The Cumulative Effect of Wetland Degradation on Water Quality at a Landscape Scale

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As the candidate's supervisor I have/ have not approved this thesis/ dissertation for submission.

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Abstract

Wetlands have been described as "one of the most globally threatened and important ecosystems", with most wetlands providing a variety of important ecosystem services, including water quality enhancement. Despite their importance the loss of wetlands is more rapid than that of any other ecosystem, which is of particular concern in South Africa, where many communities are directly and indirectly dependent on wetlands for survival.

Two useful wetland assessment tools are currently used in South Africa, but a system that assesses the extent to which wetland ecosystem services (water quality enhancement in particular) are lost as a result of wetland degradation in a landscape context does not currently exist. This study therefore aims to develop a method to determine the cumulative effect of wetland degradation on water quality, which involves the exploration and integration of a number of issues, including land-cover and its effects on water quality, wetland health and its influence on the provision of ecosystem services such as water quality enhancement, and the spatial configuration of wetlands in a landscape, and its effect on water quality at a landscape scale.

The method that has been developed is applied to a case study that comprises a quaternary catchment of the upper reaches of the Goukou River Wetlands in the Western Cape of South Africa. Prioritisation criteria are also explored in a series of scenarios, and the criterion and rehabilitation method that gives the best outcome in terms of water quality enhancement is applied to the case study catchment. The workings of the method are scrutinized and benefits and limitations are subsequently highlighted. An important benefit of the methodology is that many previously inadequately explored issues are integrated into a single tool that allows for prioritisation of wetlands for rehabilitation and conservation. This was achieved with South African contexts in mind.

Limitations include poor responses by potential questionnaire respondents, while the scope of the study limits the inclusion of detailed aspects which would have further enhanced the accuracy of the tool and of the level of water quality enhancement explored. The methodology that is developed in this research has also not been applied to catchments with good long term water quality data in order to improve its validity.

Recommendations for future research are made, which include possible refinement of the system by accounting for factors not included in the current methodology, validation of the system by applying it to a catchment with good water quality data, and the creation of software to make the system easier to use.

Preface

The experimental work described in this dissertation was carried out in the School of Environmental Science, University of KwaZulu-Natal, Durban, from June 2007 to December 2009, under the supervision of Professor Fred Ellery, Dr Fethi Ahmed, and Dr Donovan Kotze.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

Declaration

I, Charissa Jaganath, declare that

1. The research reported in this dissertation, except where otherwise indicated, is my original research.

2. This dissertation has not been submitted for any degree or examination at any other university.

3. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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   a. Their words have been re-written but the general information attributed to them has been referenced
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5. This dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed

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CHAPTER ONE: OVERVIEW

1.1 Introduction

Kotze *et al*. (2007) describe wetlands as an ecosystem that is both one of the most globally threatened and also one of the most important. They form an important feature of the landscape, both in South Africa and around the world. The value of wetlands stems from their role as an interface "between terrestrial and aquatic environments, and between groundwater and surface-water systems" (Ellery *et al.*, 2005, p3). A variety of ecosystem services are attributed to wetlands, including flood control through the storage of surface water, stream flow maintenance, nutrient cycling, erosion control, and water quality protection (Kotze and Breen, 1994) the last of which is often considered to be particularly valuable. Water quality maintenance is achieved through the removal of sediment, nutrients and toxins from the water that flows through them (Kotze and Breen, 1994).

Furthermore, the importance of wetlands to a variety of both plant and animal species is considered to be invaluable. Tree production, herbaceous plant growth, and a range of wildlife habitats are supported by wetland environments. Wetlands are also a source of fibre for craft production and homestead construction, as well as being an important source of fish and wildlife that provide protein to local people. Wetlands also provide plant foods and medicinal products that directly benefit local people living adjacent to wetland environments.

Despite the growing acknowledgement of the importance of wetlands, it has been found that their loss and degradation is more rapid than that of any other ecosystem, with between 35 and 50% of wetlands in South Africa having been drastically degraded or destroyed (Swanepoel and Barnard, 2007; Millennium Ecosystem Assessment, 2005). The conversion of wetlands to intensive agriculture, aquaculture and industrial zones, pollution, recreation, and especially a lack of awareness and appreciation of wetland value, have all contributed to this loss (Oellermann *et al.*, 1994). This is of particular concern since the recognition that many communities are directly and indirectly dependent on South Africa's wetlands for survival (DEAT, 2006; McCarthy *et al.*, 2009), highlighting the critical role that is played by the above-mentioned ‘goods and services’ that wetlands provide.

1.2 **Problem Statement (Motivation)**

Two wetland assessment tools are currently widely used in South Africa: WET-Health (Macfarlane *et* al., 2008) and WET-Ecoservices (Kotze *et al*., 2007). However, a system that assesses the extent to which wetland ecosystem services are lost as a result of wetland degradation was only recently developed by Ellery *et al.* (in review). The application of this tool to case studies, as is conducted in this research, was a necessary step in exploring its usefulness, as well as in using it to address the issues of wetland degradation and the loss of ecosystem services in a landscape context.

Swanepoel and Barnard (2007) emphasize the fact that wetlands cannot be managed in isolation, and that the entire catchment should be addressed in wetland conservation. While there has been extensive research on the areal extent of wetland degradation and loss, a gap exists in evaluating these losses in a cumulative manner at a sub-catchment or catchment scale (Tiner, 2005). These individual effects, according to Bedford and Preston (1988), are cumulative in nature, which can be defined as “the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions” (p566). Johnston *et al.* (1990) further point out that the cumulative effect of individual impacts is often larger than the sum of the individual wetland impacts, since cumulative impacts on wetlands are related both to the nature and scale of impacts as well as the spatial arrangement and functions of wetlands within the landscape context.

By building an understanding of how these wetlands function together and influence each other, decision-making may be greatly aided. By doing so, wetlands with the greatest potential for specific ecosystem service provision such as water quality maintenance, may be prioritised for rehabilitation and protected from unsuitable development in the wetland or its catchment. This is of particular value when considering that wetland managers often have limited funding with which to protect wetlands, highlighting the necessity for a tool that allows for the estimation of possible benefits of particular wetland management projects (Ji and Mitchell, 1995).

This modelled approach may further allow for the development of a model in a GIS. Lyon and McCarthy (1995) believe that there is currently an absence of spatially integrated models for water resource management. It is pointed out that “many models use spatial data but average or summarize these data by watershed and/or subwatershed, and thereby lose much of the detail of spatial variability that often influences phenomena” (p4). The inclusion of this aspect in water resource management would provide “high quality model simulations” (p4).

In South Africa, great emphasis has recently been placed on the importance of maintaining water quality, more so as awareness grows of the fact that water resources are scarce and limited (Swanepoel and Barnard, 2007). A right to water is specified in the National Water Act, that of the Reserve, which comprises the basic human needs Reserve and the ecological Reserve (Mackenzie *et al.*, 1999). The former includes water for drinking, the preparation of food and personal hygiene, while the latter must be determined for any large water resource such as rivers, streams, wetlands and lakes. Water quality and quantity maintenance is therefore of enormous importance in order to meet the requirements of the Reserve. Despite this, the widely-used tool that currently assesses wetland health in South Africa (Macfarlane *et al*., 2008) does not have a water quality component. This study has therefore chosen to focus on water quality. An Analytical Hierarchy Process was used to capture the wisdom of specialists with some understanding of catchments and the relationship of land use with water quality, in order to quantify the relationships between land use and deviation of water quality from the natural reference condition in a catchment.

It was expected that different experts will provide different scores and viewpoints on the effect of land-cover on water quality, and as is pointed out by Woods (1997), “all decision making by humans has a subjective component” (p13). Many techniques have been developed with a view to minimising subjectivity, one such technique being the Analytic Hierarchy Process (AHP), further discussed in Section 2.6, which allows for the pair-wise comparison of factors under evaluation, in this case, the different land-cover classes. The AHP in the form of a software package such as Decision Analyst (Coastal CRC, 2005) then mathematically quantifies the results of these comparisons through a series of steps, to arrive at a final weight (or score) for each factor.

1.3 **Research Aim and Objectives**

This research project aimed to develop a methodology to account for the catchment context of wetlands in assessing the cumulative effect of wetland and catchment degradation on water quality.

The specific objectives of the study were:

- To establish on a scale of 0 (no impact) to 10 (severe impact) the impact of different catchment land-cover classes on the water quality delivered to wetlands, through consultation with experts using an Analytical Hierarchy Process (AHP)
- To establish the role of wetlands in improving water quality based on water quality entering the wetland and the health of the wetland, using a loss-of-function metric that relates the water quality enhancement function of the wetland concerned to the health of the wetland
- To incorporate the effect of the spatial configuration of wetlands in a catchment on water quality in order to establish an overall catchment score for water quality as a basis for helping decision-makers prioritise wetlands for conservation, protection and rehabilitation
- To apply the developed methodology to a single case study catchment with a number of sub-catchments and wetlands: the Goukou River Catchment
- To highlight benefits and determine limitations of the developed methodology, and to propose future research possibilities

1.4 **Structure of the Dissertation**

This study is comprised of six chapters. Chapter One has highlighted the importance of, and the challenges faced by wetlands in terms of water quality and cumulative effects assessment; and the aim and objectives of the study. Chapter Two presents the literature review of wetlands and their defining elements; existing wetland assessment tools; and a recently developed tool by Ellery *et al*. (in review) entitled “A Method for Assessing the Cumulative Impacts on Wetland Functions at the Catchment or Landscape Scale”, which forms a pivotal component of this study. The variety of effects of catchment land-cover on water quality; the concepts related to landscape-level impacts and cumulative effects; the Analytical Hierarchical Process; and wetland applications of GIS are also further discussed in Chapter Two. Chapter Three focuses on the description of the case study site, while Chapter Four describes the materials and methods used in achieving the aims and objectives of the study. Chapter Five contains the results acquired and the relevant discussions thereof, while Chapter Six aims to conclude the research and to provide appropriate recommendations for future research endeavours.

Note: the word ‘effect’ has been used as much as possible in place of the word ‘impact’, even though the standard terminology is ‘cumulative impacts’. According to Bedford and Preston (1988), the word ‘impact’ connotes a value judgement. Changes brought about by the cumulative nature of a process are the cumulative effects, and those that are negative are deemed ‘impacts’. Thus, ‘effects’ is often a less loaded, more appropriate word.

CHAPTER TWO: LITERATURE REVIEW

2.1 **Wetlands: An Overview**

2.1.1 Definition

Wetlands possess a unique role in the environment as an interface between aquatic and terrestrial systems (Ellery *et al.,* 2005). Over time, many definitions have been formulated in attempts to capture the important attributes of these enigmatic systems, the reason for which is that often, "the definition of wetlands depends on the objectives and the field of interest of the user" (Mitsch and Gosselink, 1993, p28). Tiner (1999) refers to the fact that regional differences in climate, hydrological regimes, geomorphological processes and settings, and the varied presence of wetland plant communities have resulted in the emergence of many terms to describe individual wetlands. Wetland definitions have been written and re-written over time, and as of late, a widely used definition for wetlands is the one adopted by the Ramsar Convention, an international treaty for wetland conservation (Keddy, 2000, Tiner, 1999). In it wetlands are designated as:

"areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt including areas of marine water, the depth of which at low tide does not exceed 6 metres. "Wetlands" may incorporate riparian and coastal zone adjacent to wetlands, and islands or bodies of marine water deeper than 6 metres at low tide lying within the wetlands" (Ramsar Information Bureau, 1998 in Tiner, 1999).

Although useful, it has been found that this broad definition is not always appropriate at a (South African) national level, and the Department of Water Affairs and Forestry (DWAF) has subsequently chosen to define wetlands more narrowly. Wetland ecosystems are defined by the National Water Act, Act No 36 of 1998 as:

"land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil".

DWAF (2005) in Swanepoel and Barnard (2007) offers the simplest of definitions: "any part of the landscape where water accumulates for long enough and often enough to influence the plants, animals and soils occurring in that area, is a wetland" (p2). As was previously described, these definitions have been known to vary between the various stakeholders involved with wetlands, but the three main common components mentioned within them, namely, the presence of water (hydrology), unique soil conditions, and the presence of vegetation adapted to saturated conditions, are indicators that these aspects are considered to be the most important when defining wetlands.

2.1.2 Hydrology

The science of the properties of the earth's water, especially of its movement in relation to land is known as 'hydrology,' and the importance of hydrology to both the structure and function of wetlands cannot be underestimated. Bedford (1996) states that in exploring wetland mitigation, an understanding of the complexity of wetland hydrology is paramount. Mitsch and Gosselink (1993) go so far as to describe wetland hydrology as "probably the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes" (p68), and have identified five general principles which underscore the importance of wetland hydrology (Mitsch and Gosselink, 1986 in Nkosi, 2006, p24):

1) Wetland hydrology aids the establishment of a distinctive composition of wetland vegetation, but can limit or enhance species richness.
2) Flowing conditions and pulsing hydroperiod greatly enhance ecosystem functions and primary productivity, while stagnant conditions limit these processes.
3) Through its influence on primary productivity, decomposition, and export, wetland hydrology determines the accumulation of organic matter.
4) Hydrologic conditions yield considerable influence over nutrient cycling and nutrient availability.

5) Hydrology affects the development of anaerobic soil conditions, which in turn influence the loss of soil organic matter.

Mitsch and Gosselink (1993) therefore note that wetland hydrology greatly affects a variety of abiotic factors, including “soil anaerobiosis, nutrient availability and salinity” (Mitsch and Gosselink, 1993, p67). These conditions in turn affect the biotic components of the wetland in the form of plant and animal species present, which subsequently play a notable role in continuing the cycle by further altering the wetland hydrology. Clearly, a general understanding of the inflows and outflows of water and the balance between them is of immense value in aiming to understand the wetland processes which are so heavily dependent upon hydrology.

Mitsch and Gosselink (1993) highlight the factors that must be considered in the determination of the water balance of a wetland, and state that one of the most important is that of wetland hydroperiod. Defined as “the seasonal pattern of the water level of a wetland” and as its “hydrologic signature” (p72), wetland hydroperiod is based on factors such as seasonal variations in surface and subsurface water, wetland topography, and proximity to alternate sources of water. The water budget, which encompasses the inflows and outflows of water which determine the hydroperiod, can be determined through the measurement of a number of influencing factors, including net precipitation (which includes rainfall and snowfall), surface inflows (such as overland flow and channelized streamflow), evapo-transpiration (which refers to the combined effects of evaporation and transpiration on the water leaving the wetland system), surface outflows, and groundwater inflows and outflows, the last of which is often of great significance, depending on the wetland type (Mitsch and Gosselink, 1993). Groundwater inflows occur when the level of the surface water of a wetland is hydrologically lower than that of the water table of the land surrounding it, resulting in what is known as a discharge wetland. Alternatively, water will flow out of a wetland when its water table is hydrologically higher than the surrounding land, causing a recharge wetland to occur. The hydrologic pathways mentioned above allow for energy and nutrients to be transported to and from wetlands, and influence factors such as water depth, patterns of flow, and the frequency and duration at which flooding occurs. These factors subsequently influence the biochemistry of the soils prevalent in the wetland and reduce the rate of diffusion of oxygen into the soil, creating a hostile environment for plants and animals.

2.1.3 Hydromorphic Soils

The distinctive hydrologic conditions prevalent in wetlands have substantial influence on the biogeochemical processes within them (Mitsch and Gosselink, 1993). Hydrology is the main driver behind the many physical, chemical, and biological processes that transport and transform the chemicals within wetland soils, making them unique and allowing for the persistence of only specifically adapted wetland plants.

Given the hydrological cycle that determines the presence of a wetland in a landscape, it is expected that soil conditions and resultant biogeochemistry would occur as a result of prolonged flooding or exposure to water. As such, hydromorphic or hydric soil is wetland soil that the U.S.D.A. Soil Conservation Service (1985) has defined as:

"soil that in its undrained condition is saturated or flooded long enough during the growing season to develop anaerobic conditions that favour the growth and regeneration of hydrophytes".

An aquic moisture regime or signs of wetness within 50cm of the soil surface is often further used as criteria for classifying soils within aquic suborders (Kotze *et al.*, 1994).

Kotze *et al.* (1994) point out that a major distinction is often drawn between two particular soil types, both in general soil classification schemes and in hydric soil classifications - organic soils and mineral soils. The former has been categorized as having been saturated with water for prolonged periods, and displaying more than 18% organic carbon by weight if 60% or greater of the mineral fraction is clay; displaying more than 12% organic carbon by weight if the mineral fraction has no clay; or displaying a proportional content of organic carbon by weight if the clay content of the mineral fraction varies between 0 and 60%. Alternatively, mineral soils have less organic carbon than is described above.

The importance in distinguishing between these two soil types in wetlands lies in the differences in the ways that these soils react to their exposure to water. Organic soil particles are less dense than mineral soil materials, resulting in low bulk density (the dry weight of soil per unit volume) (Kotze *et al.*, 1994). The capacity of water to be held by this type of soil is thus greater than that of mineral soils. Furthermore, organic soils have a greater cation exchange capacity than mineral soils, an attribute that Ketterings *et al.* (2007) describe as the ability of the soil to hold onto positively charged ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), sodium (Na^{+}), hydrogen (H^{+}), aluminium (Al^{3+}), iron (Fe^{2+}), manganese (Mn^{2+}), zinc (Zn^{2+}) and copper (Cu^{2+}). Because negatively charged particles attract positively charged ones, the negatively charged clay and organic matter particles in organic soils draw and hold the cations by electrostatic force.

It is notable that saturated soils are forced to undergo a variety of processes: oxidation, aerobic decomposition, leaching and dehydration (Keddy, 2000), the consequences of which include the solubility of toxic chemicals such as iron, manganese and sulphides, the mobilisation of associated chemicals such as phosphates and silicates, and changes to soil pH (Barnes, 2006, pers. comm.). Given these conditions, organisms living in wetlands have a number of challenges to face, including a deficiency in oxygen, the presence of accumulated toxic gases, and atypical ion concentrations (Keddy, 2000). It is for this reason that plants that flourish in such harsh conditions, known as hydric plants, are considered to be some of the most highly adapted and specialised.

2.1.4 Vegetation

The presence of plants specially adapted to life in saturated soil conditions is often used, along with hydric soils, as an attribute that helps define wetlands (Keddy, 2000). As Keddy (2000) points out, this is for the simple reason that plants cannot move away when conditions become unfavourable, and are thus adapted to withstand the "strong environmental pressures" (p37), such as oxygen deficiency, the presence of accumulated gases, and elevated ion concentrations imposed by wetlands. While aquatic plants are not able to deal with the periodic drying that takes place in wetlands and terrestrial plants are not equipped for prolonged periods of flooding, specially adapted plant species known as hydrophytes, are (DWAF, 2005c).

As was previously mentioned, one of the most severe stresses that wetland plants are required to contend with are the prolonged periods of saturation which bring about anaerobic soil conditions (DWAF, 2005c). These conditions cause the unavailability of certain nutrients required by plants, can harmfully increase the concentrations of particular elements in the soil, and can disable plants from respiring through the usual metabolic pathways. In order to deal with such stresses, hydrophytes have developed morphological, physiological, and/or reproductive adaptations that allow them to survive and prosper in anaerobic soil conditions.

The influence of vegetation on the functioning of wetlands and river systems is often underestimated, with wetland vegetation substantially affecting water quality, hydrology (transpiration), hydraulics (flow resistance), sediment trapping, and trophic processes (Mackenzie *et al.*, 1999). As was previously mentioned, and as Rogers (1997) explains, vegetation, hydrology and geomorphology are linked along what have been described as “three hydrogeomorphic gradients” (p331), which comprise the lateral, vertical and longitudinal planes along which changes in the frequency, depth and duration of flooding occur. The characteristics along these gradients in turn affect the vegetation a distance away from the channel, an elevation above the channel, and a distance downstream (Rogers, 1997). Examples of the changing physical conditions that may instigate such responses in vegetation include hydrological disturbances, peat accumulation, changes in geology and geomorphic landform, the domination of particular species at a particular time, as well as soil chemistry. There is thus great significance in the linkages between wetland vegetation, hydrology and geomorphology, and the “hydrogeomorphic gradients” that provide these links yield considerable influence on the vegetation, the hydrology, and the soil of wetlands.

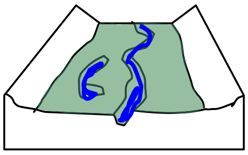
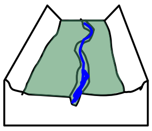
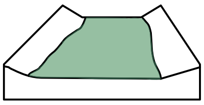
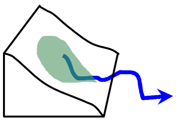
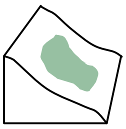
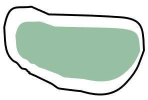
2.1.5 Hydrogeomorphic Settings of Wetlands

While all wetlands exist due to the presence of water, a particular kind of wetland and its associated species or communities develops as a result of other environmental factors, which "push and pull" to make the wetland what it is (Keddy, 2000). Keddy (2000) states that "any specific wetland encountered in the field has arisen as a temporary consequence of these multiple factors" (p10). These factors, including geology, soil-type, topography and climate (Davies and Day, 1998) further influence and restrict the biological communities and ecological processes that take place (Keddy, 2000; McCarthy *et al.*, 2009. The collaboration of these factors results in the presence of many wetland types, which Macfarlane *et al.* (2008) describe as wetland hydro-geomorphic (HGM) units.

The characterization of wetlands into HGM units is central to understanding how factors such as geomorphic setting (e.g. hillslope or valley bottom; open or closed drainage), the source of water (surface water or sub-surface water dominated), as well as the way in which water flows through a wetland unit (diffusely or channelled) yield considerable influence on the key components of wetland hydrology, and on the processes which maintain wetland functioning (Macfarlane *et al.*, 2008). Six HGM types have been identified as typically supporting inland wetlands in South Africa, and are presented in Table 1.

Floodplains attain their primary source of water and sediment from streams (Macfarlane *et al.*, 2008). During flooding, the streams of floodplains overtop their banks and deposit clastic sediment, giving rise to a range of geomorphological features such as point bars inside channel bends, scroll bars on the banks of the inside of channel bends, and oxbow lakes or channels that have been abandoned. Valley-bottom wetlands may be either channelled or unchannelled, and while both attain water from streams and adjacent slopes, the streams of unchannelled valley-bottoms disappear, making flow diffuse (Macfarlane *et al.*, 2008). Streams do not yield as much control over these systems as they do over floodplains, making fluvial deposition less important, and resulting in far fewer depositional features than would be found in floodplains. Where groundwater inputs dominate over diffuse groundwater flow from upslope, hillslope seepage zones are formed (Macfarlane *et al.*, 2008). These zones may or may not feed a stream, the former of which occurs when there is surface flow out of these systems due to low rates of groundwater discharge or atmospheric loss. When surface water

Table 1. Wetland hydrogeomorphic (HGM) types typically supporting inland wetlands in South Africa (adapted from Marneweck and Batchelor 2002; Kotze 1999; and Brinson 1993)

Hydrogeomorphic types	Description	Source of water maintaining the wetland[1]	
		Surface	Sub-surface
Floodplain 	Valley-bottom areas with a well defined stream channel, gently sloped and characterized by floodplain features such as oxbow depressions and natural levees and the alluvial (by water) transport and deposition of sediment, usually leading to a net accumulation of sediment. Water inputs from main channel (when channel banks overspill) and from adjacent slopes.	***	*
Valley-bottom, channelled 	Valley-bottom areas with a well defined stream channel but lacking characteristic floodplain features. May be gently sloped and characterized by the net accumulation of alluvial deposits or may have steeper slopes and be characterized by the net loss of sediment. Water inputs from main channel (when channel banks overspill) and from adjacent slopes.	***	*/ ***
Valley-bottom, unhandled 	Valley-bottom areas with no clearly defined stream channel, usually gently sloped and characterized by alluvial sediment deposition, generally leading to a net accumulation of sediment. Water inputs mainly from channel entering the wetland and also from adjacent slopes.	***	*/ ***
Hillslope seepage linked to a stream 	Slopes on hillsides, which are characterized by the colluvial (transported by gravity) movement of materials. Water inputs are mainly from sub-surface flow and outflow is usually via a well defined stream channel connecting the area directly to a stream channel.	*	***
Isolated Hillslope seepage 	Slopes on hillsides, which are characterized by the colluvial (transported by gravity) movement of materials. Water inputs mainly from sub-surface flow and outflow either very limited or through diffuse sub-surface and/or surface flow but with no direct surface water connection to a stream channel	*	***
Depression (includes Pans) 	A basin shaped area with a closed elevation contour that allows for the accumulation of surface water (i.e. it is inward draining). It may also receive sub-surface water. An outlet is usually absent, and therefore this type is usually isolated from the stream channel network.	*/ ***	*/ ***

disappears below the surface again, the seep will not feed a stream. Finally, depression wetlands occur as a result of the groundwater rest level intercepting the land (Macfarlane *et al.*, 2008). These are known to occur along coastal plains and in semi-arid regions where the hydrological inputs are dominated by surface water, and where the outputs are dominated by evaporation. Clearly, each HGM unit differs in its characteristics, which influences the kinds of functional benefits or ecosystem services that they provide (Kotze et al., 2007). For this reason, many current wetland assessment tools use HGM units as a basis for their assessment, allowing for more effective evaluation and for more suitable approaches to management.

2.1.6 Ecosystem Services

Ecological function has been defined by Keddy (2000) as "the capacity of natural processes and components to provide goods and services that satisfy human needs" (p56). It is pointed out that such a concept requires the acknowledgement by humans of the benefits received from ecosystems, making ecosystem services "the benefits that people derive from nature" (DEAT, 2006, p5). These ecosystems include wetlands. For many years, wetlands were considered to be wastelands and areas that needlessly occupied space that could be better utilised (Sheldon *et al.*, 2005), but more recently, they have been better recognized as key providers of a variety of ecosystem services, nationally and globally (Keddy, 2000). Sheldon *et al.* (2005, p2-6) define wetland functions as:

> "The physical, biological, chemical, and geologic interactions among different components of the environment that occur within a wetland. There are many valuable functions that wetlands perform but these can be grouped into three categories- functions that improve water quality, functions that change the water regime in a watershed such as flood storage, and functions that provide habitat for plants and animals".

It should be pointed out that the terms functions, values, functional values, and ecosystem services have all been used in the past to describe the benefits to humans that are provided by wetlands. To clarify, 'wetland functions' are the environmental processes that take place in a wetland (Sheldon *et al.*, 2005, p2-9). Alternatively, the term 'value' is described by The National Research Council in Sheldon *et al.* (2005) as a "societal perception", as the perceived value of a wetland may change with factors such as time and economy, irrespective of whether the wetland continues to function well. There are also ambiguities around the attachment of values to important environmental processes and functions, not just to the services that are being delivered; as well as around considering the importance and scarcity of an ecosystem service when assigning it a value. 'Functional values' is considered to be completely incorrect when correctly interpreted, as this term suggests "that wetland values were functioning" (p2-9). The term 'ecosystem service' has therefore been used abundantly in this research, as this term describes the environmental processes that take place in a wetland, and their role as processes that are beneficial to human beings. Table 2 highlights those ecosystem services considered to be of importance in South Africa.

Table 2. Ecosystem services considered most important for South African wetlands (Kotze et al., 2007)

Ecosystem services supplied by wetlands	Indirect benefits	Hydro-geochemical benefits		Flood attenuation
Ecosystem services supplied by wetlands	Indirect benefits	Hydro-geochemical benefits		Streamflow regulation
Ecosystem services supplied by wetlands	Indirect benefits	Hydro-geochemical benefits	Water quality enhancement benefits	Sediment trapping
Ecosystem services supplied by wetlands	Indirect benefits	Hydro-geochemical benefits	Water quality enhancement benefits	Phosphate assimilation
Ecosystem services supplied by wetlands	Indirect benefits	Hydro-geochemical benefits	Water quality enhancement benefits	Nitrate assimilation
Ecosystem services supplied by wetlands	Indirect benefits	Hydro-geochemical benefits	Water quality enhancement benefits	Toxicant assimilation
Ecosystem services supplied by wetlands	Indirect benefits	Hydro-geochemical benefits	Water quality enhancement benefits	Erosion control
Ecosystem services supplied by wetlands	Indirect benefits	Hydro-geochemical benefits		Carbon storage
Ecosystem services supplied by wetlands	Indirect benefits			Biodiversity maintenance
Ecosystem services supplied by wetlands	*Direct benefits*			*Provision of water for human use*
Ecosystem services supplied by wetlands	*Direct benefits*			*Provision of harvestable resources*[2]
Ecosystem services supplied by wetlands	*Direct benefits*			*Provision of cultivated foods*
Ecosystem services supplied by wetlands	*Direct benefits*			*Cultural significance*
Ecosystem services supplied by wetlands	*Direct benefits*			*Tourism and recreation*
Ecosystem services supplied by wetlands	*Direct benefits*			*Education and research*

As is reflected in Table 2, a number of ecosystem services may be attributed to wetlands, and includes what The Wildlife Trusts Water Policy Team (2001) refer to as the three categories of wetland values: physico-chemical functions, socio-economic functions, and conservation functions. Oellermann *et al.* (1994) point out that "wetland resources can benefit individuals via the utility or satisfaction gained from direct wetland use, and the utility gained from wetland preservation (non-use)" (p2). These direct and indirect benefits to humans range from the provision of water and food, which the Millennium Ecosystem Assessment (2005) describe as "two of the most important wetland ecosystem services affecting human well-being" (p1); to the enhancement of water quality (Kotze *et al*., 2007).

Two of the indirect wetland benefits considered to be of importance for South African wetlands are the attenuation of floods and the regulation of streamflow (Kotze *et al*., 2007). Davies and Day (1998) refer to wetlands as excellent flood-control agents, due to the presence of plants which compel floodwaters to spread out and dissipate their force, as well as by storing and gradually releasing flood waters to river channels. Such an attribute is of particular importance in areas dominated by impervious surfaces, such as urban areas (Nkosi, 2006). The presence of these surfaces decreases surface storage of storm-water which increases surface run-off (Ehrenfeld, 2000). The sinuosity, gentle slope, wetland size, and the presence of vegetation contributing surface roughness to wetlands all aid in attenuating the peak flows and the floods that would generally be caused by increased run-off (Kotze *et al.*, 2005 in Nkosi, 2006). A further indirect benefit is the ability of wetlands to sequester carbon, mainly due to the anaerobic conditions present in wetland soils which decelerate the process of decomposition of organic matter (Nkosi, 2006). This process aids in reducing the release of carbon dioxide into the atmosphere, which on a global scale, helps stabilise global climatic conditions (The Wildlife Trusts Water Policy Team, 2001; Kotze, 2009, pers. comm.). The ability of wetlands to accomplish such a feat, while producing food, makes them "some of the most productive lands on earth" (Davies and Day, 1998, p38).

Wetlands greatly enhance the quality of the water passing through them, by performing a combination of the ecosystem services highlighted above. They act as excellent natural filters by slowing down the flow of water and allowing for the trapping of sediment in the water column and the removal of chemicals attached to the sediment, also known as the sorbing of nutrients to sediments (Fisher and Acreman, 2004; Mitsch and Gosselink, 1993), and as agents for the control of erosion. These suspended particles in turn act as a sink for toxins and chemicals, and the wetland allows for vital chemical processes to occur as soil and water have time to interact (Kotze, 1996 in Nkosi, 2006; Kotze and Breen, 1994). Chemical precipitation, adsorption, and ion exchange are all examples of processes that occur in wetlands, which aid in the removal of toxins such as metals, organic pollutants and viruses (Kotze and Breen, 1994; McCarthy *et al.*, 2009). Simultaneously, microbes in the plants and soil assimilate nutrients such as phosphates and nitrates (Davies and Day, 1998). The aerobic/anaerobic interface present in wetlands aids the processes of chemical precipitation and denitrification, which removes nitrogen; while phosphorous is removed through adsorption onto mineral sediments (Mitsch and Gosselink, 1993; Kotze and Breen, 1994). The vegetation present in wetlands also assists in the water purification process, with high rates of mineral uptake by them, caused by characteristically high productivities. These processes often result in the release of water that is considerably cleaner than the water that entered it (Davies and Day, 1998; Mitsch and Gosselink, 1993). A variety of decomposers and decomposition processes; important sediment-water exchanges; and peat accumulation which aids chemical burial all further assist water quality enhancement by wetlands (Mitsch and Gosselink, 1993; Kotze and Breen, 1994).

A wetland’s ability to enhance water quality has immense value for people who rely on wetlands for domestic water use, as well as in terms of saving costs in urban areas for water purification (Nkosi, 2006). The effectiveness of wetlands in providing water quality enhancement benefits has been extensively explored, and studies include those by Kadlec (1979), Ewel (1976), Ewel and Odum (1978, 1979, 1984), and Sprangler *et al*. (1977) as cited by Mitsch and Gosselink (1993); as well as those by Fisher and Acreman (2004), Correll (1999), McJannet (2007), Nelson *et al*. (2003), Kotze and Breen (1994), and Vlok *et al.* (2006).

Wetlands are most well known for their role as a habitat for a variety of plants and animals (Davies and Day, 1998). Sheldon *et al.* (2005) divides the functions related to maintaining food webs and habitats into four main groups, namely aquatic diversity/abundance, which is comprised of wildlife diversity/abundance/migration wintering, and production export; maintenance of spatial structure and habitat, which includes maintenance of interspersion and connectivity, and maintenance of distribution and abundance of invertebrates and vertebrates; the provision of a habitat for aquatic species in the form of fish that have migrated from the sea (anadromous fish), resident fish, migratory and resident birds, and other species; and the provision of a general habitat by wetlands for invertebrates, wetland-associated birds and fish, and wetland-associated mammals. They are home to many specific wetland plants such as reeds, grasses, bulrushes and sedges (Nkosi, 2006).

The direct ecosystem services provided by wetlands are often those that are most easily recognized by the public, as it is these benefits that are tangible and easier to define. These benefits generally take the form of the "products that people obtain from the ecosystem" (Nkosi, 2006, p21), and include the provision of cultivated foods, and the provision of water for human use as well as for harvestable resources such as grazing for livestock, plants for use in crafts and construction, medicines, and food (Kotze *et al*., 2007). The last of these harvestable resources is considered to be particularly important, especially in developing countries where inland fisheries are sometimes the principle source of protein for many people (Millennium Ecosystem Assessment, 2005).

Kotze *et al.* (2007) further recognize the nonmaterial direct benefits that wetlands provide, including their use for tourism and recreation, for education and research, and their cultural significance. Nkosi (2006) describes wetlands as "excellent and inexpensive education and research laboratories" (p23), and many cultures use these water bodies as sites for religious ceremonies such as baptisms (Nkosi, 2006), and as a basis for many local traditions (The Wildlife Trusts Water Policy Team, 2001).

Wetlands have the ability to perform functions of all types which, as The Wildlife Trusts Water Policy Team (2001) explain, "do not act in isolation… (certain) individual wetlands are able to perform many vital functions in tandem" (p1.1). This makes the ecosystem services provided by wetlands tremendously valuable, and as Begg (1990) emphasizes, "a review of the major functions and values of wetlands is seen to be necessary to remind decision-makers that the strain on future resources of this country (such as freshwater) means that in the face of exponential population growth man's dependence upon wetlands is steadily increasing" (p6).

2.1.7 Linking Hydrogeomorphic Type to Hydrological Benefits

The specific hydrological benefits supplied by a wetland depend on the wetland's physical and geological presence, shape, and predominant vegetation (Vlok *et al.*, 2006). As Sheldon *et al.* (2005) point out, "wetlands perform many types of functions, but not all wetlands perform the same functions, nor do similar wetlands provide the same functions to the same level of performance" (p2-7). As such, the provision of ecosystem services by wetlands are often categorized by the type of wetland providing the service, such that once a wetland's particular HGM type has been identified, it may be known what hydrological benefits are likely to be provided by it. Table 3 reflects a preliminary rating of the hydrological benefits likely to be provided by a wetland given its particular hydro-geomorphic type. Similar correlations have been drawn by authors such as Tiner (2002), but using alternate classification criteria for categorising wetlands by hydrogeomorphic type. Given the scope of this dissertation, only those benefits identified as enhancing water quality will be focused upon herein.

Table 3. Preliminary rating of the hydrological benefits likely to be provided by a wetland given its hydrogeomorphic type (Kotze *et al*., 2007)

WETLAND HYDRO-GEOMORPHIC TYPE	HYDROLOGICAL BENEFITS POTENTIALLY PROVIDED BY THE WETLAND							
	Flood attenuation		Stream flow regulation	Erosion control	Enhancement of water quality			
	Early wet season	Late wet season			Sediment trapping	Phos-phates	Nitrates	Toxicants[2]
1. Floodplain	++	+	0	++	++	++	+	+
2. Valley bottom - channelled	+	0	0	++	+	+	+	+
3. Valley bottom - unchannelled	+	+	+?	++	++	+	+	++
4. Hillslope seepage feeding a stream channel	+	0	+	++	0	0	++	++
5. Hillslope seepage not feeding a stream	+	0	0	++	0	0	++	+
7. Pan/ Depression	+	+	0	0	0	0	+	+

Note: 2Toxicants are taken to include heavy metals and biocides
Rating:
0 Benefit unlikely to be provided to any significant extent
+ Benefit likely to be present at least to some degree
++ Benefit very likely to be present (and often supplied to a high level)

As is reflected in Table 3, floodplains are very likely to enhance water quality through the trapping of sediment and the removal of phosphates, nitrates and toxins. This is since most of the water received by floodplains is during high flow events, when water overtops the surrounding streambanks (Kotze *et al*., 2007). When this occurs, sediment and phosphorous and toxins bound to the sediment are deposited and retained within the floodplain, induced by the decreasing velocity of lateral water flow. The presence of features such as oxbow lakes and depressions further aid the phosphate and nitrate removal process to a degree that would not have been possible had they not been present in floodplains. These features allow for prolonged inundation, thereby allowing for a number of processes to occur through denitrification and through cycling between dissolved and organic forms (Kotze *et al*., 2007).

Kotze *et al*. (2007) point out that channelled valley bottom wetlands are very similar to floodplains, but what sets them apart are less active sediment deposition, a lack of floodplain features such as oxbow lakes, a narrower, deeper morphology, and a greater dependence on lateral groundwater relative to the main stream channel. Although they are generally less effective at water quality enhancement than floodplains, a degree of sediment trapping and nutrient and toxin removal may be expected.

Non-channelled valley bottom wetlands have been described as similar to floodplains in terms of their location and gentle gradient, but are different in that flow is mainly diffuse, with water from the stream channel spreading across the wetland constantly, producing areas of permanent saturation and high organic matter content (Kotze et al., 2007). This prolonged contact of the wetland soils with runoff waters means that nitrate and toxin removal is generally greater in non-channelled valley bottom wetlands than in floodplains, and the shallow nature of the water allows for exposure of particles to sunlight and the subsequent photodegradation of particular toxins.

Sub-surface inputs are the main sources of water for hillslope seepage wetlands feeding a watercourse, but according to Kotze *et al*. (2007), flows may be supplemented by surface water sources. These hydrogeomorphic types are considered to contribute several water quality enhancement benefits, including the effective removal of excess nutrients and toxins, with particularly high rates of nitrate assimilation due to the diffuse sub-surface flow that is characteristic of hillslope seepage wetlands. This high nitrogen removal potential is attributed to the emergence of groundwater through low redox potential zones within the wetlands soils, while wetland plants simultaneously contribute organic carbon. Hillslope seepage wetlands not feeding a watercourse are described as closely resembling those that do feed a watercourse in terms of sources of water and functioning, and therefore do not differ greatly with regard to their enhancement of water quality.

Pans and other depressions are not exceedingly effective at enhancing water quality. They receive both surface and groundwater flows, and their morphology means that water accumulates within them, but they are generally not connected to the drainage network (Kotze *et al*., 2007). The primary influences on the water quality in pans are pedology, geology, and local climate, which in turn dictate how these systems respond to the input of nutrients and toxins (Kotze *et al*., 2007). In temporary pans, evaporation allows for the precipitation of minerals such as phosphates, and denitrification and nitrogen removal are also prevalent.

Clearly, the importance of knowing and making provision for the hydrogeomorphic type of a wetland cannot be underestimated, as such knowledge may give valuable insight into the effectiveness of the wetland at improving water quality.

2.1.8 Wetland Rehabilitation Techniques

Based on a review of various works on wetland restoration and rehabilitation, Grenfell *et al*. (2007) define wetland rehabilitation as referring to “progression towards the attainment of former ecosystem structure, function and/or state, or the attainment of ecosystem structure, function and/or state that differs from the former” (p6). According to Grenfell *et al*. (2007), this most appropriately refers to “systems or parts of systems that have not been removed from the landscape through complete and permanent alteration but are in a degraded state, having lost a degree of ecosystem structure, function, biotic composition and/or associated ecosystem services” (p7).

In South Africa, the national government implements wetland rehabilitation procedures through the Working for Wetlands (WFWetlands) programme, which favours rehabilitation procedures that are labour-intensive, and which are guided by three principal objectives namely, to control erosion, to raise the local water table, and to promote diffuse flow within the wetland (Ellery, 2006; Grenfell *et al*., 2007).

These objectives are achievable through the implementation of one or many of a number of ‘hard’ or ‘soft’ option rehabilitation approaches. Hard option rehabilitation measures entail the implementation of structures within the wetland that serve one of the three objectives highlighted above. These structures include the concrete buttress weir, the brick arch weir, the mass gravity weir, the rock masonry weir, the concrete and rock masonry weir, the concrete baffle chute, the u-shape drop inlet chute, the soilcrete weir, armorflex, and the gabion weir (Ellery, 2006). Soft option rehabilitation measures include the earthen chute, sloping and re-vegetation of the wetland’s catchment, spreader channels which promote diffuse flow through the wetland; fencing, and landscaping and brush packing, which allows for re-vegetation to occur (Ellery, 2006).

The choice of rehabilitation measure for implementation is dependent on the problem being experienced within the wetland, and the cause of the problem. By identifying these aspects and successfully implementing the correct rehabilitation measure, many of the hydrological impacts faced by wetlands may be addressed and abated.

2.1.9 Wetlands in South Africa

Vlok *et al.* (2006) describe water in South Africa as “a critically important natural resource” (pi). The prevalent climate dictates that the country receives an average of only 60% of the world average for rainfall, just 500 mm per annum, making the region semi-arid to arid (Vlok *et al.*, 2006). Most of the country however, receives less than 500 mm per annum, with 21% of South Africa receiving even less than 200 mm per annum. This, compounded with high rates of evaporation and erratic climatic conditions such as droughts and floods, makes the management of water resources particularly difficult (Vlok *et al.*, 2006; Swanepoel and Barnard, 2007). In global terms, South Africa is a water-scarce country, with this climate classifying South Africa as a country comprised primarily of ‘drylands’, a term that Tooth (2000) and Tooth and McCarthy (2007) describe as collectively referring to subhumid, semi-arid, arid and hyper-arid regions.

Given these conditions, one is inclined to question how wetlands exist in such abundance in South Africa, particularly since by definition, the existence of wetlands is dependent on a locally positive surface water balance for a large proportion of the year (Tooth and McCarthy, 2007). Given that drylands are characterized by overall surface water deficits, the presence of wetlands in such an environment seems contradictory. One piece of the puzzle lies in the country’s topography, which has been described by Davies and Day (1998) as “high but flat” (p30). This topography, coupled with the presence of a few effectual rivers, has led to the existence of a number of wetlands across South Africa. These rivers drain the interior and supply wetlands with water, sediment, and associated nutrients (Tooth and McCarthy, 2007). Tooth and McCarthy (2007) describe the variances in river flow regimes that differ with the degree of aridity, local climatic conditions, the size of the catchment, soil type, the presence and type of vegetation cover, and the presence and nature of human-induced changes, which are present across southern Africa. Of these, there are three main river inflow types related to wetlands that are discussed by Tooth and McCarthy (2007). These are perennial inflows from rivers flowing into the dryland setting from more humid regions (such as the Okovango Delta in Botswana); inflows from rivers which have originated in the summer rainfall zone and are regular but strongly seasonal (for example, the Klip River, the lower Nyl River, and the upper Blood River wetlands in South Africa); and episodic flows from rivers that are augmented by occasional rainfall events of often high intensity (pans, such as many wetlands of the Goukou Catchment). Within each of these inflow types, local rainfall or groundwater supply may enhance the positive surface water balance, as may factors that impede drainage or reduce infiltration, such as faulting, the presence of rock outcrops and particular sealing soil types, and ponding caused by deposits from tributaries and Aeolian processes (Tooth and McCarthy, 2007). These factors, in combination with varying supplies of sediment, different vegetation communities, and differing levels of animal activity, give rise to an array of wetlands which display different hydroperiods, as well as various geomorphological and sedimentological characteristics (Tooth and McCarthy, 2007).

Davies and Day (1998) point out that given the aridity of the country, South Africa “can hardly be considered a land of mighty rivers” (p41), but rivers such as the Orange-Vaal, Tugela, Limpopo, and Pongola have helped carve a network of smaller waterways throughout the country. These waterways continually erode their catchments, and given the flatness of the land, tend to overtop their banks during floods. Water then spreads out and slows down, allowing for the deposition of eroded material as alluvium, forming a floodplain (Davies and Day, 1998). To the north-east, the most notable floodplains in southern Africa are those of the Limpopo, Luvuvhu, Pongola and Mkuze rivers. The Sundays, Swartzkops and Gouritz rivers form floodplains in the south-east of the country, while in the south-west, the Berg River forms the major floodplains. These floodplains are usually inundated with nutrient-rich silts and organic matter during the rainy season, and as Davies and Day (1998) so eloquently describe, “it is through these alluvial plains that the river meanders, sometimes cutting here, sometimes depositing there, to form a richly diverse mix of biotopes, from permanently wet to partially wet, from infrequently wet to nearly always dry, and from the river itself, to lentic wetlands and ponds…” (p42).

Most of South Africa’s wetlands are considered to be quite small, and are sparsely distributed and ephemeral, attributes which have belied their importance (Rogers, 1997). As a result, available data relating to South Africa’s wetlands is “scattered and highly unrepresentative of the variability both within and between wetland types” (Rogers, 1997, p322). For this reason, comprehensive and continued research into South African wetlands is a priority, especially given that the semi-arid climate that typifies South Africa has serious implications for water pollution.

Wetlands occurring in areas of low rainfall and high evaporation rates experience a reduction in the volume of influent water, which add to the threat of water pollution. Some of the implications of a reduction in flow into a wetland include a decrease in the dilution effect of pollutant resident water by uncontaminated water; extended residence time of polluted water, which increase the quantity of nutrients, sediments and toxins dropping out of suspension; a decrease in the frequency at which polluted water is flushed from the wetland; and the concentration of pollutants in wetland water due to high rates of evaporation (Coetzee, 1995).

2.2 **An Overview of WET-Health and WET-Ecoservices**

Two wetland assessment tools are extensively used in South Africa: WET-Health (Macfarlane *et al.*, 2008) and WET-Ecoservices (Kotze *et al.*, 2007). These tools warrant a brief overview herein, as they are referred to extensively in the tool developed by Ellery *et al*. (in review).

2.2.1 WET-Health

Described as 'a technique for rapidly assessing wetland health,' WET-Health is a tool that assesses the ecological condition or integrity of a wetland (Macfarlane *et al.*, 2008). In it, wetland health is defined as "a measure of the deviation of wetland structure and function from the wetland's natural reference condition" (Macfarlane *et al.*, 2008, pv). The WET-Health system assesses this structure and function in terms of hydrological, geomorphological and vegetation health, each of which is separately assessed in different health assessment modules. The WET-Health approach is not a direct measure of wetland health, but is rather impact-based and indicator-based. A key aspect of the WET-Health tool is the understanding that wetland health is inversely related to the magnitude of impacts. The impact-based approach is employed in the analysis of hydrological health, as alteration in hydrology does not produce visibly obvious responses in wetland structure and function. Alternatively, activities that do produce clearly visible structural and functional responses, such as alterations in geomorphology and vegetation, allow for the use of indicators in their assessments.

Macfarlane *et al.* (2008) highlight the fact that central to WET-Health is the characterization of wetlands based on hydro-geomorphic (HGM) units. By sorting wetlands into their appropriate HGM units, they can be evaluated and dealt with more effectively, since each unit differs in characteristics and provides different services, and thus demands different approaches to management.

As was previously mentioned, the underpinning concept of WET-Health is the fact that wetland health is inversely related to assessed impacts (Macfarlane *et al.*, 2008). This implies that a low habitat impact score (or deviation from natural reference condition) reflects a high habitat health score (or similarity to natural reference condition). Conversely, a high habitat impact score gained from an extensively degraded wetland, reflects a low habitat health score, i.e. the wetland is vastly different from its natural reference condition. The overall magnitude of the scores gained is a result of evaluating both the intensity and extent of the impact under evaluation, and wetland health is scored on a scale of 0 to 10.

2.2.2 WET-Ecoservices

WET-Ecoservices is based on the premise that the particular ecosystem services that are being supplied by a wetland and the efficiency of the wetland in supplying them are based not only on the characteristics of the surrounding catchment, but also on the type of wetland and its associated characteristics.

Similar to the technique employed in WET-Health, WET-Ecoservices characterizes wetlands into HGM units, each with the identical characteristics as those units used in WET-Health, the basis for which is that different wetland types provide different functional benefits (Kotze *et al*., 2007). WET-Ecoservices offers two levels of ecosystem services assessment, the first being the desktop assessment which involves the identification of the particular ecosystem services which are associated with the different HGM types based on existing research and understanding. For example, which types of wetlands provide flood attenuation, stream flow attenuation, erosion control, sediment trapping, or water quality enhancement and so forth, as is reflected in Table 3 (Kotze *et al*., 2007). This type of assessment is useful for an overview of ecosystem services supply at a catchment level. The second assessment type is a one to four hour rapid field assessment of ecosystem services based on a list of characteristics of the wetland or its catchment. These characteristics are scored, and the average of these scores is taken to reflect the extent to which a particular benefit is being supplied. The assessment of certain benefits includes the further scoring of particular characteristics that allow for the determination of potential future value, or for the opportunity for benefits to be provided by a wetland in the future.

2.3 A Method for Assessing the Cumulative Impacts on Wetland Functions at the Catchment or Landscape Scale (Ellery *et al.*, in review)

2.3.1 Introduction

Ellery *et al.* (in review) have developed a method for assessing the cumulative impacts on wetland functions at the catchment or landscape scale. This tool forms a pivotal component of the methodology conducted in this research. The tool allows the user to determine the effects of the cumulative impacts of human activities at a landscape scale on wetland functionality using two metrics: a land-cover change impact metric, and a loss of function metric. These metrics are used in conjunction to determine a functional effectiveness score for a given ecosystem service by a single wetland, which is a measure of how effectively an impacted wetland is providing a particular ecosystem service. This functional effectiveness score then allows for the determination of functional hectare equivalents for each ecosystem service. This term is a semi-quantified indication of functional effectiveness. It is a unit that describes how much of an ecosystem service is being provided by a wetland, which makes comparisons between wetlands possible.

2.3.2 Land-cover Change Impact Metric

The basis of the land-cover change impact metric developed by Ellery *et al.* (in review) is the understanding that different land-cover classes impact the hydrology of a wetland in different ways. Land-cover classes were explored in terms of their abilities to increase or decrease water inputs to a wetland; as well as, for land-cover classes present in a wetland, to increase direct water losses from a wetland, reduce surface roughness, impede the flow of water to a wetland, or to enhance the flow of water to a wetland. Each land-cover class explored was assigned an intensity of impact score for land-cover change in terms of its effect on the hydrological aspects of the wetland described above.

The product of this intensity of impact score and the extent of the given land-cover class in a catchment or wetland is described as a ‘magnitude of impact score’.

The land-cover change impact metric was developed by first grouping National Land Cover classes into 12 categories based on their impacts on runoff. Catchment land-cover classes were then analysed and described in terms of their effect on the timing and amount of runoff flow into a wetland, while wetland land-cover classes were described in terms of their effects on the pattern of water flow through the wetland and its residence time (Ellery *et al.*, in review). Based on the negative impact of these factors on the hydrological health of wetlands as determined by Ellery *et al.* (in review) and by Macfarlane *et al.* (2008) in the WET-Health tool, impact intensity scores were assigned to each land-cover class within catchments and wetlands. These scores, which do not cover water quality impacts, were presented in a table (Table 2 of Ellery *et al.*, in review), which is replicated below (Table 4).

By multiplying the extent of a particular land-cover class in a catchment by the relevant intensity of impact score for that land-cover class from Table 4, the ‘magnitude of impact’ of that land-cover class on the various aspects of wetland hydrology - such as increased or decreased water inputs, increased direct water loss, reduced surface roughness, flow impediment or flow enhancement – may be determined.

For example, a catchment may cover a total of 25 ha, containing a wetland 10 ha in extent and two categories of land-cover, namely natural, and degraded vegetation. There are a total of 14 ha of natural land-cover, 8 ha of which are in the catchment outside of the wetland, and 6 ha of which are in the wetland. Degraded vegetation covers an area of 11 ha, 7 ha of which are in the catchment outside of the wetland, and 4 ha of which are in the wetland. The magnitude of impact scores are then calculated as intensity of impact score (from Table 4) multiplied by the proportion of the catchment and wetland occupied by each land cover class (Table 5).

Table 4. Intensity of impacts scores to wetland hydrological health to be used at the landscape scale when considering land-cover change (Ellery *et al.*, in review)

Land cover category	Intensity of impact score					
	Catchment land cover		Within-wetland land cover			
	1. Increased water inputs	2. Reduced water inputs	3. Increased direct water losses	4. Reduced surface roughness	5. Flow impediment	6. Flow enhancement
Natural	0	0	0	0	0	0
Forest plantations		9 (forest) 7 (heavy alien plant infestation) 5 (modest alien plant infestation) 3 (light alien plant infestation)	9 (forest) 7 (heavy alien plant infestation) 5 (modest alien plant infestation) 3 (light alien plant infestation)			
Water bodies		5	6*** (for area of wetland below the dam in the wetland)		9 (for area of wetland above the dam in the wetland)	
Dongas and sheet erosion	5					9
Degraded vegetation	3			3		
Irrigated cultivation	3 (if IBT*)	5		5		
Dryland cultivation,		3		5		
Urban residential – high density	5 (9 if WWTW present**)			7		
Urban residential – low density	3 (9 if WWTW present**)			5		
Urban commercial	7 (9 if WWTW present**)			9		
Urban industrial/transport	9		4*** (for area of wetland above road across a wetland)	9	5 (for area of wetland above road across a wetland)	
Mines and quarries	5			9		

* Refers to irrigation that involves importation of water into the catchment by inter-basin transfer (IBT).
** Refers to the presence of wastewater treatment works (WWTW) where these occur in the catchment

*** The area of wetland used in the calculation of the magnitude of impact is scaled to account for variation in the depth of the dam.

Table 5. Magnitude of impact scores calculated using the intensity of impact scores (bold text is the intensity of impact score from Table 4) multiplied by the proportional area of each land-cover class

Land cover category	**Impacts arising in the wetland's upstream catchment***			**Impacts arising within the wetland****	
	Area (ha)	Increased water inputs	Decreased water inputs	**Area**	Reduced surface roughness
Natural	8	0	0	6	0
Degraded vegetation	7	(7/15) * **3** = 1.91		4	(4/10) * **3** = 0.60
TOTALS	**15**	1.4	0	**10**	1.2

*on the quantity and timing of water inputs
**on the distribution and retention of water

NB. Intensity of impact scores for impacts arising in the wetland's upstream catchment as well as within the wetland are scored on a scale of 0 (no impact) to 10 (critical impact).

2.3.3 Loss of Function Metric

The above-mentioned impacts on hydrological health in turn affect how effectively a wetland is able to provide a number of ecosystem services, through recognising the fact that the hydrological regime of a given wetland directly affects the structure and function of that wetland (Ellery *et al.*, in review). Ecosystem services explored included flood attenuation, stream flow regulation, sediment trapping, phosphate trapping, nitrate removal, and toxicant removal. The loss of function metric aims to create a relationship between the provision of ecosystem services and impacts to hydrological health.

In doing so, Ellery *et al.* (in review) first considered the different hydrogeomorphic settings of wetlands (as discussed in Section 2.2.5), as presented in Table 1. As is pointed out in Section 2.3, the consideration of HGM types is a key component of both the WET-Health and WET-Ecoservices tools, and is therefore essential in building an understanding of how various factors impact on the hydrology of different wetlands, as well as of how the provision of ecosystem services are affected in different wetlands. Prevalent relationships between these HGM types and different hydrological benefits (as highlighted in Section 2.2.7) were also explored, and a review of the WET-Health tool was undertaken by Ellery *et al.* (in review).

With a focus on "the most common impacts on wetland hydrological health" (Ellery *et al.*, in review, p25) for both catchment and within-wetland impacts, Ellery *et al.* (in review) aimed to draw a mathematical relationship between the functional effectiveness of wetlands in terms of the provision of ecosystem services (on a scale of 0-4 as measured in WET-Ecoservices) and the impacts of human activities on wetlands (on a scale of 0-10 as measured in WET-Health). For each of the catchment and within-wetland impacts investigated, the likely effect on each ecosystem service was plotted on a graph, resulting in a series of equations, each representing a relationship between a hydrological impact and an ecosystem service. These equations are presented in six tables, Tables 6-11 below (Tables 12-17 in Ellery *et al.*, in review), with each table containing equations that describe the relationships between a given impact (increased or decreased water inputs for catchment impacts; or direct water losses, reduced surface roughness, flow impediment, or the presence of drains or gullies for wetland impacts) and each of the six ecosystem services under evaluation.

Table 6. Equations describing the relationships between impacts that result from increased water inputs from the wetland's catchment and the provision of a number of ecosystem services (Ellery *et al.*, in review)

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of values for applying equation**	**Equation**	**Range of values for applying equation**	**Equation**
Flood attenuation	0-3	y=3.50	0-10	y=-0.08x + 2.50
	3-10	y=-0.14x + 3.92		
Stream flow regulation	0-3	y=0.33x + 2.50	0-3	y=2.50
	3-10	y=-0.14x + 3.92	3-10	y=-0.11x + 2.84
Sediment trapping	0-3	y=3.50	0-3	y=2.50
	3-10	y=-0.14x + 3.92	3-10	y=-0.11x + 2.84
Phosphate trapping	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92
Nitrate removal	0-3	y=0.33x+2.50	0-3	y=3.50
	3-10	y=-0.26x + 4.27	3-10	y=-0.26x + 4.27
Toxicant removal	0-3	y=0.33x+2.50	0-3	y=3.50
	3-10	y=-0.14x + 3.92	3-10	y=-0.26x + 4.27

Table 7. Equations describing the relationships between impacts that result from decreased water inputs from the wetland's catchment and the provision of a number of ecosystem services (Ellery *et al.*, in review)

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of values for applying equation**	**Equation**	**Range of values for applying equation**	**Equation**
Flood attenuation	0-3	y=3.50	0-3	y=0.33x + 2.50
	3-10	y=-0.14x + 3.92	3-10	y=-0.26x + 4.27
Stream flow regulation	0-10	y=-0.08x + 2.50	0-10	y=-0.17x + 2.50
Sediment trapping	0-3	y=3.50	0-3	y=2.50
	3-10	y=-0.14x + 3.92	3-10	y=-0.11x + 2.84
Phosphate trapping	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92
Nitrate removal	0-10	y=0.17x + 2.50	0-10	y=-0.18x + 3.50
Toxicant removal	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92

Table 8. Equations describing the relationships between impacts that result from increased water losses from the wetland and the provision of a number of ecosystem services (Ellery *et al.*, in review)

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of values for applying equation**	**Equation**	**Range of values for applying equation**	**Equation**
Flood attenuation	0-5	y=3.50	0-5	y=0.20x + 2.50
	5-10	y=-0.20x+4.50	5-10	y=-0.36x+5.30
Stream flow regulation	0-10	y=-0.08x + 2.50	0-10	y=-0.17x + 2.50
Sediment trapping	0-5	y=3.50	0-5	y=0.20x + 2.50
	5-10	y=-0.20x+4.50	5-10	y=-0.36x+5.30
Phosphate trapping	0-3	y=0.33x + 2.50	0-3	y=3.50
	3-10	y=-0.26x+4.27	3-10	y=-0.26x+4.27
Nitrate removal	0-10	y=-0.08x + 2.50	0-10	y=-0.10x + 3.50
Toxicant removal	0-5	y=0.20x + 2.50	0-5	y=3.50
	5-10	y=-0.20x + 4.50	5-10	y=-0.36x + 5.30

Table 9. Equations describing the relationships between impacts that result from decreased surface roughness in the wetland and the provision of a number of ecosystem services (Ellery *et al.*, in review)

	Floodplain wetlands		Valley-bottom wetlands	
Ecosystem service	**Range of values for applying equation**	**Equation**	**Range of values for applying equation**	**Equation**
Flood attenuation	0-10	y=-0.10x + 3.50	0-10	y=-0.17x + 2.50
Stream flow regulation	0-3	y=2.50	0-3	y=2.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.24x + 3.23
Sediment trapping	0-10	y=-0.10x + 3.50	0-10	y=-0.08x + 2.50
Phosphate trapping	0-10	y=-0.17x + 2.50	0-10	y=-0.18x + 3.50
Nitrate removal	0-10	y=-0.17x + 2.50	0-10	y=-0.18x + 3.50
Toxicant removal	0-10	y=-0.17x + 2.50	0-10	y=-0.18x + 3.50

Table 10. Equations describing the relationships between impacts that result from the presence of impeding features in the wetland and the provision of a number of ecosystem services (Ellery *et al.*, in review)

	Floodplain wetlands		Valley-bottom wetlands	
Ecosystem service	**Range of values for applying equation**	**Equation**	**Range of values for applying equation**	**Equation**
Flood attenuation	0-10	y=3.50	0-3	y=2.50
			3-10	y=0.14x + 2.07
Stream flow regulation	0-10	y=-0.08x + 2.50	0-10	y=-0.08x + 2.50
Sediment trapping	0-10	y=3.50	0-10	y=2.50
Phosphate trapping	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92
Nitrate removal	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92
Toxicant removal	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92

Table 11. Equations describing the relationships between impacts that result from the presence of drains or gullies in the wetland and the provision of a number of ecosystem services (Ellery *et al.*, in review)

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of values for applying equation**	**Equation**	**Range of values for applying equation**	**Equation**
Flood attenuation	0-3	y=3.50	0-1.5	y=2.50
	3-10	y=-0.14x + 3.92	1.5-10	y=-0.26x + 2.89
Stream flow regulation	0-3	y=2.50	0-1.5	y=2.50
	3-10	y=-0.11x + 2.84	1.5-10	y=-0.26x + 2.89
Sediment trapping	0-3	y=3.50	0-1.5	y=2.50
	3-10	y=-0.14x + 3.92	1.5-10	y=-0.11x + 2.84
Phosphate trapping	0-1.5	y=2.50	0-1.5	y=3.50
	1.5-10	y=-0.20x + 2.80	1.5-10	y=-0.21x + 3.82
Nitrate removal	0-1.5	y=2.50	0-10	y=-0.18x + 3.50
	1.5-10	y=-0.20x + 2.80		
Toxicant removal	0-1.5	y=2.50	0-5	y=-0.20x + 3.50
	1.5-10	y=-0.20x + 2.80	5-10	y=-0.34x + 4.20

2.3.4 The Calculation of Functional Effectiveness Scores

The determination of functional effectiveness scores for each ecosystem service for a given wetland is achieved in the methodology of Ellery *et al.* (in review) through a number of steps, depicted in Figure 1.

Mapping of the wetland and its catchment is undertaken first, which allows for areal extents of the catchment, the wetland, and land-cover classes in both the wetland and the catchment to be determined. The extents of each land-cover class are then multiplied by the relevant intensity of impact score from Table 4, which results in a magnitude of impact score for each land-cover class in the catchment and the wetland, for impacts arising in the wetland's catchment as well as for impacts arising within the wetland (catchment and onsite impacts).

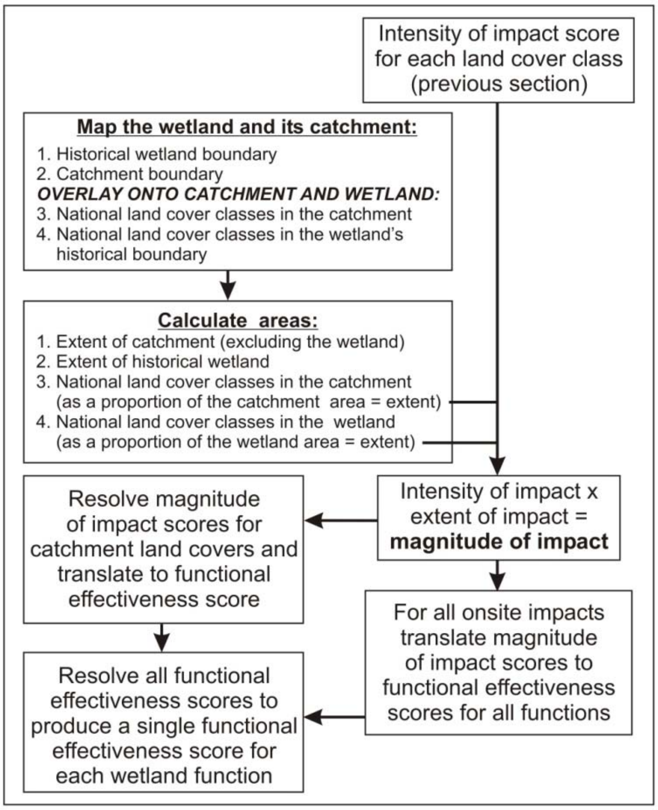


Figure 1. The series of steps described in Ellery *et al.* (in review) that lead to the calculation of a functional effectiveness score for individual wetlands (Ellery *et al*., in review)

Depending on the land-cover classes present in the catchment, resultant impacts may take the form of increased water inputs, decreased water inputs, or both. In the case of the presence of both catchment impacts, increased and decreased water inputs are resolved by subtracting the total magnitude of impacts for 'decreased water inputs' from the total for 'increased water inputs'. "This is simply because land use activities that increase water inputs offset those activities that reduce water inputs" (Ellery *et al*., in review).

The next step in Ellery *et al.*'s (in review) methodology is to consider the effect of each individual impact on the provision of ecosystem services. This is achieved by utilising the loss of function equations presented in Section 2.4.3, with each representing the relationship between one of each hydrological impacts and one of each ecosystem services. These equations are utilised by substituting the magnitude of impact score as determined in the previous step, into the relevant equation. The result is a number of functionality scores for the wetland, each of which is based on one of the impacts identified.

All of the functionality scores for impacts arising within the wetland (onsite impacts) are then resolved, since “some activities will reduce the duration and extent of inundation (direct water losses, reduced surface roughness and the presence of drains or gullies), while others might prolong it (presence of impeding features increases water retention above the impeding feature and reduces water retention below it)” (Ellery *et al*., in review). According to Ellery *et* al. (in review), the resolution of these issues is achieved by taking the lowest functionality score of the onsite functionality scores, and adjusting it for the additive effects of the other onsite activities. This is achieved by consulting a table of values that are used to scale functionality scores for a range of catchment and onsite impacts as is presented in Table 12. This results in a single functionality score for impacts arising within the wetland (onsite impacts).

What now remain are two functionality scores, one for impacts arising within the wetland (onsite impacts) and one for impacts arising in the wetland’s catchment (catchment impacts). These impacts are resolved in the same way that onsite impacts are resolved- the lowest of these scores is scaled by consulting Table 12 and adding the relevant value on the basis of the other score. The result is a final functional effectiveness score for a given ecosystem service for the wetland under evaluation.

2.3.5 The Calculation of Functional Hectare Equivalents

Functional hectare equivalents for a given ecosystem service are calculated by dividing the functional effectiveness score by 4 to scale it between 0 and 1, and then multiplying the quotient by the size of the wetland in hectares (Ellery *et al*., in review):

Functional hectare equivalents = (final functional effectiveness score / 4) * size of wetland (ha).

Table 12. Values to be used to scale functionality scores in valley-bottom wetlands as determined for a range of catchment and onsite impacts (Ellery *et al*., in review)

Functionality score range	Flood attenuation		Stream flow regulation		Sediment trapping		Phosphate trapping		Nitrate removal		Toxicant removal	
Increased water inputs	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3 – 4	0	0	0	0	0	0	0	0	0	0	0	0
2 – 2.99	0.1	0	0.1	0	0.1	0	0	0	0.1	0.1	0.1	0.1
1.2 – 1.99	0.2	0.1	0.2	0.1	0.2	0	0.1	0.1	0.2	0.2	0.2	0.2
0.5 – 1.19	0.3	0.2	0.3	0.2	0.3	0.1	0.2	0.2	0.3	0.3	0.3	0.3
<0.5	0.4	0.3	0.4	0.3	0.4	0.2	0.3	0.3	0.4	0.4	0.4	0.4
Decreased water inputs	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3 – 4	0	0	0	0	0	0	0	0	0	0	0	0
2 – 2.99	0.1	0.1	0	0	0.1	0	0	0	0	0.1	0	0.1
1.2 – 1.99	0.2	0.2	0.1	0.1	0.2	0	0.1	0.1	0.1	0.2	0.1	0.2
0.5 – 1.19	0.3	0.3	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.2	0.3
<0.5	0.4	0.4	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.4	0.3	0.4
Direct water losses	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3 – 4	0	0	0	0	0	0	0	0	0	0	0	0
2 – 2.99	0.1	0.1	0	0	0.1	0	0.1	0.1	0	0.1	0.1	0.1
1.2 – 1.99	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.2	0.2	0.2
0.5 – 1.19	0.3	0.3	0.2	0.2	0.3	0.2	0.3	0.3	0.2	0.3	0.3	0.3
<0.5	0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.4
Decreased surface roughness	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3 – 4	0	0	0	0	0	0	0	0	0	0	0	0
2 – 2.99	0.1	0	0	0	0.1	0	0	0	0	0.1	0	0.1
1.2 – 1.99	0.2	0.1	0.1	0.1	0.2	0	0.1	0.1	0.1	0.2	0.1	0.2
0.5 – 1.19	0.3	0.2	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.2	0.3
<0.5	0.4	0.3	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.4	0.3	0.4
Impeding features	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3 – 4	0	0	0	0	0	0	0	0	0	0	0	0
2 – 2.99	0.1	0.1	0	0	0.1	0	0	0	0	0.1	0	0.1
1.2 – 1.99	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.2
0.5 – 1.19	0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.3	0.2	0.3
<0.5	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.4	0.3	0.4
Drains or gullies	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**VB**
3 – 4	0	0	0	0	0	0	0	0	0	0	0	0
2 – 2.99	0.1	0	0	0	0.1	0	0	0	0	0.1	0	0.1
1.2 – 1.99	0.2	0.1	0.1	0.1	0.2	0	0.1	0.1	0.1	0.2	0.1	0.2
0.5 – 1.19	0.3	0.2	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.2	0.3
<0.5	0.4	0.3	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.4	0.3	0.4

2.3.6 Ellery *et al*.'s (in review) Tool in Relation to Cumulative Impacts

The tool developed by Ellery *et al*. (in review) proposes a method that allows for the "assessment of the provision of ecosystem services at a catchment or landscape scale, based on impacts of human activity of wetland hydrological health", given that wetland hydrology is "the most important determinant of wetland structure and function" (p12). This was achieved by Ellery *et al*. (in review) by using the WET-Health and WET-Ecoservices tools to inform the development of the loss-of-function equations which relate wetland health to ecosystem services delivery. Therefore, using the Ellery *et al.* (in review) system, ecosystem service delivery is informed by the application of a WET-Health assessment, so that a WET-Ecoservices assessment does not also need to be undertaken.

The assessment of the provision of ecosystem services at a catchment or landscape scale, based on impacts of human activity of wetland hydrological health is achieved through a series of steps, as is presented in Figure 2.

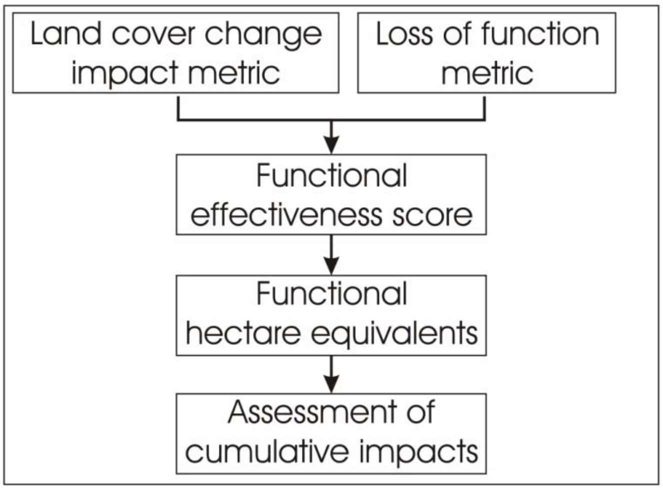


Figure 2. Summary of the relationships between different components of Ellery *et al.*'s (in review) methodology (Ellery *et al*., in review)

As is evident in Figure 2, this tool does go a step beyond the determination of functional hectare equivalents for a given ecosystem service by further proposing a method to assess cumulative functionality and impacts. Cumulative functionality in Ellery *et al.* (in review) is determined by adding together the functional hectare equivalents for each wetland in a given landscape, and cumulative effects are assessed by determining the difference between the total functionality of all wetlands in their current state and in their unimpacted state. The effects of upstream wetlands on the water quality of downstream wetlands are not integrated into this method. The authors explain that “in calculating the cumulative functionality each wetland is examined for its own subcatchment only- such that subcatchments of any wetlands upstream are excluded from the computations” (Ellery *et al*., in review, p62).

Ellery *et al.* (in review) illustrate this point by referring to a figure of a catchment containing four wetlands (Figure 3). It is explained that “although the four wetlands depicted (in Figure 3) occur within the same catchment as the catchment of wetland 4, the overall functionality of wetlands in this catchment would be computed separately for the microcatchments. As such, wetlands 1 and 3 would be considered in the light of land use in their entire catchments, but wetland 2 would be considered excluding wetland 1 and its catchment, and wetland 4 would be considered excluding the wetlands and catchments of wetlands 1, 2 and 3” (Ellery *et al*., in review, p62).

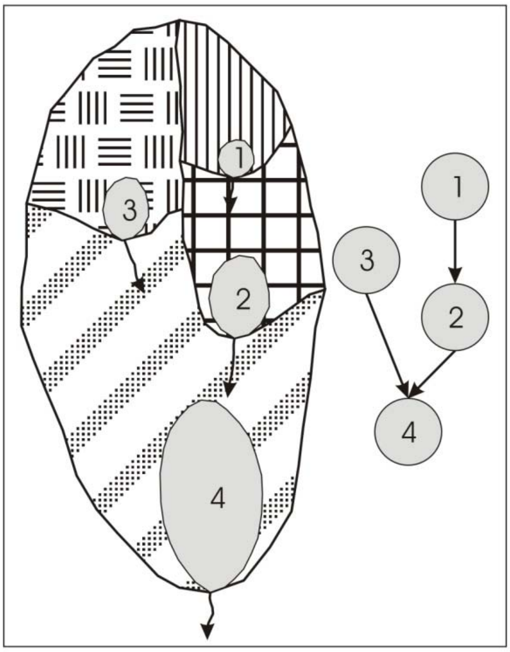


Figure 3. Configuration of nested wetlands in a hypothetical catchment, showing the configuration of subcatchments and wetlands that would be analysed in the assessment of wetland functionality and cumulative impacts. Arrows indicate the direction of water flow from the toe of individual wetlands and the inset shows the relationships between wetlands schematically (Ellery *et al*., in review)

2.4 The Effect of Catchment Land-cover on Water Quality

It is well understood that most alterations to the quality of water are initiated by human activities. This has been acknowledged by water authorities both locally and abroad, and in recent management plans, DWAF (2005a) have maintained that "effective management (of water resources) requires an understanding of the entire water supply (from the catchment and the source water, through to its consumer, and back into the water system), an assessment of the hazards and events that can compromise drinking water quality, and the implementation of preventative measures and operational controls necessary for ensuring safe and reliable drinking water" (p3). Thus, in observing catchment conditions, factors such as land-cover are pivotal contributors to the quality of the water leaving it.

2.4.1 A Review of Water Quality

In South Africa, great emphasis has recently been placed on the importance of maintaining water quality, more so as awareness grows of the fact that water resources are scarce and limited. A right to water is specified in the National Water Act, that of the Reserve, which comprises the basic human needs Reserve and the ecological Reserve (Mackenzie *et al.*, 1999). The former includes water for drinking, the preparation of food and personal hygiene, while the latter must be determined for any significant water resource such as rivers, streams, wetlands and lakes. Water quality and quantity maintenance is therefore of enormous importance in order to meet the requirements of the Reserve.

The term 'water quality' commonly refers to the state of water in terms of its use by humans, where water of 'good' quality is able to be used for consumption and agricultural and industrial purposes (Dallas *et al.*, 1994). Generally, intended water use determines the descriptive water quality parameters. Hence, there exist different parameters for expressing water quality, dependent on the intended water use and water quality benefit (Novotny, 2003; DEAT, 2006). Many terms are used to describe the factors that influence these parameters, including contamination, pollution, nuisance, and water degradation, and water quality is basically "expressed by the measured parameters that have exceeded some accepted threshold value of nuisance or interference with a beneficial use of the water body" (Novotny, 2003, p28).

The parameters outlined by the Department of Water Affairs and Forestry (DWAF) which state the boundaries within which the components of water quality should fall into, differ for different uses of water. Understandably, the parameters for drinking water are more stringent than those of the quality parameters for rivers or lakes for example, but it has been determined that the components of water quality that are most useful in indicating the quality of the water for whatever purpose, include (DWAF, 2005a):

- chemical quality, which includes total organic carbon, pH, disinfectant residuals, disinfection by-products;
- algal counts;
- microbiological quality, including Total coliforms, E.coli; and
- physical quality, which includes turbidity, colour, taste and odour.

DWAF (2005a) point out that while other water quality constituents do exist, it is not feasible, physically or economically, to test all of these constituents at the same frequency. As a result, monitoring is concentrated around the aforementioned constituents that have been identified as most indicative of the quality of a given body of water.

2.4.2 South African Land-cover

According to Yemane (2003), no universally accepted set of criteria for the classification of land in terms of use or cover exists, “and the most commonly used classifications are hybrids of land cover and land use (p1).” While land use refers to the way in which land is divided and allocated to various activities (e.g. industrial, agricultural, commercial), land cover may be defined as the natural elements that make up an area of land, including “the assemblages of plants and animals likely to be found at a particular site” (O’Callaghan, 1996, p17). In a broader sense however, land cover may include both vegetative and non-vegetative features, such as water, roads, buildings and cultivated land (Campbell, 2002).

The National Land Cover (NLC) Project was initiated by the South African Chief Directorate of Surveys and Mapping to map land-cover across South Africa, culminating in a 31-class standard land-cover classification scheme, presented in Table 133 (DEAT, 2008). The classes, which were designed to allow for class integration both nationally and internationally, all fall within four broader land-cover categories, namely natural, urban, agriculture, and degraded.

As is later explained in Section 5.2.1, an analysis of the 31 South African National land-cover classes was undertaken, and it was found that, given the scope of this research, the use of all 31 land-cover classes was far too detailed and specific, while the use of just the 4 aggregated categories proved to be too broad and general. As a result, the 31 classes were aggregated into 12 land-cover classes, with a view to combining classes of similarity in terms of their potential impacts on water quality. These particular land-cover classes- natural; forest plantations; cultivated, irrigated; cultivated, dryland; dongas and sheet erosion; degraded vegetation; urban residential- high density; residential- rural; urban commercial; urban industrial/ transport; mines and quarries; and urban informal (this final class was not included in the NLC project but was developed as part of this research in order to accommodate the growing occurrence of this class across present South African landscapes)- are used in this research and are therefore focused on in the following sections.

Table 13. NLC classes and their aggregated categories (DEAT, 2008)

NLC Code	Land-cover class	Aggregated categories
7	Improved grassland	Agriculture
8	Forest plantations	
18	Cultivated: permanent - commercial irrigated	
19	Cultivated: permanent - commercial dryland	
20	Cultivated: permanent - commercial sugar cane	
21	Cultivated: temporary - commercial irrigated	
22	Cultivated: temporary - commercial dryland	
23	Cultivated: temporary - subsistence dryland	
12	Dongas and sheet erosion scars	Degraded
13	Degraded: forest and woodland	
14	Degraded: thicket and bushland (etc)	
15	Degraded: unimproved grassland	
16	Degraded: shrubland and low Fynbos	
17	Degraded: herbland	
1	Forest and Woodland	Natural
2	Forest	
3	Thicket and bushland (etc)	
4	Shrubland and low Fynbos	
5	Herbland	
6	Unimproved grassland	
9	Water bodies	
10	Wetlands	
11	Barren rock	
24	Urban: residential	Urban
25	Urban: residential (smallholdings: forest and woodland)	
26	Urban: residential (smallholdings: bushland)	

27	Urban: residential (smallholdings: shrubland)	
28	Urban: residential (smallholdings: grassland)	
29	Urban: commercial	
30	Urban: industrial/transport	
31	Mines and Quarries	

2.4.3 The Effect of Catchment Land-cover on Water Quality

Environmental change is predominantly driven by population growth, economic activities, governance, and technology and innovation (DEAT, 2006). These drivers have coerced land-cover change, and invariably, the most consequential impacts of human-induced land-cover change involve environmental alteration and degradation (Goudie, 2000). Often, the quality of environmental resources is compromised as a result. A relevant example is the way in which the quantity and quality of water resources is strongly influenced by land-use (Lumsden *et al.*, 2003). Described as "mirrors of the landscape" (p42) by Davies and Day (1998), rivers tend to adopt the characteristics of the landscape through which they flow. It is emphasized that "if the landscape is in good condition, then the river is too. If the landscape is badly treated, then the river flowing through it will mirror that abuse" (Davies and Day, 1998, p42).

Given this, an understanding of the impacts of land-use on streamflow and water quality is integral in implementing sound wetland conservation and management procedures. Contamination may occur through natural or anthropogenic sources, and to ground water or surface water systems (Bergstrom *et al*, 2001), and understandably, the effects of land-cover on water quality will differ for each land-cover class or type. These effects essentially 'impair' the quality of water, as opposed to enhancing it. Novotny (2003) states that "pollution and impairment refer to a state of the water body and impairment of its integrity" (p28).

Pollutants commonly contributed by land-cover include Total Suspended Solids (TSS), which indicates the turbidity of water (Adbio, 2007), and includes the occurrence of small suspended particles, silt, and dead organic matter (Dallas *et al*., 1994); Total Dissolved Solids (TDS), a reflection of the total molecular, ionized or micro-granular organic and inorganic content of water (Hounslow, 1995); Biochemical/Biological Oxygen Demand (BOD), which indicates the rate at which oxygen is used up by biological organisms; Chemical Oxygen

Demand (COD), which is a measurement of the quantity of organic compounds in water; Total Kjeldahl Nitrogen (TKN), the sum of organic nitrogen, ammonia (NH_3), and ammonium (NH_4^+); as well as pollutants such as phosphorous, nitrates, ammonia, lead, zinc, and faecal coliforms, the last of which may be attributed to runoff from developed and developing areas, agricultural runoff, and sewage effluents (Vlok *et al*., 2006).

2.4.3.1 Natural Land-cover

It is often assumed that water that has only ever been in contact with a natural land-cover class such as natural forests, woodlands, and grasslands, will be unsoiled and pure, but it actually also contains chemicals, microorganisms, and sediments (Novotny, 2003). It is through the contact of rainwater with articles such as vegetation, soils, decomposed vegetation, and animal droppings that water becomes contaminated (Novotny, 2003); as well as by the underlying geology, biological processes such as evapo-transpiration, changes in pH, and anoxia caused by organic matter decomposition (DEAT, 2006). Studies conducted by Walling (1980) indicate that the chemical quality of precipitation is greatly altered when coming into contact with vegetation, and that enrichment of organic nitrogen, phosphorous, potassium, calcium, magnesium, and sodium are common. Examples of natural water contamination include the very low dissolved oxygen concentrations characteristic of streams draining natural wetlands in temperate regions, methane evolution due to highly organic wetland sediment, the sometimes naturally-induced high carbon dioxide content of some groundwater, and nutrient input into water sources by decaying aquatic vegetation (Novotny, 2003).

Novotny (2003) points out that many of the same processes that determine the natural biological and chemical composition of surface waters also generate pollution. The effect of these processes, which include rain, surface erosion, separation by suspension, and meteorological processes; differ with differences in the intensity at which the key water quality constituents are separated from soils and into receiving waters.

2.4.3.2 Forest Plantations

According to DEAT (2006), by 2006 more than 1.71 million hectares of natural habitat had been cleared for plantation forestry, which has had serious implications on natural resources.

As in the case of natural land-cover, interception of precipitation by forest canopies greatly affects the quality of water passing through, with animal droppings, decomposed vegetation, and chemicals and microorganisms trapped on the vegetation surfaces all contributing to water contamination (Novotny, 2003; Walling, 1980). Leaching by forests is a further contributor to water quality impairment, which adds potassium, calcium, and magnesium cations to groundwater (Walling, 1980).

Forest soils are known to be acidic and have high concentrations of cadmium and zinc in the soil solution (Novotny, 2003). Natural forest litter also contributes high levels of metals and the accumulation of detritus feeders (Novotny, 2003), all of which result in a progressive increase in pH as water passes through forest vegetation, soil, and litter (Walling, 1980). Forestry is further responsible for soil erosion and sedimentation of water bodies, caused in the industry by roads that are poorly managed, harvesting activities that are unsustainable, and forest fires which propagate the instability of nearby stream banks (DEAT, 2006).

A consequence of the implementation of forest plantations for timber and cheap wood that is often overlooked is the subsequent process of harvesting that often occurs. The cause for deforestation is described by Novotny (2003) as “unsustainable logging (clear-cutting)” (p79), which is most often as a result of demand for commercial lumber and wood, and limited soil fertility. The removal of trees that had previously served to bind underlying soils causes increased soil loss and elevated sediment loads carrying nutrients such as nitrogen and phosphorous to enter and impact the quality of the water of surrounding water bodies.

2.4.3.3 Cultivated, irrigated Land

Irrigated agriculture contributes nutrient (fertilizer) and agro-chemical (including herbicides and pesticides) contamination by return flows and seepage (DEAT, 2006; Kotze and Breen, 1994). Studies indicate that most sediment delivered to the world’s waters are from agricultural land, which most often are carriers of pesticide residues and excess nitrogen and phosphorous from fertilizers (Hamlett *et al.*, 1995), and indications are that sludge, manure, and soil biota are the most important sources of nitrates (Conrad *et al*., 1999).

Intensive irrigation has also been singled out as a cause of increased groundwater salinity, especially under conditions of poor drainage (Conrad *et al*., 1999). Irrigation water contains salts that are not evaporated into the atmosphere, leaving behind salt build-up in soils (Novotny, 2003; Gasser, 1980). To control this build-up of salts, excess irrigation waters must be applied, which is a further complication since this water excess containing salts and pollution, called irrigation return flow, gets deposited in surface and ground waters. Novotny (2003) highlights severe examples of such an occurrence, where the irrigation return flows entering streams have such markedly elevated salinity and pollution values such that the water becomes unsuitable for further use. Furthermore, the practices that may be implemented to manage crops, such as tillage, contouring, terracing, water harvesting and strip cropping, often impact the runoff from these cropped areas and may wield considerable influence on the water balance (Lumsden *et al*., 2003).

2.4.3.4 Cultivated, dryland Land

Examples of dryland or non-irrigated agriculture include row (e.g., corn and soybeans) and field close-grown crops such as wheat (Novotny, 2003). The primary pollutants from these croplands include sediment, nutrients, and pesticides which enter surrounding water bodies due to the practice of activities such as the disturbance of land by tillage, the application of chemical fertilizers and pesticides, and the spreading of manure (Novotny, 2003). Novotny (2003) claims that the practice of disturbing the soil by tillage is “the primary agricultural activity that causes elevated emissions of potential pollutants”, and that compared to native lands, this practice “increases sediment losses by several orders of magnitude” (p87).

Agricultural activities also included in this category are animal production on range- and pastureland, and confined livestock facilities in the form of feedlots (Novotny, 2003). The grazing of livestock on wetlands tends to contribute to erosion and the increased input of sediment into wetlands (DEAT, 2006; Kotze and Breen, 1994; Conrad *et al*., 1999; Novotny, 2003). This, along with faecal contamination, contributes large pollution loads in the form of nutrients, pathogens and organic matter. These contributions to pollution by livestock are true for both confined and unconfined animal operations, but Novotny (2003) highlights the difference between them in terms of point and nonpoint sources of pollution. While pollution from confined operations reaches water bodies by being carried by runoff during storm events, unconfined operations are nonpoint sources of pollution. Depending on the soil type and grazing practices, the free grazing of cattle has the potential to compact topsoil over a wide area, thereby reducing infiltration and increasing surface runoff that usually has a high biological oxygen demand (BOD) value (Novotny, 2003).

Dryland agricultural practices are particularly important in a South African context, where subsistence agricultural practices are the livelihood of a large number of people. Although subsistence farming is mostly practised on areas of less than 1 hectare in area, “the cumulative effect becomes very profound” (Swanepoel and Barnard, 2007).

2.4.3.5 Dongas and Sheet Erosion

Dongas (also known as gully erosion) and sheet erosion include gullies and channels that have been eroded out, and permanent or seasonal areas of very low vegetation cover in comparison with surrounding natural vegetation cover, induced by the gradual removal of soil and soft rock due to concentrated runoff (Thompson, 1996). In the creation of dongas, concentrated runoff acts to cut a deep channel into the soil, and on steep land where there is a sudden drop, a gully haed forms at the lower end of the channel and gradually deepens and widens the scar that the gully makes as it works its way back uphill (NDA, 1999).

More than 0.7 million ha of South African land is degraded and left bare by sheet and gully erosion (DEAT, 2006). Sediment is a primary carrier of other pollutants such as organic compounds, metals, ammonium ions, phosphates, and nitrates (Novotny, 2003), but the main pollutants contributed by dongas and sheet erosion are total suspended solids (TSS) in the form of sand, silt, and clay (WRC, 2007). These turbidity-causing sediments lessen in-stream photosynthesis, causing a reduction in food supply and habitat for water fauna (Novotny, 2003), while also providing a surface for the adsorption of ions which may subsequently be released into solution (Walling, 1980).

2.4.3.6 Degraded Vegetation

Degraded vegetation refers to permanent or seasonal, man-induced areas of very low vegetation cover in comparison with the surrounding natural vegetation cover (Thompson, 1996). This class is typically associated with subsistence level farming and rural population centres, where overgrazing of livestock and/or wood-resource removal has been excessive;

and is often associated with severe soil erosion problems (Thompson, 1996). This land-cover class covers more than 4.61 million ha of South African land (DEAT, 2006).

The effects of livestock grazing on water quality have been highlighted in Section 2.4.3.3.4, and include the contribution of nutrients, pathogens and organic matter from dung and urine; soil compaction and the reduced permeability of topsoils; and overgrazing and the loss of protective vegetation cover (Novotny, 2003). The effects of erosion and sedimentation include contributions of pollutants such as total suspended solids (TSS) to surrounding ground and surface water bodies, which increases turbidity and the opportunity for adsorption of ions, and their subsequent release into solution, which further impairs water quality (Walling, 1980). The degradation of land due to soil disturbance and vegetation removal accelerates the processes of natural weathering, mineralization, and leaching, which in turn disrupt mineral and nutrient cycles and negatively affect stream-flow quality (Gasser, 1980).

2.4.3.7 Urban residential- high density Land-use

Urban wetlands tend to face some of the most challenging effects from their surroundings. Ehrenfeld (2000) points out that during the 20th century, a dominant demographic characteristic was the expansion of urban and suburban areas, coupled with a rapid growth in urban population. These dramatic changes to previously sparsely populated natural areas have led to notable effects on both the hydrology and geomorphology of wetlands.

Impacts to water quality as a result of urbanisation include those caused by increased discharges; litter from unkempt urban areas entering storm water drains; settlement in riparian zones; increases in turbidity, nutrients, metals, and organic pollutants, and a decrease in O_2 (Ehrenfeld, 2000; WRC, 2007, Novotny, 2003). The increase in impervious surfaces as a result of urban development is the primary cause of increased storm water runoff in these areas, which causes an increase in the erosive force within stream channels, resulting in the input of substantially more sediment into the water system (Ehrenfeld, 2000; WRC, 2007). These challenges are exacerbated by storm water management facilities that are inadequately designed and managed, such as allowing the build-up of litter, pollution, illegal dumping, and culverts with insufficient capacities that cause upstream flooding and downstream erosion (WRC, 2007).

Unprotected soil and soil piles from new developments in urban areas also contribute exceptionally high pollutant loads, especially if appropriate erosion control measures are not implemented (Novotny, 2003). According to Novotny (2003), the loss of soil from construction sites “can reach magnitudes of over 100 tonnes per hectare per year” (p89).

There are therefore a vast assortment of pollutants contributed by urban areas, including organic chemicals from pesticides; pathogens and nutrients from sewage leaks, fertilizer use, garden refuse, and pets and animals; biochemical and chemical oxygen demand (BOD/COD) pollutants as a result of garden refuse and human and animal waste; and total suspended solids from inadequately maintained gardens, unpaved roads, and sites of construction (WRC, 2007).

2.4.3.8 Residential- rural Land-use

Approximately 50% of South Africa’s population live in rural areas (Swanepoel and Barnard, 2007). Water polluted due to the presence of rural residential areas are faced with many of the same challenges as those posed by urban residential and urban informal areas- litter from unkempt urban areas entering watercourses; settlement in riparian zones; increases in turbidity, nutrients, metals, and organic pollutants, and a decrease in O_2; but rural areas have the added issues of inadequate service provision for services such as sanitation, waste removal and pollution control (Ehrenfeld, 2000; WRC, 2007). Septic tanks, pit latrines, and the derisory way in which household and agricultural waste products are disposed of, as occurs in rural areas, greatly contribute to water pollution (Conrad *et al.*, 1999). These issues are exacerbated with grazing livestock that are more often than not kept in rural communities.

Septic tanks are the source of an extremely high total volume of wastewater that gets discharged directly to groundwater, and according to Novotny (2003), “are the most recorded sources of contamination of groundwater” (p89). When the capacity for adsorption of the disposal system runs out, contamination of groundwater and surface waters by organic and pathogenic microorganisms is likely, and is often exceptionally severe.

These sources of pollutants give rise to pollutants such as pathogens in the form of viruses, bacteria and protozoa; nutrients such as nitrogen and phosphorous; and biochemical and chemical oxygen demand (BOD/COD) pollutants (WRC, 2007). Grazing livestock further contribute to soil erosion, producing pollutants in the form of total suspended solids (TSS), and may compact soils in certain areas, thereby increasing storm water discharge.

2.4.3.9 Urban Commercial Land-use

An important characteristic of urban commercial areas is the presence of impervious surfaces in the form of buildings, roads, and parking lots. These surfaces are the primary cause of increased storm water runoff in these areas, which causes an increase in the erosive force within stream channels, resulting in the input of substantially more sediment into the water system (Ehrenfeld, 2000; WRC, 2007). This water system is further affected by litter from unkempt urban areas entering storm water drains; settlement in riparian zones; increases in turbidity, nutrients, metals, and organic pollutants, and a decrease in O_2. As in urban high density residential areas, these challenges are exacerbated by storm water management facilities that are inadequately designed and managed, such as allowing the build-up of litter, pollution, illegal dumping, and culverts with insufficient capacities that cause upstream flooding and downstream erosion (WRC, 2007).

Air pollution problems caused by traffic congestion are also a source of contamination in urban areas. Novotny (2003, p91) states that “logic would dictate that if the atmospheric pollution in megacities is much greater than in comparable cities in the developed countries, runoff pollution, for example, by toxic metals and carcinogenic PAHs should also be greater”.

Urban commercial areas are also often used as places of refuge for homeless people, giving rise to the input of pollutants such as pathogens, nutrients, and biochemical and chemical oxygen demand (BOD/COD) pollutants into water systems through insufficient sanitation practices. Further pollutants contributed to urban commercial areas to nearby water bodies include pathogens from sewage leaks and total suspended solids from unpaved roads (WRC, 2007).

2.4.3.10 Urban Industrial/Transport Land-use

The effects of industry on water quality have regularly been highlighted in the media, with hazardous and poisonous chemicals often entering the groundwater, as well as due to the elevation of nutrient, salinity, and sediment loads caused by industrial practices (DEAT, 2006). Sub-surface leaks from sewerage pipes, fuel tanks, and from storage facilities located underground; and unmanaged landfill leachate all pose significant threats to ground water (WRC, 2007). These threats are coupled with the effects of increased discharges of industrial effluents, such as those from treatment plants, laboratories, workshops, and storage areas (Farrimond, 1980); litter; and increased runoff due to the presence of impervious surfaces (WRC, 2007).

Pollutants from industry may enter water sources through a number of ways, including from industrial effluent being directly discharged into water resources, discharge or leaks of effluent into the sewer network, or through effluent entering storm water runoff (WRC, 2007). Pollutant types also differ depending on the industry type. Generally, industrial and transport areas have been known to contribute heavy metals from petrol, diesel, oil, grease, antifreeze, undercoating, brake linings, and rubber; organic chemicals from oil, petrol and grease; pathogens, nutrients, and biochemical and chemical oxygen demand (BOD/COD) pollutants in the form of hydrocarbons to surrounding water bodies (WRC, 2007).

Road surfaces are also known to impact on water quality in a number of ways, including through the input of heavy metals, the most well-known being lead; from organic pollutants contributed by vehicle exhaust fumes and bituminous road surfaces; and from spills during the transportation of hazardous loads (Pope, 1980; DEAT, 2006).

2.4.3.11 Mines and Quarries

In South Africa, mining activities have transformed greater than 200 000 hectares of natural habitat (DEAT, 2006). Coal and metallic ores are the most common minerals extracted by mining (Novotny, 2003), and activities associated with these extractions act as both point and nonpoint sources of pollution, making mining a substantial contributor to both ground and surface water contamination. Slimes dams and waste rock dumps from mining have been found to cover nearly 47 000 ha of South African land, with approximately 470 million tonnes of mining waste having been generated in the year 1997 alone (DEAT, 2006). Novotny (2003) points out that “although mining is not as widespread as agriculture, water quality impairment resulting from mining is usually more harmful” (p92).

There are three major environmental diffuse pollution impacts associated with mining and abandoned mines cited by Novotny (2003), and these include erosion of exposed lands and spoil piles, acid mine drainage, and water quality impairment caused by abandoned metal and uranium ore mining in the form of toxic metals and radionuclide pollution. Erosion and sediment discharges from both active and abandoned surface mines are known to be extremely problematic, with surface mining often stripping large areas of land of vegetation and soils, leaving them bare or covered with waste rocks and residual mining materials. “Erosion rates from surface mines are comparable to soil losses from highly disturbed lands such as construction sites or up-and-down slope-ploughed agricultural fields” (Novotny, 2003, p93). The seriousness of these impacts to water quality is exacerbated by the presence of toxic metals and pollutants associated with mining operations. This pollutant-loaded, eroded soil ultimately ends up in surrounding surface and ground water systems.

Acid mine drainage is a further example of a pollution impact associated with mining, and Novotny (2003) brings to light entire streams that become biologically dead due to acid mine drainage. He highlights the similarities in impact and chemistry between acid mine drainage and acid rainfall, and that the cause of acidity of mine drainage is the atmospheric exposure and subsequent oxidation of pyrite and similar sulphur-containing minerals. The result is that hydroxides and metals will deposit into water bodies affected by acid drainage.

Runoff from roads and old tailings and spoil piles is a further issue associated with mining (Novotny, 2003; Farrimond, 1980); as is the pumping of mine water from underground workings to prevent flooding (Farrimond, 1980); the discharge of effluent from coal washing plants; and the generation of pollutants from smelting and refining processes (DEAT, 2006), making the assortment of impacts of mining large and varied. Mining therefore negatively affects the pH and salinity of water bodies, and contributes high levels of metal and sediment from mine waste residues (DEAT, 2006; WRC, 2007). Total dissolved solids (TDS) contributed by active, abandoned, and derelict mining sites include cations such as sodium, calcium, magnesium, and potassium; and anions such as chloride and sulphate (WRC, 2007). Some forms of mining, such as uranium ore mining for example, further pose the dangers of radioactive contamination, and selenium toxicity (Novotny, 2003).

2.4.3.12 Urban Informal Land-use

Urban informal settlement areas are great contributors to water pollution. Faced with many of the same challenges as urban residential areas, urban informal areas have the added issues of inadequate service provision for services such as sanitation, waste removal and pollution control. This means that along with increased storm water discharges brought about by the erection of houses and platforms and compacted soils; litter, solid waste, and sewage spills entering drains and channels are further contributors to poor water quality (WRC, 2007). Increases in turbidity, nutrients, metals and organic pollutants are not uncommon in areas affected by urban informal areas (Ehrenfeld, 2000), as are pathogens and biochemical and chemical oxygen demand (BOD/COD) pollutants from sewage (WRC, 2007).

2.4.4 Pollutant Loadings from Catchment Land-cover

The previous section highlighted the fact that different catchment land-cover classes impact the quality of water entering a wetland in different ways. Each land-cover class was found to contribute a variety of different pollutants, and analogously, the degree of the contribution of each pollutant by each land-cover class also varies. These pollutant loadings are most commonly expressed as export coefficient and event mean concentration data. The former set of pollutant loading data refers to the average total amount of pollutant loaded annually into a system from a defined area, and allows for the estimation of loads for a number of specified pollutants for rural land-use types (U.S. Environmental Protection Agency, 2001). Loads calculated using export coefficient data are measured in lbs/ac/yr (pounds per acre per year) or in kg/ha/yr (kilograms per hectare per year) (Lin, 2004). EMC data allows for the estimation of pollutant rates for urban land-use types, and reflects the concentration of a specific pollutant contained in storm water runoff coming from a particular land-use type within a watershed (Lin, 2004). Loads calculated using EMC data are measured in mg/L (milligrams per litre).

A review of South African literature on EMC and export coefficient data brought to light the fact that EMC and export coefficient data were not easily accessible, or had not been extensively derived. While some notable works that explore the subject should be mentioned, including Ashton and Bhagwan (2001), Chiew and Vase (2003), Wimberley (1992) and Wimberley and Coleman (1993), actual contemporary values were difficult to access. Some

South African data however, were reported on in a paper by Owusu-Asante and Stephenson (2006). In order to attain some pollutant loading information for the land-cover classes explored in this study, U.S. EMC data from Lin (2004) and the U.S. Environmental Protection Agency (2001) were reviewed along with available South African data. The land-cover classes for which data were reviewed were natural, forest plantations, cultivated irrigated, high density urban residential, rural residential, urban commercial, urban industrial/transport, mines and quarries, and urban informal. Data for cultivated dryland, dongas and sheet erosion, and degraded vegetation were unavailable. Specific pollutant loading values for some pollutants were also unavailable, making comparisons between classes fairly difficult. Nevertheless, a literature review was conducted in order to gain an idea of some pollutant loading values.

Reviews of these literary sources in terms of Event Mean Concentrations showed that in terms of BOD contribution, natural land-cover, forest plantations, cultivated irrigated, rural residential, and urban informal posed the least severe impact, with between 4 and 8 mg/L being contributed by these classes. Urban industrial/transport most severely contributed BOD, at 16 mg/L; followed by high density urban residential and urban commercial, and mines and quarries. COD was highest from urban informal land-cover at 819 mg/L, followed by urban industrial/transport, urban commercial, and high density urban residential. Other classes were found to contribute approximately 35 mg/L of COD. The most severe contributors of TSS and TDS were urban informal and urban industrial/transport land-cover classes, and mines and quarries. High density urban residential, urban commercial, urban industrial/transport, and urban informal were found to contribute immensely to Total Nitrogen and TKN with up to 4 mg/L for both; while ammonia nitrogen was found to be mainly contributed by the urban land-cover classes. Reviews of organic nitrogen, total phosphorus, dissolved phosphorous, zinc, copper, lead, cadmium, chromium, and nickel showed little difference between classes, while the limited data available for faecal coliform geometric means showed that urban industrial/transport contributed up to 2300 counts per 100 mL, and forest plantations 500 counts per 100 mL (Owusu-Asante and Stephenson, 2005; Lin, 2004; U.S. Environmental Protection Agency, 2001).

2.5 **Landscape-level Impacts and Cumulative Effects**

2.5.1 Introduction

The issue of cumulative effects or cumulative impacts has long been both mysterious and contentious. Despite the many progressions made in the fields of science and the environment, the ideas behind cumulative impacts are still ill-defined and not as well understood as most other environmental concepts. The most widely used definition of cumulative impacts stems from the U.S. National Environmental Policy Act of 1969 (Bedford and Preston, 1988, p566):

"Cumulative impacts are defined as the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time".

When reflecting upon this definition it must be noted, as Bedford and Preston (1988) point out, that it is a regulatory one, whose purpose is to offer broad policy guidance in legislation. As such, this definition lacks descriptions of how effects of a cumulative nature interact or in what way they may be measured. These shortcomings have left much room for ambiguity and a lack of specific ideas of what exactly is meant by 'cumulative impacts'. Bedford and Preston (1988) began their quest to unravel these ambiguities by drawing a distinction between cumulative impacts and conventional impacts. It is pointed out that the essential differences lie in the spatial and temporal scales at which these impacts need to be considered. While the boundaries of conventional impacts are drawn by a single disturbance or project, cumulative impacts adopt a broader view, which is of particular importance when evaluating cumulative impacts in relation to water and wetlands. One may perceive the evaluation of a conventional impact to be adequate, but what are overlooked are the interrelationships and interdependencies prevalent among wetlands acting in combination as a functional unit (Tiner, 2002).

From a distance, rivers, lakes and pans often seem to have a scattered distribution pattern, creating the impression that each of these water bodies exists in total isolation from the other (Davies and Day, 1998). Further evidence to support this belief may be found in the fact that often, the biota of one aquatic system may be distinctly different to another, despite their close proximity; the transfer of materials from one to another may be extremely limited; single-direction, open-ended systems such as rivers may be affected downstream by upstream activities but often not the other way around; and in seemingly closed-system lakes which receive inputs from adjacent features but accumulate materials without transporting them. But as Davies and Day (1998) strongly point out, "…to think of water bodies as being independent of each other is not only simplistic but downright incorrect" (p44).

Davies and Day (1998) go on to justify this claim by introducing what they describe as "the basic units of the landscape" (p45): catchments. A catchment is the entire area that is drained by a single river system, whose significance lies in the fact that all the water entering this single drainage area, be it by rain, mist or snow, will either remain in the catchment through storage underground, or will enter the sea via a single estuary. This stored underground water fills underground caverns to form lakes beneath the surface of the land, inhabits the spaces between rocks and soil particles, and flows beneath the ground to essentially connect the numerous parts of the catchment and to link surface water systems.

There are thus different scales at which the assessment of wetland impacts may be conducted (Table 14), and the evaluation of impacts at larger scales allows for cumulative impact assessments to be undertaken.

Table 14. Different scales at which impact assessment might be conducted, and characteristics determining their spatial boundaries (Kotze, 1999)

Scale	Characteristics of spatial boundary
Individual wetland	• A single site defined by the boundaries of the wetland itself
Catchment or basin	• The area drained by a river or stream and its tributaries
Landscape	• Spatially repetitive cluster of interacting ecosystems • Similar geomorphology • Similar set of disturbance regimes • May contain one or more catchments
Region	• Area determined by a complex of climatic, physiographic, biological, economic, social and cultural characteristics • May contain one or more landscapes

The concept of catchments has serious implications for water quality. Ground water quality is compromised when the inflow of water recharge is contaminated, and this inadvertently affects surface water stocks, since the two flows are inextricably linked over time and geographic space (Bergstrom *et al*., 2001). As underground aquifers are recharged by surface water percolating through the overlying soil, springs and wetlands allow water from underground aquifers to join surface water bodies (Bergstrom *et al*., 2001).

A further concept linked to the landscape is that of landscape processes, described by Sheldon *et al.* (2005, p2-11) as:

> "environmental factors that occur at larger geographic scales, such as basins, sub-basins, and watersheds. Processes are dynamic and usually represent the movement of a basic environmental characteristic, such as water, sediment, nutrients and chemicals, energy, or animals and plants".

Clearly, the dynamics associated with cumulative impacts differ greatly from conventional ones. These differences pose new challenges and require the consideration of a number of issues and complexities. To address such issues is to acknowledge the situation of wetland and wetland function loss in its entirety, as more often than not, the ecosystem services provided by a wetland are determined not only by the intrinsic characteristics of that wetland in particular, but also by those wetlands related to it and by the catchment in which it is located.

2.5.2 Addressing Cumulative Effects on Wetlands

Assessing cumulative effects with regard to the loss of wetland function involves the measurement of the combined loss of functions through wetland impacts to all wetlands in a landscape (Ellery, 2008, pers. comm.), following Dube *et al*.'s (2006) claim that "cumulative environmental effects result from the incremental, accumulating, and interacting impacts of stressors on the environment" (p88). This involves recognising that because its relation to other wetlands affects the functional contribution of a wetland, the impacts to each wetland may be equivalent when considered individually, but very different when they are considered in terms of cumulative impacts given their landscape context (Kotze, 1999). This is guided by the notion that while individual actions may seem insignificant, major change may be produced when these actions are combined (Bedford and Preston, 1988). Bedford and Preston (1988) describe the broad view that is taken by cumulative effects. They describe the 'boundaries' of cumulative effects as different to those of conventional effects, with the former being dictated by aspects such as the geographic area, and time frame and quantity of prevalent disturbances.

Analysing landscape level effects on water quality therefore involves the consideration of a variety of factors. Along with the spatial scale at which the cumulative effects of wetland loss may be determined, the spatial configurations and physical attributes of the wetlands in a landscape are also of immense importance. This aspect of cumulative assessment is often overlooked, and the effect of anthropogenic activities on them often underestimated. Furthermore, the influence of these attributes on the provision of ecosystem services by wetlands is highly significant, making their consideration in cumulative effects analysis extremely important (Bedford and Preston, 1988). Furthermore, when considering the cumulative effects of wetland loss and degradation on the functional values of a catchment, it is important to recognise and determine the value of the component wetlands, "based on their relative contribution to the functioning of the entire landscape system" (Bedford and Preston, 1988, p567)

2.5.2.1 Catchment and wetland land-cover and its relation to wetland function

Bedford and Preston (1988) believe that the first step in conducting a cumulative impact analysis is to establish appropriate boundaries for the analysis and to include all anthropogenic disturbances that fall within them. As such, the consideration of land-use and land-cover is imperative in cumulative effects analysis. The 'Landscape Principle' as described by Sheldon *et al.* (2005) is a simple principle that states that "the size, shape, and spatial relationships of land-cover types influence the dynamics of populations, communities, and ecosystems" (p2-4).

This is reiterated by Wu *et al*. (2003), who emphasize the importance of incorporating land use and land-cover change, and their influence on ecosystem services. The necessity for including this aspect in landscape-level studies involving wetlands is explained by Kotze (1999), who describes the occurrence of wetlands as "patches in an intervening landscape matrix, with exchanges of material, information and energy in both directions between wetland and matrix" (p134). These exchanges imply that matrix and wetland yield influence over each other, and that changes to this matrix in the form of land-cover change for example, would influence the functioning of the wetland influenced by that matrix (Kotze, 1999). The ability of a wetland to perform a particular ecosystem service is therefore likely to be hindered or enhanced by the land-cover present even beyond the boundaries of the wetland.

This concept has been labelled the "Landscape Principle" by Sheldon *et al.* (2005), who describe this ecological principle as one that underlies a proper understanding of how wetlands function and how best they may be managed in order to protect their ability to perform ecosystem services. The Landscape Principle dictates that the landscape is comprised of a "spatial array of habitats and ecosystems" in the form of various land-cover types, whose size, shape, and spatial relationships all yield great influence over prevalent ecological processes. This is akin to the 'matrix' described by Kotze (1999), and is referred to by Sheldon *et al.* (2005) as a "landscape template" (p2-4), to which all ecological processes respond.

The importance of accounting for off-site impacts and their effect on ecosystem services provision such as water quality enhancement is expressed by Kotze (1999), in which he highlights the fact that given that South Africa is considered a 'dry' country (Section 2.2.8), much of the water supplied to wetlands is from the surrounding catchment, thereby making off-site impacts to water quality and quantity particularly consequential.

It should be noted however, that not all of the ecosystem services provided by a particular wetland may be altered with a change in the wetland's context, and that the provision of ecosystem services may alter to different degrees or in different directions (Kotze, 1999). An example offered by Kotze (1999) is that while a wetland's ability to support biodiversity may be compromised due to increased human activity in that wetland's catchment, such as irrigated agriculture for example, the same implementation of irrigated agriculture may increase the value of the wetland for providing water quality enhancement. This is because the change from natural to irrigated agriculture will impair the quality of the water entering the wetland, thereby affording the wetland greater opportunity to enhance it. However it is pointed out by Kotze (1999) that the benefits that are yielded by such a wetland are also dependent on how effectively that wetland may be able to assimilate incoming pollutants.

2.5.2.2 The spatial configuration of wetlands and its relation to wetland function

It has been established that analysing landscape level impacts involves the consideration of a variety of factors, such as the effect of wetlands at different spatial scales, the spatial configuration of wetlands within the landscape (Kotze, 1999), as well as the influence of catchment land-cover types on the wetlands.

These aspects are of importance because a drainage network links all of the wetlands within a catchment, and the groundwater interconnectivity within catchments has strong consequences: pollution of one body of water, such as a lake, often causes groundwater to become polluted and inadvertently contaminates a seemingly unconnected stream; excessive groundwater removal from boreholes may drastically drop the water-table to dry up surface wetlands; and commonly, substantial water removal from upstream of a river drastically affects downstream morphology, with the silting and shallowing of estuaries greatly disrupting the natural environmental processes necessary to keep the habitat optimal (Davies and Day, 1998). Similarly, upstream land-cover may affect downstream processes. Thus, upstream impacts potentially impact wetlands downstream. Furthermore, it is likely that the location of wetlands within a catchment influences the overall cumulative impact of factors such as wetland degradation within that catchment. Wu *et al.* (2003) point out that empirical studies suggest that the way landscape elements are configured often yields considerable influence over ecosystem processes. Despite this interconnectedness of the landscape and the influences that these interactions may yield on wetland functions, most research and management has focused on functions and controls of functions within the wetland itself, rather than on the entire landscape or watershed (Sheldon *et al.*, 2005).

The importance of considering these aspects may be illustrated by considering a simple development project. At the site scale, a project and its effects on natural resources may be evaluated and local impacts determined. When considering the bigger picture however, many critical issues may have been overlooked, such as the impacts of the project on resources as a whole, the total impacts brought by all anthropogenic activities in the vicinity, or the secondary impacts which may arise as a result from the impacts of the project interacting with prevalent anthropogenic activities (Bedford and Preston, 1988). Thus, by extending the spatial and temporal boundaries of the analysis, a more thorough and accurate assessment is gained. To illustrate the issue at hand, consider Figure 4.

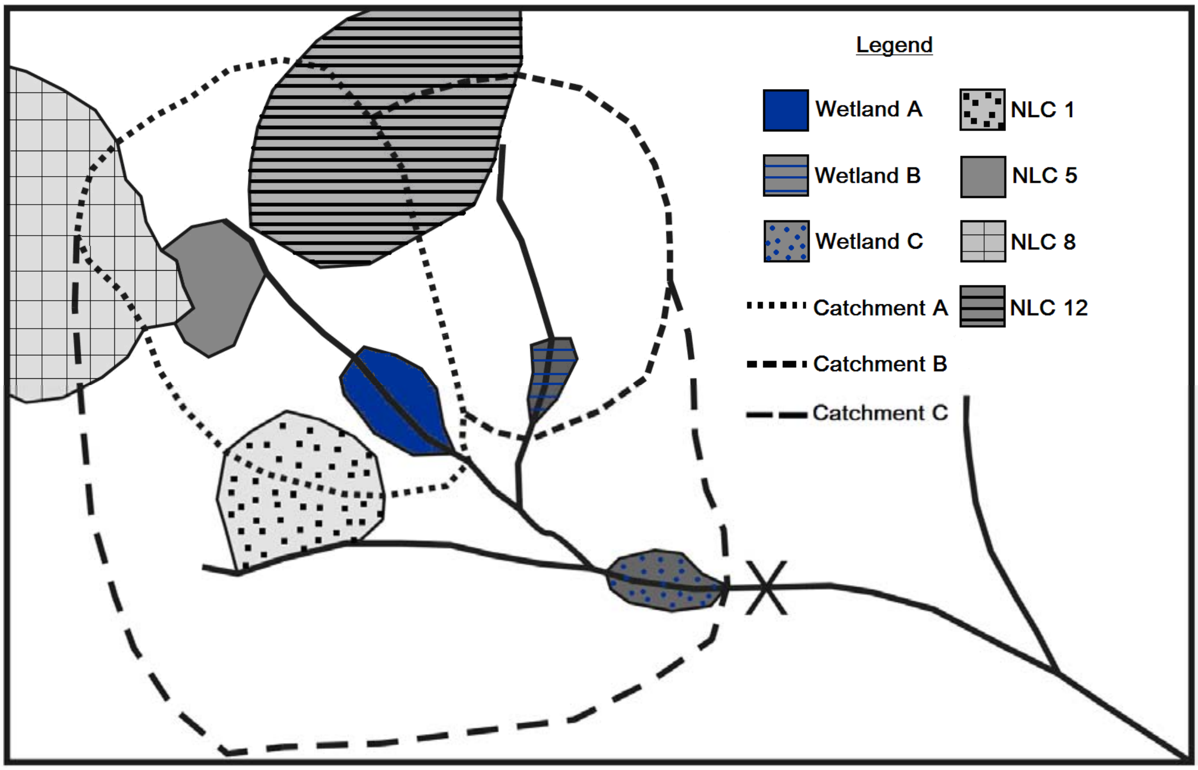


Figure 4. Example of a catchment with multiple wetlands

In the example illustrated by Figure 4, it can be seen that Catchment A and Catchment B (depicted by the dashed lines) share a portion of their boundary length, but catchments A and B are nested within Catchment C. The application of the Method for Assessing the Cumulative Impacts on Wetland Functions at the Catchment or Landscape Scale as described in Section 2.3 for toxicant removal, will result in hectare equivalents of toxicant removal function for each wetland, based on the land-cover present in their catchments, their impact scores, their respective sizes in hectares, and the wetland types. Strictly speaking however, these hectare equivalents actually describe the toxicant removals that take place in Wetlands A and B, but due to their position in the landscape, the water entering Wetland C will have now been influenced by Wetland A and Wetland B (the water entering wetland C is a product of water leaving wetlands A and B). Wetland C therefore has less ‘work’ to do in terms of performing the function of toxicant removal, as Wetland B and Wetland C have already treated the water passing through them. If Wetlands A and B were removed, however, Wetland C would be required to perform the full function of toxicant removal for its entire catchment. The ability of wetland C to remove toxins must therefore be considered given these factors.

Clearly, the dynamics associated with cumulative impacts differ greatly from conventional ones. These differences pose new challenges and therefore require an alternative approach to natural resource regulation and management. Bedford and Preston (1988, p567) beautifully illustrate the importance of considering cumulative effects in the following analogy:

"Imagine a Renaissance mosaic of a mother and child, composed of tiles of various shapes and colours. With age, the mosaic has begun to lose tiles, and we must decide which tiles to reinforce to best preserve its value. If conventional environmental assessment strategies were used, the tiles would be evaluated in terms of their individual intrinsic value. Those of highest intrinsic value would be selectively preserved. This strategy would not preserve the image of mother and child. Yet the *image* is the feature making the mosaic more valuable than the sum of the values of its component tiles; the image itself is the resource of concern. If the image in the mosaic is to be preserved, the value of each tile must be determined by its importance in conveying the central image of the mosaic within the spatial boundaries of the mosaic as a whole".

There is clearly a need to evaluate wetlands on a scale that incorporates their ability to improve water quality based on their connectivity to, and influence on, other surrounding wetlands. Their obvious interaction means that impacts that may seem insignificant when considered individually become major when considered collectively over time and space. By assessing wetlands in such a manner, decision-making may be greatly aided, so that wetlands with the greatest potential for water quality maintenance may be prioritised for rehabilitation.

2.5.3 Accounting for cumulative effects in wetland prioritisation

The analysis of cumulative effects clearly incorporates a number of concepts and influential factors, each of which requires consideration when prioritising wetlands for rehabilitation and conservation purposes given a landscape-level scenario.

Bearing in mind the concept of opportunity for providing an ecosystem service such as water quality enhancement by a wetland, a rule of thumb offered by Kotze (1999) with regard to the context of the wetland and where wetland conservation and rehabilitation should be directed in order to maintain overall catchment water quality, is that "efforts should be directed to those wetlands with human activities in their catchments" (p139), as these wetlands would be afforded the greatest opportunity for enhancing water quality. This would imply that particular land-cover classes prevalent in a wetland's catchment would offer greater potential than other land-cover classes for the opportunity for water quality enhancement by the wetland.

Kotze (1999) further suggests that "there should be representation across different wetland size classes" (p139), as limiting focus to just large wetlands for example, is likely to lead to the loss of small wetlands and therefore to higher levels of isolation; to under-representation of specific wetland types which do not occur as large areas; and to reduced effectiveness in water quality enhancement functionality.

2.5.4 Past Approaches to Cumulative Effects Assessment

The issues of landscape-level ecosystem services provision and impacts have been addressed by scholars in the past, and most notable are the works of Tiner (2002; 2005), and White and Fennessy (2005). The latter publication attempted to model the suitability of wetland restoration potential at the watershed scale. This was achieved by developing a GIS-based model that used environmental criteria as indicators to identify the total population of sites suitable for restoration, and then filtering the sites to prioritize them according to their potential to contribute to the maintenance of water quality (White and Fennessy, 2005). The study of Tiner (2005), attempted to assess the cumulative loss of wetland functions in the Nanticoke River Watershed as a consequence of wetland degradation and loss. Tiner (2005) initially identified and classified the wetlands in his area of interest, and expanded the National Wetlands Inventory (NWI) data for those wetlands to include descriptors for landscape position, landform, water flow path and waterbody types. Ten wetland functions were chosen, and correlated with the prevalent biological and physical characteristics of the wetlands using a simple weighting scale. These correlations were applied to the NWI database, analyses were undertaken, and a series of maps were produced that highlighted and summarised the functions provided by each wetland.

Dube *et al.* (2006) also highlight attempts at cumulative effects assessment put forward by the Canadian Environmental Assessment Agency, but despite the intention of the approaches to monitor and assess the environmental state and the stressors that impact upon it with a view to achieving sustainability, the approaches have been found to differ in terminologies, to lack methodology, and to have fragmented environmental quality information.

While past approaches to cumulative effects assessment are valuable in building an understanding of cumulative effects, the relationship between changes in the provision of ecosystem services with alterations in wetland health, and their effect on the overall catchment are not addressed, particularly in a South African context, nor are the influences of surrounding land-cover types. Furthermore, a method to include the consideration of wetland location in the landscape while considering all of these aspects is also not included in these studies.

2.6 An Overview of the Analytical Hierarchical Process (AHP)

Developed by statistician Thomas L. Saaty in the 1970s, the AHP is a methodology in the form of an algorithm that allows for the analysis of multiple criteria in decision-making (Nataraj, 2005), and is also known as a Multiple Criteria Decision Analyst (MCDA) Tool (Stewart *et al.,* 2001). Forman (1997) explains the appropriateness of the name of the AHP by breaking it down and describing each component: ‘Analytic’ is derived from the word ‘analysis’, which describes the process of breaking down an entity into its constituent elements; ‘Hierarchy’ is described as the simplest way to structure a complex problem; and ‘Process’ denotes that there is no single step or formula to attain a result, but that a series of actions allows for the finding of the best alternative.

The tool helps decision-makers to model complex problems, evaluate the criteria upon which to base the evaluation of alternatives, to prioritise alternatives, and to allow judgements to be made by decision-makers who may then clearly state their preferences. This is the first step toward reaching consensus on an issue in which the expertises of many people need to be considered. AHP allows for a measurable connection to be made between the subjective judgement of the decision-maker and a quantifiable decision (Nataraj, 2005).

Saaty (1990) describes the many benefits of analytic decision making, given that the approach is simple and accessible to the lay person. He describes the morphological way of modelling a decision so that people are induced to explicitly express their knowledge, which allows for a group of people to “organize and harmonise their different feelings and understanding” (Saaty, 1990, p19). He goes on to state that the process allows decision-makers to use judgements and observations to develop relations between factors, and based on the strength of these relations, to allow predictions to be made of most likely outcomes.

Furthermore, the process allows for values and influences to be incorporated with accuracy, as well as the inclusion of judgements that are based on intuition and emotion. Finally, such a formalised approach allows for revisions that are gradual and thorough, and for the task of combining the judgements of different people who have different opinions on the same subject. He concludes that the best way to deal with complexity is through the use of rationality, and that the analytical approach does just that.

2.7 **GIS Applications to Wetland Research**

The complexities associated with utilising a multi-layered approach to determine cumulative effects can be quite daunting, but the use of an appropriate GIS makes the process infinitely easier. A Geographical Information System (GIS) allows for the "entering, storing, manipulating, analyzing, and displaying" (Congalton and Green, 1995) of geographic or spatial data, which are represented by points, lines, and polygons, each of which have describing attributes.

Lyon and McCarthy (1995) describe the levels of effort and technology that are within the capabilities of GIS. At the lowest level, a GIS can provide inventory information, such as an indication of different land-cover classes within a given area and their quantities and extents. This information is certainly useful for many applications, including the analysis of spatial variability or for statistical analyses. At the highest level however, a GIS can allow for the extended utilisation of spatial database information to support modelling of water resource phenomena, allowing for the generation of results that are far more detailed and spatially averaged than sole inventory information.

Johnston (1994) points out that Geographic Information Systems (GIS) provide capabilities that are required of the complex tasks that cumulative impact assessment requires, such as the analysis of multiple wetlands and multiple perturbations spread over large distances and time scales. It is further explained that with a suitable wetland map and an appropriate GIS, many quantitative measures may be calculated, *including* the loss of wetland area, a decrease in the number of wetlands in the landscape, a decrease in wetland density, altered connectivity, the loss of different wetland types, and the loss of wetland functions. GIS and remote sensor technologies allow for useful evaluations of wetland resources across the landscape (Lyon and McCarthy, 1995).

These capabilities are as a result of great advances in technology and thinking, particularly in the water resource engineering arena (Lyon and McCarthy, 1995). This has allowed for the continual exploration into larger, more challenging projects, including the assessment of spatial and temporal water resource characteristics; as well as the evaluation of scenarios, described by Lyon and McCarthy (1995) as one of the most important contributions of GIS to data analyses. These scenario modelling exercises allow for the sensitivity of variables to the results of the model to be analysed (Lyon and McCarthy, 1995). This serves as a particularly useful planning tool, allowing wetland managers to simultaneously analyse large quantities of spatially and temporally related data within a framework of constraints (including financial) and strategies, and to prioritise wetlands and management alternatives based on the results of those analyses (Ji and Mitchell, 1995).

Amongst many studies of GIS applications to wetland research, some examples include studies by De Roeck *et al*. (2008), Tiner (2005), Rebelo *et al.* (2009), Vieux (1995), Shamsi (1995), Lyon and McCarthy (1995), Ji and Mitchell (1995), and Hamlett *et al.* (1995).

CHAPTER THREE: STUDY AREA

3.1 Introduction

On the south coast of the Western Cape province of South Africa, nestled between the towns of Mosselbaai to the east, Swellendam to the north-west, George to the north-east, Calitzdorp to the north, Stillbaai to the south, and comprising the town of Riversdale, lies the Goukou Forum of the Gouritz Water Management Area (WMA) (DWAF, 2005b) (Figure 5). The Goukou Forum encompasses a number of quaternary catchments, all of which are a product of the 67km long Goukou (formerly known as Kafferkuils) River which originates on the south slopes of the Langeberg Mountains (Carter and Brownlie, 1990; DEAT, 2008). One of these catchments comprises the study area, within which the Goukou River converges with the Vet River. The point of this convergence lies in close proximity to the town of Riversdale, which, at 34°05’33”S and 21°15’38”E, falls within the study area (Figure 6).

Figure 5. Locality map of the Goukou Forum, with study area catchment highlighted in red (adapted from DWAF, 2005b)

Figure 6. Satellite image indicating the town of Riversdale, the point of convergence of the Vet (from the north-west) and the Goukou (from the north-east) Rivers, and surrounding land-cover (Maplandia, 2005)

The Goukou region was chosen as the case study area due to the availability of good data on the locations of wetlands, the health of the wetlands, and the state of surrounding land-cover. The number of wetlands present, the range of land cover types present, and the availability of suitable spatial data and other useful information presented an ideal case study.

3.2 **Climate**

The Western Cape is a mostly winter rainfall province, with the prevailing north-westerly wind reaching the western part of the country first, and depositing large quantities of rain there (Davies and Day, 1998). This is reflected in the average rainfall data of the area surrounding Riversdale, with the area receiving the lowest rainfall (23mm) in January, and the highest (40mm) in March (SAExplorer, 2008). Despite these peaks and troughs in rainfall, this area receives rain throughout the year, classifying it as Climatic Region A according to Carter and Brownlie (1990). Figure 7 reflects the fact that rainfall does occurs throughout the year in the Goukou Forum, with the area receiving a mean annual precipitation of approximately 384mm.

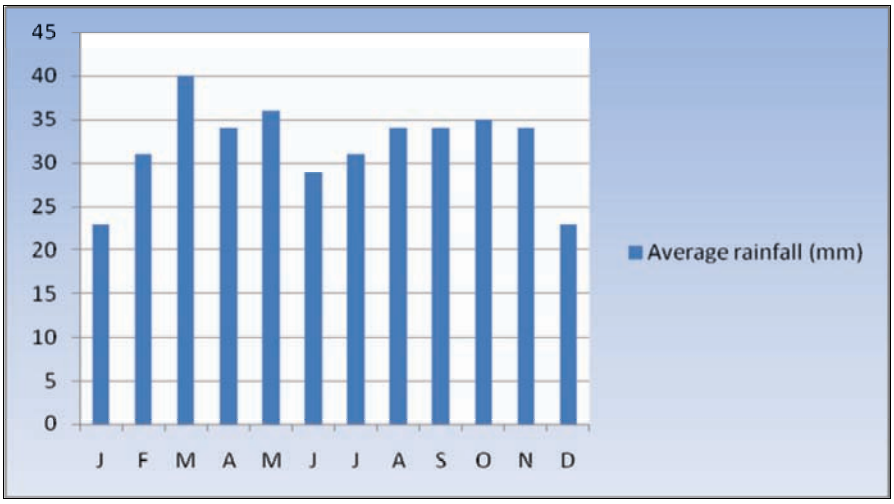


Figure 7. Average monthly rainfall of the Riversdale area (SAExplorer, 2008)

Temperatures in the Riversdale area reach their lowest in July, with the average daily maximum temperature reaching 18.1°C. With temperatures averaging 27.6°C, January and February are the Goukou region's hottest months (SAExplorer, 2008). Frosts, thunderstorms and hail in the region are rare, while snow occasionally falls on the Langeberg Mountains in winter and spring (Carter and Brownlie, 1990).

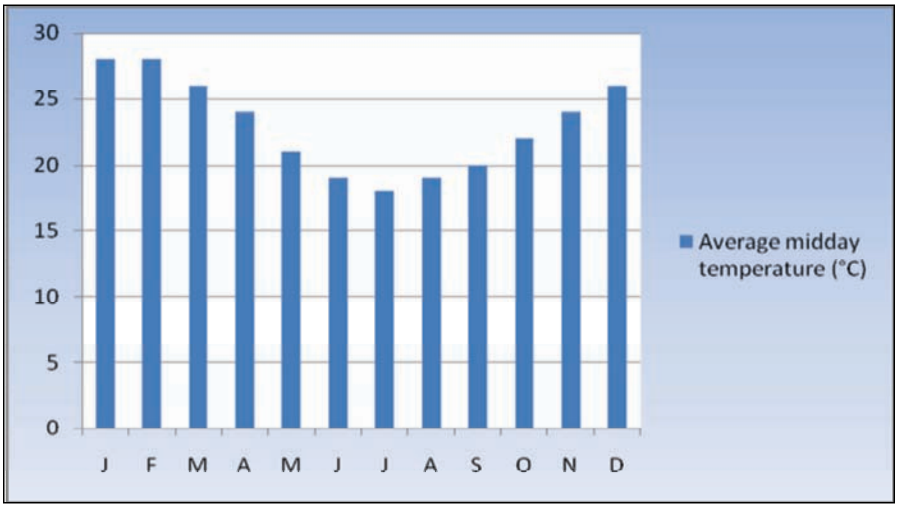


Figure 8. Average daily maximum temperatures of the Riversdale area (SAExplorer, 2008)

3.3 Geology and Soils

The geology of the Goukou region is varied, with coastal rim mountains composed mainly of solid quartzites and sandstones, which are highly resistant to erosion, in its upper regions (Rogers, 1997) but dominated by more erosive rocks toward the coastline. According to Cowan (1995) the area falls within the MCF.k wetland region, which he describes as mainly composed of Table Mountain sandstone and Witteberg quartzites of the Cape Fold mountain system. From the Langeberg Mountains of this Cape Fold Belt, the Goukou River carves its way through more than 10km of erosive Cretaceous sedimentary rocks of the Enon Formation, after which the remaining 40km of landscape is comprised mainly of Palaeozoic Bokkeveld shales (Carter and Brownlie, 1990).

According to DEAT (2000) soils with minimal development which are usually shallow on hard or weathering rock, with the occurrence of lime, dominate the Goukou region. Greyish sandy, excessively drained soils occur in the southern parts of the study area, while the northern regions are dominated by strongly structured soils with a marked clay accumulation. The geology and climate of the area have allowed for the formation of a number of wetlands, particularly in the upper reaches of the catchment.

3.4 **Vegetation**

Vegetation in the Goukou Forum is dominated by vegetation of the East Coast Renosterveld bioregion, while the southern parts of the area are classified as South Coast Fynbos (Vlok and de Villiers, 2007; Mucina and Rutherford, 2005), with many occurrences of Restionaceae, Bruniaceae and sedges (Rogers, 1997). The northern reaches of the area contain vegetation of the Succulent Karoo biome, while some Thicket occurs to the south (DEAT, 2000). Vegetation is predominantly Coastal Macchia, with the occurrence of Coastal Renoster-Bushveld in the northern regions.

Wetland plant species such as *Phragmitis australis* dominate the outer perimeter of the wetlands of the Goukou Forum, while *Typha capensis* occurs in more permanently wet areas (Vlok and de Villiers, 2007). *Prionium* dominates the riverbeds of the Goukourivier River and floodplain unit (Vlok and de Villiers, 2007). The widespread occurrence of alien invasive vegetation, such as *Conyza, Galenia, Helichrysum, Stoebe, Aristida, Bobartia,* and *Leucadendron* (Vlok and de Villers, 2007) has been identified by DWAF (2005b) as a key water resource issue in the area that requires additional attention.

3.5 Land-cover and land-use

Approximately 63% of land-cover in the area is natural (DEAT, 2008), comprising vegetation, water bodies and wetlands (Figure 9). Agriculture accounts for approximately 35% of the land-cover of the Goukou catchment, which is made up of a combination of temporary commercial dryland agriculture, commercial forestry, temporary commercial irrigated agriculture, and improved grassland (DEAT, 2008). Approximately 2% of the catchment is degraded shrubland, with just 1% in the form of urban land-cover comprised of residential and industrial developments in the towns of Stillbaai and Riversdale.

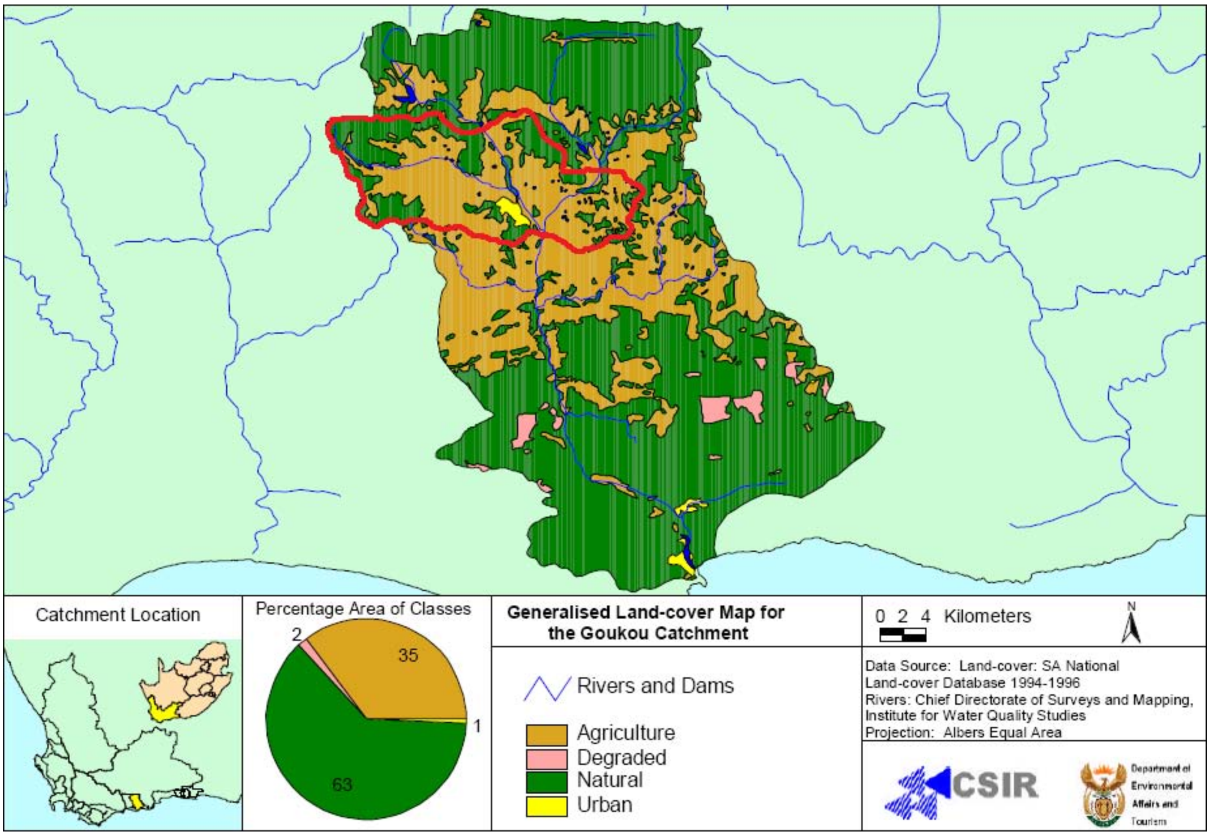


Figure 9. Land-cover of the Goukou Region with study area catchment highlighted in red (DEAT, 2008)

CHAPTER FOUR: MATERIALS AND METHODS

4.1 **Introduction**

Building a model of wetland degradation and its cumulative impact on water quality at a landscape level necessitated the incorporation of a number of steps and aspects in order to address the many associated issues. These included mapping of the catchment; the generation of impact ratios using the AHP; the use of these ratios to determine hectare equivalents of water quality impairment into each wetland; the utilization of Ellery *et al*.'s (in review) tool to determine hectare equivalents of water quality enhancement of each wetland; the subsequent determination of the overall effectiveness of water quality enhancement by each wetland; the integration of spatial configurations of wetlands in the landscape; and analyses of scenarios (Figure 10).

The differences in colour of the various steps in Figure 10 are indicative of how these steps address each of the objectives outlined in Chapter One. Those steps in red address Objective 1, the steps in blue address Objective 2, Objective 3 is addressed by the step highlighted in orange, and Objective 4 is highlighted in green. Finally Objective 5, which will be addressed in Chapters Five and Six, is highlighted in purple.

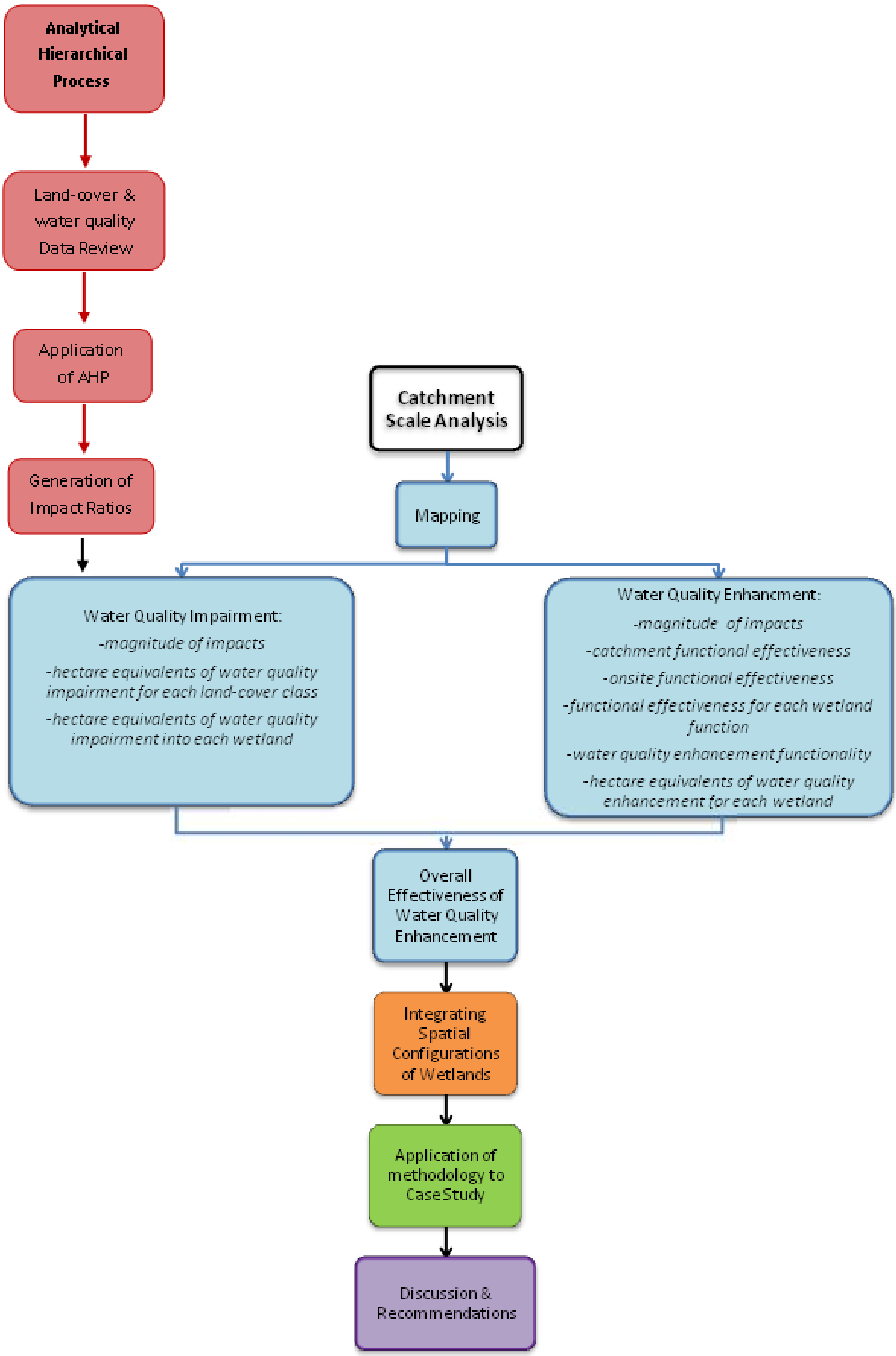


Figure 10. Flow Diagram indicating the steps undertaken in this methodology

4.2 **The Analytical Hierarchical Process (AHP)**

The first step in developing a method to determine the cumulative impact of wetland degradation on water quality was to determine how the quality of the water entering the wetland was affected by the land-cover in the catchment. This was achieved using an Analytical Hierarchical Process, which began with a review of relevant land-cover data and water quality criteria, followed by the application of the AHP and the production of impact ratios which are reflective of the intensity of the impact of that land-cover class on water quality.

4.2.1 Review of Land-cover Data and Water Quality Criteria

The data review process began with a review of South African land-cover classes (Thompson, 1996). Given the scope of this research and the nature of the Analytical Hierarchical Process, the use of all 31 land-cover classes was found to be far too detailed and specific, so these classes were aggregated into 12 land-cover classes to suit the requirements of this research.

The Department of Water Affairs and Forestry (DWAF)'s water quality parameters (DWAF, 2005a) were also explored, and were subsequently used as criteria upon which the evaluations were based in the following AHP.

4.2.2 Application of AHP

The AHP process is described by Nataraj (2005), Forman and Gass (2001), and Saaty (1990) as being comprised of three broad steps: the description of the complex problem in the form of a hierarchy; the prioritization procedure, whereby measurements are conducted on a ratio scale; and the calculation of results through synthesizing. The first of these steps involves structuring the problem hierarchically to reflect the overall goal of the decision at level 1, while the rest of the hierarchy splits the goal into sub-problems, moving from general to specific from top to bottom (Saaty, 1990). The AHP structure eventually comprises goals at the top of the hierarchy, presented in systematic branches; criteria which will be used to evaluate the problem; and the alternatives to consider in solving the problem. The further division of these branches into appropriate levels of detail allows for a previously complex, unstructured problem to be structured in a logical, manageable way through systematically incorporating a number of criteria and alternatives. Given the task of determining the effect of different land-cover classes on surface water quality, a hierarchy was constructed with level 1 representing 'water quality', level 2 representing 'water quality parameters' that require consideration, and level 3 representing the different 'land-cover classes' that need to be evaluated, as is presented by Figure 11.

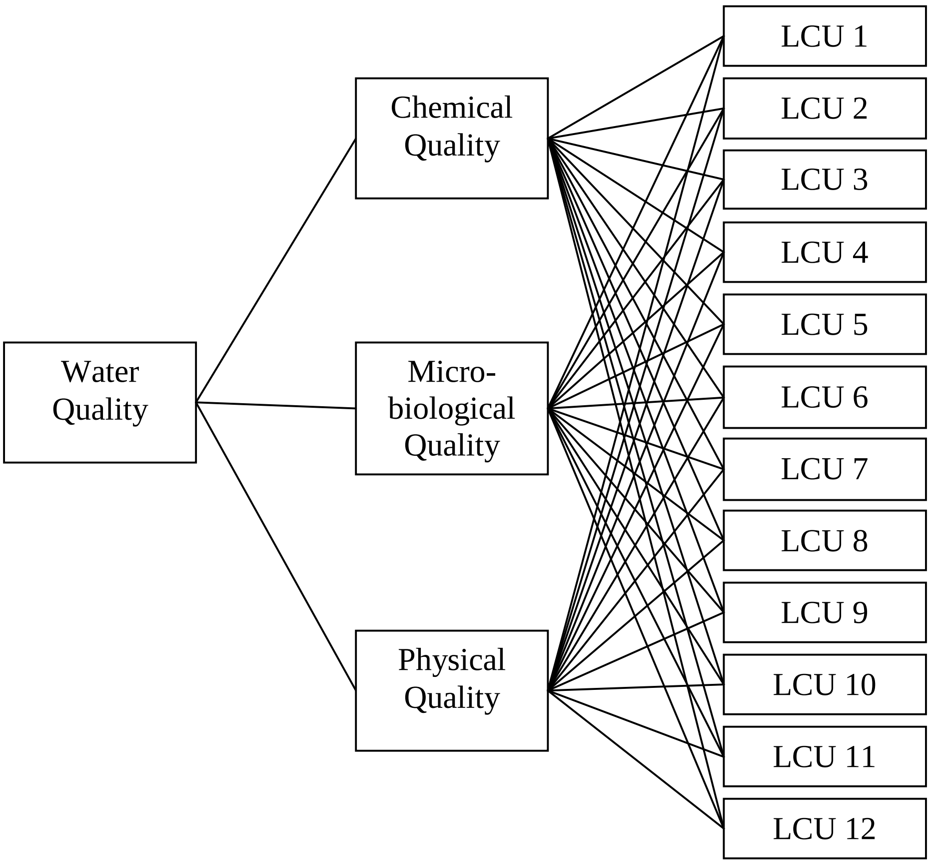


Figure 11. Hierarchical model used in the AHP

Following this, the step described by Nataraj (2005) as prioritization was undertaken. Prioritization consists of evaluating alternatives and assigning a relative score to each, from a scale developed by Saaty to represent the importance of criteria (Nataraj, 2005). In the AHP process, pair-wise comparisons of the factors under evaluation (the different land-cover classes) must be made. By comparing each factor with every other factor, a qualitative description of the relative importance (or the severity of the effect) of each factor to all the others is gained. Numerical scores are then generated from these qualitative assessments using a weight table as shown in Table 15.

Table 15. Weights table (adapted from Woods, 1997)

COMPARITIVE JUDGEMENT	ASSOCIATED WEIGHT
Extremely less severe	1/9
Slightly less severe	1/3
Equally severe	1
Slightly more severe	3
Extremely more severe	9

The number of comparative judgements and associated weights used by an analyst may vary, depending on the choice of scale. As many as 17 different judgements are often used, but given the complexities that such a scale would involve, a smaller scale ranging between 1/9 and 9 was used. A pairwise comparison form was developed (Appendix A) which explained the issue at hand, the objective of the exercise, and the criteria (water quality components) to consider. Over 20 South African academics and practitioners were chosen to assist with the assessment of catchment water quality. Each was identified as having extensive knowledge and experience in their field of expertise, and was therefore considered to be able to offer insight into catchment water quality issues. They were contacted telephonically and via email in order to explain the project, the process, and the necessity for their involvement, and the pairwise comparison form was distributed to interested individuals via email. Given the example of the comparison of the different land-cover classes, part of such a pairwise comparison form would look like this:

Describe how the first factor compares with the second. Fill in the gap with a weighting from the weight table above.

Q1. The effect of NLC 1 on water quality is ______________severe than NLC 2.
Q2. The effect of NLC 1 on water quality is _____________severe than NLC 3.
Q3. The effect of NLC 2 on water quality is ______________severe than NLC 3.
Fill in the values from the questions above in the bottom left half of the Comparison Matrix below:

Table 16. Example of a Comparison Matrix (adapted from Woods, 1997)

	NLC 1	***NLC 2***	***NLC 3***
NLC 1	1	--	--
NLC 2	Q1.	1	--

NLC 3	Q2.	Q3.	1

For example, in a set of 12 factors (land-cover classes in this case), (F_1, F_2, F_3 ...F12), the effect of F_1 on water quality may have been rated by one of the experts as being 'extremely more severe' than F_2, and 'slightly less severe' than F_3. By consulting Table 15, representative numerical scores for each land-cover class by each expert may be obtained.

Three experts responded to the pairwise comparison form that was distributed. A workshop was also held, which was attended by eight members of the University of Cape Town's Freshwater Research Unit. Experts and workshop attendees were asked to assign a score to each of the 12 land-cover classes in terms of their impact on water quality, while qualitatively considering their impact on chemical quality (including total organic carbon, pH, disinfectant residuals, phosphate and nitrate concentrations, electrical conductivity, concentration of toxins), microbiological quality (including total coliforms, *E. coli*), and physical quality (turbidity, colour, taste and odour). They were scored from 1-4, with severe impact getting a score of 4; moderate impact: 3; low impact: 2; and negligible impact: 1. This form allowed for the ranking of the land-cover classes according to the severity of their effects on water quality. The results from the comparison form were inputted into a comparison matrix, such as the one presented in Table 16.

Once the numerical scores were derived for each matrix, the logical consistencies of the matrices were checked so that weights were derived from each matrix. This was achieved using an accessible public domain AHP software package called Decision Analyst, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) based on JavaAHP (Coastal CRC, 2005). The software performed a series of mathematical tasks, which consist of producing a consistency ratio and local derived weights, which are then weighted again by each criterion to produce a further set of global derived weights (Woods, 1997). The synthesis of both sets of weights results in an overall set of weights (or scores) for each factor (land-cover class). There are several ways in which all of the judgements offered by the individuals in a group may be synthesized using the AHP, one of which is to synthesize the results of each individual and to aggregate the resulting prioritization of alternatives using an arithmetic or geometric mean (Forman and Peniwati, 1998).

The mean of the weights for each land-cover class derived from each matrix (from each respondent) was then determined to arrive at a final weight for each land-cover class, representative of the extent of the effect of that class on water quality. These results were then scaled from 0-10, with the least severely impacting land-cover class being assigned a score of 1, and the maximum an impact score of 10. The scores of the land-cover classes in between were determined relative to the highest and lowest scoring classes. Once scaling of the results from the AHP had been completed, the scaled scores were then converted to impact ratios, each of which is indicative of the intensity of the impact of that land-cover class on water quality.

4.3 **The Application of Catchment Scale Analysis**

The first step in applying a catchment scale analysis is the mapping of the wetlands, as well as of the land-cover classes present within them and their catchments. This was achieved through the use of aerial photos, orthophotos, Digital Elevation Models (DEMs), remote sensing imagery and topographic maps of the area of interest. The software used in this project included ArcCatalog and ArcMap- ArcEditor Version 9.2 (ESRI).

Much of the primary data used had already been generated, with wetland shapefiles, their classifications, vegetation maps, and land-cover grids having been compiled by members of the C.A.P.E. fine-scale planning project for the Riversdale Domain. These data were generated in conjunction with pre-existing DWAF (2004) rivers data, CapeNature sensitive wetlands (1999) data, National Wetland Map (SANBI, 2006), EIA Supplementation Project (DEAandDP, 2006) data, National Land-cover (1996) data, South African National Biodiversity Institute (2005) data, Western Cape Wetlands Directory (Dallas *et al.*, 2005), and C.A.P.E. Freshwater Assessment (van Nieuwenhuizen and Day, 1999) data (Snaddon *et al*., 2007).

These data did, however, require some manipulation in order to meet the requirements of the project. For example, the provided land-cover grid was in raster format (which is represented by a grid of uniform cells, each of which have a data value or single feature identity); and required conversion to vector format (which consists of points, nodes, lines or polygons which represent the same data values in a raster grid in a more continuous, easily recognisable format, much like a drawn map) (Shamsi, 1995; Davis, 2001). Each format has different features, beneficial for different reasons. In this case, conversion of the land-cover grid from raster to vector meant that each land-cover class became a separate polygon, making identification of each land-cover class and the retrieval of areal extents much simpler. Furthermore, because the original land-cover grid was very detailed and contained many more land-cover classes than was necessary for this research, aggregation of classes was necessary. Such aggregation is much more easily performed when the classes are in vector format and can be sorted and aggregated as required. The land-cover grid depicting the different classes was therefore converted to vector format using ArcCatalog and ArcMap-ArcEditor Version 9.2. Groups of land-cover classes were merged to produce classes that were reflective of the 12 land-cover classes used in this study.

Catchment boundaries of individual wetlands had not been delineated and each sub-catchment was thus mapped using a DEM of the area along with a rivers layer, which is widely available for South African rivers. An external application, ArcHydro, was used in ArcMap to perform this delineation of catchments. A DEM is a “discrete approximation of the continuous land surface” (Vieux, 1995, p205): a raster version of contour data that represents elevation (Davis, 2001). These types of data are useful for modelling the processes associated with watershed-scale hydrology since it allows for the extraction of model parameters to simulate the effect of topography on water (Vieux, 1995).

In ArcMap, the various layers were geo-referenced using Transverse Mercator projection to WGS_1984_UTM_Zone34S projected coordinate system such that the area of interest was co-incident with that of the quaternary catchment of the upper Goukou River, and the area of interest was extracted and subset to that of a single quaternary catchment of the upper Goukou wetlands.

Once mapping and overlaying the different land cover datasets had been completed, the areal extents of historical wetland, sub-catchments, and land-cover classes in the catchments and wetlands were calculated using GIS. Areal extents were measured using the measuring tool in ArcMap. The shape and perimeter of the wetlands were not aspects that were considered in these analyses, and the tool assumes that these aspects do not affect the result.

The relevant areal extents for each wetland and its corresponding sub-catchment were exported from the ArcMap attribute table into a Microsoft Excel spreadsheet (Table 26 in Appendix B), which allowed for easy computations.

4.3.1 Calculating the Magnitude of Impacts of Land-cover Change on Water Quality as Hectare Equivalents of Water Quality Enhancement

As was described in Section 2.3, the results of the application of the tool developed by Ellery *et al.* (in review) describe how effectively a wetland is able to provide a number of ecosystem services which include flood attenuation, stream flow regulation, sediment trapping, phosphate trapping, nitrate removal, and toxicant removal (Ellery *et al.*, in review). The tool involves the application of a number of steps that allows for the user to determine a functional effectiveness score for individual wetlands (Figure 12) for one of these ecosystem services. This functional effectiveness score then allows for functional hectare equivalents of each ecosystem service to be determined.

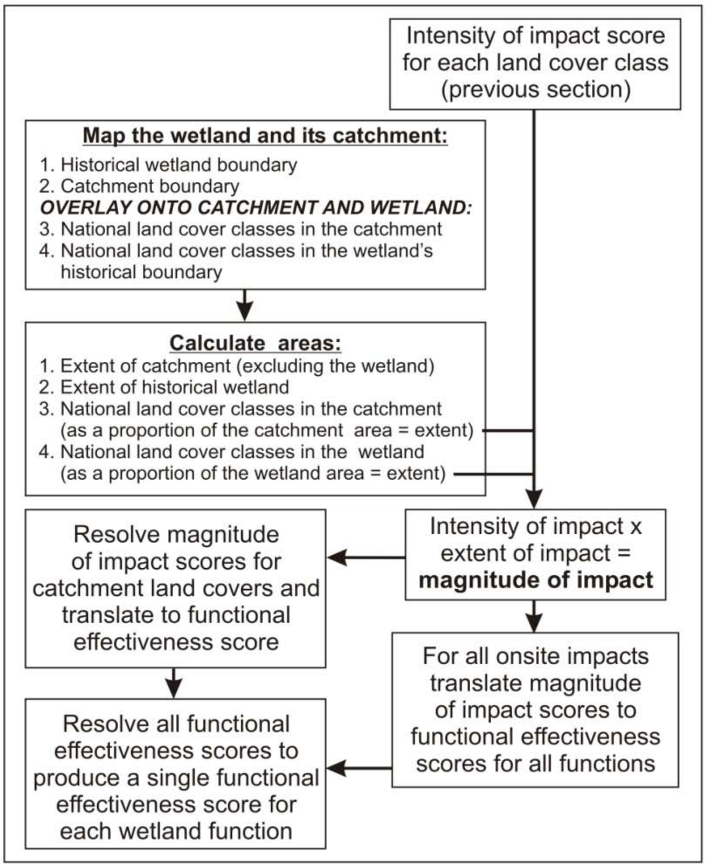


Figure 12. The series of steps leading to calculation of a functional effectiveness score for individual wetlands (Ellery *et al.*, in review)

The effectiveness of a wetland in providing water quality enhancement as an ecosystem service is not dealt with in Ellery *et al*. (in review) as a single ecosystem service, but as several different ecosystem services, each of which is directly related to water quality. These ecosystem services are sediment trapping, nitrate removal, phosphate trapping, and toxicant removal. Given that water quality enhancement is the focus of this research, it became necessary to integrate the relevant water quality-related ecosystem services included in Ellery *et al.* (in review) in order to determine a water quality enhancement functional effectiveness score. The functional effectiveness scores for all of the water quality-related ecosystem services were calculated, and their mean was taken to represent water quality enhancement. It should be noted that these functional effectiveness scores are not a quantification of the performance of a particular function, but rather provide an index of the effectiveness of the wetland in performing that function.

Once mapping and exportation of areal extents had been completed, the extent of each land-cover class for both the wetlands and their sub-catchments (Table 27) were then multiplied by the relevant intensity of impact score (from Table 4), producing a magnitude of impact score for each land-cover class for each impact for catchment and wetland impacts. For example, with reference to Wetland FID 0 given in Table 27: the wetland's catchment covers a total of 436 ha (Table 28), and contains a wetland 46.37 ha in extent and three categories of land-cover, namely natural, degraded vegetation, and irrigated cultivated. There are a total of 129.58 ha of natural land-cover, 92.49 ha of which are in the catchment outside of the wetland, and 37.09 ha of which are in the wetland. Degraded vegetation covers an area of 185.77 ha, 176.49 ha of which are in the catchment outside of the wetland, and 9.28 ha of which are in the wetland. The 120.65 ha of irrigated cultivated land-cover occurs only outside of the wetland. The magnitude of impact scores are then calculated as intensity of impact score (from Table 4) multiplied by the proportion of the catchment and wetland occupied by each land cover class (Table 17).

Table 17. Magnitude of impact scores calculated using the intensity of impact scores (bold text is the intensity of impact score from Table 2 in Ellery *et al.*, in review) multiplied by the proportional area of each land-cover class for Wetland FID 0

Land cover category	Impacts arising in the wetland's upstream catchment*			Impacts arising within the wetland**	
	Area (ha)	Increased water inputs	Decreased water inputs	**Area**	Reduced surface roughness
Natural	92.49	0	0	37.09	0
Degraded vegetation	176.49	(176.49/389.63) * **3** = 1.36		9.28	(9.28/46.37) * **3** = 0.60
Irrigated cultivation	120.65		(120.65/389.63) * **5** = 1.55	0	0
TOTALS	**389.63**	1.36	1.55	**46.37**	0.60

*on the quantity and timing of water inputs
**on the distribution and retention of water

NB. Intensity of impact scores for impacts arising in the wetland's upstream catchment as well as within the wetland are scored on a scale of 0 (no impact) to 10 (critical impact).

The impact of catchment land use activities was resolved for each wetland by computing an overall magnitude of catchment impact score, achieved by subtracting the total for 'decreased water inputs' from the total for 'increased water inputs'. Therefore, in the example above, this total was -0.19 (1.36 - 1.55). According to Ellery *et al*. (in review) the total of -0.19 that resulted in the above example indicates that there is a net decrease in water inputs with a magnitude of impact of 0.19 on a scale of 0 (no magnitude of impact) to 10 (critically impacted). This was conducted for each wetland in the Goukou Catchment, and activities in the Goukou Catchment led to both decreased and increased net water inputs for different wetlands.

It should be noted that only 2 HGM types (floodplains and valley-bottom wetlands) are focused on in Ellery *et al*.'s (in review) tool. These HGM types are spatially extensive and common in South Africa, and channelled and unchannelled valley-bottom wetlands are treated in a similar fashion. Floodplain wetlands were absent in the Goukou Catchment, with wetlands having been comprised of only valley-bottom and hillslope seepage wetlands. As a result, only valley-bottom wetlands were included in these analyses, and hillslope seepage wetlands were omitted from this study.

4.3.2 Calculating the Magnitude of Impacts of Land-cover Change on Ecosystem Services Relevant to Water Quality Enhancement

As was previously mentioned, the ecosystem services that were singled out as being directly relevant to water quality enhancement included sediment trapping, nitrate removal, phosphate removal, and toxicant removal. The functional effectiveness and hectare equivalents of each of these ecosystem services for each wetland in the Goukou Catchment were therefore determined.

4.3.2.1 Catchment Impacts

The equations from Tables 6 and 7 were used to consider the effect of each individual impact on the provision of ecosystem services for all of the wetlands in the Goukou Catchment.

For example, for Wetland FID 0, it has been determined that there is a net decrease in water inputs with a magnitude of impact of 0.19. Therefore Table 7 was consulted, bearing in mind that because impacts are scored between 0 and 10, the absolute value (positive value) of the overall catchment impacts is used, which for this example will be +0.19. For sediment trapping, the equation y= 2.50 was applied to this value, which is the equation for valley-bottom wetlands with a magnitude of impact score between 0 and 3 for the sediment trapping ecosystem service. The functionality score for sediment trapping from catchment impacts for Wetland FID 0 is therefore 2.50.

Had the absolute of the magnitude of impact score been greater than 3.0, the equation y=-0.11x + 2.84 would have been applied. For example, had the magnitude of impact score been 4.0, the functionality score for sediment trapping from catchment impacts would therefore be 2.40. Similarly, in the case of increased water inputs, Table 6 would have been consulted, whereby a value of 2.50 would have been assigned for sediment trapping functionality for impact scores with an absolute value from 0.0 to 3.0, while the equation y=-0.11x + 2.84 would have been applied for impact scores with an absolute greater than 3.0.

These steps were similarly undertaken for each of the other ecosystem services investigated. For example, for nitrate removal functionality of Wetland FID 0, the equation y=-0.18x + 3.50 was applied to the value +0.19. Table 7 was consulted for decreased water inputs, and this equation for nitrate removal for valley-bottom wetlands was applied to determine functional effectiveness. The functionality score for nitrate removal from catchment impacts for Wetland FID 0 is therefore 3.47. The functional effectiveness score ranges from 0 (minimum effectiveness) to 4 (maximum effectiveness).

Following the same methodology, the functionality scores for the other two ecosystem services evaluated, phosphate trapping and toxicant removal, were found to be 3.50 and 3.50 from catchment impacts for Wetland FID 0.

4.3.2.2 Onsite Impacts

The impacts of land use activities within wetlands were translated to magnitude of impact scores with respect to increased water use, reduced surface roughness, flow impediment, and the effect of drains or gullies. Thereafter the same method that was applied for catchment impacts to determine their effect on the provision of ecosystem services was applied to impacts that resulted from activities within wetlands. The x-value indicating the magnitude of impact for each onsite impact was substituted in the relevant equation for onsite impacts from Tables 8, 9, 10 and 11 and the functional effectiveness score for each ecosystem service was calculated.

For example, in keeping with Wetland FID 0, reduced surface roughness was the only significant impact of the four possible impacts that was identified, and the magnitude of impact of surface roughness for Wetland FID 0 was calculated to be 0.60 (Table 17). By referring to Table 9, it was determined that the equation $y=-0.08x + 2.50$ is used for onsite impact scores ranging between 0 and 10 for valley-bottom wetlands with regard to sediment trapping. As a result, Wetland FID 0 scored a functionality score of 2.45 for sediment trapping.

Similarly, in order to determine the functionality score for nitrate removal for Wetland FID 0 due to reduced surface roughness, the equation $y=-0.18x + 3.50$ from Table 9 was applied to the magnitude of impact score of 0.60 for reduced surface roughness. Wetland FID 0 was therefore found to have a functionality score of 3.39 for nitrate removal based on a reduction in surface roughness.

Often, wetlands have more than one onsite impact, in which case functionality scores for all onsite impacts need to be resolved. As Ellery *et al*. (in review) point out, this is because "some activities will reduce the duration and extent of inundation (direct water losses, reduced surface roughness and the presence of drains or gullies), while others might prolong it (presence of impeding features increases water retention above the impeding feature and reduces water retention below it)" (p52). In order to resolve onsite impacts, the lowest functionality score of the onsite impacts is taken and adjusted according to the value of functionality scores for other onsite impacts. These adjustments are made through consultation with Table 12, which contains the values to be used to scale functionality scores in valley-bottom wetlands as determined for a range of catchment and onsite impacts.

As a hypothetical example, imagine a wetland which has functionality scores for two onsite impacts: 1.60 due to reduced surface roughness, and 1.80 due to flow impediment (for sediment trapping). Table 12 would have been consulted to determine the value to be subtracted from 1.60 (the lower of the two scores) by considering the additional onsite impact that is being resolved for (which in this case is flow impediment); the functionality score range (which is 1.2- 1.99 since the higher functionality score is 1.80), the ecosystem service for which the determination of functionality is being conducted (sediment trapping); and the wetland type (valley-bottom). By doing so, it is determined that a value of 0.1 should be subtracted from the lower functionality score of 1.60 on order to resolve the scores for impacts arising within the wetland. Therefore in this example, the final functional effectiveness score for sediment trapping based on impacts in the wetland is 1.5.

By applying this methodology, the functional effectiveness scores from impacts arising in the wetland (onsite impacts) for the other ecosystem services evaluated - phosphate trapping and toxicant removal - were calculated to equal 3.39 and 3.39 for Wetland FID 0.

4.3.2.3 Catchment and Onsite Impacts

For a given ecosystem service for a single wetland, the steps described thus far result in two functional effectiveness scores: one for impacts arising in the wetland's catchment, and one for impacts arising in the wetland. As such, in much the same way that various onsite impacts were resolved in order to determine a single functional effectiveness score, scores for impacts arising in the wetland's catchment and for impacts arising within the wetland were compared and the lowest was chosen and scaled by subtracting the relevant value from Table 12.

Returning to the previous example, it has been determined thus far that for the ecosystem service of sediment trapping, Wetland FID 0 has a functional effectiveness score of 2.50 due to impacts arising in the wetland's catchment, and 2.45 from impacts arising in the wetland. Since the lower of these two values is 2.45, the value to be subtracted is retrieved from Table 12 based on the score of 2.50 for the catchment impact of decreased water inputs as previously determined using Table 17. For Wetland FID 0 the final functionality score is therefore determined as follows: 2.45 (functionality score due to impacts arising within the wetland) – 0 (decreased water input from the catchment has a functionality score between 2 and 2.99) = 2.45.

In exactly the same way, the final functionality scores for all the other ecosystem services were established. Taking nitrate removal as an added example, it was determined that due to impacts arising in the wetland's catchment, Wetland FID 0 has a functional effectiveness score of 3.47 for nitrate removal, while the functional effectiveness score of Wetland FID 0 for nitrate removal based on impacts arising within the wetland was found to equal 3.39. Through consultation with Table12, the final functionality score for nitrate removal of Wetland FID 0 was resolved to be 3.39, following the same logic as described in the previous example: 3.39 (functionality score due to onsite impacts) – 0 (decreased water input from the catchment has a functionality score between 3 and 4) = 3.39. Similarly, overall functionality with respect to phosphate trapping and toxicant removal for Wetland FID 0 were determined to be 3.39 and 3.39.

4.3.2.4 Calculating Functional Hectare Equivalents

Functional hectare equivalents were calculated by utilizing the following equation: Functional hectare equivalents = (final functional effectiveness score / 4) * size of wetland (ha).

Therefore for the example of Wetland FID 0, the functional hectare equivalents of each ecosystem service evaluated were determined as follows:

Sediment Trapping: (2.45/4)*46.37 = 28.40 ha

Nitrate Removal: (3.39/4)*46.37 = 39.30 ha

Phosphate Trapping: (3.39/4)*46.37 = 39.30 ha

Toxicant Removal: (3.39/4)*46.37 = 39.30 ha

4.3.2.5 Determining Water Quality Enhancement Functionality

The functional effectiveness scores and hectare equivalents for the ecosystem services of sediment trapping, nitrate removal, phosphate trapping, and toxicant removal for each wetland in the Goukou Catchment was determined, and the mean of these values was taken to represent water quality enhancement functionality and hectare equivalents of water quality enhancement functionality. For example, for Wetland FID 0, water quality enhancement functionality was determined to be 3.16 ((2.45 + 3.39 + 3.39 + 3.39) / 4), while hectare equivalents of water quality enhancement functionality equalled 36.58 ((28.40 + 39.30 + 39.30 + 39.30) / 4).

4.3.3 Calculating the Magnitude of Impacts of Land-cover Change on Water Quality as Hectare Equivalents of Water Quality Impairment

The determination of hectare equivalents of water quality impairment involved the application of a number of steps, fairly similar to those steps employed in the determination of hectare equivalents of water quality enhancement (Figure 13).

Once mapping and exportation of areal extents had been completed, the extent of each land-cover class (area of land-cover class/area of catchment (excluding the wetland)) in each wetland's sub-catchment (Table 27) was then multiplied by the relevant impact rating ratio, producing a magnitude of impact score for each land-cover class in each sub-catchment. This magnitude of impact score for each land-cover class was then multiplied by the area of that land-cover class in order to arrive at units of hectares, which in essence represent hectare equivalents of impact on water quality (hectare equivalents of water quality impairment). The sum of the hectare equivalents of water quality impairment of the land-cover classes in each sub-catchment is a semi-quantitative indication of the impact of the entire sub-catchment on the quality of the water entering the wetland within that sub-catchment.

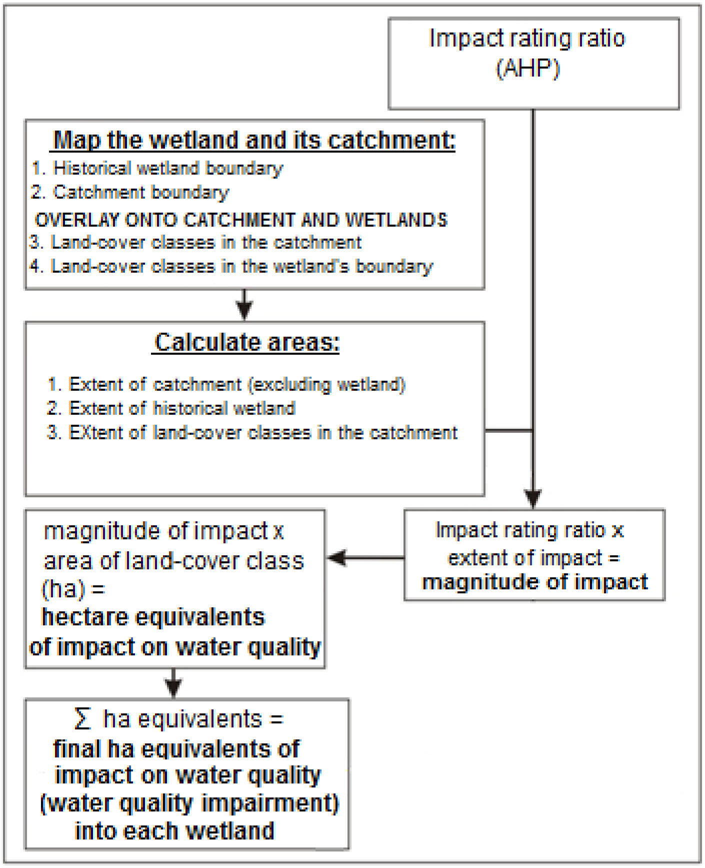


Figure 13. The series of steps leading to calculation of hectare equivalents of water quality impairment for individual wetlands

For example, in keeping with Wetland FID 0, it was determined that the catchment covers a total of 436 ha, and contains a wetland 46.37 ha in extent and three categories of land-cover, namely natural, degraded vegetation, and irrigated cultivated (Table 18).

Table 18. Hectare equivalents of water quality impairment determined for Wetland FID 0

Land-cover in catchment	Extent of LCU	LCU Score	LCU Ratio	Magnitude of Impact Score*	Ha. Equiv.Score (MOI * ha)	Final impact hectare equivalents
Natural	0.24	1	0.1	0.02	2.20	29.39
Degraded vegetation	0.45	2	0.2	0.09	15.99	
Irrigated cultivation	0.31	3	0.3	0.09	11.21	

*Magnitude of impact score = LCU ratio x Extent of LCU

There are a total of 92.49 ha of natural land-cover, 176.49 ha of degraded vegetation, and 120.65 ha of irrigated cultivated land-cover in the catchment outside of the wetland. By multiplying the extent of each land-cover class by the relevant impact ratio (from Table 25) as is described above, a magnitude of impact score is derived. In this example, the magnitude of impact score from natural land-cover was 0.02, while the magnitude of impact score from degraded vegetation was 0.09. The magnitude of impact score from irrigated cultivation was found to equal 0.09. By multiplying each of these sores by the area of that land-cover class, hectare equivalents of water quality impairment are determined. Natural land-cover contributed 2.20 hectare equivalents of water quality impairment (0.0237385346 * 92.4925), degraded vegetation contributed 15.99 hectare equivalents of water quality impairment (0.09060145 * 176.48724), and cultivated irrigated land-cover contributed 11.21 hectare equivalents of water quality impairment (0.092913031 * 120.65046). The sum of the hectare equivalents of water quality impairment of the land-cover classes in this sub-catchment, which equals to 29.39 hectare equivalents of water quality impairment, is a semi-quantitative indication of the impact of the entire sub-catchment on the quality of the water entering the wetland within that sub-catchment.

4.3.4 Calculating Overall Effectiveness of Water Quality Enhancement

By determining the extent to which water quality is being impaired by catchment land-cover, a semi-quantitative indication of the quality of the water entering each wetland may be gained. Similarly, the application of the tool developed by Ellery *et al.* (in review), allows for the determination of the effectiveness of each wetland at improving the quality of the water entering it. Essentially, by comparing each of these opposing values, one may be able to determine if the quality of the water leaving a wetland is being effectively enhanced by the wetland or not.

The calculation of overall effectiveness of water quality enhancement was based on a 3:1 ratio, meaning that 3 hectare equivalents of water quality enhancement would be required to “repair” 1 hectare equivalent of water quality impairment. This ratio was informed by relevant literature, as discussed below; consultation with wetland experts; and through the examination of some simulated examples, such as the one presented in Table 19. While it initially seemed that a 1:1 ratio would be viable (i.e. That 1 hectare equivalent of water quality enhancement would be required to “repair” 1 hectare equivalent of water quality impairment), inspection into nutrient loadings associated with the various land-cover classes under evaluation, as is discussed in Section 2.4.4, suggested that a 1:1 ratio may be an overstatement of the contribution of the wetland to assimilating nutrients. This is further supported by an investigation into wetland nutrient removal conducted by Fisher and Acreman (2004). In their article, the authors collated data from 57 wetlands from around the world, and investigated the way in which wetlands affect the nutrient loadings of waters draining through them, as well as the extent of this effect.

The investigations undertaken by Fisher and Acreman (2004) were conducted while taking into consideration factors such as the key processes which govern nitrogen and phosphorous reduction, wetland type, annual nutrient loading, nutrient concentration, and country of location; and results included the identification of how many wetlands increased, decreased, or had no effect on nutrient loadings. Results showed that while most wetlands studied showed evidence of nutrient retention, the capabilities of wetlands to reduce nutrients are strongly negatively correlated to an increase in nutrients. In other words, the more nitrogen and phosphorous loading entered a wetland on a kilogram per hectare per year basis, the lower the percentage reduction in nitrogen and phosphorous by the wetland. Evidence also showed that as wetlands 'age', wetland nutrient reduction functioning is reduced to below 40%. Evidence was also presented of wetlands increasing the nutrient loadings by increasing the loading of soluble N and P species and thereby "potentially driving aquatic eutrophication" (Fisher and Acreman, 2004, p1). This evidence brings light to the fact that a 1:1 ratio may be an overstatement of the contribution of wetlands to assimilating nutrients, and that realistically, at least 3 hectare equivalents of water quality enhancement would be required to "repair" 1 hectare equivalent of water quality impairment.

Therefore, in order to calculate the overall effectiveness of water quality enhancement, the hectare equivalents of water quality impairment for each wetland were first multiplied by 3, the total of which was subtracted from the hectare equivalents of water quality enhancement for each wetland. Should the difference between these values have been greater than or equal to zero (i.e. a positive value), the wetland was assumed to be totally assimilating the impacts to water quality from surrounding land-cover, and therefore effectively enhancing the quality of the water passing through it. Should the difference between these values have been less than zero (i.e. a negative value), it is an indication that the impact to the wetland is greater than its ability to counter the impact, leaving the remaining ‘hectares of water quality impairment’ “unassimilated”. This ratio was further investigated in a simple example.

A 10 ha valley-bottom wetland consisting of only natural land-cover within the wetland is part of a 20ha catchment which is occupied completely by mining land-cover (i.e. 10 ha of mining forms the surrounding catchment). Firstly, hectare equivalents of water quality enhancement may be calculated in the following way:

Table 19. Magnitude of impact scores calculated using the intensity of impact scores (bold text is the intensity of impact score from Table 2 in Ellery *et al.*, in review) multiplied by the proportional area of each land-cover class for Wetland FID 0

Land cover category	**Impacts arising in the wetland’s upstream catchment***		**Impacts arising within the wetland****				
	Area (ha)	Increased water inputs	**Area (ha)**	Increased water loss	Reduced surfaces roughness	Flow impediment	Flow enhancement
Natural	0	0	10	0	0	0	0
Mining	10	(10/10) * **5** = 5.0	0				
TOTALS	**10**	5.0	**10**	0	0	0	0

*on the quantity and timing of water inputs
**on the distribution and retention of water

NB. Intensity of impact scores for impacts arising in the wetland’s upstream catchment as well as within the wetland are scored on a scale of 0 (no impact) to 10 (critical impact).

There are only increased water inputs from impacts arising in the wetland’s catchment, so the functional effectiveness for these catchment impacts is simply determined by consulting the equations from Table 6 for magnitude of impact scores between 3 and 10. For sediment trapping, the functional effectiveness score is 2.29 (y=-0.11x + 2.84) for valley-bottom wetlands, 3.22 (y=-0.14x + 3.92) for phosphate trapping, 2.97 (y=-0.26x + 4.27) for nitrate removal, and 2.97 (y=-0.26x + 4.27) for toxicant removal. Functional effectiveness scores for impacts arising within the wetland are determined by consulting Tables 8 to 11. For sediment trapping, onsite functional effectiveness scores 2.50, while the functional effectiveness score for phosphate trapping, nitrate removal, and toxicant removal and all 3.50 for magnitude of impact scores of 0. Each of these functional effectiveness scores is resolved for onsite and catchment impacts and the mean of these effectiveness scores, which is an indication of water quality enhancement effectiveness, is 2.86. Final hectare equivalents are therefore equal to (2.86/4) * 10ha, which is equal to 7.15 hectare equivalents of water quality enhancement.

Alternatively, hectare equivalents of water quality impairment are calculated by first multiplying the extent of the catchment land-cover class (10/10) by the impact ratio assigned to that land-cover class, which for mining, is 1 (Table 25). This magnitude of impact score is therefore equal to 1.0. Hectare equivalents of water quality impairment are determined by multiplying this magnitude of impact score by the area of the land-cover class, therefore in this example, the land-cover in the wetland's catchment is providing 10 (1.0 * 10) hectare equivalents of water quality impairment.

Given a 1:1 ratio, this would mean that the wetland would have successfully assimilated most of the nutrients from the mining activities in its catchment, as the overall effectiveness of water quality enhancement would be a low negative value (7.15 hectare equivalents of water quality enhancement minus 10 hectare equivalents of water quality impairment = -2.85). However, based on the review of pollutant loadings of mining into water resources as discussed in Section 2.4.3.4, it is highly unlikely that the majority of the effects of 10ha of mining in a wetland's catchment would be easily assimilated by a 10ha wetland.

A more conservative 3:1 ratio was therefore decided upon which admittedly, is not based on detailed data with a high level of confidence, but is rather a simplification of an assumed reality. Given a 3:1 ratio for the example above, while there are 7.15 hectare equivalents of water quality enhancement, there would be 30 hectare equivalents of water quality impairment (3 * 10). Hectare equivalents of water quality impairment are multiplied by 3 because given a 3:1 ratio, 30 hectare equivalents of water quality enhancement would be required to "repair" 10 hectare equivalents of water quality impairment. However, only 7.15 hectare equivalents of water quality enhancement are being provided by the wetland. By multiplying the hectare equivalents of water quality impairment by 3, the deficit of hectare equivalents of water quality enhancement may be determined, which in this case is 22.85. Overall effectiveness of water quality enhancement would therefore be a negative total of -22.85 (7.15 – 30). This is a much more realistic expectation of the wetland's contribution to assimilating the effects of nutrients from various land-cover classes. It is acknowledged further that even where the hectare equivalents of water quality enhancement exceed the hectare equivalents of water quality impairment, there are certain pollutants, notable dissolved salts, for which wetlands have very limited assimilative capacity and for which the wetlands will have little effect, as discussed in Section 2.4.

The overall effectiveness of water quality enhancement for each wetland in the case study was determined before cumulative analyses were conducted. As is described in Section 2.5.2, when considering the cumulative effects of wetland loss and degradation on the functional values of a catchment, it is important to recognise and determine the value of the component wetlands, “based on their relative contribution to the functioning of the entire landscape system” (Bedford and Preston, 1988, p567)

4.3.5 Integrating the Spatial Configurations of Wetlands in a Landscape in Catchment-scale Analyses

In order to effectively account for spatial configuration and the subsequent reduced/increased responsibilities of wetlands in providing ecosystem services, it was initially proposed that stream order be used as the criterion by which wetlands could be weighted. The Strahler Stream Order divides the tributaries of a waterbody into a hierarchy, based on a simple hydrology algorithm (U.S. Corps of Engineer, date unknown). These perennial streams may range from a first-order headwater stream, to a twelve-order stream, as is present only in the Amazon River. The Strahler Stream Order system dictates that when two first-order streams come together, they make a second-order stream. When two second-order streams come together, they form a third-order stream, and so on (Figure 14). When streams of a lower order (such as a first-order stream) join a stream of a higher order (such as a second-order stream), the order of the higher stream does not change (the joint stream remains a second-order stream).

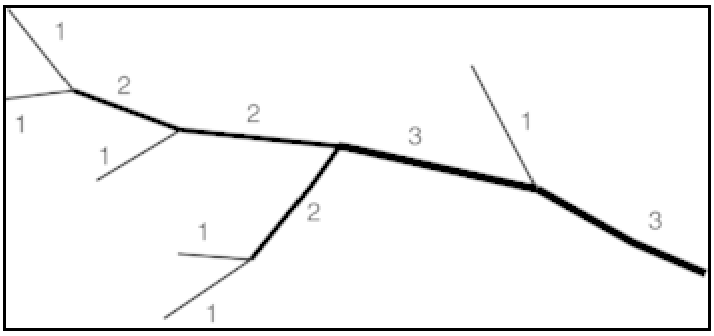


Figure 14. The Strahler Stream Order (U.S. Corps of Engineer, date unknown)

The rationale behind using the Strahler Stream Order as a criterion for integrating wetland spatial configuration stemmed from the idea that wetlands positioned on streams of a lower stream order are less likely to have other wetlands intercepting waters from upstream before reaching them. The waters reaching wetlands positioned at second or third-order streams however, are more likely to have been intercepted by upstream wetlands, which would have filtered the passing waters already, giving the higher ordered stream wetlands less function to perform. The problem with this idea is that if weightings are based solely on stream order, wetlands positioned in higher orders that are in fact servicing the lower order streams as well, will be discounted in weight unfairly. For example, two wetlands may be positioned on two different second order streams (Figure 15). Wetland A is servicing all of the area upstream of it, as there are no other wetlands positioned on the streams upstream. However while Wetland B is also positioned on a second order stream, Wetland C is already filtering passing waters from upstream, making the task of enhancing water quality easier for wetland B than it would be for Wetland A, given similar land-cover types in their respective catchments. As such, based on this idea of stream order is that of order of inflow.

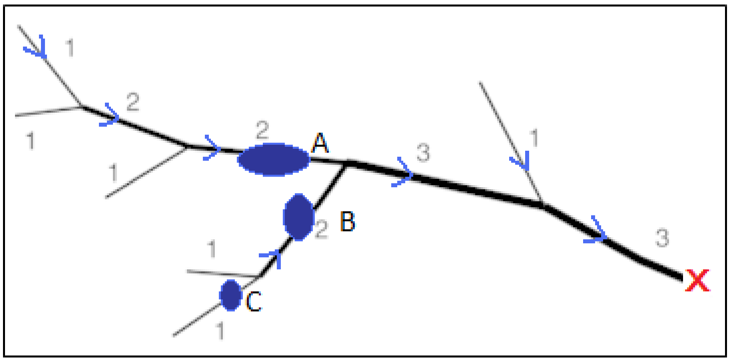


Figure 15. Hypothetical example of wetlands positioned on streams of varying orders, with arrows indicating the direction of stream flow

Wetlands which are positioned in the landscape in such a way that there are no other wetlands intercepting waters upstream, may be considered as primary inflow wetlands. The functionality of primary inflow wetlands is not influenced by any other wetlands upstream. In Figure 15 for example, Wetland A and Wetland C are primary inflow wetlands. Alternatively, the waters of a secondary inflow wetland have been intercepted by one or more primary inflow wetlands (Wetland B in Figure 15 is a secondary inflow wetland). If the single upstream primary inflow wetland is removed, the secondary inflow wetland will then become the primary inflow wetland, as it will be servicing its entire catchment upstream. A tertiary inflow wetland is positioned in the landscape in such a way that the waters reaching it have already been intercepted by two or more secondary inflow wetlands upstream.

After having determined the overall effectiveness of water quality enhancement for each wetland in the landscape, the wetlands can be ordered in this way, and the ‘unassimilated’ hectare equivalents of water quality impairment (i.e. the negative values for overall effectiveness of water quality enhancement) from upstream will be ‘carried’ to wetlands downstream. Thus, by adding these ‘carried’ negative effectiveness values to the effectiveness values of the higher ordered inflow wetlands downstream, the unassimilated hectare equivalents of water quality impairment may either be assimilated by a higher ordered wetland with a high water quality enhancement effectiveness score, or will further decrease the quality of the water leaving the higher ordered wetland should that wetland not be effectively enhancing water quality. By continuing this process downstream, the water quality enhancement effectiveness value at the outflow of the catchment (marked as X in Figure 15) will be indicative of the overall effectiveness of the entire catchment at enhancing water quality.

To illustrate this concept, consider a catchment occupied by five wetlands (A-E) in various positions in the landscape (Figure 16). The black numbers in brackets indicate the overall water quality enhancement effectiveness score of each wetland, while the number in red indicates the level of inflow of the wetland (primary, secondary, etc). Without considering the spatial arrangement of the wetlands, the sum of the overall water quality enhancement effectiveness scores of all of the wetlands in the entire catchment may be taken as the overall water quality enhancement effectiveness of the catchment, which would total -46. However by considering the spatial configuration of the wetlands as described above, the overall water quality enhancement effectiveness of the catchment is calculated to be -59, indicating that the wetlands in this catchment are in fact assimilating fewer pollutants in comparison to if the wetlands had been treated as a single group entity, which, based on the logic above, is likely to be a more accurate representation of the reality of the water quality enhancement effectiveness of the catchment as a whole.

This value was determined in the following way: the overall water quality enhancement effectiveness score of Wetland A is negative, thereby implying that the water leaving this wetland has not been sufficiently enhanced. Wetland E is downstream of Wetland A, so the un-enhanced waters from Wetland A (with an overall water quality enhancement effectiveness score of -29) will be ‘carried’ to Wetland E. To the east of the catchment, the overall water quality enhancement effectiveness score of Wetland D is positive, implying that the water leaving Wetland D has been totally enhanced. There is therefore no need for the higher ordered wetlands downstream of Wetland D to assimilate any unassimilated hectare equivalents of water quality impairment from the catchment of Wetland D. North of Wetland D is Wetland B, the overall water quality enhancement effectiveness score of which is negative, thereby implying that the water leaving this wetland has also not been sufficiently enhanced. These waters will be intercepted by second ordered Wetland C, which has a positive overall water quality enhancement effectiveness score. Therefore working from upstream to downstream, the overall water quality enhancement effectiveness score of -11 from Wetland B is added to the overall water quality enhancement effectiveness score of Wetland C (+16 + (-11)), which results in a total of +5. The waters leaving Wetland C will be intercepted by Wetland E downstream, but because the overall water quality enhancement effectiveness score from Wetland C is now positive 5, there is no need for Wetland E to assimilate any unassimilated hectare equivalents of water quality impairment. The only negative overall water quality enhancement effectiveness score that will therefore be ‘carried’ down to Wetland E is therefore that of -29 from Wetland A. The overall water quality enhancement effectiveness of the catchment is therefore -30 + (-29), which equals -59.

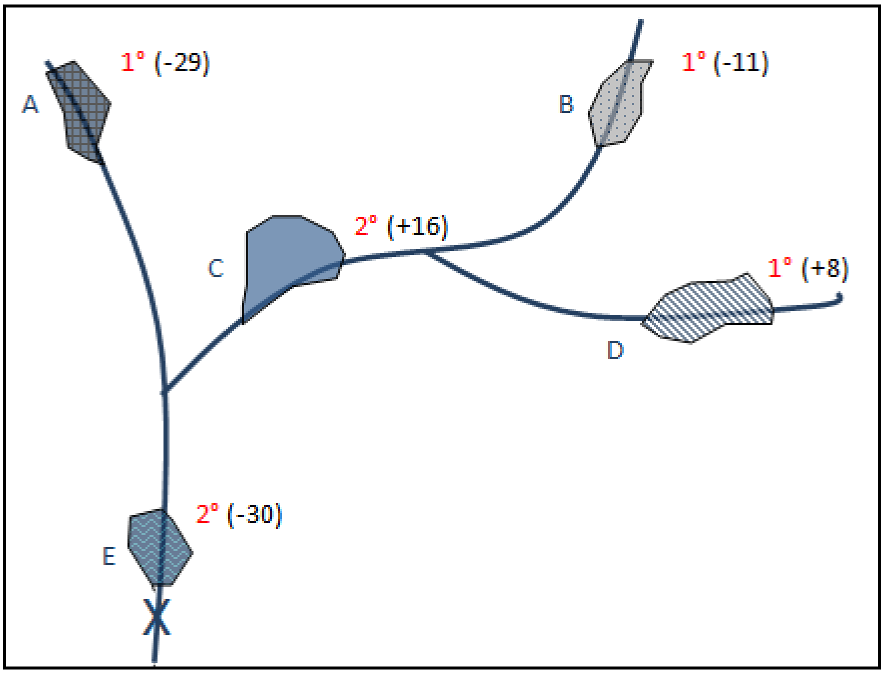


Figure 16. A hypothetical example of wetlands positioned in a landscape with black numbers in brackets indicating the overall water quality enhancement effectiveness score of each wetland and the number in red indicating the level of inflow of the wetland

The negativity of the water quality enhancement effectiveness value at the outflow of the catchment is indicative of the fact that the impacts to the catchment's water quality are greater than the ability of that catchment to totally enhance that water quality, resulting in water quality that is enhanced, but not to the degree that all impairments from surrounding land-cover have been totally assimilated. Should the result be positive, the wetlands of the catchment collectively (as a functional unit), are effectively enhancing the water leaving it, to the degree that all impairments from surrounding land-cover have been totally assimilated. It should be pointed out that a negative overall effectiveness of water quality enhancement score does not mean that the wetlands in the catchment are not enhancing water quality. The wetlands in the catchment may still be making a considerable contribution to water quality enhancement, but are just not filtering waters completely. It may be suggested then, that a less negative overall water quality enhancement effectiveness score indicates higher enhancement effectiveness than an overall water quality enhancement effectiveness score of greater negativity.

The most effective way to incorporate this method of integrating spatial configuration for multiple wetlands in a catchment was to ascertain the main drainage lines in the catchment, and to number them so that each drainage line and the wetlands feeding into that line could be dealt with separately from wetlands along another drainage line. Each drainage line will then have an effectiveness score reflecting the effectiveness of the wetlands along it. In this way, it was easier to determine the effectiveness score that was being carried downstream, and ultimately to the main drainage point of the catchment.

The drainage lines of the quaternary Goukou Catchment were generated using the ArcHydro application, and were then numbered for ease of analysis. The Goukou Catchment had two areas from which drainage occurred- from the east and from the west- and these two areas were subsequently numbered and dealt with separately (Figure 17).

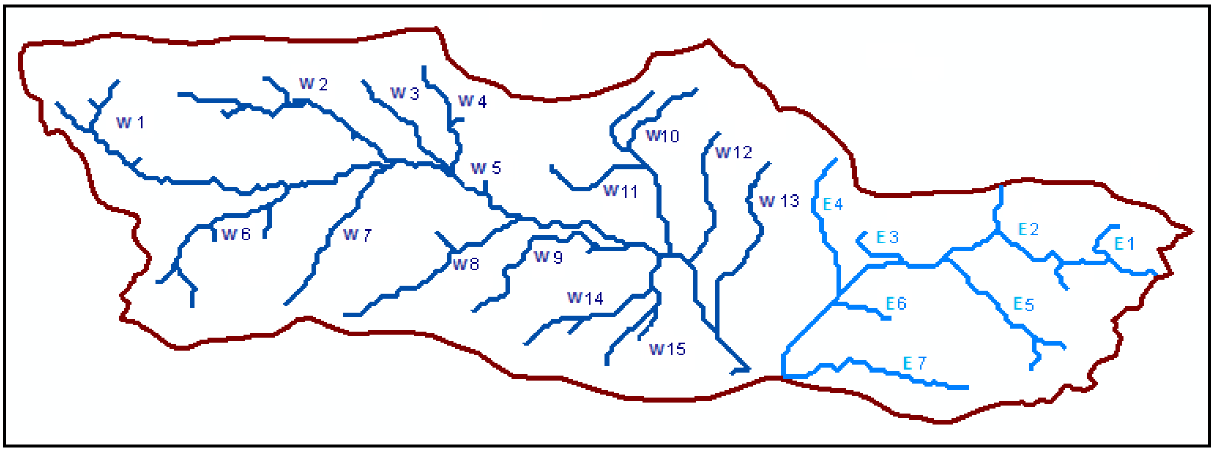


Figure 17. Drainage lines feeding wetlands of the Goukou Catchment

Drainage lines from the west of the catchment were numbered W1 to W15 (indicated in Figure 17 in dark blue), while lines draining from the east of the catchment (indicated in Figure 17 in light blue) were numbers E1 to E7. Only those drainage lines that had wetlands feeding into them were numbered and analysed.

It was then determined which wetlands occurred along which drainage lines, and the order of inflow of those wetlands. The way in which this was conducted may be illustrated by considering just the eastern portion of the catchment featured in Figure 17. A simple diagram, Figure 18, shows how the wetlands of this portion of the catchment are related and can therefore be arranged in order of inflow.

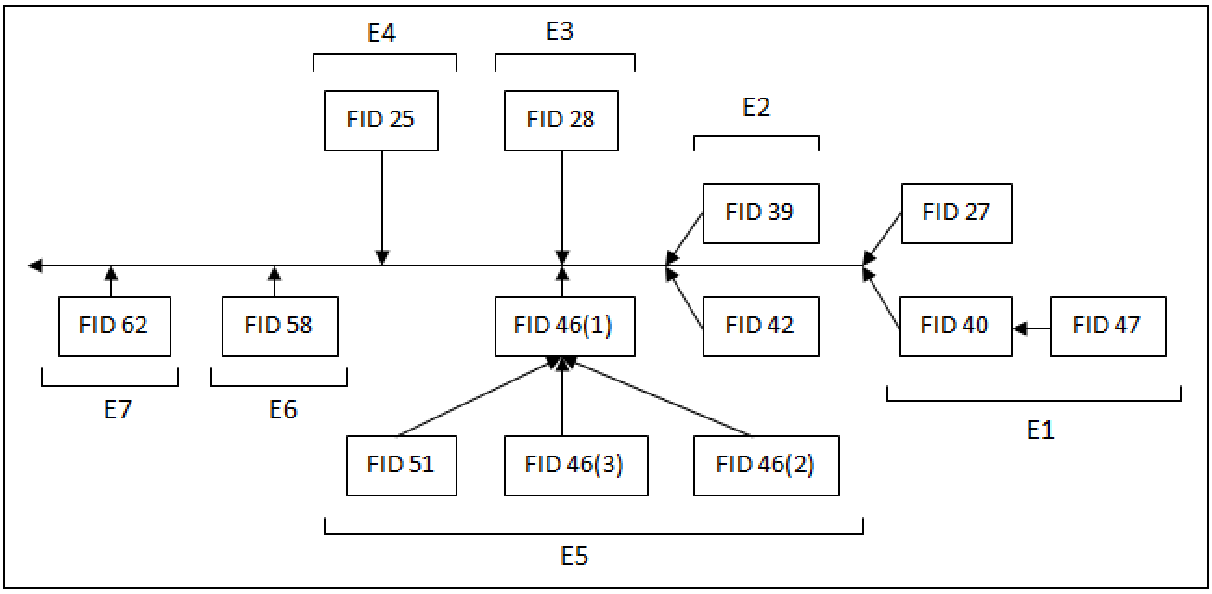


Figure 18. The spatial relationship between the wetlands of the eastern portion of the Goukou Catchment, with drainage lines labelled E1 to E7

The numbered wetlands, with their effectiveness scores and orders of inflow were then arranged in an MS Excel spreadsheet within their drainage line and in ascending order of inflow (Table 20). The effectiveness scores in each column were added together, aside from the positive effectiveness scores of primary wetlands (because the waters from these wetlands had been completely enhanced). This resulted in each drainage line having an effectiveness score, all of which were added together to determine the overall effectiveness of the catchment in enhancing water quality.

Table 20. Example of how calculations were conducted for integrating the spatial configuration of wetlands for a portion of the Goukou Catchment

E1			E2			E3			E4		
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Orde
27	-55.3719	1	39	-38.5172	1	28	-110.985	1	25	-272.27	
47	-98.8663	1	42	-182.943	1						
40	-113.43	2									
TOTAL	-267.669			-221.46			-110.985			-272.27	
E5			E6			E7					
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order			
46(2)	-23.3699	1	58	-96.48	1	62	-263.892	1			
46(3)	-35.8648	1									
51	-52.6036	1									
46(1)	-216.579	2									
TOTAL	-328.417			-96.48			-263.892		-1561.17		

4.4 Prioritisation of Wetlands

Through the ‘application of catchment scale analysis’ as is described in Section 4.3, it was possible to determine the overall effectiveness scores of individual wetlands in enhancing water quality, as well as the overall effectiveness of the catchment in enhancing water quality. These scores were derived through the consideration of factors such as land-cover present both within each wetland and within each wetland’s catchment, the subsequent hydrological health of each wetland, the ability of each wetland to provide water quality enhancement functionality, and a water quality impairment value encumbered to each wetland by its surrounding land-cover. Thus far, pictures of water quality enhancement effectiveness have been painted at both a small, single-wetland scale, and at a larger, catchment scale.

By having the ability to scrutinise wetlands at these variances in scale, it is possible to determine a combination of criteria for wetland prioritisation at both scales that are most likely to offer an optimal return on water quality enhancement effectiveness for the catchment as a whole. In order to determine the best criteria, and therefore the 'rules' for prioritising wetlands with a view to optimising water quality enhancement effectiveness in a catchment, a number of possible criteria were determined and applied to a portion of the Goukou Catchment, with the intention of choosing the criterion or combination of criteria that give the best outcome in terms of enhanced catchment water quality.

The criteria examined included prioritisation based on land-cover, prioritisation based on effectiveness of water quality enhancement, and prioritisation based on wetland degradation and onsite wetland rehabilitation. The size of the wetlands being targeted for rehabilitation has purposefully not been proposed as a prioritisation criterion, following the suggestion by Kotze (1999) that "there should be representation across different wetland size classes" (p139). As such, the criteria proposed are irrelevant to the size of the wetland.

4.4.1 Prioritisation based on Land-cover

Within this research, land-cover has been treated as the primary driver of both water quality impairment and the ability of a wetland to enhance water quality. This emphasis on land-cover has implied that all resultant water quality enhancement effectiveness values have been land-cover based. As such, in attempting to improve overall effectiveness of water quality enhancement at a catchment scale, it would seem logical that targeting particular land-cover types within the wetland and in the wetland's catchment would be an effective starting point.

An AHP was conducted as part of this research in order to determine the effect of different land-cover classes on surface water quality. Results of the AHP allowed for the land-cover classes to be arranged from most severely impacting land-cover class to least severely impacting land-cover class, and for the subsequent assignment of scaled scores to the land-cover classes (Table 21). Expert opinion derived from the AHP exercise suggested that mines and quarries most severely impact water quality, while natural land-cover least severely impacts water quality. It is expected that the rehabilitation of land-cover classes that score highest in terms of the severity of their impact on water quality will likely offer the greatest improvement in water quality. I.e. by targeting and rehabilitating the most severely impacting land-cover classes, the return on water quality improvement is likely to be greater than if a less severely impacting land-cover class were to be eradicated.

Table 21. Scaled severity of impact scores based on the AHP

LC No.	LC Class	Scaled Severity of Impact Score
1	Natural	1
2	Forest Plantations	2
3	Cultivated, irrigated	3
4	Cultivated, dryland	3
5	Dongas and Sheet Erosion	2
6	Degraded Vegetation	2
7	Urban Residential- high density	6
8	Residential- rural	5
9	Urban Commercial	6
10	Urban Industrial/Transport	9
11	Mines and Quarries	10
12	Urban Informal	9

The feasibility of the rehabilitation of a particular land-cover class is an important aspect to consider however. The rehabilitation of certain land-cover classes may be particularly difficult, such that restoration to a condition that reverses the land-cover's original negative effects may not be entirely possible. There are also certain economic costs that are encumbered during rehabilitation, and the greater the difficulty in eradicating the land-cover class and in rehabilitating the land, the greater the cost to do so. It therefore follows that a criterion for targeting particular wetlands for rehabilitation is the consideration of the land-cover classes within the wetland and its catchment, and the potential for rehabilitation of these land-cover classes.

As is reflected in Table 21, those land-cover classes that scored the highest in terms of the severity of their impact on water quality are cultivated, irrigated; cultivated, dryland; urban residential – high density; residential – rural; urban commercial; urban industrial/transport;

mines and quarries; and urban informal. Based on the rule of thumb offered by Kotze (1999), that "efforts should be directed to those wetlands with human activities in their catchments" (p139), as well as on the logic that the rehabilitation of land-cover classes that score highest in terms of the severity of their impact on water quality will likely offer the greatest improvement in water quality, the occurrence of these land-cover classes in a wetland's catchment would act as a criterion for targeting that wetland for rehabilitation.

Based on the aspect of feasibility though, realistically it may not be very feasible to eradicate land-cover types such as urban residential – high density, urban commercial, or urban industrial/transport in order to rehabilitate the land. Therefore the occurrence of land-cover classes cultivated, irrigated; cultivated, dryland; residential – rural; mines and quarries; and urban informal in a wetland's catchment may be used as criteria for which to prioritise wetlands for rehabilitation. The greater the area occupied by these land-cover classes, the greater the return on water quality effectiveness with land-cover rehabilitation.

It should be pointed out, however, that the feasibility of eradicating and rehabilitating land that is occupied by these land-cover classes is still strongly dependent on the specific context of the situation. The politics and cultural issues associated with land, particularly in South Africa, can strongly influence the feasibility of land rehabilitation. As is pointed out by Pereira (1973), "grazing practices (for example) are...deeply enmeshed in human behaviour patterns and are bounded by land tenure traditions, so that improvements in land use are usually slow and difficult to secure" (p182).

4.4.2 Prioritisation based on Effectiveness of Water Quality Enhancement

It has been established that wetlands with a positive water quality enhancement effectiveness score may be thought to be effectively improving the quality of the water passing through them. These wetlands are effectively assimilating the water quality impairment contribution by their surrounding land-cover classes, and therefore do not necessitate the targeting of them for rehabilitation.

Wetlands with negative water quality enhancement effectiveness scores do require intervention in the form of rehabilitation in order to improve their abilities to enhance water quality. A proposed criterion for targeting wetlands for rehabilitation is that wetlands should have a negative overall water quality enhancement effectiveness score.

An accompanying criterion is the consideration of how negative that overall water quality enhancement effectiveness score is. A negative overall water quality enhancement effectiveness score implies that 'hectare equivalents of water quality impairment' exceed the 'hectare equivalents of water quality enhancement'. Therefore by targeting a wetland with an exceedingly negative overall water quality enhancement effectiveness score for rehabilitation, the aim would be to lessen the difference between water quality impairment and water quality enhancement, and thereby increase the overall water quality enhancement effectiveness of that wetland.

4.4.3 Prioritisation based on Wetland Degradation and Onsite Rehabilitation

With the aim of targeting wetlands for rehabilitation, an obvious criterion would be to target those wetlands that are degraded. As Ellery *et al*. (in review) point out, wetland health affects how effectively a wetland is able to provide an ecosystem service such as water quality enhancement, through recognising the fact that the hydrological regime of a given wetland directly affects the structure and function of that wetland (Ellery *et al.*, in review). It follows then that a wetland in good 'health' or condition would enhance water quality better than one that is degraded. Therefore, given an entire catchment, targeting degraded wetlands for rehabilitation would improve the water quality enhancement effectiveness of the catchment as a whole.

In order to differentiate between degraded and pristine wetlands, and to gain insight into the degree of degradation of a particular wetland, the magnitude of impact score that is determined in the early steps of the application of the tool developed by Ellery *et al*. (in review) serves as a useful indicator. As is described in Section 2.3.4, when determining the functional effectiveness scores for each ecosystem service for a given wetland using the tool developed by Ellery *et al*. (in review), a magnitude of impact score for each hydrological impact is generated by multiplying the extent of each land-cover class by the relevant intensity of impact score from Table 4. Overall magnitude of impact scores for each hydrological impact are then determined for each wetland. Based on the WET-Health assertion that health is inversely related to the magnitude of impacts - upon which Ellery *et* al. (in review) based part of their tool - these magnitude of impact scores serve as indicators of the health of the wetland. By adding together the various magnitude of impact scores for each wetland, an overall magnitude of impact score for all impacts to the wetland is determined.

Based on the abovementioned premise that health is inversely related to the magnitude of impacts, the higher the overall magnitude of impacts score of a wetland, the more degraded it is. Therefore in prioritising wetlands for rehabilitation, those wetlands with higher magnitude of impact scores should be targeted. The number of these targeted wetlands would be project and budget dependent.

By targeting degraded wetlands for rehabilitation, with degradation being based on the extent of the hydrological impact on the wetland, one is ultimately targeting those wetlands with the intention of reducing those hydrological impacts by rehabilitation. The assimilative capacity of a wetland can be substantially increased by addressing on-site impacts currently diminishing the wetland's assimilative capacity.

The tool developed by Ellery *et al*. (in review) highlights the relationship between the impacts to a wetland's hydrological health by wetland and catchment land-cover, and the effectiveness with which that wetland is able to perform a number of ecosystem services. Wetland health affects how effectively a wetland is able to provide an ecosystem service such as water quality enhancement, through recognising the fact that the hydrological regime of a given wetland directly affects the structure and function of that wetland (Ellery *et al.*, in review).

Bearing in mind that rehabilitation is applicable to "systems or parts of systems that have not been removed from the landscape through complete and permanent alteration but are in a degraded state, having lost a degree of ecosystem structure, function, biotic composition and/or associated ecosystem services" (Grenfell *et al*., 2007, p7), by identifying the nature of the hydrological impacts faced by a wetland and therefore the way in which its structure and function have been compromised, the determination of appropriate onsite wetland rehabilitation techniques may be conducted. The implementation of the appropriate measure would address the identified issues, and thereby improve the water quality enhancement effectiveness of that wetland.

Section 2.1.8 highlighted the principle objectives of wetland rehabilitation in South Africa, as well as some of the 'hard' and 'soft' rehabilitation measures that allow for these objectives to be achieved. These objectives are erosion control, to raise the local water table, and to promote diffuse flow within the wetland (Grenfell *et al*., 2007; Ellery, 2006). By recognising the hydrological impacts faced by wetlands in a landscape and knowing how these impacts can be mitigated through the implementation of these rehabilitation techniques, degraded wetlands can be targeted for rehabilitation prioritisation, with a view to optimising water quality enhancement effectiveness in the catchment.

4.4.4 Water Quality Enhancement Scenarios

Due to the number of wetlands within the Goukou case study, a smaller group of wetlands from within the Goukou Catchment were subjected to the prioritisation options described in Section 4.4, with the aim of determining the scenario that gives the best outcome in terms of enhanced catchment water quality. The wetlands evaluated were from drainage lines E1 to E7 of the larger study (Figure 19), and comprised 12 wetlands of varying land-cover classes and water quality enhancement effectiveness scores.

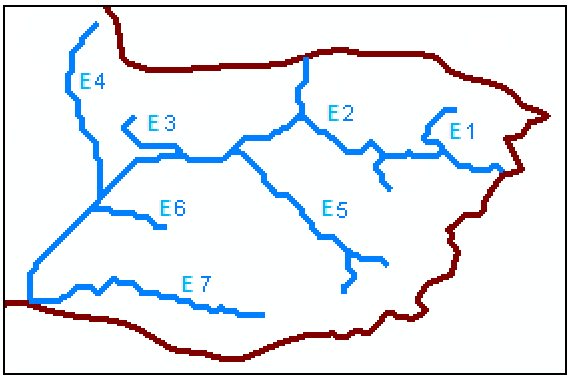


Figure 19. Drainage lines feeding wetlands of the eastern portion of the Goukou Catchment

The current scenario and state of the wetlands as determined in the larger case study were first extracted from the case study dataset. As in the larger case study, after the overall effectiveness of water quality enhancement for each wetland was determined, the wetlands were arranged in order of inflow so as to integrate the spatial configuration of the wetlands in the catchment (Figure 18).

The water quality enhancement effectiveness scores of wetlands in each drainage line were added together, and each drainage line was thereby assigned an effectiveness score, all of which were added together to determine the overall effectiveness of the catchment in enhancing water quality (Table 20). This score, which is representative of the current water quality enhancement effectiveness of this portion of the catchment, was determined to be -1561.17.

In applying the various prioritisation criteria to this portion of the catchment, a limitation of targeting only five wetlands for rehabilitation was imposed. This limitation allows for more realistic scenarios and results to be gained, as in a real-world situation, it may not be possible to rehabilitate all wetlands with a high magnitude of impact score, or all of those wetlands with a high negative overall water quality enhancement effectiveness score. Furthermore, limiting the number of wetlands being targeted for rehabilitation to five makes it easier to determine which prioritisation criterion is most effective, as there will be less overlap in terms of the same wetlands being targeted in each scenario.

4.4.4.1 Scenario One: Prioritisation based on Land-cover

The first step in running this scenario was that land-cover classes present in each of the wetlands and each of their catchments was scrutinized, such that cultivated, irrigated; cultivated, dryland; residential- rural; mines and quarries; and urban informal land-cover classes were highlighted, and the sum of the areal extents of these land-cover classes affecting each of these wetlands was determined. The wetlands with the five highest areal extents of these land-cover classes were subsequently targeted for land-cover rehabilitation (Table 45). These wetlands were Wetland FID 25, FID 28, FID 46(1), FID 58, and FID 62. The next step was to apply the simplest hypothetical rehabilitation technique to these wetlands, so land-cover classes cultivated, irrigated; cultivated, dryland; residential- rural; mines and quarries; and urban informal were removed and replaced with natural land-cover.

The process of determining overall water quality enhancement effectiveness of the catchment was reapplied to the changed land-cover classes. Magnitude of impact scores were determined for the altered land-cover classes (Table 46), and the application of relevant equations from Tables 6 to 11 were undertaken for both impacts arising in the wetland's catchment and impacts arising within the wetland. Final functionality scores were determined and resolved for sediment trapping, phosphate trapping, nitrate removal and toxicant removal, and hectare equivalents for each of these ecosystem services was established, which allowed for the determination of hectare equivalents of water quality enhancement (Table 47). Hectare equivalents of water quality impairment were also determined through the application of the process described in Figure 13. Finally, overall effectiveness of water quality enhancement was determined by subtracting three times the determined hectare equivalents of water quality impairment from the hectare equivalents of water quality enhancement (Table 48).

Newly determined water quality enhancement effectiveness scores, along with those effectiveness scores for wetlands that were unchanged, were then applied to the wetlands of the case study group and the wetlands were arranged in order of inflow so as to integrate the spatial configuration of the wetlands in the catchment. The result was that overall water quality enhancement effectiveness was improved from -1561.17 to -1029.51, indicating an improvement in the enhancement of water quality by the collective wetlands in the catchment (Table 49).

This indicates that although the catchment was still not completely filtering the waters passing through it, there was an improvement in the quality of the water leaving the catchment after rehabilitation was undertaken. Given the constraints of targeting only five wetlands with the occurrence of particular land-cover classes in their catchments, the score of -1029.51 hectare equivalents of water quality enhancement effectiveness is indicative of the optimal water quality enhancement effectiveness of that catchment under these constraints.

4.4.4.2 Scenario Two: Prioritisation based on Effectiveness of Water Quality Enhancement

In running this scenario, the overall effectiveness of water quality enhancement scores of the wetlands in their current state were scrutinized, and negative overall water quality enhancement effectiveness scores were highlighted. The wetlands with the five overall water quality enhancement effectiveness scores of greatest negativity were subsequently targeted for land-cover rehabilitation (Table 50). These wetlands were Wetland FID 25, FID 40, FID 42, FID 46(1), and FID 62.

The criterion upon which Scenario One was based (that only land-cover classes cultivated, irrigated; cultivated, dryland; residential- rural; mines and quarries; and urban informal be removed and replaced with natural land-cover due to the feasibility of their rehabilitation) was maintained, and these land-cover classes from the catchments of the aforementioned wetlands were hypothetically converted to ‘natural’ land-cover.

The calculation of the overall water quality enhancement effectiveness for the portion of the Goukou Catchment used for running these scenarios was then repeated for the ‘rehabilitated’ catchments. Magnitude of impact scores were determined for the altered land-cover classes (Table 51), and the relevant equations from Tables 6 to 11 were applied to the magnitude of impacts scores for both impacts arising in the wetland’s catchment and impacts arising within the wetland. Final functionality scores were determined and resolved for sediment trapping, phosphate trapping, nitrate removal and toxicant removal, which allowed for the determination of hectare equivalents of each of these ecosystem services analysed. The mean of these hectare equivalents was then determined to derive hectare equivalents of water quality enhancement for the catchment (Table 52). Hectare equivalents of water quality impairment were also determined through the application of the process described in Figure 13. Finally, overall effectiveness of water quality enhancement was determined by subtracting three times the determined hectare equivalents of water quality impairment from the hectare equivalents of water quality enhancement (Table 53).

The new water quality enhancement effectiveness scores from the targeted wetlands, along with those effectiveness scores for wetlands that were unchanged, were then applied to the wetlands of the case study group and in order to integrate the spatial configuration of the wetlands in the catchment, the wetlands were arranged in order of inflow. It was determined that overall water quality enhancement effectiveness was improved from -1561.17 to -927.53 (Table 54). This difference of 633.34 in the effectiveness of water quality enhancement by the collective wetlands in the catchment indicates an improvement in the enhancement of water quality due to land-cover rehabilitation for wetlands with a considerably negative initial overall water quality enhancement effectiveness score.

As in the case of Scenario One, the score of -927.53 indicates that although the catchment was still not completely filtering the waters passing through it, there was an improvement in the quality of the water leaving the catchment after rehabilitation was undertaken. Given the constraints of targeting only five wetlands with the occurrence of particular land-cover classes in their catchments, the improvement in the overall catchment water quality enhancement effectiveness score is indicative of the optimal water quality enhancement effectiveness of that catchment under these constraints.

4.4.4.3 Scenario Three: Prioritisation based on Wetland Degradation and Onsite Rehabilitation

Section 4.4.3 described the process of prioritising wetlands for onsite rehabilitation based on the sum of the overall magnitude of impact scores for each hydrological impact to a given wetland. These magnitude of impact scores are indicative of the health of the wetland, and are determined by multiplying the extent of each land-cover class present within the wetland and catchment by the relevant intensity of impact score from Table 4, which are then resolved to produce an overall score for the magnitude of catchment impacts, and overall scores for the magnitude of each onsite impact.

Through a review of the magnitude of impact scores that were determined for the wetlands of this portion of the Goukou catchment, five wetlands with the five greatest total magnitude of impact scores were targeted for onsite rehabilitation (Table 55). This total magnitude of impact score is the sum of the overall magnitude of catchment impacts, and all of the magnitude of onsite impacts. The wetlands that were targeted by the application of this method were Wetland FID 28, 42, 46(1), 51 and 62.

As was discussed in Section 4.4.3, by targeting degraded wetlands for rehabilitation, with degradation being based on the extent of the hydrological impact on the wetland, one is ultimately targeting those wetlands with the intention of reducing those hydrological impacts by rehabilitation. Section 2.1.8 highlighted the principle objectives of wetland rehabilitation in South Africa, as well as some of the 'hard' and 'soft' rehabilitation measures that allow for these objectives to be achieved. These include erosion control, to raise the local water table, and to promote diffuse flow within the wetland (Ellery, 2006; Grenfell *et al*., 2007). The choice of rehabilitation implemented would be dependent on the hydrological impact identified, based on the land-cover class present within the wetland. Catchment impacts would remain the same, since onsite rehabilitation would address only onsite hydrological impacts.

By hypothetically implementing the appropriate rehabilitation technique to the wetlands targeted for rehabilitation in this scenario, the intensity of impact score for each of these wetlands would theoretically be reduced. In running this scenario however, cognisance was taken of the fact that it is not possible to accurately predict the effect that onsite rehabilitation will have on the intensity of impact scores. However, from a hydrological health perspective it is possible to make some general assumptions on the effect of onsite rehabilitation on the intensity of impact scores for each land-cover class within a wetland, which are presented in Table 22.

As is reflected in Table 22, rehabilitation in forest plantations can be assumed to lower the intensity of impact score by 2, while for degraded vegetation, the intensity of impact score may be lowered to 1 or 2 (average of 1.5). Similarly, rehabilitation in cultivated land in a wetland can be assumed to lower the impact score to 2. Rehabilitation of dongas in wetlands generally involves preventing the advance of the gully into areas that have not yet eroded (generally natural areas) for which it can be assumed that the gully would have otherwise increased the impact score (i.e., the rehabilitation would keep the areas that are under threat of erosion in a natural state) (Kotze, 2009, pers. comm.). The areas that have already eroded and are then rehabilitated would likely reduce their impact score to 5. Rehabilitated residential rural and urban informal land-cover classes can be assumed to return to a score of 3 because they are generally not associated with major changes such as infilling and reconfiguration of drainage patterns (Kotze, 2009, pers. comm.). The intensity of impact scores for land-cover classes urban residential – high density; urban commercial; urban industrial/transport; and mines and quarries have remain unchanged, as the presence of these land-cover classes within the wetland would make rehabilitation unfeasible, as is discussed in Section 4.4.1.

In applying this scenario, the post-rehabilitation intensity of impact scores were applied to the land-cover classes present in the wetlands of the case study catchment, and the processes of determining final hectare equivalents of water quality enhancement and water quality impairment were undertaken, the steps of which are presented in Figures 12 and 13. These steps included the determination of magnitude of impact scores for each land-cover class present (Table 56), for catchment and within-wetland impacts; the resolution of catchment impacts; the application of the relevant equations from Tables 6 to 11 to determine the effect of each impact on the provision of sediment trapping, phosphate trapping, nitrate removal, and toxicant removal; the resolution and scaling of onsite and catchment impacts to determine a final functional effectiveness score; and the subsequent calculation of functional hectare equivalents of water quality enhancement functionality (Table 57). Hectare equivalents of water quality impairment were also determined by utilising the relevant impact ratio from Table 25, and both hectare equivalents of water quality enhancement and hectare equivalents of water quality impairment were used to establish overall effectiveness of water quality enhancement (Table 58). Finally, as was conducted in Scenarios One and Two, newly determined water quality enhancement effectiveness scores, along with those effectiveness scores for wetlands that were unchanged, were then applied to the wetlands of the case study group and the wetlands were arranged in order of inflow so as to integrate the spatial configuration of the wetlands in the catchment (Table 59). By doing so, it was concluded that by targeting wetlands for rehabilitation based on wetland degradation, and by altering intensity of impact scores for the five most degraded wetlands in the case study catchment, overall effectiveness of water quality enhancement improved from -1561.17 to -1363.75.

While this value of -1363.75 is indicative of an improvement in overall effectiveness of water quality enhancement, it is noted that due to the difficulty in accurately predicting the effect that onsite rehabilitation will have on the intensity of impact scores, especially since all the scores are currently solely land-cover based, this may not be an accurate reflection of the positive effect that onsite rehabilitation may have on the effectiveness of water quality enhancement by each wetland.

Table 22. Intensity of impact scores to be used for within-wetland land-cover pre- and post-rehabilitation

Land-cover Category	**Intensity of impact score for within-wetland impacts**							
	Pre-rehabilitation				**Post-rehabilitation**			
	Increased direct water losses	Reduced surface roughness	Flow impediment	Flow enhancement	Increased direct water losses	Reduced surface roughness	Flow impediment	Flow enhancement
Natural	0	0	0	0	0	0	0	0
Forest plantations	9 (forest) 7 (heavy alien plant infestation) 5 (modest alien plant infestation) 3 (light alien plant infestation)				7 (forest) 5 (heavy alien plant infestation) 3 (modest alien plant infestation) 1 (light alien plant infestation)			
Cultivated,		5				2		

irrigated								
Cultivated, dryland		5				2		
Dongas and sheet erosion				9				5
Degraded vegetation		3				1.5		
Urban residential - high density		7				7		
Residential - rural		5				3		
Urban commercial		9				9		
Urban industrial/ transport	4*** (for area of wetland above road across a wetland)	9	5 (for area of wetland above road across a wetland)		4*** (for area of wetland above road across a wetland)	9	5 (for area of wetland above road across a wetland)	
Mines and quarries		9				9		
Urban informal		5				3		

4.4.5 Summary of Scenario Results

By examining the various possible prioritisation criteria highlighted in Section 4.4, and by running scenarios based upon each criterion, it was possible to determine the criterion that gave the best outcome in terms of enhanced catchment water quality.

Scenario One prioritised wetlands based on the presence of land-cover classes cultivated, irrigated; cultivated, dryland; residential- rural; mines and quarries; and urban informal land-cover, due to these classes being feasible enough to rehabilitate as well as having scored amongst the highest in terms of the severity of their impact on water quality. The wetlands with the five highest areal extents of these land-cover classes were subsequently targeted for land-cover rehabilitation and the simplest hypothetical rehabilitation technique was applied to these wetlands - land-cover classes cultivated, irrigated; cultivated, dryland; residential- rural; mines and quarries; and urban informal were removed and replaced with natural land-cover. The result was that overall water quality enhancement effectiveness was improved from -1561.17 to -1029.51.

Scenario Two, which gave the best result by improving overall water quality enhancement effectiveness from -1561.17 to -927.53, based the prioritisation of wetlands for rehabilitation on the present effectiveness of water quality enhancement of each wetland in the catchment. Wetlands with an exceedingly negative overall water quality enhancement effectiveness score were targeted for rehabilitation, the aim of which was to lessen the difference between water quality impairment and water quality enhancement, and thereby increase the overall water quality enhancement effectiveness of that wetland, and inadvertently, of the catchment. In keeping with those classes identified as having severe impact on water quality, the wetlands with the five overall water quality enhancement effectiveness scores of greatest negativity were targeted for land-cover rehabilitation and land-cover classes cultivated, irrigated; cultivated, dryland; residential- rural; mines and quarries; and urban informal were hypothetically removed and replaced with natural land-cover. It is acknowledged, however, that this scenario had the added advantage of targeting land-cover both within the wetlands as well as within the wetlands' catchments.

Wetland degradation and onsite rehabilitation was the basis for prioritisation in Scenario Three, whereby wetlands with the five greatest total magnitude of impact scores (which included magnitude of impact scores for catchment and within-wetland impacts) were targeted for onsite rehabilitation. General assumptions were made on the effect of onsite rehabilitation on the intensity of impact scores for each land-cover class within a wetland, and these 'new' within-wetland intensity of impact scores were applied to the land-cover classes present in the wetlands of the case study catchment, and the processes of determining final hectare equivalents of water quality enhancement and water quality impairment were undertaken. It was concluded that by targeting wetlands for rehabilitation based on wetland degradation, and by altering intensity of impact scores for the five most degraded wetlands in the case study catchment, overall effectiveness of water quality enhancement improved from -1561.17 to -1363.75.

Based upon the results of these scenarios, it can be concluded that given the constraints of targeting only five wetlands in a given catchment, the greatest improvement in the overall catchment water quality enhancement effectiveness score came from prioritising wetlands based on the present effectiveness of water quality enhancement of each wetland in the catchment, and by rehabilitating land-cover that was determined to be both severely impacting on water quality, as well as feasible to rehabilitate. As was previously mentioned, it is acknowledged, however, that this scenario had the added advantage of targeting land-cover both within the wetlands as well as within the wetlands' catchments.

4.5 **Rehabilitation of Wetlands of the Goukou Catchment**

Based on the results of the scenarios as described in Section 4.4.5, the best outcome in terms of enhanced catchment water quality was achieved by prioritising wetlands based on the present effectiveness of water quality enhancement of each wetland in the catchment. This prioritisation criterion was therefore applied to the quaternary catchment of the Goukou Forum, for which present overall water quality enhancement had already been determined (as is presented in Section 5.3.5). Of the 49 wetlands of this quaternary catchment, 25 wetlands with the most negative overall water quality enhancement effectiveness scores – just over half – were targeted for rehabilitation (Table 60). This number was chosen in keeping with the fact that a limitation allows for a more realistic scenario and results to be gained, as in a real-world situation, it may not be possible to rehabilitate all wetlands with a high negative overall water quality enhancement effectiveness score.

Within the catchments of these wetlands, particular land-cover classes were hypothetically rehabilitated, by converting them to 'natural' land-cover. These land-cover classes were targeted based on the severity of their impact on water quality, as well as on the feasibility with which they may be rehabilitated, and included cultivated, irrigated; cultivated, dryland; residential- rural; mines and quarries; and urban informal. Once these land-cover classes were converted to 'natural', the process of determining hectare equivalents of water quality enhancement using the method developed by Ellery *et al.* (in review) was re-applied to the catchments of the prioritised wetlands. New magnitude of impact scores were determined for both catchment and onsite impacts (Table 61), which were later resolved using Table 12. Functional hectare equivalents of sediment trapping, phosphate trapping, nitrate removal, and toxicant removal functionality were established for each of the prioritised wetlands, the mean of which was later taken to represent hectare equivalents of water quality enhancement functionality. Hectare equivalents of water quality impairment were also determined for each wetland, and overall effectiveness of water quality enhancement was then calculated by subtracting three times the determined hectare equivalents of water quality impairment from the hectare equivalents of water quality enhancement (Table 62).

The newly determined water quality enhancement effectiveness scores, along with those effectiveness scores for wetlands that were unchanged, were then applied to the wetlands of the Goukou Catchment and the wetlands were arranged in order of inflow so as to integrate the spatial configuration of the wetlands in the catchment (Table 63).

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 Introduction

This chapter is a presentation of the results gained from the application of the steps described in Chapter Four. Figure 20 is a summary of the steps that were undertaken and has been included for referral when following the results.

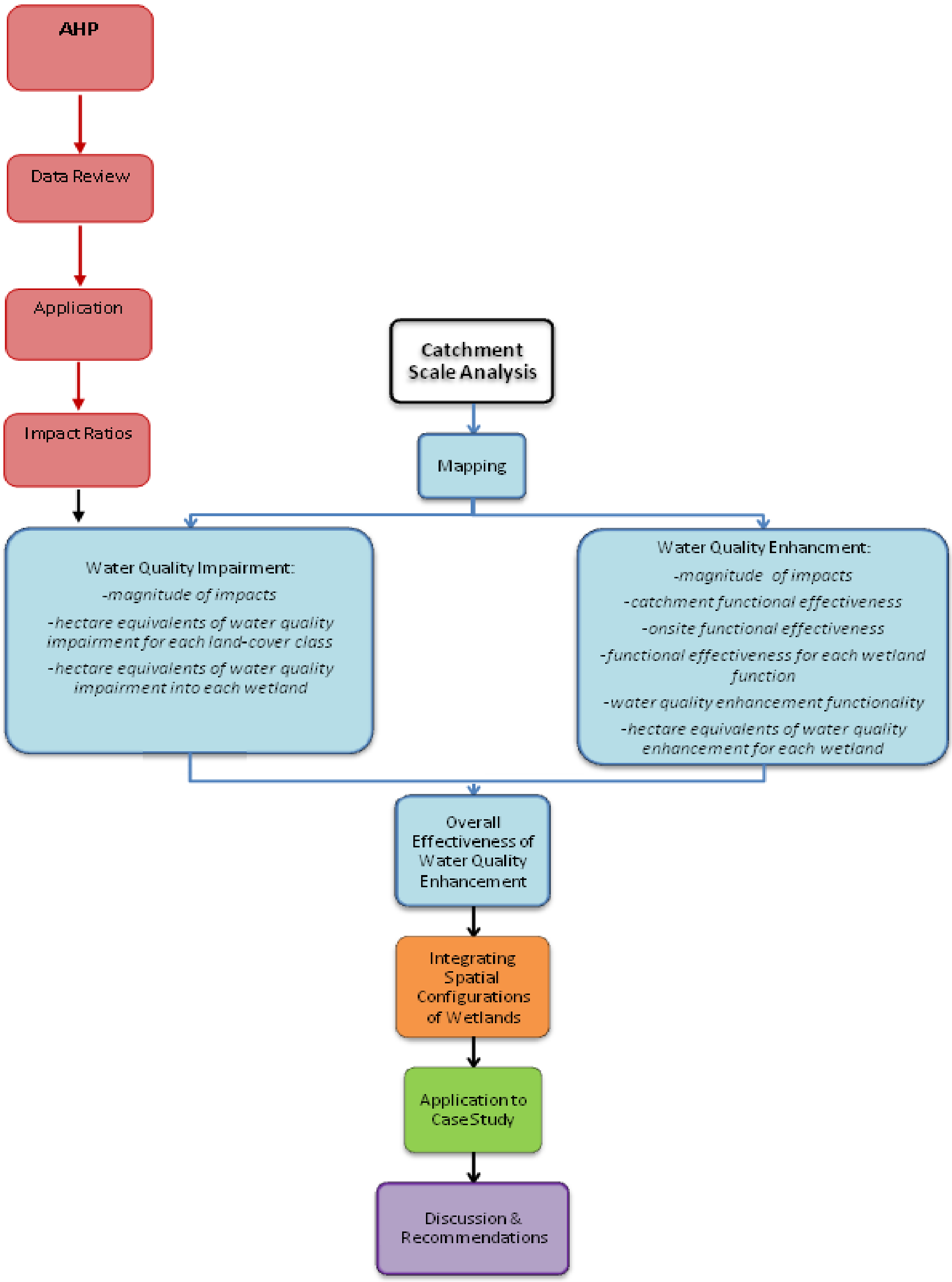


Figure 20. Flow diagram indicating the steps undertaken in this methodology

5.2 The Analytical Hierarchical Process (AHP)

It was established that the first step in developing a method to determine the cumulative impact of wetland degradation on water quality was to determine how the quality of the water entering the wetland was affected by the land-cover in the catchment. It is well known that catchment activities significantly impact the wetland within it, the understanding of which was the basis for generating a set of scores that related the National Land-cover Classes (NLCs) to their impact on water quality, using an Analytical Hierarchical Process (AHP) to capture the wisdom of specialists with some understanding of catchments and the relationship of land use with water quality.

5.2.1 Review of Land-cover Data and Water Quality Criteria

As was previously mentioned, the existing 31 South African National land-cover classes (Thompson, 1996) were reviewed and subsequently aggregated, since the use of all 31 land-cover classes was found to be far too detailed and specific, while the use of just the 4 aggregated categories proved to be too broad and general (Table 13). For example, the ‘urban’ aggregated category contains land-cover classes that differ extensively in terms of their potential impacts on water quality. As a result, the 31 classes were aggregated into 12 land-cover classes, with a view to combining classes of similarity in terms of their potential impacts on water quality. The table below (Table 23) shows which classes were aggregated to arrive at the classes that were analysed (under the heading “New Classes”), while Table 24 describes what is included in each of the aggregated classes.

Table 23. Aggregated National Land-cover Classes

NLC Code	Land-cover Class	“New Classes”	Aggregated Categories
1	Forest and Woodland		
2	Forest		
3	Thicket and bushland (etc)		
4	Shrubland and low Fynbos		
5	Herbland	Natural	Natural
6	Unimproved grassland		
9	Waterbodies		
10	Wetlands		
11	Barren rock		

8 7 18 21 19 20 22 23	Forest plantations Improved grassland Cultivated: permanent – commercial irrigated Cultivated: temporary - commercial irrigated Cultivated: permanent - commercial dryland Cultivated: permanent - commercial sugar cane Cultivated: temporary - commercial dryland Cultivated: temporary - subsistence dryland	Forest Plantations Cultivated, irrigated Cultivated, dryland	Agriculture
12 13 14 15 16 17	Dongas and sheet erosion scars Degraded: forest and woodland Degraded: thicket and bushland (etc) Degraded: unimproved grassland Degraded: shrubland and low Fynbos Degraded: herbland	Dongas and Sheet Erosion Degraded Vegetation	Degraded
24 25 26 27 28 29 30 31	Urban: residential Urban: residential (smallholdings: forest and woodland) Urban: residential (smallholdings: bushland) Urban: residential (smallholdings: shrubland) Urban: residential (smallholdings: grassland) Urban: commercial Urban: industrial/transport Mines and Quarries	Urban Residential- high density Residential- rural Urban Commercial Urban Industrial/Transport Mines and Quarries	Urban

Table 24. Descriptions of aggregated land-cover classes (adapted from Thompson, 1996)

LCU Code	Land-cover/land use Class	Description
1	Natural	All areas of vegetation grown under natural or semi-natural conditions, including forest, woodland, thicket, scrub forest, bushland, high Fynbos, shrubland, low Fynbos, herbland, and unimproved grassland; as well as natural and man-made waterbodies, natural or artificial wetlands, and natural areas of exposed sand, soil or rock.
2	Forest Plantations	Areas of systematically planted, man-managed tree resources, composed of primarily exotic species (e.g. pine, eucalyptus, wattle). No input of fertilizer is assumed.
3	Cultivated, irrigated	All areas of cultivated land that undergo systematic irrigation, including cultivated permanent commercial irrigated, cultivated temporary commercial irrigated, and planted grassland, containing either indigenous or exotic species, growing under man-managed conditions for grazing, hay or turf production, recreation (e.g. golf courses).
4	Cultivated, dryland	All areas of cultivated land that does not utilise irrigation practices, including cultivated permanent commercial dryland, cultivated permanent commercial sugarcane, cultivated temporary commercial dryland, and cultivated temporary subsistence dryland.
5	Dongas and Sheet Erosion	Gullies and channels, and permanent or seasonal areas of very low vegetation cover in comparison with surrounding natural vegetation cover, induced by the gradual removal of soil and soft rock due to concentrated runoff.
6	Degraded Vegetation	Permanent or seasonal, man-induced areas of very low vegetation cover in comparison with the surrounding natural vegetation cover. Typically associated with subsistence level farming and rural population centres, where overgrazing of livestock and/or wood-resource removal has been excessive. Often associated with severe soil erosion problems.
7	Urban Residential-high density	Areas in which people reside on a permanent or near-permanent basis in formal settlement areas with high densities.
8	Residential- rural	Areas in which people reside on a permanent or near-permanent basis in formal settlement areas, generally with low building densities. This category includes urban residential (smallholdings- forest and woodland), urban residential (smallholdings-thicket, scrub forest, bushland and high Fynbos), urban residential (smallholdings-shrubland and low Fynbos), and urban residential (smallholdings- grassland).
9	Urban Commercial	Non-residential areas used primarily for the conduct of commerce and other mercantile business, typically located in the central business district.
10	Urban Industrial/Transport	Non-residential areas with major industrial or transport related infrastructure. Examples include power stations, steel mills, dockyards and airports.
11	Mines and quarries	Areas in which mining activity has been done or is being done. Includes opencast

		mines and quarries as well as surface infrastructure (mine dumps, etc.) associated with underground mining activities. No rehabilitation is assumed.
12	Urban Informal	Areas in which people reside on a permanent or near-permanent basis in informal settlement areas within designated urban areas, ranging from high to low building densities.

It should be pointed out that Land-cover Class 12, 'Urban Residential- Informal' was not in fact included in the NLC project. This class was developed as part of this research in order to accommodate the growing occurrence of this class across present South African landscapes.

DWAF's (2005a) water quality parameters were also reviewed, such that they could be used as criteria for assessing the impact of land-cover classes on water quality. As is pointed out in Section 2.4.3.1, the constituents of water quality are categorised according to their nature and to their effect on different aspects of water quality. These aspects include chemical quality, the constituents of which include total organic carbon, pH, disinfectant residuals, and disinfection by-products; microbiological quality, including total coliforms and the presence of *E. coli*; physical quality, which includes turbidity, colour, taste and odour; and algal counts (p16). DWAF (2005a) point out that while other water quality constituents do exist, it is not feasible, physically or economically, to test all of these constituents at the same frequency. As a result, monitoring is concentrated around the aforementioned constituents that have been identified as most indicative of the quality of water necessary for human health.

5.2.2 Application of AHP

The process of AHP application involved the construction of a hierarchy (Figure 11) which included the factors under evaluation (the different land-cover classes), the criteria to consider in assessing the factors (chemical quality, microbiological quality, and physical quality), and the objective of the process at level one (the effect of the factors on water quality). This hierarchy guided the development of a pairwise comparison form, which allowed for the prioritization of the land-cover classes in terms of the severity of their impacts on water quality. The results were inputted into a comparison matrix which allowed for the derivation of numerical scores which were later utilized in Decision Analyst to produce a weight for each land-cover class, representative of the extent of the effect of that class on water quality. The results were then scaled from 0-10, with least severely impacting land-cover class being assigned a score of 1, and the maximum impact a score of 10 (Table 25).

Table 25. Scaled intensity of impact scores and impact ratios derived from application of AHP

LC No.	LC Class	Weighting from Respondent 1	Weighting from Respondent 2	Weighting from Respondent 3	Weighting from Workshop	Mean of Weightings	Scaled Severity of Impact Score	Impact Ratio
1	Natural	0.01	0.0126	0.00879	0.0104	0.010448	1	**0.1**
2	Forest Plantations	0.0236	0.0185	0.0348	0.0419	0.0297	2	**0.2**
3	Cultivated, irrigated	0.117	0.0407	0.0425	0.0419	0.060525	3	**0.3**
4	Cultivated, dryland	0.0556	0.0304	0.0221	0.0936	0.050425	3	**0.3**
5	Dongas and Sheet Erosion	0.0557	0.0326	0.0516	0.0104	0.037575	2	**0.2**
6	Degraded Vegetation	0.0678	0.042	0.0579	0.0104	0.044525	2	**0.2**
7	Urban Residential-high density	0.0818	0.189	0.113	0.174	0.13945	6	**0.6**
8	Residential-rural	0.0762	0.0558	0.0779	0.174	0.095975	5	**0.5**
9	Urban Commercial	0.0818	0.189	0.113	0.174	0.13945	6	**0.6**
10	Urban Industrial/Transport	0.17	0.279	0.26	0.0629	0.192975	9	**0.9**
11	Mines and Quarries	0.206	0.279	0.314	0.0936	0.22315	10	**1**
12	Urban Informal	0.11	-unavailable	-unavailable	0.266	0.094	9	**0.9**

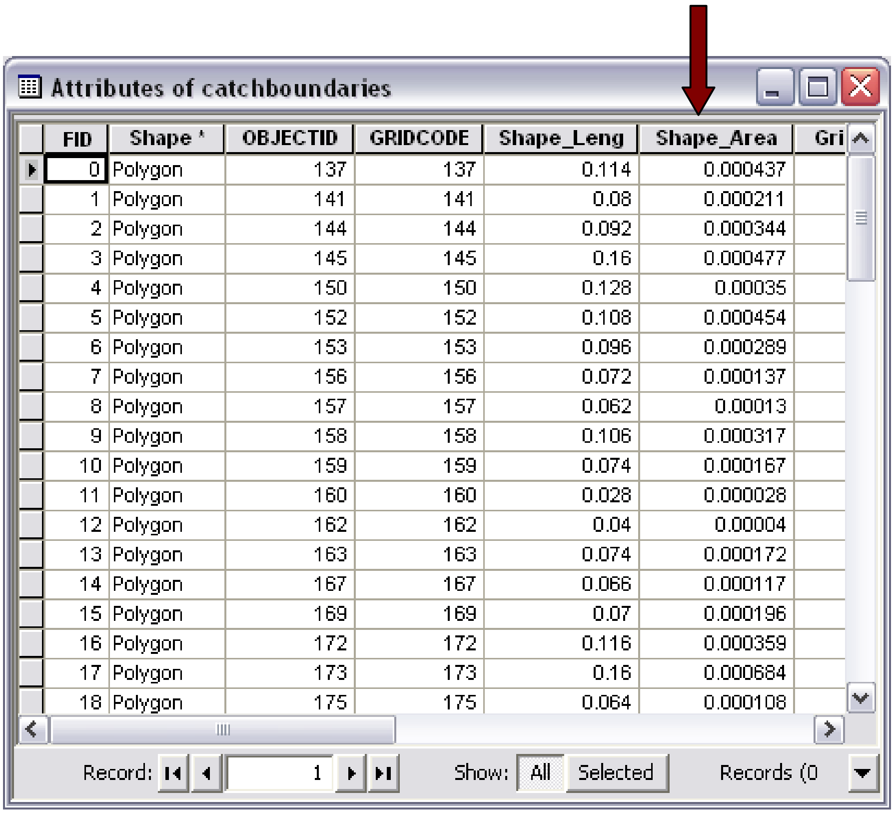
Scaled scores were then converted to impact ratios, each of which is indicative of the intensity of the impact of that land-cover class on water quality. By converting the scores to ratios rather than using them as their whole number scaled scores, the scores are made relative to each other and to the maximum possible severity. For example, the most severely impacting class - mines and quarries - had a scaled score of 10, from a scale of 0 to 10. Thus, the intensity of its impact is the maximum of 10/10, which equates to a ratio of 1. The least severely impacting land-cover class scored a scaled score of 1 out of a possible 10, thereby being assigned an impact ratio of 1/10, or 0.1 (Table 20).

It was initially proposed that the results from the AHP be used in PLOAD, a programme described by its developers, the United States Environmental Protection Agency (2001) as "an ArcView GIS tool to calculate nonpoint sources of pollution in watershed and stormwater projects". Basically put, it is a model that uses GIS to calculate pollutant loads for watersheds, based on land-cover and land-use within the watershed. Output products include maps and tables reflecting total pollutant loads by watershed, pollutant loads per acre by watershed, or event mean concentrations (EMC) by watershed. The idea was to determine pollutant loads into watersheds, which would serve as a reflection of the impact of surrounding land-cover classes on water quality. This approach was decided against after further investigation, as the data required for the method was found to be more readily available for land-cover classes prevalent in the United States of America. The process of using the results from the AHP to adjust Event Mean Concentration (EMC) and Export Coefficient values to suit South African conditions proved a greater task than it was worth as literature to support the adjustments to these values for South Africa was found to be extremely limited, and adjusting them by ratios derived from the AHP would not have sufficed. Furthermore, the successful utilisation of PLOAD requires that the user has to input many data types, and pollutant rates for urban and rural land use types are derived using different datasets.

Further exploration into the methodology that was eventually decided upon revealed that the process of integrating PLOAD into the determination of the impact of land-cover on water quality would have been an unnecessary and imprecise step, as in this case the required result was achieved without the superfluities of PLOAD.

5.3 **The Application of Catchment Scale Analysis**

The various aspects of data acquisition, mapping and data pre-processing were undertaken, and once mapping and overlaying the different land cover datasets had been completed, the areal extents of historical wetland, sub-catchments, and land-cover classes in the catchments and wetlands were calculated using GIS, as indicated in the attribute tables of each of the layers being considered (Figure 21). The relevant areal extents for each wetland and its corresponding sub-catchment were exported from the ArcMap attribute table into a Microsoft Excel spreadsheet.



FID	Shape *	OBJECTID	GRIDCODE	Shape_Leng	Shape_Area	Gri
0	Polygon	137	137	0.114	0.000437	
1	Polygon	141	141	0.08	0.000211	
2	Polygon	144	144	0.092	0.000344	
3	Polygon	145	145	0.16	0.000477	
4	Polygon	150	150	0.128	0.00035	
5	Polygon	152	152	0.108	0.000454	
6	Polygon	153	153	0.096	0.000289	
7	Polygon	156	156	0.072	0.000137	
8	Polygon	157	157	0.062	0.00013	
9	Polygon	158	158	0.106	0.000317	
10	Polygon	159	159	0.074	0.000167	
11	Polygon	160	160	0.028	0.000028	
12	Polygon	162	162	0.04	0.00004	
13	Polygon	163	163	0.074	0.000172	
14	Polygon	167	167	0.066	0.000117	
15	Polygon	169	169	0.07	0.000196	
16	Polygon	172	172	0.116	0.000359	
17	Polygon	173	173	0.16	0.000684	
18	Polygon	175	175	0.064	0.000108	

Figure 21. An example of an attribute table in ArcMap with arrow indicating area in km^2

Figure 22 shows the overlain layers analysed using the GIS. It should be noted that the grey areas in Figure 22 are not formal land-cover classes, but indicate that at the projected scale, the resolution of the land-cover grid is too high for the picture to display land-cover.

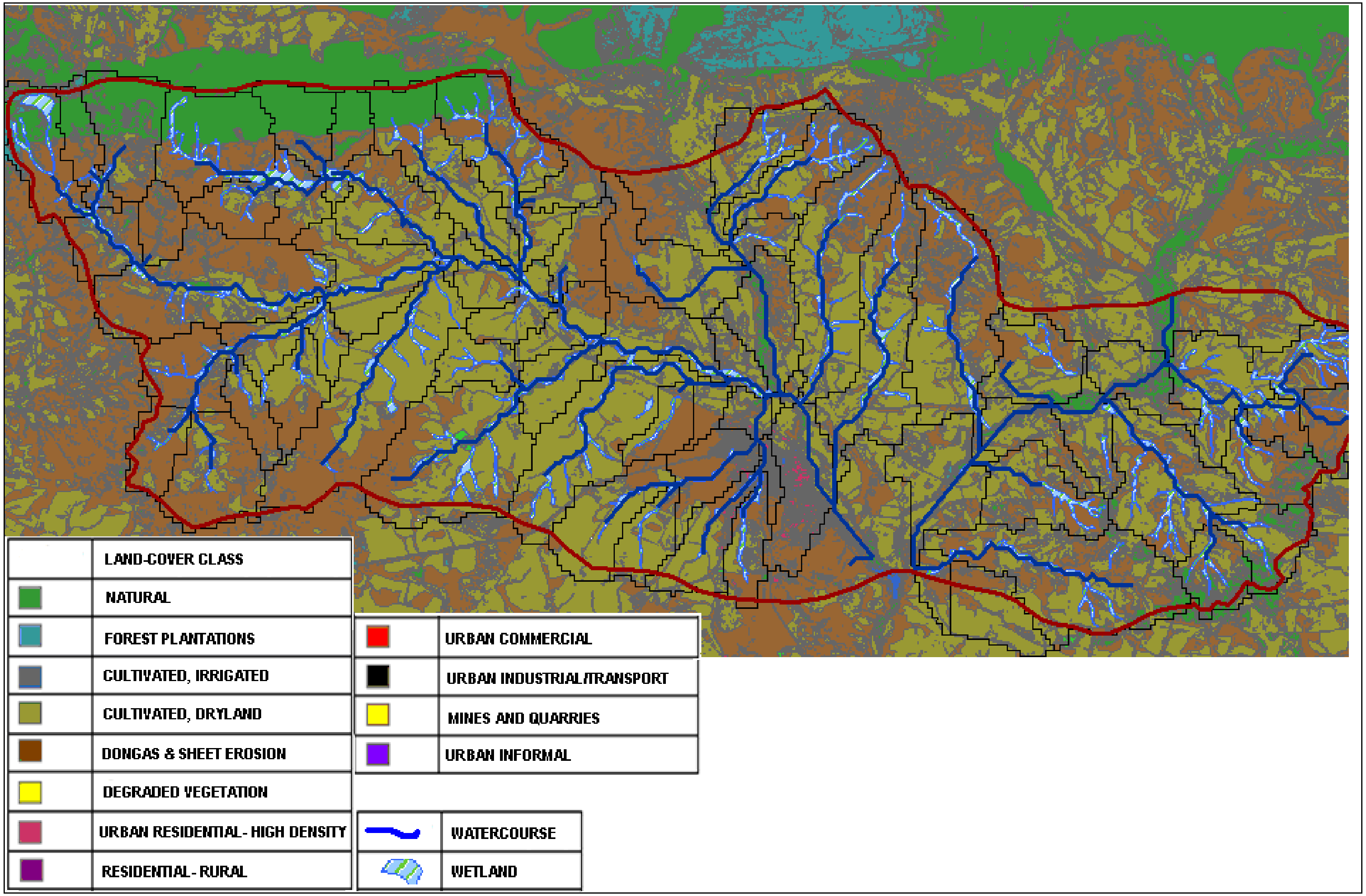


Figure 22. Mapped wetlands and their catchments

5.3.1 Calculating the Magnitude of Impacts of Land-cover Change on Water Quality as Hectare Equivalents of Water Quality Enhancement

The tool developed by Ellery *et al.* (in review) describes the impact of land-cover change on wetland hydrological health, based on the understanding that different land-cover classes impact the hydrology of a wetland in different ways. These impacts on hydrological health in turn affect how effectively the wetland is able to provide a number of ecosystem services which include flood attenuation, stream flow regulation, sediment trapping, phosphate trapping, nitrate removal, and toxicant removal (Ellery *et al.*, in review). As was described in Section 2.3.1, a functional effectiveness score was generated, which is a measure of how effectively an impacted wetland is providing a particular ecosystem service. This functional effectiveness score then allows for the determination of functional hectare equivalents for each ecosystem service. Functional hectare equivalents of sediment trapping, nitrate removal, phosphate removal, and toxicant removal were calculated, and their mean was taken to represent water quality enhancement.

An early step in the application of Ellery *et al*.'s (in review) tool is the generation of a magnitude of impact score for each land-cover class for each impact for catchment and wetland impacts. As is described in Section 4.3.1, this was achieved by multiplying the relevant intensity of impact score to the extent of each land-cover class (Table 27) for both the wetlands and their sub-catchments for all of the wetlands under evaluation.

The total magnitude of impacts score for 'decreased water inputs' was then subtracted from the total for 'increased water inputs' in order to resolve the impact of catchment land use activities. As was described in Ellery *et al.* (in review, p45), this subtraction is necessary "simply because land use activities that increase water inputs offset those activities that reduce water inputs". According to Ellery *et al*. (in review), negative totals, e.g., -0.19, indicates that there is a net decrease in water inputs with a magnitude of impact of 0.19 on a scale of 0 (no magnitude of impact) to 10 (critically impacted). These specific impacts on wetland health affect the provision of ecosystem services, hence their incorporation in the tool developed by Ellery *et al*. (in review).

5.3.2 Calculating the Magnitude of Impacts of Land-cover Change on Ecosystem Services Relevant to Water Quality Enhancement

As was previously mentioned, the ecosystem services that were singled out as being directly relevant to water quality enhancement included sediment trapping, nitrate removal, phosphate removal, and toxicant removal. The functional effectiveness and hectare equivalents of each of these ecosystem services for each wetland in the Goukou Catchment were therefore determined.

5.3.2.1 Catchment Impacts

After having determined the net increase or net decrease in water inputs for each wetland, it became possible to consider the effect of each individual impact on the provision of ecosystem services. This was achieved by applying the relevant equation for impacts arising in the wetland's catchment (catchment impacts) to the magnitude of impact score, from Table 6 or Table 7. As was described in Section 2.3 and in detail in Section 3 of Ellery *et al*. (in review), these equations are representative of the relationships between specific impacts (such as decreased water input) and how effectively an ecosystem service is being delivered by the wetland, which varies according to HGM type. The application of each equation results in a functionality score for the ecosystem service under evaluation.

These functionality scores were determined for each of the 49 wetlands examined (Table 28, Table 31, Table 34, and Table 37 in Appendix B).

5.3.2.2 Onsite Impacts

As was described in Section 4.3.1.2, the impacts of land use activities within wetlands were translated to magnitude of impact scores with respect to increased water use, reduced surface roughness, flow impediment, and the effect of drains or gullies. Equations from Tables 8, 9, 10, and 11 were used to determine functional effectiveness score for each ecosystem service based on impacts arising within the wetland. In the case of a wetland experiencing more than one onsite impact, impacts were resolved through consultation with Table 12.

The final onsite functional effectiveness scores for each of the four ecosystem services for each of the 49 wetlands examined were determined in this way (Table 29, Table 32, Table 35, and Table 38).

5.3.2.3 Catchment and Onsite Impacts

Impacts arising in the wetland's catchment and impacts arising within the wetland were resolved through consultation with Table 11 as described in Section 4.3.1.3 for each of the 49 wetlands examined, resulting in final functional effectiveness scores (Table 30, Table 33, Table 36, and Table 39).

5.3.2.4 Calculating Functional Hectare Equivalents

The final step in the employment of Ellery *et al*. (in review) to calculate functional effectiveness and the subsequent hectare equivalents for each ecosystem service is described in Section 5 of Ellery *et al*. (in review):

Functional hectare equivalents = (final functional effectiveness score / 4) * size of wetland (ha).

As Ellery *et al.* (in review) describe (p54), "this equation applies as the functionality score (which is from 0 to 4) is divided by 4 to scale it between 0 and 1, and this is multiplied by the size of the wetland (in ha)". Final functional effectiveness scores and subsequent hectare equivalents of each ecosystem service for each wetland were determined (Table 30, Table 33, Table 36, and Table 39).

5.3.2.5 Determining Water Quality Enhancement Functionality

The tool developed by Ellery *et al.* (in review) does not directly account for the provision of water quality enhancement functionality by wetlands. The tool does, however, explore the ecosystem services of sediment trapping, nitrate removal, phosphate trapping, and toxicant removal. It has been established that wetlands greatly enhance the quality of the water passing through them by performing a combination of these ecosystem services (as discussed in Section 2.2.6).

As such, the functional effectiveness scores and hectare equivalents for each of these ecosystem services for each wetland were determined, and the mean of these values was taken to represent water quality enhancement functionality and hectare equivalents of water quality enhancement functionality (Table 40).

5.3.3 Calculating the Magnitude of Impacts of Land-cover Change on Water Quality as Hectare Equivalents of Water Quality Impairment

The application of the tool developed by Ellery *et al.* (in review) allowed for the determination of the functional effectiveness of the wetlands in the Goukou landscape, expressed as hectare equivalents of water quality enhancement. Given the overall desire herein to determine the cumulative impact of wetland and catchment degradation on surface water quality at a landscape level, it followed that an analogous step was the determination of the impact of land-cover change on water quality impairment, similarly expressed as hectare equivalents. “Pollution and impairment refer to a state of the water body and impairment of its integrity” (Novotny, 2003, p28).

By determining the extent to which water quality is being impaired by catchment land-cover, a semi-quantitative indication of the quality of the water entering each wetland may be gained. Similarly, the application of the tool developed by Ellery *et al.* (in review), allows for the determination of the effectiveness of each wetland at improving the quality of the water entering it. Essentially, by comparing each of these opposing values, one may be able to determine if the quality of the water leaving a wetland is being effectively enhanced by the wetland or not. A final step in the building of the picture of water quality at a landscape level was the integration of the spatial configuration of wetlands in the landscape. As was highlighted in Section 2.4.4, there is clearly a need to evaluate wetlands on a scale that incorporates their ability to improve water quality based on their connectivity to, and influence on, other surrounding wetlands. Their obvious interaction means that impacts that may seem insignificant when considered individually become major when considered collectively over time and space. By doing so, an idea may be gained of the water quality enhancement functionality of the catchment as a whole.

The steps described in Figure 13 were applied to the sub-catchment land-cover classes of the wetlands of the Goukou Catchment, and resultant hectare equivalents of water quality impairment were calculated, the results of which are presented in Table 41.

5.3.4 Calculating Overall Effectiveness of Water Quality Enhancement

As was previously described, by determining the extent to which water quality is being impaired by catchment land-cover, a semi-quantitative indication of the quality of the water entering each wetland may be gained. Similarly, the application of the tool developed by Ellery *et al.* (in review), allows for the determination of the effectiveness of each wetland at improving the quality of the water entering it. Essentially, by comparing each of these opposing values, one may be able to determine if the quality of the water leaving a wetland is being effectively enhanced by the wetland or not.

The calculation of overall effectiveness of water quality enhancement was based on a 3:1 ratio, meaning that 3 hectare equivalents of water quality enhancement would be required to "repair" 1 hectare equivalent of water quality impairment. Therefore, in order to calculate the overall effectiveness of water quality enhancement, the hectare equivalents of water quality impairment for each wetland were first multiplied by 3, the total of which was subtracted from the hectare equivalents of water quality enhancement for each wetland.

This 3:1 effectiveness ratio was applied to the 49 wetlands of the Goukou Catchment and the overall effectiveness of water quality enhancement for each wetland was subsequently determined (Table 42).

5.3.5 Integrating the Spatial Configurations of Wetlands in a Landscape in Catchment-scale Analyses

Through the application of the method of integrating the spatial configuration of the wetlands in the Goukou Catchment as described in Section 4.3.4, the overall effectiveness of the Goukou Catchment was found to be -6802.91 hectare equivalents of water quality enhancement effectiveness (Table 43), indicating that the water quality of the catchment is being impacted more severely than the wetlands in the catchment are able to provide water quality enhancement functionality. It should be pointed out, however, that only the valley-bottom wetlands were focused on in this study, and that further water quality enhancement would have also been provided by the hillslope seepage wetlands present and in the stream channel sections linking the wetlands as well as by natural terrestrial land located between any given pollution source and the stream channel.

Figure 24 depicts a map of the studied catchment and the location of various intensities of water quality impairment, based on the land-cover classes present. As was the case with Figure 23, the grey areas in Figure 24 are not formal land-cover classes, but indicate that at the projected scale, the resolution of the land-cover grid is too high for the picture to display land-cover.

5.4 **Rehabilitation of Wetlands of the Goukou Catchment**

Section 4.5 described the process of prioritisation and rehabilitation that was applied to the wetlands of the Goukou Catchment. Of the 49 wetlands of this quaternary catchment, 25 wetlands with the most negative overall water quality enhancement effectiveness scores were targeted for rehabilitation (just over half, such that in a real-world situation it may not be possible to rehabilitate all wetlands with a high magnitude of impact score). Within the catchments of these wetlands, cultivated, irrigated; cultivated, dryland; residential- rural; mines and quarries; and urban informal land-cover classes were hypothetically rehabilitated, by converting them to 'natural' land-cover. The process of determining hectare equivalents of water quality enhancement using the method developed by Ellery *et al*. (in review) was then undertaken, as was the process of determining hectare equivalents of water quality impairment. The newly determined water quality enhancement effectiveness scores, along with those effectiveness scores for wetlands that were unchanged, were then applied to the wetlands of the Goukou Catchment and the wetlands were arranged in order of inflow so as to integrate the spatial configuration of the wetlands in the catchment.

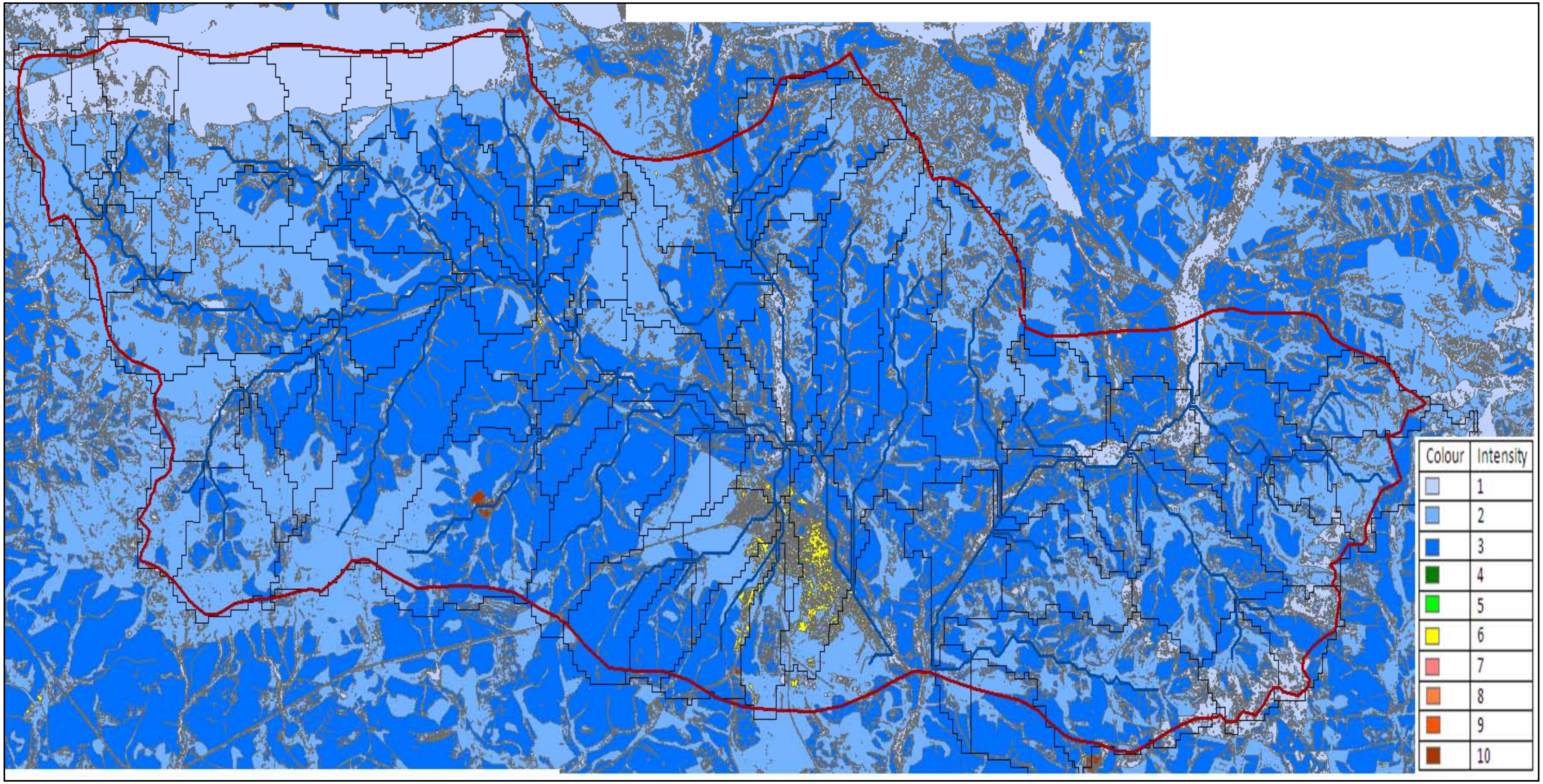


Figure 23. Image of Goukou Catchment depicting location of pollution sources, with colours depicting the intensity of impact on water quality

Prior to rehabilitation, the overall effectiveness of the Goukou Catchment was found to be -6802.91 hectare equivalents of water quality enhancement effectiveness, as was determined in Section 5.3. After prioritising just over half of the wetlands in the catchment based on their overall water quality enhancement effectiveness scores, and thereafter rehabilitating land-cover in the way described above, the overall effectiveness of the Goukou Catchment improved to -3720.91 (Tables 60 to 63). This score indicates that while water quality impairment is not being fully assimilated by the wetlands in the catchment, rehabilitation undoubtedly offers an improvement in the quality of the water leaving the catchment. As was pointed out pre-rehabilitation, it should be noted that only the valley-bottom wetlands were focused on in this study, and that further water quality enhancement would have also been provided by the hillslope seepage wetlands present and in the stream channel sections linking the wetlands.

5.5 **Benefits and Limitations of the Methodology**

The proposed methodology to determine the cumulative effect of wetland degradation on water quality at a landscape scale allows for a number of previously inadequately explored issues, such as the effect of wetland health on water quality enhancement, the effect of land-cover on wetland water quality, and the cumulative effects of wetland degradation on water quality, especially in a South African context; to be integrated into an all-encompassing tool that ultimately allows for prioritisation of wetlands to be undertaken, given a landscape scenario. Given the fact that wetlands generally do not function in isolation, such a tool allows for wetland managers to address conservation and rehabilitation measures in a way that is more suitable to the context of the wetland.

Despite having attempted to address the objectives highlighted in Chapter One, limitations were encountered, the addressing of which moved beyond the scope of this research.

In determining the effect of land-cover on water quality, the criteria upon which the effects were based were fairly simplistic. The effects of differences in climate, geologic materials, specific vegetation cover, terrain, precipitation, and soil hazard rating for example, were not considered. These factors tend to influence the quantity of pollutants that may enter a waterbody (Green *et al*., 1995). As an example, Green *et al*. (1995) highlight the fact that the effects of forest harvesting on water quality will vary spatially because of these factors. It is explained that the diversity of operations and conditions results in different areas being sensitive to forest practices in different ways, and that it is probable that no area is sensitive to all possible negative practices.

Assumptions were also undoubtedly made by the individuals involved with the AHP when determining the effect of each land-cover class on water quality. For example, it should be noted that the effects of land that is significantly degraded down to bedrock might be either positive or negative. In the case of the former, such degradation would imply that there is less sediment being released into the fluvial system; while the negative impact (which is likely assumed) is that degradation to bedrock would accelerate the flow of runoff. Similarly, dongas are not necessarily un-vegetated, and since it is difficult to ascertain exactly what assumptions guided the choices made by the individuals who participated in the AHP, the ratios should be used bearing these issues in mind.

Furthermore, the level of water quality enhancement was not specifically stipulated in this research. While the criteria for water quality for human consumption were qualitatively considered in the AHP, it cannot be determined whether the quality of the water leaving a wetland, had it been completely enhanced by the wetland, would be suitable for agricultural purposes, or for human consumption, for example.

A further limitation is that the sections of stream channel linking the wetlands and the land-cover surrounding those sections are not included in the methodology presented in this study. The land-cover surrounding these stream channel sections contribute pollutants that sometimes enter the stream in a section out of a designated catchment, and these pollutants are therefore unaccounted for in analyses. Furthermore, the water quality enhancement function provided by these stream channels is also not considered in this study, nor is natural terrestrial land located between any given pollution source and the stream channel.

Such water quality enhancement would also undoubtedly be provided by other wetland types that aren't explored in this study or by Ellery *et al*. (in review). As a result, many wetlands which do enhance water quality are left out of catchment analyses. Only valley-bottom wetlands were focused on in this study, and further water quality enhancement would have also been provided by the hillslope seepage wetlands present in the Goukou Catchment.

In proposing criteria for prioritisation, limitations were encountered in using wetland degradation and onsite rehabilitation as a criterion. Given the current available data and scope of this research, it was not possible to accurately predict the effect that onsite rehabilitation will have on the intensity of impact scores, especially since all the scores are currently solely land-cover based. General assumptions were made to alter the intensity of impact scores, which may therefore not be an accurate reflection of the positive effect that onsite rehabilitation may have on the effectiveness of water quality enhancement by each wetland.

An additional limitation is that the methodology developed in this research was not applied to catchments with good water quality data, in order to validate the outputs of the model against actual long term water quality data from the catchment/s.

5.6 **Summary**

In an attempt to address the gaps in knowledge and research mentioned in Chapter One, this study aimed to develop a method to determine the cumulative impact of wetland degradation on water quality, achieved by the development of a model that allowed for the exploration and integration of a number of issues, including land-cover and its effect on water quality, wetland health and its effect on the provision of ecosystem services such as water quality enhancement, and the spatial configuration of wetlands in a landscape and their effect on water quality at a broad, landscape scale. An Analytical Hierarchical Approach (AHP) allowed for the integration of expert opinion in determining the effect of land-cover on water quality, while the integration of the tool developed by Ellery *et al.* (in review) allowed for wetland health to be factored into the methodology.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

The ecosystem services provided by wetlands are numerous and varied. From flood control and stream flow maintenance, to their role as habitats for fauna and flora, wetlands are invaluable in providing services that benefit humankind (Kotze and Breen, 1994). Water quality enhancement and maintenance is just one of these benefits, and has been highlighted as an area of concern in water-scarce South Africa (Swanepoel and Barnard, 2007).

Despite the services that wetlands provide, rapid development and population growth have resulted in the degradation or loss of vast expanses of wetland area, both in South Africa and abroad (Swanepoel and Barnard, 2007; Millennium Ecosystem Assessment, 2005). These losses have inadvertently affected the abilities of wetland to provide the benefit of water quality enhancement, and have highlighted the necessity to address the issues associated with wetland degradation and its effect on water quality.

Such issues include the fact that most wetland analyses consider wetlands acting in isolation, despite suggestive evidence that wetlands are connected and influence each other considerably, and that therefore the entire catchment should be managed in wetland conservation (Swanepoel and Barnard, 2007; Bedford and Preston, 1988). The consideration of these cumulative impacts entails further investigation into the influence of surrounding land-cover, wetland connectivity, and wetland positions in the landscape. The complexities of these issues have stifled the progress necessary to address them, and gaps in research and the unavailability of tools to address such issues were apparent.

With the aim to develop a tool to account for the catchment context of wetlands in assessing the cumulative effect of wetland and catchment degradation on water quality, steps undertaken allowed for the consideration of the impact of different catchment land-cover classes on the water quality delivered to wetlands; the incorporation of a metric that allowed for the consideration of the health of each wetland and its subsequent ability to enhance water quality; as well as the spatial configuration of wetlands in a landscape context and the role of wetland position in influencing overall catchment water quality. The results of the application of the steps developed allow for the user to prioritise wetlands for rehabilitation and conservation, which was reflected in the application of the tool to the Goukou Catchment case study.

Benefits of the tool that were brought to light included that many previously inadequately explored issues, such as the effect of wetland health on water quality enhancement, the effect of land-cover on wetland water quality, and the cumulative effects of wetland degradation on water quality; were integrated into a single tool that allows for prioritisation of wetlands for rehabilitation and conservation. This was achieved with South African contexts in mind.

As with the development of any new tool, limitations were encountered during the development and application processes, one of which was the poor response by potential participants of the Analytical Hierarchical Process. Of the more than 20 questionnaires distributed, only 3 participants responded, thereby limiting the accuracy of the results to an extent. Furthermore, there were detailed aspects that were identified which would have further enhanced the accuracy of the tool, such as the effects of differences in climate, geologic materials, specific vegetation cover, terrain, precipitation, and soil hazard rating for example; and the level of water quality enhancement.

It was also pointed out that the sections of stream channel linking the wetlands and the land-cover surrounding those sections; as well as wetland types other than floodplains and valley-bottoms, are not included in the methodology presented in this study. These aspects could be included in a more refined model which includes other areas with the capacity to assimilate pollutants, such as hillslope wetlands, riparian areas, and natural terrestrial areas. These aspects are likely to improve the accuracy of the model. Furthermore, the methodology developed in this research was not validated against empirical water quality data from catchments with good long term water quality data. Such an exercise would undoubtedly improve the validity of the methodology, and would bring to light further adjustments necessary for improving the model.

A final limitation that was acknowledged was that in proposing criteria for prioritisation, limitations were encountered in using wetland degradation and onsite rehabilitation as a criterion. Given the current available data and scope of this research, it was not possible to accurately predict the effect that onsite rehabilitation will have on the intensity of impact scores, especially since all the scores are currently solely land-cover based. General assumptions were made to alter the intensity of impact scores, which may therefore not be an accurate reflection of the positive effect that onsite rehabilitation may have on the effectiveness of water quality enhancement by each wetland.

These limitations allow for the improvements to be made in future research endeavours. Aside from addressing the above-mentioned limitations, it may be beneficial to analyse the land-cover classes in greater detail. For example, the land-cover class ‘natural’ in this study is inclusive of grasslands, sand, soil, and even rock, even though their contributions to water quality impairment may be immensely different.

Given that the tool has been developed to be applicable to South African landscapes, considering cultural matters may also be beneficial in future developments. In prioritising wetlands, it may not always be very easy to rehabilitate the wetlands identified as most feasible for rehabilitation. For example, one should consider that “grazing practices are...deeply enmeshed in human behaviour patterns and are bounded by land tenure traditions, so that improvements in land use are usually slow and difficult to secure” (Pereira, 1973, p182). Incorporating these aspects into such a tool will be challenging, but likely very beneficial.

In light of the limitations identified and the recommendations made, there are three key elements to further developing the research conducted herein. The first of these is to refine the system by accounting for factors not included in the current methodology, such as the inclusion of other areas with the capacity to assimilate pollutants, such as hillslope wetlands and other wetland types, riparian areas, stream channels, and natural terrestrial areas; the inclusion of the effects of differences in climate, geologic materials, specific vegetation cover, terrain, precipitation, and soil hazard rating; as well as the level of water quality enhancement determined. Furthermore, the current methodology does not take into account the spatial location of the different land-cover classes within a catchment, so a useful addition would be a component that adjusts the impact that a land-cover class of a given extent in a wetland’s upstream catchment has upon the wetland based on the spatial location of the land-cover class within the wetland’s upstream catchment.

Secondly, once a more refined model is developed, system should be validated against empirical water quality data from catchments with good long term water quality data. Based upon the results of the validation, necessary further adjustments can be identified and implemented.

Finally, the ease of use of the system can be improved through the creation of software, which would most certainly be useful to wetland scientists, conservationists and planners alike. Software based upon cumulative effects concepts would most certainly be useful to wetland scientists, conservationists and planners alike. The process of doing so is both long and detailed, but not difficult given the correct expertise, and involves programming, automating, Graphical User Interface (GUI) development, and the eventual creation of software. Processing tools include the widely used ArcGIS, MS Word, MS Access, MS Excel, and Adobe InDesign or a similar graphical tool (Mead and Morse, date unknown).

The process of GIS automation begins with development of a model. Data inputs and desired results must be identified, as well as the steps that will allow the user to go from starting data to finished data (Mead and Morse, date unknown). These steps may then allow for the construction of an actual model in Model Builder in ArcGIS. The development of user-defined buttons and tools that allow for the steps to be taken to reach the desired end result may then take place, or the development of an application that may be used in another GIS application, such that information is shared between them (Mahrer, date unknown). The product of such automation is usually in the form of a Graphical User Interface (GUI), an interactive interface on computers that allows the user to use the programme via graphical components (Bishop and Horspool, 2004), as opposed to text and keyboard commands that were previously used to achieve a desired result (TechTarget, 2008). The elements of a GUI include windows, menu bars, pull-down menus, scroll bars, and buttons, each of which is encoded with a method to respond to user stimuli. The automated product may then be tested and reviewed and eventually presented as a product in the form of software.

A final thought on the applicability of a tool that considers landscape-level impacts is legislation, or the lack thereof in South Africa. This study shed light on the fact that the consideration of cumulative wetland impacts, as opposed to the analysis of wetlands at an individual site scale, is imperative in effectively conserving wetlands and wetland ecosystem services. Despite the importance of this, South African legislation does not dictate that cumulative impact issues need to be considered. Legislation was found to be unclear, and lacking in the protection of the total water system, including surface, subsurface, and the interlinkages between water systems affecting recharge (Swanepoel and Barnard, 2007).

REFERENCES

Adbio. (2007). *Water Analysis- Total Suspended Solids* [on-line], BioWorld Products, http://www.adbio.com/science/analysis/tss.htm, Accessed 12 July 2009.

Ashton, P.J. and Bhagwan, J.N. (2001). *Guidelines for the Appropriate Management of Urban Runoff in South Africa*, Integrated Report, WRC Report No. TT 155/01, Water Research Commission, Pretoria.

Barnes, K. (2006). Personal communication, March 2006, Durban.

Bedford, B.L. and Preston, E.M. (1988). Evaluating cumulative effects on wetland functions: A conceptual overview and generic framework, *Environmental Management* 12(5): 565-583.

Begg, G. (1990). *Policy Proposals for the Wetlands of Natal and KwaZulu*, The Natal Town and Regional Planning Commission, Pietermaritzburg.

Bergstrom, J.C., Boyle, K.J. and Poe, G.L. (2001). Economic value of water quality: introduction and conceptual background, In Bergstrom, J.C., Boyle, K.J. and Poe, G.L. (Eds), *The Economic Value of Water Quality*, Edward Elgar Publishing, Inc., U.K.

Bishop, J. and Horspool, N. (2004). *Developing principles of GUI programming using views*, SIGCSE, USA.

Campbell, J.B. (2002). *Introduction to Remote Sensing*, 3rd Edition, The Guildford Press, USA.

Carter, R.A. and Brownlie, S. (1990). Estuaries of the Cape Part 2: Synopses of Available Information on Individual Systems, In Heydorn, A.E.F. and Morant, P.D. (Eds), *Report No. 34, Kaffersuils (CSW 24) and Duiwenhoks (CSW 23)*, CSIR Research Report 433, Stellenbosch.

Chiew, F.H.S. and Vase, J. (2003). Study of pollutant wash-off from small impervious experimental plots, *Water Resources Research* 39 (6): 1160.

Coastal CRC. (2005). *Manual for Decision-making with Decision Analyst,* Queensland Government.

Coetzee, M.A.S. (1995). *Water Pollution in South Africa: its impact on wetland biota*, Publisher unknown, South Africa.

Congalton, R.G. and Green, K. (1995). The ABCs of GIS: An Introduction to Geographic Information Systems, In Lyon, J.G. and McCarthy, J. (Eds), *Wetland and Environmental Applications of GIS*, Lewis Publishers, USA.

Conrad, J.E., Colvin, C., Sililo, O., Görgens, A., Weaver, J. and Reinhardt, C. (1999). *Assessment of the Impact of Agricultural Practices on the Quality of Groundwater Resources in South Africa*, Report to the Water Research Commission, South Africa.

Correll, D. (1999). *Vegetated stream riparian zones: their effect on stream nutrients, sediments, and toxic substances*, Smithsonian Environmental Research Centre, Maryland, U.S.A.

Cowan, G.I. (1995). *Wetland Regions of South Africa*, Publisher unknown, South Africa.

Dallas, H.F., Day, J.A., and Reynolds, E.G. (1994). *The effects of water quality variables on riverine biotas*, Report to the Water Research Commission, Cape Town.

Davies, B. and Day, J. (1998). *Vanishing Waters*, University of Cape Town Press, Cape Town, South Africa.

Davis, B.E. (2001). *GIS: A Visual Approach*, Onword Press, Canada.

Department of Environmental Affairs and Tourism. (2000). *Environmental Potential Atlas for the Western Cape, Generalised Soil Description*, University of Pretoria and GIS Business Solutions.

Department of Environmental Affairs and Tourism. (2006). *South Africa Environment Outlook, A Report on the state of the environment*, DEAT, Pretoria.

Department of Environmental Affairs and Tourism. (2008). *Land-Cover Classification* [on-line], DEAT, www.environment.gov.za, Accessed 13 May 2008.

Department of Water Affairs and Forestry. (2005a). *A Drinking Water Quality Framework for South Africa*, DWAF, South Africa.

Department of Water Affairs and Forestry. (2005b). *Proposal for the establishment of the Gouritz Catchment Management Agency*, DWAF.

Department of Water Affairs and Forestry. (2005c). *A Practical Field Procedure for Identification and Delineation of Wetlands and Riparian Areas*, DWAF, Pretoria, South Africa.

Dube, M., Johnson, B., Dunn, G., Culp, J., Cash, K., Munkittrick, K., Wong, I., Hedley, K., Booty, W., Lam, D., Resler, O. And Storey, A. (2006). Development of a New Approach to Cumulative Effects Assessment: A Northern River Ecosystem Example, *Environmental Monitoring and Assessment* (2006) 113: 87-115.

Ehrenfeld, J.G. (2000). Evaluating wetlands within an urban context, *Ecological Engineering* 15: 253-265.

Ellery, W.N. (2006). *Wetland Ecology and Management Honours Course Notes*, University of KwaZulu-Natal, Durban.

Ellery, W.N. (2008). Personal communication, January 2008, Durban.

Ellery, W.N., Grenfell, S.E., Grenfell, M.C., Jaganath, C., Malan, H. and Kotze, D.C. (in review). *A Method for Assessing the Cumulative Impacts on Wetland Functions at the Catchment or Landscape Scale*, in review.

Ellery, W.N., Kotze, D.C., McCarthy, T.S., Tooth, S., Grenfell, M., Beckedahl, H., Quinn, N. and Ramsay, L. (2005). *The Origin and Evolution of Wetlands*, Water Research Commission Wetlands Research Programme: Wetland Rehabilitation, South Africa.

Farrimond, M.S. (1980). Impact of Man in Catchments (iii) Domestic and Industrial Wastes, In Gower, A.M. (Ed), *Water Quality in Catchment Ecosystems*, John Wiley & Sons, U.K.

Fisher, J. and Acreman, M.C. (2004). Wetland nutrient removal: a review of the evidence, *Hydrology and Earth System Sciences*, 8 (4): 673-685.

Forman, E. (1997). *Decision by Objectives*, Unpublished virtual book, ExpertChoice.

Forman, E.H. and Gass, S.I. (2001). The Analytic Hierarchy Process: An Exposition, *Operations Research*, 49 (4): 469-486.

Forman, E. and Peniwati, K. (1998). Aggregating Individual Judgements and Priorities with the Analytic Hierarchy Process, *European Journal of Operational Research* 108: 165-169.

Gasser, J.K.R. (1980). Impact of Man in Catchments (i) Agriculture, In Gower, A.M. (Ed), *Water Quality in Catchment Ecosystems*, John Wiley & Sons, U.K.

Goudie, A.S. (2000). *The Scientific Significance of Landuse and Land-cover Changes* [on-line], LUCC Science Plan, http://www.geo.ucl.ac.be/LUCC/publications/reportseries/series1/lucc.html, Accessed 18 August 2006.

Green, K., Bernath, S., Lackey, L., Brunengo, M. and Smith, S. (1995). Analyzing the Cumulative Effects of Forest Practices: Where do we start?, In Lyon, J.G. and McCarthy, J. (Eds), *Wetland and Environmental Applications of GIS*, Lewis Publishers, USA.

Grenfell, M.C., Ellery, W.N., Garden, S.E. and van der Walk, A.G. (2007). The Language of Intervention: a South African Perspective on Wetland Rehabilitation Terminology, *WaterSA* 33: 43-50..

Hamlett, J., Mertz, T. and Petersen, G. (1995). GIS Targets Agricultural Nonpoint Source Pollution, In Lyon, J.G. and McCarthy, J. (Eds), *Wetland and Environmental Applications of GIS*, Lewis Publishers, USA.

Hounslow, A.W. (1995). *Water quality data: analysis and interpretation*, CRC Press, Inc., U.S.A.

Ji, W. and Mitchell, L.C. (1995). Analytical Model-Based Decision Support GIS for Wetland Resource Management, In Lyon, J.G. and McCarthy, J. (Eds), *Wetland and Environmental Applications of GIS*, Lewis Publishers, USA.

Johnston, C.A. (1994). Cumulative impacts to wetlands, *Wetlands* 14(1): 49-55.

Johnston, C.A., Detenbeck, N.E. and Niemi, G.J. (1990). The cumulative effect of wetlands on stream water quality and quantity. A landscape approach, *Biogeochemistry* (10): 105-141.

Keddy, P.A. (2000). *Wetland Ecology Principles and Conservation*, Cambridge University Press, UK.

Ketterings, Q., Reid, S. and Rao, R. (2007). *Cation Exchange Capacity (CEC)* [on-line], Cornell University Cooperative Extension, http://nmsp.css.cornell.edu/publications/factsheets/factsheet22.pdf, Accessed 25 August 2008.

Kotze, D.C. (1996). *Wetlands and people: what values do wetlands have for us and how are these values affected by our land-use activities? WETLAND-USE Booklet 1.* SHARE-NET, Wildlife and Environment Society of South Africa, Howick.

Kotze, D.C. (1999) *A system for supporting wetland management decisions*, Unpublished PhD Thesis, University of Natal, Pietermaritzburg.

Kotze, D.C. (2009). Personal communication, September 2009.

Kotze, D.C. and Breen, C.M. (1994). *Agricultural Land-use Impacts on Wetland Functional Values*, Report to the Water Research Commission, South Africa.

Kotze, D.C., Hughes, J.C., Breen, C.M. and Klug, J.R. (1994). *The Development of a Wetland Soils Classification System for KwaZulu-Natal*, Report to the Water Research Commission, South Africa.

Kotze, D.C., Marneweck, G.C., Batchelor, A.L., Lindley, D.S. and Collins, N.B. (2007). *WET-EcoServices: A technique for rapidly assessing ecosystem services supplied by wetlands*, WRC Report No TT 339/08, Water Research Commission, Pretoria.

Lin, J.P. (2004). *Review of Published Export Coefficient and Event Mean Concentration (EMC) Data*, ERDC TN-WRAP-04-03.

Lumsden, T.G., Jewitt, G.P.W. and Schulze, R.E. (2003). *Modelling the Impacts of Land Cover and Land Management Practices on Runoff Responses*, Water Research Commission, Pretoria.

Lyon, J.G. and McCarthy, J. (1995). *Wetland and Environmental Applications of GIS*, Lewis Publishers, USA.

Macfarlane, D.M., Kotze, D.C., Ellery, W.N., Walters, D., Koopman, V., Goodman, P. and Goge, C. (2008). *WET-Health*, Water Research Commission Wetlands Research Programme: Wetland Rehabilitation, South Africa.

Mackenzie, J.A., van Coller, A.L. and Rogers, K.H. (1999). *Rule Based Modelling for Management of Riparian Systems*, Report to the Water Research Commission, South Africa.

Mahrer, J. (date unknown). *GIS: Integrating, Analyzing and Automating*, Powerpoint Presentation, usgweb.

Maplandia. (2005). *Riversdale Google Satellite Map* [on-line], Maplandia, http://www.maplandia.com/south-africa/western-cape/riversdale/, Accessed 14 November 2009.

McJannet, D. (2007). *Towards an understanding of the filter function of tropical wetlands*, CSIRO: Water for a Healthy Country National Research Flagship, Australia.

Mead, P. and Morse, C. (date unknown). *Rapid Watershed Assessments: GIS, Data, and Cartographic Elements*, Powerpoint Presentation, USDA.

Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-Being: Wetlands and Water Synthesis*, World Resources Institute, Washington D.C.

Mitsch, W.J. and Gosselink, J.G. (1993). *Wetlands*, Second Edition, Van Nostrum Reinhold, New York.

Mucina, L. and Rutherford, M.C. (2005). *Vegetation Map of South Africa*.

Nataraj, S. (2005). Analytic Hierarchy Process as a Decision-Support System in the Petroleum Pipeline Industry, *Issues in Information Systems,* Volume VI, No. 2.

Nelson, E.A., Specht, W.L., Bowers, J. A. and Gladden, J. B. (2003). *Constructed Wetlands for Removal of Heavy Metals from NPDES Outfall Effluent*, Westinghouse Savannah River Company, U.S.A.

Nkosi, M.R. (2006). *The Potential Effect of Wetland Rehabilitation on Wetland Ecosystem Goods and Services: An Investigation of Three South African Case Studies*, Masters Thesis, University of KwaZulu-Natal, Pietermaritzburg.

Novotny, V. (2003). *Water Quality: Diffuse Pollution and Watershed Management*, John Wiley & Sons, Inc., New York.

O'Callaghan, J.R. (1996). *Land use: The Interaction of Economics, Ecology and Hydrology*, Chapman & Hall, London.

Oellermann, R.G., Darroch, M.A.G., Klug, J.R. and Kotze, D.C. (1994). *Wetland Preservation Valuation, and Management Practices Applied to Wetlands: South African Case Studies*, Report to the Water Research Commission, South Africa.

Owusu-Asante, Y. And Stephenson, D. (2006). Estimation of storm runoff loads based on rainfall-related variables and power law models- Case study in Alexandra, *Water SA* (32) 2: 137-143.

Pereira, H.C. (1973). *Land Use and Water Resources in Temperate and Tropical Climates*, Cambridge University Press, Great Britain.

Pope, W. (1980). Impact of Man in Catchments (ii) Roads and Urbanization, In Gower, A.M. (Ed), *Water Quality in Catchment Ecosystems*, John Wiley & Sons, U.K.

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

Saaty, T.L. (1990). How To Make A Decision: The Analytic Hierarchy Process, *European Journal of Operational Research* 48: 9-26.

SAExplorer. (2008). *Riversdale Climate* [on-line], SA Explorer, http://www.saexplorer.co.za/south-africa/climate/riversdale_climate.asp, Accessed 14 November 2009.

Shamsi, U.M. (1995). Water Resource Engineering Application of Geographic Information Systems, In Lyon, J.G. and McCarthy, J. (Eds), *Wetland and Environmental Applications of GIS*, Lewis Publishers, USA.

Sheldon, D., Hruby, T., Johnson, P., Harper, K., McMillan, A., Granger, T., Stanley, S. and Stockdale, E. (2005). *Wetlands in Washington State- Volume 1: A Synthesis of the Science*, Washington State Department of Ecology, Olympia, W.A.

Snaddon, K., Job, N., Day, L., Nel, J. and Smith-Adao, L. (2007). *C.A.P.E. fine-scale planning project: Surface freshwater ecosystems, Methodology Report*, CSIR, South Africa.

Stewart, T.J., Joubert, A.R., Liu, D. (2001). *Group Decision Support Methods to Facilitate Participative Water Resource Management*, WRC Report No 863/1/01, South Africa.

Swanepoel, C.M. and Barnard, R.O. (2007). *Discussion Paper: Wetlands in Agriculture*, Report to the Water Research Commission, WRC Report No KV 193/07, South Arica.

TechTarget. (2008). *Windevelopment* [on-line], TechTarget, http://searchwindevelopment.techtarget.com/sDefinition/0,,sid8_gci213989,00.html, Accessed 5 January 2009.

Thompson, M. (1996). A standard land-cover classification scheme for remote-sensing applications in South Africa, *South African Journal of Science* 92: 34-42.

Tiner, R.W. (2002). *Watershed-based Wetland Planning and Evaluation, A Collection of Papers from the Wetland Millennium Event*, The Association of State Wetland Managers, Inc., Berne, New York.

Tiner, R.W. (2005). Assessing cumulative loss of wetland functions in the Nanticoke River Watershed using enhanced national wetlands inventory data, *Wetlands* 25(2): 405-419.

U.S.D.A. Soil Conservation Service. (1985). *Hydric Soils of the United States*, USDA-SCS, Washington D.C.

U.S. Corps of Engineer. (date unknown). *Strahler Number* [on-line], Wikipedia, http://en.wikipedia.org/wiki/Strahler_Stream_Order, Accessed 12 June 2009.

U.S. Environmental Protection Agency. (2001). *PLOAD version 3.0. An ArcView GIS Tool to Calculate Nonpoint Sources of Pollution in Watershed and Stormwater Projects*, U.S. Environmental Protection Agency, Place of publication unknown.

Vieux, B.E. (1995). DEM Aggregation and Smoothing Effects on Surface Runoff Modeling, In Lyon, J.G. and McCarthy, J. (Eds), *Wetland and Environmental Applications of GIS*, Lewis Publishers, USA.

Vlok, J.H.J. and de Villiers, M.E. (2007). *Vegetation map for the Riversdale domain*, Unpublished Report for CapeNature.

Vlok, W., Cook, C.L., Greenfield, R.G., Hoare, D., Victor, J. and van Vuren, J.H.J. (2006). *A Biophysical Framework for the Sustainable Management of Wetlands in the Limpopo Province with Nylsvley as a Reference Model*, Report to the Water Research Commission, South Africa.

Walling, D.E. (1980). Water in the Catchment Ecosystem, In Gower, A.M. (Ed), *Water Quality in Catchment Ecosystems*, John Wiley & Sons, U.K.

Water Research Commission. (2007). *Integrated Water Resource Management Plan Guidelines for Local Authorities*, WRC Report No. TT 304/07.

White, D. and Fennessy, S. (2005). Modeling the suitability of wetland restoration potential at the watershed scale, In *Wetland Creations, Restoration and Conservation: The State of Science*, Mitsch, W.J. (Ed), Elsevier B.V., Amsterdam.

The Wildlife Trusts Water Policy Team. (2001). *Wetland Restoration Manual: Version 1*, The Wildlife Trust.

Wimberley, F.R. (1992). *The Effect of Polluted Stormwater Runoff from Alexandra Township on the Water Quality of the Jukskei River*, MSc Thesis, University of the Witwatersrand, Johannesburg.

Wimberley, F.R. and Coleman, T.J. (1993). The effect of different urban development types on stormwater runoff quality: A comparison between two Johannesburg catchments, *Water SA* 19 (4): 325-330.

Woods, D.B. (1997). *Siting Artificial Water Points in Mkuzi Game Reserve Using GIS*, Masters Thesis, University of Natal.

Wu, J., Jenerette, G.D. and Davis, J.L. (2003). Linking Land-use Change with Ecosystem Processes: A Hierarchical Patch Dynamic Model, In Guhathakurta, S. (Ed), *Integrated Land Use and Environmental Models*, Springer, Berlin.

Yemane, M.M. (2003). *An Assessment of Changes in Land Use/Cover Patterns in the Albert Falls Area*, *KwaZulu-Natal*, *South Africa*, Unpublished MSc thesis, University of Natal, Pietermaritzburg.

APPENDIX A:

Land-cover Water Quality Questionnaire used in the Analytical Hierarchical Process

The Effects of Land-cover/land-use on Water Quality: A Pairwise Comparison

OBJECTIVE: To establish the impact of different catchment land-cover/land-use classes on the water quality delivered to wetlands.

ALTERNATIVES: 12 different land-cover/land-use (LCU) classes, numbered and described in Table 1.

CRITERIA: chemical quality (including total organic carbon, pH, disinfectant residuals, phosphate and nitrate concentrations, electrical conductivity, concentration of toxins), microbiological quality (including total coliforms, *E. coli*), and physical quality (turbidity, colour, taste and odour).

Step One: Consider each land-cover/land-use class described in Table 26, and to the best of your knowledge, assign a score for each of the above-mentioned criteria in terms of the severity of the impact of the LCU on them (you may add comments or the reasons for your opinion alongside the assigned score in the same column).

Severe Impact: 4; moderate impact: 3; low impact: 2; negligible impact: 1. These scores will assist in later making pair-wise comparisons of the different LCU classes.

In the example below, the participant believes the LCU ‘Degraded lands’ to moderately affect the chemical and microbiological quality of the water, and to severely impact the physical quality of the water in the catchment, the reasons for which are included in the relevant ‘Impact Score’ column.

LCU Code	Land-cover/land-use class	Description	Impact Score			
			Chemical Quality	Microbiological Quality	Physical Quality	Total
1	Degraded lands	Permanent or seasonal, man-induced areas of very low vegetation cover. Typically associated with subsistence level farming and rural population centres, where overgrazing of livestock and/or wood-resource removal has been excessive. Often associated with severe soil erosion problems.	3-fertilizer inputs and livestock grazing in nearby communities may impact chemical quality.	3-nearby communities & livestock may affect microbiological quality through input of fertilizers and faecal contaminants.	4-likely to be the most severe impact due to erosion of soil. Increased sedimentation is likely to cause turbidity etc.	10

Table 1 follows.

Table 1. Land-cover impact table

LCU Code	Land-cover/land use Class	Description	Impact Score			
			Chemical Quality	Microbiological Quality	Physical Quality	Total
1	Natural	All areas of vegetation grown under natural or semi-natural conditions, including forest, woodland, thicket, scrub forest, bushland, high Fynbos, shrubland, low Fynbos, herbland, and unimproved grassland; as well as natural areas of exposed sand, soil or rock.				
2	Improved grassland	Planted grassland, containing either indigenous or exotic species, growing under man-managed conditions for grazing, hay or turf production, and recreation (e.g. golf courses).				
3	Forest plantations	Areas of systematically planted, man-managed tree resources, composed of primarily exotic species (e.g. pine, eucalyptus, wattle). No input of fertilizer is assumed.				
4	Cultivated: commercial	Lands cultivated with crops for commercial purposes. Crops may occupy the area for long periods and are not replaced after harvest (such as tea, sugar cane, citrus orchards, vineyards, hops and nuts), or temporarily, whereby crops are harvested at the completion of the growing season, and land remains idle until replanted (such as maize, wheat, legumes, potatoes and onions).				
5	Cultivated: subsistence	Lands cultivated with crops for subsistence purposes. Crops are harvested at the completion of the growing season and land remains idle until replanted.				
6	Dongas and sheet erosion scars	Gullies and channels, and permanent or seasonal areas of very low vegetation cover in comparison with surrounding natural vegetation cover, induced by the gradual removal of soil and soft rock due to concentrated runoff.				
LCU Code	**Land-cover/land use Class**	**Description**	**Impact Score**			
			Chemical Quality	**Microbiological Quality**	**Physical Quality**	**Total**
7	Degraded: other	Permanent or seasonal, man-induced areas of very low vegetation cover in comparison with the surrounding natural vegetation cover. Typically associated with subsistence level farming and rural population centres, where overgrazing of livestock and/or wood-resource removal has been excessive. Often associated with severe soil erosion problems.				
8	Residential: rural	Areas in which people reside on a permanent or near-permanent basis in informal or formal settlement areas, with low building densities.				
9	Urban: formal	Areas in which people reside on a permanent or near-permanent basis in formal settlement areas, ranging from high to low building densities; as well as non-residential areas used primarily for the conduct of commerce and other mercantile business (commercial).				
10	Urban: Industrial/transport	Non-residential areas with major industrial or transport related infrastructure. Examples include power stations, steel mills, dockyards and airports.				
11	Mines and quarries	Areas in which mining activity has been done or is being done. Includes opencast mines and quarries as well as surface infrastructure (mine dumps, etc.) associated with underground mining activities. No rehabilitation is assumed.				

Step Two: Make pair-wise comparisons of the different land-cover classes. Compare each land-cover class with every other land-cover class. Numerical scores may then be generated from these qualitative assessments using the weight table shown.

COMPARITIVE JUDGEMENT	ASSOCIATED WEIGHT
Extremely less severe	1/9
Slightly less severe	1/3
Equally severe	1
Slightly more severe	3
Extremely more severe	9

Describe how the first factor (land-cover/land-use class) compares with the second, taking the criteria into consideration. Fill in the gap with a weighting from the table above.

Land-cover Class 1: Natural

Q1. The effect of LCU 1 on water quality is _____________ severe than LCU 2.

Q2. The effect of LCU 1 on water quality is _____________ severe than LCU 3.

Q3. The effect of LCU 1 on water quality is _____________ severe than LCU 4.

Q4. The effect of LCU 1 on water quality is _____________ severe than LCU 5.

Q5. The effect of LCU 1 on water quality is _____________ severe than LCU 6.

Q6. The effect of LCU 1 on water quality is _____________ severe than LCU 7.

Q7. The effect of LCU 1 on water quality is _____________ severe than LCU 8.

Q8. The effect of LCU 1 on water quality is _____________severe than LCU 9.

Q9. The effect of LCU 1 on water quality is _____________severe than LCU 10.

Q10. The effect of LCU 1 on water quality is _____________severe than LCU 11.

Q11. The effect of LCU 1 on water quality is _____________severe than LCU 12.

Land-cover Class 2: Improved Grassland

Q12. The effect of LCU 2 on water quality is _____________ severe than LCU 3.

Q13. The effect of LCU 2 on water quality is _____________ severe than LCU 4.

Q14. The effect of LCU 2 on water quality is _____________severe than LCU 5.

Q15. The effect of LCU 2 on water quality is ____________severe than LCU 6.

Q16. The effect of LCU 2 on water quality is ____________severe than LCU 7.

Q17. The effect of LCU 2 on water quality is ____________severe than LCU 8.

Q18. The effect of LCU 2 on water quality is ____________severe than LCU 9.

Q19. The effect of LCU 2 on water quality is ____________severe than LCU 10.

Q20. The effect of LCU 2 on water quality is ____________severe than LCU 11.

Q21. The effect of LCU 2 on water quality is ____________severe than LCU 12.

<u>Land-cover Class 3:</u> Forest Plantations

Q22. The effect of LCU 3 on water quality is ____________severe than LCU 4.

Q23. The effect of LCU 3 on water quality is ____________severe than LCU 5.

Q24. The effect of LCU 3 on water quality is ____________severe than LCU 6.

Q25. The effect of LCU 3 on water quality is ____________severe than LCU 7.

Q26. The effect of LCU 3 on water quality is ____________severe than LCU 8.

Q27. The effect of LCU 3 on water quality is ____________severe than LCU 9.

Q28. The effect of LCU 3 on water quality is ____________severe than LCU 10.

Q29. The effect of LCU 3 on water quality is ____________severe than LCU 11.

Q30. The effect of LCU 3 on water quality is ____________severe than LCU 12.

<u>Land-cover Class 4:</u> Cultivated: commercial

Q31. The effect of LCU 4 on water quality is ____________severe than LCU 5.

Q32. The effect of LCU 4 on water quality is ____________severe than LCU 6.

Q33. The effect of LCU 4 on water quality is ____________severe than LCU 7.

Q34. The effect of LCU 4 on water quality is ____________severe than LCU 8.

Q35. The effect of LCU 4on water quality is ____________severe than LCU 9.

Q36. The effect of LCU 4 on water quality is ____________severe than LCU 10.

Q37. The effect of LCU 4 on water quality is ____________severe than LCU 11.

Q38. The effect of LCU 4 on water quality is ____________severe than LCU 12.

<u>Land-cover Class 5:</u> Cultivated: subsistence

Q39. The effect of LCU 5 on water quality is ____________severe than LCU 6.

Q40. The effect of LCU 5 on water quality is ____________severe than LCU 7.

Q41. The effect of LCU 5 on water quality is ____________severe than LCU 8.

Q42. The effect of LCU 5 on water quality is ____________severe than LCU 9.

Q43. The effect of LCU 5 on water quality is ____________severe than LCU 10.

Q44. The effect of LCU 5 on water quality is ____________severe than LCU 11.

Q45. The effect of LCU 5 on water quality is ____________severe than LCU 12.

<u>Land-cover Class 6:</u> Dongas and sheet erosion scars

Q42. The effect of LCU 6 on water quality is ____________severe than LCU 7.

Q43. The effect of LCU 6 on water quality is ____________severe than LCU 8.

Q44. The effect of LCU 6 on water quality is ___________severe than LCU 9.

Q45. The effect of LCU 6 on water quality is ___________severe than LCU 10.

Q46. The effect of LCU 6 on water quality is ___________severe than LCU 11.

Q47. The effect of LCU 6 on water quality is ___________severe than LCU 12.

Land-cover Class 7: Degraded: other

Q48. The effect of LCU 7 on water quality is ___________severe than LCU 8.

Q49. The effect of LCU 7 on water quality is ___________severe than LCU 9.

Q50. The effect of LCU 7 on water quality is ___________severe than LCU 10.

Q51. The effect of LCU 7 on water quality is ___________severe than LCU 11.

Q52. The effect of LCU 7 on water quality is ___________severe than LCU 12.

Land-cover Class 8: Residential: rural

Q53. The effect of LCU 8 on water quality is ___________severe than LCU 9.

Q54. The effect of LCU 8 on water quality is ___________severe than LCU 10.

Q55. The effect of LCU 8 on water quality is ___________severe than LCU 11.

Q56. The effect of LCU 8 on water quality is ___________severe than LCU 12.

Land-cover Class 9: Urban: formal

Q57. The effect of LCU 9 on water quality is ___________severe than LCU 10.

Q58. The effect of LCU 9 on water quality is ___________severe than LCU 11.

Q59. The effect of LCU 9 on water quality is ___________severe than LCU 12.

Land-cover Class 10: Urban: industrial

Q60. The effect of LCU 10 on water quality is ___________severe than LCU 11.

Q61. The effect of LCU 10 on water quality is ___________severe than LCU 12.

Land-cover Classes 11 & 12: Mines and quarries, and Urban: informal

Q62. The effect of LCU 11 on water quality is ___________severe than LCU 12.

Thank you for your participation!

Name:

Additional Comments:

APPENDIX B:

Tables of Results

Table 26. Areal extent of wetlands and their sub-catchments in the upper Goukou River Quaternary catchment

Wetland FID	Wetland area (ha)	Catchment FID	Catchment area (ha)	Area of catchment (excluding wetland) (ha)
0	46.37	0	436	389.63
1	45.35	9	317	271.65
2	53.25	5	453	399.75
3	19.71	6	288	268.29
4	27.21	3	477	449.79
5	33.64	4	350	316.36
6	49.14	17	684	634.86
8	9.77	13	172	162.23
9	44.02	23	653	608.98
10	9.57	4	350	340.43
11	5.09	16	359	353.91
12	6.41	18	108	101.59
13	6.15	30	786	779.85
14	5.19	25	425	419.81
16	6.55	24	172	165.45
17	4.06	27	855	850.94
18	3.47	22	152	148.53
21	2.50	29	171	168.50
22(1)	5.33	39	144	138.67
22(2)	8.35	34	211	202.65
24	5.29	31	101	95.71
25	3.20	19	731	727.80
26	7.15	27	855	847.85
27	45.59	38	309	263.41
28	10.79	42	304	293.21
29	10.97	35	201	190.03
33	12.76	40	163	150.24
35	8.10	27	855	846.90
36	32.27	41	637	604.73
38	12.69	59	387	374.31
39	20.47	57	237	216.53
40	7.20	38	309	301.80
42	15.83	48	350	334.17
44	6.87	45	146	139.13
46(1)	48.04	53	578	529.96
46(2)	18.50	69	208	189.50
46(3)	15.63	70	235	219.37
47	4.92	60	362	357.08
48	7.91	58	191	183.09
50	11.30	47	777	765.70
51	4.79	52	195	190.21
52	14.62	47	777	762.38
53(1)	10.34	61	230	219.66
53(2)	9.14	67	333	323.86
53(3)	8.73	68	173	164.27
56	14.59	65	249	234.41
57	19.48	66	175	155.52
58	24.15	64	335	310.85
62	16.89	71	810	793.11

Table 27. Areal extent of land cover classes of wetlands and their sub-catchments in the upper Goukou River Quaternary catchment

Wetland FID	Land-cover in wetland	Area of wetland LC (ha)	Catchment FID	Land-cover in catchment	Area of catchment LC (ha)
0	Natural	37.09	0	Natural	92.49
	Degraded Vegetation	9.28		Degraded Vegetation	176.49
				Cultivated, irrigated	120.65
1	Forest Plantations	17.67	9	Forest Plantations	37.44
	Cultivated, irrigated	1.38		Natural	81.89
	Degraded Vegetation	2.63		Degraded Vegetation	152.32
	Natural	23.67			
2	Cultivated, irrigated	7.33	5	Natural	223.61
	Natural	43.33		Cultivated, irrigated	10.91
	Degraded Vegetation	2.59		Degraded Vegetation	165.23
3	Natural	8.57	6	Natural	23.42
	Cultivated, irrigated	6.50		Cultivated, irrigated	184.12
	Degraded Vegetation	4.64		Degraded Vegetation	60.74
4	Cultivated, irrigated	3.64	3	Natural	114.81
	Degraded Vegetation	18.95		Cultivated, irrigated	272.47
	Natural	4.62		Degraded Vegetation	62.51
5	Natural	20.19	4	Natural	17.04
	Degraded Vegetation	13.45		Degraded Vegetation	167.70
				Cultivated, irrigated	131.62
6	Natural	18.67	17	Natural	16.83
	Degraded Vegetation	28.01		Degraded Vegetation	235.97
	Cultivated, irrigated	2.46		Cultivated, irrigated	382.06
8	Natural	3.82	13	Degraded Vegetation	125.93
	Degraded Vegetation	5.73		Natural	0.50
	Cultivated, irrigated	0.22		Cultivated, irrigated	35.61
				Forest Plantations	0.19
9	Cultivated, irrigated	8.17	23	Urban industrial/transport	4.82
	Natural	10.75		Urban residential- low density	0.98
	Degraded Vegetation	25.09		Natural	15.21
				Degraded Vegetation	136.00
				Cultivated, irrigated	451.97
10	Cultivated, irrigated	3.83	4	Natural	24.61
	Natural	3.02		Cultivated, irrigated	128.57
	Degraded Vegetation	2.73		Degraded Vegetation	162.87
				Forest Plantations	0.32
11	Degraded Vegetation	3.41	16	Degraded Vegetation	132.17
	Natural	0.08		Cultivated, irrigated	221.09
	Cultivated, irrigated	1.60		Natural	0.65
12	Natural	1.36	18	Forest Plantations	1.59
	Degraded Vegetation	4.57		Natural	3.19
	Cultivated, irrigated	0.47		Cultivated, irrigated	60.63
				Degraded Vegetation	35.96
				Urban industrial/transport	0.23
13	Cultivated, irrigated	0.74	30	Degraded Vegetation	422.77
	Degraded Vegetation	5.42		Natural	21.47
				Cultivated, irrigated	335.61
14	Degraded Vegetation	1.95	25	Degraded Vegetation	209.30

Wetland FID	Land-cover in wetland	Area of wetland LC (ha)	Catchment FID	Land-cover in catchment	Area of catchment LC (ha)
	Cultivated, irrigated	1.23		Cultivated, irrigated	202.39
	Natural	2.02		Natural	2.34
				Forest Plantations	3.17
				Urban industrial/transport	2.61
16	Degraded Vegetation	2.37	24	Forest Plantations	1.65
	Cultivated, irrigated	0.64		Natural	2.96
	Natural	3.55		Degraded Vegetation	108.84
				Cultivated, irrigated	51.41
				Urban industrial/transport	0.59
17	Cultivated, irrigated	3.53	27	Degraded Vegetation	302.87
	Urban industrial/transport	0.05		Cultivated, irrigated	547.16
	Degraded Vegetation	0.48		Urban industrial/transport	0.91
18	Natural	0.40	22	Degraded Vegetation	24.79
	Degraded Vegetation	2.27		Cultivated, irrigated	120.38
	Cultivated, irrigated	0.80		Urban industrial/transport	1.79
				Natural	0.81
				Urban residential- low density	0.75
21	Natural	0.64	29	Natural	2.57
	Cultivated, irrigated	0.40		Degraded Vegetation	31.63
	Cultivated, dryland	0.10		Cultivated, irrigated	132.00
	Degraded Vegetation	1.35		Urban residential- low density	1.13
				Urban industrial/transport	1.17
22(1)	Natural	2.13	39	Natural	1.49
	Degraded Vegetation	3.20		Degraded Vegetation	96.20
				Cultivated, irrigated	40.83
				Mines and quarries	0.15
22(2)	Natural	2.23	34	Natural	1.11
	Degraded Vegetation	5.21		Degraded Vegetation	79.40
	Cultivated, irrigated	0.90		Cultivated, irrigated	122.14
24	Natural	0.70	31	Degraded Vegetation	13.11
	Degraded Vegetation	3.42		Cultivated, irrigated	81.40
	Cultivated, irrigated	1.17		Urban industrial/transport	1.20
25	Natural	0.35	19	Natural	7.50
	Cultivated, irrigated	0.81		Degraded Vegetation	339.21
	Degraded Vegetation	2.04		Cultivated, irrigated	381.10
26	Natural	0.23	27	Degraded Vegetation	302.87
	Degraded Vegetation	1.88		Cultivated, irrigated	547.16
	Cultivated, irrigated	5.04		Urban industrial/transport	0.91
27	Degraded Vegetation	27.36	38	Natural	9.27
	Natural	18.24		Degraded Vegetation	140.12
				Cultivated, irrigated	114.02
28	Cultivated, irrigated	1.63	42	Natural	19.34
	Forest Plantations	0.90		Degraded Vegetation	89.20
	Natural	1.79		Cultivated, irrigated	182.26
	Degraded Vegetation	6.46		Urban industrial/transport	2.41
29	Natural	2.67	35	Urban industrial/transport	0.86
	Degraded Vegetation	4.75		Natural	9.31
	Cultivated, irrigated	3.56		Degraded Vegetation	4.79
				Cultivated, irrigated	175.07
33	Natural	3.43	40	Urban industrial/transport	0.50

Wetland FID	Land-cover in wetland	Area of wetland LC (ha)	Catchment FID	Land-cover in catchment	Area of catchment LC (ha)
	Degraded Vegetation	6.57		Degraded Vegetation	10.26
	Cultivated, irrigated	2.67		Cultivated, irrigated	139.48
	Urban industrial/transport	0.09			
35	Cultivated, irrigated	5.60	27	Degraded Vegetation	406.99
	Natural	0.50		Cultivated, irrigated	436.47
	Degraded Vegetation	1.99		Natural	3.45
36	Natural	2.70	41	Cultivated, irrigated	533.68
	Degraded Vegetation	29.44		Degraded Vegetation	68.19
	Urban industrial/transport	0.13		Urban industrial/transport	2.85
38	Natural	2.72	59	Natural	3.44
	Degraded Vegetation	9.97		Degraded Vegetation	272.21
				Cultivated, irrigated	98.66
39	Natural	4.92	57	Cultivated, irrigated	65.93
	Degraded Vegetation	13.96		Natural	39.96
	Cultivated, irrigated	1.58		Degraded Vegetation	108.97
				Urban industrial/transport	1.67
40	Natural	4.87	38	Natural	8.36
	Cultivated, irrigated	0.25		Degraded Vegetation	190.72
	Degraded Vegetation	2.09		Cultivated, irrigated	102.72
42	Natural	5.72	48	Natural	15.36
	Degraded Vegetation	10.11		Degraded Vegetation	53.74
				Cultivated, irrigated	265.07
44	Natural	1.23	45	Urban industrial/transport	0.50
	Degraded Vegetation	5.64		Degraded Vegetation	87.53
				Cultivated, irrigated	51.10
46(1)	Degraded Vegetation	43.43	53	Degraded Vegetation	161.01
	Natural	4.60		Cultivated, irrigated	360.89
				Natural	7.26
				Urban industrial/transport	0.81
46(2)	Natural	4.48	69	Cultivated, irrigated	64.57
	Degraded Vegetation	13.92		Degraded Vegetation	53.92
	Urban industrial/transport	0.09		Natural	69.84
				Urban industrial/transport	1.17
46(3)	Cultivated, irrigated	0.42	70	Degraded Vegetation	41.58
	Degraded Vegetation	8.26		Cultivated, irrigated	87.99
	Natural	6.95		Natural	89.81
47	Degraded Vegetation	2.53	60	Natural	40.95
	Natural	2.38		Degraded Vegetation	199.50
				Cultivated, irrigated	116.62
48	Natural	0.87	58	Natural	5.43
	Degraded Vegetation	7.03		Degraded Vegetation	145.88
				Cultivated, irrigated	31.79
50	Mines and quarries	0.09	47	Cultivated, irrigated	494.19
	Natural	0.84		Degraded Vegetation	258.43
	Degraded Vegetation	8.27		Mines and quarries	13.08
	Cultivated, irrigated	2.11			
51	Degraded Vegetation	3.50	52	Natural	35.39
	Natural	1.29		Degraded Vegetation	60.94
				Cultivated, irrigated	93.89
52	Degraded Vegetation	10.20	47	Cultivated, irrigated	494.19
	Natural	0.79		Degraded Vegetation	258.43

Wetland FID	Land-cover in wetland	Area of wetland LC (ha)	Catchment FID	Land-cover in catchment	Area of catchment LC (ha)
	Cultivated, irrigated	3.58		Mines and quarries	13.08
	Urban industrial/transport	0.06			
53(1)	Natural	1.52	61	Natural	3.91
	Degraded Vegetation	8.53		Degraded Vegetation	154.04
	Cultivated, irrigated	0.24		Urban residential- high density	33.61
	Urban residential- high density	0.06		Urban industrial/transport	2.31
				Cultivated, irrigated	25.79
53(2)	Degraded Vegetation	7.96	67	Natural	0.28
	Natural	1.19		Degraded Vegetation	62.16
				Cultivated, irrigated	256.89
				Urban industrial/transport	4.52
53(3)	Degraded Vegetation	7.50	68	Degraded Vegetation	15.67
	Natural	1.23		Cultivated, irrigated	148.60
56	Degraded Vegetation	13.08	65	Cultivated, irrigated	143.24
	Natural	1.15		Degraded Vegetation	63.74
	Urban residential- high density	0.35		Urban industrial/transport	4.82
				Urban residential- high density	21.20
				Mines and quarries	1.42
57	Forest Plantations	3.87	66	Urban residential- high density	3.82
	Urban residential- high density	0.55		Urban industrial/transport	2.67
	Degraded Vegetation	14.72		Natural	1.28
	Natural	0.33		Degraded Vegetation	100.43
				Cultivated, irrigated	47.32
58	Degraded Vegetation	18.84	64	Natural	13.95
	Natural	4.08		Forest Plantations	1.22
	Cultivated, irrigated	1.23		Degraded Vegetation	127.04
				Cultivated, irrigated	168.63
62	Natural	0.60	71	Mines and quarries	1.97
	Degraded Vegetation	15.52		Degraded Vegetation	287.55
	Cultivated, irrigated	0.77		Natural	72.26
				Cultivated, irrigated	431.33

Table 28. Ecosystem functionality with respect to sediment trapping of wetlands in the upper Goukou River Quaternary catchment based on impacts arising in the wetlands' upstream catchments

Catchment Impacts					
Wetland	Water input decrease	Functionality Score	Wetland	Water input increase	Functionality Score
29	4.49	2.35	53(1)	2.38	2.5
33	4.41	2.36	48	1.52	2.5
53(3)	4.24	2.37	8	1.22	2.5
36	4.03	2.40	2	1.10	2.5
24	3.73	2.43	38	0.86	2.5
42	3.48	2.46	57	0.69	2.5
18	3.43	2.46	22(1)	0.61	2.5
21	3.27	2.48	1	0.44	2.5
53(2)	3.26	2.48	16	0.36	2.5
9	2.96	2.5	40	0.19	2.5
3	2.75	2.5	44	0.08	2.5
4	2.61	2.5	39	0.06	2.5
46(1)	2.48	2.5	47	0.04	2.5
26	2.15	2.5			
52	2.14	2.5			
17	2.14	2.5			
50	2.13	2.5			
28	2.12	2.5			
12	2.04	2.5			
11	2.00	2.5			
6	1.89	2.5			
22(2)	1.84	2.5			
62	1.62	2.5			
56	1.57	2.5			
58	1.52	2.5			
51	1.51	2.5			
46(3)	1.44	2.5			
25	1.22	2.5			
35	1.14	2.5			
14	0.93	2.5			
46(2)	0.79	2.5			
27	0.57	2.5			
13	0.53	2.5			
5	0.49	2.5			
10	0.46	2.5			
0	0.19	2.5			

Table 29. Ecosystem functionality with respect to sediment trapping of wetlands in the upper Goukou River Quaternary catchment based on impacts arising within the wetland

	Wetland Impacts						
Wetland	**Increased water use**	**Functionality Score**	**Reduced surface roughness**	**Functionality Score**	**Flow impediment**	**Functionality Score**	**Re**
0			0.60	2.45			
1	3.51	3.20	0.33	2.47			
2			0.83	2.43			
3			2.36	2.31			
4			2.76	2.28			
5			1.20	2.40			
6			1.96	2.34			
8			1.87	2.35			
9			2.64	2.29			
10			2.86	2.27			
11			3.58	2.21			
12			2.51	2.30			
13			3.24	2.24			
14			2.31	2.32			
16			1.57	2.37			
17			4.82	2.11	0.07	2.50	
18			3.12	2.25			
21			2.63	2.29			
22(1)			1.80	2.36			
22(2)			1.87	2.35			
24			3.05	2.26			
25			3.17	2.25			
26			4.31	2.16			
27			1.80	2.36			
28	0.75	2.65	2.55	2.30			
29			2.92	2.27			
33			2.65	2.29	0.03	2.50	
35			4.20	2.16			
36			2.77	2.28	0.02	2.50	
38			2.36	2.31			
39			2.43	2.31			
40			1.04	2.42			
42			1.92	2.35			
44			2.46	2.30			
46(1)			2.71	2.28			
46(2)			2.30	2.32	0.03	2.50	
46(3)			1.72	2.36			
47			1.55	2.38			
48			2.67	2.29			
50			3.20	2.24			
51			5.93	2.03			
52			2.13	2.33	0.02	2.50	
53(1)			2.63	2.29			
53(2)			2.61	2.29			
53(3)			2.58	2.29			
56			2.86	2.27			
57	1.79	2.86	2.47	2.30			
58			2.60	2.29			
62			3.00	2.26			

Table 30. Final scores and hectare equivalents of ecosystem functionality with respect to sediment trapping of wetlands in the upper Goukou River Quaternary catchment

Wetland	Resolved onsite functionality	Decreased water input	Increased water input	Final functionality score	Functional Ha Equiv
0	2.45	2.50		2.45	28.42
1	2.47		2.50	2.47	28.05
2	2.43		2.50	2.43	32.39
3	2.31	2.50		2.31	11.39
4	2.28	2.50		2.28	15.51
5	2.40	2.50		2.40	20.22
6	2.34	2.50		2.34	28.79
8	2.35		2.50	2.35	5.74
9	2.29	2.50		2.29	25.19
10	2.27	2.50		2.27	5.44
11	2.21	2.50		2.21	2.82
12	2.30	2.50		2.30	3.68
13	2.24	2.50		2.24	3.45
14	2.32	2.50		2.32	3.01
16	2.37		2.50	2.37	3.89
17	2.11	2.50		2.11	2.14
18	2.25	2.46		2.25	1.95
21	2.29	2.48		2.29	1.43
22(1)	2.36		2.50	2.36	3.14
22(2)	2.35	2.50		2.35	4.91
24	2.26	2.43		2.26	2.98
25	2.25	2.50		2.25	1.80
26	2.16	2.50		2.16	3.85
27	2.36	2.50		2.36	26.86
28	2.30	2.50		2.30	6.19
29	2.27	2.35		2.27	6.22
33	2.29	2.36		2.29	7.30
35	2.16	2.50		2.16	4.38
36	2.28	2.40		2.28	18.38
38	2.31		2.50	2.31	7.34
39	2.31		2.50	2.31	11.80
40	2.42		2.50	2.42	4.35
42	2.35	2.46		2.35	9.29
44	2.30		2.50	2.30	3.95
46(1)	2.28	2.50		2.28	27.42
46(2)	2.32	2.50		2.32	10.71
46(3)	2.36	2.50		2.36	9.23
47	2.38		2.50	2.38	2.92
48	2.29		2.50	2.29	4.52
50	2.24	2.50		2.24	6.34
51	2.03	2.50		2.03	2.43
52	2.33	2.50		2.33	8.52
53(1)	2.29		2.50	2.29	5.92
53(2)	2.29	2.48		2.29	5.24
53(3)	2.29	2.37		2.29	5.01
56	2.27	2.50		2.27	8.28
57	2.30		2.50	2.30	11.21
58	2.29	2.50		2.29	13.84
62	2.26	2.50		2.26	9.55

Table 31. Ecosystem functionality with respect to nitrate removal of wetlands in the upper Goukou River Quaternary catchment based on impacts arising in the wetlands' upstream catchments

Catchment Impacts					
Wetland	Water input decrease	Functionality Score	Wetland	Water input increase	Functionality Score
29	4.49	2.69	53(1)	2.38	3.50
33	4.41	2.71	48	1.52	3.50
53(3)	4.24	2.74	8	1.22	3.50
36	4.03	2.77	2	1.10	3.50
24	3.73	2.83	38	0.86	3.50
42	3.48	2.87	57	0.69	3.50
18	3.43	2.88	22(1)	0.61	3.50
21	3.27	2.91	1	0.44	3.50
53(2)	3.26	2.91	16	0.36	3.50
9	2.96	2.97	40	0.19	3.50
3	2.75	3.00	44	0.08	3.50
4	2.61	3.03	39	0.06	3.50
46(1)	2.48	3.05	47	0.04	3.50
26	2.15	3.11			
52	2.14	3.12			
17	2.14	3.12			
50	2.13	3.12			
28	2.12	3.12			
12	2.04	3.13			
11	2.00	3.14			
6	1.89	3.16			
22(2)	1.84	3.17			
62	1.62	3.21			
56	1.57	3.22			
58	1.52	3.23			
51	1.51	3.23			
46(3)	1.44	3.24			
25	1.22	3.28			
35	1.14	3.30			
14	0.93	3.33			
46(2)	0.79	3.36			
27	0.57	3.40			
13	0.53	3.41			
5	0.49	3.41			
10	0.46	3.42			
0	0.19	3.47			

Table 32. Ecosystem functionality with respect to nitrate removal of wetlands in the upper Goukou River Quaternary catchment based on impacts arising within the wetland

Wetland Impacts							
Wetland	Increased water use	Functionality Score	Reduced surface roughness	Functionality Score	Flow impediment	Functionality Score	Resolved onsite functionality
0			0.60	3.39			3.39
1	3.51	3.15	0.33	3.44			3.15
2			0.83	3.35			3.35
3			2.36	3.08			3.08
4			2.76	3.00			3.00
5			1.20	3.28			3.28
6			1.96	3.15			3.15
8			1.87	3.16			3.16
9			2.64	3.03			3.03
10			2.86	2.99			2.99
11			3.58	2.86			2.86
12			2.51	3.05			3.05
13			3.24	2.92			2.92
14			2.31	3.08			3.08
16			1.57	3.22			3.22
17			4.82	2.63	0.07	3.50	2.63
18			3.12	2.94			2.94
21			2.63	3.03			3.03
22(1)			1.80	3.18			3.18
22(2)			1.87	3.16			3.16
24			3.05	2.95			2.95
25			3.17	2.93			2.93
26			4.31	2.72			2.72
27			1.80	3.18			3.18
28	0.75	3.42	2.55	3.04			3.04
29			2.92	2.97			2.97
33			2.65	3.02	0.03	3.50	3.02
35			4.20	2.74			2.74
36			2.77	3.00	0.02	3.50	3.00
38			2.36	3.08			3.08
39			2.43	3.06			3.06
40			1.04	3.31			3.31
42			1.92	3.16			3.16
44			2.46	3.06			3.06
46(1)			2.71	3.01			3.01
46(2)			2.30	3.09	0.03	3.50	3.09
46(3)			1.72	3.19			3.19
47			1.55	3.22			3.22
48			2.67	3.02			3.02
50			3.20	2.92			2.92
51			5.92	2.43			2.43
52			2.13	3.12	0.02	3.50	3.12
53(1)			2.63	3.03			3.03
53(2)			2.61	3.03			3.03
53(3)			2.58	3.04			3.04
56			2.86	2.99			2.99
57	1.79	3.32	2.47	3.06			3.06
58			2.60	3.03			3.03

62			2.98	2.96			2.96

Table 33. Final scores and hectare equivalents of ecosystem functionality with respect to nitrate removal of wetlands in the upper Goukou River Quaternary catchment

Wetland	Resolved onsite functionality	Decreased water input	Increased water input	Final functionality score (TR)	Functional Ha Equiv
0	3.39	3.47		3.39	39.32
1	3.15		3.50	3.15	35.71
2	3.35		3.50	3.35	44.60
3	3.08	3.00		3.08	15.16
4	3.00	3.03		3.00	20.43
5	3.28	3.41		3.28	27.62
6	3.15	3.16		3.15	38.66
8	3.16		3.50	3.16	7.73
9	3.03	2.97		3.03	33.29
10	2.99	3.42		2.99	7.15
11	2.86	3.14		2.86	3.64
12	3.05	3.13		3.05	4.88
13	2.92	3.41		2.92	4.49
14	3.08	3.33		3.08	4.01
16	3.22		3.50	3.22	5.27
17	2.63	3.12		2.63	2.67
18	2.94	2.88		2.94	2.55
21	3.03	2.91		3.03	1.89
22(1)	3.18		3.50	3.18	4.23
22(2)	3.16	3.17		3.16	6.60
24	2.95	2.83		2.95	3.90
25	2.93	3.28		2.93	2.34
26	2.72	3.11		2.72	4.87
27	3.18	3.40		3.18	36.20
28	3.04	3.12		3.04	8.20
29	2.97	2.69		2.97	8.16
33	3.02	2.71		3.02	9.64
35	2.74	3.30		2.74	5.56
36	3.00	2.77		3.00	24.21
38	3.08		3.50	3.08	9.76
39	3.06		3.50	3.06	15.67

40	3.31		3.50	3.31	5.96
42	3.16	2.87		3.16	12.48
44	3.06		3.50	3.06	5.25
46(1)	3.01	3.05		3.01	36.17
46(2)	3.09	3.36		3.09	14.27
46(3)	3.19	3.24		3.19	12.46
47	3.22		3.50	3.22	3.96
48	3.02		3.50	3.02	5.97
50	2.92	3.12		2.92	8.26
51	2.43	3.23		2.43	2.91
52	3.12	3.12		3.12	11.39
53(1)	3.03		3.50	3.03	7.83
53(2)	3.03	2.91		3.03	6.93
53(3)	3.04	2.74		3.04	6.63
56	2.99	3.22		2.99	10.89
57	3.06		3.50	3.06	14.88
58	3.03	3.23		3.03	18.31
62	2.96	3.21		2.96	12.51

Table 34. Ecosystem functionality with respect to phosphate trapping of wetlands in the upper Goukou River Quaternary catchment based on impacts arising in the wetlands' upstream catchments

Catchment Impacts					
Wetland	**Water input decrease**	**Functionality Score**	**Wetland**	**Water input increase**	**Functionality Score**
29	4.49	3.29	53(1)	2.38	3.50
33	4.41	3.30	48	1.52	3.50
53(3)	4.24	3.33	8	1.22	3.50
36	4.03	3.36	2	1.10	3.50
24	3.73	3.40	38	0.86	3.50
42	3.48	3.43	57	0.69	3.50
18	3.43	3.44	22(1)	0.61	3.50
21	3.27	3.46	1	0.44	3.50
53(2)	3.26	3.46	16	0.36	3.50
9	2.96	3.50	40	0.19	3.50
3	2.75	3.50	44	0.08	3.50
4	2.61	3.50	39	0.06	3.50
46(1)	2.48	3.50	47	0.04	3.50
26	2.15	3.50			
52	2.14	3.50			
17	2.14	3.50			
50	2.13	3.50			
28	2.12	3.50			
12	2.04	3.50			
11	2.00	3.50			
6	1.89	3.50			
22(2)	1.84	3.50			
62	1.62	3.50			
56	1.57	3.50			
58	1.52	3.50			
51	1.51	3.50			
46(3)	1.44	3.50			
25	1.22	3.50			
35	1.14	3.50			
14	0.93	3.50			
46(2)	0.79	3.50			
27	0.57	3.50			
13	0.53	3.50			
5	0.49	3.50			
10	0.46	3.50			
0	0.19	3.50			

Table 35. Ecosystem functionality with respect to phosphate trapping of wetlands in the upper Goukou River Quaternary catchment based on impacts arising within the wetland

Wetland Impacts							
Wetland	Increased water use	Functionality Score	Reduced surface roughness	Functionality Score	Flow impediment	Functionality Score	Resolved onsite functionality
0			0.60	3.39			3.39
1	3.51	3.36	0.33	3.44			3.36
2			0.83	3.35			3.35
3			2.36	3.08			3.08
4			2.76	3.00			3.00
5			1.20	3.28			3.28
6			1.96	3.15			3.15
8			1.87	3.16			3.16
9			2.64	3.03			3.03
10			2.86	2.99			2.99
11			3.58	2.86			2.86
12			2.51	3.05			3.05
13			3.24	2.92			2.92
14			2.31	3.08			3.08
16			1.57	3.22			3.22
17			4.82	2.63	0.07	3.50	2.63
18			3.12	2.94			2.94
21			2.63	3.03			3.03
22(1)			1.80	3.18			3.18
22(2)			1.87	3.16			3.16
24			3.05	2.95			2.95
25			3.17	2.93			2.93
26			4.31	2.72			2.72
27			1.80	3.18			3.18
28	0.75	3.50	2.55	3.04			3.04
29			2.92	2.97			2.97
33			2.65	3.02	0.03	3.50	3.02
35			4.20	2.74			2.74
36			2.77	3.00	0.02	3.50	3.00
38			2.36	3.08			3.08
39			2.43	3.06			3.06
40			1.04	3.31			3.31
42			1.92	3.16			3.16
44			2.46	3.06			3.06
46(1)			2.71	3.01			3.01
46(2)			2.30	3.09	0.03	3.50	3.09
46(3)			1.72	3.19			3.19
47			1.55	3.22			3.22
48			2.67	3.02			3.02
50			3.20	2.92			2.92
51			5.92	2.43			2.43
52			2.13	3.12	0.02	3.50	3.12
53(1)			2.63	3.03			3.03
53(2)			2.61	3.03			3.03
53(3)			2.58	3.04			3.04
56			2.86	2.99			2.99
57	1.79	3.50	2.47	3.06			3.06

58			2.60	3.03			3.03
62			2.98	2.96			2.96

Table 36. Final scores and hectare equivalents of ecosystem functionality with respect to phosphate trapping of wetlands in the upper Goukou River Quaternary catchment

Wetland	Resolved onsite functionality	Decreased water input	Increased water input	Final functionality score	Functional Ha Equiv
0	3.39	3.50		3.39	39.32
1	3.36		3.50	3.36	38.08
2	3.35		3.50	3.35	44.60
3	3.08	3.50		3.08	15.16
4	3.00	3.50		3.00	20.43
5	3.28	3.50		3.28	27.62
6	3.15	3.50		3.15	38.66
8	3.16		3.50	3.16	7.73
9	3.03	3.50		3.03	33.29
10	2.99	3.50		2.99	7.15
11	2.86	3.50		2.86	3.64
12	3.05	3.50		3.05	4.88
13	2.92	3.50		2.92	4.49
14	3.08	3.50		3.08	4.01
16	3.22		3.50	3.22	5.27
17	2.63	3.50		2.63	2.67
18	2.94	3.44		2.94	2.55
21	3.03	3.46		3.03	1.89
22(1)	3.18		3.50	3.18	4.23
22(2)	3.16	3.50		3.16	6.60
24	2.95	3.40		2.95	3.90
25	2.93	3.50		2.93	2.34
26	2.72	3.50		2.72	4.87
27	3.18	3.50		3.18	36.20
28	3.04	3.50		3.04	8.20
29	2.97	3.29		2.97	8.16
33	3.02	3.30		3.02	9.64
35	2.74	3.50		2.74	5.56
36	3.00	3.36		3.00	24.21
38	3.08		3.50	3.08	9.76
39	3.06		3.50	3.06	15.67
40	3.31		3.50	3.31	5.96
42	3.16	3.43		3.16	12.48
44	3.06		3.50	3.06	5.25
46(1)	3.01	3.50		3.01	36.17
46(2)	3.09	3.50		3.09	14.27
46(3)	3.19	3.50		3.19	12.46
47	3.22		3.50	3.22	3.96
48	3.02		3.50	3.02	5.97
50	2.92	3.50		2.92	8.26
51	2.43	3.50		2.43	2.91
52	3.12	3.50		3.12	11.39
53(1)	3.03		3.50	3.03	7.83
53(2)	3.03	3.46		3.03	6.93
53(3)	3.04	3.33		3.04	6.63
56	2.99	3.50		2.99	10.89
57	3.06		3.50	3.06	14.88
58	3.03	3.50		3.03	18.31
62	2.96	3.50		2.96	12.51

Table 37. Ecosystem functionality with respect to toxicant removal of wetlands in the upper Goukou River Quaternary catchment based on impacts arising in the wetlands' upstream catchments

Catchment Impacts					
Wetland	Water input decrease	Functionality Score	Wetland	Water input increase	Functionality Score
29	4.49	3.29	53(1)	2.38	3.50
33	4.41	3.30	48	1.52	3.50
53(3)	4.24	3.33	8	1.22	3.50
36	4.03	3.36	2	1.10	3.50
24	3.73	3.40	38	0.86	3.50
42	3.48	3.43	57	0.69	3.50
18	3.43	3.44	22(1)	0.61	3.50
21	3.27	3.46	1	0.44	3.50
53(2)	3.26	3.46	16	0.36	3.50
9	2.96	3.50	40	0.19	3.50
3	2.75	3.50	44	0.08	3.50
4	2.61	3.50	39	0.06	3.50
46(1)	2.48	3.50	47	0.04	3.50
26	2.15	3.50			
52	2.14	3.50			
17	2.14	3.50			
50	2.13	3.50			
28	2.12	3.50			
12	2.04	3.50			
11	2.00	3.50			
6	1.89	3.50			
22(2)	1.84	3.50			
62	1.62	3.50			
56	1.57	3.50			
58	1.52	3.50			
51	1.51	3.50			
46(3)	1.44	3.50			
25	1.22	3.50			
35	1.14	3.50			
14	0.93	3.50			
46(2)	0.79	3.50			
27	0.57	3.50			
13	0.53	3.50			
5	0.49	3.50			
10	0.46	3.50			
0	0.19	3.50			

Table 3826. Ecosystem functionality with respect to toxicant removal of wetlands in the upper Goukou River Quaternary catchment based on impacts arising within the wetland

Wetland Impacts							
Wetland	Increased water use	Functionality Score	Reduced surface roughness	Functionality Score	Flow impediment	Functionality Score	Resolved onsite functionality
0			0.60	3.39			3.39
1	3.51	3.50	0.33	3.44			3.44
2			0.83	3.35			3.35
3			2.36	3.08			3.08
4			2.76	3.00			3.00
5			1.20	3.28			3.28
6			1.96	3.15			3.15
8			1.87	3.16			3.16
9			2.64	3.03			3.03
10			2.86	2.99			2.99
11			3.58	2.86			2.86
12			2.51	3.05			3.05
13			3.24	2.92			2.92
14			2.31	3.08			3.08
16			1.57	3.22			3.22
17			4.82	2.63	0.07	3.50	2.63
18			3.12	2.94			2.94
21			2.63	3.03			3.03
22(1)			1.80	3.18			3.18
22(2)			1.87	3.16			3.16
24			3.05	2.95			2.95
25			3.17	2.93			2.93
26			4.31	2.72			2.72
27			1.80	3.18			3.18
28	0.75	3.50	2.55	3.04			3.04
29			2.92	2.97			2.97
33			2.65	3.02	0.03	3.50	3.02
35			4.20	2.74			2.74
36			2.77	3.00	0.02	3.50	3.00
38			2.36	3.08			3.08
39			2.43	3.06			3.06
40			1.04	3.31			3.31
42			1.92	3.16			3.16
44			2.46	3.06			3.06
46(1)			2.71	3.01			3.01
46(2)			2.30	3.09	0.03	3.50	3.09
46(3)			1.72	3.19			3.19
47			1.55	3.22			3.22
48			2.67	3.02			3.02
50			3.20	2.92			2.92
51			5.92	2.43			2.43
52			2.13	3.12	0.02	3.50	3.12
53(1)			2.63	3.03			3.03
53(2)			2.61	3.03			3.03
53(3)			2.58	3.04			3.04
56			2.86	2.99			2.99
57	1.79	3.50	2.47	3.06			3.06

58			2.60	3.03			3.03
62			2.98	2.96			2.96

Table 39 Final scores and hectare equivalents of ecosystem functionality with respect to toxicant removal of wetlands in the upper Goukou River Quaternary catchment

Wetland	Resolved onsite functionality	Decreased water input	Increased water input	Final functionality score	Functional Ha Equiv
0	3.39	3.50		3.39	39.32
1	3.44		3.50	3.44	39.02
2	3.35		3.50	3.35	44.60
3	3.08	3.50		3.08	15.16
4	3.00	3.50		3.00	20.43
5	3.28	3.50		3.28	27.62
6	3.15	3.50		3.15	38.66
8	3.16		3.50	3.16	7.73
9	3.03	3.50		3.03	33.29
10	2.99	3.50		2.99	7.15
11	2.86	3.50		2.86	3.64
12	3.05	3.50		3.05	4.88
13	2.92	3.50		2.92	4.49
14	3.08	3.50		3.08	4.01
16	3.22		3.50	3.22	5.27
17	2.63	3.50		2.63	2.67
18	2.94	3.44		2.94	2.55
21	3.03	3.46		3.03	1.89
22(1)	3.18		3.50	3.18	4.23
22(2)	3.16	3.50		3.16	6.60
24	2.95	3.40		2.95	3.90
25	2.93	3.50		2.93	2.34
26	2.72	3.50		2.72	4.87
27	3.18	3.50		3.18	36.20
28	3.04	3.50		3.04	8.20
29	2.97	3.29		2.97	8.16
33	3.02	3.30		3.02	9.64
35	2.74	3.50		2.74	5.56
36	3.00	3.36		3.00	24.21
38	3.08		3.50	3.08	9.76
39	3.06		3.50	3.06	15.67
40	3.31		3.50	3.31	5.96
42	3.16	3.43		3.16	12.48
44	3.06		3.50	3.06	5.25
46(1)	3.01	3.50		3.01	36.17
46(2)	3.09	3.50		3.09	14.27
46(3)	3.19	3.50		3.19	12.46
47	3.22		3.50	3.22	3.96
48	3.02		3.50	3.02	5.97
50	2.92	3.50		2.92	8.26
51	2.43	3.50		2.43	2.91
52	3.12	3.50		3.12	11.39
53(1)	3.03		3.50	3.03	7.83
53(2)	3.03	3.46		3.03	6.93
53(3)	3.04	3.33		3.04	6.63
56	2.99	3.50		2.99	10.89
57	3.06		3.50	3.06	14.88
58	3.03	3.50		3.03	18.31
62	2.96	3.50		2.96	12.51

Table 40. Water quality enhancement functionality and hectare equivalents of water quality enhancement functionality scores

Wetland	Sediment Trapping Funct. Effect.	Nitrate Removal Funct. Effect.	Phosphate Trapping Funct. Effect.	Toxicant Removal Funct. Effect.	Water Quality Functional Effectiveness	Sed. Trap
0	2.45	3.39	3.39	3.39	3.16	
1	2.47	3.15	3.36	3.44	3.11	
2	2.43	3.35	3.35	3.35	3.12	
3	2.31	3.08	3.08	3.08	2.88	
4	2.28	3.00	3.00	3.00	2.82	
5	2.40	3.28	3.28	3.28	3.06	
6	2.34	3.15	3.15	3.15	2.95	
8	2.35	3.16	3.16	3.16	2.96	
9	2.29	3.03	3.03	3.03	2.84	
10	2.27	2.99	2.99	2.99	2.81	
11	2.21	2.86	2.86	2.86	2.70	
12	2.30	3.05	3.05	3.05	2.86	
13	2.24	2.92	2.92	2.92	2.75	
14	2.32	3.08	3.08	3.08	2.89	
16	2.37	3.22	3.22	3.22	3.01	
17	2.11	2.63	2.63	2.63	2.50	
18	2.25	2.94	2.94	2.94	2.77	
21	2.29	3.03	3.03	3.03	2.84	
22(1)	2.36	3.18	3.18	3.18	2.97	
22(2)	2.35	3.16	3.16	3.16	2.96	
24	2.26	2.95	2.95	2.95	2.78	
25	2.25	2.93	2.93	2.93	2.76	
26	2.16	2.72	2.72	2.72	2.58	
27	2.36	3.18	3.18	3.18	2.97	
28	2.30	3.04	3.04	3.04	2.85	
29	2.27	2.97	2.97	2.97	2.80	
33	2.29	3.02	3.02	3.02	2.84	

35	2.16	2.74	2.74	2.74	2.60
36	2.28	3.00	3.00	3.00	2.82
38	2.31	3.08	3.08	3.08	2.88
39	2.31	3.06	3.06	3.06	2.87
40	2.42	3.31	3.31	3.31	3.09
42	2.35	3.16	3.16	3.16	2.95
44	2.30	3.06	3.06	3.06	2.87
46(1)	2.28	3.01	3.01	3.01	2.83
46(2)	2.32	3.09	3.09	3.09	2.89
46(3)	2.36	3.19	3.19	3.19	2.98
47	2.38	3.22	3.22	3.22	3.01
48	2.29	3.02	3.02	3.02	2.84
50	2.24	2.92	2.92	2.92	2.75
51	2.03	2.43	2.43	2.43	2.33
52	2.33	3.12	3.12	3.12	2.92
53(1)	2.29	3.03	3.03	3.03	2.84
53(2)	2.29	3.03	3.03	3.03	2.85
53(3)	2.29	3.04	3.04	3.04	2.85
56	2.27	2.99	2.99	2.99	2.81
57	2.30	3.06	3.06	3.06	2.87
58	2.29	3.03	3.03	3.03	2.85
62	2.26	2.96	2.96	2.96	2.79

Table 41 Final hectare equivalents of water quality impairment

Wetland FID	Catchment FID	Landcover in Catchment	Extent of LCU	LCU Score	LCU Ratio	Magnitude of Impact Score	Ha Equiv Score (MOI * ha)	Final Impact Ha Equiv
0	0	Natural	0.24	1	0.1	0.02	2.20	29.39
		Degraded Vegetation	0.45	2	0.2	0.09	15.99	
		Cultivated, irrigated	0.31	3	0.3	0.09	11.21	
1	9	Forest Plantations	0.14	2	0.2	0.03	1.03	20.58
		Natural	0.30	1	0.1	0.03	2.47	
		Degraded Vegetation	0.56	2	0.2	0.11	17.08	
					0			
2	5	Natural	0.56	1	0.1	0.06	12.51	26.26
		Cultivated, irrigated	0.03	3	0.3	0.01	0.09	
		Degraded Vegetation	0.41	2	0.2	0.08	13.66	
3	6	Natural	0.09	1	0.1	0.01	0.20	40.86
		Cultivated, irrigated	0.69	3	0.3	0.21	37.91	
		Degraded Vegetation	0.23	2	0.2	0.05	2.75	
4	3	Natural	0.26	1	0.1	0.03	2.93	54.18
		Cultivated, irrigated	0.61	3	0.3	0.18	49.52	
		Degraded Vegetation	0.14	2	0.2	0.03	1.74	
5	4	Natural	0.05	1	0.1	0.01	0.09	34.30
		Degraded Vegetation	0.53	2	0.2	0.11	17.78	
		Cultivated, irrigated	0.42	3	0.3	0.12	16.43	
6	17	Natural	0.03	1	0.1	0.00	0.04	86.56
		Degraded Vegetation	0.37	2	0.2	0.07	17.54	
		Cultivated, irrigated	0.60	3	0.3	0.18	68.98	
8	13	Degraded Vegetation	0.78	2	0.2	0.16	19.55	21.90
		Natural	0.00	1	0.1	0.00	0.00	
		Cultivated, irrigated	0.22	3	0.3	0.07	2.34	
		Forest Plantations	0.00	2	0.2	0.00	0.00	
9	23	Urban industrial/transport	0.01	9	0.9	0.01	0.03	106.78

		Residential- rural	0.00	5	0.5	0.00	0.00	
		Natural	0.02	1	0.1	0.00	0.04	
		Degraded Vegetation	0.22	2	0.2	0.04	6.07	
		Cultivated, irrigated	0.74	3	0.3	0.22	100.63	
10	4	Natural	0.08	1	0.1	0.01	0.19	32.64
		Cultivated, irrigated	0.41	3	0.3	0.12	15.68	
		Degraded Vegetation	0.51	2	0.2	0.10	16.77	
		Forest Plantations	0.00	2	0.2	0.00	0.00	
11	16	Degraded Vegetation	0.37	2	0.2	0.07	9.87	51.31
		Cultivated, irrigated	0.62	3	0.3	0.19	41.44	
		Natural	0.00	1	0.1	0.00	0.00	
12	18	Forest Plantations	0.02	2	0.2	0.00	0.00	13.42
		Natural	0.03	1	0.1	0.00	0.01	
		Cultivated, irrigated	0.60	3	0.3	0.18	10.85	
		Degraded Vegetation	0.35	2	0.2	0.07	2.55	
		Urban industrial/transport	0.00	9	0.9	0.00	0.00	
13	30	Degraded Vegetation	0.54	2	0.2	0.11	45.84	89.23
		Natural	0.03	1	0.1	0.00	0.06	
		Cultivated, irrigated	0.43	3	0.3	0.13	43.33	
14	25	Degraded Vegetation	0.50	2	0.2	0.10	20.87	50.16
		Cultivated, irrigated	0.48	3	0.3	0.14	29.27	
		Natural	0.01	1	0.1	0.00	0.00	
		Forest Plantations	0.01	2	0.2	0.00	0.00	
		Urban industrial/transport	0.01	9	0.9	0.01	0.01	
16	24	Forest Plantations	0.01	2	0.2	0.00	0.00	18.87
		Natural	0.02	1	0.1	0.00	0.01	
		Degraded Vegetation	0.65	2	0.2	0.13	14.15	
		Cultivated, irrigated	0.31	3	0.3	0.09	4.71	
		Urban industrial/transport	0.00	9	0.9	0.00	0.00	
17	27	Degraded Vegetation	0.36	2	0.2	0.07	21.56	127.11

		Cultivated, irrigated	0.64	3	0.3	0.19	105.55	
		Urban industrial/transport	0.00	9	0.9	0.00	0.00	
18	22	Degraded Vegetation	0.17	2	0.2	0.03	0.83	30.12
		Cultivated, irrigated	0.81	3	0.3	0.24	29.27	
		Urban industrial/transport	0.01	9	0.9	0.01	0.02	
		Natural	0.01	1	0.1	0.00	0.00	
		Residential- rural	0.01	5	0.5	0.00	0.00	
21	29	Natural	0.02	1	0.1	0.00	0.00	32.22
		Degraded Vegetation	0.19	2	0.2	0.04	1.19	
		Cultivated, irrigated	0.78	3	0.3	0.24	31.02	
		Residential- rural	0.01	5	0.5	0.00	0.00	
		Urban industrial/transport	0.01	9	0.9	0.01	0.01	
22(1)	39	Natural	0.01	1	0.1	0.00	0.00	16.96
		Degraded Vegetation	0.69	2	0.2	0.14	13.35	
		Cultivated, irrigated	0.29	3	0.3	0.09	3.61	
		Mines and quarries	0.00	10	1	0.00	0.00	
22(2)	34	Natural	0.01	1	0.1	0.00	0.00	28.31
		Degraded Vegetation	0.39	2	0.2	0.08	6.22	
		Cultivated, irrigated	0.60	3	0.3	0.18	22.09	
24	31	Degraded Vegetation	0.14	2	0.2	0.03	0.36	21.14
		Cultivated, irrigated	0.85	3	0.3	0.26	20.77	
		Urban industrial/transport	0.01	9	0.9	0.01	0.01	
25	19	Natural	0.01	1	0.1	0.00	0.01	91.49
		Degraded Vegetation	0.47	2	0.2	0.09	31.62	
		Cultivated, irrigated	0.52	3	0.3	0.16	59.87	
26	27	Degraded Vegetation	0.36	2	0.2	0.07	21.56	127.11
		Cultivated, irrigated	0.64	3	0.3	0.19	105.55	
		Urban industrial/transport	0.00	9	0.9	0.00	0.00	
27	38	Natural	0.04	1	0.1	0.00	0.03	29.75
		Degraded Vegetation	0.53	2	0.2	0.11	14.91	

		Cultivated, irrigated	0.43	3	0.3	0.13	14.81	
28	42	Natural	0.07	1	0.1	0.01	0.13	39.56
		Degraded Vegetation	0.30	2	0.2	0.06	5.43	
		Cultivated, irrigated	0.62	3	0.3	0.19	33.99	
		Urban industrial/transport	0.01	9	0.9	0.01	0.02	
29	35	Urban industrial/transport	0.00	9	0.9	0.00	0.00	48.46
		Natural	0.05	1	0.1	0.00	0.05	
		Degraded Vegetation	0.03	2	0.2	0.01	0.02	
		Cultivated, irrigated	0.92	3	0.3	0.28	48.39	
33	40	Urban industrial/transport	0.00	9	0.9	0.00	0.00	38.99
		Degraded Vegetation	0.07	2	0.2	0.01	0.14	
		Cultivated, irrigated	0.93	3	0.3	0.28	38.85	
			0.00		0	0.00	0.00	
35	27	Degraded Vegetation	0.48	2	0.2	0.10	38.93	106.09
		Cultivated, irrigated	0.51	3	0.3	0.15	67.16	
		Natural	0.00	1	0.1	0.00	0.00	
36	41	Cultivated, irrigated	0.88	3	0.3	0.26	141.29	142.85
		Degraded Vegetation	0.11	2	0.2	0.02	1.54	
		Urban industrial/transport	0.00	9	0.9	0.00	0.01	
38	59	Natural	0.01	1	0.1	0.00	0.00	47.40
		Degraded Vegetation	0.73	2	0.2	0.15	39.59	
		Cultivated, irrigated	0.26	3	0.3	0.08	7.80	
39	57	Cultivated, irrigated	0.30	3	0.3	0.09	6.02	17.74
		Natural	0.18	1	0.1	0.02	0.74	
		Degraded Vegetation	0.50	2	0.2	0.10	10.97	
		Urban industrial/transport	0.01	9	0.9	0.01	0.01	
40	38	Natural	0.03	1	0.1	0.00	0.03	39.66
		Degraded Vegetation	0.72	2	0.2	0.14	27.62	
		Cultivated, irrigated	0.39	3	0.3	0.12	12.02	
42	48	Natural	0.05	1	0.1	0.00	0.07	64.88

		Degraded Vegetation	0.16	2	0.2	0.03	1.73	
		Cultivated, irrigated	0.79	3	0.3	0.24	63.08	
44	45	Urban industrial/transport	0.00	9	0.9	0.00	0.00	16.65
		Degraded Vegetation	0.63	2	0.2	0.13	11.01	
		Cultivated, irrigated	0.37	3	0.3	0.11	5.63	
46(1)	53	Degraded Vegetation	0.30	2	0.2	0.06	9.78	83.52
		Cultivated, irrigated	0.68	3	0.3	0.20	73.73	
		Natural	0.01	1	0.1	0.00	0.01	
		Urban industrial/transport	0.00	9	0.9	0.00	0.00	
46(2)	69	Cultivated, irrigated	0.34	3	0.3	0.10	6.60	12.25
		Degraded Vegetation	0.28	2	0.2	0.06	3.07	
		Natural	0.37	1	0.1	0.04	2.57	
		Urban industrial/transport	0.01	9	0.9	0.01	0.01	
46(3)	70	Degraded Vegetation	0.19	2	0.2	0.04	1.58	15.84
		Cultivated, irrigated	0.40	3	0.3	0.12	10.59	
		Natural	0.41	1	0.1	0.04	3.68	
47	60	Natural	0.11	1	0.1	0.01	0.47	34.19
		Degraded Vegetation	0.56	2	0.2	0.11	22.29	
		Cultivated, irrigated	0.33	3	0.3	0.10	11.43	
48	58	Natural	0.03	1	0.1	0.00	0.02	24.92
		Degraded Vegetation	0.80	2	0.2	0.16	23.25	
		Cultivated, irrigated	0.17	3	0.3	0.05	1.66	
50	47	Cultivated, irrigated	0.65	3	0.3	0.19	95.69	113.35
		Degraded Vegetation	0.34	2	0.2	0.07	17.44	
		Mines and quarries	0.02	10	1 0	0.02	0.22	
51	52	Natural	0.19	1	0.1	0.02	0.66	18.46
		Degraded Vegetation	0.32	2	0.2	0.06	3.90	
		Cultivated, irrigated	0.49	3	0.3	0.15	13.90	
52	47	Cultivated, irrigated	0.65	3	0.3	0.19	95.69	113.35

		Degraded Vegetation	0.34	2	0.2	0.07	17.44	
		Mines and quarries	0.02	10	1	0.02	0.22	
			0.00		0	0.00	0.00	
53(1)	61	Natural	0.02	1	0.1	0.00	0.01	25.63
		Degraded Vegetation	0.70	2	0.2	0.14	21.60	
		Urban residential- high density	0.15	6	0.6	0.09	3.09	
		Urban industrial/transport	0.01	9	0.9	0.01	0.02	
		Cultivated, irrigated	0.12	3	0.3	0.04	0.91	
53(2)	67	Natural	0.00	1	0.1	0.00	0.00	63.58
		Degraded Vegetation	0.19	2	0.2	0.04	2.39	
		Cultivated, irrigated	0.79	3	0.3	0.24	61.13	
		Urban industrial/transport	0.01	9	0.9	0.01	0.06	
53(3)	68	Degraded Vegetation	0.10	2	0.2	0.02	0.30	40.63
		Cultivated, irrigated	0.90	3	0.3	0.27	40.33	
56	65	Cultivated, irrigated	0.61	3	0.3	0.18	26.26	30.97
		Degraded Vegetation	0.27	2	0.2	0.05	3.47	
		Urban industrial/transport	0.02	9	0.9	0.02	0.09	
		Urban residential- high density	0.09	6	0.6	0.05	1.15	
		Mines and quarries	0.01	10	1	0.01	0.01	
57	66	Urban residential- high density	0.02	6	0.6	0.01	0.06	17.39
		Urban industrial/transport	0.02	9	0.9	0.02	0.04	
		Natural	0.01	1	0.1	0.00	0.00	
		Degraded Vegetation	0.65	2	0.2	0.13	12.97	
		Cultivated, irrigated	0.30	3	0.3	0.09	4.32	
58	64	Natural	0.04	1	0.1	0.00	0.06	37.89
		Forest Plantations	0.00	2	0.2	0.00	0.00	
		Degraded Vegetation	0.41	2	0.2	0.08	10.38	
		Cultivated, irrigated	0.54	3	0.3	0.16	27.44	
62	71	Mines and quarries	0.00	10	1	0.00	0.00	91.89
		Degraded Vegetation	0.36	2	0.2	0.07	20.85	

		Natural	0.09	1	0.1	0.01	0.66	
		Cultivated, irrigated	0.54	3	0.3	0.16	70.37	

Table 42. Overall effectiveness scores of water quality enhancement for each wetland

Wetland	WQ Enhancement Ha Equiv.	WQ Impairment Ha Equiv.	WQ Impairment Ha Equiv.*3	Effectiveness
0	36.60	29.39	88.18	-51.58
1	35.21	20.58	61.75	-26.53
2	41.55	26.26	78.77	-37.22
3	14.22	40.86	122.59	-108.38
4	19.20	54.18	162.55	-143.35
5	25.77	34.30	102.90	-77.13
6	36.20	86.56	259.69	-223.50
8	7.23	21.90	65.69	-58.46
9	31.27	106.78	320.34	-289.08
10	6.72	32.64	97.91	-91.19
11	3.43	51.31	153.92	-150.49
12	4.58	13.42	40.25	-35.66
13	4.23	89.23	267.68	-263.45
14	3.76	50.16	150.49	-146.73
16	4.93	18.87	56.60	-51.67
17	2.54	127.11	381.33	-378.79
18	2.40	30.12	90.36	-87.96
21	1.77	32.22	96.67	-94.89
22(1)	3.96	16.96	50.87	-46.91
22(2)	6.18	28.31	84.92	-78.75
24	3.67	21.14	63.42	-59.75
25	2.21	91.49	274.48	-272.27
26	4.62	127.11	381.33	-376.71
27	33.87	29.75	89.24	-55.37
28	7.70	39.56	118.68	-110.98

29	7.67	48.46	145.38	-137.71
33	9.05	38.99	116.96	-107.91
35	5.26	106.09	318.28	-313.02
36	22.75	142.85	428.54	-405.78
38	9.15	47.40	142.19	-133.04
39	14.70	17.74	53.22	-38.52
40	5.56	39.66	118.99	-113.43
42	11.69	64.88	194.63	-182.94
44	4.93	16.65	49.94	-45.01
46(1)	33.98	83.52	250.56	-216.58
46(2)	13.38	12.25	36.75	-23.37
46(3)	11.65	15.84	47.52	-35.86
47	3.70	34.19	102.57	-98.87
48	5.61	24.92	74.75	-69.15
50	7.78	113.35	340.06	-332.28
51	2.79	18.46	55.39	-52.60
52	10.67	113.35	340.06	-329.38
53(1)	7.35	25.63	76.88	-69.53
53(2)	6.50	63.58	190.73	-184.22
53(3)	6.22	40.63	121.88	-115.66
56	10.23	30.97	92.91	-82.68
57	13.97	17.39	52.17	-38.20
58	17.19	37.89	113.67	-96.48
62	11.77	91.89	275.66	-263.89

Table 43. Overall catchment water quality enhancement effectiveness

W1			W2			W3			W4			W5			W6			W7	
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiven
1	-26.53	1	2	-37.22	1	4	-143.35	1	0	-51.58	1	21	-94.89	1	48	-69.15	1	35	-313
13	-263.45	1	8	-58.46	1							16	-51.67	1	38	-133.04	1	26	-376
			11	-150.49	1							18	-87.96	1	22(1)	-46.91	1	17	-378
															22(2)	-78.75	1		
															24	-59.75	1		
Line Total	-289.98			-246.17			-143.35			-51.58			-234.52			-387.60			-1068

W8			W9			W10			W11			W12			W13			W14	
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiven
52	-329.38	1	36	-405.78	1	3	-108.38	1	14	-146.73	1	6	-223.50	1	9	-289.08	1	53(2)	-184
50	-332.28	1	44	-45.01	1	5	-77.13	1										53(3)	-115
33	-107.91	1				10	-91.19	1										53(1)	-69
29	-137.71	2				12	-35.66	1											
Line Total	-907.28			-450.79			-312.36			-146.73			-223.50			-289.08			-369

W15			E1			E2			E3			E4			E5			E6	
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiven
57	-38.20	1	27	-55.37	1	39	-38.52	1	28	-110.98	1	25	-272.27	1	46(2)	-23.37	1	58	-96
56	-82.68	1	47	-98.87	1	42	-182.94	1							46(3)	-35.86	1		
			40	-113.43	2										51	-52.60	1		
															46(1)	-216.58	2		

Line Total	-120.88			-267.67			-221.46			-110.98			-272.27			-328.41			-9
CATCHMENT TOTAL **-6802.91**																			

Table 44. Current overall catchment water quality enhancement effectiveness for the eastern portion of the Goukou Catchment

Current Scenario

E1			E2			E3			E4			E5			E6			E7			
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	
27	-55.3719	1	39	-38.5172	1	28	-110.985	1	25	-272.27	1	46(2)	-23.3699	1	58	-96.48	1	62	-263.892	1	
47	-98.8663	1	42	-182.943	1							46(3)	-35.8648	1							
40	-113.43	2										51	-52.6036	1							
												46(1)	-216.579	2							
	-267.669			-221.46			-110.985			-272.27			-328.417			-96.48			-263.892		-1561.17

Table 4527. Scenario One: Prioritisation of wetlands based on land-cover

Wetland FID	Landcover in Wetland	Area of Wetland LC (ha)	Catchment FID	Landcover in Catchment	Area of Catchment LC (ha)	Areal Total
25	Natural	0.35	19	Natural	7.50	
	Cultivated, irrigated	0.81		Degraded Vegetation	339.21	
	Degraded Vegetation	2.04		Cultivated, irrigated	381.10	381.90
27	Degraded Vegetation	27.36	38	Natural	9.27	
	Natural	18.24		Degraded Vegetation	140.12	
				Cultivated, irrigated	114.02	114.02
28	Cultivated, irrigated	1.63	42	Natural	19.34	
	Forest Plantations	0.90		Degraded Vegetation	89.20	
	Natural	1.79		Cultivated, irrigated	182.26	
	Degraded Vegetation	6.46		Urban industrial/transport	2.41	183.89
39	Natural	4.92	57	Cultivated, irrigated	65.93	
	Degraded Vegetation	13.96		Natural	39.96	
	Cultivated, irrigated	1.58		Degraded Vegetation	108.97	67.52
40	Natural	4.87	38	Natural	8.36	
	Cultivated, irrigated	0.25		Degraded Vegetation	190.72	
	Degraded Vegetation	2.09		Cultivated, irrigated	102.72	102.97
42	Natural	5.72	48	Natural	15.36	
	Degraded Vegetation	10.11		Degraded Vegetation	53.74	0
46(1)	Degraded Vegetation	43.43	53	Degraded Vegetation	161.01	
	Natural	4.60		Cultivated, irrigated	360.89	
				Natural	7.26	
				Urban industrial/transport	0.81	360.89
46(2)	Natural	4.48	69	Cultivated, irrigated	64.57	
	Degraded Vegetation	13.92		Degraded Vegetation	53.92	
	Urban industrial/transport	0.09		Natural	69.84	
				Urban industrial/transport	1.17	64.57

46(3)	Cultivated, irrigated	0.42	70	Degraded Vegetation	41.58	
	Degraded Vegetation	8.26		Cultivated, irrigated	87.99	
	Natural	6.95		Natural	89.81	88.40
47	Degraded Vegetation	2.53	60	Natural	40.95	
	Natural	2.38		Degraded Vegetation	199.50	
				Cultivated, irrigated	116.62	116.62
51	Degraded Vegetation	3.50	52	Natural	35.39	
	Natural	1.29		Degraded Vegetation	60.94	
				Cultivated, irrigated	93.89	93.86
58	Degraded Vegetation	18.84	64	Natural	13.95	
	Natural	4.08		Forest Plantations	1.22	
	Cultivated, irrigated	1.23		Degraded Vegetation	127.04	
				Cultivated, irrigated	168.63	169.87
62	Natural	0.60	71	Mines and quarries	1.97	
	Degraded Vegetation	15.52		Degraded Vegetation	287.55	
	Cultivated, irrigated	0.77		Natural	72.26	
				Cultivated, irrigated	431.33	434.07

Table 46. Scenario One: Magnitude of impact scores for 'rehabilitated' catchments

Wetland	LC Category	Catchment Impacts											
		Area	Catchment ha	Extent	Inc Water In IS	Increased water inputs	Red Water In IS	Reduced water inputs	Inc WI - Red WI	Wetland LC	Area	Weland ha	Extent
25	Natural	7.50	727.80	0.01	0	0.00	0	0.00		Natural	0.35	3.20	0.11
	Degraded Vegetation	339.21	727.80	0.47	3	1.40				Natural	0.81	3.20	0.25
	Natural	381.10	727.80	0.52	0	0.00	0	0.00	1.40	Degraded Vegetation	2.04	3.20	0.64
28	Natural	19.34	293.21	0.07	0	0.00	0	0.00		Natural	1.63	10.79	0.15
	Degraded Vegetation	89.20	293.21	0.30	3	0.91				Forest Plantations	0.90	10.79	0.08
	Natural	182.26	293.21	0.62	0	0.00	0	0.00		Natural	1.79	10.79	0.17
	Urban industrial/transport	2.41	293.21	0.01	9	0.07			0.99	Degraded Vegetation	6.46	10.79	0.60
46(1)	Degraded Vegetation	161.01	529.96	0.30	3	0.91				Degraded Vegetation	43.43	48.04	0.90
	Natural	360.89	529.96	0.68	0	0.00	0	0.00		Natural	4.60	48.04	0.10
	Natural	7.26	529.96	0.01	0	0.00	0	0.00					
	Urban industrial/transport	0.81	529.96	0.00	9	0.01			0.93				
58	Natural	13.95	310.85	0.04	0	0.00	0	0.00		Degraded Vegetation	18.84	24.15	0.78
	Forest Plantations	1.22	310.85	0.00		0.00	9	0.04		Natural	4.08	24.15	0.17
	Degraded Vegetation	127.04	310.85	0.41	3	1.23				Natural	1.23	24.15	0.05
	Natural	168.63	310.85	0.54	0	0.00	0	0.00	1.19				
62	Natural	1.97	793.11	0.00	0	0.00	0	0.00		Natural	0.60	16.89	0.04
	Degraded Vegetation	287.55	793.11	0.36	3	1.09				Degraded Vegetation	15.52	16.89	0.92
	Natural	72.26	793.11	0.09	0	0.00	0	0.00		Natural	0.77	16.89	0.05
	Natural	431.33	793.11	0.54	0	0.00	0	0.00	1.09				

Table 4728. Scenario One: Final scores and hectare equivalents of water quality enhancement functionality for 'rehabilitated' catchments

Sediment Trapping					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
25	2.35	2.50	2.35	3.20	1.88
28	2.36	2.50	2.36	10.79	6.36
46(1)	2.28	2.50	2.28	48.04	27.42
58	2.31	2.50	2.31	24.15	13.97
62	2.28	2.50	2.28	16.89	9.62
Phosphate Trapping					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
25	3.16	3.50	3.16	3.20	2.52
28	3.18	3.50	3.18	10.79	8.57
46(1)	3.01	3.50	3.01	48.04	36.17
58	3.08	3.50	3.08	24.15	18.59
62	3.00	3.50	3.00	16.89	12.68
Nitrate Removal					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
25	3.16	3.50	3.16	3.20	2.52
28	3.18	3.50	3.18	10.79	8.57
46(1)	3.01	3.50	3.01	48.04	36.17
58	3.08	3.50	3.08	24.15	18.59
62	3.00	3.50	3.00	16.89	12.68
Toxicant Removal					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
25	3.16	3.50	3.16	3.20	2.52
28	3.18	3.50	3.18	10.79	8.57
46(1)	3.01	3.50	3.01	48.04	36.17
58	3.08	3.50	3.08	24.15	18.59
62	3.00	3.50	3.00	16.89	12.68

Wetland	Total Ha Equiv	WQ Ha Equiv
25	9.45	2.36
28	32.07	8.02
46(1)	135.92	33.98
58	69.74	17.43
62	47.67	11.92

Table 4829. Scenario One: Water quality impairment and overall effectiveness scores for 'rehabilitated' catchments

Wetland	LC Category in Catchment	Area of LCU	Extent	LCU Ratio	MOI	Ha Equiv	Final Impact Ha Equiv
25	Natural	7.50	0.01	0.1	0.00	0.01	
	Degraded Vegetation	339.21	0.47	0.2	0.09	31.62	
	Natural	381.10	0.52	0.1	0.05	19.96	51.58
28	Natural	19.34	0.07	0.1	0.01	0.13	
	Degraded Vegetation	89.20	0.30	0.2	0.06	5.43	
	Natural	182.26	0.62	0.1	0.06	11.33	
	Urban industrial/transport	2.41	0.01	0.9	0.01	0.02	16.90
46(1)	Degraded Vegetation	161.01	0.30	0.2	0.06	9.78	
	Natural	360.89	0.68	0.1	0.07	24.58	
	Natural	7.26	0.01	0.1	0.00	0.01	
	Urban industrial/transport	0.81	0.00	0.9	0.00	0.00	34.37
58	Natural	13.95	0.04	0.1	0.00	0.06	
	Forest Plantations	1.22	0.00	0.2	0.00	0.00	
	Degraded Vegetation	127.04	0.41	0.2	0.08	10.38	
	Natural	168.63	0.54	0.1	0.05	9.15	19.60
62	Natural	1.97	0.00	0.1	0.00	0.00	
	Degraded Vegetation	287.55	0.36	0.2	0.07	20.85	
	Natural	72.26	0.09	0.1	0.01	0.66	
	Natural	431.33	0.54	0.1	0.05	23.46	44.97

Wetland	WQ Enhancement Ha Equiv.	WQ Impairment Ha Equiv.	WQ Impairment Ha Equiv.*3	Effectiveness
25	2.36	51.58	154.74	-152.38
28	8.02	16.90	50.71	-42.69
46(1)	33.98	34.37	103.11	-69.13
58	17.43	19.60	58.79	-41.35
62	11.92	44.97	134.90	-122.98

Table 49. Scenario One: Overall catchment water quality enhancement effectiveness

Rehab Scenario																					
E1			E2			E3			E4			E5			E6			E7			
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	
27	-55.3719	1	39	-38.5172	1	28	-42.6902	1	25	-152.383	1	46(2)	-23.3699	1	58	-41.3518	1	62	-122.984	1	
47	-98.8663	1	42	-182.943	1							46(3)	-35.8648	1							
40	-113.43	2										51	-52.6036	1							
												46(1)	-69.1288	2							
	-267.669			-221.46			-42.6902			-152.383			-180.967			-41.3518			-122.984		-10

Table 30. Scenario Two: Prioritisation of wetlands based on current water quality enhancement effectiveness

Wetland	WQ Enhancement Ha Equiv.	WQ Impairment Ha Equiv.	WQ Impairment * 3	Effectiveness
25	2.21	91.49	274.48	-272.27
27	33.87	29.75	89.24	-55.37
28	7.70	39.56	118.68	-110.98
39	14.70	17.74	53.22	-38.52
40	5.56	39.66	118.99	-113.43
42	11.69	64.88	194.63	-182.94
46(1)	33.98	83.52	250.56	-216.58
46(2)	13.38	12.25	36.75	-23.37
46(3)	11.65	15.84	47.52	-35.86
47	3.70	34.19	102.57	-98.87
51	2.79	18.46	55.39	-52.60
58	17.19	37.89	113.67	-96.48
62	11.77	91.89	275.66	-263.89

Table 31. Scenario Two: Magnitude of impact scores for 'rehabilitated' catchments

Wetland	LC Category	Catchment Impacts						Wetland Impacts					
		Area	Catchment ha	Extent	Inc Water In IS	Increased water inputs	Inc WI - Red WI	Wetland LC	Area	Weland ha	Extent	Red Surface Rough IS	Reduced surface
25	Natural	7.50	727.80	0.01	0	0.00		Natural	0.35	3.20	0.11	0	
	Degraded Vegetation	339.21	727.80	0.47	3	1.40		Natural	0.81	3.20	0.25	0	
	Natural	381.10	727.80	0.52	0	0.00	1.40	Degraded Vegetation	2.04	3.20	0.64	3	
40	Natural	8.36	301.80	0.03	0	0.00		Natural	4.87	7.20	0.68	0	
	Degraded Vegetation	190.72	301.80	0.63	3	1.90		Natural	0.25	7.20	0.03	0	
	Natural	102.72	301.80	0.34	0	0.00	1.90	Degraded Vegetation	2.09	7.20	0.29	3	
42	Natural	15.36	334.17	0.05	0	0.00		Natural	5.72	15.83	0.36	0	
	Degraded Vegetation	53.74	334.17	0.16	3	0.48	0.48	Degraded Vegetation	10.11	15.83	0.64	3	
46(1)	Degraded Vegetation	161.01	529.96	0.30	3	0.91		Degraded Vegetation	43.43	48.04	0.90	3	
	Natural	360.89	529.96	0.68	0	0.00		Natural	4.60	48.04	0.10	0	
	Natural	7.26	529.96	0.01	0	0.00							
	Urban industrial/transport	0.81	529.96	0.00	9	0.01	0.92						
62	Natural	1.97	793.11	0.00	0	0.00		Natural	0.60	16.89	0.04	0	
	Degraded Vegetation	287.55	793.11	0.36	3	1.09		Degraded Vegetation	15.52	16.89	0.92	3	
	Natural	72.26	793.11	0.09	0	0.00		Natural	0.77	16.89	0.05	0	
	Natural	431.33	793.11	0.54	0	0.00	1.09						

Table 52. Scenario Two: Final scores and hectare equivalents of water quality enhancement functionality for 'rehabilitated' catchments

Sediment Trapping					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
25	2.35	2.50	2.35	3.20	1.88
40	2.43	2.50	2.43	7.20	4.37
42	2.35	2.50	2.35	15.83	9.29
46(1)	2.28	2.50	2.28	48.04	27.42
62	2.28	2.50	2.28	16.89	9.62
Phosphate Trapping					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
25	3.16	3.50	3.16	3.20	2.52
40	3.34	3.50	3.34	7.20	6.02
42	3.16	3.50	3.16	15.83	12.48
46(1)	3.01	3.50	3.01	48.04	36.17
62	3.00	3.50	3.00	16.89	12.68
Nitrate Removal					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
25	3.16	3.50	3.16	3.20	2.52
40	3.34	3.50	3.34	7.20	6.02
42	3.16	3.50	3.16	15.83	12.48
46(1)	3.01	3.50	3.01	48.04	36.17
62	3.00	3.50	3.00	16.89	12.68
Toxicant Removal					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
25	3.16	3.50	3.16	3.20	2.52
40	3.34	3.50	3.34	7.20	6.02
42	3.16	3.50	3.16	15.83	12.48
46(1)	3.01	3.50	3.01	48.04	36.17
62	3.00	3.50	3.00	16.89	12.68

Wetland	Total Ha Equiv	WQ Ha Equiv
25	9.45	2.36
40	22.43	5.61
42	46.74	11.69
46(1)	135.92	33.98
62	47.67	11.92

Table 53. Scenario Two: Water quality impairment and overall effectiveness scores for 'rehabilitated' catchments

Wetland	LC Category in Catchment	Area of LCU	Extent	LCU Ratio	MOI	Ha Equiv	Final Impact Ha Equiv
25	Natural	7.50	0.01	0.1	0.00	0.01	
	Degraded Vegetation	339.21	0.47	0.2	0.09	31.62	
	Natural	381.10	0.52	0.1	0.05	19.96	51.58
40	Natural	8.36	0.03	0.1	0.00	0.02	
	Degraded Vegetation	190.72	0.63	0.2	0.13	24.11	
	Natural	102.72	0.34	0.1	0.03	3.50	27.62
42	Natural	15.36	0.05	0.1	0.00	0.07	
	Degraded Vegetation	53.74	0.16	0.2	0.03	1.73	1.80
46(1)	Degraded Vegetation	161.01	0.30	0.2	0.06	9.78	
	Natural	360.89	0.68	0.1	0.07	24.58	
	Natural	7.26	0.01	0.1	0.00	0.01	
	Urban industrial/transport	0.81	0.00	0.9	0.00	0.00	34.37
62	Natural	1.97	0.00	0.1	0.00	0.00	
	Degraded Vegetation	287.55	0.36	0.2	0.07	20.85	
	Natural	72.26	0.09	0.1	0.01	0.66	
	Natural	431.33	0.54	0.1	0.05	23.46	44.97

Wetland	WQ Enhancement Ha Equiv.	WQ Impairment Ha Equiv.	WQ Impairment H
25	2.36	51.58	
40	5.61	27.62	
42	11.69	1.80	
46(1)	33.98	34.37	
62	11.92	44.97	

Table 54. Scenario Two: Overall catchment water quality enhancement effectiveness

Rehab Scenario

E1			E2			E3			E4			E5			E6			E7		
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order
27	-55.37	1	39	-38.52	1	28	-110.98	1	25	-152.38	1	46(2)	-23.37	1	58	-96.48	1	62	-122.98	1
47	-98.87	1	42	6.29	1							46(3)	-35.86	1						
40	-77.27	2										51	-52.60	1						
												46(1)	-69.13	2						
	-231.51			-32.23			-110.98			-152.38			-180.97			-96.48			-122.98	

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Table 55. Scenario Three: Prioritisation of wetlands based on current magnitude of impacts

Wetland	Catchment Impacts				Wetland Impacts	
	Total Catchment Area (excl wet)	Total Increased water inputs	Total Decreased water inputs	Overall magnitude of catchment impacts	Total Wetland Area	Total Increased water use
25	727.80	1.40	2.62	1.22	3.20	0.00
27	263.41	1.60	2.16	0.57	45.59	0.00
28	293.21	0.99	3.11	2.12	10.79	0.75
39	216.53	1.58	1.52	0.06	20.47	0.00
40	301.80	1.90	1.70	0.19	7.20	0.00
42	334.17	0.48	3.97	3.48	15.83	0.00
46(1)	529.96	0.93	3.40	2.48	48.04	0.00
46(2)	189.50	0.91	1.70	0.79	18.50	0.00
46(3)	219.37	0.57	2.01	1.44	15.63	0.00
47	357.08	1.68	1.63	0.04	4.92	0.00
51	190.21	0.96	2.47	1.51	4.79	0.00
58	310.85	1.23	2.75	1.52	24.15	0.00
62	793.11	1.10	2.72	1.62	16.89	0.00

Table 5632. Scenario Three: ‘New’ magnitude of impact scores for ‘rehabilitated’ wetlands

Wetland	LC Category	Catchment Impacts								
		Area	Catchment ha	Extent	Inc Water In IS	Increased water inputs	Total increased water in	Red Water In IS	Reduced water inputs	Total reduced wate
28	Natural	19.34	293.21	0.07	0	0.00		0	0.00	
	Degraded Vegetation	89.20	293.21	0.30	3	0.91				
	Cultivated, irrigated	182.26	293.21	0.62				5	3.11	
	Urban industrial/transport	2.41	293.21	0.01	9	0.07	0.99			
42	Natural	15.36	334.17	0.05	0	0.00		0	0.00	
	Degraded Vegetation	53.74	334.17	0.16	3	0.48	0.48			
46(1)	Degraded Vegetation	161.01	529.96	0.30	3	0.91				
	Cultivated, irrigated	360.89	529.96	0.68				5	3.40	
	Natural	7.26	529.96	0.01	0	0.00		0	0.00	
	Urban industrial/transport	0.81	529.96	0.00	9	0.01	0.93			
51	Natural	35.39	190.21	0.19	0	0.00		0	0.00	
	Degraded Vegetation	60.94	190.21	0.32	3	0.96				
	Cultivated, irrigated	93.89	190.21	0.49			0.96	5	2.47	
62	Mines and quarries	1.97	793.11	0.00	5	0.01				
	Degraded Vegetation	287.55	793.11	0.36	3	1.09				
	Natural	72.26	793.11	0.09	0	0.00		0	0.00	
	Cultivated, irrigated	431.33	793.11	0.54			1.10	5	2.72	

Table 57. Scenario Three: Final scores and hectare equivalents of water quality enhancement functionality for 'rehabilitated' wetlands

Sediment Trapping					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
28	2.45	2.50	2.45	10.79	6.62
42	2.50	2.50	2.50	15.83	9.89
46(1)	2.50	2.50	2.50	48.04	30.02
51	2.50	2.50	2.50	4.79	2.99
62	2.50	2.50	2.50	16.89	10.56
Phosphate Trapping					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
28	3.39	3.50	3.39	10.79	9.16
42	3.50	3.50	3.50	15.83	13.85
46(1)	3.50	3.50	3.50	48.04	42.03
51	3.50	3.50	3.50	4.79	4.19
62	3.50	3.50	3.50	16.89	14.78
Nitrate Removal					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
28	3.39	3.12	3.12	10.79	8.42
42	3.50	3.50	3.50	15.83	13.85
46(1)	3.50	3.06	3.06	48.04	36.69
51	3.50	3.23	3.23	4.79	3.86
62	3.50	3.21	3.21	16.89	13.55
Toxicant Removal					
Wetland	Resolved onsite functionality	Catchment functionality	Final functionality score	Wetland Size (ha)	Functional Ha Equiv
28	3.39	3.50	3.39	10.79	9.16
42	3.50	3.50	3.50	15.83	13.85
46(1)	3.50	3.50	3.50	48.04	42.03
51	3.50	3.50	3.50	4.79	4.19
62	3.50	3.50	3.50	16.89	14.78

Wetland	Total Ha Equiv	WQ Ha Equiv
28	33.35	8.34
42	51.44	12.86
46(1)	150.78	37.69
51	15.24	3.81
62	53.66	13.41

Table 58. Scenario Three: Water quality impairment and overall effectiveness scores for 'rehabilitated' catchments

Wetland	LC Category in Catchment	Area of LCU	Extent	LCU Ratio	MOI	Ha Equiv	Final Impact Ha Equiv
28	Natural	19.34	0.07	0.1	0.01	0.13	
	Degraded Vegetation	89.20	0.30	0.2	0.06	5.43	
	Cultivated, irrigated	182.26	0.62	0.3	0.19	33.99	
	Urban industrial/transport	2.41	0.01	0.9	0.01	0.02	39.56
42	Natural	15.36	0.05	0.1	0.00	0.07	
	Degraded Vegetation	53.74	0.16	0.2	0.03	1.73	1.80
46(1)	Degraded Vegetation	161.01	0.30	0.2	0.06	9.78	
	Cultivated, irrigated	360.89	0.68	0.3	0.20	73.73	
	Natural	7.26	0.01	0.1	0.00	0.01	
	Urban industrial/transport	0.81	0.00	0.9	0.00	0.00	83.52
51	Natural	35.39	0.19	0.1	0.02	0.66	
	Degraded Vegetation	60.94	0.32	0.2	0.06	3.90	
	Cultivated, irrigated	93.89	0.49	0.3	0.15	13.90	18.46
62	Mines and quarries	1.97	0.00	1	0.00	0.00	
	Degraded Vegetation	287.55	0.36	0.2	0.07	20.85	
	Natural	72.26	0.09	0.1	0.01	0.66	
	Cultivated, irrigated	431.33	0.54	0.3	0.16	70.37	91.89

Wetland	WQ Enhancement Ha Equiv.	WQ Impairment Ha Equiv.	WQ Impairment Ha Equiv.*3	Effectiveness
28	8.34	39.56	118.68	-110.34
42	12.86	1.80	5.40	7.46
46(1)	37.69	83.52	250.56	-212.87
51	3.81	18.46	55.38	-51.57
62	13.41	91.89	275.67	-262.26

Table 5933. Scenario Three: Overall catchment water quality enhancement effectiveness

Post-rehabilitation Scenario																		
E1			E2			E3			E4			E5			E6			
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID
27	-55.3719	1	39	-38.5172	1	28	-110.344	1	25	-272.27	1	46(2)	-23.3699	1	58	-96.48	1	62
47	-98.8663	1	42	7.460331	1							46(3)	-35.8648	1				
40	-113.43	2										51	-51.5708	1				
												46(1)	-212.866	2				
	-267.669			-31.0569			-110.344			-272.27			-323.672			-96.48		

Table 60. Prioritisation of wetlands in the Goukou Catchment based on current water quality enhancement effectiveness

Wetland	WQ Enhancement Ha Equiv.	WQ Impairment Ha Equiv.	WQ Impairment Ha Equiv.*3	Effectiveness
46(2)	13.38	12.25	36.75	-23.37
1	35.21	20.58	61.75	-26.53
12	4.58	13.42	40.25	-35.66
46(3)	11.65	15.84	47.52	-35.86
2	41.55	26.26	78.77	-37.22
57	13.97	17.39	52.17	-38.20
39	14.70	17.74	53.22	-38.52
44	4.93	16.65	49.94	-45.01
22(1)	3.96	16.96	50.87	-46.91
0	36.60	29.39	88.18	-51.58
16	4.93	18.87	56.60	-51.67
51	2.79	18.46	55.39	-52.60
27	33.87	29.75	89.24	-55.37
8	7.23	21.90	65.69	-58.46
24	3.67	21.14	63.42	-59.75
48	5.61	24.92	74.75	-69.15
53(1)	7.35	25.63	76.88	-69.53
5	25.77	34.30	102.90	-77.13
22(2)	6.18	28.31	84.92	-78.75
56	10.23	30.97	92.91	-82.68
18	2.40	30.12	90.36	-87.96
10	6.72	32.64	97.91	-91.19
21	1.77	32.22	96.67	-94.89
58	17.19	37.89	113.67	-96.48
47	3.70	34.19	102.57	-98.87
33	9.05	38.99	116.96	-107.91
3	14.22	40.86	122.59	-108.38
28	7.70	39.56	118.68	-110.98
40	5.56	39.66	118.99	-113.43
53(3)	6.22	40.63	121.88	-115.66
38	9.15	47.40	142.19	-133.04
29	7.67	48.46	145.38	-137.71
4	19.20	54.18	162.55	-143.35
14	3.76	50.16	150.49	-146.73
11	3.43	51.31	153.92	-150.49
42	11.69	64.88	194.63	-182.94
53(2)	6.50	63.58	190.73	-184.22
46(1)	33.98	83.52	250.56	-216.58
6	36.20	86.56	259.69	-223.50
13	4.23	89.23	267.68	-263.45
62	11.77	91.89	275.66	-263.89
25	2.21	91.49	274.48	-272.27
9	31.27	106.78	320.34	-289.08

35	5.26	106.09	318.28	-313.02
52	10.67	113.35	340.06	-329.38
50	7.78	113.35	340.06	-332.28
26	4.62	127.11	381.33	-376.71
17	2.54	127.11	381.33	-378.79
36	22.75	142.85	428.54	-405.78

Table 61. Post-rehabilitation magnitude of impact scores for ‘rehabilitated’ catchments of the Goukou Catchment

Wetland	LC Category	Catchment Impacts										Wetland Impacts								
		Area	Catchment ha	Extent	Inc Water In IS	Increased water inputs	Sum Inc water inputs	Red Water In IS	Reduced water inputs	Sum red water inputs	Inc WI - Red WI	Wetland LC	Area	Weland ha	Extent	Inc water loss IS	Inc water loss	Red Surface Rough IS	Reduced surface roughness	Total red surface roughness
58	Natural	13.95	310.85	0.04	0	0.00		0	0.00			Degraded Vegetation	18.84	24.15	0.78			3	2.34	
	Forest Plantations	1.22	310.85	0.00				9	0.04			Natural	4.08	24.15	0.17	0	0.00	0	0.00	
	Degraded Vegetation	127.04	310.85	0.41	3	1.23						Natural	1.23	24.15	0.05	0	0.00	0	0.00	
	Natural	168.63	310.85	0.54	0	0.00	1.23	0	0.00	0.04	1.19								0.00	2.34
47	Natural	40.95	357.08	0.11	0	0.00		0	0.00			Degraded Vegetation	2.53	4.92	0.52			3	1.55	
	Degraded Vegetation	199.50	357.08	0.56	3	1.68						Natural	2.38	4.92	0.48	0	0.00	0	0.00	
	Natural	116.62	357.08	0.33	0	0.00	1.68	0	0.00	0.00	1.68								0.00	1.55
33	Urban industrial/transport	0.50	150.24	0.00	9	0.03						Natural	3.43	12.76	0.27	0	0.00	0	0.00	
	Degraded Vegetation	10.26	150.24	0.07	3	0.20						Degraded Vegetation	6.57	12.76	0.52			3	1.55	
	Natural	139.48	150.24	0.93	0	0.00		0	0.00			Natural	2.67	12.76	0.21	0	0.00	0	0.00	
							0.24			0.00	0.24	Urban industrial/transport	0.09	12.76	0.01			9	0.06	1.61
3	Natural	23.42	268.29	0.09	0	0.00		0	0.00			Natural	8.57	19.71	0.43	0	0.00	0	0.00	
	Natural	184.12	268.29	0.69	0	0.00		0	0.00			Natural	6.50	19.71	0.33	0	0.00	0	0.00	
	Degraded Vegetation	60.74	268.29	0.23	3	0.68	0.68			0.00	0.68	Degraded Vegetation	4.64	19.71	0.24			3	0.71	0.71
28	Natural	19.34	293.21	0.07	0	0.00		0	0.00			Natural	1.63	10.79	0.15	0	0.00	0	0.00	
	Degraded Vegetation	89.20	293.21	0.30	3	0.91						Forest Plantations	0.90	10.79	0.08	9	0.75		0.00	
	Natural	182.26	293.21	0.62	0	0.00		0	0.00			Natural	1.79	10.79	0.17	0	0.00	0	0.00	
	Urban industrial/transport	2.41	293.21	0.01	9	0.07	0.99			0.00	0.99	Degraded Vegetation	6.46	10.79	0.60			3	1.80	1.80
40	Natural	8.36	301.80	0.03	0	0.00		0	0.00			Natural	4.87	7.20	0.68	0	0.00	0	0.00	
	Degraded Vegetation	190.72	301.80	0.63	3	1.90						Natural	0.25	7.20	0.03	0	0.00	0	0.00	

	Natural	102.72	301.80	0.34	0	0.00	1.90	0	0.00	0.00	1.90	Degraded Vegetation	2.09	7.20	0.29			3	0.87	0.87
53(3)	Degraded Vegetation	15.67	164.27	0.10	3	0.29						Degraded Vegetation	7.50	8.73	0.86			3	2.58	
	Natural	148.60	164.27	0.90	0	0.00	0.29	0	0.00	0.00	0.29	Natural	1.23	8.73	0.14	0	0.00	0	0.00	2.58
38	Natural	3.44	374.31	0.01	0	0.00		0	0.00			Natural	2.72	12.69	0.21	0	0.00	0	0.00	
	Degraded Vegetation	272.21	374.31	0.73	3	2.18						Degraded Vegetation	9.97	12.69	0.79			3	2.36	
	Natural	98.66	374.31	0.26	0	0.00	2.18	0	0.00	0.00	2.18								0.00	2.36
29	Urban industrial/transport	0.86	190.03	0.00	9	0.04						Natural	2.67	10.97	0.24	0	0.00	0	0.00	
	Natural	9.31	190.03	0.05	0	0.00		0	0.00			Degraded Vegetation	4.75	10.97	0.43			3	1.30	
	Degraded Vegetation	4.79	190.03	0.03	3	0.08						Natural	3.56	10.97	0.32	0	0.00	0	0.00	
	Natural	175.07	190.03	0.92	0	0.00	0.12	0	0.00	0.00	0.12								0.00	1.30
4	Natural	114.81	449.79	0.26	0	0.00		0	0.00			Natural	3.64	27.21	0.13	0	0.00	0	0.00	
	Natural	272.47	449.79	0.61	0	0.00		0	0.00			Degraded Vegetation	18.95	27.21	0.70			3	2.09	
	Degraded Vegetation	62.51	449.79	0.14	3	0.42	0.42			0.00	0.42	Natural	4.62	27.21	0.17	0	0.00	0	0.00	2.09
14	Degraded Vegetation	209.30	419.81	0.50	3	1.50						Degraded Vegetation	1.95	5.19	0.38			3	1.13	
	Natural	202.39	419.81	0.48	0	0.00		0	0.00			Natural	1.23	5.19	0.24	0	0.00	0	0.00	
	Natural	2.34	419.81	0.01	0	0.00		0	0.00			Natural	2.02	5.19	0.39	0	0.00	0	0.00	
	Forest Plantations	3.17	419.81	0.01		0.00		9	0.07										0.00	
	Urban industrial/transport	2.61	419.81	0.01	9	0.06	1.55			0.07	1.48								0.00	1.13
11	Degraded Vegetation	132.17	353.91	0.37	3	1.12						Degraded Vegetation	3.41	5.09	0.67			3	2.01	
	Natural	221.09	353.91	0.62	0	0.00		0	0.00			Natural	0.08	5.09	0.02	0	0.00	0	0.00	
	Natural	0.65	353.91	0.00	0	0.00	1.12	0	0.00	0.00	1.12	Natural	1.60	5.09	0.31	0	0.00	0	0.00	2.01
42	Natural	15.36	334.17	0.05	0	0.00		0	0.00			Natural	5.72	15.83	0.36	0	0.00	0	0.00	
	Degraded Vegetation	53.74	334.17	0.16	3	0.48						Degraded Vegetation	10.11	15.83	0.64			3	1.92	
	Natural	265.07	334.17	0.79	0	0.00	0.48	0	0.00	0.00	0.48								0.00	1.92

53(2)	Natural	0.28	323.86	0.00	0	0.00		0	0.00			Degraded Vegetation	7.96	9.14	0.87			3	2.61	
	Degraded Vegetation	62.16	323.86	0.19	3	0.58						Natural	1.19	9.14	0.13	0	0.00	0	0.00	
	Natural	256.89	323.86	0.79	0	0.00		0	0.00										0.00	
	Urban industrial/transport	4.52	323.86	0.01	9	0.13	0.70			0.00	0.70								0.00	2.61
46(1)	Degraded Vegetation	161.01	529.96	0.30	3	0.91						Degraded Vegetation	43.43	48.04	0.90			3	2.71	
	Natural	360.89	529.96	0.68	0	0.00		0	0.00			Natural	4.60	48.04	0.10	0	0.00	0	0.00	
	Natural	7.26	529.96	0.01	0	0.00		0	0.00										0.00	
	Urban industrial/transport	0.81	529.96	0.00	9	0.01	0.93			0.00	0.93								0.00	2.71
6	Natural	16.83	634.86	0.03	0	0.00		0	0.00			Natural	18.67	49.14	0.38	0	0.00	0	0.00	
	Degraded Vegetation	235.97	634.86	0.37	3	1.12						Degraded Vegetation	28.01	49.14	0.57			3	1.71	
	Natural	382.06	634.86	0.60	0	0.00	1.12	0	0.00	0.00	1.12	Natural	2.46	49.14	0.05	0	0.00	0	0.00	1.71
13	Degraded Vegetation	422.77	779.85	0.54	3	1.63						Natural	0.74	6.15	0.12	0	0.00	0	0.00	
	Natural	21.47	779.85	0.03	0	0.00		0	0.00			Degraded Vegetation	5.42	6.15	0.88			3	2.64	
	Natural	335.61	779.85	0.43	0	0.00	1.63	0	0.00	0.00	1.63								0.00	2.64
62	Natural	1.97	793.11	0.00	0	0.00		0	0.00			Natural	0.60	16.89	0.04	0	0.00	0	0.00	
	Degraded Vegetation	287.55	793.11	0.36	3	1.09						Degraded Vegetation	15.52	16.89	0.92			3	2.76	
	Natural	72.26	793.11	0.09	0	0.00		0	0.00			Natural	0.77	16.89	0.05	0	0.00	0	0.00	
	Natural	431.33	793.11	0.54	0	0.00	1.09	0	0.00	0.00	1.09								0.00	2.76
25	Natural	7.50	727.80	0.01	0	0.00		0	0.00			Natural	0.35	3.20	0.11	0	0.00	0	0.00	
	Degraded Vegetation	339.21	727.80	0.47	3	1.40						Natural	0.81	3.20	0.25	0	0.00	0	0.00	
	Natural	381.10	727.80	0.52	0	0.00	1.40	0	0.00	0.00	1.40	Degraded Vegetation	2.04	3.20	0.64			3	1.92	1.92
9	Urban industrial/transport	4.82	608.98	0.01	9	0.07						Natural	8.17	44.02	0.19	0	0.00	0	0.00	
	Residential - rural	0.98	608.98	0.00	3	0.00						Natural	10.75	44.02	0.24	0	0.00	0	0.00	
	Natural	15.21	608.98	0.02	0	0.00		0	0.00			Degraded Vegetation	25.09	44.02	0.57			3	1.71	
	Degraded Vegetation	136.00	608.98	0.22	3	0.67													0.00	

	Natural	451.97	608.98	0.74	0	0.00	0.75	0	0.00	0.00	0.75								0.00	1.71
35	Degraded Vegetation	406.99	846.90	0.48	3	1.44						Natural	5.60	8.10	0.69	0	0.00	0	0.00	
	Natural	436.47	846.90	0.52	0	0.00		0	0.00			Natural	0.50	8.10	0.06	0	0.00	0	0.00	
	Natural	3.45	846.90	0.00	0	0.00	1.44	0	0.00	0.00	1.44	Degraded Vegetation	1.99	8.10	0.25			3	0.74	0.74
52	Natural	494.19	762.38	0.65	0	0.00		0	0.00			Degraded Vegetation	10.20	14.62	0.70			3	2.09	
	Degraded Vegetation	258.43	762.38	0.34	3	1.02						Natural	0.79	14.62	0.05	0	0.00	0	0.00	
	Natural	13.08	762.38	0.02	0	0.00		0	0.00			Natural	3.58	14.62	0.24	0	0.00	0	0.00	
							1.02			0.00	1.02	Urban industrial/transport	0.06	14.62	0.00			9	0.04	2.13
50	Natural	494.19	765.70	0.65	0	0.00		0	0.00			Natural	0.09	11.30	0.01	0	0.00	0	0.00	
	Degraded Vegetation	258.43	765.70	0.34	3	1.01						Natural	0.84	11.30	0.07	0	0.00	0	0.00	
	Natural	13.08	765.70	0.02	0	0.00		0	0.00			Degraded Vegetation	8.27	11.30	0.73			3	2.19	
							1.01			0.00	1.01	Natural	2.11	11.30	0.19	0	0.00	0	0.00	2.19
26	Degraded Vegetation	302.87	847.85	0.36	3	1.07						Natural	0.23	7.15	0.03	0	0.00	0	0.00	
	Natural	547.16	847.85	0.65	0	0.00		0	0.00			Degraded Vegetation	1.88	7.15	0.26			3	0.79	
	Urban industrial/transport	0.91	847.85	0.00	9	0.01	1.08			0.00	1.08	Natural	5.04	7.15	0.70	0	0.00	0	0.00	0.79
17	Degraded Vegetation	302.87	850.94	0.36	3	1.07						Natural	3.53	4.06	0.87	0	0.00	0	0.00	
	Natural	547.16	850.94	0.64	0	0.00		0	0.00			Urban industrial/transport	0.05	4.06	0.01			9	0.12	
	Urban industrial/transport	0.91	850.94	0.00	9	0.01	1.08			0.00	1.08	Degraded Vegetation	0.48	4.06	0.12			3	0.35	0.47
36	Natural	533.68	604.73	0.88	0	0.00		0	0.00			Natural	2.70	32.27	0.08	0	0.00	0	0.00	
	Degraded Vegetation	68.19	604.73	0.11	3	0.34						Degraded Vegetation	29.44	32.27	0.91			3	2.74	
	Urban industrial/transport	2.85	604.73	0.00	9	0.04	0.38			0.00	0.38	Urban industrial/transport	0.13	32.27	0.00			9	0.04	2.77

Table 62. Post-rehabilitation water quality impairment and overall effectiveness scores for 'rehabilitated' catchments for the Goukou Catchment

Extent	LCU Ratio	MOI	Ha Equiv	Final Impact Ha Equiv
0.04	0.1	0.00	0.06	
0.00	0.2	0.00	0.00	
0.41	0.2	0.08	10.38	
0.54	0.1	0.05	9.15	19.60
0.11	0.1	0.01	0.47	
0.56	0.2	0.11	22.29	
0.33	0.1	0.03	3.81	26.57
0.00	0.9	0.00	0.00	
0.07	0.2	0.01	0.14	
0.93	0.1	0.09	12.95	
				13.09
0.09	0.1	0.01	0.20	
0.69	0.1	0.07	12.64	
0.23	0.2	0.05	2.75	15.59
0.07	0.1	0.01	0.13	
0.30	0.2	0.06	5.43	
0.62	0.1	0.06	11.33	
0.01	0.9	0.01	0.02	16.90
0.03	0.1	0.00	0.02	
0.63	0.2	0.13	24.11	
0.34	0.1	0.03	3.50	27.62
0.10	0.2	0.02	0.30	
0.90	0.1	0.09	13.44	13.74
0.01	0.1	0.00	0.00	
0.73	0.2	0.15	39.59	
0.26	0.1	0.03	2.60	42.20
0.00	0.9	0.00	0.00	
0.05	0.1	0.00	0.05	
0.03	0.2	0.01	0.02	
0.92	0.1	0.09	16.13	16.20
0.26	0.1	0.03	2.93	
0.61	0.1	0.06	16.51	
0.14	0.2	0.03	1.74	21.17
0.50	0.2	0.10	20.87	
0.48	0.1	0.05	9.76	
0.01	0.1	0.00	0.00	
0.01	0.2	0.00	0.00	
0.01	0.9	0.01	0.01	30.65
0.37	0.2	0.07	9.87	
0.62	0.1	0.06	13.81	
0.00	0.1	0.00	0.00	23.68

Wetland	WQ Enhancement Ha Equiv.	WQ Impairment Ha Equiv.	WQ Impairment Ha Equiv.*3	Effectiveness
58	17.43	19.60	58.79	-41.35
47	3.70	26.57	79.71	-76.01
33	9.57	13.09	39.27	-29.70
3	15.48	15.59	46.77	-31.30
28	8.02	16.90	50.71	-42.69
40	5.61	27.62	82.87	-77.27
53(3)	6.22	13.74	41.23	-35.01
38	9.15	42.20	126.59	-117.43
29	8.36	16.20	48.61	-40.25
4	19.91	21.17	63.52	-43.61
14	3.99	30.65	91.94	-87.95
11	3.74	23.68	71.05	-67.31
42	11.69	22.82	68.47	-56.79
53(2)	6.50	22.82	68.46	-61.96
46(1)	33.98	34.37	103.11	-69.13
6	36.67	40.58	121.74	-85.07
13	4.37	60.34	181.02	-176.65
62	11.92	44.97	134.90	-122.98
25	2.36	51.58	154.74	-152.38
9	32.85	39.69	119.08	-86.23
35	6.35	61.61	184.84	-178.49
52	10.67	49.58	148.73	-138.05
50	8.22	49.36	148.08	-139.86
26	5.59	56.95	170.85	-165.26
17	3.22	56.74	170.23	-167.01
36	22.75	48.65	145.95	-123.19

0.05	0.1	0.00	0.07	
0.16	0.2	0.03	1.73	
0.79	0.1	0.08	21.03	22.82
0.00	0.1	0.00	0.00	
0.19	0.2	0.04	2.39	
0.79	0.1	0.08	20.38	
0.01	0.9	0.01	0.06	22.82
0.30	0.2	0.06	9.78	
0.68	0.1	0.07	24.58	
0.01	0.1	0.00	0.01	
0.00	0.9	0.00	0.00	34.37
0.03	0.1	0.00	0.04	
0.37	0.2	0.07	17.54	
0.60	0.1	0.06	22.99	40.58
0.54	0.2	0.11	45.84	
0.03	0.1	0.00	0.06	
0.43	0.1	0.04	14.44	60.34
0.00	0.1	0.00	0.00	
0.36	0.2	0.07	20.85	
0.09	0.1	0.01	0.66	
0.54	0.1	0.05	23.46	44.97
0.01	0.1	0.00	0.01	
0.47	0.2	0.09	31.62	
0.52	0.1	0.05	19.96	51.58
0.01	0.9	0.01	0.03	
0.00	0.5	0.00	0.00	
0.02	0.1	0.00	0.04	
0.22	0.2	0.04	6.07	
0.74	0.1	0.07	33.54	39.69
0.48	0.2	0.10	39.12	
0.52	0.1	0.05	22.49	
0.00	0.1	0.00	0.00	61.61
0.65	0.1	0.06	32.03	
0.34	0.2	0.07	17.52	
0.02	0.1	0.00	0.02	
				49.58
0.65	0.1	0.06	31.90	
0.34	0.2	0.07	17.44	
0.02	0.1	0.00	0.02	
				49.36
0.36	0.2	0.07	21.64	
0.65	0.1	0.06	35.31	
0.00		0.00	0.00	56.95
0.36	0.2	0.07	21.56	
0.64	0.1	0.06	35.18	
0.00	0.9	0.00	0.00	56.74

0.88	0.1	0.09	47.10	
0.11	0.2	0.02	1.54	
0.00	0.9	0.00	0.01	48.65

Table 63. Post-rehabilitation overall catchment water quality enhancement effectiveness for the Goukou Catchment

W1			W2			W3			W4			W5		
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	O
1	-26.53	1	2	-37.22	1	4	-43.61	1	0	-51.58	1	21	-94.89	
13	-176.65	1	8	-58.46	1							16	-51.67	
			11	-67.31	1							18	-87.96	
Line Total	-203.18			-162.99			-43.61			-51.58			-234.52	

W8			W9			W10			W11			W12		
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	O
52	-138.05	1	36	-123.19	1	3	-31.30	1	14	-87.95	1	6	-85.07	
50	-139.86	1	44	-45.01	1	5	-77.13	1						
33	-29.70	1				10	-91.19	1						
29	-40.25	2				12	-35.66	1						
Line Total	-347.86			-168.20			-235.28			-87.95			-85.07	

W15			E1			E2			E3			E4		
Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	Order	Wetland FID	Effectiveness	O
57	-38.2	1	27	-55.37	1	39	-38.52	1	28	-42.69	1	25	-152.38	
56	-82.68	1	47	-76.01	1	42	-56.79	1						
			40	-77.27	2									
Line Total	-120.88			-208.65			-95.31			-42.69			-152.38	

CATCHMENT TOTAL
-3720.91