Using the pollution-index method to assess water quality in the upper Olifants River Catchment, Mpumalanga Province.

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Declaration

I, Petrus Fredrik Oberholster declare that *Using the pollution-index method to assess water quality in the upper Olifant River Catchment, Mpumalanga Province* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: Petrus Fredrik Oberholster

Date…..9/10/2017

Signed…

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Abstract

The upper Olifants River catchment, situated in Mpumalanga Province, South Africa, is one of the main sources of water for this region. This region face challenges to guarantee future water security due to intensive land use activities e.g. mining, energy production, and agriculture activities. South Africa is the sixth largest producers of coal in the world and the Witbank (eMalahleni) coal fields, situated in the catchment, represents the largest conterminous area of active coal mining in South Africa. The second largest irrigation scheme (Loskop dam Irrigation Board) is also found below the Loskop Dam in the upper Olifants River catchment. The irrigation scheme of ± 480 km of irrigation channels provides water for a R1 Billion export industry of citric fruits to the European Union. Furthermore, the Olifants River in Mpumalanga is also a trans-boundary river that initially flows northwards before curving in an easterly direction through the Kruger National Park and into Mozambique where it joins the Limpopo River before discharging into the Indian Ocean. Although the Olifants River is one of the main river systems in South Africa, it has been described as one of the most polluted rivers in southern Africa, with Loskop Dam acting as a repository for pollutants from the upper catchment of the Olifants River system. Because Loskop Dam is of strategic important for the whole region the aim of the study was to show the implications of poor water quality on the local communities down stream of Loskop Dam that depend on water usage for their livelihood. (1) Developing a modified pollution index for the Loskop Dam, Mpumalanga Province using bioindicator algae species in relationship with water column physico–chemical parameters and national water guidelines as indication of pollution. (2) Analysing the threat of cyanobacteria, microsystin contaminations to crops irrigating by water from the Loskop Dam irrigation canals. (3) Discussing the social economic implication of water pollution on the Loskop Irrigation scheme and its stakeholders.

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CHAPTER 1

General introduction

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1. General Introduction

In the first research chapter (Chapter 4) of the study emphasis is placed on the water quality of Loskop Dam and the second research chapter (Chapter 5) the microcystin concentration is focus on. A significant effort will go into analysing different components that contribute to the degradation of water quality in the irrigation canals. This alone will help paint a picture of the general water quality. Additionally, many external factors will also be considered. After the water quality of Loskop Dam and the irrigation canal has been determined; the adverse effects that it will have on the farming community will be investigated and elaborated on in the third research chapter (Chapter 6). The Olifants River that flows into Loskop Dam has always been of strategic importance to the region; since it flows through the province of Gauteng, Mpumalanga, and Limpopo in South Africa before entering the Indian Ocean in Mozambique. Many strategically important land-use practices converge in the upper Olifants River catchment, and they rely heavily on a variety of goods and services derived from the catchment's aquatic ecosystem.

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Over the past fifteen years, isolated incidents of fish mortality have been recorded at different times in Loskop Dam. These incidents have become more frequent with the changes in the temperature during the winter and spring months (Driescher, 2008), and have concurred with Nile crocodile (*Crocodylus niloticus*) mortalities (Oberholster et al., 2010; Oberholster and Botha, 2011). Crocodile mortalities in Loskop Dam during this time period were associated with the sickness pancreatitis, which was possibly caused by chronic intake of rancid and decaying fish tissue (Myburgh et al., 2008). From a previous study conducted by Oberholster and Botha (2011), it was evident that the poor water quality of Loskop Dam that contains high concentrations of nutrients stimulates the growth of the nuisance algal, *Cladophora glomerata*, in the irrigation canals downstream of Loskop Dam. This raises the question of what affect poor water quality of the Loskop Dam will have on the local farming community.

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he The analysed water quality data will be brought into the context of the socio-economic impact of poor water quality on the Loskop farming community. In the first section, the water quality chapter, the aim will be to develop a pollution index that determines the status of the water quality using biotic and abiotic indicators. The incorporation and use of the pollution index will be discussed in the final research chapter (Chapter 4) of this thesis. The second part of the thesis will focus on assessing the micystin concentration found in canals. The socio-economic impact and management strategies to alleviate these difficulties and minimise the impact.

1.1 Context to the study

The thesis consist of seven chapters, wherein the first three chapters will present the aim and objectives of the study, the methods applied, and a literature overview detailing previously conducted research on water quality and socio-economic impact in the study area. Irrigation canals have for a long time been used to supply water for the irrigation of crops. The irrigation methods have changed over time, but the aim to supply crops with water to sustain them is still important. During the fourth chapter of the study, it was aimed to assess the water quality condition of Loskop Dam. In the process of assessing the potential impact of poor water quality on the community of farmers, it is important to know and understand the sources of pollution and to do so the water in the Loskop Dam and Olifants River catchment that is providing water to the dam must be studied. In both cases the sources of the canal are polluted as is evident from previous research by Driescher (2008) and Dabrowski (2014). Driescher's (2008) study focusses on the water quality of the Olifants River. According to Driescher (2008), anthropogenic activities are a major contributing factor to the pollution of the water in Loskop Dam, while Dabrowski (2014) focused on the links between the aquatic environment, diet and thyroid status of fish in the impoundment.

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There is a vast body of research on the topic of water quality, which means that a lot of sources could have been investigated to find the optimal method to measure the water quality.. However, because the selected site of the study (Loskop Dam), it means that some methods will be favoured more than others. Within the wide range of available methodologies, careful selection of suitable methods must be taken to ensure representative estimations of the water quality of Loskop Dam. In the current study, I will be developing a modified pollution index for the irrigation scheme based on the index of Jiang and Shen (2003), later modified by Costro-Roa and Pinilla-Agudelo (2014). The reason for using the latter is that the developed index will also incorporate national water quality guide lines as suggested by Costro-Roa and Pinilla-Agudelo (2014). In Chapter four, two main sections will be discussed. The first of these sections is the water quality of Loskop Dam. Secondly there was the challenge to develop a water quality pollution index based on the findings of the first topic. The water quality of Loskop Dam was assessed with the purpose to determine the general condition of the dam in relationship with water quality standards of Department of Water Affairs and Forestry (DWS, 1996). This will help to clarify the impacts of water quality on the irrigation board and farming community. Finally, bio-indicators were used as indicators of contamination during certain periods of the year.

In Chapter five the occurrence of toxic cyanobacteria in the Loskop irrigation canals with special reference to best management practices will be discussed. This section mostly focuses on assessing the presence of cyanobacteria in the water column of the canals. Evaluating the risk posed to the water users which make use of the water from the irrigation canals is of outmost importance; therefore it is essential to monitor the presence of cyanobacteria in the canal. In the literature the effects of cyanobacteria on crop production and ecosystem services is well known. For the purpose of my thesis, I will investigate the impact from the perspectives of risk and potential socioeconomic impact.

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Lastly, in Chapter six, the potential impact of receiving poor water quality on the community of farmers downstream of Loskop Dam will be deliberated. Again the chapter will be divided into two sections. The first section will be a discussion on the Loskop Dam Irrigation Board's institutional structure and operations, as the authority structure that exists in the irrigation board was investigated. There are many different theories that will be scrutinised for the purpose of evaluating the functioning of the irrigation board. One of these approaches includes the top-down or bottoms-up approach when it comes to decision making in an organisational structure. Finally, the external factors e.g. policies which play a role in the water quality status of Loskop Dam were investigated.

1.2 Problem statement

The Loskop Dam plays a major role in the economy of the Mpumalanga region. Both the agriculture and tourism sector will be affected by the degradation of the water quality of Loskop Dam. The second largest irrigation scheme in South Africa is found downstream from the Loskop Dam. The canals that are managed by the Loskop Dam Irrigation Board provide water for an area of 25 600 ha, which means that a large portion of land used for land-use activities will be affected. In this area of interest there are 624 properties (Farmers) which are dependant on the water for their livelihood. Adding to this, is the large number of workers needed for the farms to function optimal, this means that a large group of people are dependent on the farming industry in this region for their annual income (Tren and Schur, 2000).

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Loskop Dam is also been used for recreation activities that contribute to the economy of the region. These recreational activities include fishing, water sport and community events. The municipality especially is dependent on the revenue which is produced by tourists who take part in these activities. Ensuring that the water quality is up to standard will enable farmers to continue exporting their fruit abroad and will also enable tourists to visit Loskop Dam,

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consequently providing revenue for the local municipality to invest into and maintain infrastructure like roads and housing.

Deteriorating water quality will have profound effects on all the sectors of the region, in that good quality water is required in both the agriculture sector and for the tourist activity at the dam; and thus, it is evident that the degradation of the water resources will have a significant negative effect on the whole community. The poor water quality canaffect the export crop industry to the EU and local markets as well as ecosystem health. Furthermore, people will be less inclined to visit Loskop Dam when the water poses a health risk. The solution to the problem is first to find the sources of pollution. These can include both point and non-point pollution. In the latter, the sources are already known because the Olifants River that flows into Loskop Dam is polluted. The next step was to collect samples of the water in both the canals downstream from Loskop Dam and from the dam itself. This data wereanalysed and compared over a specified time frame. The compiled data was usedin the end to justify whether or not the surface water quality is poor by using national water guidelines of the Department of Water and Sanitation. After assessing the quality of the surface water, a pollution index was developed for use by the irrigation board for the general purpose of managing the water quality of the canals.

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1.3 Thesis statement and research question

The current study assumes that water quality estimates can be used for the purpose of developing a pollution index. The pollution index will help the irrigation board with management of the water quality. This will prevent long term effects of poor water quality on the local community of farmers.

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Main research question: will degradation of water quality in Loskop Dam have a negative effect on the farming industry which depends on the water that is supplied by the canals for most of their farming activities downstream from Loskop Dam?

The specific research questions that will be answered to address the main research question are:

1. What is the water quality status of the irrigation canals and Loskop Dam?
2. Which indicators can be used for the modified pollution index?
3. Do toxic cyanobacteria occur in the water column of Loskop irrigation canals?
4. How will the community of farmers be affected if water quality deteriorates?

1.4 Study aim and objectives

The aim of the study is to show what the implications of poor water quality will have on the local farmers community that depend on water usage for their livelihood; and what management practices can be introduced to improve the water quality of Loskop Dam and the irrigation canals.

- The first objective of the current study is to assess the water quality of both Loskop Dam (physical-chemical parameters) and the irrigation canals (Cyanobacteria biotoxin) that are below the Loskop Dam and to apply a modified pollution index that can be used by the irrigation board.
- The second objective of the study is to determine the social and economic implications of poor water quality on the water users served by the Loskop Dam Irrigation Board.

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1.5 Significance of the study

The Olifants River that flows into Loskop Dam is one of the main sources of water for irrigation in the region and it also supplies water for industry and mining activities in Mpumalanga. In addition, approximately 54% of South Africa's energy is produced in this region and water is also required in this process. Furthermore, the Olifants River in Mpumalanga is also a transboundary river that flows through into Mozambique.

The significance of the study is that the Loskop irrigation scheme is the second largest irrigation scheme after the Vaal-Harts irrigation scheme. Farming industry below Loskop Dam has an export market of citrus and other fruits to the EU worth R1 billion, which may be affected by degradation of water quality. As commercial agriculture is labour intensive large groups of people's livelihood will be at stake. The study will assess the water quality management practices of the irrigation board, and consider whether and in what ways they are able to supply water of good quality that falls within the guidelines as set out by the Department of Water Affairs and Sanitation and by standards of foreign countries like the European Union (EUROGAP), their largest importer of citrus and other fruits.

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It is evident that the canals below the Loskop Dam play a significant role in the irrigation of the crops, providing motivation for a detailed investigation to evaluate the condition of the water in the canals. After establishing/quantifying the water quality, a pollution index will be developed for the irrigation board to use in future management scenarios. While the main objectives of the thesis are being met, more specific characteristics of the objectives will be attended to, these include:

- Characterisation of the quality of water found in the Loskop Dam (physico-chemical parameters) and canals downstream (Cyanobacteria biotoxin).

- Applying a pollution index based on water quality indictors in the Loskop Dam.

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- Determining the adverse effects of poor water quality on the community over time.

1.6 Scope and nature of the study

The area of focus in this study will be both the Loskop Dam and the canals below it. This means that the both the Loskop Dam and the canals were sampled during the 12 month study period. The canals were sampled to assess the adverse effect of pollutants on the farming community which makes use of the irrigation system. The Loskop Dam was sampled at the point of release (at the dam wall), whilst the canals was sampled at a distance of ± 2.5 km away from the dam wall. During the process of analysing the water quality of both the Loskop Dam and the canals external factors, which contribute towards contamination, were taken into consideration to assess the general impact on the sources. The first factor would be the variation of physic0-chemical parameters that causes pollution in Loskop Dam. Seasonal changes were also investigated and their influence on the water quality. Further, bio-indicators were used to assess the condition of the Loskop Dam. During the study of the irrigation canals cyanobacteria (*Microcystis*) was collected to measure the contamination of both the irrigation canals and to assess the threat to crop production and human health.

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The local community of farmers and the irrigation board also form part of the current study. The main focus is to determine the possible effects of contamination on crop growth and yield. These farms depend greatly on canals as sources of irrigation, especially during the drought of 2016. The focus was shift to the socio-economic impact in the region as well as policies and institutional arrangements. Farming industry is one of the main forms of revenue in the Loskop Dam area. Large groups of people will be affected by the degradation of water quality, and for this reason the aim of the study was to assess how contamination impacts on the community. The livelihood and health of the farmers is at risk and for this reason the main focus is on the potential socio-economic consequences if the water quality is compromised.

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1.7 Outline of the Thesis

The first chapter of the thesis is the introduction. In this chapter, background to the study, problem statement, thesis statement and research questions, as well as study aims and objectives will be deliberated. The significance of the study will also be highlighted. In addition to what was previously stated, a brief framework of the study and the outline of the thesis will be added. The literature review will be the second chapter of the thesis. A theoretical framework and conceptual understanding that guides the study will be provided in this chapter. The second chapter will also deliberate on previously conducted research on the topic of water quality in general, and water management tools for irrigation boards in particular. The findings already reported for the Olifants River in Mpumalanga will be considered. Chapter three outlines the research design and the methodology of the thesis. The chapter presents study design, data collection methods, data analysis methods and quality control. This chapter includes a statement of research ethics and study limitations. The next chapter is chapter four, which assesses the water quality of Loskop Dam by developing and applying a pollution index that utilised both bio indicators and physical-chemical parameters. During chapter five the occurrence of toxic cyanobacteria in the Loskop irrigation canals with special reference to best management practices is discussed. In chapter six the socio-economic impacts of poor water quality will be discussed. This chapter will specifically focus on the farmer communities, dependent on the Loskop irrigation scheme and the policies that affect them. The last chapter of the thesis will include the general conclusion and recommendations that are based on the findings of the previous chapters in the thesis.[1]

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[1] Chapter five was submitted to the Journal of Limnologica for publication and chapter four was submitted to the Journal of Environmental Pollution for publication.

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CHAPTER 2

Literature Review

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2. Literature Review

2.1 Introduction

The three key focal points of the current study were to (1) develop a pollution index for the Loskop Dam, (2) determine the occurrence of toxic cyanobacteria in the Loskop irrigation canals downstream of Loskop Dam with special reference to best management practices, and (3) determine the socio-economic impact of water quality on the Loskop irrigation scheme. When discussing the water quality of the Loskop Dam canals it is important to incorporate past research that has been done on the dam and the upper Olifants River catchment, since both the dam and the catchment act as sources of water and pollution for the irrigation canals. In the study area the irrigation canals are the main sources of water for irrigation activities, so that if the water quality isn't up to standard in the irrigation canals it will negatively affect the irrigation farming community. With this in mind, the development of a pollution index will assist in the assessment of the water quality by using 'indicator species' to determine the pollution status of the water in the Loskop Dam catchment. With regards to the socio-economic impact, it is important to understand the structure of the irrigation board and the management practices of the irrigation scheme. Additionally, external stakeholders that influence decisions made by the irrigation board can also be a contributing factor determining operations of the irrigation board. Thus the structure of the irrigation board and the condition of the water in the canals collectively determines the outcome and directly impacts on the social welfare of the surrounding community of farmers and their workers. Assessing the irrigation board capacity to manage the water will help indicate their ability to prevent contamination of the water. Finally, suggestions from the study will include methods to improve monitoring of water quality by the Loskop Irrigation Board based on management practices of the irrigation board which will help improving management and water quality monitoring of the irrigation canals.

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2.2 Loskop Dam catchment

2.2.1 Upper Olifants River catchment

The Olifants River is situated in Mpumalanga Province and can be dived into three sections namely: the upper, middle and lower Olifants River catchment (Figure 2.1). The upper Olifants River sub–catchment originates near the town of Breyton in Mpumalanga province. It flows through the Highveld grassland of both Gauteng and Mpumalanga provinces. The tributaries of the upper Olifants River sub–catchment are the Klein Olifants, Elands, Klip, Wilge Rivers and the Brugspruit and Bronkhorstspruit.

The different tributaries flow into the main Olifants River before it flows into Loskop Dam. The population of the upper Olifants River catchment is ~4 million people and has approximately 201 water storage dams with a combined capacity of ~4 688 Ml3 (Van Vuuren, 2009). Most of the pollutants originate in the upper reaches of the Olifants River which flow into the Loskop Dam downstream. The cities of Witbank and Middelburg are the main economic centers in the upper Olifants River catchment and are located in the concentrated area of mining and industrial activities (McCartney and Arranz, 2007). The estimated total available water in the upper Olifants River catchment is ~409 million m3/a, whilst the requirement is ~410 million m3/a. Although availability and demand seem to balance out, the water balance in the upper catchment is actually significantly negative. This is due to the fact that water availability in the catchment is already fully allocated. The deficit is made up through transferring the exact quantities needed from other catchments (~22% of the total water available is transferred) (Basson and Rossouw, 2003).

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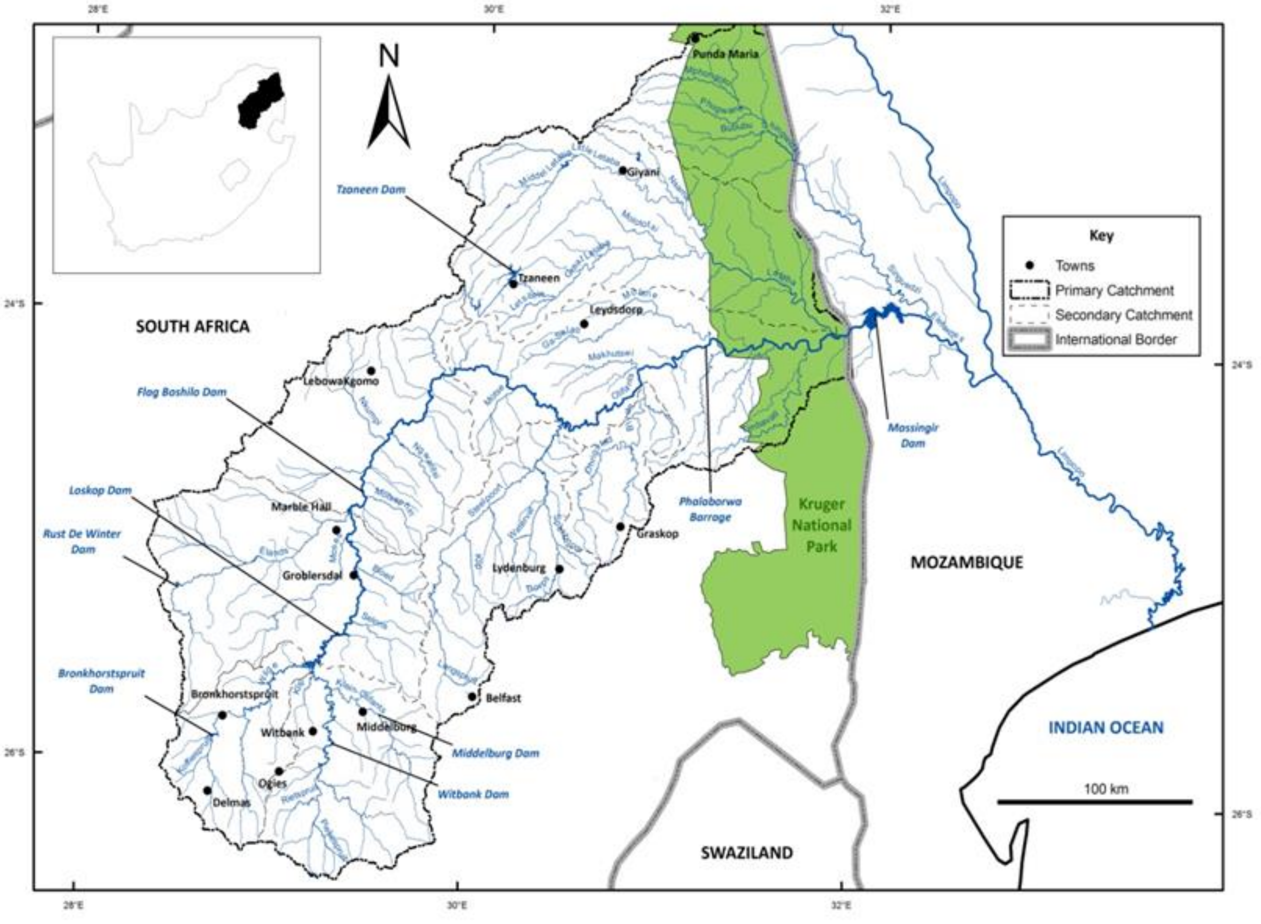

Figure 2.1 The Olifants River catchment (Ashton and Dabrowski, 2011).

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2.2.2 Land-use activities in relationship with anthropogenic pollution

Land use activities in the upper Olifants River catchment that impact on freshwater ecosystems include coal mining, power generation, industry, agriculture, and wastewater treatment works associated with urban areas (Figure 2.2).

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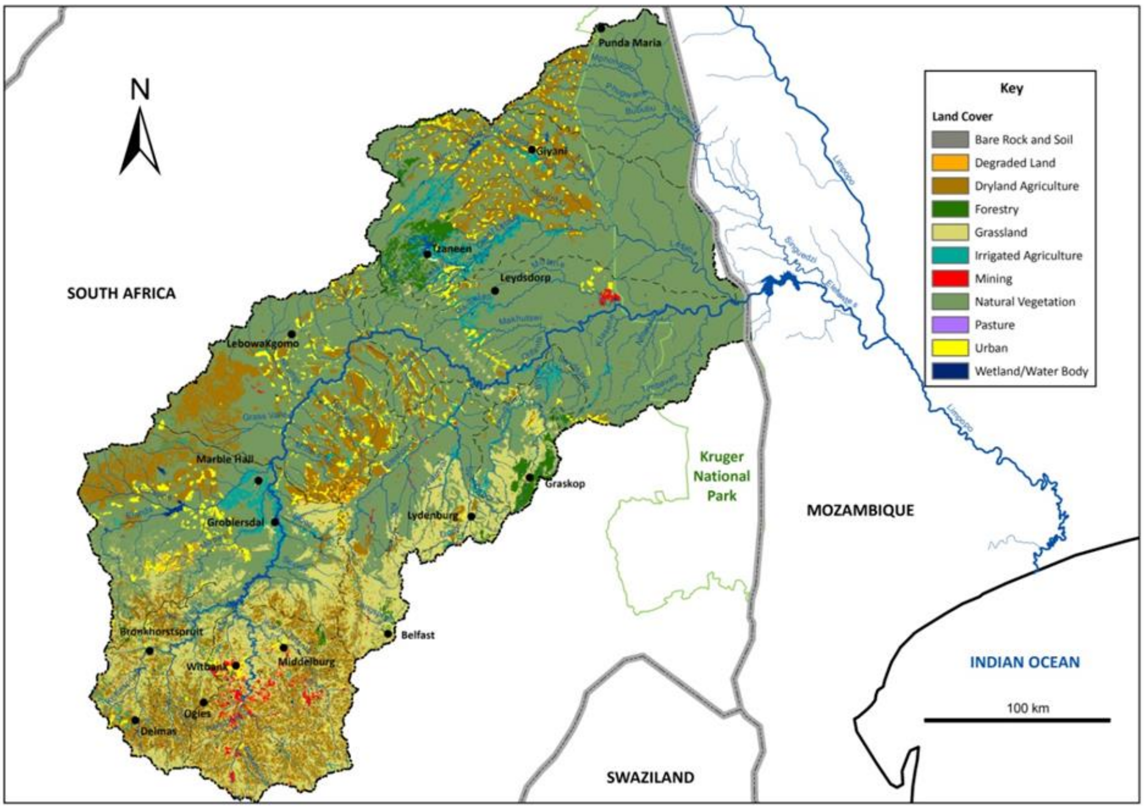

Figure 2.2 Land-use activity in the Olifants River catchment (Ashton and Dabrowski, 2011).

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2.2.3 Mining

South Africa possesses approximately five percent of the global recoverable coal reserves and is the world's sixth largest coal producer (Oberholster et al., 2014). The Witbank coalfields represent the largest conterminous area of active coal mining in the country (Figure 2.3) and mine dewatering activities result in a discharge of approximately 50 Ml per day of mine water into the upper Olifants catchment (Maree et al., 2004). Coal mining is a dominant activity in the province of Mpumalanga, and the Witbank-Highveld coalfield produces 81% of the coal in South Africa, thereby contributing significantly to the South African economy. In total, 56% of South Africa electricity is produced in this catchment through the use of coal-fired power stations. The electricity produced in this region is required to ensure that all the economic

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sectors (i.e., agriculture, mining and industrial sectors) in Mpumalanga function at it full capacity (Spalding-Fecher et al., 2003).

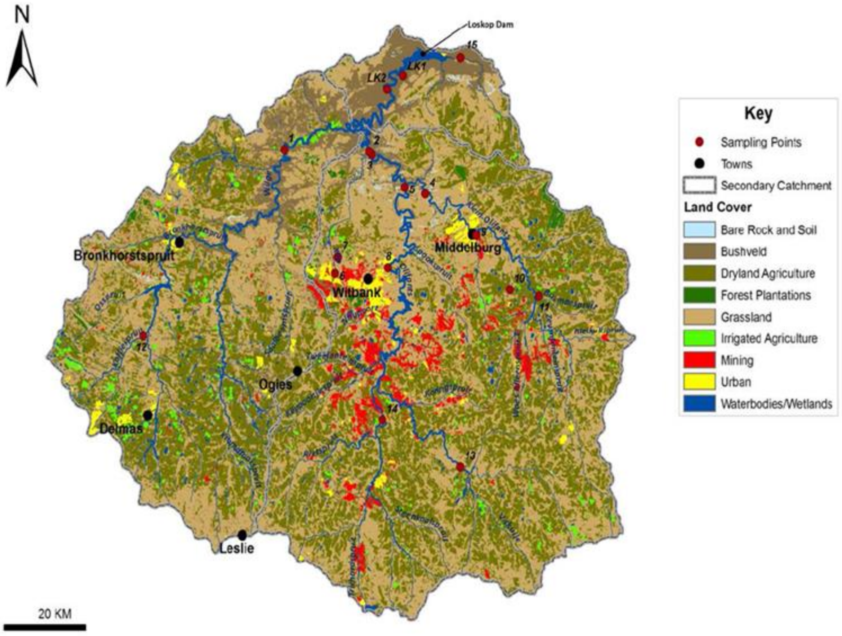

Figure 2.3 Mining activity upstream of Loskop Dam indicated in red (Ashton and Dabrowski, 2011).

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Acid mine drainage (AMD) is an increasingly important contributing factor to pollution in the upper Olifants River catchment due to mine closures. In the context of the thesis, AMD is characterised by high acidity as the results of the oxidation and/or hydrolysis of Fe and other metals. At low pH values of 2-3 in aerobic environments, acidophilic bacteria are the primary oxidisers of Fe, which then hydrolyses and precipitates out of solution (Ochieng et al., 2010). Oxidisation of pyrite which produces Ferric iron ions are capable of dissolving other heavy metal minerals, which enter into solution at low pH values (Ochieng et al., 2010). As the upper catchment area of the Olifants River is an area of intensive coal mining activity, AMD is a major problem in this region with Aluminum (Al) as a dominant trace metal in this catchment (Oberholster et al., 2013). Al is not only a by-product in steel and mining industries, it also

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occurs naturally in the underlying geology. Poléo (1994) stated that aluminum is the third most abundant element after oxygen and silicon and makes up 8% of the earth crust. In a study by Driscoll (1985), as cited in Driesher (2008), it is illustrated that Al increases exponentially in solution with decreases water pH. Al can also influence the phosphate (P)-cycle and organic carbon (Driesher, 2008).

The reactions that lead to the acidification of water sources by mining activity are illustrated below by using pyrite (FeS_2) as an example, which is one of the most common causes of AMD (Ochieng et al., 2010). The first reaction illustrated is the oxidation of the sulphide minerals into dissolved iron, sulphate and hydrogen (Duruibe et al., 2007):

$$2FeS_2(s) + 7O_2(g) + 2H_2O(l) = 2Fe^{2+(}aq) + 4SO_4^{2-}(aq) + 4H^+(aq) \qquad \text{(eq. 2.1)}$$

With sufficient oxidisation in the surrounding environment (depending on O_2, pH and bacterial activity), much of the ferrous iron will be oxidised to form Ferric iron (Fe (III)), which results in the following:

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$$4Fe^{2+}(aq) + O_2(g) + 4H^+(aq) = 4Fe^{3+}(aq) + 2H_2O(l) \qquad \text{(eq. 2.2)}$$

Pyrite can further be oxidised by Ferric iron into ferrous iron when in contact:

$$FeS_2(s) + 14Fe^{3+}(aq) + 8H_2O(l) = 15Fe^{2+}(aq) + 2SO_4^{2-}(aq) + 16H^+(aq) \qquad \text{(eq. 2.3)}$$

When this reaction occurred it generates more acidity. According to Ochieng et al. (2010) dissolution of pyrite by ferric iron (Fe^{3+}), together with the oxidation of the Fe^{2+} constitutes a

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cycle of dissolution of pyrite. Furthermore, at low pH (between 2.3 and 3.5) Fe^{3+} precipitates as Fe $(OH)^3$ and jarosite, leaving little Fe^{3+} in solution while simultaneously lowering pH:

$$Fe^{3+(}aq)+3H_2O(l)\rightarrow Fe(OH)_3\ (solid)+3H(aq) \qquad \text{(eq. 2.4)}$$

$Fe(OH)_3$ precipitates and is identifiable as the deposit of amorphous, yellow, orange, or red deposit on stream bottoms ("yellow boy") (Ochieng et al., 2010).

When AMD runs off into a more alkaline condition river or stream, the dissolved metals such as Al, Zn and Cu precipitates out. AMD affects aquatic ecosystems in the following ways: (a) communities which are affected experience lethal levels of pH and metals, which lead to a decrease in biota richness and its diversity; (b) aquatic communities are only restricted to tolerant organisms, which have adapted to survive in these conditions; and (c) the alterations of the nutrient cycles and abiotic changes.

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2.2.4 Agriculture

Water use by the agriculture sector has adverse impacts on the environment by changing terrestrial and aquatic ecosystems because of damming rivers and changing flow regimes, lowering groundwater levels, polluting soils and water, salinization, and draining of wetlands. The impacts of small-scale irrigation or water harvesting on the environment are not necessarily less when it comes to the pollution of the water sources (Beaudoina et al., 2005).

Water pollution caused by agriculture on surface and groundwater includes the following: deposition of soluble salts, agricultural chemicals (fertilizer and pesticides), toxic elements, pathogens and sediment. Improper and excessive use of fertilization can disturb soil-plant-

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water regimes as the soil texture contains nitrate and nitrite residues that pollute groundwater (De Villiers, 2007). This pollution is avoidable through better application practices of fertilizers and irrigated pest management. Poor quality irrigation water such as drainage water, saline groundwater and treated wastewater, adversely affects the environment when used. The most detrimental effects of using irrigation water that is of poor quality are unwarranted accumulation of soluble salts and/or sodium. Using poor quality irrigation water on irrigated lands requires the management of soil salinity by means of leaching and drainage of unwanted water and salt (Beaudoina et al., 2005).

2.2.5 Wastewater treatment works

Anthropogenic activities are one of the main causes of the massive increase in river nutrients concentrations (Oberholster et al., 2013), such as partially treated and untreated domestic and industrial sewage from municipal sewage treatment works upstream of Loskop Dam. The impact of wastewater treatment plants (WWTPs) on water quality exceeds that of non-point sources pollution (Oberholster et al., 2013). In a recent report it was revealed that several South African WWTPs are not operated optimally, for example in an assessment of 449 municipal WWTPs, 53% of a total 852 municipal had achieved green drop certification (Oberholster et al., 2013). The risk of eutrophication of South African water resources is therefore a cause for concern especially in areas with high population densities and low levels of basic services (van Ginkel, 2011). As stated earlier, high nutrient inputs impoverish biological diversity; modify the community structure of algae, macro invertebrates and fish causing the enhancement of tolerant species (Oberholster et al., 2013).

These pollutants have significant adverse impacts on aquatic health, and have led to widespread eutrophication (nutrient enrichment), localized toxic water quality, and the potential bioaccumulation of pollutants through the food chain. Mitigation of these pollutant sources

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would therefore be required if acceptable water quality and ecosystem health were to be attained on a sustainable basis in the catchment (Schwarzenbach et al., 2006).

2.2.6 Industrial pollution

The social and economic development of the upper Olifants River catchment is strongly based upon coal mining, coal combustion power plants, smelters and several industries using coal as energy source. Heavy metals are some of the most problematic pollutants in industrial wastewater that negatively impact on the receiving waterbodies of the upper Olifants catchment. The increased demand for heavy metals for the production of goods has resulted in significant decrease in the quality of water resources in the upper Olifants catchment (Driescher, 2008). Chromium is a good example of such a metal pollutant. Ferrometals near the city of Witbank constitutes one of the largest individual ferrochrome plants in the world and produces chrome for the steel markets. Chromium (VI) occurs most often in water and is of significant concern due to its toxicity to humans, animals, plants and other organisms (Wepener et al., 1992). Industrial wastewater is also a major contributor to toxic organic compounds that may be found in the nearby water resources. Industries that can be associated with such pollutants include tyre, dye and paper manufacturing plants (Groisman et al., 2004). According to Rajkumar and Palanivelu (2004) some of these compounds have the potential to cause serious chronic effects when exposed to low levels over a long period. A previous study by Chakraborty and Konar (2002) on the impact of steel plant effluent showed that it can severely hamper algae growth and diversity. Chakraborty and Konar (2002) showed in their study that effluent of steel plant waste in the Damor River, India, caused low transparency, pH and a high Toxic shock syndrome (TSS). The authors concluded from their study that the discharge of steel plant waste caused habitat degradation resulting in ecological modification of algae communities as observed by Oberholster et al. (2016)

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Acid rain seeps calcium, magnesium and metals from the soil; transporting these minerals through surface water run-off into streams and rivers; and negatively affecting water quality for aquatic life. Usually, when it rains contaminants gets diluted within the river system (Velikova et al., 2000). According to Wang (2008) the problem becomes more evident when air pollution occurs and there is a high concentration of air pollutants in the atmosphere. They can dissolve in the atmospheric moisture, and will increase the pollution problem in the system (Oberholster et al., 2013). Rain that has a pH lower than 5.6 is classified as acid rain. In the upper catchment of the Olifants River a pH of below 5.6 has been measured at different sampling stations during the 2010-2011 season and can possibly be contributed to the coal-fired power stations in the region (Oberholster et al., 2014).

2.3 Monitoring Ecological Integrity and Anthropogenic Impact (Pollution indices)

Numerous biological assessment tools have been developed for different types of aquatic ecosystems and for various monitoring purposes (Bain et al., 2000; Simon, 2000). In the literature, several water quality indices are reported and in this literature review, these will be briefly discussed and/or evaluated as optional methods for assessing the condition of the Loskop Dams' water quality, in order to be able to develop a suitable model applicable to the current study region. The first index is based on the work of Kumar and Sharma (2014) which was applied in the assessment of the water quality of the Kankaria Lake in India. In their index they made use of both physico-chemical and phytoplankton from the Kankaria Lake from March 2009 to February 2010 (Ashutosh and Sharma, 2014). The data in the study was categorised into three seasons (e.g. summer, monsoon, and winter season), and was transformed into the National Sanitation Foundation Water Quality Index (NSFQI) and Shannon Diversity Index (SDI) after collection by making use of mathematical equations

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(Ashutosh and Sharma, 2014). The reported NSFQI values, according to Kumar and Sharma (2014), ranged from 70 – 80 for all the seasons, while the SDI value ranged from 3.4 – 3.5.

In the second index, based on the work of Mishra et al. (2016), the authors aim was to assess the surface water quality in the Surha Lake, in India. The water quality was assessed by using four methods, namely the Comprehensive Pollution Index (used to assess the physio-chemical parameters), Organic Pollution Index (used to assess four physio-chemical parameters: COD, DO, dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphates (DIP)), Eutrophication Index (used to assess the level of eutrophication in the water body), and lastly the Trace metal pollution index (used to assess the trace metal contamination in the water body).

Another pollution index was used to assess the condition of the water in Luto Hoo Lake. In this report, Anyachebelu et al. (2015) used the pollution index to assess the physical and chemical characteristics of Luto Hoo Lake in China. The selected parameters to study were: temperature, conductivity, turbidity, dissolved oxygen, pH, and ammonium. During the assessment process each parameter was given an assigned weight to illustrate their impact on the water body which is being studied. In this index the values with the lowest number indicated a parameter with the least significance while the highest values were seen as the most important.

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Kumari et al. (2008) during their assessment of the Nagur City Lakes applied an index that was developed by Palmer in 1969. The Palmer Pollution Index (Palmer, 1969) makes use of biological parameters (phytoplankton). The Palmer Pollution Index (1969) consists of a list of algal species that are classified according to their tolerance towards contamination, especially organic pollution. The algae species are rated from 1 (intolerant) to 5 (tolerant) and the index is calculated by summing up the scores of all the relevant taxa present within the samples. When analysing a water sample, all 20 of the species chosen by Palmer (1969) are recorded,

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and an algae is considered ‘present’ if a volume of one litre contains 50 or more of the specific algae (Anon, 2010). The Shannon-Weaver Index is then used to assess the species richness and dominance (Shannon-Weaver 1949). The different patterns of dominance under the phytoplankton species and physico-chemical quality parameters observed confirmed the status of the lakes.

Indices based on species diversity are also available (Bellinger et al., 2010). These indices are derived from species counts and fall into three categories: species richness, species dominance, and richness and dominance. According to Bellinger et al. (2010) out of the species diversity indices available in the literature, Margalef developed the most commonly used index for assessing species richness (Bellinger et al., 2010). The Margalef index is based on a combination of the data collected from the total number of species identified and the total number of individuals of specific taxa (Bellinger et al., 2010). However, there are also indices that make use of the assessment of single taxa or a group of taxa, for example diatoms.

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As with lake phytoplankton indices, using a diatom index reduces complex biological communities to a single value. An example of such an index based on a single taxon is the Kothe Index. The latter is also known as the species “deficiency index.” When applying this method the amount of cells of a particular key species at a site, is compared with number of species at the site (Bellinger et al., 2010) Adding to this both the Gleason’s and Meninick’s indices can be used to assess the community diversity of the diatoms at a site (Bellinger et al., 2010).

According to Bellinger et al. (2010) another diatom index frequently used is the Descy’s index. When using this index a value of 1 to 5 is assigned to a specific sampling site. These values are allocated towards the type and the amount of diatoms collected from a site (Bellinger et al., 2010). Based on allocated score values the site can be classified as polluted or not. For

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example, the value 1 is classified as severely polluted and from there it is less polluted the higher the value given. Rendering to Bellinger et al. (2010) Coste went further and with the help of Ayphassorho in 1991 developed the generic diatom index index (GDI). This index focuses on both organic and inorganic nutrient pollution and is based on 44 diatom genera. The values allocated range from 1 – 5 (polluted and non-polluted). Coste also developed the specific pollution index (IPS) (Bellinger et al., 2010). The index is used to measure pollution sensitivity based on organic loads found at sampling sites in combination with nutrient concentration. As with previous indices developed by Coste, the assessment values range between 1 – 5.

An additional example of a developed diatom index is the trophic diatom index (TDI). This index was developed by Kelly and Whitton (1995), and consisted of 86 diatom taxa selected for their indicator value (sensitivity to inorganic nutrients) and ease of identification. Unlike some of the previous methods mentioned, the TDI determines the weighted mean sensitivity, with pollution sensitivity values ranging from 1 – 5, and indicator values ranging from 1-3 (with values of 1 implying very low nutrient concentration, while to 5 indicates very high nutrient levels). Kelly in 2002 modified this index to increase the range to 1-100 (Bellinger et al., 2010). Finally, the last index known as the Index of saprobic load(ISL) and developed by Sládeček (1986), is based on 323 diatom taxa, each with an assigned designated saprobic (soluble organic pollution or saprobity) values. Besides making use of saprobity values, it also use difference scales with the highest value of 4.5 indicative of pollution rather than no-pollution.

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2.3.1 The Costro-Roa and Pinilla-Agudelo (2014) and Jiang and Shen (2003) pollution indices

After evaluating the different pollution indices and studying their shortfalls, the one selected was developed by Jiang and Shen (2003) and then later modified by Costro-Roa and Pinilla-Agudelo (2014). This index consists of three equations where physical–chemical parameters and biological indicators are applied to assess the condition of the sample site, during which the varying sensitivity of any biological organism towards physical–chemical parameters is used as indicators of pollution. This particular index was selected for the current study based on the following reasons:

1. This index focuses both on physical-chemical parameters and biological indicators. Some of the other indices focus either on species diversity or physical chemical parameters to assess the condition of the site. This meant that it excludes one or the other factor that potentially can be a contributing factor to the contamination of sources or the physic – chemical parameters. An example of such an index is the Margalef index that just studies species diversity while excluding factors that could have led to the change in the species diversity.
2. The index can also be applied to study a complex aquatic ecosystem by giving biological communities each a single numerical value to indicate their resilience towards contamination. A common occurring problem with most indices, for example that of Kothe's, is that it only takes into account the response of a single taxon to assess the condition of site, which could include "suspect" species that can tolerate pollution.
3. Most of the indices that has been developed for biological monitoring focused on rivers organisms. This meant that the pollution index might not provide an informative data for assessment if applied to a stationary water body such as lakes, dams, and ponds. The pollution index developed by Jiang and Shen (2003) was first used to assess

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protozoan communities in the River Hanjiang, China. The method was then modified by Costro-Roa and Pinilla-Agudelo (2014) to assess the condition of five wetlands in Bogotá and one rural wetland (Brazilia) during which they used diatoms as indicators of pollution. This implied that the pollution index could be modified to assess the conditions of the Loskop Dam and other phytoplankton species could be used as indicators of contamination.

4. Most indices make use of limited data sets. When using this method there is flexibility in the type of data that can be collected and combined. In the studies of Kumari et al. (2008), Mishra et al. (2016), and Kumar and Sharma (2014) more than one method was utilised to provide a better assessment. As previously stated, most indices only focus on one specific aspect to assess pollution, so more than one pollution index then has to be implemented to have a greater understanding on the level of pollution. When utilising the chosen method, the assessment is more comprehensive as it incorporates both the biological organisms that act as "indicators" of pollution, and the national and international standards to assess physical-chemical contamination.
5. Finally, the index was selected because of its ability to make use of any organisms as "bio-indicators". According to Bellington et al. (2010) most of the other indices utilising bio-indicators only use diatoms, such as the indexes of Sládeček (1986) and Kelly and Whitton (1995). This means that these only focus on one specific group of organisms. Palmer's index (1969) makes use of bio-indicators, but it only focuses on a selected group of species and only indicates organic pollution. In a complex aquatic system such as the Loskop Dam where other sources of contamination (i.e., AMD and mixtures of pollutants containing metals) are present, the Palmer Index will not work well during monitoring because it excludes those factors. When applying the modified

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index of Costro-Roa and Pinilla-Agudelo (2014), metals will also be assessed. Further, these metals can then be chosen as factors that affects the bio-indicators.

2.4 Nutrient enrichment related to cyanobacterial blooms

Culture eutrophication is defined by the excessive algae growth resulting from nutrient enrichment by human practices. This phenomenon can be greatly accelerated by human activities that increase the rate of nutrient input in a water body, due to rapid urbanization, industrialization and intense agriculture production (Oberholster et al., 2010; van Ginkel, 2011). The occurrence of massive cyanobacterial blooms which are symptoms of culture eutrophication can cause depletion of dissolved oxygen contents of a waterbody resulting in fish kills, while the surrounding water may be discoloured by the release of pigments from lyses cells. Another symptom of eutrophication is the massive growths of higher aquatic plants that can interfere with aquatic sport such as fishing, swimming and boating (van Ginkel, 2011). Culture eutrophication is controllable, because people can take measures to minimise the impact of their activities.

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Cyanobacteria are a group of extraordinarily diverse gram-negative prokaryotes with potential use to mankind. However, problems do occur when algae blooms (overgrowth) occur and/or toxins are produced (Owuor et al., 2007). There is evidence of their existence dating back 3.5 billion years. The autotrophic cyanobacteria were once classified as ‘blue-green algae’ because of the resemblance it had to eukaryotic green algae. The blue-green colour of the cell is caused by the combination of green chorophyll pigments and a blue pigment (phycocyanin). Further, not all blue-green algae are blue-green and there can be a variation in colour pigments such as grey-blue.

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2.4.1 Cyanobacteria reproduction and structure

Cyanobacteria have the capacity to reproduce through a variety of methods, which include: binary fission, budding, or fragmentation. This may be single-celled or colonial. The factor that causes this depends on the species and the environmental conditions. Some of the single cell cyanobacteria grow in sheath of slime-like material or mucilage. The colonies of cyanobacteria may form filaments, sheets, cubed or hollow balls (Owuor et al., 2007). A few of the filamentous colonies have the ability to differentiate into three cell types. The first is the vegetative cell, which is a normal type of cell and forms under favourable conditions. The next cell type is climate-resistant spores; this is common during harsh environmental conditions. Finally, the third type is a thick-walled heterocyst. Further, it contains the enzyme nitrogenase, which is essential for nitrogen fixation.

During binary fission, reproduction occurs when the DNA duplicates and the cell divides in half. Budding or cell fission as it is also known, involves the formation of smaller cells which form larger ones (Owuor et al., 2007). Fragmentation on the other hand, involves breaking into fragments after which it regenerates to form a complete organism. Nutrients (e.g. phosphates and dissolved organic carbon) found at the sources will play a role in the growth and reproduction. Adding to this, the available light wavelength determines their growth forms.

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2.4.2 Cyanobacteria distribution and location

Certain cyanobacteria blooms can appear as foam, scum, or mats on the surface of any water body (e.g. lakes, ponds, dams, or any eutrophic water body). The blooms can vary in colour when floating on the water surface. The well-known odour and bad taste associated with cyanobacteria occurs after the cyanobacteria cell death. Additionally, removing the bad taste and odour from the water source requires expensive water treatment procedures (Paerl et al., 2001). In most temperate lakes, it is common to find seasonal succession of the bloom-forming

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phytoplankton species, and this is caused by the way they respond towards changes in physical-chemical conditions shaped by thermal stratification (Reynolds, 1998).

A large amount of cyanobacteria attach to the surface of rocks and stones (epilithic), on the bottom sediment of lakes (epiplic forms) or attached to water plants (epiphytic forms). They occur in marine, estuarine, and fresh water environments (Paerl et al., 2001). Toxic cyanobacteria are found worldwide and cause health concerns in many countries. During conditions suitable for blooming, there occurs a phase during wherein dense cell masses decompose naturally (Berg and Skulberg, 1987).

2.4.3 Environmental factors of Cyanobacteria development

The key factors in the development of cyanobacteria blooms are caused by the complex and dynamic relationships between physical, chemical and biological factors (Owuor et al., 2007). The overwhelming dominance of the cyanobacteria *Microcystis* as seen during the current study and in various lakes around the world can be the consequence of the prevailing water temperature, turbidity, nutrient levels, buoyancy regulation and zooplankton grazing or fish grazing.

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2.4.3.1 Temperature

Cyanobacteria, like most other species, tolerate a wide temperature range, but precipitous growth is achieved most of the time when water temperature exceeds 20°C. During winter overturn in dams like the Hartbeespoort Dam, the level of both dissolved nitrogen and phosphates are high, but due to the low water temperature green and blue-green algae growth was thwarted (Owuor et al., 2007).

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2.4.3.2 Turbidity

Cyanobacteria species have adapted to adjust to light intensity. Some algae species like *Microcystis* have gas vesicles, which enables them to move to lower levels in the water body to avoid the high light intensity at the water surface, or float closer to the surface when underwater light conditions are poor (Chen et al., 2003). Adding to this, *Microcystis* adapts to high light intensity by decreasing cell chlorophyll content, while more chlorophyll is produced during conditions of lower light intensity (Owuor et al., 2007). Implying that underwater light climate is a key environmental factor that strongly influence species composition and biomass of phytoplankton in aquatic systems.

2.4.3.3 pH

Water pH directly influences the development of cyanobacteria blooms with optimal pH values for bloom development at pH values between 7.5 and 10, and is therefore classified as alkalopiles (Owuor et al., 2007). It is well documented that cyanobacteria growth is hindered at low water pH (4 to 5). The pH value of the source influences algal metabolism directly through enzymatic controls, and indirectly by affecting the accessibility algal has towards nutrients, minerals and trace metals (Owuor et al., 2007).

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2.4.4 Loskop Dam and Cyanobacteria

The symptoms of eutrophication in Loskop Dam, such as cyanobacterial blooms and formation of hyperscum can bring about economic losses in the form of depressed recreation industries. *Microcystis aeruginosa* produce biotoxins that are harmful to both humans and animals (Chen et al., 2009). Fortunately, despite the documented major bloom that occurred in 2008, no instances of human and animal poisoning have been documented to date. This may be in part,

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due to the fact that the unattractiveness and foul odours of the water in which the cyanobacterial blooms occur usually deter people from using or drinking the water.

Cyanobacterial blooms in the Loskop Dam also have adverse impacts on the health of organisms other than fish. High nutrient concentrations in the water column trigger cyanobacterial blooms, which reduce light penetration. Light reduction severely limits the growth of submersed vascular plants in the dam, thus decreasing habitat and shelter available for fish and fish food organisms (Owuor et al., 2007).

In addition to loss of habitat and system-level productivity, the cyanobacterial bloom in the Loskop Dam may impact the downstream socioeconomic welfare of users. Cyanotoxins pose a health hazard to humans as the raw water of Loskop Dam is used to irrigate extensive areas of edible and forage crops downstream of the reservoir where the second largest irrigation scheme in South Africa is situated. Codd et al. (1999) reported that single cells of *Microcystis aeruginosa* and the hepatotoxin microcystin-LR were retained by salad lettuce after being sprayed with irrigation water containing microcystin-producing cyanobacterium. Wiegand and Pflugmacher (2005) suggested a negative impact on crop productivity in that uptake of cyanobacterial secondary metabolites can lead to biotransformation of toxin congeners, promoting the possibility of oxidative stress in plants under irrigation. Mainly, due to the adverse effects of cyanobacteria, more specifically *M. aeruginosa*, the potential risk posed to consumers will be addressed in chapter five.

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2.5 The social economic implications of poor water quality and institutional arrangement.

2.5.1 Institutional arrangement.

To be able to evaluate management practices in the context of this thesis, the concepts of organizations and institutions must first be defined. According to Hodgson (2006) “Institutions are the kind of structure that matter most in the social realms. It needs to be noted that institutions interact with other groups of society, and constrain and enable behavior.” The history of organisational theory starts with the works of Max Weber a sociologist (Fox et al., 1991), wherein he focused on the common elements of bureaucracies with the predominant direction now being taken by organisational theory termed a contingency or situational approach.

Fox et al. (1991) define organisations as “division of labour and a hierarchy of authority.” These two elements of an organisation are divided into sub-components of what is known as organisation structure. The latter consists of three parts, namely: complexity, formalisation, and centralisation. These three parts together represent the way in which labour is divided into distinct errands and suggests how co-ordination is achieved. Two classes of organizations exist — namely private and public ones. Private enterprises are created for the benefit of an individual or a group of individuals and derive income from the sale of products or delivering of services. However, public institutions depend on their income, for the most part, from allocated budget funds (Fox et al., 1991). Although private enterprises have to function according to regulation bylaw, their effectiveness and productivity is calculated in terms of profits. Public institutions on the other hand are subjected to a variety of regulations, which are controlled by parliamentary, executive and judicial authorities and the public (Fox et al., 1991).

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In the context of the thesis, it is also important to define stakeholders. Swanepoel and De Beer (2011) define stakeholders as a "person, a group or institution that performs a certain task", with two types of stakeholders relevant in this study: namely public sector (governmental structures, such as national, provincial and local government) and private sector (groups active in commerce).

2.5.2 Socioeconomic impact of poor water quality.

In a report from the Water Research Commission (WRC) that focusses on the formation of institutions, a model was proposed on how water markets can function efficiently and help ensure the effective distribution of water-use rights (Nieuwoudt et al., 2008). In this report three catchments were used as models, including the Olifants River catchment. In the study, the possible constraints to a water market were one of the main objectives of the study, and according to Nieuwoudt et al. (2008) a way to address these constraints will include recommended institutional adjustments. When it comes to water management, all the stakeholders, such as water users, water management agencies and government entities are influenced (Nieuwoudt et al., 2008). Nieuwoudt et al. (2008) indicated that the incentives that influence these actors are provided by the institutional arrangements applicable, such as the conditions attached to water-use rights. The factors that challenge the water market of Loskop irrigation scheme include the water monitoring of Loskop Dam and land claims. As water is metered and monitored in the Loskop and Blyde River Irrigation Schemes, there is little room for illegal use, while the opposite is true for areas outside these two irrigation schemes. Another problem in these areas is the decline in farm sales which may be attributed to the prevalence of land claims, but may also be because the climate and crops within each sub-area appear more homogeneous. Other factors include the fact that irrigation plots in the area are relatively small (25.7 ha in Loskop and 20 ha in the Blyde River Irrigation Scheme) meaning that farming cannot be continued if the water-use rights are sold (Nieuwoudt et al., 2008).

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The importance of the relationship between institution and their stakeholders should not be underestimated. One of the main factors in upholding the relationship is the term “trust.” Goldin (2005) in her work discusses the importance of trust. According to Goldin, the term “trust” has a lot of significance when it comes to the relationship between the two parties. This includes the trust that the stakeholders have in the organisation or institution to deliver services, but also to address their problems. In exchange the organisation or institution expects the stakeholders to continue to support them.

Furthermore, stakeholders sometimes do not have the capacity to meet their demands and need the help of organisations and institutions to do so (Carroll, 1991). Organisations or institutions on the other hand need stakeholders to identify current problems and bring them to light, so that it can be addressed. So, there exists an interdependence in order to function properly, for the purpose of achieving a certain objective and to solve a certain crisis (Donaldson and Preston, 1995).

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CHAPTER 3

Research design and Methodology

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3. Research design and Methodology

3.1 Introduction

The third chapter of the thesis discusses the research design and methodology. In this chapter the study design, data collection and analysis methods, quality control, statement on research ethics and study limitations is referred to. The study design of the current thesis considers the following aspects: firstly the background of the study area. This aspect includes the general information of the study area which comprises of the geology, demography, vegetation, and historical data of the area. A detailed description of the sampling sites is given as part of the description. To describe the sampling sites a visual representation will be given, also presenting the distance from Loskop Dam, and its exact location.

Secondly, data collection methods that is used include both the water quality aspects as well as the institutional arrangement aspects. In the case of the water quality chapter a quantitative method of data collection was used, while in the case of the chapter on institutional arrangement/social economy implications a more qualitative method of data collection was preferred.

The ethical clearance is also discussed in the latter chapter. A focus is placed on the importance of receiving consent to collect data from stakeholders, considering first of all what tipe consent is needed during the interview process. The question of ethical clearance is also discussed and considerations of what procedures were necessary in order to obtain consent.

At the end of the chapter the limitations of the study are presented.

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3.2 Background

The Olifants River is one of the main river systems in South Africa, and has been described as one of the most polluted rivers in southern Africa, with Loskop Dam (25°25’S; 29°2’25’E) acting as a repository for pollutants from the upper catchment of the Olifants River system (Grobler et al., 1994) (Figure 3.1). The upper Olifants River catchment measures 11, 464 km² with a mean annual precipitation of 683 mm and a mean annual runoff of 10,780 mm³. It is a summer rainfall region and the vegetation consists of Highveld Grassland in the upper region of the catchment and mixed Bushveld and Thornveld (sub-tropical woodland ecoregion with Acacia and other thorny plants) in the lower reaches around Lake Loskop. The river structure varies from narrow channel with no definite riparian zone up to a 20 - 30m wide channel with well-defined riparian vegetation and an increase in erosion.

The surrounding geology of the area is mainly composed of volcanic granite, namely Rooiberg felsite, while the southern border is composed of sediments including large pebbles of quartzite held together by a sandy matrix. The impoundment is fed by both the Olifants and Wilge River, and has an area of 2427 ha and a volume of 374, 3 m^3 at full supply capacity. Dam water is utilized mainly for irrigation supply and drinking water for the towns of Groblersdal and Marble Hall, downstream of the dam wall.

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The Limpopo River basin is comprises of different catchments of which the Olifants River catchment is the largest. The Olifants River is a transboundary river which includes four different countries, namely Botswana, Mozambique, South Africa and Zimbabwe. The surface area of the entire Olifants River catchment is approximately 85 000 km^2. This includes Mozambique with a portion of approximately11 500 km^2, while the South African portion consist of approximately 73 500 km^2 (de Klerk et al., 2016). It is a key tributary of the Limpopo River. The Olifants River was historically a strong perpetual river, but has become a very weak

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perpetual river with frequent periods of occasional flow (de Klerk et al., 2016). Important man made constructions within the Olifants River include the Phalaborwa Barrage, Loskop and Flag Boshielo dams. The Olifants River comprises of many tributaries of which the Wilge, Elands, Steelpoort, Blyde and Ga-Selati rivers are the largest (Dabrowski et al., 2013, 2014).

The Olifants River catchment consists of the upper, middle and lower Olifants River catchments. The current study was conducted in the upper Olifants River catchment where Loskop Dam is situated (de Klerk, 2016). Olifants River catchment contained around 4 million people an also has approximately 201 water storage dams with a joint total of ~4 688 ML^3 (van Vuuren, 2009). Most of the pollutants derive in the upper parts of the Olifants River ended up Loskop Dam downstream. The towns of Witbank and Middelburg, which is situated in Mpumalanga province, are the main economic hubs in the upper Olifants River catchment and are situated near the concentrated area of mining and industrial activities (de Klerk et al., 2016).

Land use activity in the upper Olifants River consists predominantly of large-scale coal mining, mineral processing, power generation, and as agricultural activities. The mining sector and other associated industries are currently expanding in the region, which will rapidly increase the demand for water in the near future (Driescher, 2008). The approximate collected available water supply in the upper Olifants River catchment is ~409 million m^3/a. This is below the total demand which is require (approximately 410 million m^3/a). Therefore, the Olifants River catchment is under severe water stress with the demand for water exceeding the available amount due to multiple land use activities in its catchment. Loskop Dam was constructed in 1937 to supply irrigation water to downstream agricultural areas. The irrigation canal system, measuring 480 km, was completed just over 10 years later, in 1948. The system provides water to the Loskop Irrigation Board, which is the second largest irrigation area in South Africa, supplying 700 properties. The irrigation scheme has an irrigation area of 25 600 ha and a total of ± 480 km of irrigation channels (Oberholster and Botha, 2011).

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The water supply for the irrigation scheme is abstracted from the upper-hypolimnia of Loskop Dam and is conducted to crops through the use of two concrete channels. The distance of these two main channels are approximately ± 46 km (short channel) and ± 330 km (long channel). The dominant crops in the irrigation area are maize, citrus, grapes and wheat. From a previous study conducted by Oberholster and Botha (2011) it was evident that the poor water quality of Loskop Dam which contains high concentrations of phosphates stimulates the growth of the nuisance algal *Cladophora glomerata* in the irrigation canals downstream. This is shown by the figure below (Figure 3.1).

Figure 3.1 Photo of Loskop Dam during a cyanobacterial bloom (Photo by Jackie Brown)

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3.2.1 Plant species in the Loskop Dam Nature Reserve

Loskop Dam forms part of the 25 000 hectare Loskop Nature Reserve which is managed by the Mpumalanga Tourism and Parks Agency (MTPA), (Oberholster et al., 2012). Loskop Dam nature reserve lies on the transition between Grassland and Savannah Biomes. The vegetation of the higher lying regions of the reserve is typical of the Grassland Biome, while the lower lying areas fall within the Savannah Biome. As a result the vegetation is very heterogeneous. The key environmental parameters of these veldtypes are fire and frost in the grassland; and fire and grazing in the savannah. The Mixed Bushveld veldtype is very heterogenic, and characterised by a range of variations and transitions. The heterogeneity of vegetation occurs due to the heterogeneous topography and environmental factors. Important factors causing heterogeneity are aspect; soil depth and altitude. The vegetation can be physiognomically divided into apparently homogenous units. Loskop nature reserve plant database has currently 1016 plant taxa listed. The spread of alien invader species is a major threat to the conservation of the local vegetation. The following species have been recorded, and are being controlled: Black wattle; Poplar; Lantana; Queen of the night; Prickly pear; Jacaranda; Syringa; Sesbania; Bluegum; Guava; Thorn apple (“Olieboom”) and Pom pom weed. The control of alien plant species constitutes a major portion of the reserve management budged needs. From the 1016 plant taxa listed in the Loskop Dam nature reserve, a total of 65 taxa currently occur on the list of protected plants. Of these, the most important species is the cycad, *Encephalartos middelburgensis.* The only viable population of this species occurs on the Loskop nature reserve. Some colonies of a threatened succulent *Haworthia koelmaniorum* also occur on the reserve.

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3.2.2 Wild animal’s species in the Loskop Dam nature reserve

A total of 70 mammal species have been recorded on the reserve of which 15 mammal predator species have been listed (Table 3.1). This includes some threatened species like the African

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wild cat, aardwolf, brown hyena and leopard. The reserve supports a healthy population of white rhino. However, seven animals were illegally killed during 2010 forcing management to dehorn the population at the end of 2010. A total of 367 bird species have been recorded on the reserve. It includes important bird species such as Cape vulture, Martial eagle, Stanley's bustard, Caspian tern, African fin foot, Bald ibis, and Blue crane. However, due to environmental stressors a resident pair of African fish eagles at Loskop Dam has not successfully reared offspring for the last 10 years, while White-breasted cormorants numbers declined in this area when compare to numbers of waterbird surveys 20 years ago

Table 3.1. Counts of wild animals in the Loskop Dam Nature Reserve

Animal type	**2007 count**	**2008 count**	**2009 count**	**2011 count**
Baboon troop (*Chacma baboon*)	24	21	19	27
Blue wildebeest (*Connochaetes taurinus*)	203	197	229	223
Buffalo (*Syncerus caffer*)	215	261	178	221
Bushbuck (*Tragelaphus* sp.)	33	29	44	44
Bushpig (*Potamochoerus larvatus*)	20	7	3	8
Common reedbuck (*Redunca arundinum*)	16	10	8	*8*
Duiker (*Cephalophus* sp.)	71	43	47	47
Eland (*Taurotragus* sp.)		59	91	108
Giraffe (*Giraffa camelopardalis*)	24	24	25	29
Hippo (*Hippopotamus amphibius*)	19	14	16	19
Impala (*Aepyceros melampus*)	953	900	1088	1229
Klipspringer (*Oreotragus oreotragus*)	24	8	30	23
Kudu (*Tragelaphus* sp.)	52	413	438	611

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Mountain reedbuck (*Redunca fulvorufula*)	375	222	332	386
Nyala (*Nyala angasii*)	70	49	48	67
Oribi (*Ourebia ourebi*)	18	5	17	19
Ostrich (*Struthio camelus*)	2	3	1	1
Red hartebeest (*Alcelaphus caama*)	2		1	1
Sable (*Hippotragus Niger*)	43	49	46	57
Steenbok (*Raphicerus campestris*)	5	1	10	2
Tsessebe (*Damaliscus lunatus*)	39	34	76	70
Warthog (*Phacochoerus africanus*)	154	71	73	116
Waterbuck (*Kobus ellipsiprymnus*)	193	122	140	155
Zebra (*Equus quagga*)	440	381	466	447

3.2.3 Description of the sampling sites

When it comes to the research process it is imperative to have specific selected sampling sites. Each sampling sites represent an area of interest when it came to collecting data on the topic. During the process of selecting sites, many factor needed to be taken into account. The following criteria were set out for the selection of sampling sites: firstly, accessibility of the site. When a person samples the sites it is important that the sample is consistent and that there is no change in the area where the samples are taken. The main reason for not changing the sites is to ensure that the data which is collected is trustworthy and remains constant. Secondly, is the distance between sampling sites. Distance between sampling sites plays an important role in the physical and chemical concentrations of surface water due to factors like dilution, precipitation of metal or increases in pH caused by resident algae. Furthermore, sampling sites further downstream from the dam wall will increase other factors e.g. pesticide spray that play a role in the contamination of irrigation water.

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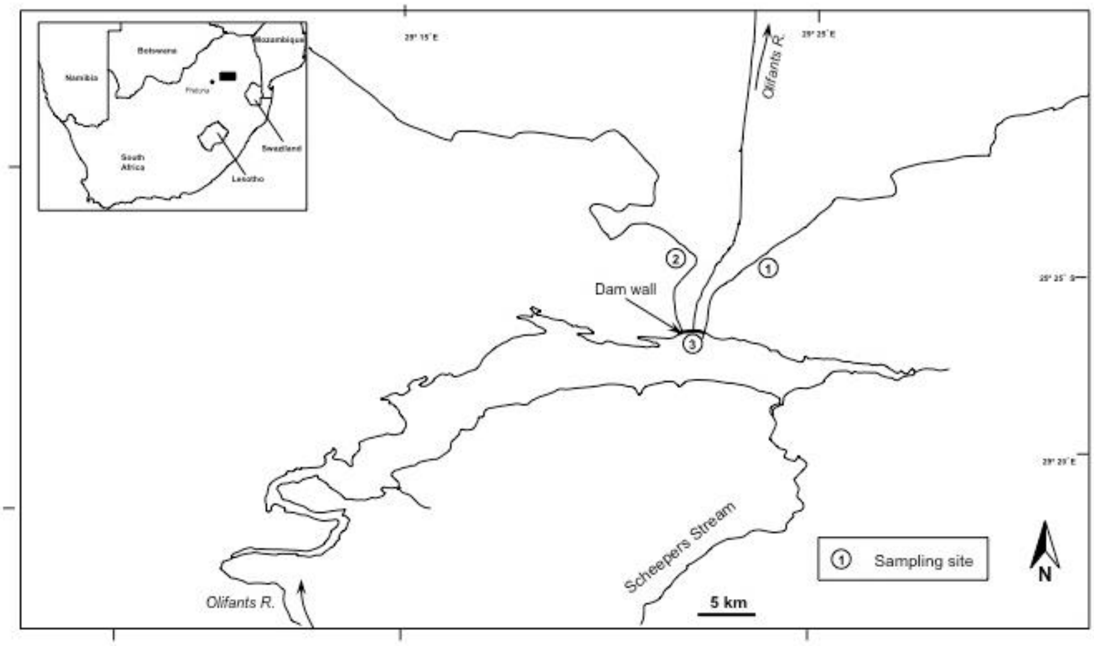

Figure 3.2 Map of Lake Loskop showing the location of the three sampling sites, and the position of inflowing Olifants River. Inset shows the location of the map area in South Africa.

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The Figure 3.2 above gives a visual illustration of the sampling sites of the irrigation canals. Each number resembles a sampling site which was used during the research proses. As illustrated by the Figure 3.2, both the canals and Loskop Dam were sampled. This was mainly to show the impact that the dam water quality will have on the water condition of the irrigation canals. As show by the figure there are two canals and one of these canals is shorter than the other. The distance of these two channels is approximately ± 46 km (short canal) and ± 250 km (long canal).

Different sampling numbers were used to represent each of the sampling sites. These sampling numbers represented the specific area of the irrigation canals which is accessible for sampling and makes it easy to differentiate between the two canals. Figure 3.3 below illustrates the two canals. As previously stated, distance from the dam wall was reduced to observe the impact that it has on the overall condition. This meant that the positions of the sampling site could not have been selected at random, but had to be as close as possible to the dam wall.

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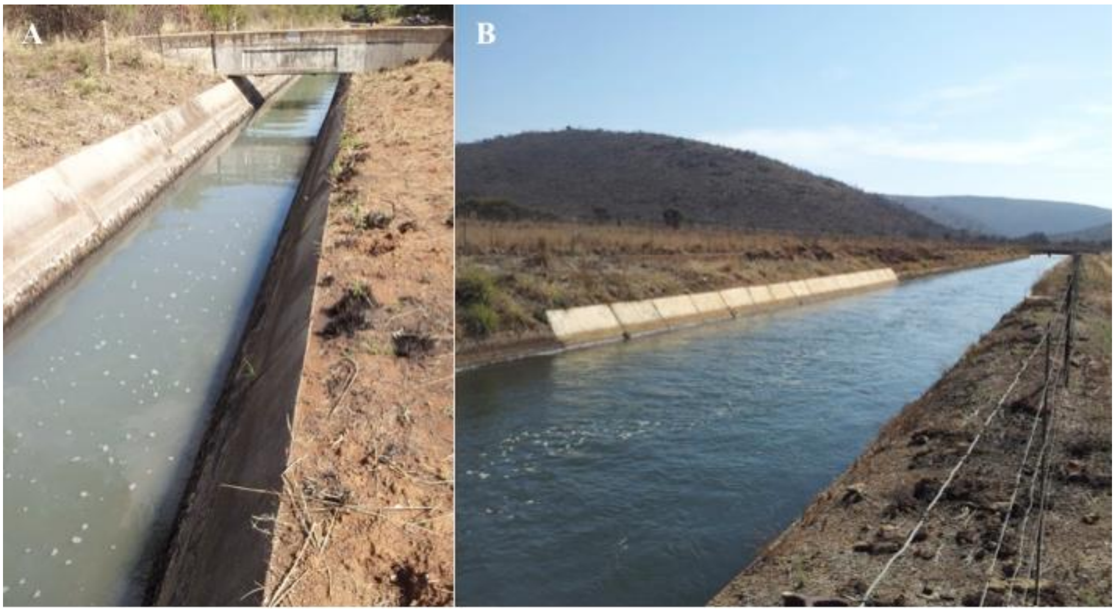

Figure 3.3 Photographs of the short (A) and long (B) irrigation canals. Sampling site 3 was selected at Loskop dam wall, while sampling sites 1 and 2 was selected on the short and long irrigation canal.

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The above sampling sites were consistent throughout the study to ensure that the findings remained consistent. It was also done to differentiate between the Loskop Dam (Site 3) and the irrigations canals (Site 1 and 2). Further, the research proses conducted on the Loskop Dam (Site 3) differed from the irrigation canals (Site 1 and 2) and thus it is needed to differentiate between the sites.

The Loskop irrigation area was selected as part of the study for the socio-economic implications and institutional structure of the irrigation board. The main focus being the individuals who were employed by the irrigation board, stakeholders that played a role in the decision making proses and the individuals that depend on the water for their livelihood. Furthermore, policies were investigated that are implemented upstream affect the Loskop Dam and the irrigation canal found below the dam wall. These policies were important in understanding the outcomes emerging throughout the study.

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3.3 Data collection methods

Different methods of data collection were applied during the research process. Each method was specifically chosen for research done at the Loskop Dam area. Firstly methods of data collection of the water quality and phytoplankton will be discussed in relationship to the sites along the irrigation canal and at Loskop Dam. During the sampling process physical and chemical parameters were collected as well as phytoplankton samples.

3.3.1.1 Physical chemical and phytoplankton sampling of Loskop Dam

Sampling was conducted on a monthly basis over a period of one year (January 2016-December 2016). On each of the sampling visits, dissolved oxygen, water temperature, pH and electrical conductivity values were measured in situ, using a Hach sensionTM 156 portable multiparameter (Loveland, USA). Dam water was sampled on a monthly basis using a six-litre Von Dorn sampler at a depth of 1.5 meter at the dam wall. The sampled dam water was then divided in three subsamples of 2 litres each for the following analyses: (a) Two liters were filtered through 0.45 µm pore size Whatman GF/filters for dissolved nutrient analyses; (b) Two liters were filtered through 1µm Gelman glassfibre filters and preserved in nitric acid for metal analyses; and (c) two litres was preserved in the field by addition of acidic Lugol's solution to a final concentration of 0.7%, followed after one hour by the addition of buffered formaldehyde to a final concentration of 2.5% for phytoplankton identification. All sampled water was stored in polyethylene bottles that had been pre-rinsed with dilute sulfuric acid (to pH 2.0). Although it would have been ideal in the current study to sample phytoplankton species on a 10 day interval as indicated by Reynolds (1984), it was not possible due to budget constraints. According to Reynolds (1984) phytoplankton occurrences in relationship to disturbances or changes in abiotic resource conditions at different responses are the following: (1) intervals less than one generation time stimulate physiological responses(20-200 hours); (2) regularities between 200 and 20 h interact with the phytoplankton development rate; and

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(3) disruptions at up to 10-day intervals can cause a successional progressions in phytoplankton growth.

3.3.1.2 Phytoplankton identification

All algal identifications were made with a compound microscope at 1250 x magnification, Zeiss (west Germany) (van Vuuren et al., 2006; Taylor et al., 2007). Strip counts were made until at least 300 individuals of each of the dominant phytoplankton species had been counted. All counts were based on the numbers of cells observed and the individual species were grouped into major algal groups (Lund et al., 1958; Willen, 1991). Samples was preserved in the field by addition of acidic Lugol's solution to a final concentration of 0.7 %, followed after one hour by the addition of buffered formaldehyde to a final concentration of 2.5 %. The integrated water samples were kept cool and in the dark during the 3-h period of transfer from the field to the laboratory.The Berger-Parker dominance index (Berger and Parker, 1970) was used to measure the evenness or dominance of each algal species at each sampling site using the following equation:

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$$D = N_{\max}/N \qquad \text{(eq.1)}$$

Where $N_{\max}$ = the number of individuals of the most abundant species present in each sample, and N = the total number of individuals collected at each site. The provisional phytoplankton trophic spectrum modified after Reynolds (1998) was used to select major phytoplankton along different trophic gradients.

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3.3.1.3 Pollution index

To apply the pollution index (PI), a modified version of Denisse Castro-Roa and Gabriel Pinilla-Agudelo (2014) and Jiang and Shen (2003) were used which is based on three steps. The first step was to calculate the pollution values of the physcio - chemical variables of Loskop Dam (for each month) using the following formula:

$$PI = \sum_{i=1}^{n} \frac{C}{CL} \qquad \text{(eq.1)}$$

Where C is the measured value of the variable in Loskop Dam, and CL is the limiting value of the variable is based on aquatic system guidelines Department of Water Affairs and Forestry (1996) legislation and ANZECC (2000) guidelines. The chemical variables used in this calculation were Al, Copper (Cu), Iron (Fe), Magnus, Total phosphorus (TP), Sulphates, Electronic conductivity (EC) and Zinc (Z). The physical variables include pH. The sum of the PI values for each of the physic – chemical variables provides an individual PI for Loskop Dam, which can vary according to the months of the year. Each PI value for a month was added together to give a total for each month of the study.

The next step was to calculate the pollution value for each taxon (*PVT*) for all the months of the year. The formula used is then:

$$PVT = \frac{\sum_{i=1}^{n}\left(\frac{\frac{PI}{s}}{n}\right)}{N} \qquad \text{(eq. 2)}$$

Where *n* is the number of measured physico-chemical variables, PI is the value calculated above, N is the sampling site, and *s* is total months of the study period. To choose upper (most

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pollution tolerant algae species) and lower (most pollution sensitive algae species) *PVT* limits, the total *PI* value for each month was calculated. The next step was to add to total amount of months of which certain species were present and then divided by *s*. According to the index phytoplankton species with a higher *PVT* is more tolerant to pollution, while those phytoplankton with a lower *PVT* value are more sensitive to pollution.

The last step was to calculate the pollution value for the algae community of the Loskop Dam in each month according to the following formula:

$$PILD = \frac{\sum_{i=1}^{n}(PVT)i}{n_s} \qquad \text{(eq.3)}$$

During the calculation n_s is the total number of species, *PVT* is the value calculated for each species, and *i* represents presentence of the species at Loskop Dam. This value is an indicator of level of pollution of the Loskop Dam for the corresponding months. To have a better representation of the applied modified pollution index (*PILD)* calculated for the phytoplankton community, a percentage conversion was calculated, where 100% was corresponding to the highest values of the *PILD* site. The obtained value was subtracted from total phytoplankton value.

3.3.2 Irrigation canal Sampling

The irrigation water samples were collected at the selected sites in the two canals at a depth of ±0.5 meters using a 6-litre capacity Von Dorn sampler. Due to the strong flow in the irrigation canals it was very difficult using the Von Dorn sampler to determine the precise depth of the sample. Dam water samples were collected at the dam wall at a depth of 1.5 meters with a 6-litre capacity Von Dorn sampler. The sample of each site was divided in two subsamples: (a) unpreserved for cyanobacterial toxin analyses and (b) preserved for microscope cyanobacterial

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identification. The latter samples was preserved in the field by addition of acidic Lugol's solution to a final concentration of 0.7 %, followed after one hour by the addition of buffered formaldehyde to a final concentration of 2.5 %. The dam and canal water samples were kept cool and in the dark during transfer from the field to the laboratory.

3.3.3 Interviews

When addressing the second objective (institutional arrangements) of the study, a more qualitative method of research was used. The snowball method was applied to gain access to key stakeholders for the purpose of collecting data. When the snowball method of data collection is utilised, a focus group is chosen consisting of key stakeholders, which know the inner workings of the organisation or institution (Bryman, 2012). These individuals who were interviewed can then give the researcher access to other members of that organisation or institution, which can expand on the information collected during the research process. The focus groups of the study were held with individuals working at the irrigation board. Data was collected by interviewing key individuals that play a role in the decision making and management of the Loskop Dam Irrigation Board. During the interviewing process, the general manager was the first to be interviewed, afterwards with the help of the general manager, interviews was conducted with three members of the irrigation board. The issue of trust was considered. Interviews were done on the basis that the person being interview knows that they have been selected for an interview and an appointment was made ahead of time. The interviews were semi-structured interviews. A list of questions was selected, with both open and closed questions. The questions were aimed at understanding the working of the irrigation board and the strategies in place for facing any water quality problem that may arise. The interviews were between twenty and thirty minutes.

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3.4 Data analysis methods

All data were recorded on standard Excel spreadsheets for subsequent processing and the statistical analysis was conducted using the SYSTAT ® 7.0.1 software package (SYSTAT 1997). Statistical differences were analyzed calculating Pearson correlation and a t test using the Sigma Plot (Jandel Scientific) program. Values of $p \leq 0.05$ were regarded as significant in the study. All analyses were carried out according to standard methods (USEPA, 1983; APHA, AWWA & WPCF, 1992). The South African Water Quality Guidelines Field Guide (TWQR)-values in mg l^{-1} (DWAF, 1996) were applied as reference.

3.4.1 Data analysis of dam samples

Normality and homogeneity of variance was evaluated for linear data using the respective Shapiro-Wilk's and Levene's tests for phytoplankton and physico-chemical parameter. Data that were non-parametric were Box-Cox transformed, or ranked if Box-Cox transformation was not effective. Pairwise differences were evaluated using *t*-tests. Correlations between water quality parameters and phytoplankton were evaluated using Spearman's Rank test. Statistical analyses were performed using XLSTAT 19.4 (Addinosoft., USA). Mean values for the water quality variables and phytoplankton assessed were calculated across the sampling events and used in the Principal component analyses (PCAs). The environmental variables were log transformed, centered, and applied as the focal plot on a PCA biplot. The program used for the creation of the biplot was XLSTAT 19.4 (Addinosoft., USA).

Concentrations of total nitrogen (TN) and total phosphorus (TP) were determined with the persulphate digestion technique. Nitrate concentrations were determined on an autoanalyzer with the cadmium reduction method, while soluble reactive phosphorus concentrations were determined by the ascorbic acid method (APHA, AWWA and WPCF, 1992).

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3.4.2 Protein Phosphatase Inhibition and ELISA Assays (irrigation canal samples)

Toxicity of cyanobacteria in the irrigation canals and Loskop Dam was determined by using the method of Boyer et al. (2004). Sampled water from the two irrigation canals and dam was poured gently through a 934 AH glass fibre filters in the field, frozen on dry ice, and returned to the laboratory in a cooler box. Filters for toxin analysis were extracted by grinding with 10 ml of 50 % methanol containing 1 % acetic acid and clarified by centrifugation. The extract was used for analysis of cyanobacterial microsystins using the protein phosphatase inhibition assay (PPIA) as described in Carmichael and An (1999). The enzyme-linked immunosorbent assay (ELISA) assay was conducted with a Quanti^{TM} Kit for Microsystins (EnviroLogix, USA). The limit of detection (LOD) of the kit is 0.147 ppb. The results were obtained by reading it on a multiskan ascent plate reader (Thermo Labsystems, USA) at 450 nm within 30 min after the addition of the stop solution.

3.4.3 *Lactuca sativa* Assay (Seed Test)

A short term (120-h) germination test was carried out in Petri dishes without soils or sediments being included to determine extracellular cyanobacteria toxicity. Seeds were provided by Starke Ayres (PTY) Ltd. Gauteng, South Africa. Upon arrival seeds were stored in glass vials kept in a desiccator at room temperature. The test was performed in accordance with the protocol described by Dutka (1989). Twenty seeds similar in size, shape and colour were placed on filter paper moistened with 6-7 ml water (filtered surface water without cyanobacterial cells) in a Petri dish from each sampling canal and Loskop Dam when cyanobacteria cells were detected microscopically in the surface water. Distilled water was used as control, while all exposures were done in triplicate. Petri dishes were covered with aluminum foil and kept in the dark for the duration of the test. After 120-h the number of germinated seeds was counted and compared to the control. The tests were based on the results obtained from tests conducted as a screen (100 % concentration of sample water). The method was use to assess the germination.

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3.4.4 Interview data analysis

The structure and operations of the Loskop Dam Irrigation Board was examined by applying the qualitative data analysis method of grounded theory (Bryman, 2012). Four individuals (general manager, three members of the board) were interviewed to collected data on the Loskop Dam Irrigation Board. The information of each individual was triangulated with one another. Recurring themes among the interviewees were identified. This also ensured that the data which was collected stayed consistent and that no information was lost. The main themes that were explored were around the structure of authority and each key member's role in the Loskop Dam Irrigation Board.

3.5 Ethical clearance.

Ethical clearance was obtained from the Research Ethics Committee (REC) of Stellenbosch University under the protocol ethical clearance for research involving human participants. Title of project 'Assessing the potential risk of heavy metal pollution in the irrigation water to food security in the Loskop Dam irrigation area'. Project leader: Prof A-M Botha, Faculty of AgriSciences (Project number: SU00017).

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3.6 Limitations of the study

There were a few limitations during the research process. The first limitation was distance to the sampling area. The sampling area is found in the province of Mpumalanga, which is more or less 2000 km from the University of the Western Cape. This made it hard to visit the sampling sites more than once a month.

The seconded limitation was funding as the only funding received during the study was from the Loskop Dam Irrigation Board, and that was allocated towards analysing of samples and transport costs (sample transport, flights and vehicle hire). Other expenditures had to be

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covered by the student. This included the cost of living during the sampling period, transport money and also accommodation.

The third limitation is time. Like any other study, there is a time limit in which the project had to be finished. During the study, the time period in which this project had to be completed was two years, which was the period of the Master's thesis. This mean that during the two year period, data needed to be collected, analysed, and finally discussed.

The fourth limitation was the environmental conditions at the sampling site. Weather can play a key role in the outcome of the study. During the early months of 2016, South Africa was experiencing a drought. The outcome was that the Loskop Dam levels dropped below what is normally expected during that time. This also meant less water was released into the canals for irrigation. This phenomenon might have had an effect on the data generated during the study period.

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CHAPTER 4

Applying a surface water pollution index to determine status of Loskop Dam, South Africa using phytoplankton and various physico-chemical variables

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This chapter was submitted for publication in the Journal of Environmental Pollution

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4.1 Introduction

South Africa possesses approximately five percent of the global recoverable coal reserves and is also the world's sixth largest coal producer. The Witbank coalfields, in Mpumalanga Province, South Africa, represent the largest area of active coal mining in the country and are located in the Olifants River catchment, resulting in the river deemed one of the most polluted rivers in southern Africa. Mining activity causes mine dewatering which results in a discharge of approximately 50 Ml per day of mine water into the upper Olifants River catchment (Maree, 2004). In this catchment, Loskop Dam acts as a repository for pollutants (Grobler, 1994).

Supplementary sources of pollution are acid mine drainage (AMD) from a number of abandoned coal mines and the discharge of treated, partially treated and untreated domestic and industrial sewage from municipal sewage treatment works upstream of Loskop Dam (Oberholster et al., 2016, Dabrowski et al., 2014). The pollutants generated and ecological processes affected by these activities in the upper Olifants River catchment include acidification of the system and the input or mobilisation of heavy metal ions plus sulphates and other contaminants via acid mine drainage and excessive nutrient inputs (phosphorus and nitrogen) from agricultural activities and sewage effluent causing culture eutrophication (Oberholster et al., 2016; Dabrowski et al., 2014).

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The second largest irrigation scheme (Loskop Dam Irrigation Board) is also found below the Loskop dam. This irrigation scheme of ± 480 km of irrigation canals provides water for to farmers who export fruits to the European Union resulting in significant revenue and creating job opportunities to more than 30,000 farmworkers (Loskop Dam Irrigation Board) (Tren and Schur, 2000). The Olifants River in Mpumalanga Province is also a trans-boundary river that initially flows northwards before curving in an easterly direction through the Kruger National Park and into Mozambique where it joins the Limpopo River before discharging into the Indian

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Ocean. Over the past twenty years isolated incidents of fish mortality have been recorded at different times in Loskop Dam (Dabrowski et al., 2013). These incidents in Loskop Dam coincided with Nile crocodile (*Crocodylus niloticus*) mortalities; with reported declines in the crocodile population from approximately 30 animals to a total of 6 in 2008 (Paton, 2008). Crocodile mortality in Loskop Dam during this period of time was ascribed to pancreatitis, which is associated with the intake of rancid fish fat after a fish die-off (Paton, 2008).

To preserve the aquatic ecosystem of Loskop Dam and ensure that adequate sources of good quality water is provided to the Loskop irrigation scheme and its stakeholders, an adequate knowledge base of management structures, as well as proper tools to conduct reliable and accurate assessments and monitoring programs are imperative. Making use of bio-indicators species may prove an accurate description of the statuses and cumulative deterioration of this ecosystem. Diatoms have been used frequently as bio-indicators because they have some advantages over other groups of organisms (Castro-Roa and Pinilla-Agudelo, 2014), such as their occurrence in nearly all aquatic habitats; their quantification even when the substrate has dried because their frustules (silica shells) are conserved Reynolds (2006); and they are also excellent indicators of their environmental conditions (Castro-Roa and Pinilla-Agudelo, 2014). Phytoplankton is of key ecological importance because of their major role they play in aquatic food web interactions. Phytoplankton communities are extremely dynamic and respond to changes in light, nutrients and sediment loads, rapidly changing in biomass distribution and species composition, thereby making phytoplankton good indicators of aquatic health and water quality (Castro-Roa and Pinilla-Agudelo, 2014). The presence of blue-green algae (Cyanophyta) such as *Anabaena*, *Oscillatoria*, *Lyngbya* and *Microcystis*, for example may indicate freshwater nutrient enrichment as genera commonly respond to increases in nutrients, as do certain green algae (Chlorophyta) from the genera *Chlorella*, *Chlamydomonas*, *Spirogyra*, and *Tetraedron* (Lally et al., 2012). Other green algae from the genera

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Merismopedia, *Staurastrum*, and *Ankistrodesmus* are found mainly in clean, oligo-trophic freshwaters, as are the diatoms (Bacillariophyta) *Cycotella* and *Pinnularia*. Based on these factors, phytoplankton has been used in numerous cases to detected contamination in aquatic systems.

There is an urgent need to generate instruments that can help to preserve this threatened aquatic ecosystem; and to identify and prevent the contamination of the sources of irrigation water downstream of Loskop Dam. Thus, during this chapter the developed modified pollution index was used to assess the condition of the Loskop Dam by utilizing both physico-chemical parameter and bio-indicators.

4.2 Results

4.2.1 Physical and chemical parameters

The pH values over the 12-month sampling period range between 7.0 and 8.0. Variation in EC concentrations was observed throughout the study period from January 2016 to December 2016. Table 4.1 shows that the EC levels were 43.9 mS/m in January and 43.5 mS/m in February 2016. However, EC concentrations increase during lake overturn (i.e., temperature induced water column mixing, Wetzel 1983) in March to 46.5 mS/m. During the months that follow there was a steady incline with some fluctuations in EC level with the month of July having an EC concentration of 52.7 mS/m, while the highest EC (63.5 mS/m) was measured during December 2016 (Table 4.1). The total sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg) also follow the same trend as EC throughout the study. However, some differences were observed between potassium (K) concentrations and the other chemical variables measured. K concentrations were lower in January (6.9 mg l^{-1}) in comparison to

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February (7.8 mg l^{-1}). The Al and Fe concentrations remained high at the sampling site throughout the study, with the highest concentrations recorded during May (Al 0.05 mg l^{-1} and Fe 0.2 mg l^{-1}) and October (Al 0.05 mgl^{-1} and Fe 16 mg l^{-1} (Table 4.1). The maximum concentrations of Al and Fe detected during these months were higher than the allowable South African Water Quality Guideline values for Al (≤ 5 µg l^{-1}) and Fe (< 100 µg l^{-1}) for domestic water consumption (DWAF, 1996). Cu and manganese (Mn), both had lower in concentrations in January 2016, but showed some similarity with Al concentrations (also low in January) in comparison with the other months but start increasing from April onwards. Other chemical parameters, which also follow the same trends, were NO_3-N (which in April changes to May from 0.06 to 0.37 mg l^{-1}) and hardness (changes from 146.29 to 165.98 mg $CaCO_3$ l^{-1}). There was also a noticeable change that occurred to alkalinity and hardness during the months of September and October. Alkalinity increased from 14 to 64 mg l^{-1} during this time, while hardness decreased in concentration (169.44 to 166.03 mg $CaCO_3$ l^{-1}).

During the study, SO_4 concentrations ranged between 123 and 208 mg l^{-1} (Table 4.1) while Total phosphates (TP) varied between 0.02 and 0.1 mg l^{-1}. The total phosphates concentration was the highest during the month of October (0.13 mg l^{-1}) when there was a shift towards late spring early summer with lake overturn. Table 4.1 illustrates that NH_4-N concentration varied between 0.11 and 0.49 mg l^{-1}. There are some noticeable changes from month to month. Unlike, some of the other chemical parameters, NH_4-N didn't increase steadily from the start of the year towards the end.

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Table 4.1 The average physico-chemical parameters measured from January 2016- December 2016 (n = 12).

Parameters	**Units**	**Months**											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
pH	@25°C	7.5	8.1	7.7	7.4	7.0	7.5	7.7	7.9	7.9	8.0	7.9	7.7
EC	(mS/m)	43.9	43.5	46.5	46.9	47.8	49.3	52.7	56.5	58.0	57.6	60.3	63.5
Na	mg l^{-1}	25.9	25.6	28.5	25.3	28.3	28.5	32.8	32.3	33.1	33.0	39.0	39.8
K	mg l^{-1}	6.9	7.8	6.6	6.4	7.5	6.7	7.0	7.1	6.7	7.1	6.8	8.3
Ca	mg l^{-1}	31.5	29	30.5	30.5	34.9	30.7	32.8	36.9	34.4	35.0	32.7	36.1
Mg	mg l^{-1}	19.0	16.4	17	17.7	19.1	17.5	19.7	19.6	20.3	19.1	19.2	20.4
Fe	mg l^{-1}	0.01	0.11	0.08	0.03	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1
Mn	mg l^{-1}	0.03	0.007	0.004	0.009	0.05	0.04	0.05	0.12	0.06	0.07	0.07	0.05
Cl	mg l^{-1}	18.0	20.0	20.0	19.0	20.0	17.0	25.0	24.8	29.3	27.0	27.0	28.0
SO_4	mg l^{-1}	140.0	127.0	125.0	123.0	158.0	125.0	157.0	152.0	162.0	168.0	178.0	208.0
B	mg l^{-1}	0.07	0.03	0.07	0.03	0.1	0.09	0.1	0.12	0.22	0.1	0.12	0.09
Alkalinity	mg l^{-1}	61.0	58.025	59.0	57.0	61.0	65.0	66.0	43.03	14.0	64.0	49.842	62.0
Hardness	mg l^{-1}	156.97	139.86	146.45	149.29	165.98	148.89	162.96	172.81	169.44	166.03	160.54	174.12
Al	mg l^{-1}	0.002	0.007	0.001	0.003	0.05	0.04	0.0011	0.006	0.03	0.05	0.021	0.04
Cu	mg l^{-1}	0.001	0.002	0.03	0.002	0.04	0.04	0.03	0.03	0.01	0.04	0.03	0.04
Zn	mg l^{-1}	0.005	0.008	0.02	0.01	0.05	0.04	0.05	0.04	0.01	0.05	0.04	0.05
TP	mg l^{-1}	0.07	0.06	0.02	0.01	0.02	0.08	0.02	0.03	0.1	0.13	0.03	0.02
NH_4-N	mg l^{-1}	0.32	0.14	0.18	0.3	0.29	0.3	0.3	0.32	0.28	0.49	0.3	0.11
NO_3-N	mg l^{-1}	0.009	0.03	0.01	0.06	0.37	0.38	0.38	0.37	0.39	0.44	0.39	0.41
Temp	°C	6.3	9.7	9.8	7.6	8.2	6.8	9.0	0.9	6.0	7.7	9.7	9.4
Si	mg l^{-1}	0.83	0.8	0.63	0.91	1.1	0.84	0.48	0.21	0.26	0.21	0.22	0.62

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4.2.2 Phytoplankton community structure trophic spectrum

A clear phytoplankton species succession was recorded for the sampling site in Loskop Dam from January to December 2016. During January and February the dominant (Berger and Parker index: 4.23; 3.34) phytoplankton species was the cyanobacterial species *Microcystis aeruginosa* (Kützing ex Lemmermann), which is normally found in nutrient enriched lakes, pounds, and reservoirs or slow-flowing eutrophic rivers, *Microcystis aeruginosa* was replaced by the larger, slower-growing late summer species *Ceratium hirundinella* (Müller). *Ceratium hirundinella* was the dominant (Berger and Parker index, 3.64; 3.21; 2.98 and 2.67) phytoplankton species from March to June. Table 4.2 illustrates that the diatom *Melosira varians* (Agargh) became dominant during the mid- winter month of July and stayed dominant (Berger and Parker index, 2.91; 2.54) until August. The latter species was replaced by *Cryptomonas erosa* (Ehrenberg), which became the dominant (Berger and Parker index, 3.13) species during early spring in Loskop Dam. In the month that followed a community of small and rapidly reproducing phytoplankton *Trachelomonas intermedia* (Ehrenberg) become dominant. After lake overturn in October, the occurrence of the cyanobacteria *Microcystis aeruginosa* become more prominent for the months of November and December when blooms of the cyanobacteria *Microcystis aeruginosa* was observed.

The diatom *Melosira variant* was present in 10 of the 12 months during the study period. This species was absent in the water column only during September and October. The months with the highest phytoplankton assemblage were February and March, while Augustus, September and October had the lowest assemblage (Table 4.2). The second most prominent phytoplankton species observed was the cyanobacteria *Microcystis aeruginosa*, which was present in the samples eight of the 12 months. *Microcystis aeruginosa* was not present during the months of July to October. The third most noticeable species was *Ceratium hirundinella*, which was present during seven of the 12 months. *Ceratium hirundinella* was absent during the months of

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January, July, August, September and November. The phytoplankton species, the diatom *Aulacoseira granulate* and the green algal *Scenedesmus quadricauda* were less common during the study period. *Aulacoseira granulate* was only present during the month of December and *Scenedesmus quadricauda* during the month of March. According to Table 4.2, there was a variation of diatom species collected during the study. However, only one diatom species *Melosira variant* was dominant in the winter months while the rest was present. The trophic spectrum of the major phytoplankton of Loskop Dam (Figure 4.1) indicates that the dominant phytoplankton species cluster along the meso to eutrophic axes over the period of 12 months.

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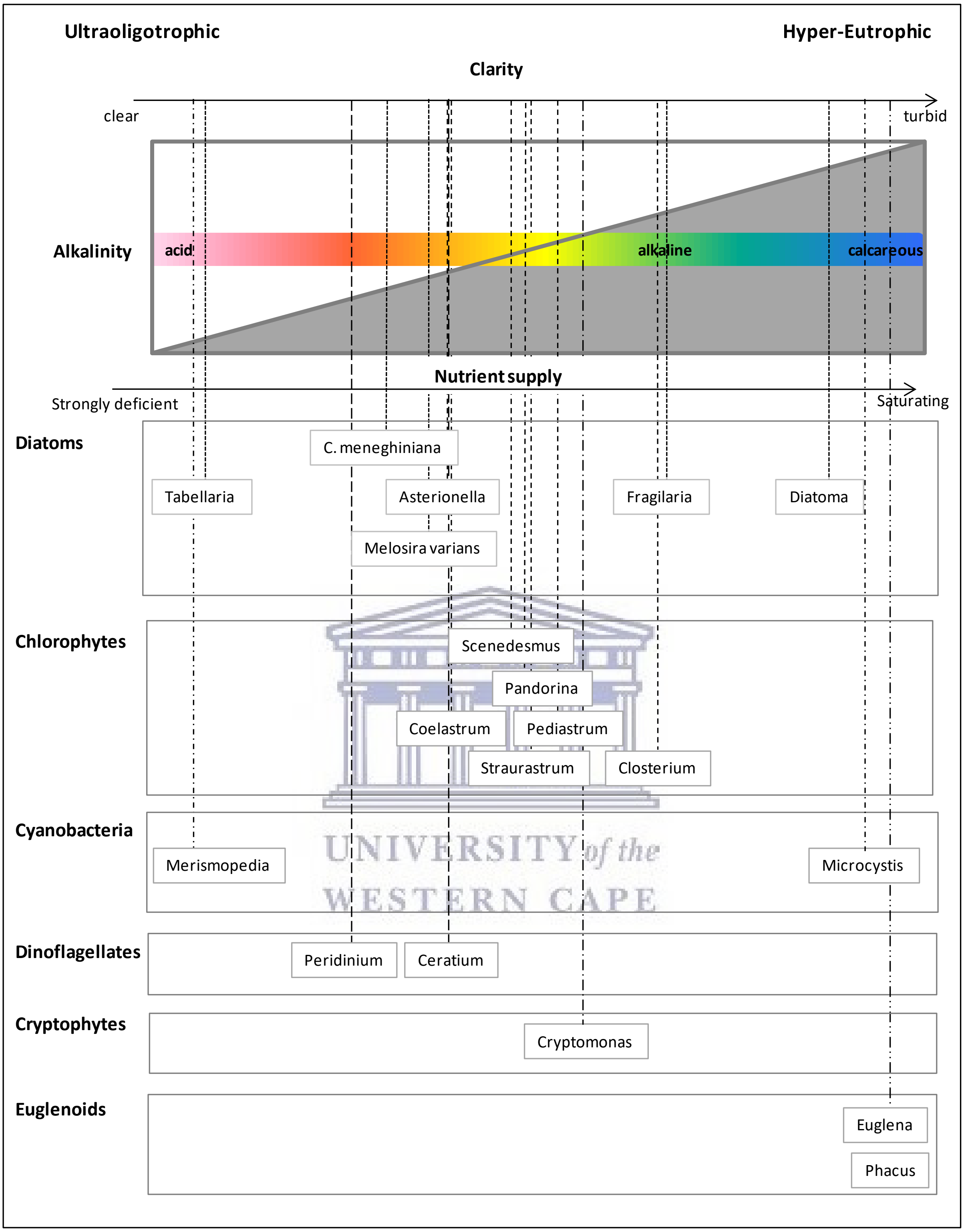

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Figure 4.1. Trophic spectrum of some of the major phytoplankton species observed in Loskop Dam over the period January to December 2016 (Modified after Reynolds, 1998).

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Table 4.2 Dominant phytoplankton species collect over the 12-month period (D = Dominant; P= Present).

Code	**Algal species**	**Months**											
		Jan	**Feb**	**Mar**	**Apri**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Aul	*Aulacoseira granulate*												P
Cera	*Ceratium hirundinella .*		P	D	D	D	D				P		P
Cryp	*Cryptomonas erosa*	P	P	P	P					D			
Cyc	*Cyclotella meneghiniana*	P	P		P	P		P					
Fra	*Fragilaria crotonensis*											p	P
Mel	*Melosira varians.*	P	P	P	P	P	P	D	D			p	P
Mic	*Microcystis aeruginosa*	D	D	P	P	P	P					D	D
Ooc	*Oocystis rupestris*	P	P	P									
Ped	*Pediastrum duplex*		P				P	P		P			
Sce	*Scenedesmus armatus*			P									
Tab	*Tabellaria flocculosa*			P			P						
Trac	*Trachelomonas volvocina*				P	P	P	P			D		

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4.3.3 Phytoplankton in relationship with Physical and chemical parameters

Figure 4.2 illustrates phytoplankton species in association with physical and chemical parameters over the time period of 12 months. The ordination plot describes 52.51% of data variations, with 37.19% on the first axis of the biplot and 15.32% on the second axis. As illustrated by the biplot, the species *Melosira*, *Ceratuim* and *Microcystis* correlated strongly with the variables alkalinity, Si and surface water temperature. Furthermore, there was a strong correlation observed between the metals Cu and Zn, and the diatom species *Fragilaria crotonensis*. However, the metals Al and Fe did not correlated with any of the phytoplankton species observed during the study.

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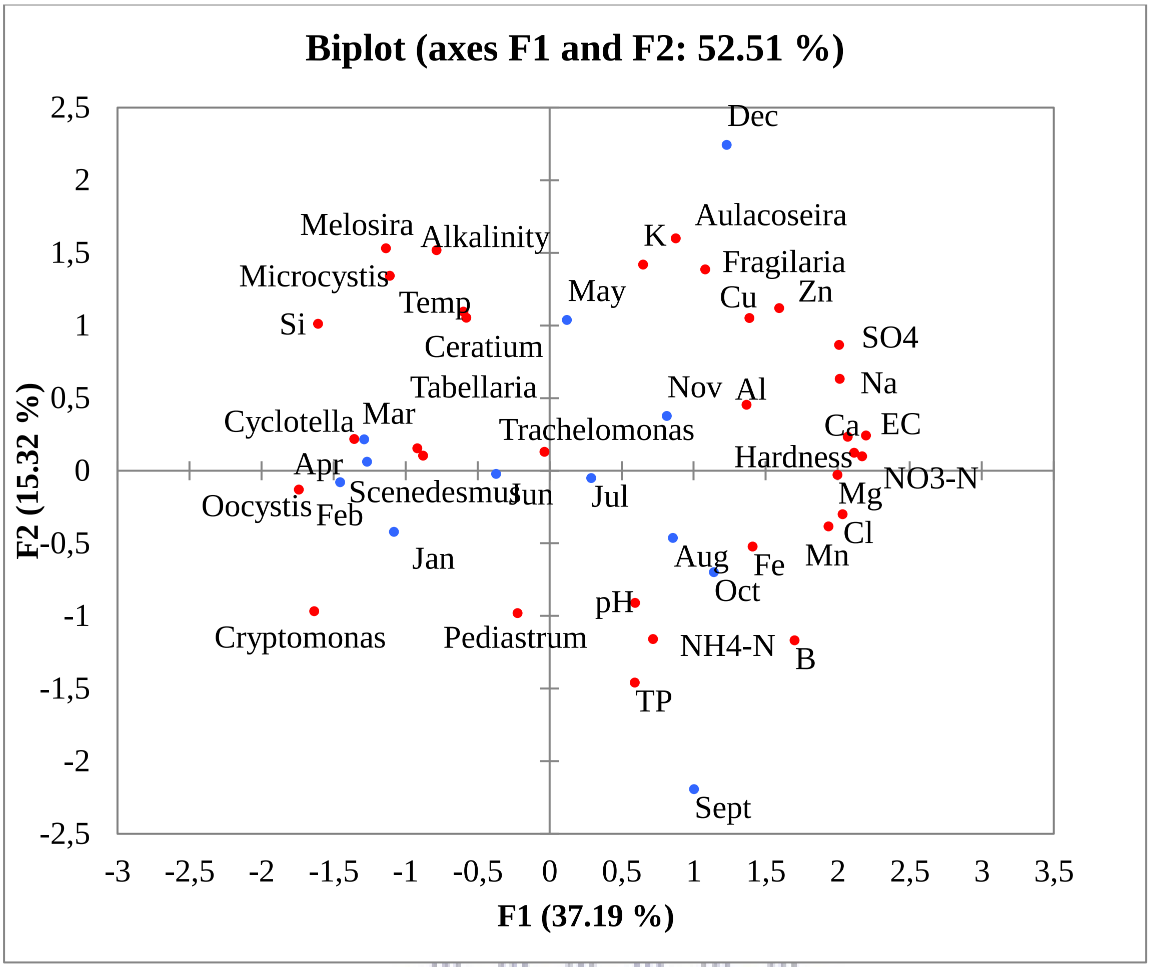

Figure 4.2 A principal component analysis (PCA) biplot indicating the associations between algae assemblage, and selected water quality parameters. The biplot include a depiction of phytoplankton species (e.g. *Melosira*, *Microcystis*, *Ceratuim*, *Tabellaria*, *Trachelomonas*, *Aulacosieira*, *Fragilaria*, *Cyclotella*, *Oocystis*, *Scenedesmus*, and *Pediastrum*), physical and chemical parameters (e.g. pH, TP, B, Fe, Al, Mn, EC, Si, Temp, Cl, K, NA, SO_4, Cu, Ca, Zn, NH^4-H, NO^3-H, and Alkalinity), and the sampling months of the year (Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sept, Oct, Nov, and Dec). These three variables were compared with one another in the biplot.

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4.2.4 Pollution index analyses of Loskop Dam (PILD)

The PI calculated during the study did vary between the different physico-chemical variables. As illustrated in Table 4.3, some of the elements were higher than others, as seen by the PI for Cu which fluctuated between the ranges of 3.33 and 133.33, while the element Mn fluctuated between 0.02 and 0.39. Furthermore, most of the trace metals PI's increased between the months of April and May during lake overturn; which is support by what is illustrated by in Table 4.2. The highest PI was observed in October while the lowest was observed during the summer month of January 2016

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Table 4.3 PI values of physical and chemical parameters measured over a period of 12 months (n=12) in Loskop Dam.

PI values	**Months**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Al	0.4	1.4	0.2	0.6	10.0	0.8	0.22	1.2	6.0	10.0	4.2	0.8
Cu	3.33	23.3	100.0	6.67	133.33	133.33	3.67	100.0	33.33	133.33	100.0	133.33
Fe	0.1	1.1	0.8	0.3	2.0	1.0	1.0	1.0	2.0	2.0	1.0	1.0
Mn	0.17	0.04	0.02	0.05	0.28	0.22	0.28	0.67	0.33	0.39	0.39	0.28
Z	2.5	4.0	10.0	5.0	25.0	20.0	25.0	20.0	5.0	25.0	20.0	25.0
EC	0.63	0.62	0.66	0.67	0.68	0.7	0.55	0.81	0.83	0.82	0.86	0.91
pH	1.07	1.2	1.1	1.07	1.0	1.07	1.1	1.13	1.13	1.14	1.13	1.1
SO4	0.35	0.32	0.31	0.31	0.4	0.31	0.39	0.38	0.41	0.42	0.45	0.52
TP	1.4	1.2	0.4	0.2	0.4	1.6	0.4	0.6	2.0	2.6	0.6	0.4
Total PI values	9.95	33.18	113.49	14.87	173.09	159.03	32.61	125.79	51.03	175.7	128.63	163.34

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The PI value for the trace metal Al was the highest during the months of May and October, while the metal Cu was the highest during the months of May, June, October and December. Furthermore, the PI value for Fe was the highest during the months of May, September and October, whereas the highest month for Mn was August. Additionally, the PI value for Z was the highest during the months of May, July, October and December. The month with the highest PI for both TP and pH was October. However, during the summer month of December the highest PI value was recorded for SO_4 and EC.

Table 4.4 PVT value of each phytoplankton species observed over a 12-month period (January to December 2016 in Loskop Dam).

Phytoplankton Species	**Code**	***PVT***
Aulacoseira granulate	**Aul**	1.7
Ceratium hirundinella	**Cera**	8.67
Cryptomonas erosa	**Cryp**	2.32
Cyclotella meneghiniana.	**Cyc**	2.75
Fragilaria crotonensis.	**Fra**	3.04
Melosira varians	**Mel**	9.94
Microcystis aeruginosa	**Mic**	8.29
Oocystis rupestris.	**Ooc**	1.63
Pediastrum duplex	**Ped**	2.87
Scenedesmus armatus	**Sce**	1.18
Tabellaria flocculosa	**Tab**	2.84
Trachelomonas volvocina	**Trac**	5.78

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During assessment each of the phytoplankton species it was evident that some were more susceptible towards the physical and chemical parameters chosen in the current study. As

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illustrated by Table 4.4, the less tolerant phytoplankton species to the selected variables were *Scenedesmus* (PVT 1.18), *Aulacoseira* (1.7) and *Oocystis* (1.63). Nevertheless, from the species collected during the study period the most pollution tolerant species were the diatom *Melosira* (9.94), followed by the dinoflagellate *Ceratuim* (8.67), and the cyanobacteria *Microcystis* (8.29). This observation was also supported by Table 4.2, which shows the presence of each species throughout the year.

Table 4.5 Illustrates the different levels of contamination based on the findings of the PILD (Modified table after Castro-Roa and Pinilla-Agudelo (2014).

***PILD* (%)**	**Interpretation**	**Implications**
>85	Slightly contaminated	Slight pollution, high phytoplankton diversity. Dam with good or acceptable limnological conditions.
65-85	Moderately contaminated	Polluted at moderate level or is nutrient enriched. Dam with moderate or intermediate limnological conditions.
33-65	Highly contaminated	Heavily polluted, only pollution resistant species abundant. Sensitive species severely reduced. Dam with poor or deficient limnological conditions.
<33	Severely contaminated	Severely polluted, Only a few tolerant phytoplankton species dominant. Very reduced phytoplankton diversity. Dam with poor or severely impaired limnological conditions.

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Table 4.6 General classification of the Loskop Dam according to the *PILD* over the study period January to December 2016.

Months	***PILD* (%)**	**Interpretation based on Phytoplankton species**
January	61	Highly contaminated
February	85	Moderately contaminated
March	79	Moderately contaminated
April	89	Slightly contaminated
May	86	Slightly contaminated
June	81	Moderately contaminated
July	49	Highly contaminated
August	32	Severely contaminated
September	8	Severely contaminated
October	29	Severely contaminated
November	51	Highly contaminated
December	76	Moderately contaminated

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As illustrated by Table 4.6, there was a fluctuation in the condition of Loskop Dam throughout the year. It was evident that the water quality condition of the dam did progressively deteriorated over the 12-month period and could possibly be related to the prevailing drought conditions that persist during the sampling period. The month with the highest *PILD* percentage was April (89%) and the worst was September with an 8% *PILD* value.

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4.3 Discussion

4.3.1 Physical and chemical parameters

It was evident from the current study that certain chemical variables sampled during the 2016 survey exceeded the standards set by the South African Water Quality Guideline (DWAF, 1996). These chemical variables were metals which included Al, Fe, Zn, Cu and Mn of which Al and Fe are significant indicators of acid mine drainage (AMD) that originated from the upper Olifants River catchment. According to Bell and Bullock (1996), the high Al concentrations observed in the upper Olifants River catchment were possibly derived from alumino-silicate minerals associated with coal seams. In the current study fluctuations in the Al concentration could have been the consequence of prevailing weather patterns in relationship to decanting of AMD from abundant mines. Relatively low levels of Al were observed during the months of January to April which coincided with below average levels of rainfall in the upper Olifants River catchment. The latter may have caused the decrease in the seepage of acidic water from abandoned coal mines in the catchment.

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However, there were in January to April 2016 lower levels of trace metals observed which increased later in the year.. Throughout the year (January to December) the dam water levels gradually dropped from 96% to 49% causing the concentrations of contaminants to increase. Other metals which followed this trend during the same time period were Mn and Cu. Mn is a natural occurring mineral in the sediment, especially in this region. Furthermore, lake overturn could have played a major role in the fluctuation of some metal and minerals concentrations in Loskop Dam. Metal and minerals concentrations in Loskop Dam did increase during the transition from summer to autumn and from winter to spring. Mixing of the different water column layers during lake overturn causes chemicals in the bottom sediment of the lake to mix with the surface water column due to temperature fluctuation (Table 4.1). Furthermore, based

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on the findings, sulphate concentrations which is a good indicator of AMD was always lower than the South African Water Quality Guideline (TWQR) value of 400 mg l^{-1} for domestic water supplies (DWAF, 1996).

The high concentrations of NH4-N and total phosphorus measured in Loskop Dam during certain months of the study indicated that the Dam water was eutrophic most of the time. The main contribution to the high levels of NH4-N and TP was possibly the inactive and/or badly maintained wastewater treatment plants found upstream from Loskop Dam. Adding to this, non-point return flows from agricultural activities in the Olifants River catchment could have also caused nutrient enrichment. The run-off from excessive land use activities like mining and farming could also be contributing factors for the gradual increase of the EC of Loskop Dam over the study period. The lower levels (14 mg l^{-1}) of alkalinity observed in the month of September may have caused a decrease in algae biomass. Wurts and Durborow (1992) suggested that alkalinity below 25 mg l^{-1} reduce phosphorus from being available to algae and could even limit algae growth due to low mineralised carbon levels.

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4.3.2 Phytoplankton community responses and trophic spectrum

In temperate zone lakes, oligotrophic systems support minimal phytoplankton biomass with low species diversity, while eutrophic and hypereutrophic lakes sustain very high average algal biomass often dominated by very few taxa, usually cyanobacteria, diatoms or in some waterbodies, dinoflagellates (Jensen and Pedersen, 1994). In the current study it was evident that the dominance of certain phytoplankton species was strongly related to specific environmental conditions (Appendix 1). Most field observations showed more than 1 – 3 dominant species at any phase of seasonal development as predicted by the competitive exclusion theory (Hardin, 1960). The reasons are found in the different responses of phytoplankton on the frequency of disturbances or changes in abiotic resource conditions at

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different scales (Reynolds, 1984). These different scales are (1) shorter than one generation time induces physiological responses, (2) frequencies between 200 and 20 h interact with the phytoplankton growth rate, and (3) disturbances at up to 10 days intervals can initiate a successional sequence in phytoplankton development. The dominance of the cyanobacterial species *Microcystis aeruginosa* during the summer months of January, February and December 2016, correlated strongly with alkalinity and temperature (Fig 4.2). The latter data findings supported a previous study by Brewer and Goldman (1971) that found that additional alkalinity correlated with shifts in algal groups when ammonium is available to provide nitrogen. Furthermore, Kruger and Eloff (1978) found a correlation between the surface water temperature and the development of *Microcystis* blooms in eutrophic reservoirs in South Africa. The authors reported that *Microcystis* blooms started to develop in open lake water, once water temperatures reach 16 -17 ºC. Their results showed that the effect of temperature on specific growth rate occurs after the upper temperature limit is surpassed. From their observations, Kruger and Eloff (1978) suggested that the low surface water temperatures in the South African Highveld reservoirs during winter months (7-8 ºC) may be a barrier to growth of bloom forming cyanobacterial species.

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Ceratium hirundinella that was predominant during lake overturn in March was also strongly correlating with increases in Si concentrations (Table 4.2) and may be due to the fact that this element is a major constituent of *Ceratium* cell walls (Sigee et al., 1999). However, numerous experimental studies have demonstrated that the toxicity of Al concentrations to aquatic organisms decreases when Si is added to culture medium (Camphell et al., 2000; Camilleri et al., 2003). The latter, may have played a role in the dominance of *C. hirundinella* during higher concentrations of Al in May 2016. However, a negative relationship was observed in the current study between the dominance of *C. hirundinella* (a slow-growing inedible algae) and the lower measured phosphate concentrations in the months March, April and May (Table 4.2;

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Fig 4.2), which likely indicated that the higher abundance of this species was associated with low concentrations of P enrichment (Willen, 1991; Reynolds et al., 2002), while higher concentrations of P by the end of June did cause the absence of this species. Supporting evidence for these findings comes from Pollingher (1988). Padisák (1985) reported that at higher concentrations of P, *C. hirundinella* abundance was suppressed, while a study by Watson et al. (1997) showed that dinoflagellates have low average biomass in oligotrophic systems and increase rapidly with an increase in P in meso-eutrophic lakes.

The increase of *M. aeruginosa* during the summer months, are likely related to the higher water temperatures since phosphorus recycling (number of phosphorus molecules recycled per unit time) is more intensive in warmer waters, while processes of phosphorus release from lake sediment and mineralisation are highly temperature dependent (Hamilton et al., 2001). Furthermore it is a known that cyanobacterial blooms usually occur during warm periods at temperatures above 20 ºC (Robarts and Zohary, 1987).

The dominance of the diatom *Melosira varians* — favoured by higher growth rates and lower sinking losses — during the months of July and August can possibly be related to low surface water temperatures (Corbelas and Rojo, 1994). A study conducted by Peterson and Stevenson (1989) on the Ohio River and six Kentucky tributaries indicated that the abundant diatom *M. varians* correlated positively with lower surface water temperatures, while van Dam et al. (1994) suggested that this diatom species is an indicator of eutrophic to hypertrophic water conditions. As illustrated by Table 4.2, the diatom *M. varians* was the only diatom that was dominant during the months of July and August while other species were only present during that sampling period. This phenomenon was likely not related to a shortage of Si, as Willen (1991) stated that Si concentrations as low as 0.2 mg l^{-1} should be sufficient for diatom reproduction. Therefore, it seems unlikely that it was the reason for the low dominance of diatoms, but rather the high concentrations of metal ions that have adverse effects on the

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development of diatom species (Willen, 1991). It was evident that Loskop Dam had a diversity of trophic spectrums which indicated there were species that showed higher requirements for specific nutrients, and these would be at a disadvantage at a low amount of this given nutrient. Further, their extra ability to exploit enrichment would have helped certain species to achieve dominance when the opportunity arises e.g. *C. hirundinella* that needs large quantities of skeletal silica. This was especially evident during this study, where *C. hirundinella* was dominant during periods with high Si levels (Table 4.2). According to Nalewajko (1978), there is a noticeable difference in the cell-specific rates of nutrient-uptake and also in the external concentrations to saturate each of the different phytoplankton species. Consequently, the uptake of nutrients by certain phytoplankton species is faster than others (i.e., they are affinity-adapted). This implies that performance characteristics of nutrient uptake didn’t just differ among phytoplankton species, but among the various nutrients as well.

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Adding to this, some phytoplankton species can function better than others at lower concentrations of one nutrient (i.e., silica), but is less capable of taking up another (i.e., phosphorus). An additional outcome is that when the phytoplankton develops in a natural waterbody where Si or P amounts are consistently or frequently at such low concentration, that one species has a consistent or frequent growth advantage over the other and in time, it is more likely to become dominant over the other. In dams where the nutrient levels are a growth-sustaining requirement (limited resources), it will be in favour of phytoplankton species which are able to maintain the best net performance against the environmental deficiency. This implies that where P concentration is significantly below 1-2 µg l^{-1} P, the phytoplankton is likely to tend quickly towards dominance by high-affinity phytoplankton species. According to Reynolds (1998) the same principle can be applied towards dams where the nitrogen concentrations are substantially below 50-100 µg l^{-1} N. In both cases, outcome is independent on nutrient ratios (Reynolds, 1998). During the months of January, November and December,

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Loskop Dam experienced cyanobacterial blooms and can be classified as a meso-eutrophic dam when the phytoplankton trophic spectrum of Reynolds (1998) was employed as guideline for trophic status. From this trophic spectrum, it is evident that the system was located near its nutrient threshold and consistently fluctuating beyond what is classified as a tolerable amounts of a given nutrient (e.g., a sudden increase of nutrients during summer months causing massive blooms of cyanobacteria) (Table 4.2).

4.3.3 Pollution index

Although the *PILD* indicated that the species *Scenedesmus*, *Aulacoseira* and *Oocystis* were less pollution tolerant, previous reports by Taylor et al. (2007) and van Vuuren et al. (2006) showed that these species are indicators of nutrient enrichment conditions. Therefore, it was evident from the selected variables used in the *PILD* that their low presence over the 12-month period was related to different prevailing environmental conditions and not only to nutrient enrichment. Nevertheless, from the species collected during the study period, the most pollution tolerant species was the diatom *Melosira* (9.94), followed by the dinoflagellate *Ceratuim* (8.67), and the cyanobacteria *Microcystis* (8.29). The main factor for their high level of tolerance could likely attribute to the high levels of Si observed through the study by Table 4.1. During the month with the lowest *PILD* value (September), the most dominant specie was *C. erosa*.

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CHAPTER 5

Determining the occurrence of toxic cyanobacteria in the Loskop irrigation canals with special reference to best management practices

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5.1 Introduction

Cyanobacterial blooms have become an increasing problem in South African freshwater bodies (van Ginkel, 2011). Incidents of fatal cyanobacterial poisoning in South Africa are not uncommon, and occur annually and to date, reports have only involved stock deaths and some domestic animal poisonings (Bengis et al., 2016). The massive proliferation of these organisms is largely caused by over enrichment (eutrophication) of waterbodies which is due to progressive increase in anthropogenic pollution (de Klerk et al., 2016). Cyanobacteria produce some of the most potent toxins known and have no known antidotes (Ndele et al., 2016). These biotoxins fall into three categories namely neurotoxins, hepatotoxins and lipopolysaccharides (Nchabelenga et al., 2014). The biotoxins in the first two groups can produce severe reactions in animals and humans, while the third group appears to be less virulent (Oberholster et al., 2005). However the latter have been less intensively studied. Any release of these biotoxins into surrounding water can present a significant hazard to humans and the ecosystem (Bittencourt-Olivthateria et al., 2014). The existence of gastrointestinal disorders linked to the ingestion of cyanobacterial biotoxins, as well as the chronic risks posed by hepatotoxins make these toxins a serious threat to human health when they are present in drinking water supplies. Based on the cyanobacteria toxins (microcystins and their toxicity) the World Heatlh Organization (WHO) developed guidelines for microcystin-LR (the most commonly known and most toxic type of microcystin) in drinking water which is 1 µg l^{-1} (Falconer et al., 1994). A recent study by Chen et al. (2009) indicated the presence of microcystins in serum of chronically exposed human populations (fishermen at Lake Chaohu, China) together with signs of hepatocellular damage according to Zhang et al. (2009). Humans usually do not consume high doses of microcystins such that lethal acute effects are perceived, but rather by chronic exposure from low doses in drinking water. The majority of the Loskop commercial farmers used irrigation canal water to irrigate their crops. Because these canal water supplies may

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contain cyanobacterial cells the possibility exist that edible crop plants can be exposed to cyanobacterial toxins which can accumulate in plant tissues (Codd et al., 1999). The introduction of these toxins into the human food chain is therefore a strong possibility, which may pose great risks to human health if these crops were ingested. However, nothing to date is known about this exposure route in South Africa.

Furthermore, spray irrigation may permit cyanobacterial biotoxins to affect commercial plant industries as this method of irrigation has previously been shown to be an exposure route for cyanobacterial biotoxins (Abe et al., 1996). Whether spray irrigation promotes cyanobacterial biotoxin release on crops due to cell breakdown via sheer stress, is not yet known. However, strong evidence exist that cyanobacterial biotoxins inhibited the germination of pollen which could have an adverse effect on crop yield of farmers (Metcalf et al., 2004). Currently very little is known in Africa about cyanobacterial toxin and their distribution in irrigation canals (Mohamed et al., 2006)

During this chapter the presence of cyanobacterial toxin and their distribution in irrigation canals was discussed.

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5.2 Results

5.2.1 Cyanobacteria toxicity in the irrigation canals

From the data generated, cyanobacteria only occurred in the water column of the two irrigation canals during the month of May 2016 (Table 5.1). The cyanobacteria detected was *Microcystis aeruginosa* (Kütz) which occurred in low cell numbers (1.4 x 10 3 cells l^{-1}) in the long canal and 1.2 x 10 3 cells l^{-1} in the short canal. Microcystin-LR concentration (µg l^{-1}) measured in the long canal was 0.58 µg l^{-1}, while a concentration of 0.74 µg l^{-1} were measured in the short

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canal. In both canals, microcystin concentrations did not exceed the safety limit (1.0 µg l^{-1}) set by the World Health Organization for drinking water (WHO, 1996).

5.2.2 Cyanobacteria toxicity in the dam

The cyanobacteria *Microcystis aeruginosa* was observed during 7 of the 12-month sampling period at site 3. Toxicity assays (PP2A and ELISA) confirmed that the cyanobacterial cells sampled contain microcystin-LR toxin. Although *Microcystis aeruginosa* was detected during lake overturn (i.e., temperature induced water column mixing, Wetzel, 1983) in the month of May in both the dam and irrigation canals water samples, it was absent during late August during the second lake overturn. The lowest cell numbers of *Microcystis aeruginosa* measured was in May (1.7 x 10 3 cells l^{-1}) while the highest (1.2 x 10 4 cells l^{-1}) was measured at site 3 during November 2016.

5.2.3 *Lactuca sativa* Assay (Seed Test)

The results from the *Lactuca sativa* Assay is summarized in Table 5.2. The results indicated that the surface water of the dam did have a higher adverse effect on seed germination than the two irrigation canals.

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Table 5.1 The occurrence of cyanobacterial species in the water column of the two selected irrigation canals and Loskop Dam over a 12 month period (p= present; a=absent).

Sampling Site	**Cyanobacteria species**	**Months**											
		Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Site 1 (Short canal)	*Microcystis aeruginosa*	*a*	*a*	*a*	*a*	*P*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Site 2 (Long canal)	*Microcystis aeruginosa*	*a*	*a*	*a*	*a*	*P*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
Site 3 (Dam wall)	*Microcystis aeruginosa*	*a*	*p*	*P*	*P*	*P*	*P*	*a*	*a*	*a*	*a*	*p*	*p*

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Table 5.2 Comparison of ELISA and Protein Phosphatase inhibition (PP2A) assays as determinants of intracellular cyanobacterial toxicity in the water column of the two irrigation canals over a period of 12 months in 2016 (+ = positive toxic; - = negative toxic).

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Sampling Site	**Toxin measurement**	**Cyanobacteria species**	**Months**											
			Jan	**Feb**	**Mar**	**April**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Site 1 (Short canal)	ELISA [LR] µg l^{-1}	*Microcystis aeruginosa*					0.74							
Site 2 (Long canal)		*Microcystis aeruginosa*					0.58							
Site 3 (Dam wall)		*Microcystis aeruginosa*	3.9	3.1	2.8	2.7	2.4						2.7	3.1
Site 1 (Short canal)	PP2A	*Microcystis aeruginosa*	-	-	-	-	+	-	-	-	-	-	-	-
Site 2 (Long canal)		*Microcystis aeruginosa*	-	-	-	-	+	-	-	-	-	-	-	-
Site 3 (Dam wall)		*Microcystis aeruginosa*	+	+	+	+	+	-	-	-	-	-	+	+

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Table 5.3 *Lactuca sativa* Assay response to a screen (100% concentration) of surface water of the selected sampling site during May 2016, when cyanobacterial cell was observed in the surface water column.

Sample sites	***L. sativab*** **Germination assay**
Site 1 (Short canal)	90
Site 2 (Long canal)	85
Site 3 (Dam wall)	72
Control	98
Mean	82
SD[b]	1.89
CV[c]	1.81

Germination (%) in each sampling site compared to that of the control, 120h.

[b] ·Standard deviation (SD).

[c] ·Coefficient of variation (CV) = (standard deviation) x 100/mean.

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5.3 Discussion

Cyanobacteria toxin microcystin-LR is a potential hepatotoxin and has been also implicated in liver tumor promotion (Nishiwaki-Matsushima et al., 1991). Microcystins are synthesized by a large number of cyanobacterial genera and are globally distributed (Tian et al., 2013). More than 80 structural variants have been identified from field samples or isolated strains of

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cyanobacteria. The most commonly occurring/abundant microcystin (MC) toxins include microcystin-LR (MC-LR), microcystin-RR (MC-RR) and microcystin-YR (MC-YR). Water borne MCs has resulted in the death of 76 patients in Brazil (Jochimsen et al., 1998), while epidemiological investigations suggested that MCs may be responsible for most incidences of liver cancer in populations depending upon drinking water contaminated by MCs in China (Ueno et al., 1996), Serbia (Svircev et al., 2009), and the United States (Florida, Fleming et al., 2002), as well as colorectal cancer in China (Zhou et al., 2002).

The occurrence of the cyanobacteria *Microcystis aeruginosa* containing microcystin-LR in the water column of the two irrigation canals during the May 2016 sampling period can possibly be related to temperature induced mixing (lake overturn) causing the vertical warm and cold water layers in Loskop Dam to mix due to changes in net heat input. The increase in mixing depth did induce similar temperature and chemical conditions from the top to the bottom of the water column (Wetzel, 1983). Withdrawal of irrigation water from the upper-hypolimnia during this period may have contained and transport phytoplankton species usually occurring in the epilimnon layer of the dam to end up in the water column of the two irrigation canals. Furthermore, *Microcystis aeruginosa* is known to prefer stratify water column conditions and is therefore absent in systems with high flushing rates and unstratified water columns (Sommer et al., 1986). Due to the latter it is unlikely that this species will occurred under natural conditions in elevated numbers in the two irrigation canals with high flows (Matzinger et al., 2007). Although the *Lactuca sativa* Assay showed adverse effect on seed germination from all three selected sites, with the lowest germination in seed exposed to dam water in comparison to the control during May 2016, it was not evident that it was due to cyanobacterial extracellular toxin or other pollutants in the surface water. However, higher concentrations of intracellular microcystin-LR in *Microcystis* cells were detected in the dam during this sampling period in

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relationship with the two canals (Table 5.2). Furthermore, it is a known fact that decomposing of toxic cyanobacterial blooms producing extracellular microcystins (Nchabeleng et al., 2014).

Water quality predictions like these are important for water quality management in the irrigation canals, especially if it happened on a sufficient timely basis, since large amounts of the water from Loskop Dam are used directly or indirectly for irrigation purposes. In a previous report, Codd et al. (1999) measured detectable amounts of MCs and *Microcystis* cells in spray irrigation water and on sprayed-irrigated salad lettuce intended for human consumption. Another report by Hoppu et al. (2002) stated that irrigation water contaminated by cyanotoxins may lyses the cells and aerosolizes the toxins which can then be inhaled by farm workers. It is also possible that dairy cows, after oral exposure, might secrete cyanobacterial toxins in their milk, although, tests to date after administration of MCs to lactating cows by gavage have not confirmed the presence of MC in milk (Feitz et al., 2002).

According to Crush et al. (2008), the levels of MCs in exposed crops can exceed the tolerable daily intake of 0.04 µg kg^{-1} of body weight/day recommended by the WHO. Adding to this, there is a possibility that plants, especially those that are part of the human diet, could be contaminated by irrigation water (Bittencourt-Olivthateria et al., 2014). Consequently, many studies have discussed the accumulation of MCs in leaf tissue and the effect it has. The increase in health concerns was brought on by an assessment of the carcinogenicity of MC-LR by the International Agency for research on Cancer that concluded that it is carcinogenic to people (Crush et al., 2008). The effect that MCs have on plants include negative enzymatic activity, decrease in growth, reduction in photosynthetic activity, interferes with metabolism and biomass of aquatic and terrestrial plants, oxidative stress, causes the decrease of protein phosphatases 1 and 2A, and even apoptosis. Natural contact between terrestrial plants and MCs are not that commune without human intervention (Bittencourt-Oliveria et al., 2014). Additionally, irrigated plants containing MCs can directly or indirectly contribute to

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cyanotoxin transfer. Microcystin contaminated irrigation water can also cause economic impact by decreasing germination rate of seeds, and effecting quality, productivity, and yield of crop plants. According to Sagrane and Oudra (2009) an increase in antioxidative enzymes in spinach plants were observed after six weeks of exposure, which clearly indicated that oxidative stress is promoted in plants which come in contacted with MC-LR. Furthermore, there are currently no standards for MCs intake by farms animals and MCs contaminated water can cause MCs bioaccumulation in farm animals (Crush et al., 2008). In New Zealand, widespread cyanotoxins released by cyanobacteria in surface water is common with intermittent reports of stock and dog mortalities resulting from animals consuming water during heavy blooms of cyanobacteria (Crush et al., 2008). Consequently, a study done by Crush et al. (2008) found that there are a potential for the movement of MCs into the human and animal food chain through irrigation water, and thus constitute a potent health risk source.

5.4 Best management practices

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Although lake overturn cannot always be predicted, since it is strongly related to climatic conditions, the following management practices can be put in place (a) reduce the use of copper sulfate during lake overturn periods to reduce filament growth in irrigation canals. The use of the latter chemical can cause the die off of *Microcystis* cells and the release of large concentrations of external cellular microcystin, (b) test leafy crop produce for signs of MCs concentrations when cells are present; and (c) protect farm workers from exposure to water containing MCs concentrations. It is also recommended that a cyanobacterial toxicity monitoring program is set in place and test irrigation balance dam for MCs concentrations during lake overturn periods.

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CHAPTER 6

Socioeconomic implications

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6.1 Introduction

In this chapter the focus shifts from the Loskop Dam towards the Loskop Dam Irrigation Board and the community of farmers that depend on the water for irrigation of crops. The Loskop irrigation scheme, found downstream from the Loskop Dam, plays an important role in the economic development of the area. The farming community mostly makes use of water from the Loskop Dam irrigation canals to provide water for the irrigation of crops. Some members of the farming community also make use of boreholes to supply their crops with water. The Loskop irrigation scheme is comprised of two canals providing irrigation water for agricultural use in both the Limpopo and Mpumalanga provinces. The canals can be divided into a short and long canal, each running on opposite sides of the dam. The Loskop irrigation scheme, located downstream of Loskop Dam, is the second largest irrigation scheme in South Africa, and was constructed between 1933 and 1940. The irrigation scheme has an irrigation area of 16,117 ha and a total of ± 450 km of irrigation channels, and consists of an extensive system of concrete irrigation channels supplying 624 properties with irrigation water (Dabrowski et al., 2013).

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The agricultural sector in the Loskop region is characterised by high value irrigated crops that make a substantial contribution to the regional economies and to the total export value of the agricultural sector. The total economic output of the region is approximately R1 billion, of which citric fruit exports towards the European Union contributes most (van Vuuren, 2010). Pollution in the upper Olifants River and the associated water quality problems for the purposes of drinking water and irrigation of crops grown in the Loskop Dam valley region have had a direct negative impact on the health of citizens and the export markets. Additionally, the agricultural sector plays a key role in supporting local communities, including farmworkers who depend on the wealth produced for their livelihood. Job losses due to poor water quality

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could have an impact on the total supply chain. This could be devastating in a region already ravaged by unemployment.

The structure of this chapter will consist of the following: 1) discussion on the operational function of the irrigation scheme and their management practices; 2) the economic impact of water quality from the previous chapters’ findings; and 3) which other factor upstream from Loskop Dam may determine the overall socioeconomic conditions.

6.2 Loskop Dam Irrigation Board, Water User Associations and Catchment Management Agencies

In 1995 a legislative review process was initiated for water resources management (WRM) in South Africa, concluding in the 1997 White Paper on a National Water Policy for South Africa and the National Water Act (NWA, Act 36 of 1998). These provide the necessities for WRM by defining the purpose and objectives as well as certain requirements for performing WRM. The responsibility of Department of Water Affairs and Sanitation (DWS) is to design and realise bulk water supply infrastructure. In future, the responsibility of DWS will also include policy formulation, legislation, national strategy formulation, institutional development, coordination and support as well as monitoring and auditing water resource management. DWS oversees the establishment of Catchment Management Agencies (CMAs) and once these become operational, DWS’s role in authorization will decrease.

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The Minister of Water Affairs and Sanitation under section 92 of the National Water Act also established statutory bodies known as Water User Associations (WUAs). They are cooperative associations of water users who wish to undertake water related activities for their mutual benefits (Tren and Schur, 2000). The implementation of such systems means that existing

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irrigation boards must transform into WUAs. The difference between WUAs and the irrigation boards is that WUAs should incorporate all users of any water resources within the local area.

The Loskop dam irrigation scheme is the second largest in South Africa, after the Vaal-Harts irrigation scheme. The Loskop Dam Irrigation Board was initiated to manage and operate the water distribution across the scheme; which prevented exclusion of any member of the farming community from water user rights for irrigation. South Africa has two overall types of irrigation schemes, private and irrigation board schemes. The development of these different types is associated with different economic development phases experienced during the counties history (Tren and Schur, 2000).Private irrigation schemes are privately owned and members can extract water unswervingly from weirs, boreholes, and farm dams, with all costs covered by the farmers. Irrigation board schemes, on the other hand, were created under the previous water legislation. They are autonomous, democratically run institutions elected by participating irrigation farmers from the local farming. Even though the scheme was privatised in 1992, authority over the scheme still rests with DWS. Furthermore, there is no other government department or non-government organisation that has any effect on the management of the Loskop irrigation scheme. The Loskop Dam is run by the DWS based Groblersdal and it is their obligation to establish the annual water quota grounded on the amount of water in the dam. According to Tren and Schur (2000), during the months of April and March is when the total annual quota for the water year is set and cannot surpass the total acceptable irrigation rights of 124 million m^3. However, this amount of irrigation water can be lowered due to extreme weather conditions, such as drought. The management and operation of the scheme has become proficient since it was privatised 1992. One of the main reasons is that while it was fully managed by the DWS, 30 percent of the water was lost and after privatisation the percentage of water loss dropped to between 21 and 24 percent. A main factor for the decrease was the improvement in the level of maintenance and repair on the irrigation canals. The billing

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system and the gathering of fees have improved since privatisation.[2] The billing system works as follows: farms have to settle their account within 90 days or they face the risk of having their sluice gates closed and they would then have to pay interest. Any financial surpluses produced by the Loskop Dam Irrigation Board are allocated into development and improvement of the scheme. Management has improved after privatisation due to the efficiency to which the canal system was maintained.[3] While DWS was in full control of the scheme, they employed over 300 labourers to remove grass from the side of the canals. However, because of the length of the canals it would take then between 3 to 4 months to complete the task, but they have to start all over again once completed. After privatisation, however, the Loskop Dam Irrigation Board collaborated with the members of the scheme, and each farmer tasked a few of their farm labours to remove grass on the edges of a specific section of the canal.

The total quantity of water delivered to individual farmers is controlled by the amount to which the various sluice gates along the canal are opened. When the sluice gate is opened, depending on the scope, more water will be delivered from $17m^3$/hour to $200m^3$/hour.[4] The method by which they monitor the total quantity of water delivered is by comparing the water released from the Loskop Dam, with the water that returns to the Olifants River downstream. Voting rights depend on the amount of hectares a farmer owns. According to Tren and Schur (2000), a single vote is allocated to 6 hectares up and this goes up to 10 votes per piece of irrigation plot. The main economic activity for farmers of the irrigation scheme is irrigation farming. However, there are some that run small bed and breakfasts and a few have livestock on their farms although this does not compare to the financial inflow from irrigation farming.[5] There

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[2] Interview Johan van Stryp member of the Loskop Dam Irrigation Board (personal communication)

[3] Ibidem (Ibid)

[4] Ibid

[5] Ibid

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are 67 full time employees working for the Loskop Dam Irrigation Board (e.g. 16 technicians and managers and unskilled labourers bringing the number to 51). The Board supervises the day-to-day running of the Loskop Dam Scheme.

The management is accountable for ensuring that water is meritoriously and well delivered to the applicable party (farmers). Some of the employees administer the water requirements and request the right quantity of water from the DWS in Groblersdal; while others administer the billing, fee collection, and monitoring of water usage. The unskilled labourers are tasked with the responsibility of opening and closing the different sluices, found along the scheme, to the specified level set by the farmers. Furthermore, they conduct daily maintenance and upkeep of the irrigation canals. When construction (repairs of canals) is needed the unskilled labourers are employed for the work. The Loskop Dam Irrigation Board consists of 8 members, who are chosen from the sub-districts that make up the Loskop Dam Irrigation area. Members are elected every three years.

6.2.1 Loskop Dam Irrigation Board institutional arrangement

The Loskop Dam Irrigation Board consists of different levels of authority, with specific roles in general management practice of the irrigation scheme. Like any organisation, there is a group of individuals responsible for the decision making process. When referring to the Loskop Dam Irrigation Board, the highest levels of authority are the elected members of the board (Figure 6.1). The board is instrumental in the decision making process concerning the amount of allocated funds towards expenditures like canal maintenance and construction, and also the amount of water released from the dam and the allocated water usage. Adding to this, the board makes decisions based on information collected, and then shares it with the general manager.

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The next level of authority lies with the general manager. The responsibility of the general manager is to oversee all activities concerning general management relating to staff, infrastructure maintenance and water usage, and he/she also reports back to DWS. Adding to this, the general manager reports the findings from the operational manager to the board. The general manager also gives guidance towards the operational manager on what to do.

Underneath the general manager is the operational manager. The operational manager oversees the works of two divisions, which include construction and maintenance, and the water division. These departments inform the operational manager of problems facing them, which is then relayed back to higher levels of authority. Adding to this, the operational manager acts as mediator between lower level employers in the organisational structure, and the management of the organization (Appendix 2).

The construction and maintenance division is responsible for the maintenance of the concrete irrigation canals. Due to ageing, the canal infrastructure must be repaired on a continuous base. When it comes to reconstructing the concrete canals the division leader must first ask the boards permission before going any further with construction; as the board is constrained by a financial budget and an adequate reason most by give before any funding can be allocated towards a project. Adding to this, they are also responsible for the operation and maintenance of the equipment in the canals that helps with the distribution of water along the whole canal.

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The structure of the water division consists of eight district managers who’s main focus is to interact with the Loskop Dams irrigation boards’ biggest contributing stakeholder, the farming community. These district managers are responsible for overseeing the usage of water in their specific districts, and their task is to manage water distribution and prevent over utilisation or wastage of irrigation water. It is this group that is the most affected by the contamination of the

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irrigation water in the canal. As they are in direct contact with the stakeholders they are confronted with the problem of contaminated water use.

6.3 Social economic implications of anthropogenic pollution.

6.3.1 Nutrient enrichment and algae pollution

The biggest stakeholder, as previously stated, is the farming community. This is the group mostly affected by the findings of the previous chapter, because they are the main users of the irrigation water. de Lange et al. (2016) estimated the monetary valuation of the impact of algae pollution in the form of clogging the control gates, crop sprayers and canal maintenance on commercial agriculture in the Loskop Dam region by focusing on the impacts of pollution on farm profitability (Figure 6.1). The authors of this study estimated the value of impact in terms of Rand per hectare per year as a percentage of the pre-harvest production cost.

Figure 6.1 Show long strings of filamentous algae in extreme cases up to 10 meter in length in the Loskop irrigation canals.

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The input data for the calculations were obtained from interviews with prominent farmers in the study area and the operations and general managers of the Loskop irrigation scheme. For this survey, de Lange et al. (2016) selected representative crops in terms of hectares under irrigation in the study area (Table 6.1). Citrus was taken as the representative perennial crop, while maize represented summer cash-crops and wheat the winter cash-crops. According to de Lange et al. (2016) the latter represented 66% of the total area under irrigation in the study area. However, these are not the only crops grown within the Loskop Dam Irrigation Scheme. Other crops of importance that are grown in the valley include tobacco (R11.50/kg), cotton (R2.65/kg), soya bean (R1,300/tonne), groundnuts (R1,800/tonne), and peas (R1,335/tonne) (Tren and Schur, 2000). The winter wheat covers the highest sum of hectares as per season, as the crop makes use of both capital and labour. Planting winter crops improves the cash inflow and allows farmers to use land that would probably lie uncultivated. The other crops produced are primarily summer crops with the most water-intensive crop being maize, which needs 6500m3/ha and has a moderately small return of only R900/tonne (Tren and Schur 2000). The total cost of irrigation water (including electricity used and maintenance which amounts to R21.6/m3) is R0.07/m3.

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The region provides job opportunities to many farmworkers as the activities are labour intensive, although the extent of labour being used and employed varies from farm to farm. Some farmers have a full time staff component, employed throughout the year and others depend on provisional labour during harvesting season (Tren and Schur, 2000). Because of high levels of unemployment, there is a large supply of labour in and around Groblersdal.

Another factor that has implications for the socioeconomic wellbeing of the community is the price of land. This may depend on the extent of the irrigation rights and the type of equipment being employed, for example when comparing grazing land (R1,000-R1,500 per hectare), irrigation land with only drag lines (R6,000-R7,000 per hectare), land with irrigation pivots

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(R10,000 per hectare), land covered with deciduous crops like citrus and grapes which are grown using drip or micro irrigation (R10,000 per hectare), and lastly tobacco farms (R25,000-R32,000 per hectare).

The climate and rainfall of the region forces the majority of farmers to use irrigation water for their crops. On average the size of the farm is 35 hectares and each farm receives water rights for 25.7 hectares, which amounts to 77,000 m^3 of water allocated per hectare. As an individual farmer is entitled to 197,890 m^3 per annum, then roughly 124 million m^3 of Loskop Dams water is extracted by the scheme to meet the needs of 624 farmers (Tren and Schur, 2000). However, a portion of the famers own more than one farm, which will bring the total of farmers to 400.

Table 6.1: Water yield relationship and irrigation seasons of tobacco, maize, citrus, and table grapes (from Tren and Schur 2000).

Crop	**Yield (Kg/ha)**	**Irrigation (m^3/ha)**	**Water-yield (kg/m^3)**	**Irrigation season**
Tobacco	2,200	5,500	0.4	October – March
Maize	8,000	6,500	1.23	August- February
Citrus	45,000	10,000	4.5	12 months
Table Grapes	13,500	77,000	1.75	12 months

Being an institutionalised irrigation water board, the Loskop Dam Irrigation Board does have some obligation to provide water to industries, municipalities and other non-agricultural water users. The allocated water towards non-agricultural users amounts to 4,376,000 m^3, which includes 2,600,000 m^3 to municipalities of Groblersdal and Marble Hall, 30,000 m^3 for the hospital, 44,000 m^3 for two schools, and more (Tren and Schur, 2000). Apart from the latter,

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the irrigation board is required to deliver 2,6 million m^3 of water per annum to the population of KwaNdebele. This is only necessary when there is not water in the Renosterkop Dam.[6]

The Loskop Dam Irrigation Scheme consisted of farmers who vary in their level of income. Income determines farm size, the methods used and crops grown. Lately, the region also has a few emerging black farmers. The majority of the general farm community gets the same amount of water for irrigation, with 15 farms receiving 30 ha and a few minute farms receive 2.8 ha making the running cost of Loskop Dam Irrigation Scheme a total of R1, 332,600 during 1999 and 2000.

In an effort to assess the added costs to farmers due to pollution, prominent farmers/producers of a variety crops were interviewed to obtain their assessments on the impacts of algae pollution on their business focusing on the impacts of algae on the cultivation practice. De Lange et al. (2016) followed a pragmatic approach by first identifying the practical consequences of algae pollution on cultivation practice, where after farmers were asked to try and distinguish between a "heavy" load and a "normal" algae load scenario. This was done since it was assumed that algae are always present in the water and that a difference in concentration level is considered the distinguishing factor determining the mitigation strategy and hence cost implications and consequent profitability impacts.

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In the final analysis, the cost implications of the impacts of algae were determined by systematically accounting for the cost variables involved in mitigating (i.e. managing) the impacts of algae (de Lange et al., 2016). This process was done in close collaboration with the farmers because mitigation strategies for algae differ between farms. This variance has led to the need to derive a representative cost for a particular pollution mitigation strategy in order to represent the cost of algae across farms. Consequently, the cost impacts were structured

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[6] Johan van Stryp member of the Loskop Dam Irrigation Board (personal communication)

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according to the crop enterprise budget for each representative crop based on data obtained from Grain SA and the Citrus Grower Association and Nulandis, resulting in the estimated cost per hectare per year due to the algae pollution as R 2890 (de Lange et al., 2016).

6.3.2 Metal pollution of irrigation water

The metals (e.g., lead, copper, iron, aluminum, zinc) contained in AMD water from the upper Olifants River catchment can be present for prolonged periods of time in soil, groundwater, rivers or sediments (Maldonado et al., 2008). High concentrations of these metal pollutants have a direct impact on ecosystems and water quality, thus impacting on the environment and also potentially impacting on local communities health (Klinck et al., 2005) — excluding the adverse effects that metal pollution have on soil, surface and ground water sources.

Globally, the effects of AMD on streams AMD and metal pollution of South African rivers which results in fish mortalities have also been documented (DeNicola and Stapleton, 2002; Driescher, 2008). The Olifants River catchment in South Africa is one of the most affected river systems in the country due to mining, industrial and agricultural activities in the region. However, the large number of fish deaths during the year 2007, as well as the large number of crocodile mortalities (de Villiers and Mkwelo, 2009) associated with potential AMD and metal pollution of the Olifants River of South Africa, caused major concerns for ecosystems services and the health of local communities (Ashton et al., 2001).. This led to the founding of the 'Consortium for the Restoration of the Olifants Catchment' initiative (Van Vuuren, 2009). Despite these efforts, the exact cause for episodic fish and crocodile deaths in the river system remains unknown.

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Metals from AMD can be found in agricultural soils, which are deposited when irrigating soils are irrigated with AMD polluted water. These metals can be absorbed by the plants and then accumulate in their tissues (Trueby, 2003). Traces of metal where found inside animals that

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feed on plants that absorbed metal polluted water. During a previous study conducted in India, environmental exposure of animals to lead (Pb) culminates in the accumulation of high levels of lead in milk collected from these animals which is a serious health concern (Swarup et al., 2005). A study conducted by Alonso et al. (2000) showed that toxic metals contained in animal feed could be transferred to the animal's milk. Moreover, a study conducted by Ettinger et al. (2004a, 2004b) in Mexico City indicates that lead may be transferred to babies via mother's milk. Additionally, Ettinger et al. (2004a, 2004b) found a correlation between the level of lead contamination in the breast milk of lactating mothers and that of the corresponding blood samples of lead in infants.

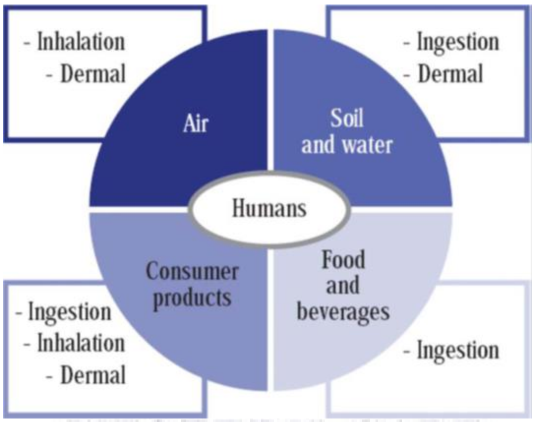

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Figure 6.2 Conceptual exposure routes of pollution from mining to humans (Source WHO, 2010).

People may be exposed to AMD pollutants either through direct ingestion of polluted water or through intake of water via dermal absorption. As shown by Figure 6.2, indirect exposure to AMD is also possible through consumption of fish caught from water sources which has been polluted by AMD or through food crops (e.g. fruits and vegetables) that have been exposed to AMD via irrigation water, or milk and meat from animals that has been exposed to AMD (e.g., drinking AMD polluted water) as illustrated by the study conducted by Ettinger et al. (2004a, 2004b).

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AMD increases the accumulation of metals in agricultural soil around mining areas or downstream of mining activities, increasing the threat to local communities due to absorption of metals by food crops (Pruvot et al., 2006). McBride (2003) reported metal absorption from contaminated soil via plant roots, as well as accumulation of contaminants from the atmosphere on the plant surfaces of crops and suggested that it may pose possible health risks to humans. McBride (2007) showed that accumulation of metals in edible plant may pose a risk to human and animal health. The presence of arsenic in soils and plants close to mining activities have been frequently reported (Wild, 1974; de Koe, 1994).

Metal pollutants can have a negative effect on crop production and growth with high levels of metals being toxic to the plants and the natural microbial soil populations associated with them (Figure 6.3). Metals induce abiotic stress on plants and adversely affect biomass production and yields in almost all major crops (Athar and Ahmad, 2002) and many have the ability to lower soil pH levels (Chunilall et al., 2005). Athar and Ahmad (2002) illustrated that metal pollution not only decreases plant growth rates (ranging from 13 % to 70 %), but also results in a lower yield of wheat (40-83 %). Furthermore, protein content of plants decreases between 19 to 71 % when exposed to different concentrations of metal pollution. Alarmingly, metals can be absorbed in relationship to the amount applied (Chunilall et al., 2005), though less when metals were added in combination, and stored in, for instance, grains (Athar and Ahmad, 2002). Previous work done by Botha et al. (2013) on crops in the Loskop irrigation region showed that AMD had an adverse effect on wheat roots due to mobilization of Al in agriculture soils. Another study by Delhaize and Ryan (1995) has shown that Al could affect root growth and development, even at low levels. The latter metal was predominant in the Loskop Dam during the current study. Solubilisation of Al increases under lower pH conditions and is thus toxic to plants (Ryan and Kochian, 1993). Athar and Ahmad (2002) observed in their study that the number of *Azotobacter chroococcum*, free-living nitrogen fixers in agriculture soil, also was

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lower with build-up of metals. A decrease of the latter of up to 84 % in the presence of Cd, and even 100 % when metals were applied in collectively, has been reported. *Azotobacter* species is favourable to agriculture crops in that it secretes anti-fungal materials, vitamins, growth promoting substances and helps with phosphate solubilisation for crops growth. These latter organisms are very sensitive to metals and can therefore be used as indicators of metal pollution.

Gorbunov et al. (2003) observed in their study that a mixture of toxic and metals [chrome, iron (Fe), nickel, (Ni), Cu, Zn, As, Cd, antimony (Sb), mercury (Hg), Pb] in agricultural products (including meat, eggs, bread, etc.) which were not only dependent on the amount of metals in the agriculture soil, but also upon the quality of the irrigation water applied as well as the processing and growing practices. The concentrations of these metals in food were also determined by their mobility, i.e. their chemical form, and the ease with which they could be absorbed by the crops. The authors concluded that if farm-lands were watered with polluted "sewage" water, a build-up in the amount of metals can be observed in the end product if the water contained metals. Chunilall et al. (2004) after studying accumulation of metals in spinach leaves showed that metals (such as Pb, Hg, Cd and Ni) were easily absorbed when grown under higher than usual concentrations. Furthermore, the authors concluded that changes in the soil environment could lead to chemical changes and more mobile forms of metals could arise.

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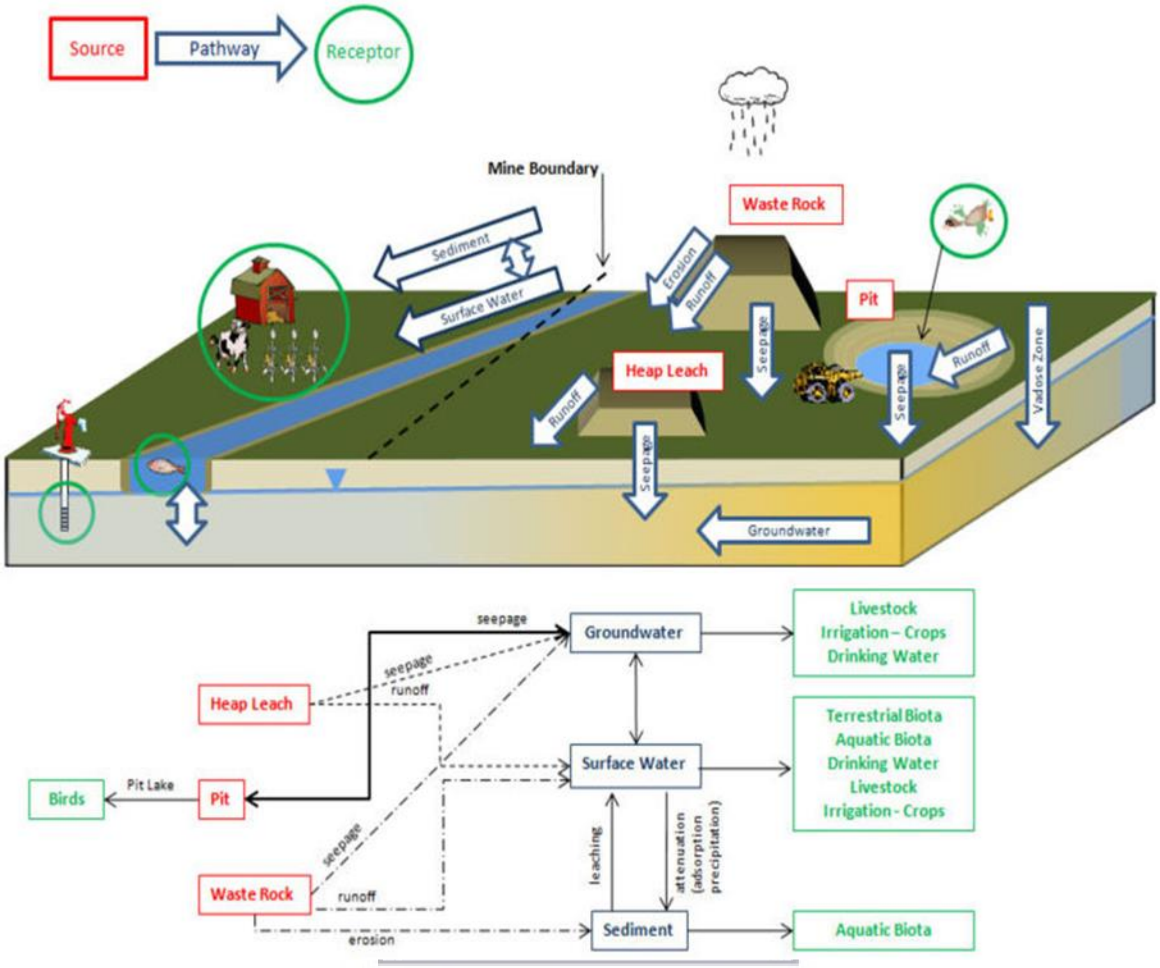

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Figure 6.3. Schematic representation of human exposure potential to acid mine drainage (Source INAP, 2010). The red boxes indicate “sources”, the blue arrows indicate “pathways” and the green circles indicate “receptors”.

6.3.3 Eco-tourism

Eco-tourism has become one of South Africa’s largest income generators. Eco-tourism has in recent years developed rapidly, and state and private game reserves have become global players attracting tourists from around the world to view the unique combination of typical African big wildlife surrounded by highly unique small animals and plant communities. It is thus

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problematic that aquatic ecosystems are also impacted by pollution, as these areas provide an important service to many nature conservation areas. In the case of Loskop Dam situated in the Loskop nature reserve, isolated incidents of fish mortality have been recorded at different times over the last two decades. These incidents have become more frequent and coincided with Nile crocodile *(Crocodylus niloticus*) deaths. The crocodile population in the Loskop Dam has declined from approximately 30 animals to a total of 6 in 2008 (Paton, 2008). Crocodile mortality in Loskop Dam during this period of time was ascribed to pansteatitis, which is associated with the intake of rancid fish fat after fish die-off, which appears to have resulted from sporadic incidents of AMD flowing into the lake causing fish mortalities (Paton, 2008).

The lack of continuous assessment of surface waters for the appearance of cyanobacterial blooms, as well as the limnological drivers behind the development of cyanobacterial blooms in national parks poses another major problem. Death of wildlife due to cyanobacteria has a negative impact on the growing economy of South Africa, as ecotourism relies on wildlife (i.e. game farming) as the main tourist attraction. This is especially so in semi-rural areas like the Loskop Dam where local communities rely heavily on the game park for job opportunities or to sell their handcraft to tourists locally and from abroad for a sustainable livelihood.

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Cyanobacterial blooms, as in the case of Loskop Dam, spoil the aesthetic aspects of the dam by imparting tainted and unpleasant odours in affected waters as the cells of bloom lyses or if it is later windrowed at dam edges. The occurrence of massive cyanobacterial blooms causes depletion of dissolved oxygen contents resulting in fish kills, and the surrounding water may be discoloured by the release of pigments from lyses cells. Compounds such as geosmin and 2MIB, that cause taste and odour problems in drinking waters have been either directly or indirectly associated with cyanobacteria. These compounds may also affect the flavour of fish, since fish tissues readily absorb off-flavours from water, this can prevent the fish from being marketable with serious commercial consequences (Wnorowki, 1992).

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6.4 Drivers causing social economic impacts

6.4.1 Mining

Although coal mining can bring economic benefits by stimulating the local economy of the upper Olifants River catchment and creating more employment opportunities in this region, it can also have adverse effects on the aquatic ecosystems of Loskop Dam. Coal mining has the potential to affect and disturb water ecosystems throughout the life cycle of a mining operation, by point and nonpoint source pollution. Impacts of direct water pollution can result from any activities that involve direct discharges into water bodies such as riverine tailings or tailing impoundment releases or AMD from abandoned mines (Ashton et al., 2001). Indirect pollution can result from activities associated with mining operation, such as land clearance. The abundance of coal in the upper Olifants River gives way to the construction of 12 electrical-generating power stations. Consequently, the mining of the Witbank coalfield's coal also culminates into the development of industrial, agriculture and mining activities in the vicinity of the towns of Witbank and Middelburg. These developments have therefore turned the Highveld region into a major economic hub, with the Olifants River catchment alone contributing just over 5% of the gross domestic product (GDP) of SA (Driescher, 2008).

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6.4.2 Sewage

Eutrophication is the natural ageing process of dams, and is characterized by a geologically slow shift from in–dam biological production driven by allochthonous loading of nutrients, to production driven by autochthonous processes. It typically is a slow process that happens over centuries but can be greatly accelerated to within decades by human intervention in the natural biogeochemical cycling of nutrients within a watershed (Rast and Thornton, 1996). Eutrophication is mainly caused by the addition of nutrients from human activities, and in this

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context it is known as “anthropogenic eutrophication” (van Ginkel, 2011). This phenomenon is generally the consequence of release from large sewage systems associated with major metropolitan areas (Pitois et al., 2001). A previous study by Dabrowski (2014) applying the SWAT (soil and water assessment tool) to predict ortho-phosphate loads in the upper Olifants catchment, showed that poorly operating waste water treatment plants (WWTPs) were the major contributors to catchment nutrient enrichment. In the upper Olifants catchment, large numbers of WWTPs are not operated optimally and didn’t meet the requirements as detailed in the National Green Drop (GD) Report of 2010 (DWA, 2010; Oberholster et al., 2013). Most of the WWTPs in the region had an overall score of less than 30%, indicating that they are dysfunctional and in a critical condition. Previous assessments of individual river basins around the world have found that up to 50% to 90% of annual nutrient inputs in river systems originates from WWTP. Eutrophication is a natural process which takes centuries to occur, but the fact that Loskop Dam only took 18 years (1938 – 1956) for its transformation from oligotrophy to meso-eutrophic status strongly suggested that such process had been catalysed and exacerbated by anthropogenic activities (Kruger, 1968).

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6.4.3 Acid precipitation

The electricity supply sector plays a pivotal role in the South African economy and there is a high concentration of coal-fired power plants in and adjacent to the study area. Large volumes of atmospheric emissions from these power plants (as well as associated industries in the area) and favourable local atmospheric conditions result in relatively high deposition levels of oxides of sulphur and nitrogen.

The upper Olifants River catchment is furthermore the most urbanised region of the whole catchment with the majority of the urban population located in the industrial city of Witbank

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and the town of Middelburg. In the city of Witbank, industrial activities are totally based upon coal mining, coal combustion power plants, smelters and several industries using coal as energy. Jossipovic et al. (2011) showed that due to the concentration of large portions of the industrial infrastructure on the Highveld plateau, which include the upper Olifants River catchment, approximately 90% of South Africa's scheduled emissions of industrial dust, sulphur dioxide and nitrogen oxides is produced in this region (Figure 6.4).

Usually, atmospheric precipitation provides a dilution effect on contaminants within the river system. However, when air pollutants occur in high concentrations from, for example coal fired power stations, industrial activities and smelters, it can dissolve in atmospheric moisture and deceases pH thereof, thereby adding to the water pollution problem in a system. Wang et al. (2008) classifies "acid rain" as wet atmospheric deposition that has a pH of less than 5.6. Atmospheric precipitation is however naturally acidic since atmospheric carbon dioxide dissolves in moisture to form carbonic acid (H_2CO_3) this could result in uncontaminated rainwater having a pH of as low as 5.0 (Schindler, 1988). During rain runoff, this weak carbonic acid dissolves minerals from geologic substrates it interacts with, thereby liberating minerals for plant uptake (Wang, 2008). Though small amounts of nitrous oxides can be attributed to lightning storms (Levine et al., 1984), large amounts of contaminants like sulphur dioxide (SO^2) and nitrous oxides (NOx) are released during fossil fuel combustion (Wang et al., 2008). When these substances come in contact with moisture, two strong acids, sulphuric and nitric acid are produced. Not only can these acids cause severe damage to infrastructure, but they can also release toxic metals that are only soluble at lower pH levels, thereby leading to increased metal toxicity within the river system. However, it can be difficult to distinguish between the different causes of acidification in a river system on a catchment scale if the main drivers for acidification in the system are both AMD and acid rain.

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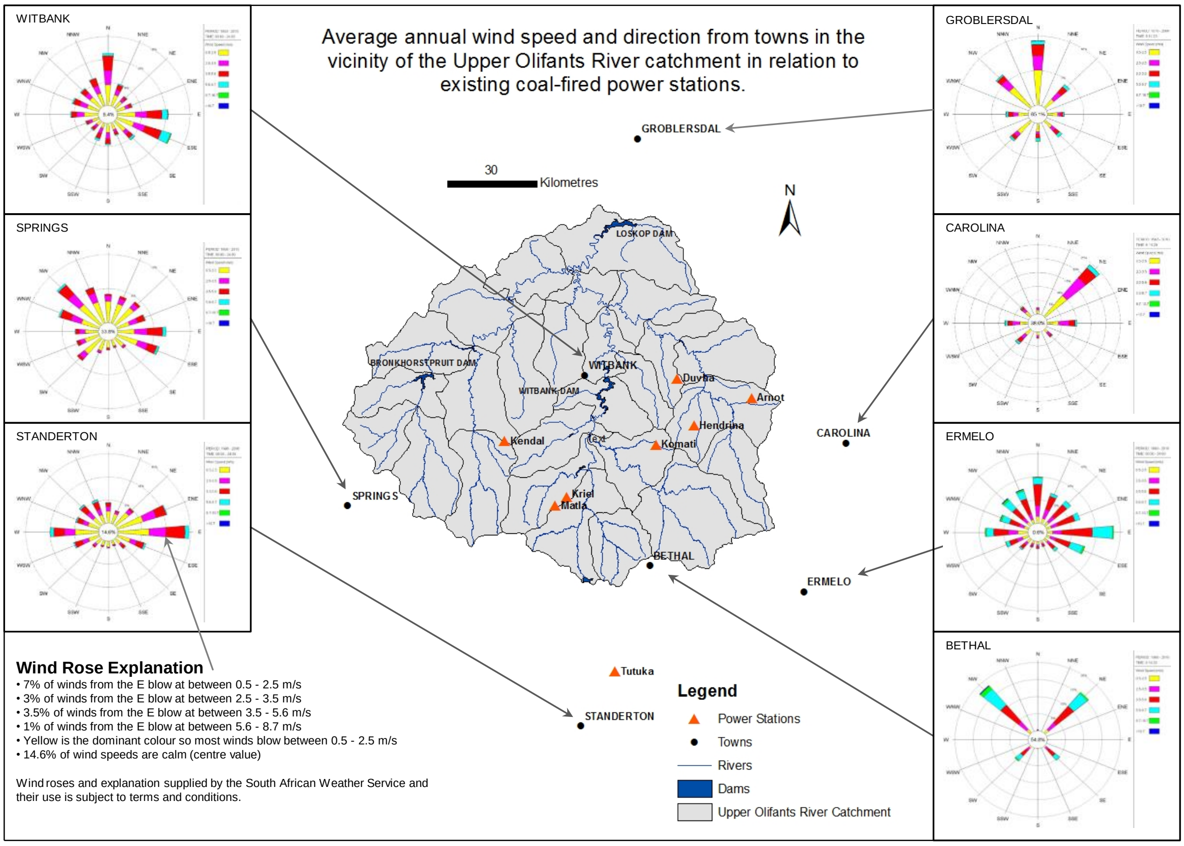

Wind Rose Explanation

- 7% of winds from the E blow at between 0.5 - 2.5 m/s
- 3% of winds from the E blow at between 2.5 - 3.5 m/s
- 3.5% of winds from the E blow at between 3.5 - 5.6 m/s
- 1% of winds from the E blow at between 5.6 - 8.7 m/s
- Yellow is the dominant colour so most winds blow between 0.5 - 2.5 m/s
- 14.6% of wind speeds are calm (centre value)

Wind roses and explanation supplied by the South African Weather Service and their use is subject to terms and conditions.

Figure 6.4 Dominant wind directions in the study area.

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6.5 Regulation

The upper Olifants River catchment includes the Olifants River and its major tributaries, the Klein Olifants and the Wilge Rivers. According to DWAF (2007), the Olifants River is of low ecological importance and sensitivity; which means that a large loss of natural habitat, biota and basic ecosystem functions has occurred. This water resource is highly polluted to a point of failing to adequately support its ecological functions (DWAF, 2007). In spite of efforts by the Department of Water Affairs and Sanitation (DWS) to manage the Olifants River; the water quality of this catchment continues to decline (DWAF 2007). The overarching legal framework for wastewater services regulation is embedded in the Constitution of South Africa (Act 108

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of 1996) being the highest legislation (Ntombela et al., 2016). Additionally, a combined effort of the Constitution, the Municipal Structure Act (Act 117 of 1998) and the Water Services Act (Act 108 of 1997), allocated the responsibility for the delivery of wastewater services to the local sphere of government (i.e., local municipalities) (RSA, 1998; RSA 1997). The regulation of wastewater services is the responsibility of the national sphere of government and therefore resides with DWS (RSA, 1998).

6.5.1 Local municipality and sewage pollution

In response to the deteriorated quality of water, DWS has initiated the Blue Drop and Green Drop certification scheme, to assist in the monitoring and regulation of drinking water quality, as well as in the management of wastewater to ensure that the requirement of the regulation program is met (Barradas, 2011). In 2011, the Blue Drop Scheme assessment showed that Gauteng and Western Cape have the highest scores (95.1% and 94.1% respectively), indicating good tap water quality in these areas as compared to other areas such as the Eastern Cape, Mpumalanga and North West (Barradas, 2011). In the Green Drop assessment, it was observed that the bulk of Free State municipalities did not meet the requirement of the regulation program (Barradas, 2011), which implies that millions of litres of untreated or poorly treated sewage were being discharged into rivers and streams each day, which affects usable water availability. Despite the fact that municipalities have sound policies aiming to tackle water issues in the country, these are not implemented at a practical level (Barradas, 2011). This not noncompliance not only puts the national water supply system in jeopardy, but also hinders the economic growth of South Africa (Oberholster and Ashton, 2008).

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6.5.2 Green Drop Program

Water service authorities (WSA's) are responsible for the provision of water services to customers located inside their respective areas of jurisdiction in South Africa (RSA, 1997).

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These services include the management of domestic wastewater treatment works (WWTWs) and sewage disposal systems (Ntombela et al., 2016). Currently, South Africa’s wastewater services are provided by a total of 152 WSA’s, which oversee the running of 824 wastewater collectors and treatment facilities (Ntombela et al., 2016). A total of 70% of the country’s WWTWs fall into the category of micro-, small- or medium sized (DWS, 2012). As knowledge and equipment required for operation of WWTWs are often very expensive, many of them fail. In fact, most of the sewage in South Africa’s urban areas, especially small towns and heavily populated areas is inadequately treated before discharge as a result of incomplete or non-functional WWTWs (Oberholster et al, 2010). As such, poor and insufficient wastewater treatment is a main contributing factor to South Africa’s water pollution problems.

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The Green Drop Program was initiated in 2008, and was aimed at being an incentive-based program to enable fulfillment of regulatory objectives and standards through inspiration and reward rather than direct regulation, rather than a command-and-control type program (Ntombela et al., 2016). Additionally, since 2013, DWS runs the Green Drop water services audit, which is a tool to conduct incentive- and risk-based regulation in South Africa. The programmes’ main focus is to measure and compare the performances of the different WSA’s, and to allocate incentives or penalize the WSA’s based on the findings of DWS. The findings are based on meeting of minimum standards or requirements set by DWS where after an evaluated Green Drop score for each municipal WWTW and the accumulative risk rating for each municipal WWTW were given (DWS, 2013). WSA’s that scored 90% and more was given a Green Drop certification, while those that scored 30% and below received a Purple drop symbolising poor condition.

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6.5.2.1 Success of Green Drop program

Despite many failures, the Green Drop Program had some success by raising awareness regarding the need for improved performances throughout the wastewater sector by recognising and accepting problem cases, and introducing procedures to address these. Before the Green Drop Program was implemented there was no measure to verify the condition of wastewater treatment in South Africa (Ntombela et al., 2016). The cumulative risk rating analysis showed there was an improvement in wastewater services from 2011 to 2013, with the underperforming WWTPs (scoring percentages of 30% and below) dropping from 154 to 121 during 2012 and 2013 (DWS, 2013).

6.5.2.2 Problems facing the Green Drop Programme

The Green Drop report of 2013 indicated that even though 50.4% of WWTWs scored more than 50% in 2012 and 2013, almost the same number of WWTWs (49.6% or 409) still scored below 50% (DWS, 2013). Reasons for underperformance include lack of management and implementation skills, inadequate knowledge, insufficient human resources and budgetary constraints, as well as incidences of theft, misuse, and vandalism at WWTWs, especially in the rural areas such as the province of Mpumalanga where the current study is situated (Ntombela et al., 2016). Additionally, a complete lack or insufficient long-term planning makes it challenging to continue with wastewater services. Some local municipalities are even unable to plan the budget for any events one year in advance. Also, maintenance of WWTWs are generally not directed at preventative basis but rather on a reactive basis.

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Another challenge facing the Green Drop Program is the ability of municipalities to acquire goods and services. The Municipal Finance Management Act (Act No. 5 of 2003) was not modified to reflect the current cost of WWTW maintenance and repair, which implies that only limited funds are allocated to repair WWTWs and most of the costs have increased over the

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past years (Ntombela et al., 2016). Adding to this is the ever-changing and high standards set by the Green Drop Program. Because of these high standards and maintenance problems, municipalities often dose the water with chlorine to meet the standards (Ntombela et al., 2016).

6.6 Mining regulation

The South African mining, environmental and water legislation and related regulations were completely rewritten after the transfer of power in 1994. Also, the requirements associated with water, mining, environment, and waste as suggested in the various Acts and Regulations have changed over the years (Mey and Van Niekerk, 2009). The first mining-related legislation focusing on environmental protection on mines was the Minerals Act (Act No. 50 of 1991). This Act had specific requirements for the environmental management on mines and was known as the Environmental Management Program Reports (EMPR). The EMPR had to approve any form of mining practices. Furthermore, the Department of Minerals and Energy also needed confirmation by other Government Department before approval, which culminated in the establishment of the mine water balance and mine water management plan (Mey and Van Niekerk, 2009).

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This Minerals Act of 1991 was replaced by the Minerals and Petroleum Resources Development Act No. 28 of 2002 (MPRDA), which also required a broad Environmental Management Plan (EMP) (Mey and Van Niekerk, 2009). The MPRDA stipulated the need for public participation during the development of an EMP. An additional requirement stipulates a post closure plan that needed consideration during the EMP process, as without any post closure plan it would be impossible to gain mining authorisation.

The main focus of the Department of Water and Environmental Affairs, now the Department of Water and Sanitation, was during the 1990's to control pollution and manage point sources pollution generated from mining activities. The establishment of the National Water Act 36 of

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1998 (NWA) (RSA, 1998) lead to the national resource management being given a new legal basis. Water usage of all types was issued with license by regulators to regulate their water usage (RSA, 1998). The National Environmental Management Act (NEMA) stipulated the needed actions required for Basic Assessment and full Environmental Impact Assessments, and both entailed the support of public participation and stakeholder consultation process.

6.7 Opencast mining and mine management

The impact that mining has on the environment depends mostly on the geology, climate and other conditions; one of these conditions is the amount of water. The mining activities tend to affect the hydrological and topographical characteristics of the mining areas. In the Mpumalanga province coal region, opencast mining is most commonly used mining method of extracting coal (Mey and Van Niekerk, 2009). During opencast mining operations, the main aim of water management is to limit the amount of water that comes into contact with the mining operation. This is done through the creation of cut-off trenches and collection dams upslope of the mine working to prevent unsoiled water from entering the mine. Despite these measures, the possibility of water that comes into contact with the coal seam during the mining proses or with waste rocks and soil still exists; with rainfall, groundwater seepage, and run-off, and seepage from the spoils, the major contributing amount of water Therefore, the condition of post mining rehabilitation is the key driver in the long-term for water level management (Mey and Van Niekerk, 2009).

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Mine water management is implemented through the following methods: rehabilitation and inclining of disturbed surfaces; storage of water in underground, opencast mine works or constructed surface dams; making use of mine water in coal beneficiation and mine waste transportation to disposal site; separating of clean and dirty water to additional diminish level of impacted water; implementing of better surface rehabilitated practices; free drainage of

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rehabilitated and disturbed areas; and using mine water as irrigation source to improve the rehabilitation of vegetation (Mey and Van Niekerk, 2009).

In addition, solutions to water management are offered by progression in mine water treatment technology such as desalination, be it through pre-treatment before desalination, or polishing treatment after desalination. The two broad categories of mine water desalination treatments based on different technologies that are being applied are the following: Biological Sulphate Remove ensued by polishing treatment and membrane based desalination treatment (Mey and Van Niekerk, 2009). Although there have been numerous other desalination processes such as the Ettringite process (chemical precipitation based process), Sparro process (seeded slurry membrane based process), Gypcix process (ion exchange based desalination process), and Barium carbonate process (chemical precipitation based process). Out of these, the preferred method of recovering high quality product water remains the membrane-based mine water desalination method.

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Water treatment still faces some challenges due to the handling and disposal of sludge and brines created by treatment practices. One such treatment plant is the Emalahleni water reclamation plant. Weaknesses of the plant include; (1) build-up of brine as by product, (2) use of sodium hypochlorite to clear UF membranes from algae built up, (3) clogging of green sand filters, (4) periodic failure of feed pumps, (5) periodic difficulties in optimizing the clarifier performance with changes in plant condition, and (6) currently the plant is being restricted by the ability to remove the 200 tons/day sludge being produced. Lastly, an additional economic burden is the number of operators (35) and intensive skills required to operate the plant on a daily bases as the plant requires constant qualified care and monitoring to keep it fully operational.

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CHAPTER 7

Conclusion

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Water supplied from the Loskop Dam, located in the Mpumalanga Province, is important to the socioeconomic well-being of large farming communities in the Groblersdal and Marble Hall districts. However, the upper Olifants River that feeds into the dam has been described as one of the most polluted rivers in South Africa. The anthropogenic pollutants originate from several land-use activities such as mining, industry, agriculture and urbanization in the upper Olifants River catchment. It was evident from the study that *Microcystis aeruginosa*, *Ceratium hirundinella*, and *Melosira varians* were the most resilient phytoplankton species to pollution conditions. Furthermore, the current study showed that the pollution index (*PILD*) can effectively be used to determine the environmental conditions of Loskop Dam. From the study it was apparent that phytoplankton species responded differently towards changes in environmental conditions of Loskop Dam during certain periods of the year. These conditions include high levels of metal ions and other elements. TP levels were higher than the Australia and New Zealand guidelines. The average pH values of the water column of Loskop Dam over the 12-month sampling period range between 7.0 and 8.0. Variation in electric connectivity (EC) concentrations was observed throughout the study period from January 2016 to December 2016. However, EC concentrations increase during lake overturn (i.e., temperature induced water column mixing) in March to 46.5 mS/m. During the months that follow there was a steady incline with some fluctuations in EC level with the month of July having an EC concentration of 52.7 mS/m, while the highest EC (63.5mS/m) was measured during December 2016. The total phosphates concentration was the highest during the month of October (0.13 mg l^{-1}) when there was a shift towards late spring early summer with lake overturn. Although aluminum (Al) and iron (Fe) concentrations remained high throughout the study period, the highest concentrations were however recorded during lake-overturn periods in May (Al 0.05 mg l^{-1} and Fe 0.2 mg l^{-1}) and October (Al 0.05 mg l^{-1} and Fe 16 mg l^{-1}). The maximum

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concentrations of Al and Fe detected at the sampling sites were higher than that allowed by the South African Water Quality Guideline values for Al (≤ 5 µg l^{-1}) and Fe (< 100 µg l^{-1}) for domestic water consumption and aquatic ecosystems. The latter Al and Fe concentrations can possibly be contributed to AMD inflow from mining activities in the upper catchment of Loskop Dam. The water column environmental conditions observed in the dam during the 12-month study period can pose a risk for the social and economic activities downstream from Loskop Dam, which include the second largest irrigation scheme (Loskop Dam irrigation scheme) in South Africa. The pollution index (*PILD*) further showed that the environmental conditions of the dam was poor during the year of 2016, with the months of September, August, and October being classified is severely polluted. Each of these months displayed low levels of phytoplankton species diversity, meaning only a few phytoplankton species were pollution tolerant.

The majority of commercial farmers downstream of the Loskop Dam make use of irrigation canal water to irrigate their crops. As these canal water supplies may contain cyanobacterial cells, exposure to cyanobacterial toxins which can accumulate in plant tissues exists. Measured levels of microcystin-LR concentrations in both irrigation canals, did not exceed the safety limit (1.0 µg l^{-1}) set by the World Health Organization for drinking water. It was evident that the method of irrigation water withdrawal (i.e., from the upper-hypolimnia) of Loskop Dam prevent *Microcystis aeruginosa* cells that usually occurs in the epilimnon layer of the dam to end up in the downstream irrigation canals. However during the lake overturn period when all the water column layers mixed in the dam due to temperature variation, *Microcystis aeruginosa* cells can end up in the irrigation canals. Although lake overturn cannot always be predicted, since it is strongly related to climatic conditions, the following management practises can be put in place by (a) reducing the use of copper sulfate during lake overturn periods to reduce filamentous algalge growth in irrigation canals. The use of the latter chemical can cause the die

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off of *Microcystis* cells and the release of large concentrations of external cellular microcystin, (b) test leafy crop produce for signs of MCs concentrations when *microscystis* cells are present; and (c) protect farm workers from exposure to water containing MCs concentrations. It is also recommended that a cyanobacterial toxicity monitoring program is set in place and test irrigation balance dam for MCs concentrations during lake overturn periods.

Finally, findings from the study on Loskop Dam and the irrigation canals reveal that external factors like mining (AMD), nutrient enrichment (Eutrophication) and acid precipitation, which collectively contribute towards pollution of the upper Olifants River catchment, imposed a risk to the socioeconomic wellbeing of the local community downstream of Loskop Dam. The agricultural sector in the Loskop region is characterised by high value irrigated crops that make a substantial contribution to the regional economies and to the total export value of the agricultural sector. The total economic output of the region is approximately R1 billion, of which exports towards the European Union contributes most. Pollution in the upper Olifants River and the associated water quality problems can have a direct negative impact on the farming communities and the export markets. Additionally, the agricultural sector plays a key role in supporting local communities, including farmworkers who depend on the wealth produced for their livelihood in this region. Job losses due to poor water quality could have an impact on the total supply chain. This could be devastating in a region already ravaged by unemployment.

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Despite the development of numerous policy documents (e.g. National Environmental Management Waste Act, National Water Act) for both mining (Mineral and Petroleum Resources Development Act) and WWTWs (Green Drop Program) to manage and regulate the flow of pollutants into waters sources, their implication was only partly successful. The sustainability of Loskop Dam is crucial for this region because it not only provides water for 624 farms with irrigation water, but also to nearby towns like Groblersdal and Marble Hall.

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Collectively, major research findings from the current study revealed the following:

(i) From the pollution index it was evident that the water quality from Loskop Dam range from slightly to highly contaminated over the 12 month study period. Although the water quality falls within the set values of the South African Water Quality Guideline for most of the time, the lake overturn periods in May and October month were problematic. Water in the Loskop Dam irrigation scheme are still of good quality despite the high levels of pollution in the upper Olifants River catchment. The Loskop Irrigation Board therefore fulfil their mandate by providing stakeholders with irrigation water that falls within the set values of the South African Water Quality Guideline;

(ii) Measured levels of microcystin-LR concentrations in both irrigation canals, did not exceed the safety limit (1.0 µg l^{-1}) set by the World Health Organization for drinking;

(iii) Improved implementation of regulation measures relating to AMD and WWTW sewage inflow is imperative, and should be prioritise to end the inflow of pollutants into waters sources as these posed risk to the socioeconomic well-being of communities living downstream of Loskop Dam.

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From the findings of the study the following recommendations can be made:

(i) Implementation of the Pollution Index (LPI) by the Loskop Irrigation Board to assist with the management of the water quality in the canals;

(ii) Catchment management plans must focus on lowering phosphorus inputs by improving the performance of WWTWs, while solutions to the inflow of mine-water contamination from abandoned and working coal mines should be prioritised. As both these pose a risk to the socioeconomic well-being of stakeholders downstream of Loskop Dam.

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Appendix

Appendix 1. Composition of the different algae in the Loskop Dam over the study period. Where + = rare, + + =scarce, + + + = common, + + + + = abundant, + + + + + = predominant.

Division	Major species	Loskop Dam
Chrysophyta		
Chrysophyceae	*Dinobryon divergence*	+
Bacillariophyceae	*Cocconeis pediculus*	
	Craticula cuspidate	
	Cyclotella meneghiniana	+
	Diatoma vulgaris	+
	Flagilaria ulna	+
	Flagilaria crotenesis	+ ++
	Nitzschia intermedia	+
	Nitzschia umbonate	
	Nitzschia pura	
	Gyrosigma Rautenbachia	+ +
	Pinnularia viridiformus	+
	Pinnularia subcapitata	
	Surirella ovalis	
	Synedra ulna	+ +
	Melosira varians	+ ++
	Stephanodiscus hantzchii	+
	Eunotia formica	+
	Asterionella Formosa	+ ++
Pyrrhophyta		

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Dinophyceae	*Peridinium bipes*	+ ++
	Ceratium hirundinella	+ ++++
Chlorophyta		
Conjugatophyceae	*Closterium polystictum*	+ ++
	Closterium stellenboschense	+
	Spondylosium sp.	
	Cosmarium pseudopraemorsium	+ ++++
Chlorophyceae (Cladophorales)	*Cladophora glomerate*	
Chlorophyceae (Oedogoniales)	*Oedogonium crissum*	
Chlorophyceae (Chlorococcales)	*Scenedesmus armatus*	+ +
	Oocystis rupestris	+ +
	Sraurastrum anatinum	+ +
Euglenophyta		
Euglenophyceae	*Trachelomonas intermedia*	+ +
	Phacus pleuronectes	+
Cyanophyta		
Oscillatoriaceae	*Oscillatoria limosa*	+

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Appendix 2: Questionnaire (based on the structure of the Loskop Dam Irrigation Board)

1. What is the structure of the Loskop Dam Irrigation Board?
2. Who are the main stakeholders?
3. What type of work does the Loskop Dam Irrigation Board?

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