The Ecological and Functional Assessment of Wetlands: Case Study of a Constructed Wetland, Dundee, KwaZulu-Natal

By

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ABSTRACT

This dissertation focused on the constructed wetland at a disused coal mine in Dundee, KwaZulu-Natal. A sequence of 10 wetland cells was constructed by the Department of Water and Sanitation (DWS) to remediate seepage from the mine. The main aspects that this dissertation is focused on are the water quality and geochemistry of the wetland; the ability of the wetland in providing ecological goods and services, and the rehabilitation of the wetland system.

The results of the water quality analysis revealed that the water in the system is of inferior quality. Several of the parameters exceeded South African water quality standards indicating that the water is detrimental to aquatic health and neither is it suitable for human consumption. The geochemical analysis revealed that whilst heavy metals are present in the sediments the enrichment factor (EF) values are low although certain elements may be bioavailable. This possibility is enhanced by the predominance of larger grained sediment which have low adsorption capacities, allowing for relatively easy remobilisation into the water column. PCA analysis indicated a predominance of some heavy metals in the wetland cells but that this was influenced by anthropogenic impacts via discard coal. The ability of the wetland system in providing ecosystem goods and services was found to be compromised due to the wetland being in a state of malfunction.

The final part of this dissertation comprises of a proposed rehabilitation plan for the constructed wetland. The rehabilitation plan focuses on the causes of degradation of the system due to the prolonged lack of maintenance and monitoring resulting in dysfunctional connectivity of wetland cells; inhibition of wetland conditions; the proliferation of terrestrial and alien invasive plants and, the inappropriate original structural composition of the basal sediments used which initially would have worked counter to the original intention to reduce acidity of mine derived groundwater. The rehabilitation plan is intended to aid in the re-establishment of hydrological, geomorphological and ecological processes in the wetland system.

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

Signed: _______________

Name: Dr Srinivasan Pillay

Date: _________________

PREFACE

The experimental work described in this dissertation was carried out in the School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Durban, Westville, from February 2017 to November 2018, under the supervision of Dr. Srinivasan Pillay and Dr. Kuben Naidoo.

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 1 - PLAGIARISM

I, Nivarya Naidoo, declare that

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

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

3. This thesis 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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DECLARATION 2 - PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, *in press* and published and give details of the contributions of each author to the experimental work and writing of each publication)

Publication 1

Naidoo, N., Pillay, S., Naidoo, K. & Naicker, D. A study of the functional efficiency of a series of constructed wetlands in the remediation of acid mine drainage. *In Prep.*

Publication 2

Naidoo, N., Pillay, S. & Naicker, D. Heavy metal analysis of sediment and water in a constructed wetland, Dundee, South Africa. *In Prep.*

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List of Abbreviations

AEV – Acute Effect Value

AIPs – Alien Invasive Plants

AMD – Acid Mine Drainage

BOD – Biochemical / Biological Oxygen Demand

CEV – Chronic Effect Value

COD – Chemical Oxygen Demand

DAFF - Departments of Agriculture, Forestry and Fishery

DEA - Departments of Environmental Affairs

DO – Dissolved Oxygen

DOM - Dissolved Organic Matter

DWA – Department of Water Affairs

DWAF – Department of Water Affairs and Forestry

DWS - Departments Water and Sanitation

EC – Electrical Conductivity

ECO – Environmental Control Officer

EF – Enrichment Factor

ENSO – El Nino Southern Oscillation

EPA – Environmental Protection Agency

FWSF – Free Water Surface Flow

GPS – Global Positioning System

HCW - Hybrid Constructed Wetlands

HGM – Hydrogeomorphic

HLR – Hydraulic Loading Rate

HSSF - Horizontal Sub-surface Flow

ICP-OES - Inductively-Coupled Plasma Optical Emission Spectrometry

IPCC – Intergovernmental Panel on Climate Change

IWMI – International Water Management Institute

KZN – KwaZulu-Natal

LOI – Loss on Ignition

NBA – National Biodiversity Assessment

NEMA - National Environmental Management Act

NWA – National Water Act

PCA – Principal Component Analysis

PES – Present Ecological State

QC – Quality Control

SA – South Africa

SANBI - South African National Biodiversity Institute

SAWQG – South African Water Quality Guidelines

SOC – Soil Organic Carbon

SSF – Sub-surface Flow

TDS – Total Dissolved Solids

TSS – Total Suspended Solids

TWQR – Target Water Quality Range

USA – United States of America

VSSF - Vertical Sub-surface Flow

WHO – World Health Organization

List of Units

°C – Degrees Celsius

g – Grams

Hz – Hertz

km – Kilometres

m – Metres

mg/L – Milligrams per litre

ml – Millilitres

mm – Millimetres

μg/g – Micrograms per gram

μm – Micrometres

μS/cm – Microsiemens per centimetre

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Chapter 1: Introduction

1.1. Introduction

Wetlands can exist in all climate zones, from the tropics to the tundra, with Antarctica being the only continent that has no wetlands (Mitra *et al*., 2005). Wetland systems provide several functions and ecosystem services and are immensely valuable (Mitra *et al*., 2005). They occupy approximately 4-6% of the world's land area; however they contain around 12% of the global carbon pool (Watson *et al*., 1996; Ferrati *et al*., 2005; Mitra *et al*., 2005; Erwin, 2009). Wetlands are commonly known as biological filters and are able to mitigate a wide range of both environmental and water quality problems (Sheoran and Sheoran, 2006).

According to the National Water Act (NWA), (Act No. 36 of 1998), a wetland is defined as *"land that 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"* (Macfarlane *et al*., 2009, p. 9). Wetland systems are considered sinks for waste due to their capability to assimilate large quantities of environmental contaminants (Groudev *et al*., 1999; Gray *et al*., 2000).

Since the mid-1990s, constructed wetlands have been utilised increasingly as a low-energy method to treat polluted water (Lee *et al*., 2009). Constructed wetlands or treatment wetlands are wetlands which are artificially created or man-made and are used to treat various forms of water pollution (Scholz and Lee, 2005). These systems emulate the properties of natural wetland systems (Sheoran and Sheoran, 2006). Both natural and constructed wetlands offer cost-effective water purification (Kotze, 2000). Wetland systems use basic processes, viz. bacterial degradation and oxidation of contaminants, uptake of nutrients by plants and sedimentation and adsorption of particles and dissolved substances, to purify contaminated water (Sheoran and Sheoran, 2006).

1.2. Contextualisation of the problem and motivation for the study

Water scarcity is currently a major issue in South Africa (SA), with most of South Africa's water supply being greatly dependent on the maintenance and conservation of catchment areas, wetlands and riparian zones (Turpie *et al*., 2008). Water pollution is one of the leading influential environmental factors in South Africa's water shortage and is caused by activities such as mining, discharge from industrial effluents and agricultural run-off (Kotze, 2000). Pollution in South Africa emanating from extensive mining activities is a particularly serious problem and amongst the many types of pollution possible from this avenue, acid mine drainage is particularly severe.

Acid mine drainage (AMD) is recognised as a serious environmental problem in both the historic and current mining industry (Johnson and Hallberg, 2005; Akcil and Koldas, 2006). AMD has a devastating impacts on water resources, and demands serious attention in this water scarce country. Of the various treatments proposed and used, one that is gaining interest is the use of constructed wetlands. The load rates and removal efficiencies of most metals are greater in constructed wetlands than in natural wetlands (Mays and Edwards, 2001).

Wetland ecosystems are economically important resources because they increase biodiversity and serve as nutrient traps (Hansson *et al*., 2005). Their multifunctional abilities have led to an increased interest in the restoration and construction of wetlands (Hansson *et al*., 2005). Presently, focus is placed either on nutrient dynamics or biodiversity, but seldom on both (Hansson *et al*., 2005). Although many countries have implemented wetland construction programmes, knowledge on designing a wetland which takes both nutrient reduction and biodiversity into consideration is scarce (Hansson *et al*., 2005).

Constructed wetlands have been recommended as a low-cost and low-maintenance alternative to the chemical treatment of AMD (Wieder, 1989), making it imperative to investigate and understand the effectiveness of constructed wetlands in removing water pollutants. This will assist to improve and apply this technique in the future.

The assessment of wetlands can take place at various levels and with different foci. In South Africa, an ecological approach is generally adopted, focussing on the ecoservices provided and wetland ecological health. This study employed the assessment of the functional and ecological status of the constructed wetlands at a disused coal mine in Dundee, KwaZulu-Natal (KZN), which was initially constructed by the then Department of Water Affairs (DWA). A series of 10 wetland cells were constructed to remediate the seepage from the mine. This site was chosen due to the presence of constructed wetlands and the opportunity to assess the efficiency of these wetlands in purifying the water.

1.3. Aim and Objectives

1.3.1. Aim

The aim of this study is to investigate the efficiency of a series of constructed wetlands in remediating acid mine drainage.

1.3.2. Objectives

The objectives of this study were to:

(1) Evaluate the regional and local physiographic character of the study area, including soil and vegetation characteristics.

(2) Assess the discharge rates, water quality and potential pollutant loading.

(3) Study the characteristics of the constructed wetlands and their efficacy.

(4) Assess the water quality of the final discharge after passing through the wetlands.

(5) Assess the impacts of this quality downstream of the site.

(6) Make final recommendations and conclusions.

1.4. Structure of the Dissertation

Chapter one briefly outlines previous research and contextualises the study. The second chapter discusses various literature and theoretical concepts relating to the study. Key areas reviewed in this chapter include water scarcity, characteristics of natural and constructed wetlands, ecosystem services and functions of natural and constructed wetlands and wetland degradation and rehabilitation. Chapter three describes the regional setting and physical characteristics of the study area. The fourth chapter discusses the research methodology adopted in this study. It includes details of sampling and laboratory procedures as well as data analysis. Chapter five presents the results obtained from the WET-Health and WET-EcoServices assessments. It also presents the water quality analysis and soil analysis to provide a description of current conditions prevalent in the constructed wetland system. Chapter six discusses the above-mentioned results by comparing it to existing data. The seventh chapter proposes a rehabilitation plan to aid in the restoration of the hydrological, geomorphological and ecological processes of the constructed wetland system. The eighth chapter, which is the final chapter, summarises the conclusions of the study and recommendations for future research.

Chapter 2: Theoretical Framework

2.1. Water scarcity

The current global challenge has arisen from the extensive ecological and health crises, which are associated with the inadequate access and management of fresh water (Srinivasan *et al*., 2012). Consequently, the increasing growth rate in human population of between 6.9 and 12.6 billion people by 2100, as stated by the Intergovernmental Panel on Climate Change (IPCC), has resulted in recurrent regional conflicts over water, ecological degradation, as well as illness and death (Srinivasan *et al*., 2012; Rogelj *et al*., 2018).

At present, water scarcity is a major issue in South Africa (SA), with most of the country's water supply being greatly dependent on the conservation of catchment areas, wetlands and riparian zones (Turpie *et al*., 2008). One of the leading influential environmental factors in South Africa's water shortage is water pollution caused by mining, discharge from industrial effluents and agricultural run-off (Kotze, 2000). The country is now classified as a water-stressed country, with limited freshwater supplies (South African Government Online, n.d.). In addition, the annual average rainfall of South Africa is 464mm, that of which is far below the international annual average of 860mm (Pollard and Du Toit, 2008; Chetty & Luiz, 2014; South African Government Online, n.d.).

Due to the link between catchment condition and river health, freshwater systems worldwide face major threat as these systems have suffered a rapid loss of species (Abell, 2002; Groves, 2003; Jenkins, 2003). In southern Africa, this threat is further aggravated due to the region ranking as a high water-stress zone, largely because of the competition between water users (Alcamo *et al*., 2003; Nel *et al*., 2007). Pressure to supply water to keep pace with rapid economic growth is intensified by water scarcity and difficulties to meet the requirements of the South African National Water Act (NWA) for ecological reserves (Rivers-Moore *et al*., 2011). Moreover, flow regulation and the change in land use compromise the health of river systems in South Africa (Davies *et al*., 1993). On the contrary, good catchment condition and river functioning provide ways in which to alleviate water stress in drier regions of South Africa (Rivers-Moore *et al*., 2011).

2.2. Climate of Southern Africa

The climate of southern Africa exudes a prominent gradient, with humid conditions in the east and arid conditions in the west (Kandji *et al*., 2006). There is a clear latitudinal distribution of rainfall in southern Africa, which divides the region into two climatic groups: i) South, viz. Botswana Lesotho, Namibia, South Africa and Swaziland, which present with a low rainfall index; and ii) North, viz. Angola, Malawi, Mozambique, Zambia and Zimbabwe, which have an annual rainfall index higher than that of the south (Kandji *et al*., 2006). Interestingly, variability in the climate is directly related to food insecurity in southern Africa (Kandji *et al*., 2006). The driving force behind climate variability is the El Nino Southern Oscillation (ENSO) (Kandji *et al*., 2006).

ENSO is a phenomenon that affects weather and climate variability worldwide (Stenseth *et al*., 2003). It is a natural part of the global climate system and is a result of large-scale interactions between the atmosphere and oceans, occurring mainly across its core region in the tropical-subtropical Pacific to the Indian Ocean basins (Diaz and Markgraf, 2000). Although, it is an irregular phenomenon, occurring every four years, it is apparent through alternations between its two phases, viz. El Nino and La Nina events (Diaz and Markgraf, 2000; Yu *et al*., 2002). El Nino events refer to the warming of tropical regions of the Pacific and Indian Oceans, which leads to the movement of major rainfall-producing systems from the continents to the aforementioned oceanic regions, resulting in large redistributions of climatic regimes (Diaz and Markgraf, 2000). The opposite refers to La Nina events which results in cooling of the tropical regions of the Pacific and Indian Oceans (Diaz and Markgraf, 2000).

While El Nino originates in the Eastern Pacific region, its warming effect is rapidly spread by winds blowing across the ocean, thus altering weather patterns in more than sixty percent of the planet’s surface (Kandji *et al*., 2006). The disasters associated with El Nino events include droughts, floods, frosts and heavy snowfalls, while those associated with La Nina events include floods and heavy rainfall which eventually result in landslides, decreased crop production, water logging of soils and leaching of soil nutrients (Kandji *et al*., 2006).

According to Dilley (2000), southern Africa is susceptible to inter-annual climate variation. During an ENSO event, the region tends to be anomalously warm and dry (Ropelewski and Halpert, 1987; Halpert and Ropelewski, 1992). ENSO events and anomalies in sea-surface temperatures in the Indian and South Atlantic Oceans have significant influences on rainfall variability as these may affect temperate and tropical atmospheric circulations as well as moisture fluctuations over the subcontinent (Mason and Jury, 1997).

2.3. Water usage in South Africa

Irrigation accounts for the highest usage of water in South Africa, with the usage by domestic, industrial and forestry sectors following closely behind (Chetty and Luiz, 2014). Chetty and Luiz (2014) attributed the failure to provide drinking water to all South Africans to poor governance and inadequate management and technical skills. Water quality has great influence on the quantity of usable water and the cost of converting it to drinking water; hence, the conservation of water bodies is of growing (Strydom *et al*., 2010). The International Water Management Institute (IWMI) predicted that South Africa will experience water scarcity by 2025 due to the rapid pace of urbanisation and current lack of water supply and infrastructure (Seckler *et al*., 1996).

2.4. Value of wetlands

The value of wetlands as service providers and water sources is well-recognised (Mitsch and Gosselink, 2000). Wetland services are expressed as ecosystem services in order to emphasise their value to society (Mitsch and Gosselink, 2000). The allocation of economic value to wetlands makes it necessary to enforce legal protection of these systems (Mitsch and Gosselink, 2000). However, as the majority of services provided by wetlands have no market-value, a non-market valuation has to be applied to calculate the value of the wetland (Woodward and Wui, 2001). Woodward and Wui (2001) summarised this widely-used approach into comparable measures in effort to determine the factors which influence the value of the wetland. The key determining factors included habitat provision, nutrient cycling and water quality control (Woodward and Wui, 2001).

The perceived value of wetlands allows prioritisation of maintenance, protection and rehabilitation to be outlined accordingly (Woodward and Wui, 2001). Prime Africa

Consultants (2011) reported an estimated overall value of between \$100/ha/year to \$10 000/ha/year for the services provided by wetlands, with the provision of habitat being the most valued wetland service. Prime Africa Consultants (2011) attributed under-valuation to wetland delineation, scale issues, vulnerable communities, poor scientific evidence and the incorrect valuation of regulatory systems.

2.5. Definition of wetlands

Wetlands are identified as areas with water-saturated soil (Kayranli *et al*., 2010). According to the National Water Act (Act No. 36 of 1998), a wetland is defined as *"land that 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"* (Macfarlane *et al*., 2009, p. 9). The most widely used international definition is the one provided by the Convention on Wetlands of International Importance, more commonly referred to as the Ramsar Convention (Finlayson and van der Valk, 2012). There are approximately 80 countries from around the world which are contracting parties to the convention and have accepted the following definition for international purposes (Finlayson and van der Valk, 2012): *"wetlands include a wide variety of habitats such as marshes, peatlands, floodplains, rivers and lakes, and coastal areas such as saltmarshes, mangroves, and seagrass beds, but also coral reefs and other marine areas no deeper than six metres at low tide, as well as human-made wetlands such as waste-water treatment ponds and reservoirs"* (Ramsar, 1971; Ramsar Convention Secretariat, 2013, p. 7).

2.6. Climate change and its impact on wetlands

Globally, climate change is considered a major threat to the integrity of ecosystems and the survival of species (Hulme, 2005). Climate change is anticipated to act in conjunction with a variety of other pressures and may be of great concern for wetlands and their water supply in the short to medium term, depending on the region (Erwin, 2009). Wetlands are susceptible to changes in water quality and water supply making these systems particularly vulnerable (Erwin, 2009). Alterations in hydrological regimes such as the variability of the hydro-period and the amount of and severity of extreme events as a result of climate change are expected to have a pronounced effect on wetlands (Erwin, 2009). Other factors related to climate may also play a major role in defining regional and local impacts such as; increased temperature, altered evapotranspiration, changes in the amount and patterns of suspended sediment loadings, altered biogeochemistry, oxidation of organic sediments, fire and the physical effects of wave energy (Watson *et al*., 1998; Burkett and Kusler 2000). The effect of climate change on the hydrology of individual wetland systems will vary due to the global variability of temperature and precipitation (Erwin, 2009). Due to the diversity of wetlands and their individual characteristics, restoration methods will need to be customised to a certain extent in order to alleviate the impacts resulting from climate change (Erwin, 2009). This makes it imperative to define expected future changes in climate and its impact on wetlands in specific regions (Erwin, 2009).

2.7. Wetland distribution

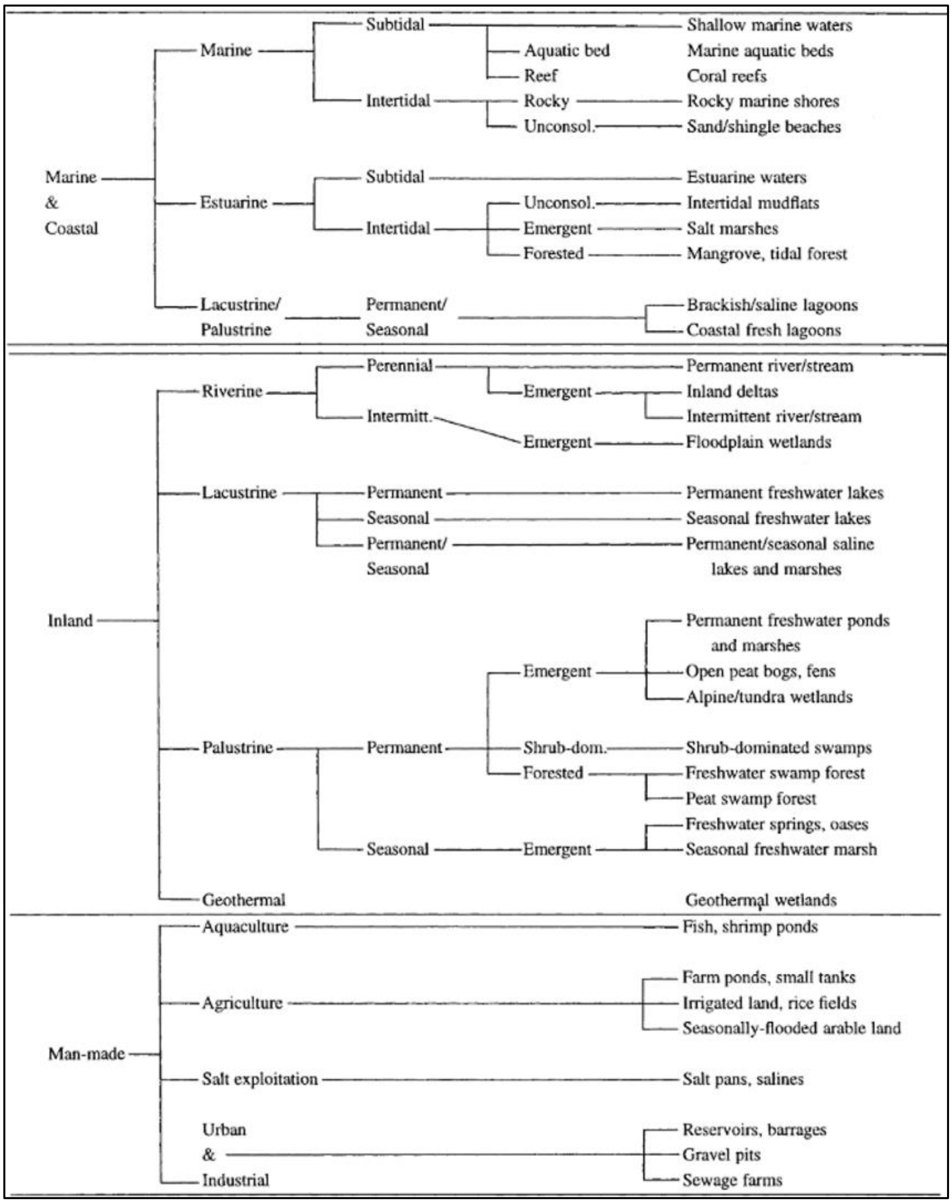
From the tropics to the tundra, wetlands generally exist in all climate zones, with the exception of Antarctica (Mitra *et al*., 2005). While they occupy approximately 4-6% of the world's land area, wetlands contain around 12% of the global carbon pool (Watson *et al*., 1996; Ferrati *et al*., 2005; Mitra *et al*., 2005; Erwin, 2009). Wetland systems are immensely valuable as they provide several functions and ecosystem services (Mitra *et al*., 2005). In addition, they are diverse structures differing in habitat, hydrology, shape and size (Oberholster *et al*., 2014).

2.8. Classification of wetlands

Wetland classification systems have been developed at both national and international levels. National classification systems focus on the distinctive characteristics of wetlands in a specific country or region (Scott and Jones, 1995). The purposes and values of international wetland classification systems were summarised by Scott and Jones (1995, p. 3-16), viz. 1) "To provide readily understood terminology for use in scientific research and conservation projects with an international dimension"; 2) "To provide a framework for implementing international legal instruments for wetland conservation"; and 3) "To assist international dissemination of information to as many relevant individuals and organisations as possible".

Scott (1980) employed one of the first international wetland classifications in 'A Preliminary Inventory of Wetlands of International Importance for Waterfowl in West Europe and Northwest Africa'. This classification was based on work being undertaken in Paris in relation to the then fledgling Community-wide Directive on the Conservation of Wild Birds (Scott and Jones, 1995). In addition to wetlands, the classification also included dryland habitats that are commonly associated with Western Palearctic wetlands (Scott and Jones, 1995). Several subsequent international wetland inventories have followed the classification described above. In the late 1980s, the Contracting Parties to the Ramsar Convention acknowledged the necessity of creating a database of wetlands (Scott and Jones, 1995). Due to this initiative, in 1990, the Contracting Parties adopted a reference approving the information and hierarchical classification of wetland type (Scott and Jones, 1995). The Ramsar Classification uses three broad groups of wetlands, viz. Marine and Coastal, Inland and Man-made (Semeniuk and Semeniuk, 1997). The system is further split into 35 types of wetlands within the three groups (Table 2.1) (Semeniuk and Semeniuk, 1997).

Table 2.1: Wetland Classification used by the Ramsar Convention Bureau (Finlayson and van der Valk, 2012)



2.9. Wetland classification in South Africa

Regardless of climate, soils, vegetation or origin; hydrology and geomorphology are the two fundamental features which determine the way in which an inland aquatic ecosystem functions (Semeniuk and Semeniuk, 1995; Finlayson *et al*., 2002; Collins *et al*., 2009; Ellery *et al*., 2011). The hydrogeomorphic (HGM) approach to wetland classification was established by using geomorphological and hydrological characteristics to distinguish primary wetland units (Brinson, 1993). Consequently, hydrogeomorphic (HGM) units have been classified according to the geomorphic setting (viz. hillslope, valley bottom), water source (viz. surface water dominant, subsurface water dominant), pattern of water flow through the wetland unit (viz. diffuse, channelled) and whether the drainage is opened or closed, (Macfarlane *et al*., 2007) (Table 2.2).

Table 2.2: Wetland hydrogeomorphic (HGM) types typically supporting inland wetlands in South Africa (Macfarlane *et al*., 2007)

Hydrogeomorphic types	Description	Source of water maintaining the wetland[1]	
		Surface	Subsurface
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, unchannelled 	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	*/ ***	*/ ***

[1] Precipitation is an important water source and evapotranspiration an important output in all of the above settings

Water source: * Contribution usually small

*** Contribution usually large

*/ *** Contribution may be small or important depending on the local circumstances

Wetland

2.10. Characteristics of wetlands

Three key aspects characterise a wetland, viz. water, substrate and biota (National Research Council, 1995). These characteristics are defined by recurrent saturation or sustained inundation at or near the surface as well as the occurrence of physical, chemical and biological features associated with recurrent saturation or sustained inundation (National Research Council, 1995). Hydric soils and hydrophytic vegetation are the two most common indicative features of wetlands (National Research Council, 1995). The state of the three key aspects that characterise wetlands are the criteria for the identification of wetlands (National Research Council, 1995). In terms of hydrology, the criterion is recurrent, sustained saturation. The physical and chemical conditions of the substrate should reflect that of recurrent, sustained saturation. In terms of biological criterion, organisms present should be specifically adapted to recurrent and sustained saturation of the substrate (Table 2.3 and Table 2.4).

The presence of both aerobic and anaerobic components in the soil, water and accumulated organic matter of wetlands allows for the formation of gaseous end-products under such conditions (Scholz *et al*., 2007; Kayranli *et al*., 2010). However, the water-saturated conditions of wetlands reduce the gas exchange rates between the atmosphere and sediments considerably, thus resulting in largely anaerobic sediments (Brix, 1990; Ponnamperuma, 1972). While the decomposition of organic matter forms carbon dioxide and methane under anaerobic conditions, only carbon dioxide is formed under aerobic conditions (Kayranli *et al*., 2010). Furthermore, the rates of decomposition and mineralisation of organic matter, which are manufactured by primary producers, are greatly reduced under anaerobic conditions and result in an accumulation of organic matter on the sediment surface (Rogers, 1983).

Table 2.3: Substrate and biota criteria for the determination of wetland zonation (Kotze, 1999)

	DEGREE OF WETNESS		
SOIL	Temporary	Seasonal	Permanent/Semi-permanent
Soil depth 0-10 cm	Matrix brown to greyish brown (chroma 0-3, usually 1 or 2) Few/no mottles Nonsulphidic	Matrix brownish grey to grey (chroma 0-2) Many mottles Sometimes sulphidic	Matrix grey (chroma 0-1) Few/no mottles Often sulphidic
Soil depth 30-40 cm	Matrix greyish brown (chroma 0-2, usually 1) Few/many mottles	Matrix brownish grey to grey (chroma 0-1) Many mottles	Matrix grey (chroma 0-1) No/few mottles Matrix chroma: 0-1
VEGETATION If herbaceous:	Predominantly grass species; mixture of species which occur extensively in non-wetland areas, and hydrophytic plant species which are restricted largely to wetland areas (see TABLE 3)	Hydrophytic sedge and grass species which are restricted to wetland areas, usually <1m tall.	Dominated by: (1) emergent plants, including reeds (*Phragmites australis*), **sedges** and bulrushes (*Typha capensis*), usually >1 m tall (**marsh**); or (2) floating or submerged aquatic plants.
If woody:	mixture of woody species which occur extensively in non-wetland areas, and hydrophytic plant species which are restricted largely to wetland areas (see TABLE 3)	Hydrophytic woody species which are restricted to wetland areas	Hydrophytic woody species which are restricted to wetland areas. Morphological adaptations to prolonged wetness (e.g. prop roots).

Table 2.4: Grass, rush and sedge species indicative of wetland conditions (Kotze, 1999)

Agrostis eriantha fw	
Agrostis lachnantha ow	CYPERACEAE (SEDGES)
Andropogon appendiculatus fw	*Ascolepis capensis* ow
Andropogon eucomis fw	*Bulbostylis schoenoides* ow
Arundinella nepelensis fw	*Carex acutiformis* ow
Brachiaria eruciformis fw	*Carex austro-africana* ow
Diplachne fusca ow	*Carex cognata* ow
Echinochloa crus-galli fw	*Carex glomerabilis* ow
Echinochloa jubata fw	*Cyperus articulatus* fw
Eragrostis lappula fw	*Cyperus denudatus* ow
Eragrostis plana fw(dry climate); f (wet climate)	*Cyperus difformis* ow
Eragrostis planiculmis ow	*Cyperus dives* ow
Festuca caprina fw	*Cyperus fastigiatus* ow
Fingerhuthia sesleriiformis ow	*Cyperus latifolius* ow
Helictotrichon turgidulum fw	*Cyperus longus* fw?
Hemarthria altissima fw	*Cyperus marginatus* fw
Imperata cylindrica w(dry climate); f(wet climate)	*Cyperus pulcher* ow
Ischaemum fasciculatum ow	*Cyperus sexangularis* fw
Koeleria capensis fw	*Cyperus sphaerospermus* ow
Leersia hexandra ow	*Eleocharis acutangular* ow
Merxmuellera macowanii fw	*Eleocharis dregeana* ow
Miscanthus capensis fw	*Eleocharis limosa* ow
Miscanthus junceus ow	*imbristylis complanata* fw
Panicum coloratum fw	*Fuirena pubescens* ow
Panicum hymeniochilum ow	*Isolepis costata* ow
Panicum repens ow	*Isolepis fluitans* ow
Panicum schinzii fw	*Isolepis prolifera* ow
Paspalum dilatatum fw	*Kyllinga erecta* fw
Paspalum distichum ow	*Kyllinga melanosperma* ow
Paspalum scrobiculatum fw	*Kyllinga pauciflora* ow
Paspalum urvillei fw	*Mariscus congestus* fw
Pennisetum macrourum ow	*Mariscus solidus* ow
Pennisetum natelense ow	*Pycreus cooperi* ow
Pennisetum sphacelatum ow	*Pycreus macranthus* ow
Pennisetum thunbergii ow	*Pycreus mundii* ow
Pennisetum unisetum fw	*Pycreus nitidus* ow
Phalaris arundinacea ow	*Pycreus sp1* ow
Phragmites australis ow	*Pycreus unioloides* ow
Phragmites mauritianus fw	*Rynchospora brownii* ow
Setaria sphacelata fw	*Schoenoplectus brachyceras* ow
Stiburus alopecuroides fw	*Schoenoplectus decipiens* ow
	Schoenoplectus paludicola ow
JUNCACEAE (RUSHES)	*Scirpus burkei* fw
Juncus dregeanus w	*Scirpus ficinioides* fw
Juncus effusus w	*Scleria dietelenii* ow
Juncus exsertus/oxycarpus w	*Scleria dregeana* ow
Juncus krausii w	*Scleria welwitschii* ow
Juncus lomatophyllus w	*Scleria woodii* ow
Juncus punctorius w	
Juncus tenuis w	TYPHACEAE (BULRUSHES)
	Typha capensis w

Table 2.5: Properties of wetland plants as biological filters (Russel, 2009)

Species	Typical features of the plant
Emergent species	
Typha capensis	Removes heavy metals, particularly nickel, copper, lead, zinc and cadmium. Also ameliorates heavy nutrient loading.
Phragmites australis	Removes iron, lead, zinc, cadmium and copper. Also heavy nutrient loading.
Burnatia enneandra	Suitable for heavy nutrient loading
Limnophyton obtusifolium	As above
Heteranthera callifolia	As above
Schoenoplectus brachyceras	As above
Schoenoplectus paludicola	As above
Schoenoplectus decipiens	As above
Eleocharis dulcis	As above
Eleocharis limosa	As above
Cyperus fastigiatus	As above
Cyperus marginatus	As above
Cyperus papyrus	As above
Flood-tolerant plants	
Bolboschoenus maritimus	Salt-tolerant, accumulates minerals
Eleocharis dregeana	Suitable for heavy nutrient loading
Fimbristylis complanata	As above
Fimbristylis dichotoma	As above
Panicum subalbidum	As above
Panicum repens	As above
Bacopa monnieri	Accumulates large quantities of heavy metals, hyperaccumulator
Submerged plants	
Ceratophyllum demersum	Accumulates large quantities of heavy metals, hyperaccumulator
Najas graminea	Suitable for heavy nutrient loading
Najas horrida	As above
Potamogeton thunbergii	As above
Potamogeton crispus	As above
Potamogeton pusillus	As above
Nymphoides thunbergiana	As above
Nymphoides indica	As above
Nymphaea nouchali	As above
Free-floating plants	
Ceratopsis cornuta	Easily removed
Spirodela polyrrhiza	Easily removed
Lemna gibba	Easily removed
Lemna minor	Easily removed
Lemna aequinoctialis	Easily removed

2.11. Ecosystem services and functions of wetlands

Wetlands have the ability to provide high-value ecosystem services and this can be attributed to their position in the landscape (Clarkson *et al*., 2013). They act as conduits, recipients as well as sources and sinks of abiotic and biotic resources (Clarkson *et al*., 2013). The services they provide are a vital part of human well-being (Clarkson *et al*., 2013). Kumar (2012) classified the benefits people obtain from ecosystems into four categories namely: provisioning services, regulating services, habitat or supporting services and cultural services. Provisioning services refer to vegetation, animal and mineral products that can be harvested for both personal and commercial use (Clarkson *et al*., 2013). Some important food products that are grown in wetlands include rice, sago, cooking oil, sugar, vinegar, alcohol, fodder and honey (Clarkson *et al*., 2013). Fish are one of the most significant resources from wetlands as it is the main source of protein for a large part of the population and generates employment and income (Clarkson *et al*., 2013). Other wetland products include animal fodder, fibres, fuelwood, traditional medicines, horticultural peat, dyes and tannins (Clarkson *et al*., 2013). Three regulating services are globally important, viz. water quality improvement, flood abatement and carbon management (Greeson *et al*., 1979). Habitat services such as gene pool protection and lifecycle maintenance are essential for the sustenance of vital ecosystem functions as well as the production of other ecosystem functions (Clarkson *et al*., 2013). The impact of habitat services on people and societies is often indirect and occurs over a long period of time whereas changes in other categories (provisioning services, regulating services and cultural services) have a fairly direct and short term impact (Russi *et al*., 2013). Cultural services refer to non-material benefits such as cultural, spiritual, educational and aesthetic values (Clarkson *et al*., 2013). This category also includes recreational and tourism opportunities (Clarkson *et al*., 2013). Table 2.6 below outlines wetland benefits that are considered most important in South Africa.

Table 2.6: Ecosystem services included in, and assessed by, WET-EcoServices (Kotze *et al.*, 2009)

Ecosystem services supplied by wetlands	Indirect benefits	Regulating and supporting benefits	Flood attenuation		The spreading out and slowing down of floodwaters in the wetland, thereby reducing the severity of floods downstream
			Streamflow regulation		Sustaining streamflow during low flow periods
			Water quality enhancement benefits	Sediment trapping	The trapping and retention in the wetland of sediment carried by runoff waters
				Phosphate assimilation	Removal by the wetland of phosphates carried by runoff waters
				Nitrate assimilation	Removal by the wetland of nitrates carried by runoff waters
				Toxicant assimilation	Removal by the wetland of toxicants (e.g. metals, biocides and salts) carried by runoff waters
				Erosion control	Controlling of erosion at the wetland site, principally through the protection provided by vegetation.
			Carbon storage		The trapping of carbon by the wetland, principally as soil organic matter
	Direct benefits	**Biodiversity maintenance**[2]			Through the provision of habitat and maintenance of natural process by the wetland, a contribution is made to maintaining biodiversity
		Provisioning benefits	Provision of water for human use		The provision of water extracted directly from the wetland for domestic, agriculture or other purposes
			Provision of harvestable resources		The provision of natural resources from the wetland, including livestock grazing, craft plants, fish, etc.
			Provision of cultivated foods		The provision of areas in the wetland favourable for the cultivation of foods
		Cultural benefits	Cultural heritage		Places of special cultural significance in the wetland, e.g. for baptisms or gathering of culturally significant plants
			Tourism and recreation		Sites of value for tourism and recreation in the wetland, often associated with scenic beauty and abundant birdlife
			Education and research		Sites of value in the wetland for education or research

As biological filters, wetlands are able to mitigate a wide range of both environmental and water quality problems (Sheoran and Sheoran, 2006). Oberholster *et al.* (2014) equated the function of a wetland within an ecosystem to that of a kidney as it filters the water flowing through and improves its quality. Wetlands provide numerous valuable ecosystem services such as water purification, filtration, ground-water recharge, flood control, nutrient retention, recreation and environmental aesthetics (Boyer and Polasky, 2004). They act as a cycling system of elements and flood attenuation, thus enabling recharge of groundwater that simultaneously stabilises soil and particle retention (Kent, 2000).

Wetland systems have been reported to act as sinks for waste due to their capability to assimilate large quantities of environmental contaminants (Groudev *et al*., 1999; Gray *et al*., 2000). Due to the ability to adsorb carbon dioxide from the atmosphere and capture it within the sediment, wetlands serve as greenhouse gas sinks and are considered to be a source of greenhouse gases, specifically with regard to methane gas emission into the atmosphere (Kayranli *et al*., 2010). Wetland areas are generally associated with high productivity and a high water table (Whiting and Chanton, 2001). However, the characteristic low decomposition rates lead to carbon storage within detritus, sediment and soil (Whiting and Chanton, 2001). The hydrological conditions or level of flow determines the physico-chemical and biotic components of a wetland (Coetzee, 1995). As a result, the sediment chemistry, water chemistry, macrophytes and other organisms supported by the system, will be determined by the level of flow and flow speed of the water (Coetzee, 1995). Wetlands provide both aquatic and wildlife habitats to a variety of species (Boyer and Polasky, 2004). Fennessy and Mitsch (1989) described wetlands as low maintenance continuous systems which provide a habitat for fish and birds. In addition to the environmental role of wetlands, they also fulfil the recreational and agricultural needs of humans (Kent, 2000).

2.12. Wetland degradation

According to the 2011 National Biodiversity Assessment (NBA), 65% of South Africa's wetland types are under threat. This 65% can be further categorised according to their threat status; 48% critically endangered, 12% endangered and 5% vulnerable. A meagre 11% of wetland ecosystem types are well protected, with 71% not protected at all (Working for Wetlands, n.d.).

Previously, wetlands were regarded as potential surplus agricultural land and were therefore drained for agricultural use (Keddy *et al*., 2009). The Mississippi River Basin in the United States of America (USA) is the largest global example of a developed wetland, which made way for canals and levees (Keddy *et al*., 2009). The fragmentation of this system caused increased risk of flooding in downstream New Orleans as well as nutrient starvation in the downstream wetland areas (Keddy *et al*., 2009).

Due to damage caused by the disturbance of biota and draining, the health of these water bodies are threatened by human activities (Coetzee, 1995). Agricultural and mining activities are the main cause of wetland degradation as these activities result in an increase of acidity, heavy metals, salinity and suspended solids, with potential eutrophication (Coetzee, 1995). Industry, urban runoff and sewage plant effluent are also contributors to wetland pollution (Coetzee, 1995).

Some of the consequences of wetland loss are, viz. diminished water security, reduced food security, desertification, reduction in biodiversity, lost livelihoods and increased vulnerability to natural disasters such as floods and droughts (Working for Wetlands, n.d.).

2.13. Acid mine drainage (AMD)

Acid mine drainage (AMD) is recognised as a serious environmental pollutant in both the historic and current mining industries (Johnson and Hallberg, 2005; Akcil and Koldas, 2006). It is characterised by high concentrations of dissolved metals, viz. aluminium, iron, manganese, as well as high concentrations of dissolved sulphates and a low pH (García *et al*., 2001).

AMD results from the exposure of sulphide-containing ore (pyrite) to water and oxygen in an environment that lacks buffering capacity (Tsukamoto *et al*., 2004). Pyrite oxidation is a robust passive acid-producing reaction that produces four moles of hydrogen ions from one mole of pyrite (Johnson, 1995). It is mediated by microbes, particularly in the case of iron sulphides, and highlights a multi-step reaction of ferric iron on the minerals present (Johnson, 1995). As a result, ferrous iron is regenerated and sulphur compounds are reduced to sulphates (Johnson and Hallberg, 2005). Oxidation of the sulphide mineral produces hydrogen ions, which are responsible for the production of acid, a characteristic of AMD (Johnson, 1995). The amount of buffering minerals present, viz. carbonates, affects the amount of acid produced (Johnson, 1995). Since mining heaps and tailings are exposed to the atmosphere through weathering, they are the primary locations for acid production (Johnson, 1995). Furthermore, a subsequent decrease in a pH below 4, causes metal solubility as noted by Tsukamoto *et al*. (2004) for pyrite oxidation in the equation below:

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3^- + 8H_2SO_4$$

Several factors influence the production rate of AMD, viz. chemical activation energy required for the initiation and bacterial activity, degree of saturation with water, chemical activity of Fe_3+, exposed surface area of metal sulphide, oxygen concentration, oxygen content, pH and temperature (Akcil and Koldas, 2006).

2.14. Constructed Wetlands

Natural wetlands are considered to be among the most endangered ecosystems in the world. Dini (2004) estimated a loss of between 35% and 50% in South African wetlands and wetland services. South Africa's wetlands cover a meagre 7% of the country's surface area (Strydom *et al*., 2010).

Since 1980, constructed wetland systems have gained popularity and have been applied successfully (Kadlec *et al*., 2000). Since the mid-1990s, constructed wetlands have been utilised increasingly for purification purposes as these systems are easy to use, have low construction costs and require little maintenance (Machate *et al*., 1997; Lee *et al*., 2009).

Constructed or treatment wetlands are artificially-created or man-made wetlands that are used for the treatment of various forms of water pollution (Scholz and Lee, 2005). They are passive treatment systems that provide cost-effective methods for remediation (Dini, 2004).

2.14.1. Types of constructed wetlands

Constructed wetlands can be classified according to several design constraints however, the three most important criteria are hydrology, type of macrophytic growth and flow path in sub-surface wetlands (Vymazal, 2014). The hydrology of the constructed wetland can be categorised into three groups, viz. free water surface flow (FWSF), sub-surface flow (SSF) and hybrid systems (Kadlec and Knight, 1996; (Barton and Karathanasis, 1999; Vymazal, 2007). Vymazal *et al*. (1998) stated that the dominant macrophytic life form can be categorised into three groups, viz. free-floating, submerged and emergent. In order to utilise the specific benefits of the different systems, the different types of constructed wetlands can be combined with each other, known as hybrid systems (Vymazal, 2005; 2008).

2.14.1.1. *Free water surface flow (FWSF)*

Free water surface flow constructed wetlands are generally characterised by their shallow sealed basin or series of basins or channels, a water surface which is above the substrate and emergent vegetation (Kadlec and Knight, 1996). Reed *et al*. (1988) reported that low flow velocity, shallow water depth and the presence of litter and plant stalks regulate water flow and ensure plug-flow conditions, especially in long narrow channels. The emergent macrophytes serve as land-intensive biological treatment systems (Vymazal, 2014). Kadlec *et al*. (2000) stated that settling of colloidal particles and microbial degradation is the main pathway for organic removal in FWSF. Sedimentation, aggregation, surface adhesion and filtration through dense vegetation are major removal mechanisms for suspended solids (Kadlec *et al*., 2000; Vymazal, 2014). FWSF systems usually have aerated zones near the water surface due to atmospheric diffusion and anaerobic and anoxic zones in and near the sediments however, anoxic zones can be found quite close to the water surface in heavily loaded systems (Vymazal, 2014). In FWSF treatment wetlands with floating macrophytes, the plants cover the water surface completely, preventing the penetration of light into the water column (Vymazal, 2014). Surface flow wetlands are aerobic systems where hydrolysis and oxidation reactions favour the precipitation of metals and do not raise the pH sufficiently (Barton and Karathanasis, 1999). In FWSF systems, removal efficiencies of above 70% can be achieved for biochemical / biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and pathogens (Kadlec and Wallace, 2008). Nutrient removal in FWSF systems is variable and depends largely on both the size of the system and the hydraulic loading rate (HLR) (Vymazal, 2007). FWSF therefore show limited capacities for nutrient reduction (especially phosphorus), with removal efficiencies ranging from 40% to 50% for nitrogen and from 40% to 90% for phosphorus (Vymazal, 2007). This type of constructed wetland provides an effective buffer between natural waterways and tertiary wastewater treatment plants (Kadlec and Wallace, 2008). As a result, free water surface flow constructed wetlands are a viable option for ecological restoration of polluted rivers (Wang *et al*., 2017).

2.14.1.2. Sub-surface flow (SSF)

Sub-surface flow constructed wetlands can be categorised into two groups according to their flow regime, viz. horizontal sub-surface flow (HSSF) and vertical sub-surface flow (VSSF) (Vymazal, 2014). Subsurface flow wetlands are anaerobic systems that have hydrolysis and oxidation reactions at the surface where the oxygen levels are higher, with microbial reduction at the lower levels (Barton and Karathanasis, 1999). The reduction of microbial sulphates raises the pH to adequate levels (Barton and Karathanasis, 1999).

2.14.1.2.1. Horizontal sub-surface flow (HSSF)

Horizontal sub-surface flow constructed wetlands are characterised by their horizontal flow regime through a permeable medium under the surface of the bed (Vymazal, 2014; Zhang *et al*., 2014). The system is usually rectangular in shape and water leaves the outlet via level control arrangement (Vymazal, 2014; Hickey *et al*., 2018). The wastewater will pass through a network of aerobic, anaerobic and anoxic zones along its flow path (Vymazal, 2014). In HSSF systems, the decomposition of organic matter is carried out by filtration of particulate organic matter and sedimentation as well as through aerobic and anaerobic microbial processes (Vymazal, 2014). In systems which are lightly-loaded, dissolved oxygen may be carried out by inflowing wastewater whereas systems which are heavily-loaded with continuous saturation of the filtration bed restrict aerobic processes to small zones, allowing anaerobic and anoxic processes to prevail (Vymazal and Kröpfelová, 2008). Roots and rhizomes leak oxygen into the substrate causing the occurrence of aerobic zones (Brix, 1987; Cooper *et al*., 1997). The primary removal mechanism of suspended solids in HSSF's is the flocculation and settling of colloidal and supracolloidal particulates (Vymazal, 2014). Gravity sedimentation, adsorption on biomass film attached to gravel and root systems as well as straining and physical capture are also considered as effective removal mechanisms (Vymazal, 2014).

2.14.1.2.2. Vertical sub-surface flow (VSSF)

Vertical sub-surface flow constructed wetlands are characterised by their vertical flow regime through a solid media (Hickey *et al*., 2018). These constructed wetlands consist of a flat bed of graded gravel, sand as well as macrophytes (Vymazal, 2014). The VSSF constructed wetlands are fed intermittently in large amounts causing flooding at the surface (Vymazal, 2014). The wastewater is collected by a drainage network at the base after percolating through the bed (Vymazal, 2014). Once the bed is completely drained, air refills the bed resulting in good oxygen transfer and the ability to nitrify (Cooper *et al*., 1997). In VSSF constructed wetlands, macrophytes play a major role in maintaining hydraulic conductivity of the bed (Vymazal, 2014). Many vertical sub-surface flow systems are staged systems with parallel and series beds however, recently systems with only one bed have been used, known as 2nd generation vertical sub-surface flow wetlands or compact vertical flow beds (Cooper, 1999; Arias and Brix, 2005).

2.14.1.3. Hybrid Constructed Wetlands (HCW)

Hybrid systems are systems consisting of various types of constructed wetlands arranged in series (Vymazal, 2013). These systems were introduced because wastewaters are often difficult to treat in a single stage (Wang *et al*., 2017). Most hybrid systems are derived from original hybrid systems which were developed by Seidel at the Max Planck Institute in Krefeld, Germany (Vymazal, 2014). HCW systems are generally a combination of both horizontal sub-surface flow and vertical sub-surface flow constructed wetlands (Hickey *et al*., 2018). The design comprises of two stage of several parallel vertical sub-surface flow beds followed by two or three horizontal sub-surface flow beds (Vymazal, 2014). The VSSF beds serve as filtration beds while the HSSF beds serve as elimination beds (Vymazal, 2014). Hybrid systems used to comprise usually of VSSF and HSSF systems however, all types of constructed wetlands can be combined (Vymazal, 2014). In hybrid systems, the advantages of various systems are combined to complement each other and achieve greater treatment performance (Vymazal, 2014; Maucieri *et al*., 2017).

Interestingly, these systems emulate the properties of natural wetland systems as they demonstrate basic ecosystem functions, viz. water storage, hydrologic transfers, primary productivity, biogeochemical transformations, decomposition, habitat/community, bacterial degradation and oxidation of contaminants, uptake of nutrients by plants and sedimentation and adsorption of particles and dissolved substances, to purify contaminated water (Richardson, 1994; Sheoran and Sheoran, 2006).

Dissolved organic matter (DOM) is an important water quality parameter used to indicate the performance of treatment wetland systems (Kayranli *et al*., 2010). The performance of treatment wetlands varies depending on the type of wetland, climate, vegetation and microorganism communities (Waddington *et al*., 1996; Joabsson *et al*., 1999; Picek *et al*., 2007; Weishampel *et al*., 2009).

Wetlands, both natural and artificial are seen as one of the more financially-attractive treatments of AMD (Fennessy and Mitsch, 1989). Artificial wetlands are generally constructed for the treatment of AMD or mine-polluted water (Fennessy and Mitsch, 1989). This treatment method is a cheaper alternative to the chemical treatment of water (Fennessy and Mitsch, 1989).

Several treatment methods have been developed to prevent the adverse effects of AMD (Fiset *et al*., 2003; Hong *et al*., 2014). Although chemical treatment is a widely used method of remediation for AMD, it is an expensive process (Fiset *et al*., 2003; Hong *et al*., 2014). While this process neutralises the pH of mine effluent, the metals and sulphates may not be completely remediated (Fiset *et al*., 2003; Hong *et al*., 2014).

The success of a constructed wetland is measured by its ability to enhance water quality from that of the effluent (Coetzee, 1995). The water quality is monitored through the chemical testing of both effluent and influent water, as well as the metal-adsorbing macrophytes (Coetzee, 1995).

2.15. *Utilisation of constructed wetlands in South Africa*

The concept of the utilisation of constructed wetlands in southern Africa has gained popularity since the mid-1980's (Wood and Hensman, 1989; Batchelor *et al*., 1990). By the year 1990, there were approximately 30 constructed wetland systems either in operation or under construction (Wood and Hensman, 1989; Batchelor *et al*., 1990). These treatment plants were intended to serve several functions, viz. treatment of secondary domestic effluent and raw sewage, septic tank and oxidation pod effluents, agricultural and aquaculture wastes, stormwaters as well as a range of industrial and mining wastewaters (Kadlec and Wallace, 2008). Wood (1990) reported that research to date, mainly pilot-scale studies in South Africa have shown that constructed wetlands can meet the general standards in terms of chemical oxygen demand (COD) and suspended solids.

Wood (1990) summarises the use of artificial wetlands in South Africa as follows: In 1985, the first full-scale artificial wetland was designed and constructed specifically for the treatment of sewage effluent of the Mpophomeni community situated on the shore of a phosphorus-limited impoundment in KwaZulu-Natal. At the Vaal Reefs Gold Mine, several reed bed units have been used to improve biofilter effluent phosphate levels prior to the local catchment whilst also forming an important part of a nature reserve within a mine complex and supplying recycled water to the metallurgical plant. In the village of MaKwane, Qua Qua, two parallel reed beds have been designed to collect oxidation pond effluent. The Nkowan Kowa municipality has an effluent treatment facility which uses screening and grit removal followed by anaerobic pond reactors to accommodate the sewage treatment for 22 000 people. A group of low-cost housing units on an agricultural holding at Bothaville in the Free State uses a wetland treatment system to dispose of domestic wastewater. An artificial wetland is used for effluent disposal from a Cotton Gin near Warmbaths in the Limpopo province. The Umzimkulu Sugar Mill in KwaZulu-Natal uses a system consisting of an anaerobic dam and an aeration pond for the treatment of effluent and waste ash disposal. During the year 1990, a reed bed system was constructed at a disused coal mine in Northern KwaZulu-Natal. Constructed wetlands as a treatment mechanism in southern Africa has many advantages over conventional technologies and is suitable for various applications due to its versatility (Wood, 1990).

2.16. Wetland rehabilitation

The main purpose of rehabilitation is to return the wetland to its pristine condition by alleviating floods, conserving the biodiversity, and extending the water retention time (Sieben *et al*., 2011; Selala *et al*., 2013). Working for Wetlands (n.d., online) listed the strategies used in South Africa for wetland rehabilitation, viz. 1) “Building concrete, earthen or gabion structures to arrest erosion, trap sediment and re-saturate drained wetland areas”; 2) “Plugging artificial drainage channels”; 3) “Addressing other causes of degradation, such as poor agricultural practices and invasive alien plants”; 4) “Plant propagation, re-vegetation and bio-engineering"; 5) "Building boardwalks, bird hides and interpretive signboards to enhance the recreational, tourism and educational value of rehabilitated wetlands"; 6) "Concluding contractual agreements with landowners to secure the rehabilitation work, prevent further degradation of wetlands and influence land use practices"; and 7) "Providing community members with part-time employment and training to monitor completed rehabilitation once the work is completed". The above-mentioned strategies aim to improve the state and functioning of the ecosystem as well as address the causes and effects of degradation.

Apart from the rehabilitation strategies mentioned above, liming is an alternate method of counteracting the impacts of AMD, whereby the pH of the water is increased amounts of metals and sulphides are removed (Hartman *et al*., 2008; Pound *et al*., 2013). This method was found to be detrimental to microbial communities as it resulted in a decrease in diversity and an increase in metabolic stress, thus opposing the efforts of restoration (Hartman *et al*., 2008; Pound *et al*., 2013). On the other hand, biomonitoring methods are considered to be more successful for wetland restoration (Walter *et al*., 2012). Walter *et al*. (2012, p. 431-440) listed a few short-comings of this method, viz. 1) "various monitoring programs are restricted by the indicator organisms used leading to methodological bias", 2) "erroneous data reporting, due to the biota recovery lagging behind improved water recovery" and 3) "full recovery of the wetland limited by broader watershed stressors such as agricultural activities and draining".

As one of the world's largest producers of coal, seventy-five percent of South Africa's energy is provided by coal (Energy Sources, n.d.). While, the Department of Water Affairs (DWA) has spent over R120 million over the past ten years, much more will be required (Hobbs *et al*., 2008). The new Constitution, instated after 1994, designated the Government as the custodian of all natural resources in South Africa (Hobbs *et al*., 2008). The National Water Act (Act 36 of 1998), was established to protect the water resources of the country (Hobbs *et al*., 2008). In addition to the National Environmental Management Act (NEMA), which addressed the impacts of AMD and other mining impacts, there was strong enforcement of the 'Polluter Pays Principal'. The act stipulated that those who contributed to pollution would be held liable for the cost of clean-up, i.e.

'Polluter Pays Principal'. After many years of lack of environmental governance, Hobbs *et al*. (2008) identified this as the first step in conservation of aquatic resources.

In South Africa, the Departments of Agriculture, Forestry and Fishery (DAFF), Environmental Affairs (DEA) and Water and Sanitation (DWS) (previously known as Water Affairs - DWA), have combined their efforts with that of the South African National Biodiversity Institute (SANBI) by establishing a programme called Working for Wetlands (South African National Biodiversity Institute, 2014). This joint initiative enables them to collaborate on the protection, rehabilitation as well as the sustainable use of wetlands (South African National Biodiversity Institute, 2014). The Working for Wetlands programme also places particular attention on the creation of employment within communities through skills development (Working for Wetlands, n.d.).

There are over 120 000 wetlands in South Africa which cover about 7% of the country, accounting for approximately 544 000 hectares of the country's surface area (Working for Wetlands, n.d.). Of these wetlands, nineteen have been declared Ramsar sites (Strydom *et al*., 2010). A Ramsar site is defined as a wetland that is identified as being of international importance (Ramsar, 2004).

Wetland rehabilitation has become increasingly important in South Africa due to the significance of these diverse water bodies (Zedler, 2000). The degradation and loss of wetlands may occur as a result of numerous anthropogenic activities within the catchment (Ehrenfeld, 2000; Zedler and Kercher, 2005). The rehabilitation of wetlands is not only important for conservation and restoration, but also provides a means to reverse the effects on the biota of these ecosystems (Zedler, 2000).

Improving the design, construction and operation of wetlands utilised for conservation and treatment purposes may help mitigate global warming (Kayranli *et al*., 2010). Moreover, over-utilisation of wetland services or values may result in the loss of associated wetland functions (Richardson, 1994). In addition, constructed wetlands have been recommended as a low-cost and low-maintenance alternative to the chemical treatment of AMD, (making it imperative to investigate and understand the effectiveness of constructed wetlands in removing water pollutants (Wieder, 1989). This will assist to improve and apply this technique in the future.

Chapter 3: Regional Setting

3.1. Introduction

This section describes the study area for this project. It describes the study area in terms of its regional location and its regional physiographic factors. Thereafter, the physical location and characteristics of the sample sites are discussed.

3.2. Regional physiographic description

3.2.1. Locality

This study is based on a constructed wetland situated alongside a disused coal mine in northern KwaZulu-Natal (KZN) province. The Bannockburn abandoned coal mine and constructed wetland is located in Dundee, KwaZulu-Natal, South Africa (SA) (Figure 3.1). KwaZulu-Natal is situated in eastern South Africa (Fairbanks *et al*., 2001). The area of the province is approximately 92 285 km^2 (Schulze, 1997). Dundee (28°10’ S; 30°14’ E) is a coal mining town situated in the valley of the Biggarsberg Mountains in northern KwaZulu-Natal. The town is a part of the Endumeni Municipality and the Umzinyathi District Municipality.

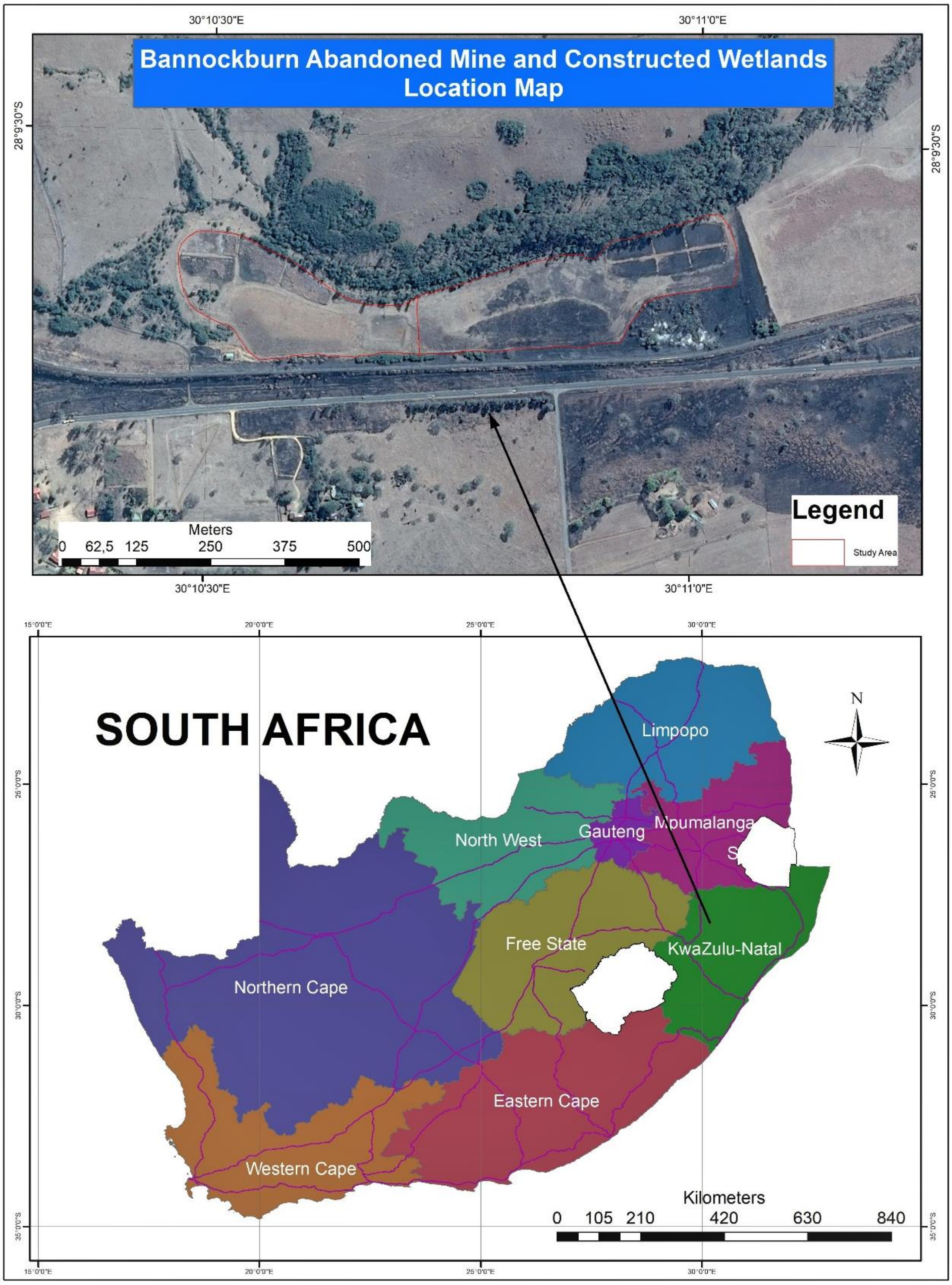


Figure 3.1: Location Map: Bannockburn Abandoned Mine and Constructed Wetlands (Map drawn by: Ballabh, 2018)

3.2.2. *Topography of KwaZulu-Natal*

KwaZulu-Natal has an altitudinal range of 0-3292 m. According to Schulze (1997), there are five dominant terrain morphological units in KwaZulu-Natal, viz. high mountains on the south eastern side of KwaZulu-Natal, where it shares the border with Lesotho; low mountains are spread over the length of KwaZulu-Natal; highly dissected low undulating mountains; mountains and lowlands; and irregular undulating lowlands with hills. The land rises from the relatively flat coastal plain bordered by the Indian Ocean on the east to the Drakensberg escarpment which forms the western boundary (Eeley *et al*., 1999; Mabaso *et al*., 2003). As can be seen in Figure 3.1, Dundee and the study site is located in the north-western part of the province with undulating hilly terrain whilst mountainous terrain lie immediately north and west of the town.

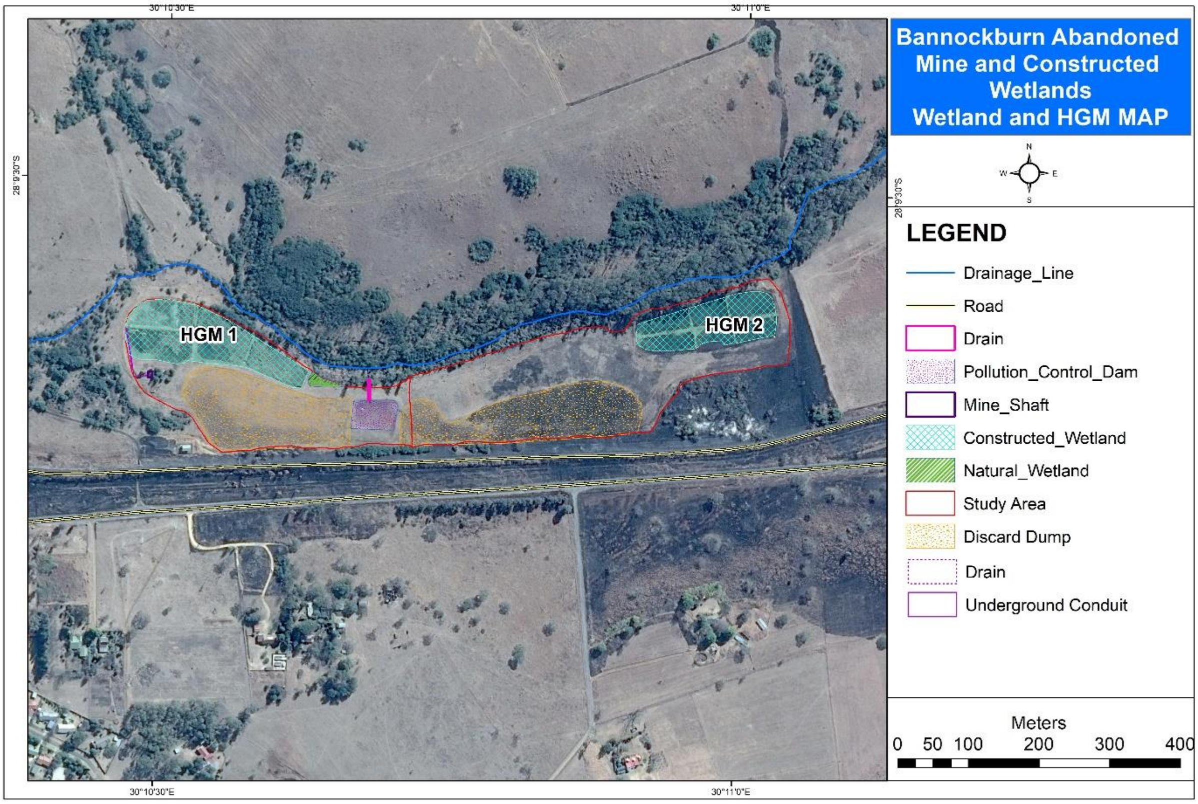


Figure 3.2: The abandoned mine, discard dumps, constructed wetlands and natural drainage: Bannockburn Abandoned Mine and Constructed Wetlands (Map drawn by: Ballabh, 2018)

3.2.3. *Climate of KwaZulu-Natal*

The climate of KwaZulu-Natal is characterised by the influence of the Indian Ocean's warm Agulhas current (Fairbanks *et al*., 2001). This results in a wide sub-tropical coastal region with high humidity and high temperatures (Fairbanks *et al*., 2001). The province is a predominantly summer rainfall region and has the highest annual precipitation in South Africa (Schulze, 1979; Pillay *et al*., 2003). The summers are warm and wet while the winters are cool and dry (Fairbanks *et al*., 2001). A marked climatic gradient is formed by the Drakensberg Escarpment (Fairbanks *et al*., 2001). There is a prominent variability in temperature between the warm coastlands and the cool interior highlands (Fairbanks *et al*., 2001). Temperatures along the coast increase gradually from the south to the north and there is also a gradual climatic transition from the coast to the westerly plateau (Fairbanks *et al*., 2001).

Dundee has a subtropical highland climate which is warm and temperate. The location is classified as a Cwb climate by Köppen and Geiger. According to the Köppen climate classification, a Cwb climate is a humid subtropical climate with dry winters and temperate summers (Alvares *et al*., 2013). Temperatures of the coldest month are ≥ -3°C and < 18°C while temperatures of the hottest month are < 22°C with four months having temperatures above 10°C (Alvares *et al*., 2013). Rainfall of the wettest month in summer is ≥ 10 times rainfall of the driest month in winter (Alvares *et al*., 2013). Dundee has an average annual temperature of 17.1°C (Climate-Data.org, n.d.). The average annual rainfall is 765mm with most of the rainfall being during the summer months (Climate-Data.org, n.d.). Precipitation reaches its peak in the month of January with an average of 132mm (Climate-Data.org, n.d.). June is the driest month with an average of 8mm of rainfall (Climate-Data.org, n.d.). January is the warmest month and June is the coldest month with an average temperature of 21.5°C and 10.8°C respectively (Climate-Data.org, n.d.).

3.2.4. *Vegetation of KwaZulu-Natal*

There is broad similarity shown between the boundaries of terrain morphological units and the vegetation types of KwaZulu-Natal. Snelder *et al*. (1999) attributed this similarity to the hierarchical classification scheme whereby higher-level control variables such as topography affect lower-level variables such as vegetation. The vegetation ranges from complex in the north-east, becoming noticeably less complex to the south (Fairbanks *et al*., 2001). Acocks (1988) listed the most prominent vegetation types in KwaZulu-Natal: 1. Coastal Forests and Thornveld, which runs along the coast; 2. Ngongoni Veld; 3. Highland Sour Veld and Dohne Sour Veld; 4. Southern Tall Grassland; 5. Valley Bushveld, which runs along the rivers; 6. Ngongoni Veld of Natal Mist Belt; 7. Northern Tall Grassveld; and 8. Zululand Thornveld. Figure 3.3 shows the vegetation type of the study area to be classified as Northern KwaZulu-Natal Moist Grassland.

Figure 3.3: Vegetation Map: Bannockburn Abandoned Mine and Constructed Wetlands (Map drawn by: Ballabh, 2018, adapted from SANBI database)

3.2.5. *Geology of KwaZulu-Natal*

Geologically, KwaZulu-Natal is dominated by the Beaufort Group and the Ecca Group with the Ecca Group being dominant in the Dundee area (Figure 3.4). The Beaufort and Ecca groups form part of the main lithostratigraphic subdivisions of the Karoo Supergroup, which also includes the Dwyka and Stormberg-Drakensberg groups

(Catuneanu *et al*., 2005). The Beaufort Group consists of mudstone, siltstone and subordinate lenticular and tabular sandstone (Catuneanu *et al*., 2005). The Beaufort Group shares a transitional and diachronous boundary with the underlying Ecca Group. Rocks of the Ecca Group consist of clastic mudstone, sandstone, siltstone, minor conglomerate and coal outcrops (Catuneanu *et al*., 2005).

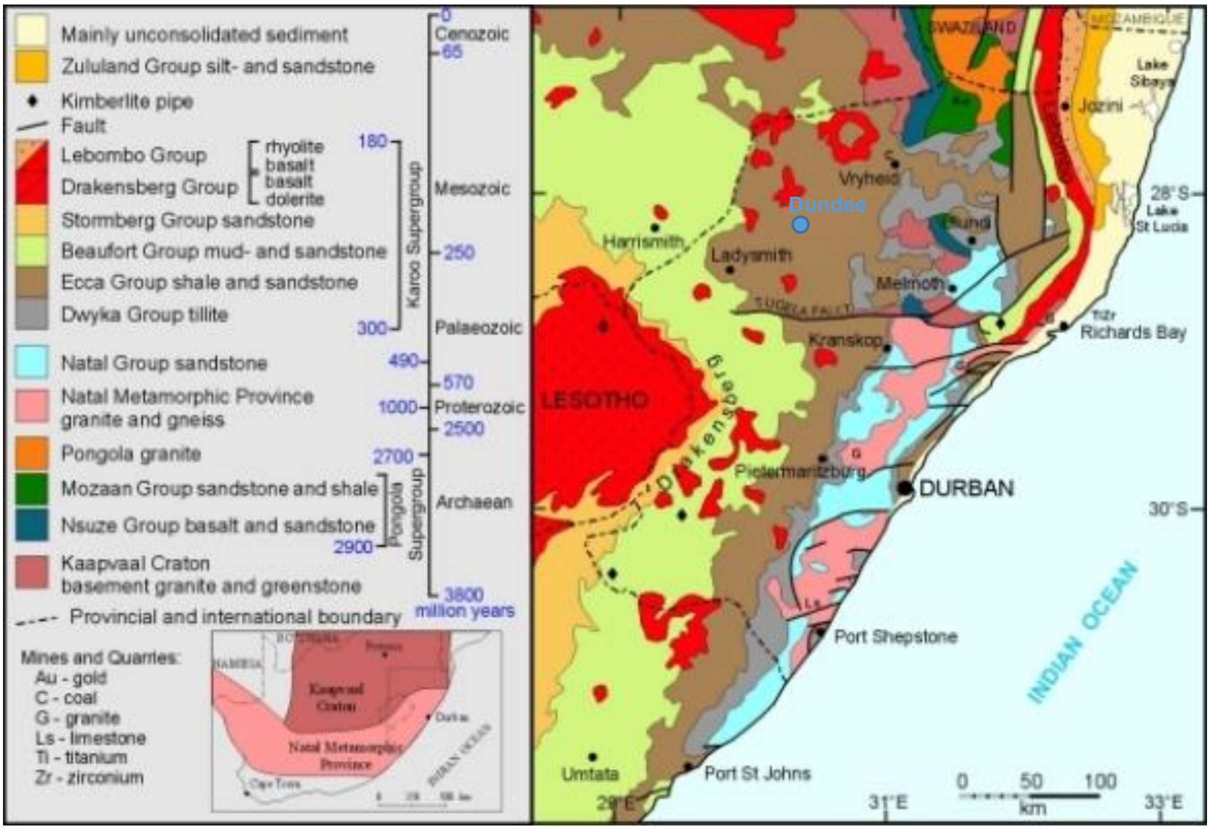


Figure 3.4: Geological map of KwaZulu-Natal (Geology Education Museum UKZN, n.d.)

3.3. Bannockburn abandoned coal mine and constructed wetland

The Bannockburn abandoned coal mine and constructed wetland, is located at (28°09’ S; 30°10’ E) and approximately 306km north of Durban. The wetland was constructed to remediate acidic seepage from the abandoned coal mine by the then Department of Water Affairs and Forestry (DWAF) in the 1998/1999 financial year. It was maintained by the DWAF for several years but recently has fallen into neglect due to the lack of funding for its maintenance. Despite the neglect and deterioration of the constructed system, it still appears to function, particularly during the rainy season as evidenced by the proliferation of wetland type vegetation during this time.

3.4. Morphometric characteristics

The site consists of two sets of interlinked wetland cells. Figure 3.6 (not to scale) is a schematic diagram that shows the main features on the site. Water from the mine shaft passes through a decant before entering the network of constructed wetland cells. Mine water is led successively from cells 1 and 2 through to cells 3 and 4. These cells comprise the first section of the constructed wetland. A sub-surface pipeline conveys water from cell 4 to cell 5 and 6 of the second set of constructed wetland cells. From cells 5 and 6, excess water moves successively to cells 7 to 10. From the latter water is allowed to flow into the adjacent Sterkstroom River. Given that the constructed wetland functions efficiently, it was anticipated that the flow into the river would exhibit no or acceptably low acidity.

The Sterkstroom River flows along the northern side of the constructed wetland. On the south side of the constructed wetlands, there are two large rehabilitated discard dumps. A pollution control dam (PCD) is situated between two rehabilitated discard dumps.
The dimensions of each of the constructed wetland cells is given in Table 3.1 below:

Figure 3.5: Historical Maps of the Bannockburn Abandoned Coal Mine and Constructed Wetlands showing seasonal variations in the extent of vegetation within the wetland cells for June 2017 and October 2010 (Map drawn by: Ballabh, 2018)

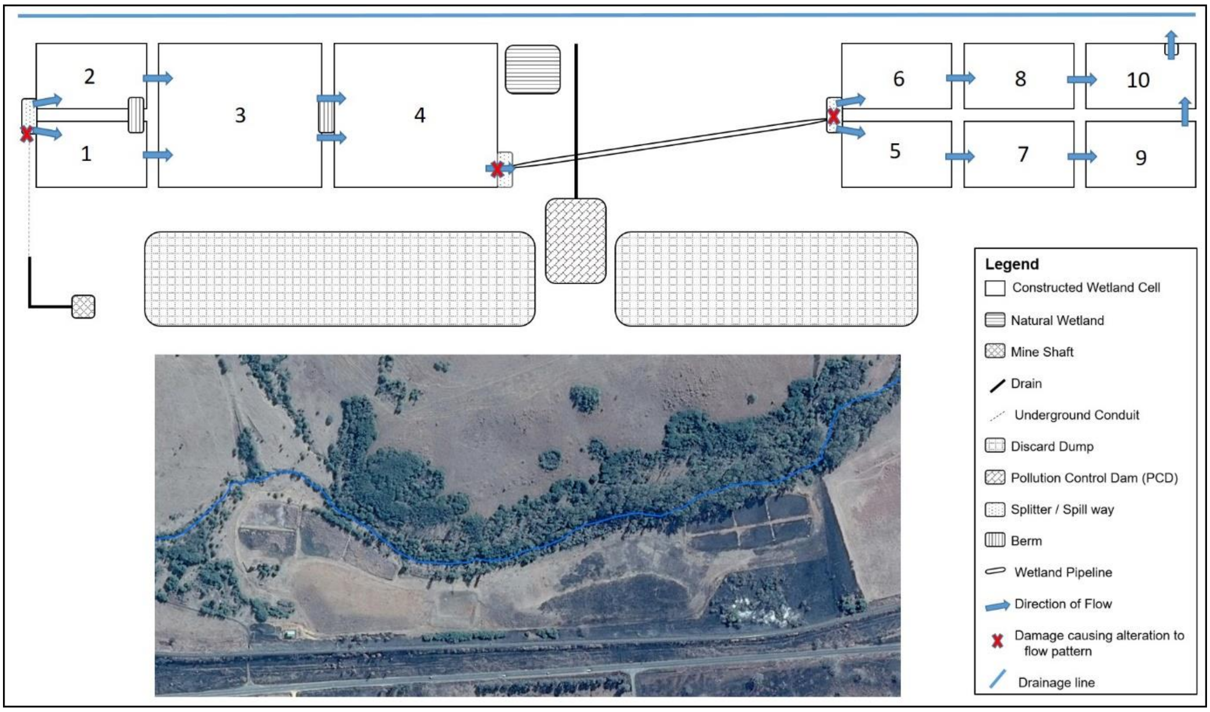


Figure 3.6: Schematic Diagram: Bannockburn Abandoned Mine and Constructed Wetlands

Table 3.1: Morphometric characteristics of Bannockburn abandoned coal mine and constructed wetland

Feature	L(m)x B(m)	Area (m²)
Cell 1	98,8 x 36,7	4520
Cell 2	98,8 x 42,3	3909
Cell 3	75,8 x 44	5605
Cell 4	87,1 x 28,5	3722
Cell 5	75,7 x 32,9	2800
Cell 6	75,7 x 30,7	2314
Cell 7	51,6 x 39,9	2118
Cell 8	51,6 x 33,3	1787
Cell 9	63,8 x 30,5	2171
Cell 10	63,8 x 25,5	2444
PCD	78,2 x 60,8	4952
Discard Dump 1	204 x 40,9	7911
Discard Dump 2	291 x 67,7	16897

Chapter 4: Research Methodology

4.1. Introduction

This section describes the sampling procedures and laboratory analysis which comprises both chemical and sediment/soil analysis. Details of data analysis including wetland assessments and statistical analysis are also outlined.

4.2. Desktop Study

The desktop assessment of natural features like wetlands initially involves the use of aerial photography to identify the location of the features. For this study, since the study is focused on constructed wetlands of known areal extent and location, a full desktop delineation of the wetlands was not necessary. However, since the wetlands were actually constructed several years ago, and since it has fallen into some neglect, it may have naturally changed (increased or diminished in size). This possibility necessitated an initial desktop aerial photographic study using images from Google Earth® and available wetland/river coverage's obtained from the South African National Biodiversity Institute (SANBI) website. Physiographic information on the vegetation type, climate, geology, soils and current land-use activities was acquired from secondary data sources.

4.3. Field Surveys

Field surveys were conducted on a seasonal basis, specifically during the two main seasons experienced in KwaZulu-Natal: winter and summer, with an additional sampling conducted in autumn.

4.3.1. Wetland Delineation

Following the desktop study, field delineation of the constructed wetlands and the associated riparian areas was conducted with the aid of the Department of Water Affairs & Forestry guideline manual '*A practical field procedure for the identification and delineation of wetlands and riparian areas*' (DWAF, 2005). The wetland delineation procedure identifies the outer edge of the temporary wetland zone, which marks the boundary between the aquatic and adjacent terrestrial areas. Wetland delineation began at the lowest lying point of the wetland. During this process, wetland mapping was conducted to identify the temporary, seasonal and permanent wetland zones using the designated criteria, i.e. position in the landscape, soil form, wetland vegetation species and redoxymorphic soil feature (DWAF, 2008).

4.3.2. Wetland Classification

The above step was followed by classification of the delineated wetlands/riparian areas through the use of the National Wetland Classification System for Wetlands and other Aquatic Ecosystems in South Africa (SANBI, 2013). The classification system aided in differentiating between natural and artificial areas which constitute the inland wetland system (Ollis *et al*., 2013). The wetland areas were classified into identifiable habitats or sections known as hydrogeomorphic (HGM) units according to the National Wetland Classification System developed by DWAF (2008) and SANBI (Ollis *et al*., 2013). The HGM classification system uses the geomorphological and hydrological features of the delineated wetland unit to determine its classification. The features that are assessed relate to the way in which water behaves in the wetland system. From the acquired information, a series of wetland maps showing the extent of wetland areas and related features was developed.

4.3.3. Soil Samples

During the field assessment, a Dutch soil auger was used to extract sediment cores from up until 1 meter below the surface. The sample was placed in a 1 meter soil tray (e.g. Figure 4.2) where the soil profile was photographed and evaluated on-site for soil colour, redoxymorphic soil features, soil wetness and gleying. The sample was then allotted into plastic bags which were labelled with a brief site description including GPS coordinates and stored in a cooler box that was transported back to the laboratory.

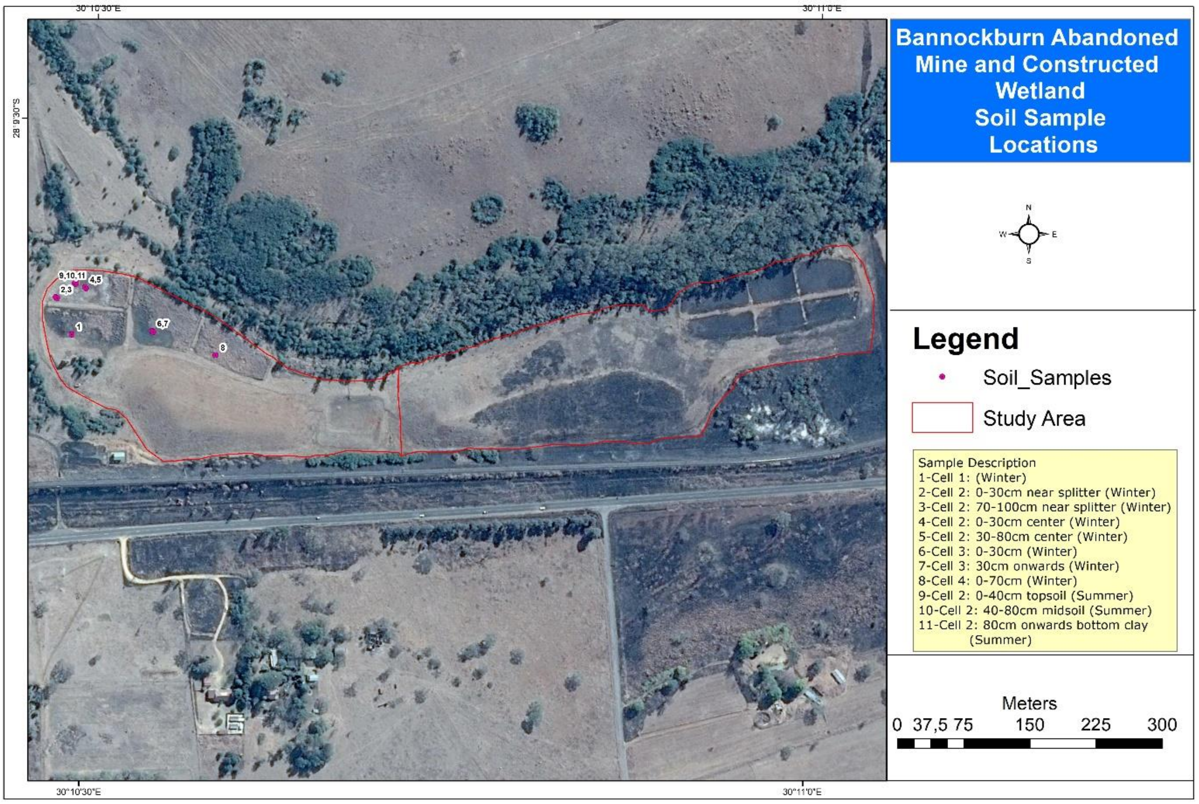


Figure 4.1: Bannockburn Abandoned Mine and Constructed Wetland Soil Sample Locations

Figure 4.2: Examples of sediment cores extracted with the soil auger

4.3.4. Soil Colour

The Munsell® Soil Colour Charts were used to determine the soil colour as well as redoxymorphic features. The Munsell Colour System is used to standardise the quantification of soil colour (Munsell, 2013). The system notes three colour dimensions of the soil, viz. hue, value and chroma (Malacara, 2011). Each chart comprises 29-42 colour chips with all chips on an individual chart being of the same hue (Presley *et al*., 2016). Within each hue, values are displayed in rows and chromas are displayed in columns (Presley *et al*., 2016). Hue refers to the quality of pigmentation, describing how much red (R), yellow (Y), green (G), blue (B) or purple (P) is in the colour (Malacara, 2011; Presley *et al*., 2016). Value refers to the lightness or darkness of the pigmentation and chroma refers to the richness (pale to bright) of the pigmentation (Malacara, 2011; Presley *et al*., 2016). The chart containing the 10YR hue was used to assess the soil colour. Soil samples were matched to the chip of the same colour with redoxymorphic features (mottles) being matched separately. The colour of the soil was then noted accordingly as hue value/chroma, viz. 10YR 2/1.

4.3.5. Water Samples

During the field assessment, an Oaklon PCD 650 Multiparameter Meter was used to measure the pH, conductivity, dissolved oxygen content and temperature of the water entering and exiting each cell, respectively. Water samples were collected at the entrance and exit of each cell of the constructed wetlands. The bottles were labelled with a brief site description including Global Positioning System (GPS) coordinates and stored in a cooler box to be transported back to the laboratory for water quality analysis.

4.3.6. Wetland Ecological Assessment

The biodiversity field work component of this assessment was conducted during daylight hours in both summer and in winter. During the field assessment, general information on the vegetation type, climate, geology and soils and current activities was acquired.

The assessment focussed on both floral and faunal species. Checklists of floral and faunal species were compiled by traversing the study area on foot and recording species as they were encountered. Plant names follow Oudtshoorn (1999) and Van Wyk and Gericke (2000) for grasses; Van Wyk and Malan (1998), Onderstall (1984), Pooley (1998) for herbs and shrubs; and Coates Palgrave (1992) for trees. It is possible that a few species may have been overlooked if they were in a resting stage or were not in flower. However, the majority of the dominant and common species present at the sites were recorded. This information was then used to determine potentially sensitive habitats and to determine the extent to which the constructed wetland evolved to a natural ecological/biodiversity status.

An assessment of the importance of the constructed wetland areas in providing ecosystem goods and services according to the WET-EcoServices Level 2 assessment tool was done (Kotze *et al*., 2009). The tool provides information on the importance of a HGM wetland unit in delivering different ecosystem services under a number of different categories (Kotze *et al*., 2009). These categories are illustrated in Figure 4.5. Thereafter, recommendations of management and mitigation measures to deal with potential impacts to wetlands/rivers were developed.

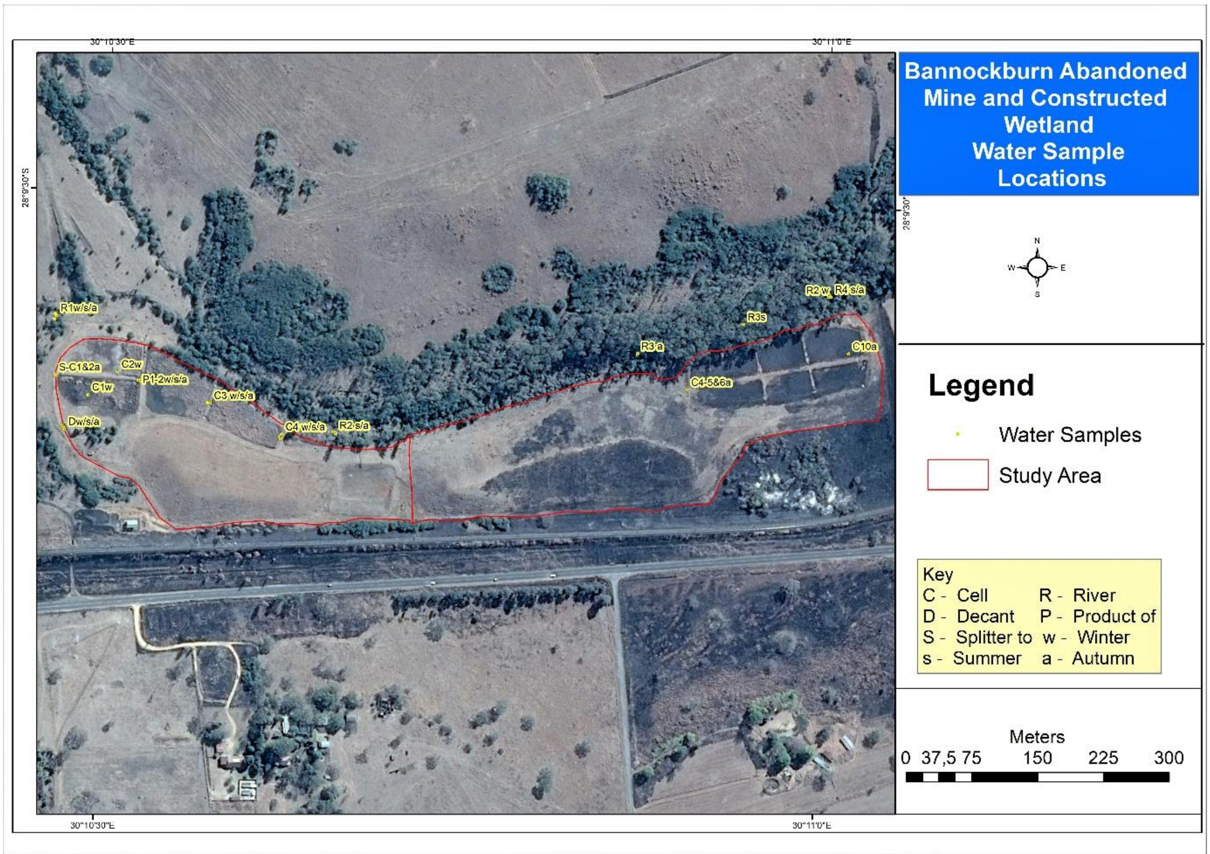


Figure 4.3: Bannockburn Abandoned Mine and Constructed Wetland Water Sample Locations

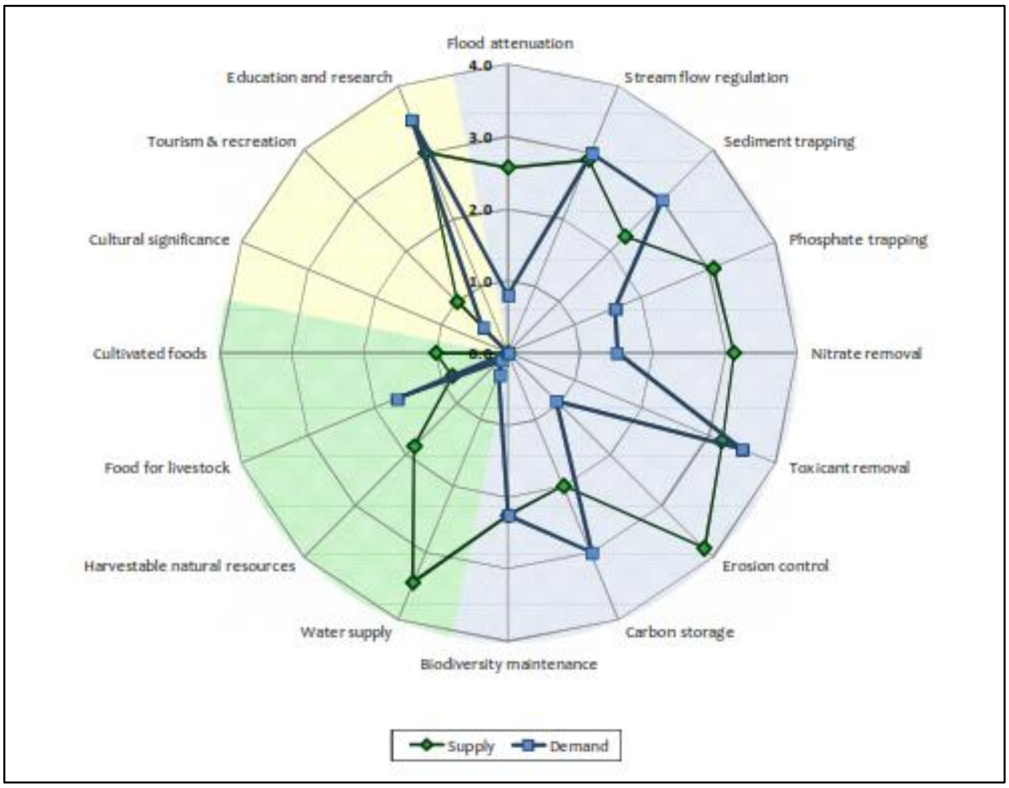


Figure 4.4: Wetland ecosystem goods and services assessed by the WET-EcoServices tool (SANBI, 2013)

(The ecoservices supplied by the wetland systems are ranked according to the following: 0 – Low, 1 – Moderately Low, 2 – Intermediate, 3 – Moderately High, 4 – High)

4.3.7. Wetland Functional Assessment

A wetland functional assessment was conducted as per the methods outlined below.

A WET-Health Level 1 assessment was conducted to establish the Present Ecological State (PES) of the wetland environments (Macfarlane *et al*. 2009). The WET-Health index considers the state of the three main functional aspects of the wetland units, namely: (1) hydrology, (2) geomorphology and (3) vegetation. Each of the above-mentioned components follows a broadly similar approach and is used to determine the extent to which anthropogenic impacts have affected the health status of the wetland. The overall score is integrated and expressed as a PES category with the relevant change of trajectory class (Table 4.1 and 4.2).

Table 4.1: Present Ecological Score categories used by WET-Health for describing the integrity of wetlands

Impact Category	Health Category	Description	Range
None	A	Unmodified/natural	0 – 0.9
Small	B	Mostly Natural with a few modifications. A slight change in ecosystem processes is discernable and a small loss of natural habitats and biota may have taken place.	1 – 1.9
Moderate	C	Moderately modified. A moderate change in the ecosystem processes and the loss of natural habitats has taken place but the natural habitat remains predominantly intact	2 – 3.9
Large	D	Largely modified. A large change in ecosystem processes and loss of natural habitat and biota has occurred.	4 – 5.9
Serious	E	A very large change in ecosystem processes and loss of natural habitat and biota but some of the remaining natural habitat features are still recognizable.	6 – 7.9
Critical	F	The modification has reached a critical level and the ecosystem processes have been modified completely with an almost complete loss of natural habitat and biota	8 +

Table 4.2: Trajectory of Change classes and scores used to evaluate likely future changes to the present state of the wetland used by WET-Health

Change Class	**Description**	**HGM change score**	**Symbol**
Substantial improvement	State is likely to improve substantially over the next 5 years	2	↑↑
Slight improvement	State is likely to improve slightly over the next 5 years	1	↑
Remain Stable	State is likely to remain stable over the next 5 years	0	→
Slight deterioration	State is likely to deteriorate slightly over the next 5 years	-1	↓
Substantial deterioration	State is expected to deteriorate substantially over the next 5 years	-2	↓↓

4.4. Laboratory Procedures

4.4.1. Soil

Soil samples were analysed to investigate characteristics such as particle size distribution, organic matter content, calcium carbonate content as well as for the presence of heavy metals. These characteristics were analysed to determine its impact on the functioning of the wetland.

4.4.1.1. Sample Preparation

The soil was air-dried after which a mortar and pestle were used to grind the soil sample. The sample was then employed in the procedures as follows:

4.4.1.2. Determination of the Particle Size Distribution

The following mechanical sieve method was adapted from Kroetsch and Wang (2008) with modifications.

The Retsch AS 200 Basic Vibratory Sieve Shaker was used to determine the particle size distribution of the soil sample.

Procedure:

The sieves were stacked on the shaker in descending order of aperture size (2mm, 1mm, 500µm, 250µm, 125µm, 53µm), with a catching pan at the bottom. The air-dried sample was transferred into the top sieve and the sieve cover was screwed down firmly. The sieve shaker was set for 5 minutes at amplitude of 80Hz. The sample retained on each sieve as well as in the catching pan, was then transferred into pre-weighed trays (W_1) and the mass of the tray with the sieved sample (W_2) was quantified and documented.

Calculations:

$$Mass\ of\ soil\ retained\ on\ each\ sieve\ (W3)\ =\ W2 - W1$$

$$Total\ mass\ of\ sample\ (W4)\ =\ \Sigma W3$$

$$\%\ of\ Total\ (W5)\ =\ W3/W4\ x\ 100$$

$$\%\ Finer\ than\ (W6)\ =\ 100 - W5$$

A graphical representation of the results was attained by plotting the percent finer than against the grain size on a logarithmic graph (Figure 5.2).

Figure 4.5: Retsch AS 200 Basic Vibratory Sieve Shaker

4.4.1.3. Organic Matter Content Determination (Loss on Ignition Method)

The following loss on ignition (LOI) method was adapted from Schumacher (2002). The Carbolite Gero AAF 1100 Muffle Furnace was used for ignition in order to determine the organic matter content of the sample.

Sample Preparation:

100g of soil was passed through a 2mm sieve. The particles >2mm were discarded and the remaining sample was placed in a foil tray and oven-dried overnight at 110°C.

Procedure:

The mass of an empty crucible was determined and recorded (W_1). The oven-dried sample was then transferred into the crucible and the mass of the crucible with the oven-dry soil (W_2) was estimated and noted. The crucible was placed in the muffle furnace overnight at 440°C. The crucible was carefully removed from the furnace using tongs and allowed to cool to room temperature. The mass of the crucible with ash (W_4) was calculated and documented. .

Calculations:

$$Mass\ of\ oven - dry\ soil\ /soil\ before\ furnace\ (W3)\ =\ W2 - W1$$

$$Mass\ of\ ash\ /\ soil\ after\ furnace\ (W5)\ =\ W4 - W1$$

$$Organic\ Matter\ Content\ (W6)\ =\ W3 - W5$$

$$\%\ Organic\ Matter\ Content\ =\ W6/W3\ x\ 100$$

A graphical representation of the results was attained through the use of a bar graph (Figure 5.3).

Figure 4.6: Crucibles with soil after undergoing loss on ignition and a comparison of the soil sample before and after undergoing loss on ignition

4.4.1.4. Organic Matter Content Assessment (Walkley-Black Method)

The following Walkley-Black method was adapted from Schumacher (2002).

Sample Preparation:

10g of soil was passed through a 2mm sieve. The particles >2mm were discarded and the remaining sample was placed in a foil tray and oven-dried overnight at 110°C. Ferrous ammonium sulphate solution was standardised and the volume of the solution required to produce a colour change (V_1) was recorded.

Procedure:

0.3g of oven-dry soil was placed in a pre-weighed 500ml conical flask (W_1). The mass of the flask with soil was calculated (W_2). 10ml of Potassium dichromate was added and the sample was gently swirled to disperse the soil. 20ml of Sulphuric acid was then added and the sample was again swirled and allowed to stand for 20 minutes. Thereafter, 200ml of distilled water was added. 10ml of Orthophosphoric acid and 1ml of Diphenylalmine were added. At this point of the procedure, the colour of the solution was dark blue/black. The start level in the burette was noted. Ferrous ammonium sulphate was added in 0.5ml increments, whilst swirling the flask continuously until the contents changed from blue/black to green. A further 0.5ml of Potassium dichromate was added to the contents, changing the colour back to blue/black. Ferrous ammonium sulphate was then added drop by drop, whilst continuously swirling until the colour changed back to green with the addition of a single drop. The total volume of Ferrous ammonium sulphate (V_2) used was recorded.

Calculations:

$$Volume\ of\ Potassium\ dichromate\ used\ in\ test\ (V3) = 10.5\ x\ [1 - (V2/V1)]$$

$$Mass\ of\ oven-dry\ sample\ (W3) = W2 - W1$$

$$\%\ Organic\ Content\ of\ sample = (0.67\ x\ V3)\ /\ W3$$

A graphical representation of the results was attained through the use of a bar graph (Figure 5.3).

Figure 4.7: Titrated Samples

4.4.1.5. Calcium Carbonate Content Determination (Sequential Loss on Ignition Method)

The following loss on ignition (LOI) method was adapted from Howayek *et al*., (2012). A Carbolite Gero AAF 1100 Muffle Furnace was used for ignition in order to determine the calcium carbonate content of the sample.

Sample Preparation:

100g of soil was passed through a 2mm sieve. The particles >2mm were discarded and the remaining sample was placed in a pre-weighed foil tray and oven-dried for 15 minutes at 110°C. The mass of the foil tray with the sample was deduced. The sample was oven-dried and reweighed at 5 minute intervals until constant weight was achieved. The sample was then placed in the dessicator and allowed to cool.

Procedure:

The mass of an empty crucible was determined and recorded (W_1). The oven-dried sample was then transferred into the crucible and the mass of the crucible with oven-dry soil (W_2) was calculated. The crucible was placed in the muffle furnace at 445°C for 6 hours. The crucible was carefully removed from the furnace using tongs, placed in the dessicator and allowed to cool. The cooled sample was removed from the dessicator and the mass of the crucible with ash (W_3) was estimated. The crucible was then placed in the muffle furnace at 800°C for 6 additional hours. The crucible was carefully removed from the furnace using tongs, placed in the dessicator and allowed to cool. The cooled sample was removed from the dessicator and the mass of the crucible with ash (W_4) was ascertained.

Calculations:

$$\%CaCO3 = 2.27\ x\ (W3 - W4\ /\ W2 - W1)\ x\ 100$$

A graphical representation of the results was attained through the use of a bar graph (Figure 5.3).

Figure 4.8: Sediment samples immediately after sequential loss on ignition

4.4.1.6. Heavy Metal Analysis

The analysis of heavy metals was conducted using the Inductively-Coupled Plasma Optical Emission Spectrometry (ICP-OES). This procedure is based on the principle that the component elements (atoms) of a sample move to a higher energy state when energy is transferred from a plasma source to a sample (Helaluddin *et al*., 2016). Emission rays are released as the excited atoms return to a low energy state and those which correspond to the photon wavelength are measured (Helaluddin *et al*., 2016). The constituent elements are identified according to their characteristic emission lines and quantified by the intensity of the same lines (Helaluddin *et al*., 2016).

The following heavy metal analysis was adapted from Mdegela *et al*., (2009) with modifications.

<u>Procedure:</u>

10ml of Aqua Regia was added to 1 gram of soil. The mixture was then heated to 90°C using a hotplate and the beaker was covered with a wash glass. Following pre-concentration of the soil sample, the sample was filtered out into a 100ml volumetric flask and then filled to the marked volume using double distilled water. The sample was then analysed using the ICP-OES. The analysis was performed in triplicate. The following heavy metals were analysed: Calcium (Ca), Copper (Cu), Iron (Fe), Lead (Pb), Magnesium (Mg), Manganese (Mn), Nickel (Ni) and Zinc (Zn). The concentration of elements were compared to Clarke Values (Martinez *et al.*, 2007) through the use of Enrichment Factors (EF). Currently, there are no sediment quality guidelines available for South African sediments, therefore 'Clarke values' which serve as background values for the average elemental composition of earth's crust were applied. (Martinez et al., 2007; Orr, 2007). The enrichment factor (EF) for each site was calculated based on the abundance of the element present in the sample relative to the earth's crust average concentration (Harikumar and Jisha, 2010). Computation of the EF is as given below, where EF is the enrichment factor, [Concentration element] is mean concentration of the element analysed in sediment, [Concentration Fe] is mean concentration of Fe in sediment, [Clarke Element] is Clarke value of element, and [Clarke Fe] is Clarke value of Fe (Martinez *et al.*, 2007).

<u>Calculations:</u>

$$EF = \frac{[(Concentration\ Element)\ /\ (Concentration\ Fe)]}{[(Clarke\ Element)\ /\ (Clarke\ Fe)]}$$

The results were presented in the form of a table (Table 5.6).

4.4.2. Water Quality

Water samples were analysed for the presence of heavy metals, nutrients and general water chemistry, which included physico-chemical parameters such as pH, salinity, dissolved oxygen (DO), total dissolved solids (TDS) and electrical conductivity (EC). The results of these analyses were compared to the Target Water Quality Range (TWQR) for aquatic ecosystems/domestic/industrial use in the South African Water Quality Guidelines, World Health Organization (WHO) Guidelines for Drinking-water Quality and/or the US Environmental Protection Agency (EPA) Guidelines (DWAF, 1996a, b, c; WHO, 2008; EPA, 2013).

These water quality analyses were performed to determine the efficacy of the wetlands in purifying potential acid-enriched waters emanating from the closed coal mine.

4.4.2.1. Physico-Chemical Parameters

The pH was measured using the Metrohm 827 pH Meter. The Microprocessor Oximeter - Oxi 321 was used to measure the dissolved oxygen (DO) content. The analysis of electrical conductivity (EC), total dissolved solids (TDS) and salinity was conducted using the Inolab Con Level 1 Multiparameter Meter.

The results were presented in the form of a table (Table 5.8).

4.4.2.2. Nutrient Analysis

The nutrient analysis was conducted using the Thermo Scientific™ Gallery™ Automated Photometric Analyser.

<u>Procedure:</u>

A syringe was used to pass water samples through a 0.2 micro-filter and into 2ml vials. Quality control (QC) and calibration was carried out. Thereafter samples and reagents were loaded and the analysis was performed using the Colorimetric method. The analysis was performed in triplicate. The following nutrients were analysed: Nitrite (NO_2^-), Nitrate (NO_3^-), Sulphate (SO_4^{2-}) and Orthophosphate (PO_4^{3-}).

The results were presented in the form of a table (Table 5.9).

4.4.2.3. Heavy Metal Analysis

The analysis of heavy metals was conducted using the Inductively-Coupled Plasma Optical Emission Spectrometry (ICP-OES). This procedure is based on the principle that the energy from a plasma source which is transferred to a sample excites the component elements (atoms) causing it to move to a higher energy state (Helaluddin *et al*., 2016). As the excited atoms return to a low energy state, emission rays are released and those which correspond to the photon wavelength are measured (Helaluddin *et al*., 2016). The constituent elements are identified according to their characteristic emission lines and quantified by the intensity of the same lines (Helaluddin *et al*., 2016).

The following heavy metal analysis was adapted from Mdegela *et al*., (2009) with modifications.

<u>Procedure:</u>

10ml of sample was added to a 100ml volumetric flask. 1ml of Aqua Regia was used for the digestion. The mixture was then filtered into a 10ml volumetric flask. Double distilled

water was used to increase the solution to the marked volume. A 0.45 micro-filter was used to filter the solution into ICP vials and the analysis was performed using ICP-OES. The analysis was performed in triplicate. The following heavy metals were analysed: Aluminium (Al), Calcium (Ca), Copper (Cu), Iron (Fe), Lead (Pb), Magnesium (Mg), Manganese (Mn), Nickel (Ni), Silicon (Si), Strontium (Sr) and Zinc (Zn).
The results were presented in the form of a table (Table 5.10).

4.5. Statistical Analysis

All data collected were tabulated using Microsoft Excel 2016. Summary tables were created using the 'Autosum' function on Microsoft Excel 2016.
Multivariate analysis, namely principal component analysis (PCA) was conducted to summarise the variation in soil characteristics and water quality across the wetland system. The PCA was done using Microsoft Excel 365.

Chapter 5: Results

5.1. Introduction

Delineation of the wetland system, wetland assessments, laboratory and statistical procedures were conducted on all soil and water samples. The detected values were compared to accepted standards to determine the health of the wetland system.

5.2. Wetland delineation and classification

Two HGM units were delineated and classification of the system was not necessary as the system is a constructed wetland. However, a small natural wetland has formed within the area of the constructed wetland. HGM 1 consists of cell 1 to 4 and HGM 2 consists of cell 5 to 10.

5.3. WET-Health (Present Ecological State)

Wetland health is defined as a degree of the similarity of a wetland to a natural or reference condition (Macfarlane *et al*., 2009). The state of a wetland is a measure of the extent to which human impacts have caused the wetland to differ from the natural reference condition (Macfarlane *et al*., 2009). In this study, the WET-Health procedure (Macfarlane *et al*., 2009) was used which examines deviation from the natural reference condition in terms of three components of health; hydrology, geomorphology and vegetation. Table 5.1 below depicts the PES assessment scores and change in trajectory for the two constructed HGMs and the relative contribution of the Hydrology, Geomorphology and Vegetation components to the overall PES.

Table 5.1: PES Assessment Scores for the constructed wetlands HGMs 1 and 2

HGM Unit	Ha	Extent (%)	Hydrology		Geomorphology		Vegetation	
			Impact Score	Change Score	Impact Score	Change Score	Impact Score	Change Score
1	5	44	1,0	0,0	0,1	0,0	4,0	-2,0
2	7	56	2,0	0,0	0,0	-1,0	13,0	-2,0
Area weighted impact scores*			1,6	0,0	0,0	-0,6	9,0	-2,0
PES Category (See Table 3.1 and 3.2)			B	→	A	↓	F	↓↓

5.4. WET-EcoServices (Ecological Goods and Services)

The WET-EcoServices tool provides guidelines for scoring the importance of an HGM unit in delivering fifteen different ecosystem goods and services (Kotze *et al*., 2009). Ecosystem services include flood attenuation, streamflow regulation, sediment trapping, phosphate trapping, nitrate removal, toxicant removal, erosion control, carbon storage, maintenance of biodiversity, water supply for human use, natural resources, cultivated foods, cultural significance, tourism and recreation and education and research (Kotze *et al*., 2009). Figure 5.1 illustrates the ecosystem services scores for HGM1 and HGM2.

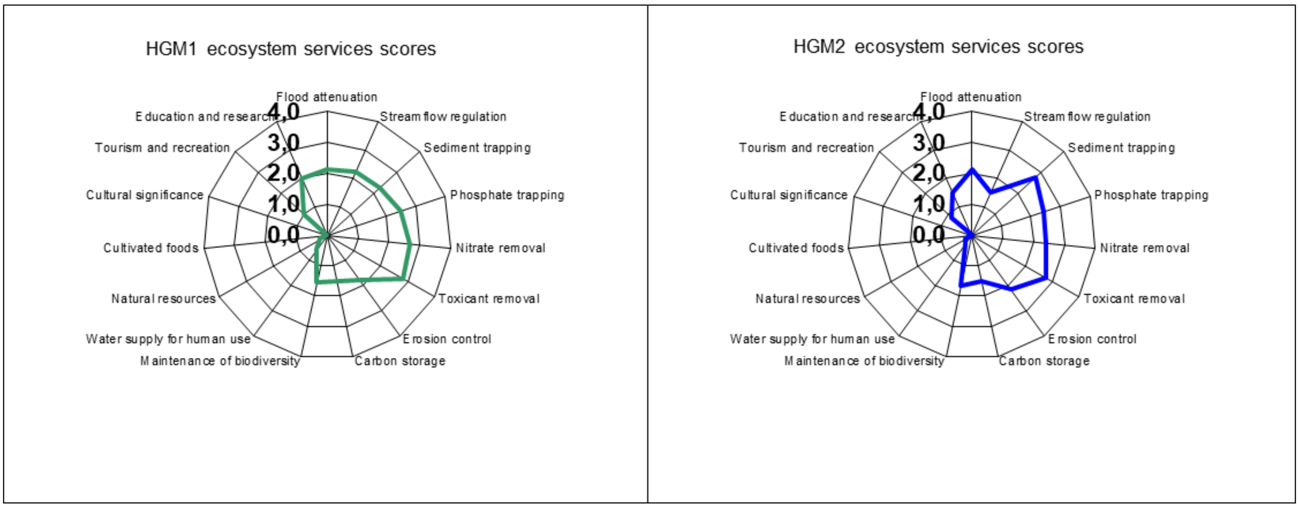


Figure 5.1: WET-EcoServices Score for HGM 1 (left) and HGM 2 (right)

5.5. Biodiversity Assessment

5.5.1. Floral Characteristics

The vegetation characteristics of the wetland cells during the winter and summer seasons are presented in Tables 5.2 and 5.3. During winter (dry season), the majority of the cells had a saturation extent and vegetation coverage of less than 50%. During summer (wet season), the majority of the cells had a saturation extent and vegetation coverage of more than 50%. The three main types of wetland vegetation present across the site were *Typha capensis* (Bulrushes), *Phragmites australis* (Common reed) and Cyperaceae (Sedges). *Typha capensis* was present in all 10 cells. Terrestrial vegetation was found to be dominant in cells 5, 6, 9 and 10. Cells 5 and 6 also had a significant amount of alien vegetation. Table 5.4 presents a list of alien invasive species found across the constructed wetland. Alien species present were Eucalyptus (Gumtree) and Acacia (Wattle).

Table 5.2: Vegetation characteristics of the individual cells for the winter survey

Cell No.	Vegetation Cover (%)	Extent of Saturation (%)	Types of Vegetation		
			Wetland	Terrestrial	Alien
1	50	40			
2	50	45	Mostly		
3	50	60			
4	80	50			
5	30	dry			Dominant
6	10	dry			
7	40	dry			
8	60	dry			
9	5	dry			
10	70	dry			

Table 5.3: Vegetation characteristics of the individual cells for the summer survey

Cell No.	Vegetation Cover (%)	Extent of Saturation (%)	Types of Vegetation		
			Wetland	Terrestrial	Alien
1	80	80	Bulrushes (*Typha capensis*), Reeds (*Phragmites australis*), Sedges (Cyperaceae)		
2	20	50	Bulrushes (*Typha capensis*)		
3	50	90	Bulrushes (*Typha capensis*), Reeds (*Phragmites australis*)		
4	100	90	Bulrushes (*Typha capensis*) & Elephant grass (*Pennisetum purpureum*)		
5	50	60	Bulrushes (*Typha capensis*)	Dominant	Dominant
6	50	10	Bulrushes (*Typha capensis*)	Dominant	Dominant
7	40	5	Bulrushes (*Typha capensis*)		
8	80	55	Bulrushes (*Typha capensis*)		
9	50	30		Dominant	
10	80	40	Bulrushes (*Typha capensis*)	Dominant	

Table 5.4: Alien Invasive Plants (AIPs) found within the cells of the constructed wetlands

Alien Invasive Plants (AIPs)
Phragmites australis
Acacia dealbata (Silver Wattle)
Acacia mearnsii (Black Wattle)
Rubus spp. (American bramble)
Agave americana
Ageratina adenophora
Ageratina conyzoides
Albizia lebbeck
Anredera cordifolia
Argemone mexicana
Canna indica
Cardiospermum grandiflorum
Catharanthus roseus
Celtis occidentalis
Cereus hexagonus
Cestrum laevigatum
Datura ferox
Eucalyptus sp.
Ipomoea alba
Lantana camara
Nasturtium officinale
Pennisetum purpureum
Solanum mauritianum
Tropaeolum speciosum

5.5.2. Faunal Characteristics

Whilst not visually observed during the survey periods, a review of background literature shows that a range of faunal species may be common to the area. These are discussed briefly below:

Up to 56 mammal species may occur in the area including: Bushbuck, Grey Rhebuck, Steenbok, Duiker, Mountain Reedbuck, Water Mongoose, Porcupine, Dassie, Slender Mongoose, Genet, & Lynx. More than 50 snake species may occur within the study area including: Southern African Python, Striped Harlequin snake, Agamas, Chameleons, Monitors, Skinks, Cordylids, Geckos, Marsh Terrapins & Tortoises. Many amphibians may occur in the study area including: Natal sand Frog, Whistling Rain Frog & Long toed tree frog. Avifaunal species include: Southern Bald Ibis, Lanner Falcon, Lesser kestrel, White backed Vulture, Amur falcon, Black Bellied Bustard & White Korhaan.

5.6. Sediment Characteristics

Sediment samples were analysed for colour, redoxymorphic features, particle size distribution, organic matter content, calcium carbonate content and heavy metals. The sediment characteristics of the wetland cells during the winter and summer seasons are presented in Tables 5.4 and 5.5. Figure 5.2 is a cumulative curve illustrating the sediment analysis. Figure 5.3 depicts the content of organic matter and calcium carbonate in soil samples. Table 5.7 presents the heavy metal concentrations.

Table 5.5: Sediment characteristics of the individual cells for the winter survey

Cell No.	Depth (cm)	Degree of Saturation (%)	Colour		Mottling %	Mottling		Clay & Silt Content (%)	Description
1	0-65		10YR 3/1	very dark gray	30		orange	14,32	coal discard, sandy clay
1	0-10	100							rich in organic carbon
	0-20								peat
	75 onwards								anoxic, pebbles present from discard
2	0-30 (near splitter)	slightly dry	10YR 3/3	dark brown	50	10YR 4/6	dark yellowish brown	14,1	discard present, strong sulphur odour, minor penetration of air
	30-40								minor penetration of air
2	70-100		10YR 2/2	very dark brown				21,1	
2	0-30 (centre)	saturated	10YR 2/1	black		10YR 4/6 and 10YR 5/8	dark yellowish brown and yellowish brown	5,58	discard, coal, shale
2	30-80		10YR 4/2	dark grayish brown		10YR 6/6	brownish yellow	21,14	
	80 onwards								fine grey sand, coal discard
3	0-30		10YR 3/1	very dark gray	20	10YR 4/6	dark yellowish brown	14,13	
3	30 onwards	100	10YR 2/2	very dark brown	30	10YR 4/3 and 10YR 7/8	brown and yellow	24,79	fine mud, discard
4	0-70		10YR 4/2	dark grayish brown	40	10YR 4/6	dark yellowish brown	13,59	
4	0-10	100							peat
	10-40								clay
	40-70								artificial discard on natural soil
5		dry							
6		dry							
7		dry							
8		dry							
9		dry							
10		dry							

Table 5.6: Sediment characteristics of the individual cells for the winter survey

Cell No.	Depth (cm)	Degree of Saturation (%)	Colour		Mottling %	Mottling		Clay & Silt Content (%)	Description
1		90							
2	0-40	50	10YR 3/2	very dark grayish brown	30	10YR 4/4	dark yellowish brown	12,13	top soil, wash over orange sand
2	40-80		10YR 2/1	black				6,65	coal discard
	65-80	100							
	75 onwards			orange					dense orange clay
2	80 onwards		10YR 2/1	black	40	10YR 4/2 & 4/6	dark grayish brown and dark yellowish brown	4,17	
3		100							
4		80							
5		50							
6		10							
7		10							
8		70							
9		65							
10		70							

Table 5.7: Heavy Metal Analysis of Sediment Samples

Sample Site	Heavy Metals																							
	Calcium (Ca) (µg/g)			Copper (Cu) (µg/g)			Iron (Fe) (µg/g)			Lead (Pb) (µg/g)			Magnesium (Mg) (µg/g)			Manganese (Mn) (µg/g)			Nickel (Ni) (µg/g)			Zinc (Zn) (µg/g)		
	CLARKE VALUE	SAMPLE	EF	CLARKE VALUE	SAMPLE	EF	CLARKE VALUE	SAMPLE	EF	CLARKE VALUE	SAMPLE	EF	CLARKE VALUE	SAMPLE	EF	CLARKE VALUE	SAMPLE	EF	CLARKE VALUE	SAMPLE	EF	CLARKE VALUE	SAMPLE	EF
1		1296.17	0.089814		11.50	0.000413		19878.33	1		20.83	0.003275		382.67	0.046054		258.67	0.000651		6.05	0.000190		13.17	0.000251
2		751.33	0.143105		11.33	0.001119		7231.67	1		20.00	0.008643		136.67	0.045212		84.33	0.000583		6.00	0.000519		8.00	0.000419
3		1541.00	0.249325		38.50	0.003230		8513.33	1		27.50	0.010094		154.17	0.043324		195.83	0.001150		2.83	0.000208		47.50	0.002113
4		610.87	0.071865		7.83	0.000478		11708.33	1		7.33	0.001956		297.33	0.060753		67.33	0.000288		8.00	0.000427		16.00	0.000518
5		1328.67	0.079335		157.33	0.004872		23068.33	1		316.72	0.042905		627.00	0.065024		158.76	0.000344		29.17	0.000790		72.67	0.001193
6	36.3	1587.00	0.159591	70	23.50	0.001225	50	13697.17	1	16	37.33	0.008517	20.9	1007.17	0.175912	1000	392.50	0.001433	80	17.17	0.000783	132	23.83	0.000659
7		373.50	0.019323		14.83	0.000398		26625.00	1		13.67	0.001604		401.50	0.036076		47.33	0.000089		16.33	0.000383		15.33	0.000218
8		505.13	0.085639		8.67	0.000762		8124.50	1		5.50	0.002116		287.00	0.084510		36.00	0.000222		10.00	0.000769		11.13	0.000519
9		552.00	0.049652		27.67	0.001291		15313.33	1		54.33	0.011087		142.17	0.022211		35.00	0.000114		2.33	0.000095		7.00	0.000173
10		2308.67	0.298637		10.67	0.000716		10648.33	1		33.00	0.009685		256.17	0.057553		97.50	0.000458		4.50	0.000264		12.67	0.000451
11		296.67	0.034817		6.00	0.000365		11736.67	1		18.00	0.004793		154.17	0.031425		16.50	0.000070		3.17	0.000169		6.50	0.000210

Colour coding – Blue = Lowest concentration; Red = Highest concentration

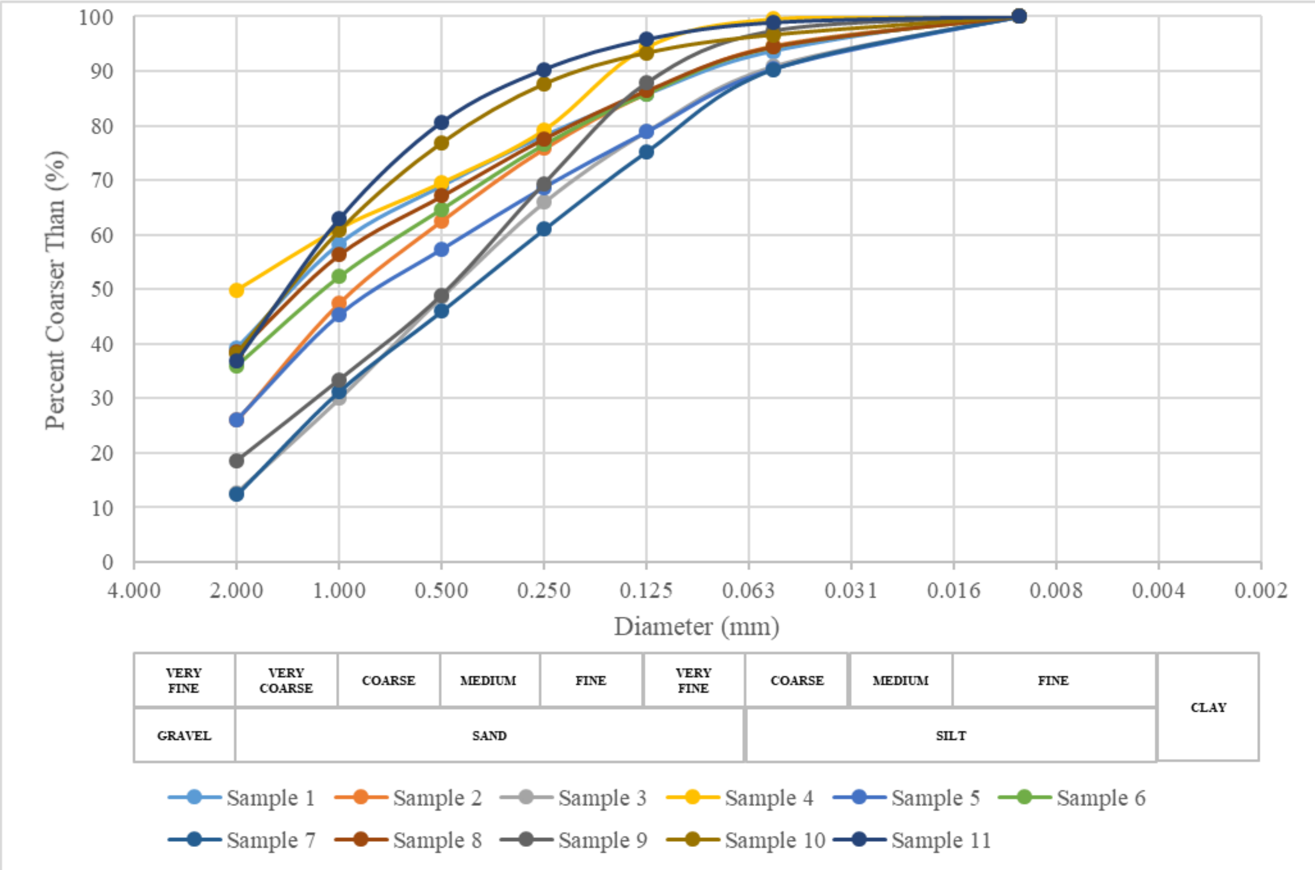


Figure 5.2: Cumulative curve showing sediment textural analysis

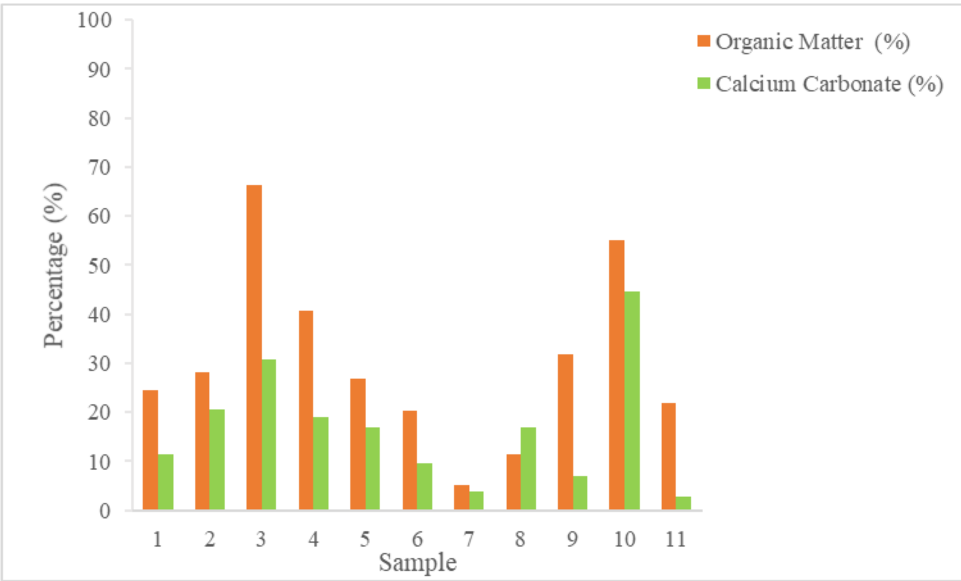


Figure 5.3: Bar graph showing the organic matter content and calcium carbonate content of sediment samples

5.6.1. Sediment Principal Component Analysis (PCA)

The principal component analysis (PCA) presented in Table 5.7 and Figures 5.4 and 5.5 shows no correlation of heavy metals in sediment samples.

Table 5.8: Eigenvalues

	F1	F2	F3	F4	F5	F6	F7	F8
Eigenvalue	4.341	1.687	1.118	0.455	0.245	0.127	0.026	0.002
Variability (%)	54.257	21.091	13.978	5.686	3.062	1.583	0.32	0.023
Cumulative %	54.257	75.348	89.326	95.012	98.074	99.658	99.977	100

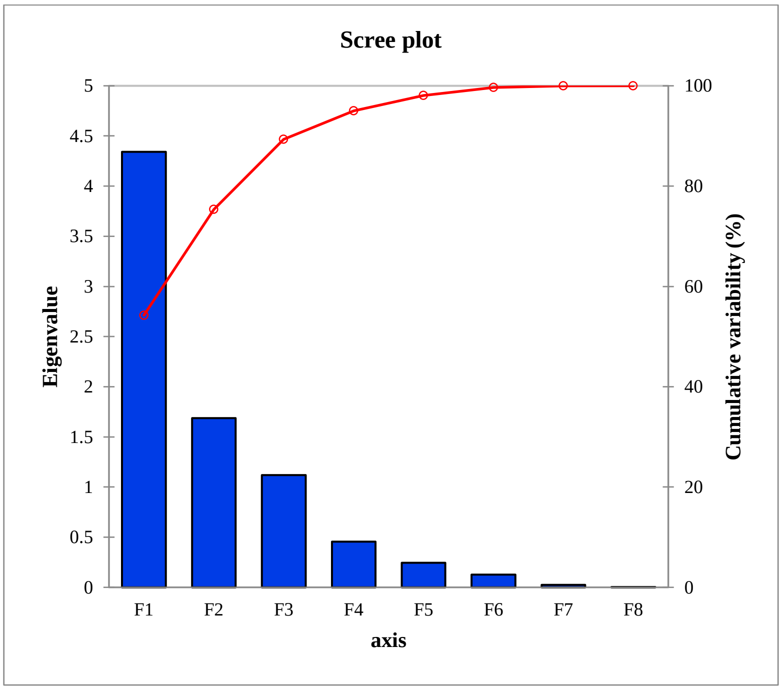


Figure 5.4: Scree plot

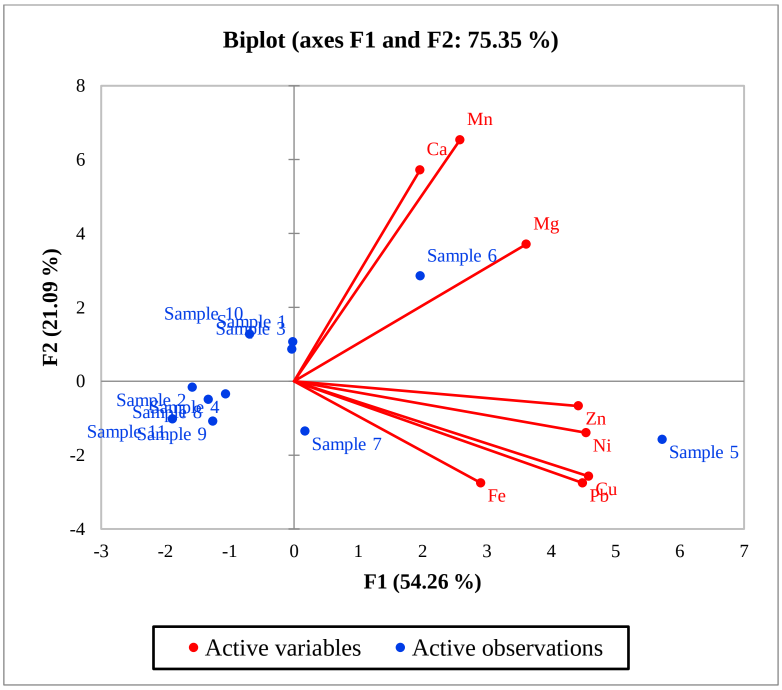


Figure 5.5: Biplot (axes F1 and F2: 75.35 %)

5.7. Water Quality Characteristics

Water samples were analysed for physical parameters, nutrients and heavy metals. The results of these analyses are presented in Tables 5.9, 5.10 and 5.11 respectively, and are compared to the Target Water Quality Range (TWQR) for aquatic ecosystems/domestic use in the South African Water Quality Guidelines (DWAF, 1996a; c). Heavy metals such as nickel, silicon and strontium, which were not available in the above mentioned guidelines were compared to TWQR's in other guidelines. Nickel concentrations were compared to the TWQR in the World Health Organization (WHO) Guidelines for Drinking-water Quality (WHO, 2008). Silicon concentrations were compared to the TWQR for industrial use in the South African Water Quality Guidelines (DWAF, 1996b). Strontium concentrations were compared to the US Environmental Protection Agency (EPA) Guidelines (EPA, 2013).

5.7.1. Physical Parameters

The parameters measured included pH, Salinity, TDS, EC and DO, the results of which, together with the TWQR standards, are presented in Table 5.9. The pH of 50% (four out of eight) of the winter samples were highly acidic and below the TWQR while the pH of 36% (four out of eleven) autumn samples were acidic and below the TWQR. The TDS of 88% (seven out of eight) of the winter samples, 50% (four out of eight) of the summer samples and 73% (eight out of eleven) of the autumn samples exceeded the TWQR. The EC of 25% (two out of eight) of the winter samples, 50% (four out of eight) of the summer samples and 9% (one out of eleven) of the autumn samples exceeded the TWQR. The DO concentrations of all samples did not meet the TWQR.

Table 5.9: Physical Parameters of Water Samples

Sample Site	Physical Parameters									
	pH		Salinity		TDS (mg/L)		EC (µS/cm)		DO (%)	
	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE
R1w		1.99		4.20		1943.33		7.62		0.00033
Dw		7.60		0.60		653.00		1519.00		0.00024
C1w		7.48		1.20		1112.30		2.58		0.00030
C2w		6.86		1.10		1042.00		2.42		0.00011
P1&2w		2.33		2.10		1739.00		4.04		0.00034
C3w		8.05		0.70		7.32		1702.00		0.00032
C4w		2.21		2.80		1826.67		5.24		0.00029
R2w		2.16		2.70		1583.33		5.09		0.00031
R1s		7.70		0.00		162.00		377.00		0.00048
Ds		7.90		0.60		674.00		1566.00		0.00049
P1&2s		7.73		0.60		671.00		1560.00		0.00055
C3s		8.75		0.80		809.00		1882.00		0.00052
C4s		8.60		0.60		898.00		1624.00		0.00052
R2s	6 - 9	7.61	NA	0.00	0 - 450	153.00	0 - 700	355.00	80% - 120% of saturation	0.00053
R3s		7.52		0.00		182.00		424.00		0.00051
R4s		7.28		0.00		230.00		531.00		0.00053
R1a		6.69		0.00		173.00		401.00		0.00054
Da		6.30		664.30		791.50		1.41		0.00052
S-C1&2a		7.02		664.00		797.20		1.42		0.00056
P1&2a		6.35		682.00		822.60		1.40		0.00060
C3a		5.60		700.00		855.00		1.50		0.00061
C4a		7.29		693.00		831.00		1.40		0.00050
R2a		5.23		575.90		724.30		1.38		0.00051
R3a		6.51		0.00		117.00		273.00		0.00056
C4-5a		5.36		556.20		686.00		1.18		0.00057
C10a		7.23		381.20		461.00		805.20		0.00054
R4a		5.40		220.00		272.00		480.00		0.00060

BDL = Below detectable levels; NA = Not available; TWQR = Target water quality range

Colour coding – Green = within acceptable TWQR; Red = exceeds TWQR; Grey = Below detectable level

R = River; D = Decant; C = Cell; P = Product of; S = Splitter to; w = winter; s = summer; a = autumn

5.7.2. Nutrient Analysis

Nutrients analysed for are nitrites, nitrates, sulphates and orthophosphates. These results together with their water quality standards (TWQR) are shown in Table 5.10. All nitrite and nitrate concentrations were either within the acceptable TWQR or below detectable levels. The sulphate concentration of 9% (one out of eleven) of the autumn samples exceeded the TWQR. All orthophosphate concentrations were below detectable levels.

Table 5.10: Nutrient Analysis of Water Samples

Sample Site	Nutrients							
	Nitrite (NO_2^-) (mg/L)		Nitrate (NO_3^-) (mg/L)		Sulphate (SO_4^{2-}) (mg/L)		Orthophosphate (PO_4^{3-}) (mg/L)	
	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE
R1w	0 - 6	BDL	0 - 6	BDL	0 - 200	73.05	should not be changed by > 15 % from that of the water body	BDL
Dw		BDL		0.02		78.80		BDL
C1w		0.002		2.24		98.75		BDL
C2w		0.07		0.09		144.24		BDL
P1&2w		BDL		BDL		83.91		BDL
C3w		BDL		0.39		82.75		BDL
C4w		BDL		0.12		73.78		BDL
R2w		BDL		BDL		74.94		BDL
R1s		BDL		BDL		96.03		BDL
Ds		0.07		BDL		141.05		BDL
P1&2s		BDL		BDL		102		BDL
C3s		BDL		BDL		84.09		BDL
C4s		BDL		1.24		156.50		BDL
R2s		0.08		BDL		99.33		BDL
R3s		BDL		BDL		76.54		BDL
R4s		BDL		BDL		77.85		BDL
R1a		BDL		0.16		85.85		BDL
Da		BDL		0.01		65.10		BDL
S-C1&2a		BDL		0.004		32.42		BDL
P1&2a		0.08		0.06		43.43		BDL
C3a		BDL		BDL		38.85		BDL
C4a		BDL		BDL		20.69		BDL
R2a		BDL		BDL		3.89		BDL
R3a		BDL		0.13		18.54		BDL
C4-5&6a		0.07		0.18		252		BDL
C10a		BDL		BDL		4.29		BDL
R4a		BDL		0.18		31.60		BDL

BDL = Below detectable levels; NA = Not available; TWQR = Target water quality range

Colour coding – Green = within acceptable TWQR; Red = exceeds TWQR; Grey = Below detectable level

R = River; D = Decant; C = Cell; P = Product of; S = Splitter to; w = winter; s = summer; a = autumn

5.7.3. *Heavy Metal Analysis*

The heavy metal analysis is presented in Table 5.11. The concentrations of several of the heavy metals analysed for exceeded the Target Water Quality Requirements (TWQR) as set by DWAF (1996) for aquatic systems.

Table 5.11: Heavy Metal Analysis of Water Samples

Sample Site	Aluminium (Al) (mg/L)		Calcium (Ca) (mg/L)		Copper (Cu) (mg/L)		Iron (Fe) (mg/L)		Magnesium (Mg) (mg/L)		Manganese (Mn) (mg/L)		Nickel (Ni) (mg/L)		Silicon (Si) (mg/L)		Strontium (Sr) (mg/L)		Zinc (Zn) (mg/L)	
	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE	TWQR	SAMPLE
R1w		3.54		70.96		0.02		5.74		21.36		1.49		BDL		6.90		0.53		BDL
Dw		0.01		6.17		0.02		BDL		3.14		0.09		BDL		11.33		0.56		0.09
C1w		0.60		28.85		0.05		5.72		5.32		0.26		0.01		5.38		0.08		0.03
C2w		0.30		122.95		0.05		5.15		8.08		0.08		BDL		20.44		2.32		0.03
P1&2w		2.04		20.47		0.10		1.11		4.29		0.04		0.02		8.91		0.63		0.02
C3w		0.39		20.65		0.03		0.40		3.94		0.05		BDL		7.46		0.56		0.01
C4w		1.49		19.32		0.05		0.62		3.49		0.02		BDL		6.84		0.48		BDL
R2w		0.54		49.45		0.08		0.82		20.96		0.49		BDL		10.32		0.29		0.27
R1s		0.04		44.63		BDL		BDL		12.49		0.13		BDL		5.62		0.29		BDL
Ds		1.56		16.02		0.02		49.55		3.85		0.34		BDL		11.06		0.76		BDL
P1&2s		0.09		11.25		0.03		1.87		4.74		0.05		BDL		8.21		0.61		BDL
C3s		0.31		18.22		0.02		0.54		4.29		0.07		BDL		5.61		0.60		BDL
C4s		0.13		32.38		0.02		1.54		4.70		0.02		BDL		1.84		0.76		BDL
R2s	At pH<6.5, 0 - 0.005 At pH>6.5, 0 - 0.01	BDL	0 - 32	42.45	0 - 1	0.02	0 - 0.1	BDL	0 - 30	12.39	0 - 0.05	0.02	0 - 0.07	BDL	0 - 5	5.71	0 - 4	0.26	0 - 3	BDL
R3s		BDL		40.30		0.01		BDL		12.51		0.02		BDL		3.55		0.27		BDL
R4s		0.03		42.76		BDL		BDL		13.94		0.15		BDL		6.47		0.31		BDL
R1a		0.46		53.58		0.01		0.35		16.83		0.06		BDL		10.43		0.39		0.01
Da		BDL		15.88		0.01		BDL		3.67		0.03		BDL		11.13		0.53		0.05
S-C1&2a		0.06		17.24		0.01		BDL		2.39		0.04		BDL		10.67		0.49		0.05
P1&2a		0.40		17.01		0.06		BDL		2.76		0.08		BDL		9.36		0.37		0.11
C3a		0.56		16.93		0.04		0.31		3.48		0.09		BDL		8.83		0.54		0.17
C4a		0.05		17.99		0.01		BDL		3.33		0.02		BDL		8.68		0.44		0.04
R2a		0.09		16.61		0.03		BDL		1.96		0.04		BDL		7.95		0.33		0.06
R3a		0.07		31.67		0.02		BDL		6.42		0.03		BDL		8.41		0.17		0.03
C4-5&6a		BDL		84.87		0.01		BDL		34.05		0.03		BDL		2.75		0.46		0.01
C10a		0.06		24.70		0.02		3.68		8.34		1.70		BDL		10.02		0.12		0.18
R4a		0.13		30.50		0.01		0.02		8.93		0.05		BDL		9.45		0.19		0.01

BDL = Below detectable levels; NA = Not available; TWQR = Target water quality range

Colour coding – Green = within acceptable TWQR; Red = exceeds TWQR; Grey = Below detectable level; R = River; D = Decant; C = Cell; P = Product of; S = Splitter to; w = winter; s = summer; a = autumn

5.7.3.1. Water Principal Component Analysis (PCA)

The principal component analysis (PCA) presented in Table 5.12 and Figures 5.6 and 5.7 yielded variable results with no clear pattern of heavy metal correlation in the water samples except for principal components F1 and F2. The reason for this pattern is discussed in the following chapter.

Table 5.12: Eigenvalues

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Eigenvalue	2.275	1.98	1.736	1.454	1.31	0.533	0.351	0.232	0.082	0.048
Variability (%)	22.749	19.796	17.356	14.54	13.1	5.331	3.509	2.316	0.823	0.48
Cumulative %	22.749	42.546	59.901	74.441	87.541	92.872	96.381	98.697	99.52	100

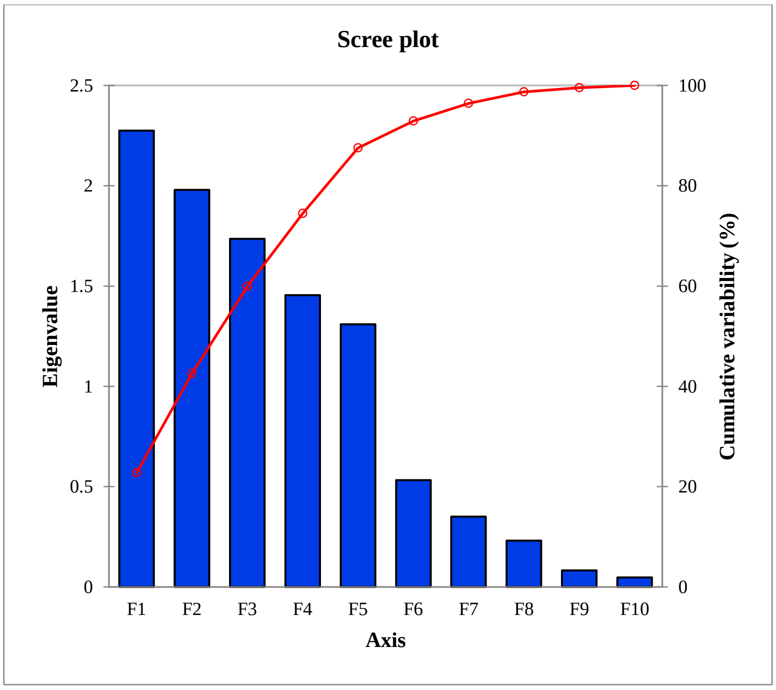


Figure 5.6: Scree plot

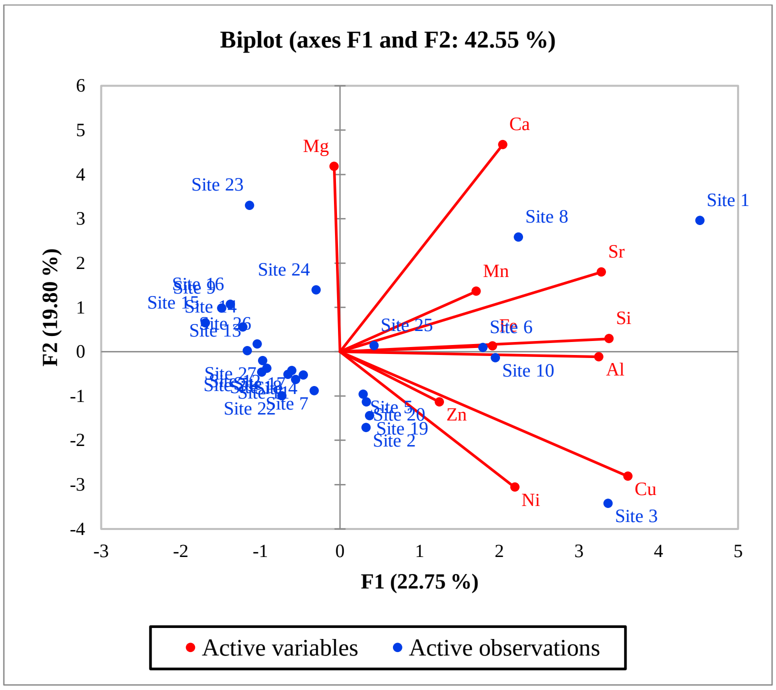


Figure 5.7: Biplot (axes F1 and F2: 42.55 %)

Chapter 6: Discussion

6.1. Introduction

In order to make inferences on the health of the wetland system, the results are further deliberated in conjunction with accepted standards and relevant literature. Based on the findings of analytical assessments, the health status of this system will be discussed prior to the identification of appropriate rehabilitation, management and monitoring procedures to be implemented.

6.2. Wetland delineation and classification

The constructed wetland system consists of two hydrogeomorphic (HGM) units, HGMs 1 and 2 that occupy 44% and 56% respectively of the area of the wetland system.

6.3. WET-Health (Present Ecological State)

The Present Ecological State (PES) of a wetland is determined by its hydrological, geomorphological and vegetation health (Macfarlane *et al*., 2009). Hydrology is the defining feature of wetlands and forms a key component of the assessment of wetland health. The hydrological conditions of a wetland affects many essential processes, including the development of anaerobic soil conditions, nutrient availability and sediment fluxes (Macfarlane *et al*., 2009). These factors have a strong influence on the fauna and flora which inhabit the wetland, which in turn have a feedback effect on the hydrological conditions of that wetland (Macfarlane *et al*., 2009).

PES determination for HGM1 shows that in its present state, the wetland hydrology falls into PES category B indicative of a system which is largely natural with few modifications, the wetland geomorphology falls into PES category A indicative of an unmodified, natural system and the wetland vegetation falls into PES category D indicative of a largely modified system (Macfarlane *et al*., 2009).

The HGM has an identifiable reduction in flows. This can be attributed to the extent of impact to drainage and the minor (5%) extent of impact to on-site water use. The connectivity of wetland cells is has, due to neglect, not been functioning properly, therefore affecting the drainage. The increased on-site water usage is exacerbated by alien invasive plants (AIPs) which have higher water demand than the indigenous vegetation, resulting in minor desiccation. The PES determination confirms that the hydrological state of HGM1 is likely to deteriorate slightly over the next five years. There is a 20% extent of impact to indirect organic matter loss as a result of oxidation. Although identifiable, the impact of this modification on geomorphic integrity of the affected area is small. The geomorphological state of HGM1 is likely to remain stable over the next 5 years. In terms of disturbance classes, there is a 20%, 20%, 10%, 100% and 25% extent of impact attributable to alien vegetation invasion, sediment deposition and infilling, eroded areas, recently abandoned areas and untransformed areas, respectively. The present vegetation state of HGM1 is expected to deteriorate substantially over the next 5 years.

PES determination for HGM2 shows that in its present state, the wetland hydrology falls into PES category C indicative of a moderately modified system, the wetland geomorphology falls into PES category A indicative of an unmodified system and the wetland vegetation falls into PES category F indicative of a system where modifications have reached a critical level.

The HGM has a small but identifiable reduction in flows. This can be attributed to the 10%, 20%, 25% and 10% extent of impact related to deteriorating drainage, surface roughness changes, on-site water use and deposition, respectively. The mechanical splitter to cell 5 and 6 was found to be clogged with debris and dense algal growth and the connectivity of wetland cells was no longer in a sound working state, therefore affecting the drainage (Figure 6.1). There is a moderate reduction in roughness caused by vegetation changes from tall robust vegetation of *Typha* and *Phragmites* reeds (Figure 6.2), to various alien invasive vegetation species resulting in the reduction in water retention. The increased on-site water usage is caused by alien invasive plants which dominate much of HGM2. Further, minor changes to the water flow patterns and wetness regimes are clearly apparent due to water flow being preferentially concentrated towards the north-east corner of each cell due to the manner in which the cells were constructed. The hydrological state of HGM2 is expected to deteriorate substantially over the next 5 years. There is a 10%, 15%, 10% and 20% extent of impact to infilling, erosional features, depositional features and organic matter loss, respectively. The erosion intensity is serious and the modification has a clearly adverse effect of geomorphic integrity of the area. Infilling and deposition is identifiable, although the impacts of these modifications on geomorphic integrity on the affected areas are small. The organic matter loss is caused indirectly as result of oxidation through desiccation. The modification has a clearly detrimental impact on geomorphic integrity of the affected area with approximately 50% of the integrity of the affected area being lost. The geomorphological state of HGM2 is likely to deteriorate slightly over the next 5 years. In terms of disturbance classes, there is a 55%, 20%, 20%, 100%, 10% and 25% extent of impact from alien vegetation, sediment deposition and infilling, eroded areas, recently abandoned areas, seepage and transformed areas, respectively. The present vegetation state of HGM2 is expected to deteriorate substantially over the next 5 years.

Figure 6.1: Splitter to cell 5 and 6 clogged with debris and dense algal growth (a) winter; (b) summer

Figure 6.2: Two cells separated by a berm with dense growth of *Typha*

6.4. WET-EcoServices (Ecological Goods and Services)

Analysis of the ecological goods and services provided indicate that both HGM1 and HGM2 provide thirteen out of the fifteen ecosystem goods and services, with cultivated foods and cultural significance being the only two that they do not provide.

However, the values recorded for ecoservices for the two HGM's were low to moderately high. Water supply for human use and natural resources provided by HGM1 and HGM2 was low to moderately low. Carbon storage and maintenance of biodiversity provided by HGM1 and HGM2 was moderately low to intermediate. Flood attenuation, sediment trapping, phosphate trapping, nitrate removal and toxicant removal were intermediate to moderately high for both HGM1 and HGM2. Streamflow regulation was intermediate to moderately high in HGM1 and moderately low to intermediate in HGM2. Erosion control was moderately low to intermediate in HGM1 and intermediate to moderately high in HGM2. Threats to HGM1 were moderately high while threats to HGM2 were high but similarly, opportunities for both HGM1 and HGM2 were moderately high.

The assessment suggests that the most important regulating services provided are toxicant removal and nitrate removal for HGM1 and toxicant removal and sediment trapping for HGM2. The low slope and intermediate to moderately high surface roughness suggests that the wetland is likely to be intermediately effective in attenuating floods. The decrease in streamflow regulation from intermediate to moderately low from HGM1 to HGM2 can be attributed to the dysfunctional connectivity between cells, especially via the subsurface pipe from HGM1 to HGM2 (Figure 6.3 and 6.4).

There is an increase in sediment trapping from HGM1 to HGM2. Phosphate trapping, carbon storage, maintenance of biodiversity, remained relatively stable from HGM1 to HGM2. The decrease in nitrate removal from HGM1 to HGM2 is due to the diminishing wetland characteristics in HGM2. Erosion control increased from moderately low to intermediate from HGM1 to HGM2. However, the degraded nature of the system provides an opportunity to assess the effects of rehabilitation on the overall functioning of the wetland.

Figure 6.3: Splitter to sub-surface pipe from cell 4 which connects to the splitter to cell 5 and 6, (a) upper part shows cell 4, lower part shows splitter; (b) left side shows splitter; right side shows cell 4

Figure 6.4: HGM 1 in the background and HGM 2 in the foreground (Distance between HGM 1 and 2 is approximately 489 metres)

6.5. Overall ecological and functional assessment

In terms of the health of the wetland system as a whole, it is only the geomorphology that has maintained its natural state (category A). However, the geomorphological characteristics are degrading over time as a result of animals trampling through the wetland breaking waterways and causing erosion of embankments. Due to these geomorphological changes, the trajectory of change indicates a downward change over the next five years. The hydrology is a category B indicating that it's not at its best. The hydrological status is not expected to change over time because the water inputs and outputs of the system are expected to remain the same however, the water quality is expected to deteriorate. The expected deterioration in water quality is due to alien vegetation using an increased amount of water, disturbances caused by animals (cattle and horses) grazing there and contributing to increased nutrient input. The principle area of concern is the vegetation because it is a category F indicating that the vegetation status is extremely poor and the change of trajectory suggests that it will deteriorate drastically in the next five years. This is due to the incursion of alien vegetation, a decrease in water flowing through the wetland and a change in the geomorphology. The above will result in the entire area, overtime, changing to one with dense growth of alien vegetation and terrestrial plants. This will cause a serious deterioration of the functionality of the wetland. Whilst there are numerous ecosystem services provided, especially physical services such as sediment trapping, nitrate removal and phosphate trapping, these services will be compromised overtime as a result of the health of the wetland being compromised. A decline in the essential physical components and functionalities of the wetland will result in the deterioration of the geomorphological and vegetation status of the wetland making re-establishment of the wetland to be of critical importance from a health perspective.

6.6. Biodiversity Assessment

6.6.1. Floral Characteristics

When the wetland was initially constructed, it consisted predominantly of wetland type vegetation however, it is now being gradually taken over by terrestrial type vegetation and alien invasive vegetation. There are parts of the wetland that has remnants of wetland type vegetation especially in the eastern part of each cell where water accumulates. The other parts seem to be drying out because the system is not functioning as it should, allowing alien vegetation and terrestrial vegetation to proliferate.

The system was dominated by three types of wetland vegetation, namely; *Typha capensis* (Bulrushes), *Phragmites australis* (Common reed) and Cyperaceae (Sedges). *Typha capensis* is known to remove heavy metals, particularly cadmium, copper, lead, nickel and zinc and also ameliorates heavy nutrient loading (Russel, 2009). *Phragmites australis* and plants of the Cyperaceae family are also suitable for heavy nutrient loading (Russel, 2009).

There is a significant amount of alien invasive vegetation present in the wetland system, as shown in Table 5.4. The alien invasive plants (AIPs) present were Eucalyptus (Gumtrees) and Acacia (Wattle). The riparan vegetation appears to be largely Acacia and Eucalyptus that runs along the margins. The presence of *Asclepias* (Milkweed), which is not a typical wetland species is evidence of community changes. Remnants of Bulrushes in some parts of the wetland indicate that wetland species were gradually being taken over by terrestrial species. In the winter survey presented in Table 5.2, the dominant type of vegetation was alien vegetation. In the summer survey presented in Table 5.3, cells 5 and 6 was dominated by alien and terrestrial vegetation while cells 9 and 10 were dominated by terrestrial vegetation. The above-mentioned cells will require critical attention with regard to the removal of terrestrial and alien invasive vegetation.

Wetland cells were significantly more saturated in summer than in winter (Tables 5.2 and 5.3) which is attributable to summer rainfall causing an accumulation of water in the cells. The vegetation surveys suggest that higher saturation results in greater vegetation. This is specifically evident in cell 4 of the summer survey which had 90% saturation and 100% vegetation cover which can be contrasted with cell 7 of the summer survey which had 5% saturation and 40% vegetation cover. This indicates that vegetation cover is dependent on saturation which is critical for any wetland. The degree of saturation needs to be improved and that can only be achieved when the system in functioning completely. In order for the system to function completely, all waterways need to be re-established. Therefore, the hydrological status of the cells is one of the key aspects in restoration of the wetland.

6.6.2. Faunal Characteristics

There is an abundance of wetland type birds present in areas of dense vegetation, where there are thick stands of *Typha*. The birds are nesting amongst the dense vegetation suggesting that this vegetation provides a habitat for wetland type birds. Given that the wetland re-establishes itself fully, the biodiversity will increase significantly in that area.

6.7. Sediment Characteristics

Sediment characteristics were investigated by analysing samples for colour, redoxymorphic features, particle size distribution, organic matter content, calcium carbonate content and heavy metals. The colour and redoxymorphic features of the sediment samples during the winter and summer surveys are presented in Tables 5.4 and 5.5. The sediment samples were dark brown to grayish brown in colour with evidence of mottling. The dark brown to grayish brown colour of the soils from both HGMs with redoxymorphic features is accordingly indicative of water logging and a fluctuating water table. Soils which have a high water table for a significant portion of the year tend to have gray matrix colours (Presley *et al*., 2016). Mottling of gray, yellow and/or orange colours are usually caused by a fluctuating water table (Presley *et al*., 2016). The orange brown colours found in well-drained areas are a result of iron oxidation (Presley *et al*., 2016). The presence of coal discard in the majority of cells is due to coal discard being used as a base layer during the construction of the wetland system.

Figure 5.2 is a cumulative curve illustrating the sediment analysis. The grain size analysis revealed that the sediment is dominated by the presence of larger sized particles. The sediment samples constituted approximately 12% gravel, 76% sand and 12% silt. The 12% gravel is very fine gravel. The 76% sand consists of 18% very coarse sand, 16% coarse sand, 15% medium sand, 14% fine sand and 13% very fine sand. The 12% silt consists of 6% coarse silt, 4% medium silt and 2% fine silt.

Part of the reason why this wetland is not functioning at its optimum is probably related to the low silt and clay content of the soil. In rehabilitating the wetlands, consideration should be given to the proportions of fines that are incorporated into the basal sediments.

Figure 5.3 depicts the content of organic matter and calcium carbonate in soil samples. The graph shows a general trend between the organic matter content and calcium carbonate content whereby an increase in organic matter is accompanied by an increase in calcium carbonate. Samples 7, 8 and 9 are anomalies. Sample 7 shows a decrease in organic matter and an increase in calcium carbonate while samples 8 and 9 show an increase in organic matter and a decrease in calcium carbonate. Samples 4 and 10 have significantly high organic matter contents of above 50%. Samples 5 and 11 have significantly low calcium carbonate contents of below 5%. The general trend shown amongst the majority of soil samples suggests that organic matter content is directly proportional to calcium carbonate content. An increase in soil organic carbon (SOC) results in an increase in dissolution and re-precipitation of carbonates into the soil solution (Bronick and Lal, 2004). According to Bronick and Lal (2004), soil organic carbon increases microbial respiration as well as carbon dioxide, and is a source of calcium and magnesium.

The generally high organic matter content is currently being compromised in parts of most cells due to desiccation. Drying of parts of the cells leads to rapid mineralization and loss of organic constituents of the soils hence the need to re-establish the functioning of the wetlands.

Table 5.7 presents the heavy metal concentrations. The highest and lowest value for each heavy metal is highlighted. Heavy metal concentrations varied across the wetland system. Cell 2 (sample site 5 and 10) had the highest concentrations for five out of the eight heavy metals, namely; copper, nickel, lead, zinc and calcium. Cell 3 (sample site 6 and 7) had the highest concentrations of magnesium, manganese and iron. According to Chatterjee *et al*. (2006), granulometry has a significant influence on the elemental concentrations in sediments. A higher concentration of elements is expected around finer sediments due to their high adsorptive capability (Chatterjee *et al*., 2006).

The concentration of elements were compared to Clarke Values (Martinez *et al*., 2007) through the use of Enrichment Factors (EF). Enrichment factors (EF) are considered as useful indicators for assessing geochemical trends as well as for the comparison of differences and similarities between sites (Harikumar and Jisha 2010). All values were below the Clarke value at which enrichment occurs. All EF values were below 0.5. This indicates that heavy metal concentrations of sediments within the wetland cells are reflective of the background geology and that there is no anthropogenic influence in increasing heavy metal concentrations. An EF value greater than 2 is an indication of contamination concentrations of elements that are twice the magnitude of the background values and are generally directly associated with anthropogenic pollution (Martinez et al., 2007). Harikumar and Jisha (2010) stated that EF values between 0.5 and 1.5 are an indication of elemental input from natural sources.

6.8. Water Quality Characteristics

6.8.1. Physical Parameters

Table 5.9 presents the pH, salinity, total dissolved salts/solids (TDS), electrical conductivity (EC) and dissolved oxygen (DO) of water samples. The four winter samples which were found to be highly acidic had a pH value of below 4 and the four autumn samples which were found to be acidic, had a pH ranging between 4 and 6. These acidic pH values indicate toxic effects associated with dissolved metals (DWAF, 1996a). The acidity present in the constructed wetland is evidence that the system is not functioning as intended. The use of coal discard in the basal layer of the constructed wetland enhances the potential for acidity rather than eliminating it. The coal discard contains minerals such as iron sulphide and pyrite which reacts with ground water, producing acid. The low pH values or high acidity found in the constructed wetland is primarily due to the poor structural design used in the original construction of the wetland cells. The target water quality range (TWQR) for salinity was not available and is assessed through the use of TDS and EC values, as noted by DWAF (1996c). TDS and EC values which exceeded the TWQR were still not high enough to have any adverse effects, as stated by DWAF (1996a; c). All DO values were below 40% of saturation which is considered lethal and is likely to cause acute toxic effects on aquatic biota (DWAF, 1996c).

6.8.2. Nutrient Analysis

As presented in Table 5.10, all nitrite, nitrate, sulphate and orthophosphates concentrations were found to be either within the TWQR or below detectable levels

(BDL), with the exception of one sample with regard to its sulphate concentration. The sulphate concentration of sample site C4-5 & 6a exceeded the TWQR. The high sulphate concentration is emanating from coal discard in that area which is mostly likely enriched with sulphur or pyrite. It is also possible that the sulphate is emanating from the two discard dumps situated between HGM 1 and 2. All orthophosphate concentrations were BDL. Orthophosphate concentrations of below 5g/L are indicative of oligotrophic conditions. Systems with these conditions usually contain moderate levels of species diversity and are low productivity systems with rapid nutrient cycling (DWAF, 1996c). As a whole, the system is very poor in terms of providing nutrients. The deficient nutrient provision is due to the lack of suitable wetland vegetation which would aid in nutrient recycling.

6.8.3. Heavy Metal Analysis

As presented in Table 5.11, there is a significant amount of heavy metals in the water, the majority of which exceed the Target Water Quality Requirements (TWQR) as set by DWAF (1996) for aquatic systems:

- The aluminium concentrations of 88% (seven out of eight) of the winter samples, 75% (six out of eight) of the summer samples and 82% (nine out of eleven) of the autumn samples exceeded the TWQR. All samples which exceed the TWQR fall either within or above the acute effect value (AEV) indicating that these concentrations have acute effects to aquatic ecosystems, as stated by DWAF (1996c). The solubility of metals are aided at certain pH ranges with aluminium solubility beginning to increase at pH 6 (DWAF, 1996a).
- The calcium concentrations of 38% (three out of eight) of the winter samples, 63% (five out of eight) of the summer samples and 18% (two out of eleven) of the autumn samples exceeded the TWQR. The calcium concentration of sample site C4-5&6a was significantly higher than all other sites. The high calcium concentration is emanating from coal discard in that area which is mostly likely enriched with calcium. It is also possible that the calcium is emanating from the mineralisation of the discard coal used in the construction of the basal layers of the cells.

- The iron concentrations of 88% (seven out of eight) of the winter samples, 50% (four out of eight) of the summer samples and 27% (three out of eleven) of the autumn samples exceeded the TWQR. The iron concentration of sample site Ds was significantly higher than all other sites.
- The magnesium concentration of 9% (one out of eleven) of the autumn samples exceeded the TWQR. The magnesium concentration of sample site C4-5 & 6a exceeded the TWQR. The high magnesium concentration is emanating from coal discard in that area which is mostly likely enriched with magnesium. It is also possible that the magnesium is emanating from the two discard dumps situated between HGM 1 and 2.
- The manganese concentrations of 63% (five out of eight) of the winter samples, 50% (four out of eight) of the summer samples and 36% (four out of eleven) of the autumn samples exceeded the TWQR. Manganese concentrations for sample sites R1w and C10a were higher than that of all other sites. The high manganese concentration is emanating from coal discard in that area which is mostly likely enriched with manganese.
- The silicon concentrations of all winter samples, 75% (six out of eight) of the summer samples and 91% (ten out of eleven) of the autumn samples exceeded the TWQR. The high silicon concentration in sample site C2w is emanating from coal discard in that area which is mostly likely enriched with silicon.
- Lead was not present in any of the water samples. All copper, nickel, strontium and zinc concentrations were either within the acceptable TWQR or below detectable levels.

There were significant amounts of aluminium, calcium, iron, manganese and silicon in solution across the wetland system indicating that the system is not functioning well enough to sequestrate contaminants. The decant water is of relatively good quality suggesting that heavy metals are being picked up as water traverses through the wetland, however silicon appears to be coming from the decant water. There are geochemical reactions occurring between the sediment and water which is aided by the low pH for some heavy metals. The mobilisation of aluminium, calcium, iron, manganese and silicon is due to these geochemical reactions at low pH. Heavy metals such as copper, magnesium, nickel, strontium and zinc displayed very low concentrations throughout the system. Since these concentrations were also low upstream of the wetland, it is unlikely that it is reflective of the functioning of the wetland in sequestrating these heavy metals.

6.9. Principal Component Analysis (PCA)

The results of the total variance, eigenvalues, scree plot and biplot of the sediment data set are presented in Table 5.8 and Figures 5.4 and 5.5. The results showed two PCs with eigenvalues greater than 1 explained just over 75% of the total variance of the data set. The first PC accounted for 54% of the total variance whilst the second accounted for 21% of the variance with principal metals Ca, Mn, Mg, Zn, Ni, Cu, Fe and Pb representing anthropogenic and natural sources.

Similar data for the water samples are presented in Table 5.12 and Figures 5.6 and 5.7. Here the results show that two principal components F1 and F2 explain 42.55% of the variance. Positive loading of Ca, Mn, Sr, Si, Zn, Al, Ni, and Cu.

The principal component analysis shows some correlation of heavy metals for both sediment samples and water samples. The association of heavy metals is not reflective of the efficiency of the constructed wetland in retaining metals as the system is currently not functioning efficiently. The association of metals is rather of a distribution of metals which are emanating from the manner in which the base layers of the wetland were constructed and is therefore anthropogenically influenced.

The floor of the wetland is graded to a level with a gentle slope to the outlet. The base layers constitutes a layer of coal discard overlain by a layer of sediment followed by coal discard and thereafter sediment again. Since the discard dump contains a mixture of coal and sediment as the coal was mined from different underground fronts and, the processing and subsequent dumping of discard material is not done in a systematic manner, distributions of metals on the floor of the wetland cells would be irregular. This indicates e.g. that coal from a part of the seam enriched with a particular heavy metal will result in a spike of that heavy metal in the cell in which it forms part of the base layer, but not in other cells. The above explains why the highest enrichment factor (EF) value for each element were found to be variously distributed in parts of the constructed wetland. Low EF values with water quality exceeding the TWQR can be clarified by the predominance of larger grained sediment which enables contaminants to be easily remobilised into the water column.

The spike in specific heavy metals at various parts of the site is reflective of the coal discard used in the base layer and the element of which it was enriched with. The underlying layer of coal discard also poses the danger of leaching particular heavy metals into the stream as a result of the way in which the wetland was constructed.

6.10. Maintenance

On assessment, the wetland was deemed dysfunctional. On enquiry, it was found that the wetland has not been maintained for at least five years. Following this study, it is clear that the consequence of this neglect has resulted in the following:

- The splitter to cell 1 and 2 has a plate missing where water leads to cell 1 resulting in more water flowing to cell 1 than cell 2 (Figure 6.5);
- The waterway between cell 1 and 2 is broken down due to animals (cattle and horses) trampling on it (Figure 6.6);
- A small amount of the water from cell 4 flows through the subsurface pipe while most of it overflows into the natural vegetation, creating a natural wetland;
- The splitter to cell 5 and 6 is clogged with algae and grass, preventing water from entering cell 5 and 6 (as shown in Figure 6.1);
- Erosion is visible along the embankments of wetland cells and,
- The dysfunctional water flow regime from HGM1 to HGM2 impedes wetland conditions in HGM2. This has allowed the proliferation of terrestrial and alien invasive plants (AIPs) to dominate HGM2;
- The functioning of the wetland in improving water quality has been compromised.

Due to the neglect and deterioration of the constructed wetland, a rehabilitation plan was developed and is presented below.

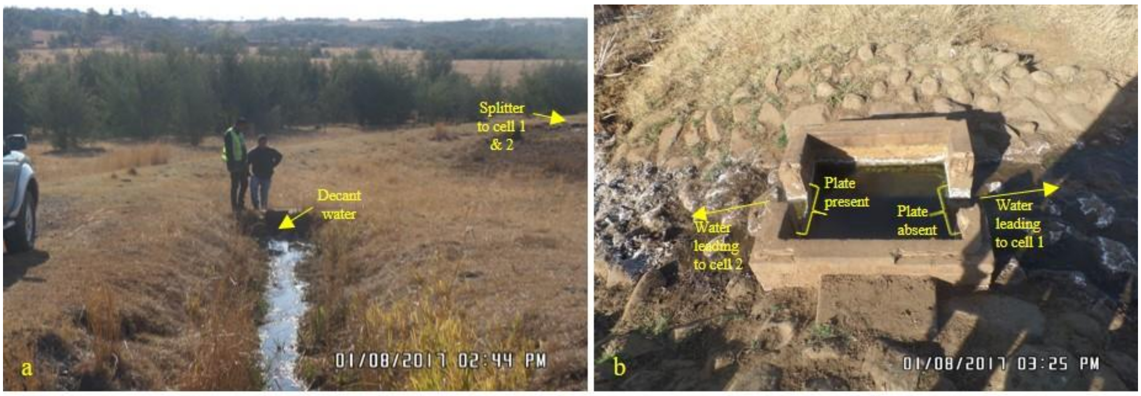


Figure 6.5: (a) Positioning of decant water in relation to splitter; (b) Splitter to cell 1 and 2 showing where the plate is present and absent

Figure 6.6: Degraded berm between cell 1 and 2 due to trampling by animals

6.11. Conclusion

The overall structure of the wetland is appropriate however, the mechanism by which acidity was expected to be reduced worked counter to what was intended. The basal layer which consisted of coal discard enhances the potential for acidity rather than eliminate it. The dysfunctional water flow regime can be attributed to the lack of maintenance and monitoring of the system. The inferior water quality is not reflective of the efficiency of the wetland in extracting or concentrating contaminants but rather of the contaminants emanating from the coal discard utilised in the base layer whilst constructing the wetland. There is a significant amount of heavy metals in solution making it evident that the wetland has extremely low sequestration of heavy metals and the plants are not taking up heavy metals. This is due to the lack of sufficient wetland vegetation. The use of suitable material including sediment with high nutrient value for the base layer of the wetland would allow for water to infiltrate through showing some retention of dissolved material, indicative of a trend in enrichment in the upper cells and gradually decreasing downslope. The use of suitable wetland vegetation would also facilitate the uptake of heavy metals. The water quality would then be depictive of the functioning of this wetland.

Chapter 7: Rehabilitation of the Bannockburn Constructed Wetland

7.1. Introduction

This section presents a recommended wetland rehabilitation plan for the Bannockburn constructed wetland system situated alongside a disused coal mine in northern KwaZulu-Natal.

"Wetland rehabilitation is the process of assisting in the recovery of a wetland that has been degraded or in maintaining the health of a wetland that is in the process of degrading" (Kotze *et al*., 2008, p. 14).

The main concern regarding the ecological and functional assessment of the constructed wetland was that the system deteriorated and needed to be rehabilitated.

Also, the main issues currently impacting the functioning of the wetland arise from inappropriate sediment composition used in the base layer during construction, erosion of embankments, lack of maintenance and monitoring resulting in the degradation of water ways, splitters and the subsurface pipe, lack of restriction of livestock entering the wetlands (Figure 7.1 and 7.2) and invasion of terrestrial and alien vegetation.

Figure 7.1: Animals present in the wetland (a) horses; (b) cattle and horses

Figure 7.2: Waterway from cell 3 to cell 4 with animal footprints beside it

7.2. The Rehabilitation Process

The purpose of wetland rehabilitation is to identify and recommend approaches to aid in the mitigation of degradation to the Bannockburn constructed wetland and to re-establish the hydrological, geomorphological and ecological processes (Russel, 2009). Aspects of wetland rehabilitation for the Bannockburn constructed wetland comprises of the following processes:

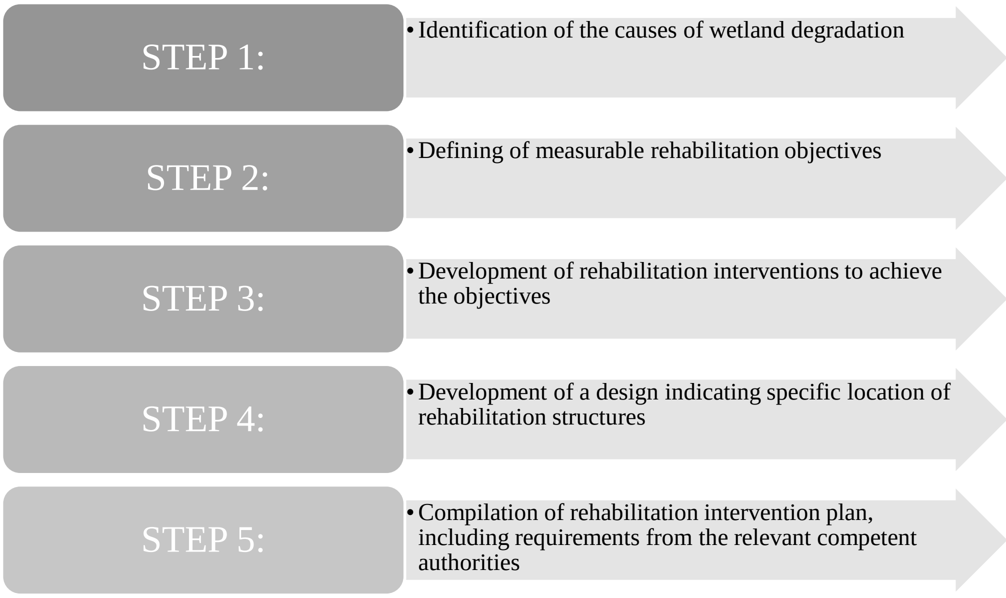


Figure 7.3: Steps in the rehabilitation process (Kotze *et al.*, 2009; Edwards, 2014)

Step 1: Identification of the causes of wetland degradation

The identification of the causes of wetland degradation prior to developing rehabilitation interventions is of critical importance in order to ensure that the rehabilitation procedures target the causes of the problem rather than the symptoms of the problem (Kotze *et al.*, 2009). For the Bannockburn constructed wetland, the causes of wetland degradation were identified during on-site evaluation:

- The lack of maintenance and monitoring of the constructed wetland system, resulting in the system deteriorating into a state of malfunction (Figure 7.3).
- The inappropriate use of coal discard in the base layer of the wetland cells.
- The dysfunctional connectivity of wetland cells preventing flow of water from one cell to the next, hence inhibiting the development of wetland conditions.
- Erosion of embankments.
- Proliferation of terrestrial and alien invasive plants (AIPs).

Figure 7.4: Mechanism leading water out of the wetland (from cell 10) and into the river. This part of the wetland has not been functional for a significant amount of time

Step 2: Defining of measurable rehabilitation objectives

The main purpose of rehabilitation is to return the wetland to its pristine condition (Sieben *et al*., 2011; Selala *et al*., 2013). The primary objective is to introduce rehabilitation measures for the Bannockburn constructed wetland system achieved by mitigating the causes of degradation identified in Step 1 via the rehabilitation interventions outlined in the table of composite interventions (Table 7.1):

Steps 2, 3 and 4: Implementation and management of rehabilitation measures

Table 7.1: Implementation and management of the rehabilitation measures

Impact	Location	Severity	Geology/Soils	Vegetation	Rehabilitation Measures	Monitoring
Contamination of water due to coal discard in base layer	All wetland cells	Moderate to serious, depending on the extent of leaching	Terrestrial and wetland soils infilled during construction of the wetland, including coal discard layers: a double layer of coal discard interleaved with terrestrial sediments	HGM 1: Wetland vegetation with little terrestrial and AIPs; HGM 2: Wetland vegetation but dominated by terrestrial and AIP's.	The base layers (terrestrial and coal discard layers) needs to be removed and wetland cells need to be relayered with a sequence of suitable sediment and material which will foster growth and help the wetland function more effectively.	The wetland system should be monitored once every three months. Generally, this is done by a representative of the relevant competent authorities.
Erosion of embankments resulting in infilling and deposition in wetland cells. Degradation of the embankments also alters the water flow regime.	All wetland cells	Moderate to serious	Terrestrial and wetland soils – as above (Mostly terrestrial soils in HGM 2)	Embankments have sparse grass cover, some alien invasives and erosion caused by animal movement and runoff from rain events	The embankments must be filled, reshaped and stabilized, then vegetated with suitable vegetation such as grasses in order to prevent erosion.	Visual checks as above
A missing plate in the first splitter between cells 1 & 2, causing more water to flow to cell 1 than cell 2. This affects the vegetation cover within the cells.	Splitter to cell 1 and 2	Moderate to serious	Terrestrial and wetland soils	Natural grasses around the splitter	The splitter to cell 1 and 2 needs to be repaired by replacing the missing plate.	Visual checks as above
Poor connectivity of wetland cells due to cemented water-way to cell 5 and 6 being clogged with algae and grass. This is preventing the flow of water hence inhibiting wetland conditions in the forthcoming cells.	Splitter to cell 5 and 6	Serious	Mostly terrestrial soils	Connection zones are cemented with inlain boulders to reduce flow velocity. They are not vegetated Overgrowth of grasses; Dense algal growth in the pooled water	The splitter to cell 5 and 6 needs to be repaired by removal of algae and grass which is clogging it.	The wetland system should be monitored once every three months by the relevant competent authorities.

Impact	Location	Severity	Geology/Soils	Vegetation	Rehabilitation Measures	Monitoring
Dysfunctional connectivity to the subsurface pipe resulting in water not flowing through the pipe but rather overflowing into the natural vegetation and creating a small natural wetland which then overflows into the river. This also prevents water from flowing from HGM 1 to HGM 2, hence inhibiting wetland conditions in HGM 2.	Between HGM 1 and HGM 2	Serious	Terrestrial	The surrounding area is characterised by natural grasses	The design of cell 4 needs to be reconsidered (e.g. higher embankments) in order to direct water to flow through the subsurface pipe rather than overflow into the natural vegetation.	Regular visual checks
Damage to cemented water-ways between cells preventing free flow of water from one cell to the next, hence preventing wetland conditions in the latter part of the wetland.	All wetland cells	Serious	Terrestrial and wetland soils (Mostly terrestrial soils in HGM 2)	Cemented areas – no vegetation; surrounding area may or may not have grasses or wetland vegetation	The waterways, splitters and the subsurface pipe need to be repaired where possible. Where necessary, these structures need to be redesigned and renovated.	The wetland system should be monitored once every three months by the relevant competent authorities.
Proliferation of terrestrial and alien invasive vegetation.	Mostly HGM 2	Serious	Terrestrial and wetland soils (Mostly terrestrial soils in HGM 2)	HGM 1: Wetland vegetation with little terrestrial and AIPs; HGM 2: Wetland vegetation but dominated by terrestrial and AIP's.	The terrestrial and AIPs need to be mechanically removed from the wetland cells. The cleared areas need to be re-vegetated with suitable obligate and facultative wetland vegetation.	Visual checks for the first 3 months, thereafter quarterly checks by the relevant competent authorities.
grazing by cattle and horses resulting in disturbance to vegetation as well as vegetation community changes; damage to wetland soil and structures	All wetland cells	Moderate to serious	Terrestrial and wetland soils (Mostly terrestrial soils in HGM 2)	HGM 1: Wetland vegetation with little terrestrial and AIPs; HGM 2: Wetland vegetation but dominated by terrestrial and AIP's.	Restriction of entry needs to be implemented. The wetland area should be barricaded.	Visual checks for the first 3 months, thereafter quarterly checks by the relevant competent authorities.

Impact	Location	Severity	Geology/Soils	Vegetation	Rehabilitation Measures	Monitoring
Trespassing.	All wetland cells	Moderate	Terrestrial and wetland soils (Mostly terrestrial soils in HGM 2)	HGM 1: Wetland vegetation with little terrestrial and AIPs; HGM 2: Wetland vegetation but dominated by terrestrial and AIP's.	Restriction of entry needs to be implemented. The wetland area should be barricaded.	The relevant competent authorities should maintain checks.

Terrestrial and alien invasive plant control programme

The presence of terrestrial and alien invasive plants (AIPs) in the wetland were noted. HGM 1 was noted to little terrestrial and AIPs however, HGM 2 was noted to be dominated by terrestrial and AIPs. Rapid control measures and management is required to ensure that the terrestrial and AIPs do not negatively affect the system further. The main species identified within the wetland system were Eucalyptus (Gumtrees) and Acacia (Wattle).

For the purpose of the Bannockburn constructed wetland system, the mechanical control method will be required for the clearing phase. Mechanical removal refers to removal of plants by hand and with the aid of a hand held instrument for small individual plants and saplings. Techniques such as ring barking or cutting or slashing of the stump just above the soil surface may be required for larger plants.

Re-vegetation of the wetlands following clearing of terrestrial and AIPs

The re-vegetation of wetlands with an assortment of indigenous hydrophilic species is imperative for numerous reasons, such as:

- Indigenous vegetation coverage of the wetland increases surface roughness which aids in decreasing the velocity of water moving through the system, trapping of contaminants and sediment as well as improving water quality.
- Indigenous vegetation will assist in preventing erosion.
- Increase the value of the wetland in terms of the habitat and biodiversity.
- Re-establishment of the water regime will foster the growth of hydrophilic species and characteristics of a wetland community.

The re-vegetation of the wetland using indigenous plants can occur once the area has been cleared of terrestrial and alien invasive vegetation. Locally occurring species such as *Typha capensis, Phragmites australis* and Cyperaceae as well as other obligate and facultative wetland species can be used to re-vegetate the wetland. Some of the other suitable species are presented in Table 7.2 below.

Table 7.2: Indigenous wetland species that can be used in the re-vegetation

Indigenous vegetation for rehabilitation
Hyparrhenia hirta
Themeda triandra
Tristachya leucothrix
Eragrostis racemosa
Eragrostis chloromelas
Microchloa caffra
Diheteropogon amplectens
Trachypogon spicatus
Cymbopogon plurinoides
Cymbopogon excavatus
Digitaria tricholaenoides
Elionurus muticus
Cynodon nlemfuensis
Cynodon dactylon
Cynodon incompletes
Haemanthus humilis
Drimiopsis burkei
Drimiopsis lachenaloides
Ledebouria ovatifolia
Ledebouria floribunda
Gladiolus aurantiacus
Gladiolus crassifolius
Hypoxis hermrocallidea
Euphorbia clavaroides
Pycreus macranthus
Cyperus rotundus
Fimbristylis complanata
Imperata cylindrical
Typha capensis
Ziziphus mucronata
Acacia sieberiana
Acacia karoo
Acacia caffra
Searsia pyroides
Stenostelma umbelluliferum
Vernonia gerradii
Hermannia oblongifoli
Habenaria kraenzliniana
Aloe modesta
Bowkeria citrina

7.3. Overall Monitoring

Monitoring of a rehabilitation is imperative in order to know whether the rehabilitation plan is successful. Regular on-site monitoring aids in the identification of problems which may arise during the rehabilitation process. During the initial phases of the rehabilitation project, monitoring should occur frequently to ensure the successful application of interventions. The basic time framework for the monitoring programmed of the wetland rehabilitation plan for the constructed wetland is as follows:

- Once a month for a duration of 6 months;
- Thereafter at least once every three months

7.4. Conclusion

The primary objective of developing a rehabilitation plan is to aid the recovery of the constructed wetland back to the originally envisaged state of fostering growth and helping the wetland function more effectively. The rehabilitation interventions will improve the health of the wetland as well as the delivery of ecosystem services. The majority of the rehabilitation will involve improving the connectivity between cells and removal of terrestrial and AIPs and re-vegetation using suitable indigenous wetland species. The recommended site-specific measure of removal of the basal sediments, particularly the layers of coal discard, will greatly assist in remediating the system and allow it to perform the function of water purification more effectively.

Chapter 8: Conclusion and Recommendations

8.1. Conclusion and key findings of this study

The aim of this study was to investigate the efficiency of a series of constructed wetlands in remediating acid mine drainage. The results of the research indicate that:

- The water quality of the Bannockburn Constructed Wetland is of poor quality and has been deteriorating for more than five years. The water is unfit for domestic usage and is likely to present negative impacts on aquatic life, as per South African Water Quality Guidelines (SAWQG).
- The inferior water quality is not reflective of the efficacy of the wetland system in the removal of contaminants but rather of the contaminants emanating from the coal discard utilised in the base layer during construction of the wetland.
- The elemental distribution is similar across the sites indicating that the wetland is not functioning.
- Even though enrichment factor values were generally low, the predominance of coarse sediments suggests that contaminants are likely to be easily remobilised into the water column.
- The proliferation of terrestrial and alien invasive plants is as a result of the inhibition of wetland conditions, especially in HGM 2, which is caused by the dysfunctional water flow regime.
- The degradation of the system is essentially due to a lack of maintenance and monitoring for at least five years.

8.2. Recommendations

The constructed wetland system needs to be rehabilitated accordingly, as per rehabilitation plan outlined in Chapter 7. Regular maintenance and monitoring of the system by the relevant competent authorities is imperative.

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