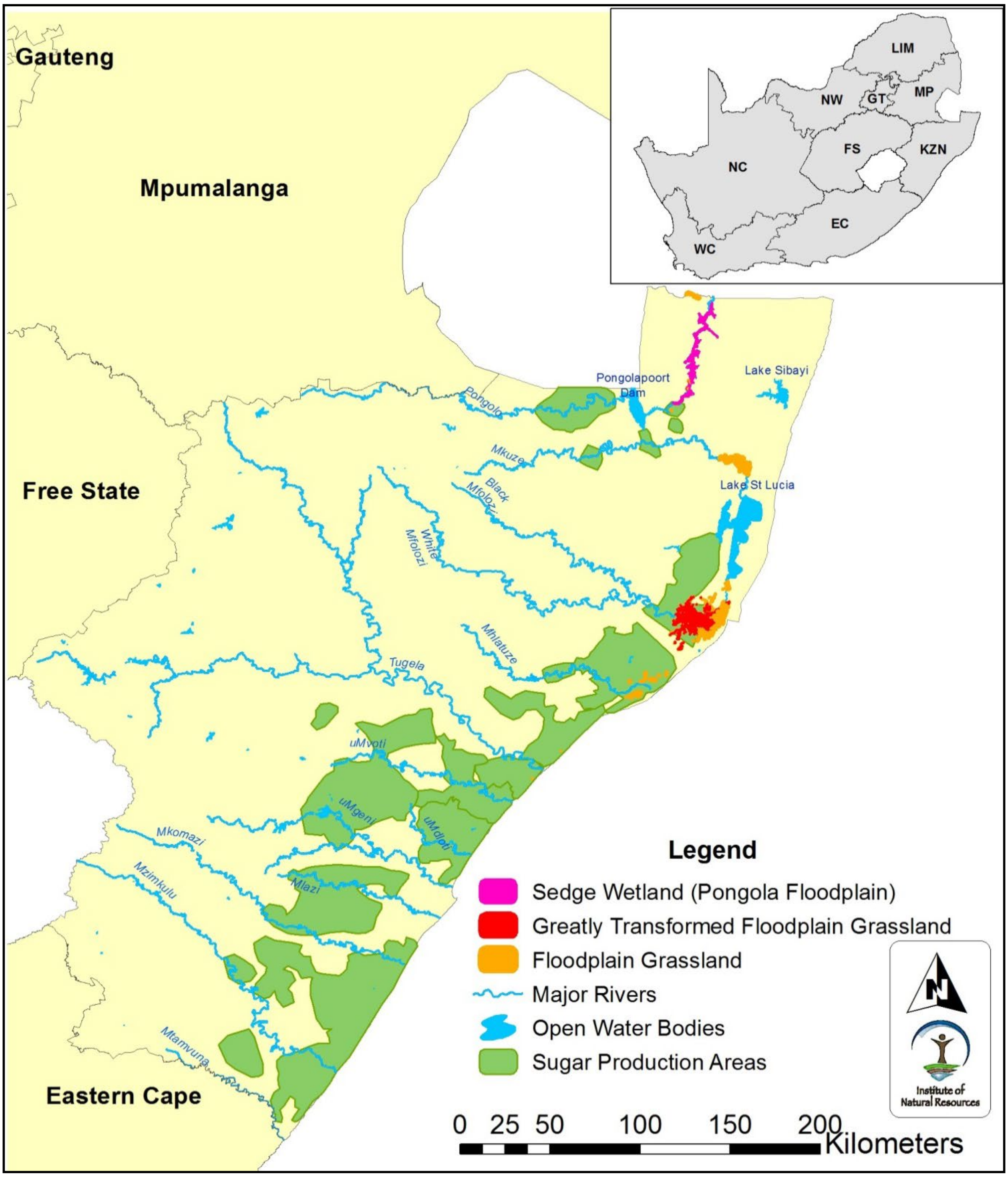

Figure A5-1: Distribution of floodplains, according to the provincial wetland layer, and sugarcane production areas in KZN.

The retention of sediment in reservoirs restricts the movement of sediments downstream and onto the floodplain, compromising the ecological integrity of downstream ecosystems. For example, the Pongola River has a relatively low sediment load; the trapping of sediments in the Pongolapoort dam reduces the river's sediment loads even further compromising the health of the downstream floodplain (Heeg and Breen, 1982).

The channelization of rivers and the construction of artificial levees alters the connectivity between river channels and the floodplain which restricts the spread of sediment onto adjacent floodplains increasing river sediment loads (Hupp et al., 2009). While sediment is important for maintaining floodplain health, high river sediment loads have an adverse impact on downstream ecosystems. For example, the Mfolozi floodplain is inextricably linked to St. Lucia Estuary; any land-use / land management practices implemented on the floodplain have a knock-on effect on the ecological integrity of the lake system (Van Heerden, 2011).

Based on the literature review (see Deliverable 3 this project), existing evidence indicates that KZN's floodplains have been significantly transformed, with each floodplain being influenced by different processes. While some initial guidelines for improved management of floodplains planted with sugarcane have been recommended, it is important to note that due to the uniqueness of the individual floodplains, and the drivers of transformation, it is suggested that the management of floodplains be approached on a 'system by system' basis. Thus, allowing for specific management measures taking into account the uniqueness of each system, to be determined for the respective floodplains planted to sugarcane.

Initial guidelines for the improved management of floodplains planted with sugarcane include:

1. Reconnect the floodplain to restore the interactions between the river and its floodplain by increasing the frequency of overbank flows, resulting in a regaining of hydrologic and ecological function. This could be achieved through:
    a. Sugarcane fields that are below or close to sea level should be allowed to revert back to wetlands (i.e. rehabilitated wetland habitat in key areas / locations along a floodplain);
    b. The lower portions of the floodplain, including where sugarcane is present, should be used as overflow pathways to remove suspended sediments before water exits the floodplain system (this is especially important during periods of drought).
2. Spillways or training works should be implemented within the floodplain as a means of diverting sediment-laden flood waters to low-lying basins to capture sediments so that relatively free flood waters reach downstream (i.e. estuary) during flood events.
3. Alien invasive plants and other forms of disturbances should be removed to allow indigenous grasses, reeds and sedges to regenerate. A mulch of grass heads from similar habitats should be applied to severely degraded areas.
4. Where appropriate, key local riverine tree species should be planted along the river course. Trees should be planted in clumps at stress points in degraded areas. The areas should be maintained by watering saplings, controlling weeds and protecting the area to encourage natural processes to rehabilitate stream bank vegetation.

5. Managing runoff water on the floodplain can minimize soil erosion and maintain river water quality. Filter strips can be installed on the floodplain to filter nutrients and sediments from runoff and groundwater flows. The planting of grasses, reeds and sedges in drainage areas can prevent and / or trap the loss of nutrients, as plant roots can facilitate the breakdown of nutrients and pesticides.

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