Determining attainable ecological quality requirements for the Upper Wonderfonteinspruit Catchment, based on human community requirements: The case of Bekkersdal

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Summary

In order for an economy to survive and thrive it requires resources. Water is a resource that not only the economy is dependent on but also ecological and human communities. The deteriorated state of South African rivers suggests the intensive use of the country's freshwater reserves by the population and industry. Such a source of freshwater is the Wonderfonteinspruit. It flows through an area that requires water for gold mining that has taken place in the area for more than 120 years. Furthermore, the Wonderfonteinspruit runs past communities such as Bekkersdal and eventually forms part of the source waters for the Boskop Dam, the main drinking water reservoir for Potchefstroom.

Literature suggests that the Wonderfonteinspruit is impacted by anthropogenic activities, in particular impacts associated with both historical and current gold mining activities. The Wonderfonteinspruit has its origin in the Tudor Dam in Krugersdorp (now Mogale City), and then flows into Donaldson Dam from where it is piped in a 32 km long pipeline, before its confluence with the Mooi River which subsequently flows into the Boskop Dam. The study area specifically focuses on the Upper Wonderfonteinspruit from just downstream of the Donaldson Dam to just upstream of the dam. The study area was selected due to the close proximity of the Donaldson Dam to the community of Bekkersdal which formed the second part of the investigation for this thesis.

Bekkersdal is primarily a mining community that has historically faced issues with sufficient land provision, housing, unemployment and service delivery. It is located in the Gauteng Province and falls under the jurisdiction of Westonaria Local Municipality. Recent protests by community members have occurred due to the lack of service delivery and inappropriate development of infrastructure with regards to water services. Due to the close proximity of Bekkersdal to the Wonderfonteinspruit (as it is situated on the border of the Donaldson Dam) the community provided an ideal study area to explore the use of the river by the community.

In order to determine the relationship between the Wonderfonteinspruit and the community of Bekkersdal the study comprised two parts: during the first part of the study, the ecological state of the Wonderfonteinspruit was determined through the evaluation of the quality of water, sediment and biota within the river; while in the second part an assessment of Bekkersdal (both formal and informal sections) was undertaken through the use of questionnaires in order to determine past, current and future water use of both municipal water and water sourced from the Wonderfonteinspruit. The final outcomes of both the environmental and social assessments were then compared with national and international standards.

Water quality assessment of the Wonderfonteinspruit was done by assessing the following:

- *in situ* water quality parameters (such as pH, total dissolved solids and dissolved oxygen)
- metal and ionic composition analysis of water samples using inductively coupled plasma mass spectrophotometry (ICP-MS)
- nutrient loads using a spectrophotometer and Spectroquant® test kits
- bacteriological quality by determining presence of total coliforms and faecal coliforms through the growth of bacterial cultures on M-ENDO and m-FC agar plates
- the Physico-chemical Driver Assessment Index (PAI) was applied according to DWAF 2008
- statistical relevance between sites and results through principal component analysis (PCA)

Finally, these results, where applicable, were compared to both national and international standards for human and ecological use.

The results indicated that the water quality levels exceeded the guideline values of national and international standards for the following uses: drinking water, certain industrial activities, watering of certain livestock and crop types as well as aquaculture. It was also found that the water quality was acceptable for certain activities (e.g. recreation) only if precautions and further analysis are performed. The guideline values of national water quality standards for ecological status were also exceeded, while the PAI results indicated that the ecological category (EC) for the Wonderfonteinspruit is a D which indicates that the state of the water quality in terms of the ecology is fair.

The sediment quality of the Wonderfonteinspruit was determined by ICP-MS. The metal composition of the sediment was compared to that of other rivers and the following indices were applied: enrichment factor (EF), contamination factor (CF), pollution load index (PLI) and geo-accumulation index (I_{geo}). It was found that the sediment composition is comparable to that of other rivers impacted by gold mining and that uranium, cobalt and nickel enriched the sediment according to the indices.

Biotic indicators that were assessed included fish, diatoms and invertebrates. The fish health assessment index (HAI) was applied to fish caught in the Donaldson Dam. The muscle tissue was also removed and its metal concentration was determined by ICP-MS. Thereafter, the edibility of the fish muscle tissue was determined and the following indices were applied: condition factor (CF), hepatosomatic index (HSI), gonadosomatic index (GSI) and spleen somatic index (SSI). The diatom community composition was assessed by applying the Biological Diatom Index (BDI), Specific Pollution Sensitivity Index (SPI) and the percentage pollution tolerant valves (%PTV). The Macroinvertebrate Response Assessment

Index (MIRAI) was applied in order to determine the state of the macroinvertebrate community.

The fish assessment indicated that arsenic contamination may negatively impact the health of consumers. Diatom indices indicated that the EC of the Wonderfonteinspruit is a D/E which indicates poor water quality; likewise, this is supported by the MIRAI results as the EC for MIRAI was a D which indicates that the river is largely modified.

The investigation into the water use of the Bekkersdal community, with a special focus on the use of the Wonderfonteinspruit, was achieved through the use of questionnaires that were distributed in both formal and informal sections in Bekkersdal. The research forms part of a larger Integrative Multidisciplinary study and was given ethical clearance under the NRF Community Engagement Project (see Ethical Clearance: no. FH-BE-2013-0014. The National Research Fund (NRF) provided the funding for the research, the views expressed is that of the author and not those of the NRF.

The aim of the questionnaire was to determine the following aspects in terms of the community of Bekkersdal:

- Demographic details, such as language preference, employment status and age distribution.
- Current water use practices .
- Use of the Wonderfonteinspruit.
- Future water use of the Wonderfonteinspruit.
- Water quality perceptions of the Wonderfonteinspruit.
- Field notes that included any relevant observations of the fieldworkers.

The unemployment rate of the Bekkersdal community was found to be high (78.20%) and 86.40% of the residents are South African citizens. The community relies heavily on municipal provision of sources of water with 100% of the respondents indicating that it is their primary source of water. However, several issues were identified in terms of municipal water supply in the community. Some 10.14% of the residents indicated that they make regular use of the Wonderfonteinspruit (in particular the Donaldson Dam) most often for drinking water, laundry and washing of cars, etc. Regarding the state of the Wonderfonteinspruit, the overall viewpoint of the Bekkersdal community was that it is largely polluted with sewage, litter and mining waste. However, some 87.80% of the residents expressed their willingness to participate in environmental clean-up initiatives in their area.

The link between the ecological state of the Wonderfonteinspruit and human health and wellbeing was explored through the use of spider diagrams where rank scores were assigned to both index results and human water quality use categories. These were compared and it was found that ecological indicators are more sensitive than human water quality use scores and therefore can aid in acting as early detection indicators of possible negative impacts on human health and wellbeing.

Key words:
Community, water, environment, water management, biotic indices, human health

HSI: hepatosomatic index

ICP-MS: Inductively coupled plasma mass spectrophotometry

I_{geo}: geo-accumulation index

MIRAI: Macroinvertebrate Response Assessment Index

MPRDA: Mineral and Petroleum Resources Development Act

NEMA: National Environmental Management Act

NGO: non-governmental organisation

NRF: National Research Fund

NTU: nephelometric turbidity units

NWA: National Water Act No. 36 of 1998

NWU: North-West University

PAI: Physico-chemical Driver Assessment Index

PCA: principal component analysis

PEC: probable effect concentration

PES: present ecological state

PLI: Pollution Load Index

%PTV: percentage pollution tolerant valves

QRB: Quesnel River Basin

r: Pearson's correlation coefficient

RDA: redundancy analysis

R-DRAM: Rapid-Diatom Riverine Assessment Method

SABS: South African Bureau of Standards

SADI: South African Diatom Index

SALGA: South African Local Government Association

SANS: South African National Standard

SAR: sodium absorption rate

SEM: scanning electron microscope

SPI: Specific Pollution Sensitivity Index

SQG: sediment quality guidelines

SSI: splenosomatic index

TDS: total dissolved solids

TEC: threshold effect concentration

TWQR: Target Water Quality Range

UNICEF: United Nations Children's Fund

USEPA: United States Environmental Protection Agency

WHO: World Health Organization

WLM: Westonaria Local Municipality

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1. General Introduction

1.1. Problem statement and background information

1.1.1. The state of water resources and water service provision in South Africa

Freshwater is considered to be a limiting natural resource in South Africa (van Ginkel 2011). The mean annual runoff is only 8.6% (Opperman 2008) and 54% of South Africa's main river systems are considered critically endangered (Nel et al. 2007). The concern regarding the use of South Africa's water resources is increased by the lack of monitoring and decline in monitoring systems since the 1980s, despite the significant increase in water use. As an example, the number of useful rain gauges has declined from a peak in the 1970s (>2 000 rain gauges) to less than 1 000 gauges in 2004 which is roughly equal to the total number of rain gauges in 1920 (Pitman 2011).

Media and researchers recently reported on the increasing number of protests pertaining to water service delivery (Karamoko 2011; de Waal 2012; Bega 2014; Powell et al. 2014). Furthermore, in the National Water Resource Strategy (2013) government emphasises the absolute centrality of water to upholding human rights and the need for water of a sufficient quantity and quality to provide for socio-economic development that is both sustainable and equitable (DWA 2013a). Yet, in achieving these outcomes other complexities arise.

1.1.2. Quality water a growing challenge

The water resource issues within South Africa are not only related to quantity but are also associated with quality. Many human activities rely on the use of water for processes and the subsequent disposal of wastewater. Current water quality problems that are considered to be most challenging include: acid mine drainage (AMD), salinization, eutrophication and faecal pollution (Coetzee et al. 2006; Winde 2010a; DWA 2012).

Acid mine drainage (AMD) and salinization

South Africa's mineral resources are plentiful, providing a plethora of opportunities for economic development (Gu 2011; Norgate and Haque 2012; Bambas-Nolen 2013). Gold mining in particular has provided the backbone for economic development and the mining of numerous minerals has further resulted in the economic upliftment of South Africa (Manders et al. 2009). However, prolonged mining in the country has also resulted in several adverse effects, both environmentally and socially (Bambas-Nolen et al. 2013). Gold mining has been operational in South Africa for over 120 years and has been active in the West Rand since 1887 (Macnab 1987; Oxley 1989; van Eeden 1994). The negative side of the legacy imposed by mining has become a growing concern, both for present and future generations (Coetzee et al. 2006; Council for Geoscience 2010; Kardas-Nelson 2010; Bambas-Nolen et al. 2013; Moodley 2014). In particular, local communities have been left with the residue footprint of gold mining operations with limited job opportunities available because of the downscaling being experienced in the gold mining sector in South Africa (Nicol and Leger 2011).

Mining places considerable pressure on water resources, through both direct and indirect use (e.g. energy generation). A trend has been noted whereby large amounts of water have been rendered non-potable due to pollution originating from mines (Manders et al. 2009). In 1989 it was estimated that some 19 300 km of streams and rivers globally were seriously impacted by mine effluents (Hallberg and Johnson 2005). One of the foremost impacts of gold and coal mining is acid mine drainage (AMD), and it is estimated that some 350 ML/day of AMD is released in the Witwatersrand gold fields (Manders et al. 2009). Mining pollution poses not only environmental impacts but also economic and social impacts as it threatens every person’s right to a clean and safe environment that is not harmful to his/her health and wellbeing (RSA 1996; Cronje et al. 2013).

Salinization is another impact associated with mining that can occur in both the coal and gold mining fields (DWA 2012). Certain other industries such as tanneries and paper mills as well as irrigation and farming can also contribute to salinization (NSW 2000; McCarthy 2011). Releases of AMD from the gold mining basins in South Africa will furthermore result in increased salinity in systems that are already stressed, such as the Vaal River (DWA 2013b).

Cultural eutrophication and faecal pollution

Cultural eutrophication is the process whereby human activity causes an increase in nutrients, such as phosphorus and nitrogen compounds, entering the freshwater system. Eutrophication is often associated with excessive plant growth and changes in dissolved oxygen (van Ginkel 2011). Cultural eutrophication is often associated with poor sanitation or ineffective effluent treatment. These same factors can thus result in faecal pollution. Under extreme conditions, eutrophication is associated with algal or cyanobacterial blooms that result in cyanobacteria proliferating and producing cyanotoxins that are harmful to human and animal life (DWA 2012). Eutrophication has become an increasingly widespread and serious problem in many of South Africa’s freshwater systems, especially those impacted by urban areas (Turton 2009; van Ginkel 2011).

Faecal pollution can be caused as a result of human sewage runoff into freshwater systems. Faecal coliforms and in particular *Escherichia coli* (*E. coli*) are used to indicate the extent and severity of faecal pollution (DWA 2012). The presence of coliforms can also indicate the increased likelihood of bacterial pathogens such as *Vibrio cholerae* and *Salmonella* spp.

being present in the aquatic system (DWAF 1996a). Monitoring done by the Department of Water Affairs (now the Department of Water and Sanitation (DWS)) indicated that all microbial hotspots in 2012 were not under ideal conditions and that most of these hotspots had poor or unacceptable *E. coli* counts (DWA 2012). In addition, the discharge of partially treated or untreated sewage may also affect the mobility and release of metals from sediments within the Wonderfonteinspruit which can add to the threat of mining pollution in the system (Coetzee et al. 2006).

1.2. Study area

The Wonderfonteinspruit study area extends from Westonaria (south-west of Johannesburg) to just outside of Carletonville further south-west. The ecological assessment of the Wonderfonteinspruit was undertaken at five sites, namely two sites above the Donaldson Dam, one site within the Donaldson Dam, one site downstream of the Donaldson Dam at a point just before the inflow of water into the pipeline (downstream of Donaldson Dam the river is contained in a pipeline), and another site at the outflow of the pipeline close to Carletonville. The Donaldson Dam forms the upstream boundary of the Lower Wonderfonteinspruit (Swart et al. 2003a). The social assessment was performed in the community of Bekkersdal which falls under the Westonaria Local Municipality within the broader West Rand District Municipality.

1.2.1. The Wonderfonteinspruit

The Wonderfonteinspruit is a well-studied river (Swart et al. 2003a; Coetzee et al. 2006; Hamman 2012). However, the focus of past studies has been almost solely on the impacts of mining on the system (Swart et al. 2003a; Opperman 2008; Hamman 2012; Barnard et al. 2013). The Wonderfonteinspruit flows through a dolomitic karstic aquifer partitioned by syenite dykes forming large compartments; in pre-mining years these dykes gave rise to many springs that were used for farming (Swart et al. 2003a; Winde 2010b). The name Wonderfonteinspruit, if translated, means “wonderful fountain spring” and the river was aptly named due to the succession of springs in the Wonderfonteinspruit. Early settlers described the area surrounding the Wonderfonteinspruit as being lush and rich in flora and fuana (van Eeden 1994).

Mining impacts (environmentally and socially) are undoubtedly significant in this system; however, they should not be viewed in isolation. The study by Marara et al. (2011) is one of the few to highlight the social implications of such a polluted system. Though it is apparent that the mining effluents can have an impact on both human health and wellbeing, the implications of biological contamination should not be overlooked.

The Wonderfonteinspruit along with the Mooirivierloop forms the main drainage channel for the Wonderfonteinspruit catchment which forms the eastern catchment of the Mooi River (Coetzee et al. 2006). The Wonderfonteinspruit has its origin in the Tudor Dam in the Krugersdorp area at the Continental Divide from where it flows to the south over the Zuurbekom compartment and into Donaldson Dam (Hamman 2012; Potgieter 2014). The Wonderfonteinspruit then flows through the Eye of Wonderfontein and enters an underground phase in the Turffontein compartment. The river exits the compartment at the Turffontein eye and the Gerhard Minnebron (GMB) eye (Potgieter, 2014). The Wonderfonteinspruit flows for approximately 80 km from its source to its confluence with the Mooi River (Swart et al. 2003a; 2003b).

The Wonderfonteinspruit is impacted by mining activities; even its natural flow pattern is constricted as its water is transferred to a 1 m diameter pipeline that is approximately 32 km long so as to drain the Oberholzer, Bank and Venterspost compartments and allow for mining operations (Opperman 2008). The water of the Wonderfonteinspruit is affected both in quantity and quality. In order to allow for mining in certain water-containing dolomitic areas, water had to be pumped out of underground compartments. Large-scale dewatering of these compartments started in the 1960s and resulted in the lowering of the water table by up to 300 m in some areas (Coetzee et al. 2006). The water that was pumped out of the underground chambers between the early 1960s and 1990s was largely pumped back into the Wonderfonteinspruit further downstream so as to avoid water flowing back into the mining compartments as sinkholes had developed due to the dewatering process (Coetzee et al. 2006; Winde 2010a). Water was also pumped across water divides into other river systems, thus resulting in a decreased quantity of water being available in the Wonderfonteinspruit. The decreased water table resulted in sinkholes, drying up of boreholes and a decrease in water quantity in areas of the Wonderfonteinspruit that were previously fed by underground water sources (Venter and Gregory 1987; Coetzee et al. 2006). Problems associated with dewatering are not limited to those that have occurred in the past but also relate to problems associated with rewatering. The cessation of pumping can result in the rewatering of the underground basins. An increase in water may seem inherently good; however, it can result in flooding of underground mines as is occurring in the West Rand already and it can result in AMD decanting into the Wonderfonteinspruit, thus further polluting it (Swart et al. 2003a; Coetzee et al. 2006; Council for Geoscience 2010).

The quality of the Wonderfonteinspruit water is severely impacted by mining effluents. These effluents result in increased sediment loads containing dissolved pollutants such as metals and sulphates (Hamman 2012). Mining waste can enter the Wonderfonteinspruit in a number of pathways, including both controlled (point source) and uncontrolled (diffuse) sources. The intensity of pollutants contained in point-source mining wastes can vary according to the processes applied to treat the effluents, such as making use of settling ponds (Coetzee et al. 2006). Diffuse sources, usually associated with tailings deposits, cannot be treated in the same way; Coetzee et al. (2006) estimated that some 24 t of dissolved uranium was released into the environment from the tailings alone. Windblown dust and storm-water runoff from tailings can also cause pollution as well as release of pollutants from the tailings used to fill the over 1 000 sinkholes caused by dewatering (Coetzee et al. 2006). The metals entering the Wonderfonteinspruit are likely to be adsorbed onto streambed sediments due to the more alkaline pH of the river water caused by the buffering capacity of the dolomitic aquifer; furthermore, it is possible that mines are using lime dosing to treat the AMD effluent (Hamman 2012).

Mining waste is not the only pollutant entering the Wonderfonteinspruit. Other activities such as agriculture, industry and effluents from sewage treatment works as well as formal and informal settlements also have an effect on the river water quality (Hamman 2012). The storm runoff from the numerous informal settlements is likely to enter the system, especially in more impoverished areas such as Bekkersdal that face challenges in terms of sanitation provision (Marara et al. 2011).

1.2.2. Bekkersdal

Bekkersdal is a township situated in the Westonaria local municipality in the Gauteng Province of South Africa. The Donaldson Dam and thus the Wonderfonteinspruit runs along the lower-most western portion of Bekkersdal. The community is located some 7 km east of Westonaria and there are more than 40 000 households; the township comprises both a formal and informal section (WLM 2011). The following sections form part of Bekkersdal: Formal section (uptown Bekkersdal), Skierlik, Spook Town; Mandelaville, Silver City, X-section, Y-section; Section Ghana, Winnie/Holomisa and the Tambo section (Figure 1.1).

Figure 1.1. Map of Bekkersdal (van Eeden 2014)

Bekkersdal was originally formally established in 1949 as a mining community to provide residence for a predominantly black labour force (Van Eeden 2014). The first mine shaft in the area, the Pullinger Shaft, was sunk in 1910 which resulted in the development of Westonaria in 1938 and subsequently Bekkersdal. In the early years, Westonaria was first known as Venterspost and was managed by Western Areas Limited and Venterspost Gold Mining Company. Bekkersdal is currently managed by the Westonaria Local Municipality (WLM) under the jurisdiction of the Far West Rand District Municipality (FWRDM). The WLM is mainly governed by members of the African National Congress (ANC) since 1994 (Van Eeden 2014).

Bekkersdal has seen rapid expansion since its early development. Informal dwellings have been steadily surrounding the original formal settlement. Since the apartheid days the struggle to provide sufficient services for the expanding township has led to dissatisfaction among the Bekkersdal residents, particularly from the 1980s onwards (Van Eeden 2014). In recent years, the unrest and service delivery protests, particularly within Bekkersdal, have earned the township some notoriety in news media (Tau 2013; Paton 2014; Sithole 2014). Protests are mainly due to the fact that residents perceive service delivery, including water service delivery, as being poor when compared to services received by other communities (Simelane and Nicolson 2014). So far, research results have indicated that these and several other complex issues necessarily impact negatively on the health and wellbeing of the Bekkersdal community (Van Eeden 2014).

1.3. Research methodology

1.3.1. Assessment of freshwater aquatic systems

In order to accomplish a comprehensive and accurate assessment of an aquatic system physical, chemical and biotic components must be assessed (Jiang 2006). These physicochemical attributes form part of many indices used to determine the state of an aquatic system as they act as the drivers that determine the community structure within a system (Taylor et al. 2009; Kleynhans 2008; Thirion 2008). Furthermore, it can be argued that physicochemical factors alone cannot wholly indicate the impact and pathways of pollution; therefore is it often important to use biological indicators in conjunction with physicochemical factors, especially if a holistic view of the system is to be achieved (Reynoldson and Metcalfe-Smith 1992; Dallas and Day 2004).

A number of water quality guidelines have been developed for various water uses in both the national and international sphere (DWAF 1996a-g; WHO 2006). These guidelines give an indication of acceptable water quality ranges for different activities as well as for healthy aquatic environments and include guidelines for *in situ* readings, dissolved minerals, Health Organization (WHO) nutrients and indicator organisms (DWAF 1996a-g; WHO 2006). The World Health Organization has developed water quality criteria for drinking water to aid countries in developing national standards for drinking water (WHO 2006). South Africa has developed a series of water quality guidelines that define the water quality parameters for various uses, namely: domestic activities (DWAF 1996a); recreation (DWAF 1996b); industrial activities (DWAF 1996c); irrigation (DWAF 1996d); livestock watering (DWAF 1996e); aquaculture (DWAF 1996f); and to maintain a healthy aquatic ecosystem (DWAF 1996g). The South African National Standard (SANS) 241 stipulates the standard for drinking water in South Africa (SABS 2011). Other incentives such as the Blue and Green Drop Certification Programmes provide incentive- and risk-based regulation of drinking water and wastewater services, respectively (DWA 2010; DWA 2011).

1.3.2. Biotic indices

The composition of lotic biological communities will be determined by the flow, water quality, biotope availability, historical distribution of species, interactions between biota present in the system and temporal changes such as the periodicity of droughts and floods (Dallas and Day 2004; Thirion 2008). Aquatic organisms have become adapted to specific environmental conditions and thus rely on a certain combination of the aforementioned drivers (Thirion 2008). Species have varied environmental requirements that must be fulfilled for their survival. This variation in tolerances and the adaptability of species is what allows for biotic indices to be implemented (Dallas and Day 2004). Thus, human impacts on a lotic system that result in a change in the quantity and quality of water will produce a change in the species composition within the river system and this change can then be quantified using biotic indices (Dallas and Day 2004).

Numerous biotic indices have been developed and used internationally for several decades to determine the state of freshwater systems (Graça and Coimbra 1998; Czerniawska-Kusza 2005; Hodkinson and Jackson 2005; Jiang 2006). In general, biotic indices concentrate on the species composition found within a system (Danilov and Ekelund 1999). According to Graça and Coimbra (1998), biotic indices can be described as "numerical expressions coded according to the presence of bioindicators differing in their sensitivity to environmental conditions." Biotic indices are thus a combination of quantitative species diversity found within freshwater aquatic systems as well as qualitative descriptions of the requirements and sensitivities between taxa (Czerniawska-Kusza 2005). Furthermore, biotic indices are frequently applied on a comparative basis such that present findings are compared to ecological reference conditions for the system. In this way it can be determined whether the findings are normal and part of the natural heterogeneity of lotic systems or due to anthropogenic impacts (Dallas and Day 2004).

Biological monitoring can make use of a number of indicators. These can be divided into three broad categories: natural processes (e.g. rate of nutrient cycling), biotic communities (e.g. species composition) or individual species monitoring (e.g. the behaviour or growth rate of the species) (Dallas and Day 2004). Monitoring of natural processes and biotic communities often comprises field-based analysis, while toxicity testing is usually performed for species monitoring and in some cases the monitoring of biotic communities (Dallas and Day 2004). For the purpose of this study only field analyses in the form of biotic community monitoring was investigated.

Biological monitoring provides a relatively cost-effective and reliable alternative to physical and chemical analyses of freshwater systems (Jiang 2006). Chemical and physical analyses often provide only a time specific indication of the pollution present in a system as opposed to organisms that can indicate changes over time in the aquatic system (Dallas and Day 2004). Thus, events causing stress that may have occurred before the monitoring event may be observed in the community structures of the aquatic organisms (Jiang 2006; Kosnicki and Sites 2011). Another factor making bio-monitoring preferable is that a range of factors are taken into account while often only a few variables are measured for physicochemical water quality monitoring. Synergistic and antagonistic relationships between variables may also be overlooked by using only physicochemical monitoring. Finally, water quality and river health are dependent on more than just the physicochemical factors and also rely on factors such as flow and habitat availability (Dallas and Day 2004). Such factors are of concern not only to aquatic organisms but also to human wellbeing as they can have an impact on, for example, water and food quantity and quality as well as concentration of pollutants and pests (DWAF 1996a-g; Dallas 2008).

When applying biotic indices it is of utmost importance to use indices developed for a particular locality. This is of value as variations in flow, physicochemical variables, habitat availability and resource availability exist between different localities (Graça and Coimbra 1998). For this reason it is imperative that indices specifically developed for South African rivers are applied in this study, such as: Fish Health Assessment Index (HAI) (Heath et al. 2004), Macroinvertebrate Response Assessment Index (MIRAI) (Thirion 2008) and Rapid-Diatom Riverine Assessment Method (R-DRAM) (Koekemoer and Taylor 2009).

1.3.3. Assessment of social aspects

The Integrative Multidisciplinary research model

This project forms part of an Integrative Multidisciplinary (IMD) research project on the ecohealth and wellbeing status of mining communities such as Bekkersdal. The first phase of this research established baseline conditions using a questionnaire titled “Integrative multidisciplinary-focused (IMD) research on the health and wellbeing status of mining communities” (van Eeden 2014). The questionnaire covered a wide range of topics that included, but was not limited to, health care, social structure, demographics, safety, employment regimes and environmental issues. The IMD model is a newly developed research methodology model based upon the integrative and transdisciplinary theories of internationally acclaimed researchers (van Eeden 2014). This approach cuts across various disciplines to create new conceptual innovations in order to address complex problems with multiple causes.

The IMD research model represents three research phases. The aim of the first two phases is to allow researchers to become acquainted with the research focus and in the second phase of research various disciplines then cluster and actively integrate knowledge systems. The focus of the final phase is on having meaningful and representative discussions with the community (inclusive of professional experts of the area) under investigation, namely Bekkersdal (van Eeden 2011; van Eeden 2014). The first phase is called the “Disciplinary phase” in which individual knowledge, experience and understanding from each discipline on the research matter is explored solo as well as discussed in organised meetings between the broader research team, so as to guide the next phase. Phase Two is called the

“Interdisciplinary phase”. This phase is guided by the information defined in the first phase but now with active attempts to cluster disciplines to explore particular research questions. In Phase Two the researchers also rely on group discussions and formal community engagement meetings to share knowledge and experience in a spirit of open-mindedness and inclusiveness in an effort to streamline the research results and identify the gaps (van Eeden 2014). In the final “Transdisciplinary phase” the aim of the model is to move beyond the discipline-specific approach and leverage the expertise of researchers working in different disciplines. This collaborative team approach allows their perspectives to be integrated in a single research project. A final report is then compiled to disseminate the findings; the overall aim is to translate the scientific findings (emanating from several research publications) into policy and practice. All the IMD-clusters of Phase Two then share their information with the research team and build upon their interaction with the community by sharing the research outcomes and drawing on the community’s perspectives and experiences (van Eeden 2014). During the development and planning stage of this research, it had been placed in the broader IMD-project, all the phases had been acknowledged and executed as discussed, though not with the intention to predominantly discuss this research method.

Questionnaires

Interviews are to be conducted in such a way that a conversation takes place in a manner that will be comfortable for the respondent (Spradley 1980; Brewer 2000). Language is another important factor to take into consideration as South Africa is a multilingual country and many residents relate better to languages other than English. Abrahams and Mauer (1999) found that respondents who do not speak English or Afrikaans found it difficult to understand the questions; this finding indicates the importance of conducting questionnaire surveys in the participant’s first language.

The manner in which questionnaire surveys were conducted was paramount to the success of gathering reliable information that is not biased. Furthermore, ethical considerations with regards to data gathering were not overlooked. The ethical conduct in research involving humans requires that the following principles were upheld: autonomy and the associated respect for their human dignity; non-maleficence, which aims at protecting a participant from harm; beneficence which entails that the participant draws benefits from the research; justice which can be summarised as distributive justice whereby risks and benefits are distributed between communities (Benatar et al. 2002). These principles are contained in the North-West University’s (NWU) *Information Guide for the NWU Ethics Application Form* and are taken from *Book 1: General Principles* including research on children, vulnerable groups, international collaboration and epidemiology.

The aim of the questionnaire survey is to answer the following research questions with regards to the social assessment:

- What water source is currently being utilized by the people of Bekkersdal and what issues are associated with this source?
- Is the Wonderfonteinspruit utilized and if so to what purposes?
- Is there a need for better provision of water resources and what part would the Wonderfonteinspruit play in solving these needs?
- What is the viewpoint of the residents of Bekkersdal with regards to the current state of the Wonderfonteinspruit, are they aware of the river and do they take responsibility for the resource?

The overall aims and objectives of this research study will be discussed in greater detail in Section 1.4; however, the explicit research objectives with regards to the questionnaire are:

- Determine the current use of water within Bekkersdal.
- Establish issues regarding water use in terms of both municipal water and water from the Wonderfonteinspruit.
- Suggest future development of water resources as suggested by the determination of the wants and needs of the residents of Bekkersdal.
- Investigate and provide comment on the viewpoint of the Bekkersdal residents with regards to the state and importance of the Wonderfonteinspruit to the community.

1.4. Hypotheses, aims and objectives

The aims, objectives and hypotheses of this dissertation can be divided into three sections: environmental, social and combined outcome. The aim of the environmental assessment of the Upper Wonderfonteinspruit is to demonstrate the health of the Wonderfonteinspruit using physical, chemical and biological indicators. These findings will then be related to the residents' perceptions of their environment as well as the health status of any current and potential users of the river. It is hypothesised that the physical and chemical results for the Wonderfonteinspruit will indicate unacceptable pollution in terms of utilization of the river for human activities and that the indices used will give an indication of the polluted state of the Wonderfonteinspruit. The objective of the environmental assessment is to determine the Ecological Category (EC) of the Wonderfonteinspruit, using: R-DRAM (Koekemoer and Taylor 2009); MIRAI (Thirion 2008); fish HAI (Heath et al. 2004); water quality both *in situ* and *ex situ*; as well as heavy-metal analysis of sediment, water and fish tissue.

The aims of the social assessment are to determine whether the water services and proficiency of delivery of the services, currently available for the formal and informal part of Bekkersdal, are viewed by the community members as adequate or inadequate, as well as to determine the use and awareness of the people regarding the Upper Wonderfonteinspruit. In addition, the objective is to establish and reveal the perceptions of community members with regards to the natural environment of the Upper Wonderfonteinspruit and its effect upon their health and wellbeing. It is hypothesized that there will be limitations in providing for the rights of the people of Bekkersdal in regards to the water use as determined by the perceptions and experiences of the participants from Bekkersdal; and that the natural environment with regards to the Wonderfonteinspruit will be regarded as unimportant to their present and future health and wellbeing.

The combined aim of this study is to determine the relationship that exists between indices applied to indicate the ecological health of the Wonderfonteinspruit and the impact of the river water on human health and wellbeing. In addition, some comments and suggestions will be provided regarding the possible water use as reflected by the wants and needs of the Bekkersdal community, and secondly the issue of apportionment of responsibility will be deliberated. Thus the objectives are to establish the link, if any, between ecological indices and human health and wellbeing with regards to river water use, and secondly to provide some solutions and comments on the issue of which entity or entities should take responsibility for the remediation and maintenance of the Wonderfonteinspruit. It is hypothesised that there will be a link between human health and wellbeing with regards to water use of the Wonderfonteinspruit and the ecological state of the river as indicated by indices. Furthermore, it is expected that more than a single entity should assume responsibility for the care, remediation and maintenance, and that uses and solutions to improve the state of the Wonderfonteinspruit are available.

1.5. Summary of chapters

This dissertation is divided into eight chapters and six appendices and will give an account of the state of the Wonderfonteinspruit as well as the findings of the investigation on past, current and future use of water by the residents of Bekkersdal. The water quality and sediment quality of the Wonderfonteinspruit in terms of various indices and national as well as international guidelines are presented in Chapters 2 and 3. The EC of the Wonderfonteinspruit as predicted by diatom, macroinvertebrate and fish indices is described in Chapters 4 and 5. Chapter 6 presents the findings of the questionnaire survey with regards to water use of the Wonderfonteinspruit and municipal water by Bekkersdal residents. Chapter 7 discusses the links between ecological health and human health in terms of the findings of the Wonderfonteinspruit assessments as well as the perceptions of the Bekkersdal residents, in order to determine whether a relationship exists between environmental indicators and human health and wellbeing with regards to rivers. Chapter 8 presents the main conclusions and makes recommendations.

2. Water quality of the Wonderfonteinspruit

2.1. Introduction

The importance of clean water resources for human activities is well established (USEPA 2013). Furthermore, many activities both in urban and rural communities depend on the surrounding natural resources of a freshwater system also being of an acceptable condition for activities over and above the use of water for drinking; for example, the United States Environmental Protection Agency (USEPA) has set regulations for *Escherichia coli* and enterococci counts for bathing purposes (USEPA 1986). Another example is the impact of polluted water on fish health and the associated human health hazards if these fish are used for human consumption (Castilhos et al. 1998; Watanabe et al. 2003).

National and international standards for the use of water have been established and criteria have been set to ensure that water of an acceptable standard is available for environmental and human use (DWAF 1996a; DWAF 1996g; WHO 2006). A number of indicators can be used to determine the state of freshwater resources. Physical and chemical indicators include: *in situ* readings of pH, temperature and total dissolved solids (TDS) and *ex situ* tests to determine nutrient content and dissolved mineral concentrations. These physical and chemical indicators can often be used to determine the effect of the indicators, such as metal concentrations, on human health for various activities. Similarly, bacteriological tests can indicate issues with potable water supplies due to faecal coliform, *E. coli* and *Enterococcus* contamination.

The aim of this section is to determine the water quality of the Wonderfonteinspruit through the use of *in situ* and *ex situ* water quality methods so that these results can be compared to national and international standards for the responsible use of water for human activities. It is hypothesised that the Wonderfonteinspruit will be unacceptable for use with regards to water quality for most anthropogenic uses.

2.2. Methods and materials

2.2.1. Study area

Table 2.2 gives provides the GPS position of the five sites along the Wonderfonteinspruit and Figure 2.1 indicates these locations on a regional map. The sites are within the Upper Wonderfonteinspruit from just below the Cooke Attenuation Dam to just below the Wonderfonteinspruit mining pipeline outlet near Carletonville; the pipeline is approximately 32 km long and drains the Oberholzer, Bank and Venterspost compartments to allow for mining operations (Opperman 2008). Five sites were selected for this study; four of these were river sites and one (Site 3) was located in an impoundment (Donaldson Dam). As indicated in Table 2.2, Site 4 was dry during the low-flow assessment while all four other sites had water for both the high- and low-flow assessment.

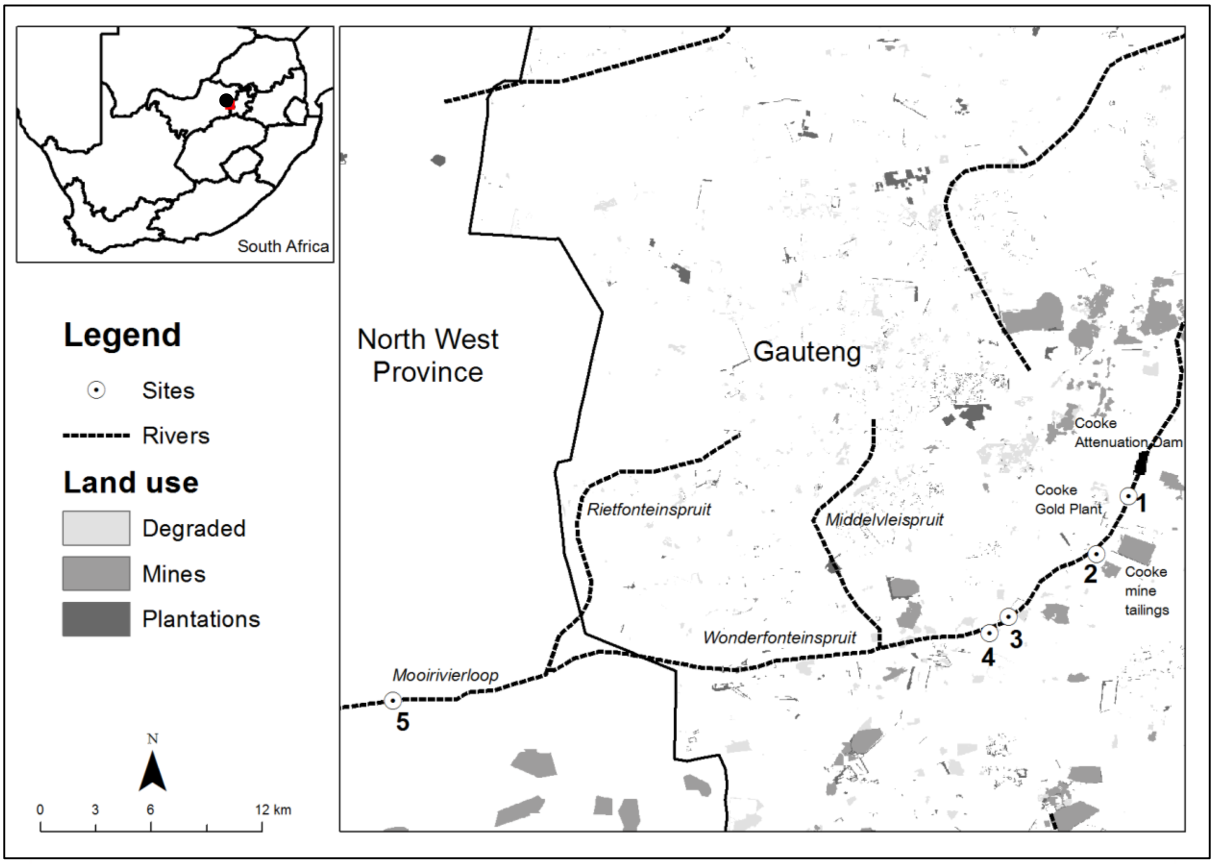


Figure 2.1. Sites along the Wonderfonteinspruit.

2.2.2. *In situ* water quality

In situ water quality analysis was done using Extech DO610: Waterproof Multimeter Kit. At each site the following variables were measured: temperature, pH, dissolved oxygen (mg/L and percentage oxygen saturation) and EC. TDS was calculated according to DWAF (1996a):

TDS (mg/L): EC (mS/m at 25 °C) x 6.5

Observations were also made as to the clarity and colour of the water.

2.2.3. *Ex situ* water quality

Water samples were collected for nutrient, biological and mineral analysis as outlined in: *Quality of Domestic Water Supplies. Volume 2: Sampling Guide* (DWAF, Department of Health and WRC 2000). A total volume of 3 L of water was collected from each site, thus a 1 L water sample for metal, nutrient and biological analysis, respectively. Sterile 1 L glass bottles that were autoclaved prior to sampling were used to collect bacteriological samples, while 1 L plastic bottles were used for nutrient and mineral analysis water samples.

Mineral analysis

For each water sample 50 mL were filtered through a 45 µm cellulose nitrate Millipore filtering system. Mineral analyses were carried out using an inductively coupled plasma mass spectrophotometer (ICP-MS). The Sodium Absorption Rate (SAR) was determined using the following equation from DWAF (1996d):

SAR: [sodium]/([calcium] + [magnesium])0.5 (DWAF 1996d).

Total hardness was determined using the following equation from DWAF (1996d):

(mg $CaCO_3$/L) = 2.497 x [mg Ca/L] + 4.118 x [mg Mg/L] (DWAF 1996c).

Nutrients

Spectroquant test kits and Merck Spectroquant Pharo 100 Spectrophotometer (Merck KGaA 2007) were used to determine the following nutrients in the samples: ammonium, chloride, nitrite, nitrate, phosphate and sulfate. The alkalinity of the samples was determined using an Aquamerck® test kit for alkalinity.

Bacteriological

Bacteriological samples were sampled as outlined in the *Quality of Domestic Water Supplies. Volume 2: Sampling Guide* (DWAF, Department of Health and WRC 2000). Fifty mL of the water was filtered in triplicate through a 45 µm cellulose nitrate filter. Care was taken that all handling of the filter paper was done only with sterile tweezers dipped in ethanol and heated over a flame until the ethanol has burnt off. The filters were then placed onto previously prepared M-ENDO and m-FC agar plates. These were incubated for a period of 24 hours at 36 °C. Thereafter the colonies were enumerated per 100 mL.

2.2.4. Statistical analysis

Principal component analysis (PCA) was performed for dissolved metal, nutrient and anion concentrations per site per assessment period using Canoco 5. Ordination allows for the determination of differences, if found, between samples and sites (van den Brink et al. 2003). Multiple linear regression between each variable in its turn is used to create best fit values that are analysed together with environmental variables and are used to replace the original data (Shaw 2003). In order to perform ordination the assumption is made that one of the sets of environmental variables are “dependent” while the other set is “independent” (Ter Braak and Šmilauer 2002) The PCA method makes use of weighted summations that allows for the modelling of absolute data and allows for the presentation of a linear modelled response (van den Brink et al. 2003).

2.2.5. Physico-chemical Driver Assessment Index

The Physico-chemical Driver Assessment Index (PAI) score was determined using high- and low-flow variables at all sites as adapted from the methods described in DWAF (2008). The PAI process involves defining the study area and identifying water quality variables to be tested; these are based on what is required of the study and usually include (as in this study): inorganic salts (e.g. sodium, calcium, magnesium, sulfates), nutrients (e.g. nitrates, phosphates, ammonium), *in situ* (systems) variables (e.g. pH, temperature, DO and turbidity), and toxic substances as listed in DWAF (1996g) (e.g. metals, organic substances) (DWAF 2008). Thereafter data manipulation is performed and the model is applied. Fewer sites (5 sites) and a shorter monitoring period (one sample per high and low flow assessment) were used. Turbidity and pesticides were not measured. Table 2.1 provides an example of the determination of the PAI for all sites during both assessment periods.

Table 2.1. Physicochemical category and score determination.

Physicochemical metrics	Rank	%weight	Rating	Confidence*	Weighted rating	Comments
pH	5	50	2.00	1.00	1.00	
Salts	3	70	3.50	1.00	2.45	
Nutrients	2	80	4.00	1.00	3.20	
Temperature	4	60	1.00	1.00	0.60	
Turbidity	4	60	1.00	1.00	0.60	Not measured, observed
Oxygen	3	70	2.00	1.00	1.40	
Toxic substances	1	100	4.00	1.00	4.00	No pesticides
Physicochemical % score	45.92					
Physicochemical category	D					

2.3. Results

2.3.1. *In situ* water quality

Temperatures for all five sites varied between 15.1 °C (Site 2) and 25.3 °C (Site 5). As indicated in Table 2.2, the temperatures for all sites were higher during the low-flow assessment, while no major temperature differences were observed between the high- and low-flow assessments per site, with Site 5 observed to have the biggest difference of 4.1 °C. The pH was alkaline for all five sites and varied from Site 2 with a pH of 7.68 to the most alkaline at Site 3 of 9.08. The pH was more alkaline during the low-flow assessment (Table 2.2). Dissolved oxygen was lowest at Site 2 (3.55 mg/L and 35%) during the high-flow assessment and highest at Site 1 (14.75 mg/L and 159.1%) during the low-flow assessment. Once again an increase in dissolved oxygen during the low-flow assessment can be observed for Sites 1, 2 and 5; however, Site 3 was observed to have a higher dissolved oxygen content during the high-flow assessment. The TDS of the sites increased during the low-flow assessment for Sites 1, 2 and 3 with Site 5 showing a negligible decrease in TDS during the low flow assessment. As indicated in Table 2.2, Site 2 had the lowest TDS for both high-flow (4 387.5 µg/L) and low-flow (5 187 µg/L) assessments, while Site 5 had the highest TDS for both the high-flow (6 909.5 µg/L) and low-flow (6 825 µg/L) assessments.

The best clarity, turbidity and colour were observed at Site 2 (Table 2.2). The poorest clarity was observed at Site 5 with a brown-green colour during both the high- and low-flow assessments. Most commonly the water colour at all the sites was green to brown.

Table 2.2. *In situ* water quality results.

Site	Coordinates	Date (flow)	Temp (°C)	pH	DO (mg/L)	DO (%)	TDS (µg/L)	Clarity (cm)	Colour
1	-26.215416° 27.741438°	16/4/14 (high)	17.1	7.94	4.4	45.9	4790.5	Average	Greenish
		7/11/14 (low)	19.3	8.55	14.75	159.1	5642	Good	Greenish
2	-26.245644° 27.730816°	16/4/14 (high)	15.1	7.68	3.55	35.0	4387.5	Good	Clear
		7/11/14 (low)	16.8	7.73	4.8	50	5187	Good	Greenish
3	-26.276326° 27.687895°	16/4/14 (high)	17.0	9.08	11.9	126	5499	Average	Brown-green
		7/11/14 (low)	21.1	8.72	7.84	74.1	6662.5	Average	Brown-green
4	-26.284458° 27.678655°	16/4/14 (high)	19	8.85	5.62	60.7	5551	Average	Brown-green
		7/11/14 (low)	DRY	DRY	DRY	DRY	DRY	DRY	DRY
5	-26.317325° 27.388199°	16/4/14 (high)	21.2	8.31	4.32	48.5	6909.5	Poor	Brown-green
		7/11/14 (low)	25.3	8.55	9.4	114	6825	Poor	Brown-green

2.3.2. Nutrients and anions

Table 2.3 shows the nutrient data of the five sites for both assessments. Site 2 was found to have the highest chloride concentration of greater than 250 mg/L during the high-flow assessment followed by Site 5 (177 mg/L). Conversely, Site 2 had the lowest concentration during the low-flow assessment (38 mg/L). Chloride concentrations increased for Sites 2 and 5 during the high-flow assessment while Sites 1 and 3 showed no change to negligible changes in chloride concentrations. Sulphate concentrations were consistently higher at Site 5 for both the high-flow (316 mg/L) and low-flow (141 mg/L) assessments. Site 1 was observed to have the lowest sulphate concentration of 95 mg/L for the high-flow assessment while Sites 1 and 2 had concentrations of less than 25 mg/L for the low-flow assessment. Sulphate concentrations were consistently lower for all sites during the low-flow assessment. Phosphate concentrations were marginally lower during the high-flow assessment for Sites 1, 2 and 3 while Site 5 was shown to have lower concentrations of phosphate during the low-flow assessment. The highest concentrations of phosphate were observed at Site 2 for both assessment periods with Site 1 showing similar values. Site 3 showed the greatest difference in phosphate concentrations between the assessment periods with a difference of 2.78 mg/L. Site 5 had the lowest concentrations of phosphate for both the high-flow (1.06 mg/L) and low-flow (0.84 mg/L) assessments.

Table 2.3. Nutrient data for the five sites along the Wonderfonteinspruit during the high- and low-flow assessments.

Assessment period	**High flow**					**Low flow**				
Site	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Chloride (mg/L)	40	>250	46	44	177	40	38	47	Dry	46
Nitrate (mg/L)	5.7	11.5	7.8	7.1	5.3	1.8	3.9	2.3	Dry	2
Nitrite (mg/L)	0.036	0.038	0.031	0.057	0.5	0.51	0.31	>0.05	Dry	0.48
Ammonium (mg/L)	9.3	2.83	0.23	0.06	0.53	4.83	1.64	1.2	Dry	0.51
Phosphate (mg/L)	2.98	3.24	0.99	0.89	1.06	3.53	3.77	1.48	Dry	0.84
Sulphate (mg/L)	95	105	155	179	316	<25	<25	127	Dry	141

Ammonium concentrations were higher during the high-flow assessment. The highest ammonium concentrations were recorded at Site 1 for both the high- and low-flow assessment periods of 9.3 mg/L and 4.83 mg/L, respectively. The lowest ammonium concentration during the high-flow assessment was observed at Site 4 (0.06 mg/L) while Site 5 showed the lowest value for the low-flow assessment (0.51 mg/L). Nitrite values were highest during the low-flow assessment for Sites 1, 2 and 3. Conversely, Site 5 was shown to have a lower nitrate concentration during the low-flow period and also had the highest nitrite concentration for both assessment periods. Nitrate was highest during the high-flow assessment with Site 2 showing the greatest nitrate concentration of 11.5 mg/L. Site 5 had the lowest nitrate concentration during the high-flow assessment of 5.3 mg/L and Site 1 had the lowest for the low-flow period of 1.8 mg/L.

2.3.3. Mineral analysis

The dissolved metals, metalloids and non-metals in water samples collected from the five sites during the low- and high-flow periods are presented in Figures 2.2 and 2.3. Only aluminium was found to be above detection limits at three sites (Sites 1 and 2 during the high-flow and Site 3 during the low-flow period), while all other dissolved elements were found in measurable concentrations at all sites and assessment periods. Aluminium was highest at Site 1 during the high-flow assessment. Arsenic was highest in all samples during the low-flow assessment and peaked at Site 5. Cobalt concentrations during the low flow showed elevated levels as compared to the high-flow assessment, with the highest concentrations during the low- and high-flow assessments found at Site 5. A similar increase in chromium can be observed during the low-flow as compared to the high flow assessment; however, the chromium concentrations during the low-flow period decreased as sites progressed downstream. Iron concentrations were highest during the high-flow assessment with Site 1 having the highest concentration during this assessment.

The concentrations of manganese were elevated during the high-flow period with a spike in concentrations at Site 2 during this assessment period. A spike in platinum was observed at Site 1 during the low-flow assessment, while Site 2 during the high-flow assessment showed a smaller spike in the platinum concentration. During the low-flow assessment Site 3 showed the highest concentrations of uranium with Site 5 during the same assessment period also showing higher than expected concentrations. Vanadium was found to be highest during the low-flow assessment for all sites excluding Site 5, with Site 2 having the lowest concentrations during both assessment periods.

The measured concentrations for calcium and magnesium were highest at Site 5 for both the high- and low-flow assessments. Calcium and magnesium showed a similar trend in their concentrations as sites and assessment periods progressed downstream. Potassium concentrations were highest for all sites during the low-flow assessment with Site 1 showing the highest concentrations. Similarly, the phosphorus concentrations were found to be highest during the low-flow assessment. Similar trends can be seen between sites and assessment periods for potassium and phosphorus. The SAR value was greatest at Site 2 during the high-flow assessment and Site 1 during the low-flow assessment. Site 5 showed the highest values for total hardness during both assessment periods.

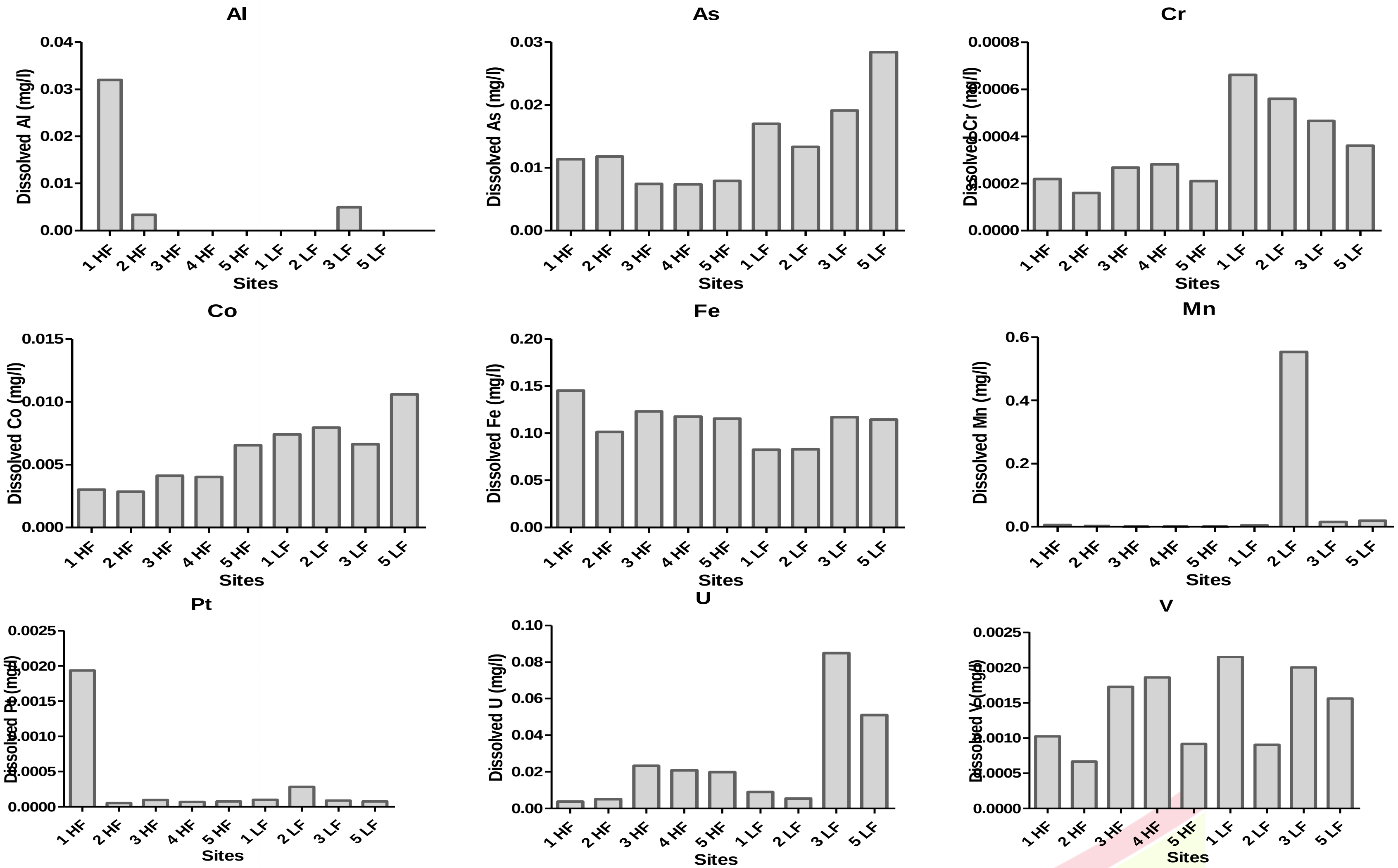


Figure 2.2. Dissolved metals at the five sites along the Wonderfonteinspruit.

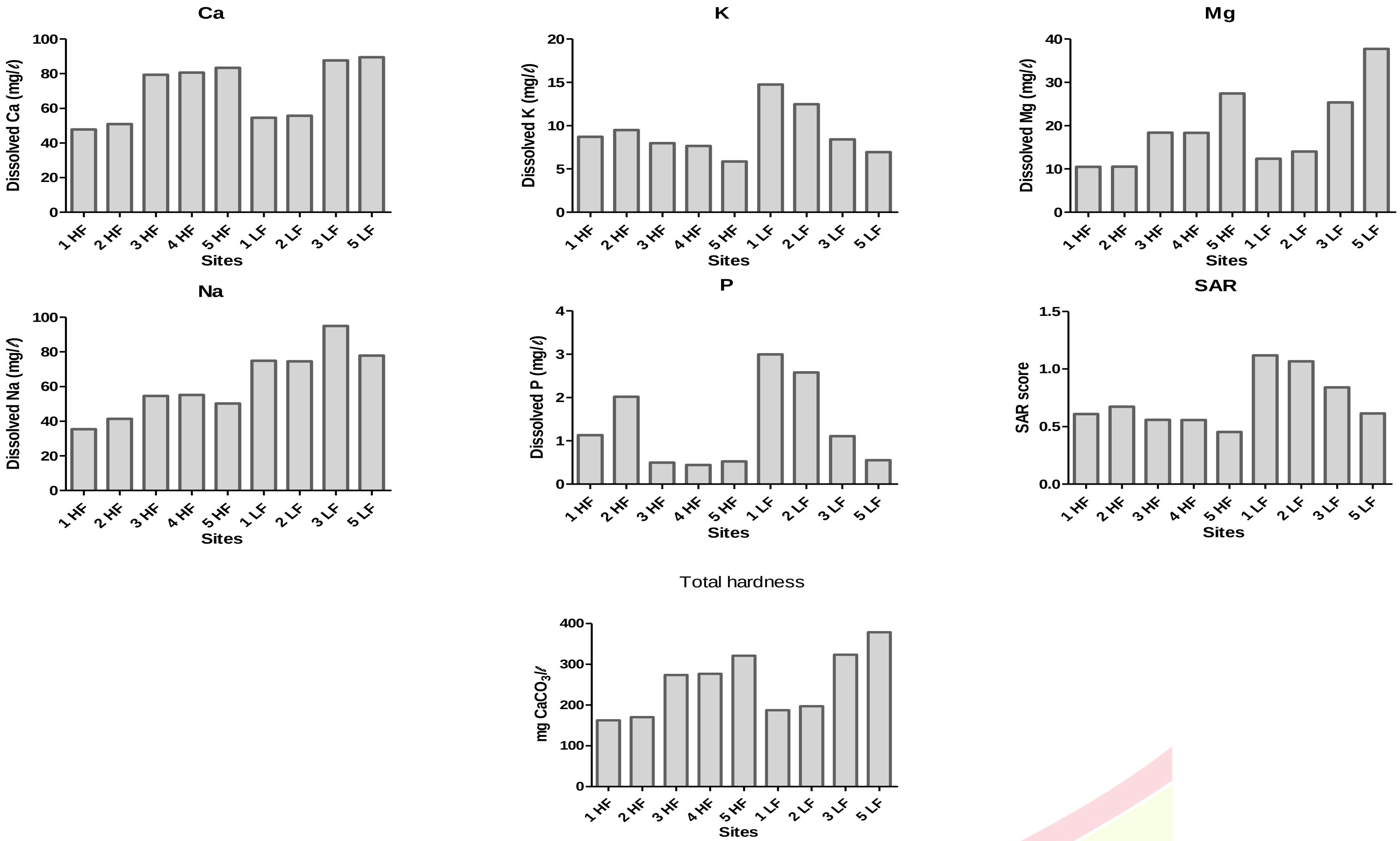


Figure 2.3. Dissolved minerals in water sampled from five sites along the Wonderfonteinspruit.

2.3.4. Bacteriological results

The total coliform counts throughout the five sites were high (Table 2.4). Site 1 during the low-flow assessment was the only site that had total coliform counts of below 500 colonies. Faecal colony counts were lowest at Site 3 during both the high (16 cfu/100 mL) and low (22 cfu/100 mL) flow assessments. At Site 5 counts of more than 500 cfu/100 mL were recorded consistently for both assessment periods. Site 1 showed an improvement in faecal colony counts from 178 cfu/100 mL for the high-flow assessment to 22 cfu/100 mL for the low-flow assessment. Site 2 showed an increase of 238 cfu/100 mL from the high- to the low-flow assessment. Site 4 was found to have 300 cfu/100 mL during the high-flow assessment.

Table 2.4. Bacterial counts for the high- and low-flow assessment periods for the five sites along the Wonderfonteinspruit.

Site	**Total coliform count per 100 mL (mean)**		**Faecal coliform count per 100 mL (mean)**	
	High flow	**Low flow**	**High flow**	**Low flow**
1	>500	350	178	22
2	>500	>500	180	418
3	>500	>500	16	22
4	>500	DRY	300	DRY
5	>500	>500	>500	>500

2.3.5. Principal component analysis

The PCA of the metal concentrations in the water samples indicated a total variation of 84.35%, of which 48.89% is represented by Axis 1 and 35.46% is represented by Axis 2 (Figure 2.4). The metal pair arsenic and cobalt were shown to be most closely associated (Figure 2.4). Site 2 during the low-flow assessment shows the highest concentrations of manganese while Site 1 during the high-flow assessment shows the highest concentrations of aluminium (Figure 2.4). This is also demonstrated in Figure 2.2 with Sites 1 and 2 showing unexpectedly high concentrations of aluminium and manganese, respectively (Figure 2.4). During the high-flow assessment Sites 3, 4 and 5 were shown to be closely associated with regards to dissolved metal concentrations with Sites 3 and 4 showing the most similar metal concentrations. However, during the low-flow assessment Sites 3 and 5 are not closely associated (Figure 2.4). The PCA of nutrients and anions at each site and assessment period describes 81.26% of the variation on the first two axes (50.83% on Axis 1 and 30.43% on Axis 2) (Figure 2.4). Strong positive correlations were observed between chloride and nitrate as well as between ammonium and phosphate (Figure 2.4). During the high-flow assessment Sites 3 and 4 were most closely associated with regards to anions and nutrients (Figure 2.4).

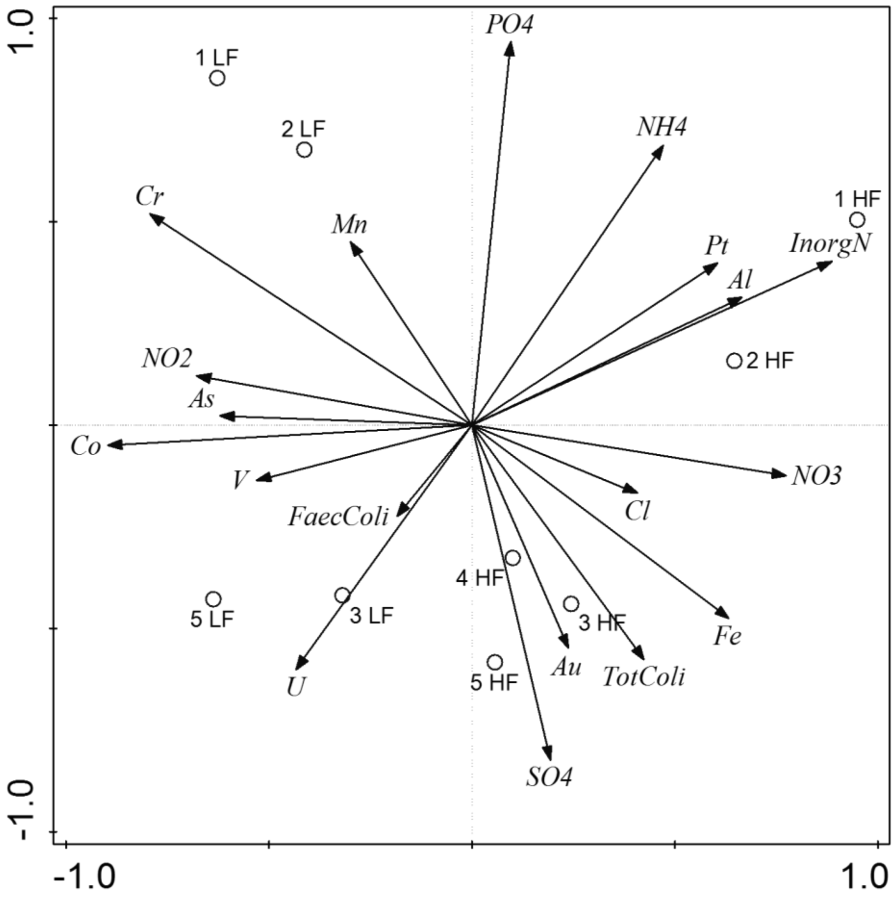


Figure 2.4. Principal component analysis (PCA) of the metals, total coliforms, faecal coliforms, nutrients and anions for the five sites along the Wonderfonteinspruit during the high- and low-flow assessment period.

2.3.6. Physico-chemical Driver Assessment Index

The physicochemical index percentage score is calculated using a set range of criteria for each of the parameters assessed. An example of the calculation of the PAI is presented in Table 2.5. The resulting physicochemical percentage is allocated a water quality category (Table 2.6). The PAI scores and their categories for the sites and surveys sampled during this study are presented in Table 2.6

The determined physicochemical percentage score varied between a minimum of 45.69% at Site 3 (low flow) and a maximum of 46.20% at Site 1 (high and low flow) as well as at Sites 4 and 5 (high flow) (Table 2.5). This score gave a physicochemical category of D, as shown in Table 2.6.

Table 2.5. Physicochemical category and percentage of each site along the Wonderfonteinspruit per assessment period.

Site	**High flow**		**Low flow**	
	Physicochemical percentage	**Physicochemical category**	**Physicochemical percentage**	**Physicochemical category**
1	46.20	D	46.20	D
2	46.04	D	45.40	D
3	45.94	D	45.69	D
4	46.20	D	Dry	Dry
5	46.20	D	45.92	D

Table 2.6. The ratings, scores and ecological categories used for the implementation of the Physico-chemical Driver Assessment Index (PAI) (DWAF 2008).

Rating	**Deviation from reference conditions**	**Categories**	**Natural – poor categories**	**Score**
0	No change	A	Natural	≥ 92.01
1	Small change	B	Good	82.01 – 87.4
2	Moderate change	C	Fair	62.01 – 77.4
3	Large change	D		42.01 – 57.4
4	Serious change	E	Poor	22.01 -37.4
5	Extreme change	F		0 -17.4

2.4. Discussion

For the purposes of this discussion of the water quality of the Lower Wonderfonteinspruit all of the parameters measured will be assessed against the South African and international guidelines for the different water user classes (DWAF 1996a-g; WHO 2006; WHO 2011; Ansoborlo et al. 2015).

2.4.1. Drinking water

The EC and TDS for all sites are above the Target Water Quality Range (TWQR) for drinking water and do not satisfy the guidelines for TDS set in the SANS 241 Drinking Water Quality Guide (SABS 2011). The TDS values fall into the worst category listed. If this water is used likely effects would include salty/bitter taste, corrosion, scaling and disturbances in the body's salt balance (DWAF 1996a). The WHO indicates, however, that reliable data are not available to support the possible health effects associated with a high TDS but supports the possibility that such elevated concentrations (above 1 000 mg/L) may result in the water being objectionable to customers (WHO 2011).

The pH values for the majority of the sites are within the TWQR for drinking water as well as within Class I of the SANS 241 Drinking Water Quality Guidelines. The pH at Site 3 during the high-flow assessment was only marginally higher than the TWQR value. Amphoteric oxide dissolution is possible at Sites 1 (low flow), 3, 4 (high flow) and 5 (low flow) as these oxides begin to dissolve at a pH greater than 8.5 (DWAF 1996a). For example, aluminium oxide (Al_2O_3) which is associated with aluminium and gold mining can become dissolved

(Bakar 2013). However, this relationship is not observed as can be noted in Figure 2.2 where increased aluminium concentrations do not correspond with the aforementioned sites.

Colour and clarity were based on visual observations. The TWQR for drinking water measures turbidity in nephelometric turbidity units (NTU) and is strongly associated with colour. A relationship between taste, odour and turbidity does exist but is not explicitly the case (DWAF 1996a). For all sites, excluding Site 2 (high flow) a colour could be observed usually varying between brown and green.

Aluminium concentrations were found to be within the guidelines set by the TWQR, the only possible negative association from the concentrations observed was at Site 1 during the high-flow assessment where a spike in dissolve aluminium was detected (Figure 2.2). This might be related to the silt-like turbidity observed at this site during the same assessment (Table 2.2) as residual aluminium in water has been associated with increased turbidity (WHO 2006). Arsenic concentrations are above the regulations set for drinking water by the WHO and the TQWR; Sites 1 and 2 during the high-flow assessment and all sites (excluding Site 4) during the low-flow assessment exceeded the regulatory limit of 0.01 mg/L (DWAF 1996a; WHO 2011). The concentrations of arsenic detected at these sites may present low carcinogenic risks to a number of organs (Chen et al. 1992; DWAF 1996a; WHO 2011).

Constituents commonly associated with mining such as lead, vanadium, chromium and mercury are considered to be highly dangerous to human health and ingestion of even small amounts can result in acute and irreversible health effects (DWAF 1996a). The drinking water requirements for these constituents are therefore strict, yet none of these metals were found to be above the TWQR set by in the South African Water Quality Guidelines (DWAF 1996a). Iron and manganese were found to be above the TWQR. During the low-flow assessments only Sites 1 and 2 were within the TWQR for iron while only Site 2 during the low-flow assessment exceeded the TWQR for manganese (DWAF 1996a). Site 2 was the only site to show uncharacteristically high concentrations of manganese during the low-flow assessment and thus it is expected that a possible error occurred with this sample with regards to the reading of manganese concentrations. The concentrations of iron may present only marginal changes to taste and aesthetics, but no health risks are expected; however, iron deposits may occur in plumbing systems (DWAF 1996a). The guidelines set for drinking water by WHO allow for iron concentrations of 2 mg/L, thus all sites were found to comply with the regulatory limit (WHO 2006). Despite the spike in manganese levels observed at Site 2 during the low-flow assessment, the concentrations found are still not expected to result in health hazards, but can cause severe staining and issues with taste (DWAF 1996a; WHO 2006).

The guideline set by the WHO for drinking water for uranium is 0.015 mg/L based on the chemical toxicity of uranium and tends to be a tentative precautionary value due to the lack of epidemiological studies (WHO 2006). Sites 3, 4 and 5 during the high-flow assessment and Sites 3 and 5 during the low-flow assessment showed concentrations exceeding the guideline limit and consumption of this water may result in nephrotoxicity (WHO 2006; Seldén et al. 2009). The Agency for Toxic Substances and Disease Registry (ATSDR) in 2011 allowed for uranium concentrations of 0.03 mg/L to prevent toxicological impacts on human health; if this guideline limit is applied then only Sites 3 and 5 during the low-flow assessment pose potential toxicological risks (Ansoborlo et al. 2015). This is supported in the WHO 2011 revised guidelines for drinking water (WHO 2011).

The concentrations of calcium measured for all sites are outside of the TWQR but do not pose health risks. Severe scaling and soap lathering impairment are expected to occur only at Sites 3, 4 and 5 for both assessment periods (DWAF 1996a). Only Site 5 during the low-flow assessment period exceeded the TWQR for magnesium, though the concentration of 37 mg/L is not expected to cause health issues and may only cause slight scaling issues (DWAF 1996a). The high concentrations and related hardness of the waters in the Wonderfonteinspruit are not unexpected due to the presence of dolomite in the area. Dolomite is a variety of limestone with a composition containing high concentrations of calcium and magnesium carbonate (Swart et al. 2003b; Winde 2010a). The sodium concentrations for all assessments and sites are within the limits recommended by the TWQR. Similarly, potassium concentrations are also in line with the recommendations made by the TWQR (DWAF 1996a).

The chloride content of the samples taken from the Wonderfonteinspruit is not of concern as chloride concentrations measured mostly fall within the TWQR for drinking water. Sites 2 and 5 during the high-flow assessment were the only two sites that showed chloride concentrations above the TWQR (Table 2.3) although the likelihood of health effects experienced from these concentrations is negligible (DWAF 1996a). The only concern with regards to the chloride concentrations exceeding 250 mg/L as at Site 2 (high flow) is with regards to taste, whereby such concentrations may result in a salty taste (WHO 2011). Site 5 during the high-flow assessment was the only site that showed sulphate concentrations above the TWQR which can pose risks to non-adapted and sensitive individuals if the water is ingested as it may cause diarrhoea and can also affect the taste of the water (DWAF 1996a; WHO 2011). The TWQR for ammonium is 0-1 mg/L; as listed in Table 2.3, the ammonium concentrations for Sites 1, 2 and 3 (low flow) exceeded the TWQR which can indicate compromised chlorination and might lead to issues with taste and odour (DWAF 1996a). Sites 2, 3 and 4 during the high-flow assessment exceeded the TWQR for nitrate;

however, the only possible health effects are rare instances of methaemoglobinaemia (increase in methaemoglobin in the blood) in infants (DWAF 1996a).

The TWQR for drinking water is between 0-5 total coliform colony counts per 100 mL while SANS 241 drinking water quality guidelines require *E. coli* colonies to be undetectable for 95% of the samples. Only 1% of the samples may have a count of 1 cfu/100 mL according to SANS 241. All samples from the Wonderfonteinspruit fall above these regulatory limits and indicate a significant risk to human health as infectious disease transmission risk increases. The presence of colony counts greater than 100 cfu/100 mL is indicative of pollution and poor water treatment (DWAF 1996a).

2.4.2. Recreation

Poor clarity of river water is seen as a potential risk for swimmers as hazardous objects (such as rocks, concrete blocks from roads, fishing line and hooks) cannot be identified; this could be a possible risk at most sites (DWAF 1996b). The pH values of Site 1 (low flow), Sites 3 and 4 (high flow) and Site 5 (low flow) pose possible risks of irritation to eyes, skin, mucous membranes and ears; however, swimming is still considered to be acceptable in these conditions (DWAF 1996b). The TWQR for swimming water requires a pH of between 6.5 and 8.5; this limits eye irritation to a minimum and skin, ear and membrane irritation is absent (DWAF 1996b).

No impacts are expected to occur as a result of the metal concentrations detected in the water samples if the water is used for recreational purposes (DWAF 1996b). The associated impacts and risks of nutrient loads in a freshwater system are associated with increased eutrophication. Eutrophication most often leads to excessive plant growth resulting in algal or cyanobacterial blooms. Cyanobacteria produce toxins that can pose a health risk to swimmers (Pilotto et al. 1997).

The TWQR for recreational use of water in terms of *E. coli* and faecal coliforms allows for counts of up to 130 cfu/100 mL for bathing waters. Donaldson Dam (Site 3) satisfies this criterion as the faecal coliform count is below this range in both the high- and low-flow assessment and thus would allow for recreational activities to occur in the Donaldson Dam. The gastrointestinal risk is expected to be low causing less than 8 illnesses per one thousand swimmers (DWAF 1996b).

2.4.3. Irrigation and livestock watering

The TWQR for pH is between 6.5 and 8.4 of which only Sites 1 and 5 (high flow) as well as Site 2 during both high- and low-flow assessments fall into this category. At pH values of between 6.5 and 8.4 the water should not cause foliar damage, will encourage soil sustainability and will cause no major problems with irrigation equipment (DWAF 1996d).

According to DWAF (1996d) and Bauder et al. (2014) the pH at Site 1 (low flow), Sites 3 and 4 (high flow) and Site 5 (low flow) poses risks in terms of foliar damage, long-term availability impacts on micro- and macro-nutrients as well as damage to irrigation equipment damage due to scaling which may require acid input to prevent these impacts.

As shown in Table 2.2, the TDS of all the sites along the Wonderfonteinspruit exceed the TWQR limits and it is recommended that this water only be used if very good management is practised and only on selected crops (DWAF 1996d). Using water with a TDS such as those found at all five sites will most likely cause soil management and crop sustainability issues (DWAF 1996d). However, it should be noted that certain crops are less sensitive to salt concentrations than others even during germination, such as maize, potato, durum wheat, sunflowers and sugar beet (Mass 1984; Katerji et al. 2002; van Rensburg et al. 2011).

The TDS levels of all sites are above the TWQR values for all livestock types. Sites 1 and 2 during the high-flow assessment would require only that sheep and cattle be made familiar with water of an increased salinity. Horses, dairy, pigs and poultry would most likely experience a decline in production; however, horses could become accustomed to the higher salinity. All other sites have unacceptable TDS values (DWAF 1996e).

The chloride content for most sites is within the TWQR for irrigation water; once again Sites 2 and 5 during the high-flow assessment were above this range which may result in toxic chloride accumulation in more sensitive crop species and foliage wetting should be avoided (DWAF 1996d). The only sites to comply with the TWQR of inorganic nitrogen content for irrigation are Sites 3 and 5 during the low-flow assessment. However, only sensitive crops are likely to be affected by the concentrations of inorganic nitrogen at the rest of the sites and groundwater contamination should only become problematic if large volumes of water are used (DWAF 1996d). The chloride, nitrite, nitrate and sulphate concentrations for the watering of livestock are all within the TWQR (DWAF 1996e).

Manganese concentrations for Sites 2 and 5 exceed TWQR for irrigation and may result in manganese toxicity in some crops. However, up to 10 mg/L is considered acceptable for fine-textured soils varying from neutral to alkaline (DWAF 1996d). Sites 1 and 2 during both the high- and low-flow assessments fall within the TWQR for uranium. However, plant yield can be maintained in soils with uranium concentrations of below 10 mg/kg. The ranges of uranium concentrations in the water samples from the remaining sites are considered to be suitable for the irrigation of crops in neutral to alkaline fine-textured soils (DWAF 1996d). These guidelines are, however, considered to be tentative and the time of irrigation (20 years) using these guidelines should be adjusted according to fluctuations in uranium concentrations (DWAF 1996d).

The SAR index gives an indication of the potential of water to induce sodic soil conditions due to the concentrations of sodium, calcium and magnesium in the water. All sites are compliant with the TWQR for the SAR range. This should prevent sodium toxicity in sodium-sensitive plants if crop foliage is not wetted (DWAF 1996d).

Irrigation standards are dependent on the time of irrigation, as a greater risk is expected if irrigation is done immediately preceding harvesting (DWAF 1996d). The TWQR for faecal coliforms allows for only one count of faecal coliforms per 100 mL. This would indicate that all sites are above the recommended range; however, allowance is made for faecal coliform counts of up to 1 000 cfu/100 mL for the irrigation of fruit trees and grapes, if the fruit are not watered directly, as well as crops and pastures that are allowed to dry before harvesting and are not consumed raw. Water containing colony counts of greater than 1 000 cfu/100 mL should only be used where contact with humans is avoided and for such activities as parks, plantations and nurseries (DWAF 1996d). Table 2.4 shows that the Donaldson Dam water could be considered acceptable for certain irrigation purposes such as mentioned for counts above one colony. The Donaldson Dam water furthermore falls within the TWQR for drip irrigation systems (DWAF 1996d). A specific TWQR for coliforms is not given for livestock watering; however, transmission of pathogens through milk from cows grazing on crops irrigated with water containing coliform counts of above 1 cfu/100 mL can pose risks in pathogen transmission (DWAF 1996d).The WHO allows for faecal coliforms in irrigation water to be 1 000 cfu/100 mL but cautions that helminth eggs and protozoan parasite cyst counts should be restricted to ≤1 (WHO 1993).

2.4.4. Industrial activities

The guidelines for industrial activities as contained in DWAF (1996c) detail the TWQR for three industrial process categories. These take into account the quality of water used for a range of industrial activities which includes the effects of the water quality on equipment, processes and products (DWAF 1996c). These activities can include car washing, fire fighting, gold processing, domestic cleaning, dust suppression and sewerage infrastructure, all of which are viable uses of water within the area of study and many of which are practised as will be demonstrated in Chapter 6.

Water with a pH of greater than 8 such as observed at Sites 1 (low flow), 3, 4 and 5 can cause scaling, affect acidic processes and decrease product quality (DWAF 1996c). The TDS of all the sites can result in significant damage to equipment by causing fouling, corrosion and scaling; interfering with processes and impairing product quality (DWAF 1996c). Furthermore, such high TDS values can result in demineralisation plants having to be more frequently replaced or repaired and result in increased disposal of highly saline effluent (DWAF 1996c).

The iron concentrations found at most sites exceeded the TWQR for industrial activities and may present negligible to minor interference with processes and impairment of products as well as minor to moderate damage to equipment due to iron compounds precipitating (DWAF 1996c). Manganese concentrations were within the TWQR for all sites and assessment periods excluding Site 2 during the low-flow assessment (DWAF 1996c). Water abstraction and subsequent use for Category 1 industrial processes may result in moderate to significant impacts, impairment and interference with equipment, product quality and processes, respectively. These impacts are considered to be only moderate for Category 2 industrial processes and minor to negligible for Category 3 and 4 processes (DWAF 1996c). Water hardness ranged between moderately hard to very hard water which can result in moderate to significant and even major damage to equipment, interference with processes and impairment of product quality for Category 1 industrial processes (DWAF 1996c). Only Sites 1 and 2 would result in moderate impacts due to the total hardness of the water, while Sites 3, 4 and 5 could cause significant and major impacts to Category 1 industrial processes. The total hardness may present only mild to significant impacts to Category 2 industrial processes and moderate to significant impacts to Category 3 industrial processes (DWAF 1996c).

The chloride TWQR for industrial activities is between 0 and 20 mg/L; all sites were found to be non-compliant, as indicated in Table 2.3. Once again it is clear that Sites 2 and 5 during the low-flow assessment have the highest chloride concentrations and this can cause major corrosion to structures and equipment, serious damage of product quality and interference with processes as well as requiring major decreases in and treatment of chloride contents in effluents (DWAF 1996c). Sites 1 and 2 during the low-flow assessment were the only two sites to comply with the sulphate TWQR for industrial processes. The sulphate concentrations for Sites 1 and 2 during the high-flow and Sites 3 and 5 during the low-flow assessment may result in moderate impacts to product quality, process interference as well as equipment and structural damage due to scaling and corrosion. Disposal of wastewater may require prior treatment at these concentrations with increased frequency of regenerating demineralisation plants. The sulphate concentrations during the high-flow assessment for Sites 3, 4 and 5 can result in the aforementioned effects on industrial processes worsening (DWAF 1996c).

2.4.5. Aquaculture

Although there are no aquaculture activities within the study area, the assessment of the water quality in relation to the aquaculture guidelines does provide an indication of the suitability of the water quality to support healthy fish populations. This could thus provide an indication of possible future aquaculture opportunities and provide insight into the state of the fish population in the Donaldson Dam commonly used for angling (African Gold 2014; Best Fishing Spots 2014). The pH values for all sites were within the TWQR for aquaculture which should allow for optimal production, should there have been such activities (DWAF 1996f). The temperature requirements for aquaculture will vary according to the species used. Table 2.2 gives an indication of the temperatures recorded at the various sites for high- and low-flow assessments; these temperature ranges suggest that intermediate species would be most suited to the temperature fluctuations of the Wonderfonteinspruit (DWAF 1996f). The effect of TDS is largely dependent on the fish taxa and life cycle stage and therefore should be examined per species. Viruses should also be taken into consideration especially in systems with less-than-ideal water quality conditions as the immune systems of the fish are more likely to be compromised (DWAF 1996f; Arkoosh et al. 1998).

Site 1 during the high-flow assessment showed aluminium concentrations of just above the TWQR value of <0.03 mg/L at a pH of 6.5. This value is not expected to present any adverse effects to aquatic life. The TWQR for iron is <0.01 mg/L; however, the lethal threshold concentrations are given only at 0.2 mg/L and higher. This would place all sites below the lethal threshold concentration. Once again the TWQR concentrations for manganese are exceeded only at Site 2 during the low-flow assessment and may pose sublethal and possible lethal effects to aquaculture fish species.

The TWQR for ammonia can be divided into two separate ranges; one for cold-water species and another for warm-water species. None of the sites were compliant with the TWQR for cold-water species and only Sites 2 and 3 during the high-flow assessment complied with the TWQR for warm-water fish species. The effects of ammonia on the fish species will be dependent on the species, life cycle stage and other health impacts on the fish. The Donaldson Dam site (Site 3), which is a popular angling site would be more ideal for the survival of warm-water species (DWAF 1996f). Most aquatic fish species should be able to survive in the concentrations of chloride, nitrite and nitrate at all sites though reproduction may not be optimal (DWAF 1996f).

It is unexpected that fish would pose a human health risk as most pathogens are destroyed upon cooking; however, the TWQR for fish used for human consumption is set at 10 *E. coli* per g of fish flesh (DWAF 1996f). Parasites are only seen to be an issue if fish have chronic infections. According to the results of the health assessment index there were no observed parasites that should pose a human health risk (DWAF 1996f).

2.4.6. Aquatic ecosystems

The TWQR for pH is limited to a variation of no more than 0.5 pH units or 0.5% (according to whichever measure is most conservative) of the background pH values for the specific site (DWAF 1996g). The TWQR for DO is based on a set of criteria that require either instantaneous measurement at sunrise, or the mean of measurements over a 24-hour cycle or 7-day cycle. The saturation for DO is set at 80-120% such that the majority of the expected South African species are protected (DWAF 1996g). Only instantaneous measurements were taken; however, it can be noted that only Sites 1 (low flow) and 3 (high flow) conformed to the TWQR. In order for a system to comply with the TWQR for temperature the change in temperature should not exceed 2 °C or 10% (whichever estimate is more conservative) of the background average daily temperature reading at a specific site and time (DWAF 1996g). The TDS of a site should not exceed 15% of the natural background TDS for unimpacted conditions and the frequency and amplitude of natural TDS cycle changes should not be changed (DWAF 1996g).

The concentration for aluminium at Site 1 during the high-flow assessment is the only concentration above the TWQR of 0.01 mg/L for a pH of greater than 6.5 as all sites had (DWAF 1996g). The concentration of aluminium at Site 1 can be expected to cause chronic effects but is below the acute effect value. The concentrations of arsenic for most sites are below the chronic effect value but just above the TWQR value of 0.01 mg/L (DWAF 1996g). Only Site 5 has an arsenic concentration above the chronic effect value but below the acute effect value (DWAF 1996g). The TWQR for iron is based on a variation in iron concentrations of no more than 10% of the background dissolved iron concentrations for a specific site at a specific time (DWAF 1996g). The manganese concentration at Site 2 (low flow) was the only site to exceed both the TWQR and chronic effect value but was below the acute effect value (DWAF 1996g).

The guidelines for nutrients are set for ammonia, inorganic nitrogen and inorganic phosphorus, which were not measured (DWAF 1996g).

2.4.7. Principal component analysis

Parinet et al. (2004) demonstrated that principal component analysis (PCA) can be useful for describing the relationship between several variables which may be more effective than using water quality variables individually. In essence the PCA aims to create groupings of variables, through the study of a provided matrix, to describe the observed principal tendencies. This is produced mathematically through the eigenvector decomposition of the correlation matrix, allowing relationships between water quality variables, sites and assessment periods to be observed (Bengraïne and Marhaba 2003).

The correlation during the high-flow assessment between Sites 3, 4 and 5 is most likely explained by the fact that Sites 4 and 5 are downstream of Site 3. The water quality of the impoundment (Site 3) thus would affect the water quality of the sites downstream thereof. Site 4 would be expected to be most similar to Site 3 due to its close proximity and because the only water Site 4 receives comes directly from Donaldson Dam. However, Site 5 is located some 32 km (Opperman 2008) away from Site 3 due to the pipeline. During the high-flow season, the water arriving at Site 5 most likely originates from the upstream impoundment with inputs from other sources. During the low-flow season, however, the input from Site 3 to downstream sites was greatly diminished, resulting in the drying-up of Site 4; thus it is expected that Site 5 would show dissimilarities from Site 3 during the low-flow assessment period.

Sites 3 and 4 once again show a close relationship with regards to nutrient and anion concentrations though these sites are not as closely associated. This may be expected due to additional inputs into Site 4 by grazing cattle and possible runoff from nearby roads. It is expected that there are additional inputs of nutrients and anions into the pipeline resulting in differences between Sites 3 and 5.

2.4.8. Physico-chemical Driver Assessment Index

The PAI acts as a component of the Ecological Reserve determination process. The PAI model requires specialist opinions with regards to water quality and aquatic biotic components (DWAF 2008). Thus, as both water quality and several biotic components were assessed for this study, the model can be applied with some confidence. However, in order to produce even a low confidence report a minimum of 12 sites monitored over a 60 day period is required (DWAF 2008). This implies that the use of this method may not be ideal for the present study as only five sites along the Wonderfonteinspruit were surveyed and these were only sampled twice, once per flow season. Despite the limitations presented by applying this model with the limited data available, a difference between expected historical conditions and present conditions can still be predicted. It was expected that the toxic components would most likely have an effect on the physicochemical category, especially metals due to mining impacts, while nutrients and salts were also expected to be important factors due to other inputs arising from sewage discharges and industrial activities (Coetzee et al. 2006; Hamman 2012). Though mine drainage, especially in the West Rand is often acidic, the buffering capacity provided by the large quantities of dolomite present in the

Wonderfonteinspruit should, however, prevent this from being a major impacting factor (Swart et al. 2003a; Coetzee et al. 2006; Hamman 2012). It should also be noted that turbidity was not measured and only observational data could be used.

When these physicochemical metrics, including the observed turbidity, are considered and the PAI model is applied, the physicochemical percentage of all sites falls into the physicochemical category D. A category D indicates that a large change from reference conditions has occurred. It also indicates that the Wonderfonteinspruit water is considered to be of a fair category (DWAF 2008).

2.5. Conclusion

From the four data sets for water quality tested, the most concerning issue observed is that of biological contamination which poses the greatest threat for use by humans. The only concern regarding metals and nutrients is if the inputs for these constituents do not remain constant. It is therefore recommended that regular monitoring be performed by regulatory agencies, polluting as well as interested and affected parties and that potential pollution sites be closely monitored and mitigated, such as mine effluent sources and sewage treatment facilities. The result nonetheless suggests that though the Wonderfonteinspruit is representative of the most critical water quality threats facing most of South Africa's freshwater systems (DWA 2012), it can still be meaningfully utilised by surrounding communities for certain practices such as recreation, irrigation, watering of cattle and certain industrial activities. Most of these applications will require little to no remediation of the current water quality within the Wonderfonteinspruit. However, the precautionary principle should apply and further monitoring of upstream inputs during changes in flow patterns and inputs is recommended. The data indicate that the aquatic ecosystem may be under stress; however, many of the guidelines are based upon background (historical) values which are not available, thus it is recommended that these background values be better established. However, biological indices are expected to provide better and more accurate information as to the state of the aquatic ecosystem than that provided by the water quality. This will therefore be investigated and discussed in the chapters to follow.

3. Sediment quality of the Wonderfonteinspruit

3.1. Introduction

The sediments of the Wonderfonteinspruit have already been identified as highly polluted and especially the uranium in the sediments has been extensively studied (Coetzee et al. 2006; Winde 2010a; Winde 2010b; Hamman 2012). The concentration of uranium in the milled ore and mined tailings surrounding the Wonderfonteinspruit is high and therefore the runoff and associated contamination of the sediment within the river is expected to be elevated (Winde 2010a). Other metals such as cadmium, chromium, lead and zinc are also expected to leach from the mining operations surrounding the Wonderfonteinspruit (Coetzee et al. 2006).

The geo-accumulation index (I_{geo}) is one of the most commonly implemented indices for the measurement of pollution in sediment and provides a quantitative measurement of the degree of pollution in the sediment (Rabee et al. 2011). The Pollution Load Index (PLI) gives a summative description of the number of times the guideline limits for metals in sediment have been exceeded (Rabee et al. 2011). Both the contamination factor (CF) and enrichment factor (EF) provide an indication of the concentration of a metal contained in the sediment above that expected in the continental upper crust (Diop et al. 2015; Salah et al. 2012).

Several different sets of sediment quality guidelines (SQGs) for freshwater systems have been developed based on a plethora of approaches (Long and Morgan 1991; Smith et al. 1996; MacDonald et al. 2000). Those suggested by MacDonald et al. (2000) take into account these diverse results in order to form composite data for the SQGs in the form of two values: the threshold effect concentration (TEC), as well as the probable effect concentration (PEC). Such values have not been determined for all the metals evaluated and therefore in order to expand the analysis of the possible impacts of metal pollutants on the Wonderfonteinspruit, threshold values from the literature were considered (Pheiffer et al. 2014).

The aim of the analyses of the metals within the sediment of the study area is to determine the degree of contamination within the sediments of the Wonderfonteinspruit and the possible associated impacts on the environment and possible threats regarding human use of the Wonderfonteinspruit. It is hypothesised that the sediment of the Wonderfonteinspruit will be contaminated with metals and this will result in risks to the environment and humans in the study area.

3.2. Methods and materials

3.2.1. Sediment sample preparation

Sediment samples were collected from all sites during both assessments except Site 4 during the low-flow assessment as the site was dry and overgrown with grass. The sediment from each site was placed into different 500 mL marked acid pre-washed glass jars for each site. The sediment was kept frozen until analysis. Samples were weighed in triplicate in 100 mL glass jars. The weight of the glass jars alone as well as the weight of the glass jars with the sediment was measured using a Sartorius Basic scale. Thereafter the samples were placed into a Memmert oven and dried at 60 °C for a minimum of 96 hours or until constant weight had been achieved. Microwave digestion

The procedure for digestion of the sediment was adapted from Hassan et al. (2007) and performed as follows: Between 0.3 g to 0.5 g of dried sediment was accurately weighed using a Zeiss West scale and placed into Teflon reaction vessels. Thereafter 10 mL of 65% Suprapur nitric acid was added to the reaction vessels and subsequently digested in a CEM Mars 5 Microwave Accelerated Reaction System. The digested fluid was then decanted into a 50 mL volumetric flask and topped up to the 50 mL mark with 1% nitric acid solution. The mixture was then filtered through 45 µm nitrate cellulose filter paper and decanted into 50 mL Falcon tubes. The digested sediment was then transferred into 10 mL tubes prior to metal analysis using an ICP-MS Agilent 7500 CE.

3.2.2. Sediment indices

The following sediment indices were calculated as described in the equations below according to Salah et al. (2012):

$$\text{Enrichment Factor (EF): } (Me/Al)_{sample} / (Me/Al)_{background}$$

Where:

$(Me/Al)_{sample}$: Metal to iron ratio of sample

$(Me/Al)_{background}$: Metal to iron ratio of world average

$$\text{Contamination Factor (CF): } C_m Sample / C_m Background$$

Aluminium was selected as the metal for normalization due to the relatively constant relationship between aluminium and other metals, the reliability involved in the measurement of aluminium concentrations as well as the conservative nature of the element (Schropp and Windom 1988; Cato 2007).

Where:

C_mSample: Metal concentration in sample in mg/kg

C_mBackground: Metal concentration of world average in mg/kg (see Table 3.1)

Pollution Load Index (PLI): $(CF_1 \times CF_2 \times CF_3 \times \ldots CF_n)^{1/n}$

Where:

n: number of metals

Mercury was excluded from this calculation as mercury was not detected at all sites for all assessments.

Geo-accumulation index (I_{geo}): $Log_2[C_m Sample/(1.5 \times C_m Background)]$

Where:

C_mSample: Metal concentration in sample in mg/kg

C_mBackground: Metal concentration of world average in mg/kg (see Table 3.1)

TEC and PEC were compared to the concentrations in the sampled sediments as taken from the consensus based sediment quality guidelines by MacDonald et al. (2000). Sediments below the TEC are expected to be non-toxic while sediments exceeding the PEC are expected to be toxic; a value between the TEC and PEC is not purposed to provide any guideline toxicity (MacDonald et al. 2000). The TEC and PEC values of metals that were unavailable for threshold values, which were the most conservative to protect aquatic life, were taken from a composite list by Pheiffer et al. (2014) (Friday 1998; ANZECC 2000; Sheppard et al. 2005). Table 3.2 provides the EF categories, Table 3.3 provides the description for CF values and Table 3.4 provides Muller's classification for the I_{geo} values.

Table 3.1. Background world average for metal concentrations in sediment used in calculations as well as threshold effects concentrations (TEC) for metals in aquatic ecosystems to prevent harmful effects.

Metal (mg/kg)	Al	As	Ba	Cd	Co	Cr	Cu	Hg	Mn	Ni	Pb	Ti	U	V	Zn
World average concentration*	84700^{+}	130	75.9	413	1679	74.5	61.1	12.1	39.1	3.3	129	$130^{\dagger}$	75.9	413	1679
TEC (MacDonald et al. 2000)	NA	9.79	NA	0.99	NA	43.4	31.6	0.18	NA	22.7	35.8	NA	NA	NA	121

*Viers et al. 2009 unless otherwise indicated; +Schropp and Windom 1988; †Binning and Baird 2001

Table 3.2. EF categories (Mmolawa et al. 2011).

EF	Enrichment categories	Colour code
EF <2	Deficiency – minimal enrichment	
≥2 EF <5	Moderate enrichment	
≥5 EF <20	Significant enrichment	
≥20 EF <40	Very high enrichment	
≥40	Extremely high enrichment	

Table 3.3. Description of CF values (Salah et al. 2012).

CF	Level of contamination	Colour code
<1	Low	
≥1 CF <3	Moderate	
≥3 CF <6	Considerable	
>6	Very high	

Table 3.4. Muller's classification of I_{geo} values as taken from Salah et al. (2012).

I_{geo} value	Class	Sediment quality	Colour code
≤0	0	Unpolluted	
0-1	1	Unpolluted to moderately polluted	
1-2	2	Moderately polluted	
2-3	3	Moderately to strongly polluted	
3-4	4	Strongly polluted	
4-5	5	Strongly to extremely polluted	
>6	6	Extremely polluted	

3.3. Results

The metal concentrations in sediments from the different sampling sites are presented in Figures 3.1 and 3.2 as well as Appendix A. For the purposes of this chapter all metals are discussed in terms of the EF, CF and I_{geo} indices. Based on all three indices, the sediments at Site 1 during the high-flow assessment were contaminated the most by uranium (Tables 3.5 and 3.6). Site 3 (high flow) was also contaminated with uranium but to a lesser degree than Site 1 (Table 3.5). According to the EF and CF, Site 3 fell within the same categories as Site 1 (high flow), while the I_{geo} value indicated that the sediment is moderately to strongly polluted (Table 3.6). Although Site 5 (high and low flow) sediments were also polluted with uranium, cobalt and nickel were shown to have higher index values (Tables 3.5 and 3.6). All three of these metals caused very high contamination/enrichment of the sediment according to the CF and EF (Table 3.5). The sediments were moderately to strongly polluted according to the I_{geo} (Table 3.6).

The index values were lower during the low-flow assessment for most sites with the exception of Site 5 which showed an increase in the same metals (cobalt, nickel and uranium) that were responsible for the contamination in the high-flow survey (Tables 3.5 and 3.6). The CF was still "very high" but the I_{geo} for cobalt and nickel increased in severity and sites were considered to be strongly polluted (Tables 3.5 and 3.6). Site 2 (low flow) also showed a slight increase in the uranium concentration with CF values indicating moderate contamination and I_{geo} values indicating unpolluted to moderately polluted conditions (Table 3.6). However, the EF indicated that the enrichment of the sediment with uranium was very high (Table 3.5). Sediment at Site 3 (low flow) was observed to have elevated uranium with EF values indicating very high enrichment, CF values that indicated considerable contamination and I_{geo} values that indicated moderately polluted conditions (Tables 3.5 and 3.6). In addition to the above, almost all metals that were considered were observed to be contaminating sediments at least at one site (Table 3.5). These contaminating metals were: arsenic, cadmium, chromium, copper, manganese, titanium and zinc (Tables 3.5 and 3.6). Only mercury, lead and vanadium did not contribute to sediment contamination of the Wonderfonteinspruit (Table 3.5).

The greatest PLI value was recorded at Site 5 during both the high- and low-flow assessment (Figure 3.1) followed by Site 3 during both assessments and Site 4 during the high-flow assessment period. Only Site 1 during the high-flow assessment had cobalt concentrations below the threshold value guidelines for cobalt (Figure 3.1). All sites exceeded the guideline threshold values for manganese with Site 3 during the high-flow assessment being tenfold higher than the threshold value. The threshold value for uranium was within the guideline limit for Sites 2 (high flow) and 1 (low flow); however, Site 1 during the high-flow assessment had the highest uranium concentration (Figure 3.1). Sites 3 and 5 showed consecutive high concentrations for uranium.

Table 3.5. Enrichment factors (EF) and contamination factor (CF) values for the five sites along the Wonderfonteinspruit. The codes and colours to interpret these factors and indices are presented in Tables 3.2 and 3.3.

Site		As	Ba	Cd	Co	Cr	Cu	Hg	Mn	Ni	Pb	Ti	U	V	Zn
1HF	EF	5.95	2.75	3.09	29.67	15.10	7.28	0.017	16.05	13.44	3.46	50.30	1093.55	3.25	7.57
	CF	0.15	0.07	0.08	0.77	0.39	0.19	0.00	0.42	0.35	0.09	1.31	28.40	0.08	0.20
2HF	EF	8.25	6.14	0.44	28.12	28.58	9.62	0.000	11.55	13.96	4.24	82.64	10.40	8.52	2.47
	CF	0.34	0.25	0.02	1.16	1.18	0.40	0.00	0.48	0.58	0.18	3.42	0.43	0.35	0.10
3HF	EF	3.63	5.36	2.08	19.68	20.90	5.03	0.001	23.68	16.14	3.39	27.18	72.89	5.23	6.44
	CF	0.41	0.60	0.23	2.21	2.35	0.56	0.00	2.66	1.81	0.38	3.05	8.18	0.59	0.72
4HF	EF	2.48	2.81	0.99	9.01	9.27	3.47	0.010	18.03	6.0	5.86	23.64	17.38	3.16	4.90
	CF	0.31	0.35	0.12	1.11	1.14	0.43	0.00	2.23	0.74	0.72	2.92	2.15	0.39	0.61
5HF	EF	8.71	1.72	2.36	60.89	5.99	9.66	0.000	7.58	57.70	3.93	12.41	46.40	2.03	7.49
	CF	1.39	0.27	0.38	9.70	0.95	1.54	0.00	1.21	9.19	0.63	1.98	7.39	0.32	1.19
1LF	EF	3.09	6.55	0.15	11.48	39.40	4.60	0.000	11.17	7.70	2.11	31.08	6.14	7.44	0.99
	CF	0.24	0.51	0.01	0.89	3.05	0.36	0.00	0.87	0.60	0.16	2.41	0.48	0.58	0.08
2LF	EF	15.81	5.67	4.49	53.71	15.39	7.79	0.000	25.88	29.80	5.14	20.94	95.80	3.58	12.86
	CF	0.36	0.13	0.10	1.23	0.35	0.18	0.00	0.59	0.68	0.12	0.48	2.19	0.08	0.29
3LF	EF	3.59	2.29	1.60	15.61	21.78	4.30	0.000	7.53	12.89	3.11	24.18	74.08	5.03	5.11
	CF	0.26	0.16	0.11	1.12	1.56	0.31	0.00	0.54	0.92	0.22	1.73	5.31	0.36	0.37
5LF	EF	7.82	0.97	2.29	69.33	5.22	9.54	0.000	4.48	69.06	3.52	11.38	39.08	1.68	7.04
	CF	1.49	0.19	0.44	13.24	1.00	1.82	0.00	0.86	13.19	0.67	2.17	7.46	0.32	1.34

Table 3.6. Geo-accumulation index (Igeo) values for the five sites along the Wonderfonteinspruit. The codes and colours to interpret these factors and indices are presented in Table 3.4. Concentrations not detected represented by ND.

Site	As	Ba	Cd	Co	Cr	Cu	Hg	Mn	Ni	Pb	Ti	U	V	Zn
1HF	-3.28	-4.39	-4.22	-0.96	-1.94	-2.99	-11.73	-1.85	-2.10	-4.06	-0.20	4.24	-4.15	-2.93
2HF	-2.14	-2.56	-6.37	-0.37	-0.34	-1.92	ND	-1.65	-1.38	-3.10	1.19	-1.80	-2.09	-3.87
3HF	-1.88	-1.32	-2.69	0.56	0.65	-1.41	ND	0.82	0.27	-1.98	1.02	2.45	-1.35	-1.05
4HF	-2.30	-2.11	-3.62	-0.43	-0.39	-1.81	-10.19	0.57	-1.02	-1.05	0.96	0.52	-1.94	-1.31
5HF	-0.11	-2.45	-2.00	2.69	-0.65	0.04	-14.44	-0.31	2.62	-1.26	0.40	2.30	-2.21	-0.33
1LF	-2.65	-1.56	-6.98	-0.75	1.03	-2.07	ND	-0.79	-1.33	-3.20	0.68	-1.66	-1.38	-4.29
2LF	-2.05	-3.53	-3.87	-0.29	-2.09	-3.07	ND	-1.34	-1.14	-3.67	-1.65	0.55	-4.19	-2.35
3LF	-2.54	-3.19	-3.71	-0.42	0.06	-2.28	ND	-1.47	-0.70	-2.75	0.21	1.82	-2.06	-2.03
5LF	-0.01	-3.02	-1.78	3.14	-0.59	0.28	ND	-0.81	3.14	-1.16	0.54	2.31	-2.22	-0.16

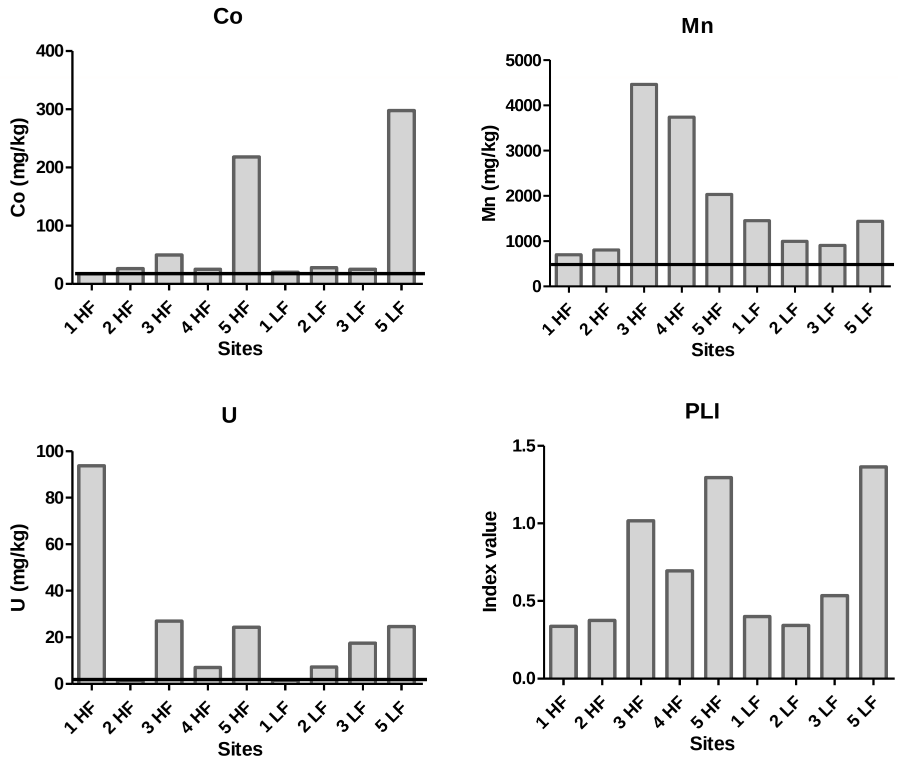


Figure 3.1. Concentration of metals and threshold values (—) (Pheiffer et al. 2014) as well as the Pollution Load Index (PLI) per site and assessment period.

Sites 1 (high and low flow) and 3 (low flow) were found to have concentrations below the TEC for arsenic (Figure 3.2). Site 5 was the only site to exceed the TEC for arsenic for both the high- and low-flow assessment. All sites were below the TEC for cadmium (Figure 3.2). The TEC for chromium was exceeded at all sites and only Sites 1 (high flow) and 2 (low flow) were below the PEC (Figure 3.2). Sites 3, 4 and 5 during the high-flow assessment as well as Site 5 during the low flow assessment exceeded the TEC but were all below the PEC (Figure 3.2) for copper. The only site to exceed the TEC for mercury was Site 1 during the low-flow assessment. The nickel TEC was exceeded at all sites and only Sites 1 (high flow and low flow) and 2 (low flow) were below the PEC (Figure 3.2). Sites 4 and 5 during the high-flow survey as well as Site 5 during the low-flow survey exceeded the TEC for lead but were within the PEC (Figure 3.2). No sites exceeded the PEC for zinc but Sites 3 and 4 during the high-flow survey along with Site 5 during the high- and low-flow survey exceeded the zinc TEC (Figure 3.2). Aluminium concentrations were highest at Site 5 during the high- and low-flow assessment while iron concentrations were highest at Site 3 during the high-flow survey and at Site 1 during the low-flow assessment (Figure 3.3).

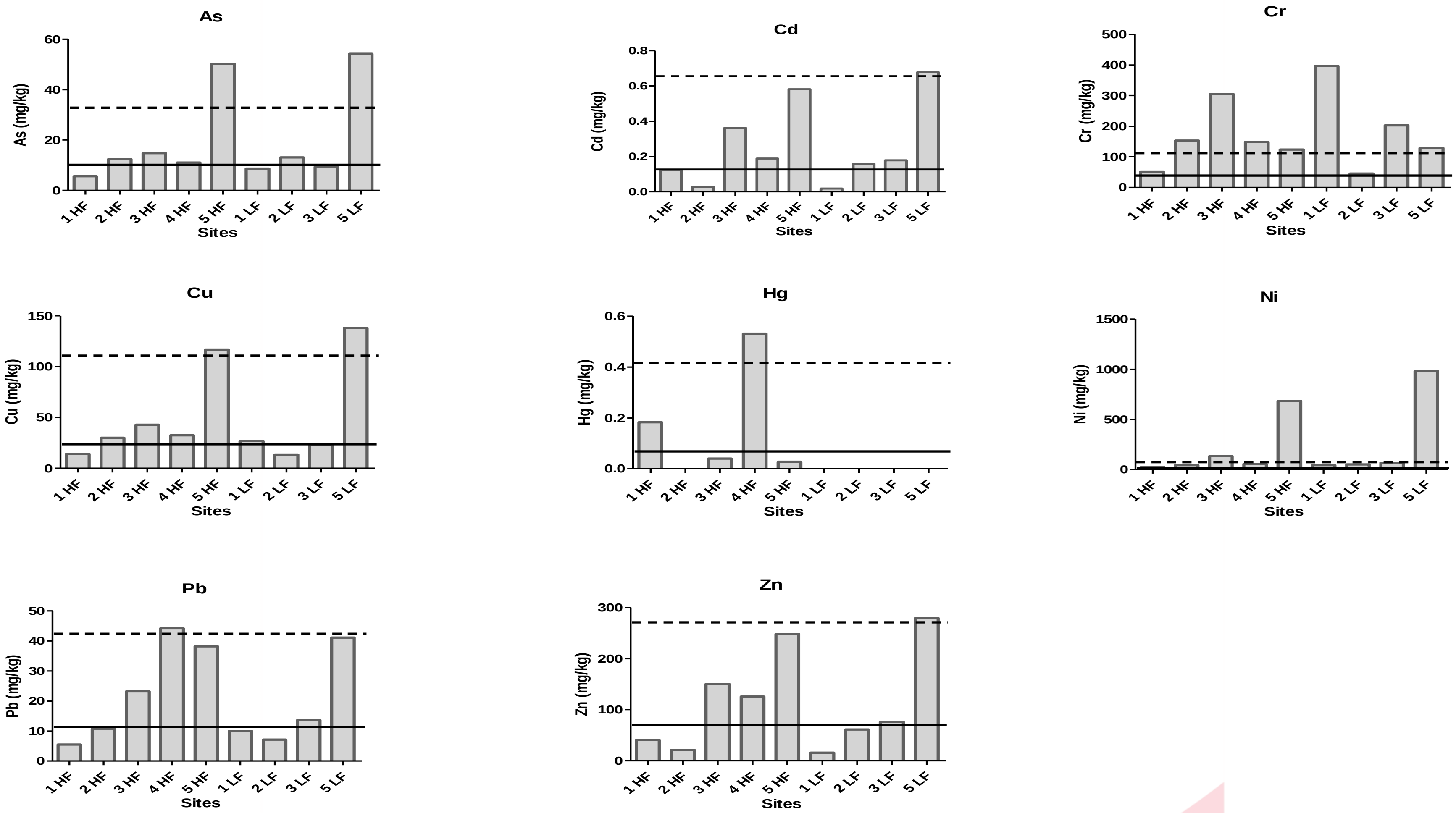


Figure 3.2. Concentration of metals with Threshold Effect Concentrations (─) (TEC) and Probable Effect Concentrations (- - -) (PEC) values (MacDonald et al. 2000).

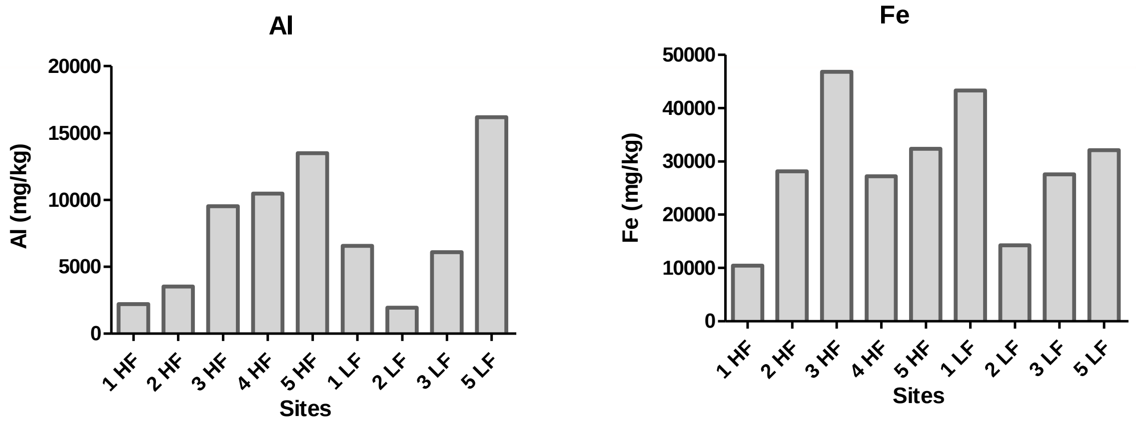


Figure 3.3. Aluminium and iron concentrations in the sediment of the Wonderfonteinspruit during high- and low-flow assessments. No thresholds, PEC or TEC were available for these metals.

3.4. Discussion

In comparison to a study performed in the Plankenburg and Diep Rivers of the Western Cape, the aluminium concentrations of the sediments within the Wonderfonteinspruit were observed to fall within a similar range; however, the iron concentrations within the Wonderfonteinspruit exceeded the maximum concentrations found in the Plankenburg River but not in the Diep River (Jackson et al. 2009). Malherbe et al. (2015) showed similar results where iron and subsequently aluminium concentrations were found to be highest in the sediment of the Harts River. Since iron is the most abundant in the earth’s crust (35%) it is often found in greater concentrations than other metals, while aluminium is the third most abundant metal in the earth’s crust and therefore would also be expected to be found in greater concentrations than most other metals (Jackson et al. 2009).

Chromium, copper and lead concentrations exceeded the average concentrations found in the Harts River for most sites except Sites 1 (high flow) and 2 (low flow) (Malherbe et al. 2015). Sites 2 (high flow) and 1 (low flow) were below the maximum average recorded for the Harts River in terms of zinc concentrations (Malherbe et al. 2015). Zinc concentrations were lower than the maximum recorded for all sites except Site 5 (low flow) as compared to the Plankenburg River, while all sites along the Wonderfonteinspruit were below the maximum recorded concentrations for lead and copper in both the Plankenburg and Diep Rivers (Jackson et al. 2009). Cobalt concentrations were higher than all the average concentrations recorded for the Harts River (Malherbe et al. 2015). Sites 3 and 4 were the only sites to exceed the average concentrations measured for manganese in the sediment of the Harts River but all sites exceeded the maximum concentration found in the Plankenburg River (Jackson et al. 2009; Malherbe et al. 2015). Manganese concentrations exceeded the maximum concentrations found in the sediment of the Diep River except for Sites 1 and 2 during the high-flow survey and Sites 2 and 3 during the low-flow survey (Jackson et al. 2009). Site 1 during the high-flow assessment was the only site to fall below the maximum average measured for nickel in the Harts River (Malherbe et al. 2015).

Mining processes result in the extraction of minerals ordinarily not present, or that are available only in small quantities in a system being made more readily available for deposition into river sediments (Serfor-Armah et al. 2006). The further processing of the rock material results in fine particulate matter being deposited on the surface as tailings and may result in the increased runoff of metals into river systems (Serfor-Armah et al. 2006). Winde (2010b) found that in 1997 a total of 2.5 t/a of uranium was released from only three mining effluent discharge points in the Far West Rand directly into the Wonderfonteinspruit; it was furthermore found that mining was the main contributor to uranium pollution in the Wonderfonteinspruit in both the West and Far West Rand. The problem has not abated as can be noted from the concentrations recorded in the sediments measured for the Wonderfonteinspruit, shown in Figure 3.1, where most sites exceeded the threshold values for uranium. The fluctuations shown in Figure 3.1 with regards to uranium concentrations at the various sites can be attributed to the dams separating each site which may have affected the concentration of uranium downstream from sites with higher concentrations such as Sites 1 and 2 or 3 and 4 during the high-flow assessment. Winde (2010b) describes a number factors such as rainfall events, timing of mining processes and instream chemistry affected by sunlight and photosynthesis all contributing to uranium concentration fluctuations within the Wonderfonteinspruit.

A comparison between the mean concentrations of metals within the Quesnel River Basin (QRB), Canada, impacted by mining operations and those found in the current study indicate similar arsenic concentrations, except for Site 5 where concentrations were found to be considerably higher than the mean of 15 mg/kg reported for the QRB (Smith and Owens 2014). Chromium was higher than those within the QRB for all sites excluding Site 2 (low flow) (Smith and Owens 2014). During both assessment periods Site 5 was the only site to equal and surpass the mean copper concentrations recorded for the QRB (Smith and Owens 2014). Sites 3, 4 and 5 were found to have concentrations of manganese elevated above those found in the mining-impacted sediments of the QRB (Smith and Owens 2014). The variation between the two manganese concentrations found in both mining-impacted river systems can be attributed to the natural presence of manganese in dolomite over which the Wonderfonteinspruit flows (Swart et al. 2003b). Only Site 1 (high flow) was observed to have concentrations of nickel below those found in the QRB, while concentrations of lead were below the mean for QRB only at Sites 1 and 2 (Smith and Owens 2014). Finally, zinc concentrations recorded in the QRB were exceeded at Sites 3 (high flow) and 5 (high and low flow) (Smith and Owens 2014). The mining activities in the QRB are primarily gold and copper mining; this may explain why copper at most study sites was observed at lower concentrations than in the QRB (Smith and Owens 2014).

The Luvuvhu and Olifants Rivers showed similar trends between aluminium and iron concentrations as in the Wonderfonteinspruit with iron concentrations exceeding aluminium concentrations; however, the Letaba River had more similar concentrations of iron and aluminium. Cadmium, cobalt and copper concentrations at Site 5 exceeded those found in the Luvuvhu, Letaba and Olifants Rivers (Smit et al. 2013). Chromium concentrations at Sites 2 and 3 (high flow) as well as Sites 1 and 3 (low flow) exceeded the maximum concentrations in the Luvuvhu, Letaba and Olifants Rivers. Arsenic concentrations in the Wonderfonteinspruit exceeded the concentrations in the Luvuvhu River, except for Site 4 on the Luvuvhu River which had similar results to that of Site 5 on the Wonderfonteinspruit (Smit et al. 2013). The arsenic concentrations in the Letaba and Olifants Rivers exceeded those of several sites in the Wonderfonteinspruit with especially the Olifants River showing greater concentrations than the maximum found in the Wonderfonteinspruit. Manganese and lead concentrations in the Wonderfonteinspruit all exceeded even the maximum concentrations found in the Luvuvhu, Letaba and Olifants Rivers (Smit et al. 2013). Sites 3 and 5 exceeded the maximum nickel concentrations recorded in the Luvuvhu and Olifants Rivers; however, all sites in the Wonderfonteinspruit exceeded those for Letaba River (Smit et al. 2013). All sites in the Luvuvhu, Letaba and Olifants Rivers had lower uranium concentrations than those found in the Wonderfonteinspruit. Zinc concentrations at Sites 3, 4 and 5 (high flow) as well as Site 5 (low flow) exceeded the maximum zinc concentrations in the Luvuvhu and Olifants Rivers, while Sites 1 (high and low flow) and 2 (high flow) were below the minimum concentrations found in the Luvuvhu and Olifants Rivers and below the zinc concentrations in the Letaba River (Smit et al. 2013).

The relationship between the various sediments of the several rivers that were compared thus indicates that variation naturally occurs between systems. These variations may also arise due to the land uses impacting upon the various rivers. The Harts River receives water from the Vaal River and has upstream impacts including agriculture, urban runoff and small-scale mining (Malherbe et al. 2015). The Harts River most commonly had lower average concentrations while the maximum concentrations of the Western Cape rivers often exceeded those of the Wonderfonteinspruit. The impacts upon the Plankenburg River may explain the results as the highest concentrations of metals were often detected at sites affected by industrial activities, while the Diep River experienced impacts from a wastewater treatment works as well as a boating club (Jackson et al. 2009). When comparing the Diep

River, Plankenburg River and QRB concentrations, the QRB mean concentrations were frequently found to correspond to those observed in the Wonderfonteinspruit; this may be attributed to the similar metal composition being released into rivers impacted by gold mining (Smith and Owens 2014). The Luvuvhu, Letaba and Olifants River sites were in the Kruger National Park, with pollution arising only from further upstream sources such as informal rural settlements, thus the overall less polluted state of these three rivers and especially their protection within the Kruger National Park would explain the overall decreased metal concentrations in comparison to the Wonderfonteinspruit (Smit et al. 2013). The often elevated metal concentrations found at Site 5 may also be attributed to the released pipeline water that contains significant amounts of pumped mine water (Coetzee et al. 2006).

Hamman (2012) compared the average metal concentrations recorded in light and dark sediments within the Wonderfonteinspruit in 2012; these were compared to the concentrations shown in Figure 3.1 to 3.3. It was found by Hamman (2012) that light sediments had lower metal concentrations than dark sediments. Site 5 during the low-flow survey exceeded the highest concentration of cobalt found in Hamman (2012); however, during both assessment periods Sites 1, 2 and 3 were observed to have lower concentrations than those found in the light sediments by Hamman (2012). Nickel and zinc concentrations were all below those found for dark soils; however, Site 5 exceeded the concentrations found in light soils for both metals. Cadmium concentrations were found to range between the concentrations found in light and dark soils, except for Sites 2 (high flow) and 1 (low flow) which were well below the concentrations found for light soils by Hamman (2012). Sites 3, 4 and 5 during the high-flow assessment as well as Site 5 during the low-flow assessment exceeded the lead concentrations for dark sediments (Hamman 2012). Site 1 during the high flow was the only site to have higher concentrations of uranium than those found in the dark sediments of the Wonderfonteinspruit in 2012; however, only Sites 2 (high flow) and 1 (low flow) had uranium concentrations below those observed for light sediments (Hamman 2012). Copper concentrations at Site 5 exceeded the concentrations found for dark sediments while all other sites were nearer the concentrations found in light sediments (Hamman 2012). It should be noted that the location of the sites selected along the Wonderfonteinspruit for the current study differed as Hamman (2012) used sites that were situated further downstream than those used in the current study. This may account for some observed differences especially with regards to the often higher concentrations found at Site 5 which was situated closer to the mining pipeline and thus sites further downstream may have decreased metal concentrations due to metals settling out.

From an examination of the sediment pollution indices as well as the guideline values for the protection of aquatic species (MacDonald et al. 2000; Pheiffer et al. 2014) it is clear that the sediments within the Wonderfonteinspruit are contaminated and enriched with metals. The sites of greatest concern are clearly identified by the PLI values that indicate Sites 3 and 5 as the most polluted sites. The relationship between the sediment indices that were applied was very similar with the I_{geo} values generally being less severe and this may be due to the greater distinctions available in the index. The information represented by all three indices suggests contamination within the sediments of the Wonderfonteinspruit. The high PLI value for Site 3 is of particular concern as this site is located in the Donaldson Dam which is utilised by the Bekkersdal community for numerous activities including subsistence fishing and drinking water (Chapter 5).

The metals recorded are some of the most toxic metals, for example chromium, nickel, lead, cadmium and arsenic are carcinogenic and can also cause a range of other pathological conditions if found in excess within the environment (Moore et al. 2009). Metals commonly occur within an aquatic system naturally; however, their occurrence is usually limited to trace amounts as can be suggested by the international averages provided in Viers et al. (2009). The elevated metal concentrations observed especially at Sites 3 and 5 are most likely as a result of anthropogenic impacts, in particular gold and uranium mining in the area (Winde 2010a; Hamman 2012). The presence of metals within the Wonderfonteinspruit at such high concentrations especially for cobalt, nickel and uranium is an issue of concern as the sediments act as sources for metals within the water and can also become bioaccumulated within organisms (MacDonald et al. 2000; Salah et al. 2012). As the sediment is the ultimate sink for metals it can pose one of the greatest threats to the aquatic ecosystem and subsequently to human activities (Wepener and Vermeulen 2005). Thus elevated metal concentrations within the sediment of the Wonderfonteinspruit pose high risks to users of the Wonderfonteinspruit due to their potential adverse impacts on water quality and fish edibility.

3.5. Conclusion

The contamination or the sediments within the Wonderfonteinspruit is apparent and can result in the release of the metals into the water column thereby resulting in water pollution and increasing the risk of water use by both aquatic organisms and humans. Sites 3 and 5 are of particular concern due to the elevated number of metals that have been found to exceed the guideline metal concentrations in sediment. Mining activities in this particular area appear to be the main source of these sediment-enriching metals (Winde 2010a; Hamman 2012). The following section will discuss the assessment of fish health an tissue analyses.

4. Health assessment and metal bioaccumulation in *Micropterus salmoides* from the Donaldson Dam, Wonderfonteinspruit

4.1. Introduction

Micropterus salmoides, the largemouth bass, is an introduced species of fish that has become widespread throughout South Africa (Skelton 2001). It is commonly found within impoundments and is predaceous (Skelton 2001). The introduction of this popular angling species has contributed to the decline in indigenous species populations (Cambray 2003). The Donaldson Dam is known for carp and bass fishing (African Gold 2014; Best Fishing Spots 2014).

The Health Assessment Index (HAI) for fish is an attempt to combine several fish health indices, such as the condition factor (CF) and hepatosomatic index (HSI), into a holistic overall fish health index (Heath et al. 2004). The index is based on the assumption that any deviation from the norm will reflect the possibility of a negative change in water quality and relies upon the ease of observing both internal and external fish tissues and organs (Heath et al. 2004). The fish HAI is commonly applied as a tool to assess fish health together with other indices such as the splenosomatic index (SSI), HSI, gonadosomatic index (GSI) and CF (Crafford and Avenant-Oldewage 2009; Rohlenová et al. 2011; Sadekarpawar and Parikh 2013).

The use of bioaccumulation for monitoring metal accumulation in a system may be more useful than measuring metal concentrations in water or sediment (Gilbert and Avenant-Oldewage 2014). The concentration of metals in water is often transitory, while metal concentrations in the sediment do not necessarily reflect the bioavailability or dissolution of the metals in water. The use of metal bioaccumulation in fish tissue can thus provide an indication of the accumulation of bioavailable metals from the system (Wang et al. 2012; Gilbert and Avenant-Oldewage 2014). Bioaccumulation is dependent on several biological, physical and chemical factors (Tate and Husted 2014). Some metals are essential for aquatic life (e.g. iron and zinc) but exert harmful effects if present at elevated levels. Other metals (e.g. lead and mercury) are found at very low concentrations and are harmful if they become elevated (Addo-Bediako et al. 2014). Sequestration or storage of metals takes place in inert tissues such as muscle and bone tissue and therefore provides a more historically accurate record of metal accumulation (Martiniaková et al. 2012).

The aim of this chapter was to determine the health of *M. salmoides* as well as the possible human health risk associated with the ingestion of bioaccumulated metals in the fish tissue. It is hypothesised that the health of the captured large-mouth bass will be poor and in turn its edibility, if consumed by humans, will be poor.

4.2. Methods and materials

4.2.1. Fish Health Assessment

Nine *M. salmoides* were collected in the Donaldson Dam using electro-shocking, angling and fyke nets (Figure 4.1). The sampling took place during the low-flow season as it is expected that metal concentrations and therefore bioaccumulation by fish would be greatest due to the reduction of the dilution effect of rainfall. The captured fish were kept in a holding tank and all dissections were carried out within one hour of fish capture. Blood was drawn from the dorsal aorta at the caudal peduncle using sterile heparinised Vacuette® 10 mL containers with Vacuette® needles (0.80 mm x 38 mm). The blood samples were stored in Vacutainers® on ice until total plasma protein determination. Plasma protein was removed from the blood by centrifuging the samples for 15 min at 3 000 r/min. The plasma was then decanted into 2 mL CryoTubes® and stored at -80 °C until plasma samples were prepared using a Roche total protein kit. The plasma preparation was then analysed in triplicate using a universal BioTek micro-plate reader at wavelengths of 540 nm (McHugh et al. 2011). The gender, total weight (calibrated lip-grip scale), total length and standard length were determined for all sampled fish.

Figure 4.1. Sampling of *Micropterus salmoides* at Donaldson Dam.

The fish were sacrificed by severing the spinal cord and an external examination of organs and tissue was performed which included eyes, skin, fins, gills and opercula as well as external parasites prior to dissection. Internal organs and tissue were examined; these included: internal parasites, mesenteric fat, bile, liver, spleen, hindgut and kidney. The examination of both internal and external health factors was performed as described in Adams et al. (1993) and Heath et al. (2004). The gonads, spleen and liver were removed from the specimens and weighed on a balanced Sartorius scale in the field. The CF was calculated according to Crafford and Avenant-Oldewage (2009).

Condition Factor (CF): (weight (g) × 10^5) ⁄ (total length (mm))^3.

The GSI and HSI were calculated according to Sadekarpawar and Parikh (2013).

Gonadosomatic index (GSI): (Gonad weight (g) / Fish weight (g)) × 100

Hepatosomatic index (HSI): (Liver weight (g) / Fish weight (g)) × 100

Finally, the SSI was calculated according to Rohlenová et al. (2011)

Splenosomatic index (SSI): (spleen weight (g) / body weight (g)) x 100

Statistical analysis was done using SPSS to determine the correlation between total length and SSI, HIS, CF and GSI. The tests used included Pearson's correlation coefficient (also known as Pearson's *r* correlation test) to calculate the correlation coefficient (r). The strength of the relationships according to the Pearson's *r* test was based on those provided by Dancey and Reidy (2004).

4.2.2. Fish tissue collection

Upon the completion of the fish HAI, muscle samples were removed from all nine fish specimens for metal analyses. The scales were removed from the *M. salmoides* specimens and the muscle was filleted by removing both the light and dark muscle tissues along the lateral line by separating the muscle from the rib cage and spine.

4.2.3. Microwave digestion

Metal analysis was performed in order to determine the accumulation of metals in muscle tissue from the environment by *M. salmoides* and subsequently to establish the edibility of captured largemouth bass.

The digestion of fish muscle tissue was adapted from Hassan et al. (2007) and performed as described below. Between 0.3 g to 0.5 g of dried muscle tissue was weighed using a scale

(Zeiss West Germany Pty. Ltd.) and placed into the reaction vessels. Thereafter, 10 mL of 65% Suprapur® nitric acid was added to the reaction vessels and subsequently digested in a CEM Mars 5 Microwave Accelerated Reaction System. The digested fluid was then decanted into a 50 mL volumetric flask and topped up to the 50 mL mark with 1% nitric acid. The mixture was then filtered through a filter of 45 µm mesh size and decanted into 50 mL Falcon tubes. The digested sediment and muscle tissue was then transferred into 10 mL tubes prior to metal analysis using an ICP-MS Agilent 7500 CE.

4.2.4. Metal analysis in tissue

A calculation to determine the ratio between the metals available in the sediment and water and those available in the fish tissue was performed using the equation from Gilbert and Avenant-Oldewage (2014), known as the bioconcentration factor (BCF):

$$\mathrm{BCF} = C_{\mathrm{muscle}} / C_{\mathrm{water\ or\ sediment}}$$

Where:

C_{muscle}: Concentration of metal in muscle of fish in mg/kg
C_{water}: Concentration of metal in water in mg/L during the low-flow assessment
C_{sediment}: Concentration of metal in sediment in mg/kg during the low-flow assessment

Edibility of fish tissue

The following edibility calculations were performed according to Bester (2013) to determine the associated human health risk with consuming fish tissue:

$$\text{Total dose (mg)}: C_m \times \mathrm{IR} \times \mathrm{ED}$$

Where:

C_m: Concentration of metal in muscle (mg/kg)
IR: Daily intake rate (kg)
ED: Exposure duration (days)

The IR and ED values were based upon scenarios provided in Heath et al. (2004) as the recommended general derived values for exposure studies (Table 4.1).

$$\text{Average Daily Dose (ADD)}: (C_m \times \mathrm{IR}) / \mathrm{BW}$$

Where:

BW: Average adults body weight (kg)

The BW was recommended by USEPA (2000) as the mean body weight for adults, which includes women of a reproductive age (Table 4.1).

$$\text{Hazard Quotient (HQ)}: \mathrm{ADD} / \mathrm{RfD}$$

Where:

> RfD: Reference dose values as provided in Table 4.2 taken from the Integrated Risk Information System (IRIS) as provided by USEPA, which provides a toxicological review of various chemicals (USEPA 2014). A value of greater to or equal to one is expected to be potentially toxic.

4.3. Results

4.3.1. Fish health assessment

The gender profile of the fish caught indicated seven males and two females as shown in Table 4.3, while the full HAI results are represented in Appendix B and C. Both females had slightly inflamed hindguts (Figure 4.2A) and large ovaries filled with eggs. Due to the hindgut inflammation the two female specimens were of the few to receive a less than perfect HAI score. Only one male showed abnormalities with regards to the HAI scores; this male was dead upon dissection and this resulted in limited blood being drawn from the fish which was expected to have caused an inaccurate reading of its blood plasma protein. The mean total length for the fish was 413.44 mm with the largest fish being 458 mm and the smallest 325 mm. The largest and smallest fish in terms of standard length were 404 mm and 283 mm, respectively, with a mean standard length of 361.44 mm (Table 4.3). Furthermore, in almost all males the gonads were observed to be deformed with nodules as well as being rubbery and hard to the touch (Figure 4.2B).

The mean CF for the sampled *M. salmoides* was 1.8 with minimum and maximum values of 1.51 and 2.16, respectively. The GSI mean value was 0.82% with females with egg-filled gonads having the highest GSI values of 1.84% and 3.25%. The highest GSI value amongst male *M. salmoides* was 0.45% with smaller males having lower GSI indices. Correlation values are given in Table 4.4. The relationship between total fish length and CF was found to have a strong negative correlation ($r = -0.743$; $p = 0.022$). The GSI was found to have a strong negative correlation ($p = 0.023$; $r = -0.822$) to CF when comparing only the male specimens. The GSI was also found to have a strong positive correlation ($r = 0.713$) to total length but was not significant at the 0.05 level ($p = 0.072$) when females were excluded. There was also found to be a strong positive correlation between GSI and HSI ($p = 0.016$; $r = 0.766$) when the entire sample was considered. A weak negative and non-significant ($p = 0.677$; $r = -0.194$) relationship was found between GSI and HSI when only males were considered.

4.3.2. Fish tissue

Gold, lead and zinc were not detected in water samples. The metals found to have accumulated the most within the fish muscle was iron and zinc, while platinum was found to be the lowest (Table 4.2). Copper and manganese were the only two other metals found to exceed a concentration of 1 mg/kg (Table 4.2).

The total dose of metals is highest for iron followed by zinc and lowest for platinum. The ADD is likewise highest for iron and zinc and lowest for platinum (Table 4.2). Arsenic was found to be the most significant metal as its hazard quotient (HQ) exceeded the value of 1 (Table 4.2).

Most BCF values were greater for water than for sediment (Table 4.5). The metals showing the greatest BCF values with regards to the metal concentrations in water were chromium and iron (Table 4.5). Silver and platinum had the highest BCF values with regards to the bioaccumulation of metals from sediment (Table 4.5).

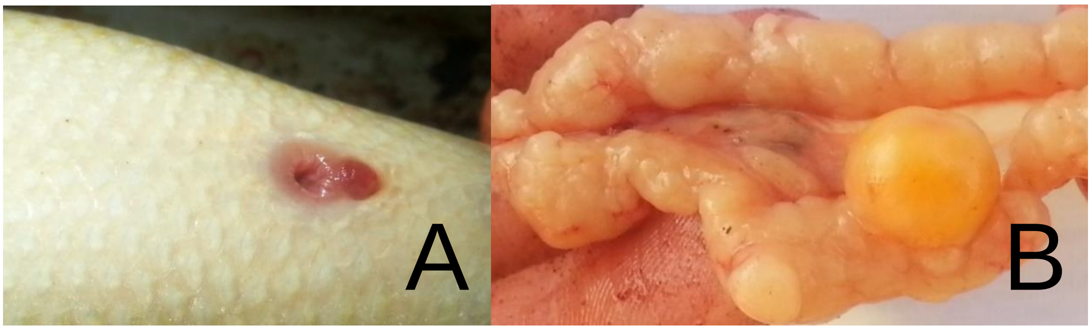


Figure 4.2. Photographs of anomalies found during the Fish Health Assessment of *Micropterus salmoides* from the Donaldson Dam (A: inflamed hindgut; B: testes).

Table 4.1. Values of variables in calculations for edibility.

Variable	Value	Reference
IR	0.150 kg/day	Heath et al. 2004
ED	10 958 days (30 years)	Heath et al. 2004
BW	70 kg	USEPA 2000

Table 4.2. Metal concentration in fish tissue (C), total dose (TD), average daily dose (ADD), hazard quotient (HQ) and reference dose (RfD) values according to USEPA 2014. Missing values are represented by the symbol NA (not available).

	C*	RfD	TD	ADD	HQ
Ag	0.185	0.005	304.7	$3x10^{-4}$	0.079
As	0.185	$3x10^{-4}$	303.8	$3x10^{-4}$	1.32
Au	0.309	NA	507.8	0.001	NA
Co	0.128	0.03	210.1	$6x10^{-4}$	0.009
Cr	0.553	0.003	909.3	0.001	0.395
Cu	4.781	0.04	7858.4	0.01	0.256
Fe	50.195	0.7	82506.1	0.108	0.154
Mn	2.616	0.14	4300.8	0.006	0.04
Ni	0.614	0.02	1008.4	0.001	0.066
Pb	0.136	NA	222.9	$2x10^{-4}$	NA
Pt	0.017	NA	27.3	$3x10^{-5}$	NA
Se	0.538	0.005	883.9	0.001	0.23
Th	0.139	NA	228.8	$2x10^{-4}$	NA
U	0.1	0.003	165	$2x10^{-4}$	0.072
Zn	14.092	0.3	23162.6	0.03	0.101

*mg/kg

Table 4.3. Fish Health Assessment Index results.

Sample number	Gender	Standard length*	Total length*	Total body mass (g)	External HAI score	Internal HAI score	CF	GSI (%)	HSI (%)	SSI (%)	Comments
M. sal 1	Male	375	435	1 360	0	0	1.65	0.38	0.79	0.04	Testes deformed with nodules, rubbery to the touch
M. sal 2	Male	283	325	700	0	0	2.04	0.25	0.60	0.03	
M. sal 3	Male	316	376	1 040	0	0	1.96	0.16	0.63	0.07	Testes deformed with nodules, rubbery to the touch
M. sal 4	Male	342	394	1 320	0	0	2.16	0.16	0.77	0.05	
M. sal 5	Male	386	432	1 220	0	10	1.51	0.45	0.83	0.11	Blood lysed; testes deformed with nodules, rubbery to the touch
M. sal 6	Female	389	440	1 520	0	10	1.78	1.84	0.95	0.03	Gonads filled with eggs
M. sal 7	Female	404	458	1 460	0	10	1.52	3.25	1.18	0.07	Gonads filled with eggs
M. sal 8	Male	369	427	1 360	0	0	1.75	0.41	0.32	0.12	Testes deformed with nodules, rubbery to the touch
M. sal 9	Male	389	434	1 520	0	0	1.86	0.44	0.51	0.08	Testes deformed with nodules, rubbery to the touch
Mean		361.44	413.44	1 277.78	0	3.33	1.80	0.82	0.73	0.07	

*In mm

Table 4.4.Correlation values of Pearson's r test between fish health indices and total length.

Description	Excluding	P value (significant < 0.05)	r value	Strength of correlation (Dancey and Reidy 2004)
CF and total length	None	0.022	-0.743	Strong negative
GSI and HIS	None	0.016	0.766	Strong positive
GSI and total length	Females	0.072	0.713	Strong positive
GSI and HIS	Females	0.677	-0.194	Weak negative
GSI and CF	Females	0.023	-0.822	Strong positive

Table 4.5. Bioconcentration factor (BCF) for sediment and water in fish tissue during the low-flow assessment.

Metal	Water	Sediment
Ag	NA*	1.25
As	9.65	0.02
Au	111.01	0.89
Co	19.29	0.01
Cr	1 187.88	0.00
Fe	428.65	0.00
Mn	170.45	0.00
Ni	45.72	0.01
Pb	NA	0.01
Pt	192.66	1.70
Th	185.01	0.05
U	1.18	0.01
Zn	NA	0.19

*NA: not available

4.4. Discussion

4.4.1. Fish health assessment

Micropterus salmoides is listed by Heath et al. (2004) as one of the recommended species to investigate chemical contamination. The family Centrarchidae, of which *M. salmoides* is a member, has been used for contaminant studies and *M. salmoides* is known to be captured by both anglers and subsistence fishermen (Heath et al. 2004). For South African rivers it is recommended that a minimum of five individual fish samples be collected and a total of nine were collected for this assessment (Heath et al. 2004). The fish HAI values determined for *M. salmoides* in the Donaldson Dam were found to be good. No abnormalities were observed in any fish in terms of the HAI assessment except in the case of the two female specimens whose vents of their hindguts were slightly inflamed.

When performing the HAI it is essential to bear in mind that the tissue in a fish will change to maintain homeostasis in reaction to environmental changes; only when environmental changes are severe and/or persistent enough will these changes be reflected in the appearance of the tissue or organ (Heath et al. 2004). When considering the observed deformity of the testes, it is indicative of environmental stress and it is likely that further histological examination will indicate more specific abnormalities within the testes (van Dyk and Pieterse 2008).

Limited literature exists that comprehensively summarises the expected index values for CF, HSI, SSI and the GSI, in particular for *M. salmoides*. The CF is based on the assumption that heavier fish will be in a better condition. The CF is therefore dependent on variables such as food availability, season, temperature and sexual maturity (McHugh et al. 2013). Peles et al. (2006) determined the CF for *M. salmoides* from five reservoirs in South Carolina. The values obtained are similar to those obtained from the Donaldson Dam and showed no significant difference between sexes.

Brown and Murphy (2004) indicated that the GSI values varied between 0.0001% and 0.0126% while the HSI values varied between 0.001% and 0.9302% for *M. salmoides* sampled in Aquilla Lake in Texas. The GSI values of all samples from the Donaldson Dam were found to be well above the upper limit of those found by Brown and Murphy (2004) with the lowest value at 0.16%. The females had GSI indices of 1.84% and 3.25% well above those observed in Brown and Murphy (2004) even during the spawning season. The HSI values observed in the samples from Donaldson Dam were mostly within the upper limit described in Brown and Murphy (2004) excluding those observed for the female fish that were both found to be above the upper limit. The greatest increase in HSI values for the *M. salmoides* from Texas was during spring months; this could explain why HSI values were also high in the Donaldson Dam and most closely resembled the upper limit of the HSI as reported by Brown and Murphy (2004).

The SSI values recorded for *M. salmoides* in two tributaries (Cedar Creek in California and Etonia Creek in Florida), used as reference sites, were found to have a mean value of approximately 0.24% (Sepúlveda et al. 2004). Fish from sites affected by pulp mill effluent had lower SSI percentages which was indicative of decreased hematopoietic capacity leading to a decline in red blood cell counts (Sepúlveda et al. 2004). Sepúlveda et al. (2004) also indicated a large difference between the SSI values of mainstream and tributary sites and a study by Borton et al. (1996) found that *M. salmoides* in sites contaminated with 8% pulp mill effluent showed no changes in SSI. The SSI value most comparable to the ones found in this study is the mean for contaminated mainstream sites reported in the study by Sepúlveda et al. (2004), as the highest SSI value found for largemouth bass from Donaldson Dam was 0.12% with a mean value of 0.07%.

The strong negative and statistically significant relationship between the CF and total length as well as the positive relationship between GSI and total length (excluding females) may indicate that larger and possibly longer-lived specimens that have been exposed to pollutants for prolonged periods within Donaldson Dam have been negatively affected. Streit (1998) found that some relationship existed between increasing size and increased contaminant concentration, which may explain deteriorating health in fish, though the same relationship was not found in the fish from Donaldson Dam. Furthermore, the strong negative and significant relationship between CF and GSI indicates that as CF declines so GSI increases which suggests that the increase in the size of gonads indicates a decline in fish health; however, this relationship can also be explained by the energy trade-off that occurs in preparation for spawning (Brown and Murphy 2004). This study cannot definitively state which explanation is more likely, because only one sampling survey was performed; however, the deformed appearance of the male gonads does suggest an impact on fish health indicated by increased gonad size as compared to CF. Finally, the strong positive and significant correlation between GSI and HSI is only observed when females are included in the correlation test. A study by Dahle et al. (2003) on Atlantic cod found that liver sizes in female fluctuated during the spawning season, with some showing maintained or increased HSI levels and other studies showing decreases in liver sizes, while males consistently showed a decrease in liver size prior to and during spawning. A weak negative and non-significant relationship between HSI and GSI was found when only males were considered, therefore it is recommended that further tests should be performed to determine the relationship between HSI and GSI in largemouth bass within the Wonderfonteinspruit, such that it can be determined whether fluctuations in HSI percentages between populations are due to environmental factors or time of sampling that correlates with fish life-cycle stages.

4.4.2. Fish tissue

A number of studies have found that zinc and iron are accumulated to the greatest extent in fish muscle of various species throughout Africa (Gilbert and Avenant-Oldewage 2014; Tate and Husted 2014); this is also evident in the accumulation of these metals in *M. salmoides* within the Wonderfonteinspruit (Table 4.2).

The BCF demonstrates the relationship that exists between the concentration of metals within the water and sediment to what has been accumulated within the fish tissue and can suggest the segregation that exists between the environment and the fish species (McGeer et al. 2003). The results indicate that accumulated metals in the fish tissue exceed the concentrations of metals available in the water (BCF > 1) and thus suggest that metals may have an impact upon fish beyond what is indicated by the current concentrations of metals in the water. Conversely, the BCF values for metals in sediment suggest that the values for metals in the sediment are greater than those in fish tissue (BCF < 11). This observation supports the previous findings reported in the literature that have suggested that a large proportion of the metals in the sediment are not necessarily bioavailable and that sediments act as natural sinks for metals (Wepener and Vermeulen 2005; Gilbert and Avenant-Oldewage 2014). The differences observed between the BCF values of water and sediment can also be attributed to the feeding habit of *M. salmoides* which is piscivorous but can feed on invertebrates, fish, amphibians and even small mammals (Skelton 2001; Shoup and Wahl 2009). Species that are known as bottom feeders may thus have greater accumulation of metals from the sediment than predaceous fish species (Kidwell et al. 1995).

In terms of edibility, the metal of greatest concern is arsenic as it was the only metal to have an HQ value of greater than 1, whereas none of the other metals had a value of above 0.4 (Table 4.2). Arsenic is often associated with gold-bearing ores that have high sulphate-containing deposits, which are essential components in the formation of AMD and which is associated with mines in the West and Far West Rand (Coetzee et al. 2006; Straskraba and Moran 2006). The arsenic concentrations in water were above the regulatory limits for drinking water. Arsenic, especially in water, is considered to be one of the most significant causes of cancer in humans and has been found to have a statistically relevant association with cancers of the skin, bladder and other internal organs (Abernathy et al. 1999; Kapaj et al. 2007). Studies have also found that arsenic can likewise be associated with diabetes and hypertension and that individuals with poor nutrition or less-than-ideal health would suffer most severely from the effects of arsenic (Abernathy et al. 1999; Kapaj et al. 2007). The exposure of human populations to arsenic above the regulatory limit is therefore not advisable.

4.5. Conclusion

The fish HAI was not indicative of a polluted state; however, the GSI values and visual observation of the gonads do indicate possible water quality issues. The relationship observed between CF and GSI with the total length of the largemouth bass also indicates a possible link between larger fish sizes and decreased fish health. The elevated levels of arsenic within fish muscle indicate that the water and/or sediment quality within the Donaldson Dam is less than ideal, especially for human use. Furthermore, the edibility study indicates that arsenic concentrations within the fish tissues should first be addressed before individuals are permitted to consume the fish. This would also indicate that activities such as aquaculture are not advisable if similar arsenic concentrations are to continue to accumulate in fish muscle tissue.

It is therefore recommended that a more in-depth histological examination of the fish within the Wonderfonteinspruit be performed. This would most likely also increase the likelihood of being able to establish a correlation between fish and human health as the fish HAI levels gave little indication as to the polluted state of the Donaldson Dam. The chapter to follow will investigate the diatom and macroinvertebrate community composition and assemblages of the Wonderfonteinspruit.

5. Biological indices: Diatoms and macroinvertebrates

5.1. Introduction

Despite the effectiveness of using chemical components to determine the state of a system at a particular point in time, a number of limitations exist when using only chemical analysis. Chemical constituents are constantly changing in a system, changing chemical composition and physical states, and being sequestered both organically and inorganically (Harding and Taylor 2011; Hamman 2012). The concentrations and chemical components detected within a freshwater system are also dependent on point or non-point source runoff events and rainfall patterns (Harding and Taylor 2011). The measure of chemical constituents within a system therefore provides only a snapshot of the whole system both temporally and spatially. The use of biological indicators that are often rapid and cost-effective can complement chemical analysis to improve upon its limitations, therefore providing a more integrated and holistic view of an aquatic system (Kitner and Poulíčková 2003; Heath et al. 2004; Kleynhans 2008; Thirion 2008; Harding and Taylor 2011).

In terms of their characteristics, implementation of biological indicators should be simple, and the observed results should be able to quantify the changes occurring in a system over time (including water quality and physical changes to habitat); these indices should be applicable over a large spatial geography and should provide data on historical or reference conditions. Biological indicators such as diatoms, invertebrates and fish have been used in models both nationally and internationally to primarily indicate the condition of freshwater systems (Graça and Coimbra 1998; Jiang 2006; Kleynhans 2008). However, these biological indices do not directly relate to the associated human health effects with decreased species abundance and diversity (Thirion 2008).

Diatoms occur in all types of aquatic ecosystems and share similarities over a large geographical distribution (Weilhoefer and Pan 2007). The various taxa show variation in their tolerance to pollution and preferences for certain physical conditions, thus reflecting changes in a system (Jüttner et al. 2010; Harding and Taylor 2011). The diatom community composition changes as water quality deteriorates or improves. More tolerant taxa will dominate as water quality decreases (Harding and Taylor 2011). Work on diatoms in South Africa and internationally has been done for a number of decades thus providing background information which is key to implementing a successful biological indicator (Potapova et al. 2004; Jüttner et al. 2010). Diatoms are excellent indicators of changes in water quality, as opposed to macroinvertebrate indices that in turn provide better information on habitat modification and some chemical changes (Newall et al. 2006). Furthermore, diatoms often form the base of the aquatic food chain and are key to ensuring a productive ecosystem (Harding and Taylor 2011).

Globally, macroinvertebrates have been used for several decades to assess the biological integrity of aquatic systems (Coimbra et al. 1996; Thirion 2008). The macroinvertebrate assemblages within a freshwater system provide a good indication of water quality, habitat and flow regime changes (Thirion 2008). Macroinvertebrates play vital roles in maintaining the functional integrity of streams (Wallace and Webster 1996).

It is hypothesised that both diatom and macroinvertebrate indices will reflect the degraded state of the Wonderfonteinspruit. The aim of this section is to determine the state of the Wonderfonteinspruit according to diatom and macroinvertebrate indices.

5.2. Methods and materials

5.2.1. Diatoms

Collection, preservation and assessment of the diatom abundance and diversity were performed as outlined in Koekemoer and Taylor (2009) and Taylor et al. (2007a). The hot HCl and $KMnO_4$ cleaning method was used as recommended by Taylor et al. (2007a). Identification of the diatoms was done using Taylor et al. (2007b) and Lavoie et al. (2008) (Appendix D). The following indices were applied to the classification results: Biological Diatom Index (BDI) according to Lenoir and Coste (1996), Specific Pollution Sensitivity Index (SPI) and the percentage pollution tolerant valves (%PTV) according to Harding and Taylor (2011). BDI score limits and classes are provided in Table 5.1. Table 5.2 provides SPI score limits, classes and EC.

Table 5.1. Biological Diatom Index (BDI) classes and limits (Taylor et al. 2007c).

BDI score	BDI class
>17	High quality
15 – 17	Good quality
12 – 15	Moderate quality
9 – 12	Poor quality
<9	Bad quality

Table 5.2. Specific Pollution Sensitivity Index (SPI) classes, limits and ecological categories (EC) (Harding and Taylor 2011).

SPI score	SPI Class	EC
>17.3	High quality	A
16.8 - 17.2		A/B
13.3 - 16.7	Good quality	B
12.9 - 13.2		B/C
9.2 - 12.8	Moderate quality	C
8.9 - 9.1		C/D
5.3 - 8.8	Poor quality	D
4.8 - 5.2		D/E
< 4.8	Bad quality	E

5.2.2. Macroinvertebrates

The methodology for site selection and sample collection was implemented as outlined in Macroinvertebrate Response Assessment Index (MIRAI) by Thirion (2008). Stones, vegetation, gravel, sand and mud were sampled, both in and out of current, for four of the five sites. Site 3 was located in an impoundment, so sampling was limited to vegetation, gravel, sand and mud and limited flow was present, as expected in an impoundment. The five sites along the Wonderfonteinspruit fall into the 11.01 Highveld Level II Ecoregion in the Lower Foothills zone within an altitude range of 1 300 -1 700 m amsl.

The invertebrates collected were thereafter preserved in 70% ethanol in 500 mL jars. Invertebrates were sorted and separated under a dissecting microscope. The invertebrates were identified using Gerber and Gabriel (2002) for identification to family level and into more refined taxa using the *Guides to the Freshwater Invertebrates of Southern Africa* (Day et al. 2001a; Day et al. 2001b; Day et al. 2001c; Day and de Moor 2002a; Day and de Moor 2002c; Day et al. 2003; de Moor et al. 2003a; de Moor et al. 2003b; Stals and de Moor 2007). Identification for the various taxa was done under a dissecting microscope and compound light microscope, as required. Further identification of Chironomidae was done using a scanning electron microscope (SEM).

The MIRAI model was applied to the identification results, using only the families provided in the MIRAI model and an Ecological Category (EC) was determined as suggested by Thirion (2008). The steps for EC determination using MIRAI include: establishing reference conditions, selecting sites, collecting data and assessing the habitat at each site (Thirion 2008). In summary, MIRAI generates an EC for macroinvertebrates by integrating the ecological requirements of natural macroinvertebrate assemblages in terms environmental tolerances, requirements and preferences and relating this to modified flow, instream habitat and water quality conditions; the deviation of macroinvertebrate assemblages from the reference condition is interpreted as the responses to changes within the environment by the macroinvertebrate assemblages (Thirion 2008). Table 5.3 provides the EC scores, respective categories and descriptions. By means of electronic communication, expert opinion was obtained from C. Thirion on 13 March 2015, in order to determine baseline conditions. The macroinvertebrate habitat was also assessed according to Dickens and Graham (2002) whereby a score was given to each biotope, with 1 representing limited habitat diversity (very poor) and 5 representing a wide diversity in habitat (highly suitable).

5.2.3. Statistical analysis

Redundancy analysis (RDA) was performed for both invertebrate and diatom species in relation to water quality variables. RDA is a linear constrained ordination method using direct gradient analysis (Lepš and Šmilauer 2003). The graphs for invertebrates and diatoms were created through the forward selection of the water pollutants that explained the greatest variation within the samples.

Table 5.3. Ecological categories (EC) as determined by the Macroinvertebrate Response Assessment Index (Thirion 2008).

EC score	EC category	Description
>89	A	Unmodified, natural
80-89	B	Largely natural
60-79	C	Moderately modified
40-59	D	Largely modified
20-39	E	Seriously modified
<20	F	Critically/ extremely modified

Statistical analysis was performed using Primer 6 to determine the following: number of taxa, abundance, Margalef's species richness, Pielou's evenness index, Brillouin and Fisher's alpha. Margalef's species richness determines the total number of taxa in a community sampled. Pielou's evenness index provides a measure to determine how uniformly individuals within a sampled community are distributed between the different taxa, in other words how similar the number of individuals between the different taxa are. The Brillouin and Fisher's test similarly determines evenness as does Pieolou's evenness index but is more sensitive towards species abundance.

5.3. Results

5.3.1. Diatoms

The total number of taxa found during both the high and low flow assessment period was 41 with both flow assessments having ten unique taxa during both assessment periods (Appendix D). Figure 5.1 indicates the three most abundant species for the high and low flow assessment *N. palea* was in the top abundant species for both the high and low flow. *C. menghiniana* and *A. granulate* were ranked first and second in terms of abundance for the high flow assessment while *G. parvulum* and *S. seminulum* were second and third most abundant during the low flow assessment. Figure 5.2 shows light microscope images of the most common species found during high and low flow assessments. Table 5.4 gives an indication of the number of taxa and index values for the high and low flow assessments of the diatom community within the Wonderfonteinspruit. The average number of taxa per site per flow assessment was 21 with Site 2 showing the lowest number of taxa for both the high and low flow and Site 1 the highest for the high flow assessment while Site 5 had the greatest number of taxa for the low flow assessment.

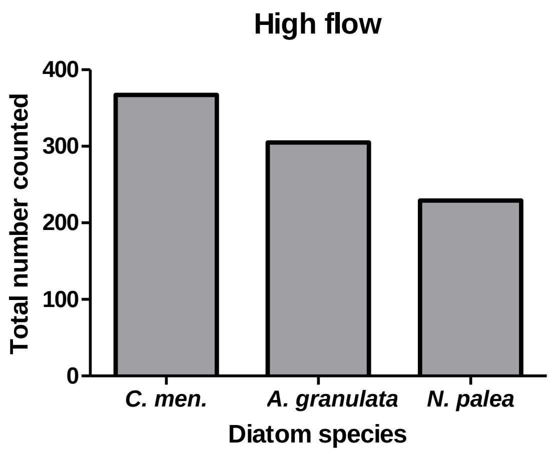
The mean percentage %PTV for the high flow was 33.32% with Site 1 having the greatest percentage of 66%. Site 2 had the greatest %PTV and the average for this assessment was 55.23%. The average for the SPI was 5.86 and 5.03 for the high and low flow respectively. Site 3 had the best SPI during the high flow with an index value of 8.4 while Site 5 had the best index value (7.1) for the low flow. Conversely, the lowest value during the high flow was found at Site 5 (4.2) and during the low flow at Site 2 (3.5). The mean values for the BDI during the high flow assessment were 7.7 and for the low flow 7.05. Site 3 (9.9) during the high flow assessment and Site 5 (9.9) during the low flow assessment both had the highest BDI scores. While Site 1 (5.9) and 2 (4.7) had the lowest BDI scores during the high and low flow assessments respectively.

The explanatory variables forward selected for diatoms were nickel, nitrates and nitrites which explained 57.8% of the total variation. The first and second axes show 28.08% and 16.50% of the 57.8% variation, respectively. A relationship between Sites 2, 3 and 4 during high-flow assessment as well as between Sites 2 and 3 during the low-flow assessment is observable (Figure 5.3). Sites 1 and 5 were found to be less related to the other sites during the high-flow assessment, but were closely related to one another during the low-flow assessment.

Table 5.4. Diatom results and indices.

Site	High flow						Low flow					
	No. of taxa	%PTV*	SPI*	EC*	BDI*	Class*	No. of taxa	%PTV*	SPI*	EC*	BDI*	Class*
1	30	66	4.8	D/E	5.9	Bad quality	27	48.8	4.9	D/E	8	Bad quality
2	17	30.5	6.6	D	8.1	Bad quality	15	75.8	3.5	E	4.7	Bad quality
3	22	12.8	8.4	D	9.9	Poor quality	15	73	4.6	E	5.6	Bad quality
4	20	19.8	5.3	D	7.9	Bad quality	DRY	DRY	DRY	DRY	DRY	Bad quality
5	20	37.5	4.2	E	6.7	Bad quality	29	23.3	7.1	D	9.9	Poor quality
Mean	21.8	33.32	5.86	D	7.7	Bad quality	21.5	55.23	5.03	D/E	7.05	Bad quality

*%PTV: Percentage pollution tolerant valves; SPI: Specific Pollution Index; EC: Ecological category (Harding and Taylor 2011); BDI: Biodiversity Index; Class according to Taylor et al. 2007c.



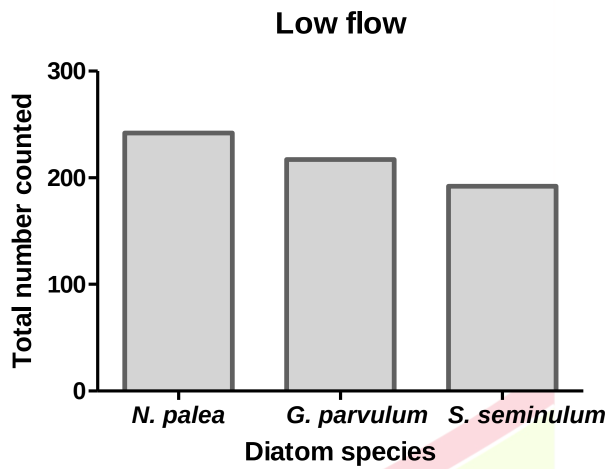


Figure 5.1. Top three most abundant diatom species per flow assessment.

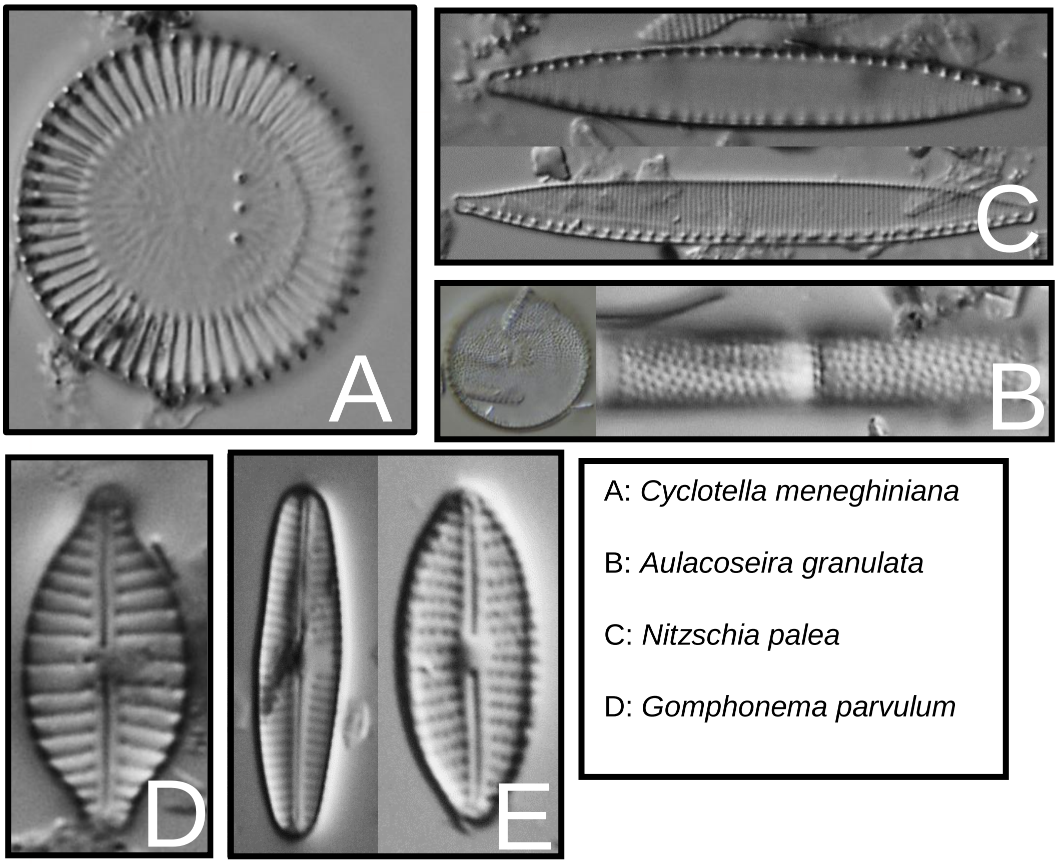


Figure 5.2. Light microscope images of most abundant taxa found.

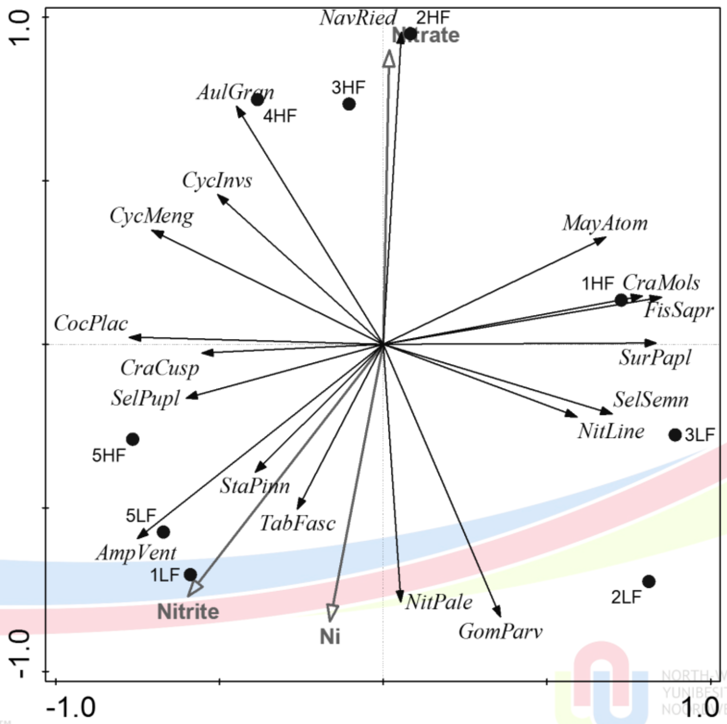


Figure 5.3. Redundancy analysis (RDA) of diatom species composition, sites and water quality.

5.3.2. Macroinvertebrates

In total 40 taxa were identified during both assessment periods, with 12 taxa unique to the high-flow and seven to the low-flow assessment period; these taxa are represented in Appendix E. The most abundant taxa during both assessments for Site 1 are *Daphnia pulex* and *Daphnia longispina.* During the low-flow assessment period at Site 1, *Simuliidae* were the third most abundant taxa while *Pseudorthocladius* sp. was the third most abundant. Site 1 was found to have a total of 13 taxa during the high-flow assessment period and nine taxa in the low-flow assessment. *Pseudorthocladius* sp. and *Tanytarsus* sp. were the most abundant taxa for Site 2 during the high-flow assessment while *Nais elinguis* was the most abundant during the low-flow assessment. The dominant taxa during the high flow assessment for Site 3 were *Pseudorthocladius* while *Tanytarsus* was most abundant during the low-flow assessment. Only one assessment was conducted at Site 4, namely during the high-flow period, as the site was dry during the low-flow period. The taxa with the highest abundance for Site 4 were *Simuliidae* (Metomphalus); this *Simulium* subgenus was found only at Site 4. *Simuliidae* (Pomeroyellum) had the greatest abundance during the high-flow assessment of Site 5 while *Daphnia longispina* was most abundant during the low-flow assessment.

Sites 3 and 5 were found to be the sites with the greatest number of taxa during the high- and low-flow periods, respectively (Table 5.5). Site 1 consistently had the greatest abundance as can be noted in Table 5.5. In terms of Margalef's species richness, Brillouin's evenness index and Fisher's alpha, the greatest richness for the high-flow period was at Site 2 while Site 5 had the greatest richness during the low-flow period (Table 5.5). Pielou's evenness index indicates that, for both the high- and low-flow assessments, Site 5 had the greatest diversity when abundances are taken into consideration (Table 5.5).

The overall EC for the sites along the Wonderfonteinspruit is a category D according to the MIRAI and the sites all fall into 11.01 Highveld Level II Ecoregion in the Lower Foothills zone within an altitude range of 1 300-1 700 m amsl. The difference between reference data and the results found are demonstrated in Table 5.6; from the data it is clear that the current ASPT and SASS score are far lower than those for the reference conditions. The biotope scores indicate that Site 1 had the highest score for stones-in-current and stones-out-of-current biotope groups, Sites 4 and 5 had the highest score for aquatic vegetation and Site 3 was the least diverse (Table 5.7). A total variation of 54.7% was explained by the forward selected explanatory variables of ammonium and arsenic; 34.85% was presented on the first axis and 10.83% on the second axis. Site 1 was closely associated with *Daphnia* sp. The RDA results indicated that Sites 2, 3, 4 and 5 were closely associated; while Site 1 showing some variation from the other sites during the same period (Figure 5.4). However, sites were less closely associated during the low-flow period; Site 5 was most closely associated with arsenic concentrations during low flow, while Site 1 (high flow) was most closely associated with ammonium concentrations (Figure 5.4).

Table 5.5. Species data analysis for invertebrates.

Site	Assessment period	Number of taxa	Abundance	d*	J'*	h*	α*
1	High flow	13	125 158	1.02	0.30	0.77	0.51
2		14	659	2.00	0.65	1.72	0.75
3		17	3 059	1.99	0.55	1.54	0.71
4		11	3 030	1.25	0.63	1.52	0.71
5		7	490	0.97	0.73	1.42	0.72
1	Low flow	9	129 497	0.68	0.33	0.74	0.50
2		14	8 894	1.43	0.24	0.62	0.28
3		15	919	2.05	0.73	1.97	0.81
5		17	2 061	2.10	0.74	2.10	0.84

*d: Margalef's species richness; J': Pielou's evenness; h: Brillouin; α: Fisher's

Table 5.6. Comparison of SASS scores and ASPT between reference and current conditions as well as invertebrate EC.

	SASS score	ASPT	Invertebrate EC	Invertebrate EC category
Reference	200	6.5	NA	NA
Current study	64	3.76	42.482	D

Table 5.7. Macroinvertebrate biotope rating. A biotope score of 1 indicates that the biotope is very poor and 5 that the biotope is highly suitable.

Biotope group	Score								
	High flow					Low flow			
	1	2	3	4	5	1	2	3	5
Stones in current	4	3	1	3	2	4	3	1	3
Stones out of current	4	2	1	3	2	4	2	1	3
Bedrock	1	1	1	1	1	2	1	1	1
Aquatic vegetation	2	3	3	4	4	3	3	3	4
Gravel	3	2	1	3	3	3	2	1	3
Sand	2	2	1	3	3	2	2	1	3
Mud	3	3	5	1	4	3	3	5	4
Hand picking/observation	3	3	3	3	3	3	3	3	3

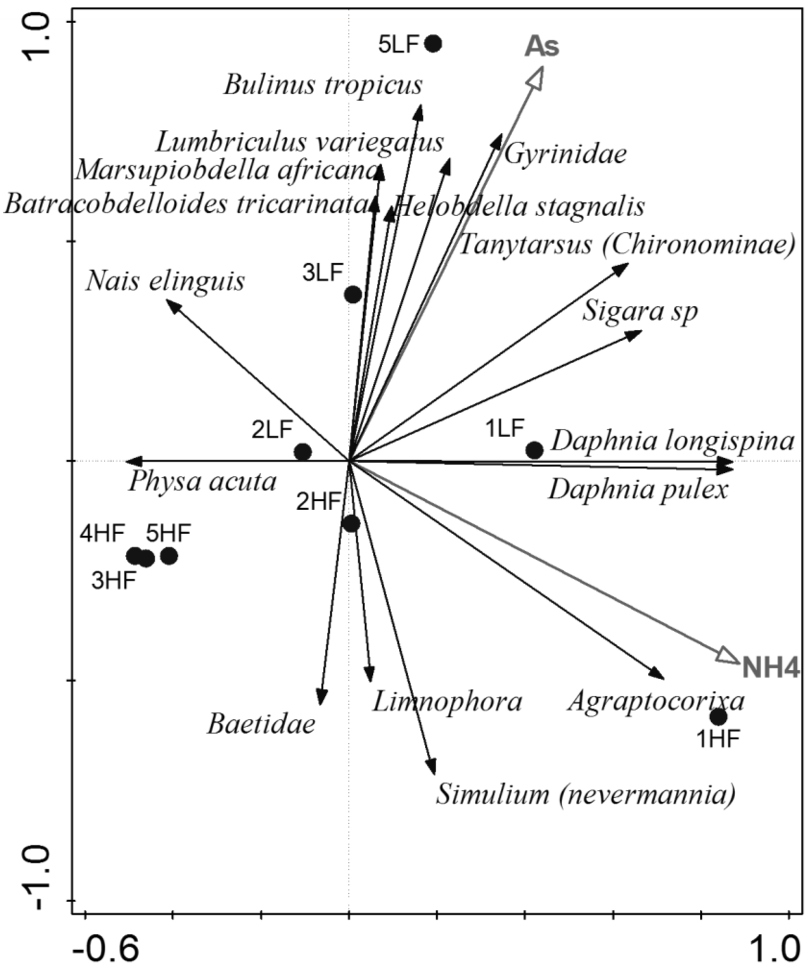


Figure 5.4. Redundancy analysis (RDA) of invertebrate species composition, sites and water quality.

5.4. Discussion

5.4.1. Diatoms

The South African Diatom Index (SADI) is a version that has been modified from the French Specific Pollution Sensitivity Index (SPI). This index is an autecological index that combines the values for diatom species tolerance and sensitivity as weighted by the abundances per species. The sensitivity and tolerance of each species are predetermined and abundance counts for one site and/or survey should be 400 cells or more (Harding and Taylor 2011). SADI is very similar to the European SPI as it was found that some 98% of the species were similar to those found in South Africa and therefore the additional endemic species in South Africa made no statistical difference (Taylor et al. 2005). Harding and Taylor (2011) indicate that issues with European indices only arose when applying the indices in mountainous streams where a greater number of endemic species occur thus necessitating the use of a

South African index. Therefore, the use of SPI within the Wonderfonteinspruit is justified as it is both an impacted and non-mountainous stream.

The SPI values indicated that all sites within the Wonderfonteinspruit fell into the poor quality class or worse. The Ecological Categories per site ranged between D and E and therefore the Ecological Category for the Wonderfonteinspruit according to the diatom assessment is D/E. This is not unusual for rivers in Gauteng as similar results were found in an assessment by Harding and Taylor (2011) of urban streams in Gauteng.

The Biological Diatom Index (BDI) was also developed in France to monitor the quality of water courses (Harding and Taylor 2011). The BDI was improved upon from the original model as described by Lenoir and Coste (1996) and Prygiel and Coste (2000) in 2006 so as to improve the accuracy of the results achieved (Coste et al. 2009). The BDI takes into consideration 838 key species that reflect seven water quality classes due to their varying pollution sensitivities. The BDI scores ranged between 0 and 20, with a sample score of 0 indicating bad quality and 20 indicating high quality (Coste et al. 2009). According to Taylor et al. (2007c), the BDI showed the best correlation with water quality when Vaal and Wilge Rivers were assessed in South Africa. Only Site 3 (high flow) and Site 5 (low flow) fell into the Poor Quality Class while the rest of the sites were all within the Bad Quality Class.

The %PTV furthermore supports the impacted state of the Wonderfonteinspruit as indicated by the SPI. The %PTV was developed to complement the Trophic Diatom Index but can provide useful information by itself (Kelly 1998). Any score above 20% indicates that a site is significantly impacted by organic input (Harding and Taylor 2011). Only Sites 3 and 4 during the high-flow assessment had %PTV below 20%. It is clear from this assessment thus that the majority of the sites are significantly impacted by organic material. The %PTV values for Site 1 (low flow), and Sites 2 and 3 (high flow) were over 50% which indicates serious organic contamination as these nutrient-tolerant valve species dominate and out-compete other species within the diatom community.

Cyclotella meneghiniana is common in electrolyte-rich and eutrophic rivers and was found to be the most abundant during the high-flow assessment (Taylor et al. 2007b). *Aulacoseira granulata* was the second most abundant species counted during the low-flow assessment and is commonly associated with eutrophic waters (Taylor et al. 2007b). The third most abundant species during the high-flow assessment, *Nitzschia palea*, was also found to be the most common species during the low-flow assessment. *Nitzschia palea* along with *Gomphonema parvulum* and *Sellaphora seminulum* (ranked 2nd and 3rd in abundance during the low-flow assessment) show similar ecological tolerances toward extremely polluted waters with high electrolyte content and eutrophic waters (Taylor et al. 2007b). These species are thus indicative of poor water quality within the Wonderfonteinspruit and especially evident in terms of the species most abundant during the low-flow assessment that can tolerate extremely high levels of pollution.

The observed relationship between the species composition at Sites 1 and 5 during the low-flow assessment may be due to the mining effluents of similar quality being received at both sites. Site 1 is located below the Cooke Attenuation Dam (Figure 2.1) while Site 5 is located below the mining pipeline outlet (Opperman 2008), hence the observed association between nickel and these sites during the low-flow assessment. Their close association in terms of nitrates may also be explained by nutrient inputs at both sites from sewage inflow. In the case of Site 1 raw sewage discharge from nearby communities has been observed while grazing cattle with free access to the river and possible sewage discharge into the pipeline may have an effect on the nitrate content at Site 5. *Amphora veneta* and *Nitzschia palea* tolerate critical and heavy pollution. The association between the species *Nitzschia palea*, *Staurosirella pinnata* and *Tabularia fasciculata* is expected to occur at Sites 1 and 5 during the low-flow period as these species are known to be associated with polluted waters. *Staurosirella pinnata*, *Nitzschia palea* and *Tabularia fasciculata* are found in waters with moderate to high electrolyte content (Taylor et al. 2007b); these species can also be seen to be associated with one another in Figure 5.3. *Tabularia fasciculata* has been found in industrial wastewater considered to be critically polluted (Taylor et al. 2007b). *Nitzschia palea* is also known to occur in eutrophic waters hence its association with increasing nitrite pollution. Similarly, *Navicula riediana* is a common species found in eutrophic and electrolyte-rich waters, most often associated with alkaline waters, and *Aulacoseira granulate* is often associated with eutrophic freshwater bodies (Taylor et al. 2007b). These last two species were closely associated with increased nitrate pollution. It can be noted from Figure 5.3 that Site 2 (high flow) was most closely associated with increased nitrate concentrations which could be due to upstream pollution from sewage inflows at Site 1 or due to runoff from a nearby chicken farm.

Ingress of water into mined areas, such as mine shafts or open-cast pits, is the first step in creating AMD (Fripp et al. 2000). Acid mine drainage (AMD) is formed when sulphide-bearing material such as iron pyrite, often associated with coal and gold bearing rock, is exposed to water and oxygen (Hallberg and Johnson 2005). This can occur through ingress of water from diffuse pollution sources, through existing drainage ditches or existing canals (Fripp et al. 2000). The highly acidic water also results in metals and metalloids previously part of the mined rock becoming available in the water column and subsequently transported to freshwater environments (Hallberg and Johnson 2005; Manders et al. 2009). According to the SPI scores, Sites 1 and 5 were the most polluted sites and are the sites most likely to be directly impacted by mine effluent. Site 1 is located below a pollution control dam, while Site 5 receives piped water from mining areas (Coetzee et al. 2006; Opperman 2008).

5.4.2. Macroinvertebrates

The species identified in this study are typical of polluted systems; this is especially evident from the macroinvertebrate families' preferences for water quality as the families identified either have no or low preferences for water quality. The two most abundant taxa considered in the MIRAI were Chironomidae (bloodworms) and Simuliidae (black flies). The abundance of Simuliidae is not unexpected as Day et al. (2002) indicate that Simuliidae can make up to 95% of the total abundance of individuals collected in the stones in rapids biotope. Several species *of Simulium* (Metomphalus) are considered to be serious pests in South Africa (Day et al. 2002). The most common and widespread species, which is frequently found below impoundments is *Simulium medusaeforme* which is tolerant of poor water quality (Day et al. 2002). Chironominae is the largest and most commonly found subfamily of the Chironomidae; some species occur in such large numbers that the presence of their wings in the air can cause asthma (Day et al. 2002). Orthocladiinae also forms a large subfamily within Chironomidae but is most commonly found in mountainous streams; however, some species have been found to occur in the lower reaches of rivers (Day et al. 2002).

In order to identify the chironomids collected a scanning electron microscope (SEM) had to be used as the features needed for identification are too small to be seen on a compound light microscope. The identification of *Pseudorthocladius* sp. was based upon the features identified in Figure 5.5 according to Day et al. (2002). Figure 5.6 indicates some of the features used to identify these subfamilies of Chironominae. It was also noted that the larvae of *Tanytarsus* were found in fixed cases which is another defining feature (Day et al. 2002).

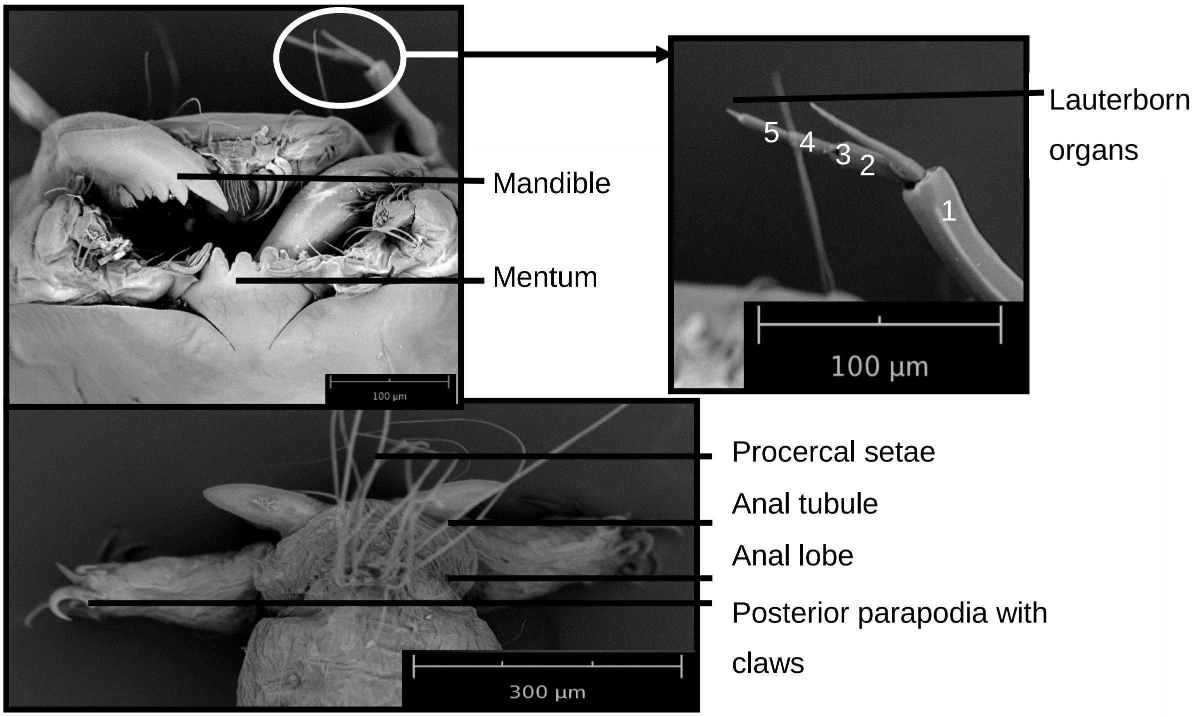


Figure 5.5. SEM image of larvae of *Pseudorthocladius* sp. showing characteristic features.

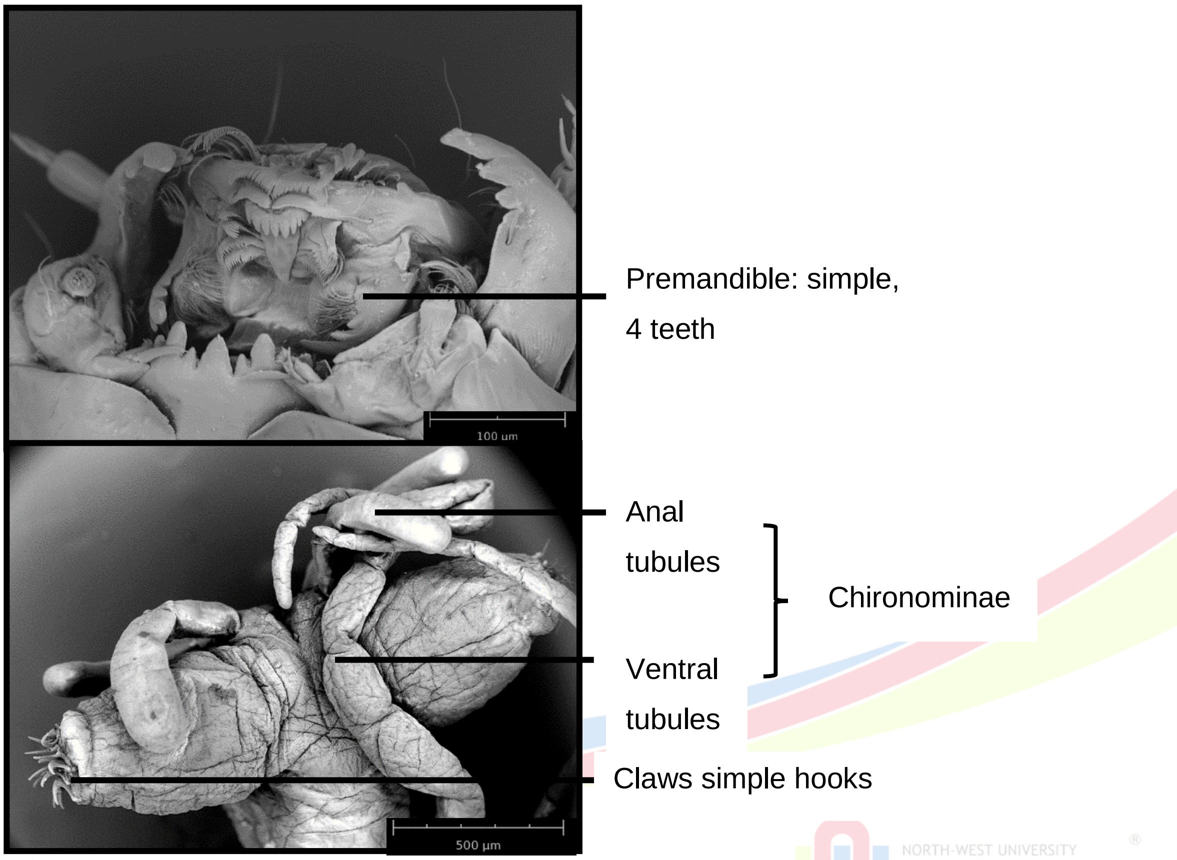


Figure 5.6.SEM image of *Tanytarsus* sp. showing characteristic features.

The identification of the family Baetidae was made difficult due to the high algal content in samples such that defining features such as gill lamellae and cerci of the specimens were lost. From the limited number of whole specimens found, a tentative identification of the Baetidae to the genera *Pseudocloeon* or *Labiobaetis* could be made. These two genera are still under taxonomic scrutiny and *Labiobaetis* is seen to be in a state of flux as some taxa are still not clearly defined as being part of either *Pseudocloeon* or *Labiobaetis* (de Moor et al. 2003a).

The cladocerans dominated the sites in terms of abundance especially at Sites 1 and 5 (Table 5.5). *Daphnia* sp. were most common at these two sites and this may be due to the greater stream width of these two sites as these species are limnetic; their great abundance may also indicate enrichment in this area as they are filter feeders and increased particulates would allow for increased population sizes (Day et al. 1999). This association between increased eutrophication and *Daphnia* sp. is observable in Figure 5.4 where Site 1 has the highest ammonium concentration as well as the greatest abundance of *Daphnia* sp. *Ceriodaphnia* sp. was found at Site 3 which is Donaldson Dam and this is expected as *Ceriodaphnia* are known to occur in impoundments (Day et al. 1999). The aforementioned is an example of the impact of a change in flow regime with regards to the distribution of taxa in a freshwater system. Similarly, Myburgh and Nevill (2003) found a clear link between impoundment construction and the spread of *Simuliidae* species. Sites 1, 2, 4 and 5 were all located downstream of impoundments while Site 3 itself was located in an impoundment, thus it is expected that black fly species will occur in great numbers.

Several main drivers are taken into consideration for the determination of an EC. These can be summarised into four sections for macroinvertebrates, namely: flow regime, water quality, physical habitat, and energy inputs (Thirion 2008). With regards to the flow regime, Site 4 showed the greatest variation as no sampling could be performed during the low-flow period because the site was dry. Site 5 was the only site to receive more water during the low-flow assessment and this may be due to increased releases from the pipeline directly upstream of Site 5. Subsequently an increase in the species richness can also be observed in Table 5.5.

Water quality changes can have immediate, short-term and long-term effects according to the pollutants present. Acute events may cause immediate loss of abundance and diversity and may have an impact on the recovery of the macroinvertebrate community (Tate and Husted 2015). A long-term water quality impact can also be related to habitat availability. When heavy metals are removed out of solution under the appropriate conditions (raised pH and presence of oxygen) the metals form deposits on the floor of a stream and can cause cementing (Fripp et al. 2000). As invertebrates require specific substrates and habitats to survive, this precipitate, often referred to as yellow-boy, causes important habitats to be covered such that organisms can no longer use them (Fripp et al. 2000; Kleynhans 2008; Thirion 2008; Koekemoer and Taylor 2009).

Another contributing factor would be the proximity of populations able to aid in re-colonizing areas (Yount and Niemi 1990). The species of black flies that were found are common pests of poultry and cattle. During the assessments it was noted that cattle were led regularly through the Wonderfonteinspruit and grazed nearby the river. A chicken farm was also located between Sites 1 and 2; these were also the sites that were found to have the greatest abundance of the genus *S.* (Nevermannia) of which its species *Simulium nigritarse* is known as a poultry pest (Day et al. 2002). Several of the southern African species of *S.* (Nevermannia) are known to tolerate a wide range of polluted waters (Day et al. 2002). *S.* (Nevermannia) was also most closely associated with ammonium (shown in Figure 5.4) which supports the finding that they are capable of surviving in polluted waters.

Sites 3, 4 and 5 (high flow) as well as Sites 3 and 5 (low flow) showed similar associations as seen in Figure 2.4 with regards to water quality variables only. Almost all species of the family Glossiphoniidae (excluding *Placobdelloides multistriata*) were closely associated with one another and with arsenic concentrations at Site 5 (Figure 5.4). Leeches are known to be indicators of heavy metal pollution and therefore this association between arsenic and the presence and abundance of Glossiphoniidae is indicative of the usefulness of using leeches to possibly predict heavy metal pollution (Day and de Moor 2002a).

Considering the wide range of impacts within the Wonderfonteinspruit, as discussed throughout the previous chapters, the EC of a class D as calculated by the MIRAI is telling. This class indicates that the Wonderfonteinspruit is largely modified which corresponds with the results obtained for diatoms. MIRAI forms part of the ecological classification process which aims to determine and categorise the Present Ecological State (PES) of several biophysical attributes as compared to natural or near natural reference conditions (Thirion 2008). A number of metrics are integrated such that an EC can be determined. In particular, the diversity of the macroinvertebrate taxa is determined in relation to the requirements each invertebrate taxon has for biotope type and availability, velocity preference and physicochemical requirements (Thirion 2008). According to the Present Ecological State (PES) (DWA 2013c) determined for the Wonderfonteinspruit, provided all drivers are taken into consideration, the Wonderfonteinspruit is expected to be a Class E, which would indicate that the Wonderfonteinspruit is even more deteriorated than suggested by the diatom and macroinvertebrate indices.

5.5. Conclusion

The state of the Wonderfonteinspruit is aptly reflected by the diatom and macroinvertebrate indices as both indicate largely, and in some cases seriously modified, conditions as indicated by the diatom indices per site. It is key to note that these indices are not solely dependent on water quality and therefore may not reflect the absolute impact of the Wonderfonteinspruit on human populations. However, sediment, water and habitat changes may also lead to impacts on human health, such as by sediments acting as pollution sinks, or decreased vegetation resulting in increased erosion and pollution inputs and therefore there may be stronger link between these indices and human health than solely predicted by water quality. The following chapters will outline and combine the human requirements of the Wonderfonteinspruit and the subsequent impacts on health and wellbeing with the outcomes found in the previous chapters, which indicated that water from Wonderfonteinspruit poses risks with regards to human use especially if water is ingested. Furthermore, it was found that the sediment of the Wonderfonteinspruit can act as secondary sources of metal pollution in particular with regards to uranium, nickel and cobalt. Finally, biotic indices indicated that the Wonderfonteinspruit is in a poor condition and that ingestion of fish muscle tissue may pose health risks due to unacceptable arsenic concentrations in the fish muscle tissue.

6. A social assessment of Bekkersdal community's requirements with regards to the use of municipal water and the Upper Wonderfonteinspruit

6.1. Introduction

A relationship between man and nature has long been established (Frumkin 2001; van Kamp et al. 2003; Wilson 2006; Ryff and Singer 2009; Jones et al. 2012). To date, much of the research has focused on the negative effects of harmful nature-human interactions, such as for example climate change, eutrophication as well as the effects of diseases and pests on human health and wellbeing (de Magalhães et al. 2001; Juliano and Lounibos 2005; McMichael et al. 2006). However, these interactions can also be beneficial for both man and the environment (Frumkin 2001; Maller 2005). When investigating an area such as Bekkersdal and the nearby Wonderfonteinspruit where negative anthropogenic impacts are prevalent, the negative relationship between humans and the environment is apparent. According to the World Health Organization (WHO 1948) health (including features of wellbeing) is defined as: "A state of complete physical, mental, and social wellbeing and not merely the absence of disease or infirmity." Several studies have highlighted the importance of a clean and healthy environment for human health (Wells and Evans 2003; Maller et al. 2005; Ryff and Singer 2009). Thus, in order for the Bekkersdal community to achieve a satisfactory state of health and wellbeing, the surrounding environment should likewise not be harmful to health and wellbeing. The emphasis for this discussion will be placed on the status of an essential natural resource, namely water.

Ethical considerations associated with water use and management as a topic of study have become more urgent and intensive in recent times (Falkenmark and Folke 2002; Llamas 2003; Rahaman and Varis 2005; Amery 2009). This is warranted due to the urgency of securing water for everyday use, especially freshwater which is required for economic and social development as well as to satisfy basic human rights (UN General Assembly 1948). The Universal Declaration of Human Rights (1948) provides for the basic right to life and human dignity (Donnelly 2013). In this regard water should be regarded as essential for human life and therefore is indivisible as a basic need to fulfil the right to life and human dignity. The requisite need for water to support human life and development is proposed to be linked with basic human rights on several levels (Moench et al. 2003; Kemp et al. 2010).

Ordinarily the ethical concerns with regards to water management and availability within a social context will revolve around issues of: basic rights to life, dignity and provision of basic needs; water as a common and shared good; the rights and responsibilities related to water access; the economic importance of water as well as the environmental and ecological impacts of such activities; and the importance of water in terms of human health and wellbeing (Llamas 2003). These issues will be discussed in the context of the community of Bekkersdal in terms of their use and observations of the Wonderfonteinspruit and municipal water.

6.1.1. Historical background

During a time of booming economic growth in South Africa with budding mining communities expanding in the Far West Rand of South Africa, Bekkersdal was established as a mining community in 1945 (van Eeden 1988). Bekkersdal was planned to house the growing number of people associated with the rapid expansion of gold mining in the West Rand. The mining operations in the West Wits Gold Mining Area of which Bekkersdal formed a part created numerous economic and developmental opportunities against the background of stringent government ideologies and policies (van Eeden 2014).

Bekkersdal has recently been labelled as one of the most controversial and violence-driven communities in South Africa. Furthermore, what is concerning within this context is that South Africa itself has been dubbed the “protest capital of the world” (van Eeden 2014; Alexander 2012). Records show service protests in Bekkersdal dating back to the 1970s and 1990s (van Eeden 2014). These reports would suggest a community striving for an improvement in their living conditions. The latest history of Bekkersdal (especially the informal section) has been riddled with social and political unrest. News media have reported on a number of service delivery strikes and violent clashes within Bekkersdal (Tau 2013; Sithole 2014).

6.1.2. Hypotheses, objectives and aims

The aims of the discussion are to determine whether the water services currently delivered to Bekkersdal are viewed by the community themselves as adequate or inadequate, as well as to determine the use and awareness of the people regards the Upper Wonderfonteinspruit. By means of ethical considerations, it will be assessed whether the rights of the people of Bekkersdal are being upheld with regards to water availability and to determine the context of water as a shared good amongst the community of Bekkersdal and beyond. Finally, to establish and reveal the perceptions of the Bekkersdal people with regards to the natural environment of the Upper Wonderfonteinspruit and its effect upon their health and wellbeing. It is hypothesized that there will be limitations in providing for the rights of the people of Bekkersdal with regards to water use as observed from the perceptions and experiences of the people in Bekkersdal; that water as a shared good is a neglected concept to the users of the Wonderfonteinspruit and Bekkersdal water services and that the natural environment with regards to the Wonderfonteinspruit will be seen from a negative perspective and regarded as unimportant to their present and future health and wellbeing.

6.2. Methods and materials

6.2.1. Study site

The community of Bekkersdal falls under the Westonaria Municipality which is situated in the West Rand Districts Municipal region and is located in the Gauteng Province of South Africa as can be noted in Figure 6.1. It comprises a formal section (±3 313 households) and an informal section (±13 000 households), with areas of the informal section bordering the Donaldson Dam which forms part of the Wonderfonteinspruit (Sosibo 2013; WLM 2014). The areas considered to be informal are: Mandelaville, Winnie/Holomisa, Silver City, Spook Town, Thambo and X-Section. The formal area includes Bekkersdal Proper and Skierlik. Mandelaville and Winnie/Holomisa are located the closest to Donaldson Dam and the formal section is one of the areas furthest away from the dam.

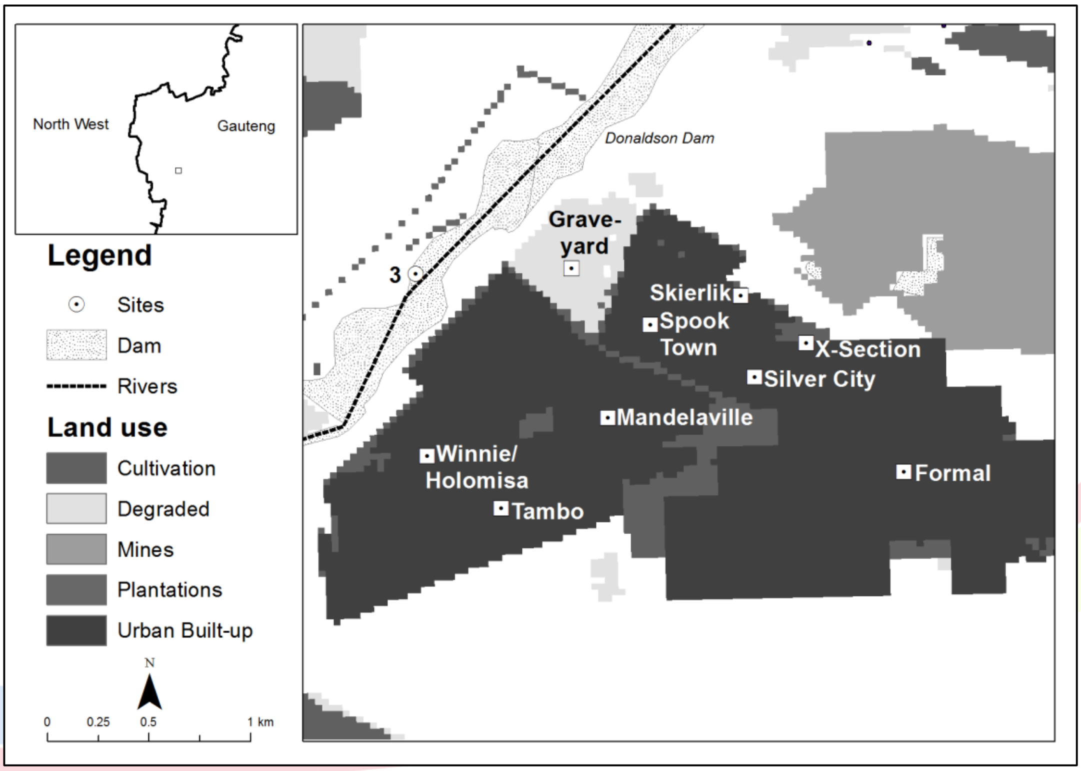


Figure 6.1. Map of Bekkersdal Township close to Donaldson Dam.

6.2.2. Composition of questionnaire

The questionnaire entitled *Questionnaire on: Water use of the Upper-Wonderfonteinspruit by the people of Bekkersdal* was compiled based on baseline research that has been previously conducted within the Bekkersdal community, especially bearing in mind the level of education and language competency of individuals within the Bekkersdal community (Van Eeden 2014). The baseline research was conducted with the intention to cover the research needs of several disciplines. The questionnaire of the current study was developed as a more focused effort to complement the aforementioned baseline research such that a more in-depth understanding of the Bekkersdal community's sense of water needs, understanding and availability in their environment could be established. This questionnaire was thoroughly reviewed by experts during its development and was divided into the following sections: demographic details; current water use; use of the Wonderfonteinspruit; future water use from the Upper Wonderfonteinspruit; water quality perceptions of the Wonderfonteinspruit; and field notes (Appendix F).

6.2.3. Selection of fieldworkers

The fieldworkers selected for this study were recruited among individuals who had assisted with the broader project's baseline questionnaire within the Bekkersdal community in 2013. These individuals formed part of a group of home-based care workers as was arranged with the local municipality. Each individual had to meet the following criteria: being able to read and write English, minimum of Grade 10 and being able to interpret the questionnaires. All fieldworkers were Bekkersdal residents in order to complement the community engagement focus related to the project, so as to put the participants at ease and allow for open and honest answers. For this study the fieldworkers received two training sessions on the questionnaires so as to introduce them to the questions and allow them to study the questionnaire and provide ideas for corrections or recommendations. Thereafter, the participants were interviewed as follows: each fieldworker performed a mock interview where they were asked to translate some of the questions into the anticipated South African languages within Bekkersdal, to answer queries that may be asked by the interviewees and to explain what they understood about some of the questions. Based on the outcome of this exercise, the ten best performing fieldworkers were selected from the larger group to assist with the fieldwork survey.

6.2.4. Conducting questionnaire surveys

This project will comply with the ethics mandate of the greater National Research Fund (NRF) project (see Ethical Clearance: No. FH-BE-2013-0014). The fieldworkers were divided into groups of two each such that they could assist one another and to provide for their own safety. Each group was assigned a section of Bekkersdal each week with a stipulated number of questionnaires. The number of questionnaires per section was based on the size of the section, for example Mandelaville was a large section and a total of 115 questionnaires were administered while X-section was a small section and only 50 questionnaires were administered. In the sections of an appropriate size every fifth house was interviewed while in the even smaller sections every second house was interviewed, such that a representative sample from each section could be attained. Each week the fieldworkers returned the allotted number of questionnaires from the previous week to the researcher and received the next allotted number of questionnaires, but only on condition that all the questionnaires would be correctly filled in and completed. As expected, some questionnaires did not meet the desired standards and were discarded; however, the sample size of 642 questionnaires, of the original 650 questionnaires, was still large enough to provide a statistically representative sample.

6.3. Results

The respondents were composed of 38.62% of formal households and 61.37% of informal households in order to equally represent the profile of Bekkersdal. The mode for the length of time respondents have lived in Bekkersdal is 10 years. The majority of respondents were South African citizens (86.40%) as can be noted in Figure 6.2. The household dynamics with regards to employment status indicated that 64.73% of household members were dependents and 35.27% were providers (Figure 6.4) with households showing an unemployment rate of 78.20% and a fulltime employment rate of 48.30% (Figure 6.3).

All households indicated that their main source of water is municipal water, when available. Some 96.4% of the formal residents and 30.9% of informal residents indicated that collecting water from municipal taps was very easy (minimum effort required), while the majority of the informal households indicated that collecting water ranged from being difficult (45.2%) to being extremely difficult (8.9%) (Figure 6.5).

The relationship between the residents within the formal and informal areas with regards to the difficulty involved in collecting water from the municipal water supply was shown to be strong in terms of the Phi-coefficient (φ) and Cramer's V test with a value of 0.652; while the statistical difference between the relationship between the formal and informal sections and the difficulty involved in collecting water was found to be relevant according to the Pearson Chi-Square test. Similarly, significant differences between the formal and informal households with regards to distance travelled and time taken to collect water were observed. Almost exclusively, 99.6% of the formal households indicated that collecting water from the municipal water supply took less than 5 min while the majority of informal respondents indicated that collecting water from the municipal water supply took between 6 and 15 min

(35.20%) or more than 20 min (38.37%) (Figure 6.6). Most of the residents (54.70%) indicated that they could collect water on a daily basis while some residents (44.20%) had continuous access to piped water within their homes (Figure 6.7). Yet the majority of respondents (70.09%) indicated that problems have occurred and continue to occur in Bekkersdal with regards to water service delivery by the municipality. Individuals often had multiple complaints and in total 539 separate complaints were noted that were divided into seven distinct categories as can be noted in Figure 6.8. Of the 539 complaints, 25.42% were related to payment issues; 23.56% to taps being few and/or far away; 22.63% were about interruptions in water supply without prior notice from the municipality; 15.40% of the complaints were about broken taps; 9.28% of respondents were distressed about the long queues to collect water; 2.60% indicated the problems associated with burning shacks and the lack of water to extinguish the fires; and 1.11% claimed to have no water at all. Other concerns not included in this summary, but mentioned in the survey, are the lack of security resulting in broken pipes, the need to collect water from mines when water is unavailable in Bekkersdal and the health hazards of water especially when the Donaldson Dam is used as an alternative water source. Reasons for the strike in 2013 were identified as being the result of the unwillingness of unemployed residents to pay for the water services and the limitations in the availability of taps, thus leaving residents with no other choice but to walk long distances and wait in queues to collect water (Table 6.1; Appendix G).

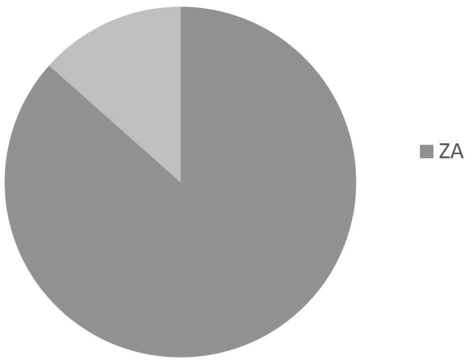


Figure 6.2. Percentage of South African citizens versus immigrants in Bekkersdal.

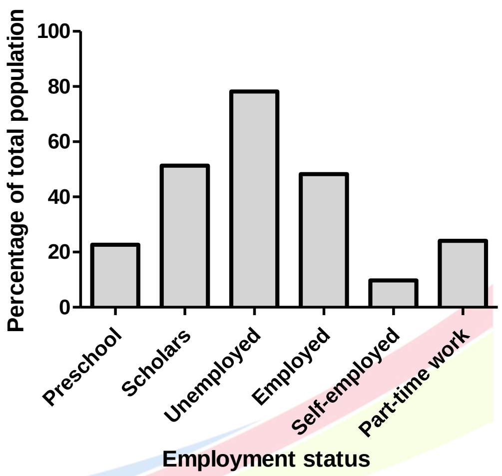


Figure 6.3. Employment status of households in Bekkersdal for 2014.

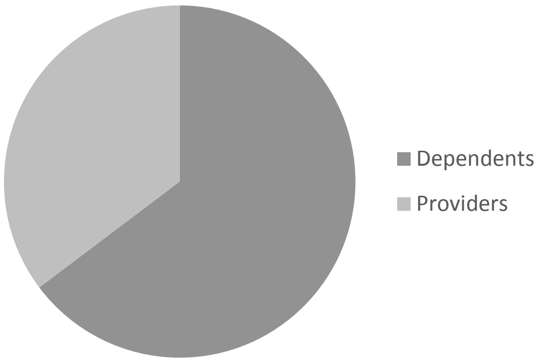


Figure 6.4. Ratio of dependents to providers within Bekkersdal households.

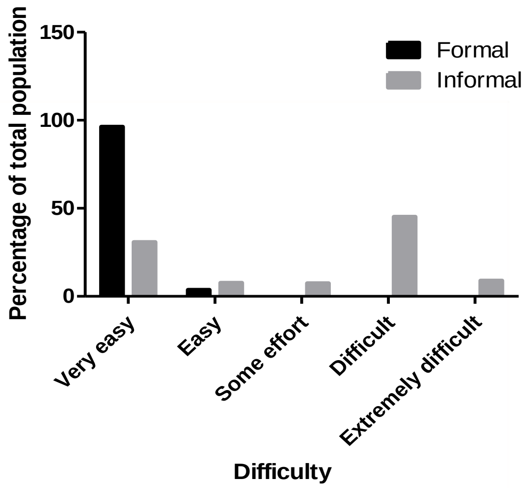


Figure 6.5. Difficulty involved in collecting water by households in Bekkersdal.

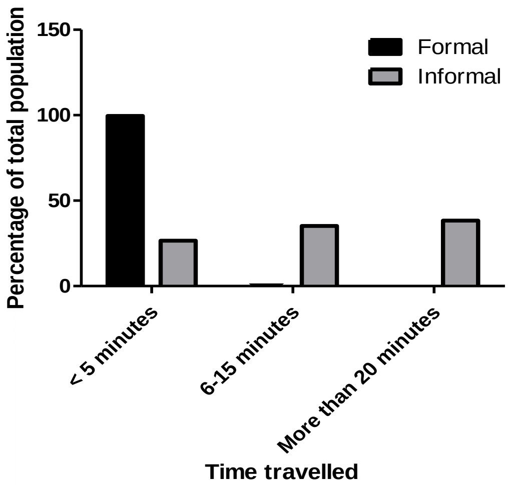


Figure 6.6. Distance travelled to collect water for the households of Bekkersdal.

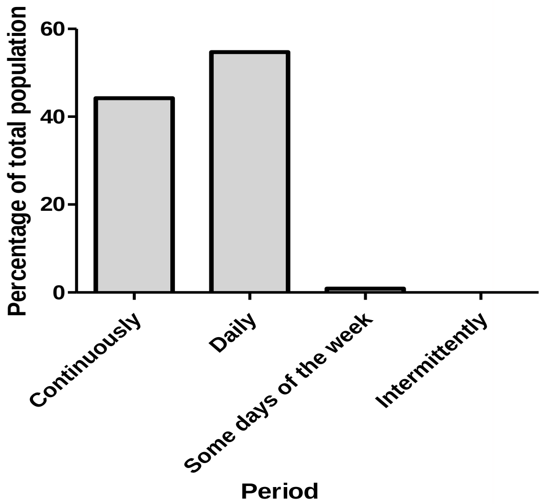


Figure 6.7. Periodicity of access to water.

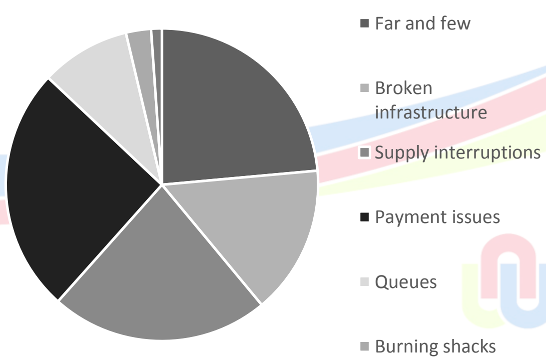


Figure 6.8. Past and current complaints about water delivery.

Table 6.1. Quotes from the Bekkersdal questionnaire survey regarding respondents' issues with water service delivery in the community.

Issue	Quote
Paying for water services	*In the past few months there was a toy-toy here in Bekkersdal because our municipality want us to pay for water*
Taps are far and too few	*I had to travel to collect water and I had a swollen foot*
Water services infrastructure broken	*Water from the taps is running in the street, most are dumping dirty water into the street and the streets become dirty and smell bad, which causes sickness in our community*
Water closed without informing the community	*The municipality closes the water and do not inform us and we only get water after 5pm, they do not care about us*
Long queues for access to water	*Have to wait in very long queues for hours to get water and the taps are very far from our houses*
Burning shacks	*Burning of shacks because the water taps are too far away to stop the fires*
No water	*There is no water so we use water from the Donaldson Dam and that causes stomach diseases*

The Bekkersdal households indicated that 10.14% make use of the Donaldson Dam (as part of the Wonderfonteinspruit) as their principal source of water while more indicated that they make use of the Donaldson Dam when water services are unavailable or to supplement water for other activities. Most of the Wonderfonteinspruit users either continuously (7.17%) or occasionally (6.70%) drink the Donaldson Dam water (Figure 6.9). The next most frequent use of the dam is for washing. Some 4.52% of the respondents indicated that they use the water continuously for washing (Figure 6.9). Other uses also included irrigation, watering of livestock, recreation and religious practices. Health effects from generally using the water in the Wonderfonteinspruit were experienced by 11.54% of the respondents. These can be grouped under the following: diarrhoea (45.45%); skin problems (33.77%); drowning (6.49%); and other afflictions (14.29%) such as pest problems from mosquitoes, unsavoury smells, effects from mining chemicals and general reference to people dying as a result of the water

(Figure 6.10; Table 6.2). The groups that were seen to make most use of the dam water were identified to be traditional healers (35.45%), unemployed residents (25.60%) and fishermen (23.01%) (Figure 6.11). Most respondents indicated that they do not fish in the Dam; however, some 4.5% do fish in Donaldson Dam (Figure 6.12) while it was also mentioned that some residents purchase resources from fishermen fishing in the Dam. Figure 6.13 shows that 54.84% of the respondents were aware that some Donaldson Dam resources were being sold. Fish and mud cakes were the most commonly identified resources being sold.

Table 6.2. A selection of quotes from the Bekkersdal community regarding health issues experienced as a result of using the Wonderfonteinspruit water.

After school children go to the dam and swim and they swallow water and get diarrhoea
Always getting sick with a rash, diarrhoea is the greatest risk to our health
Because our children escaped after school and swim there and that caused cholera and skin problems
Children getting sick from that dirty water because of sewage
If you drink that water always you get diarrhoea
In the past there was scarcity of water and many people used water from the dam. In those days many people suffered from diarrhoea and scabies
In those years without municipal water people were dying from the dam water and had body sores
My neighbour use to fish at the dam and I use to buy from him, but not anymore because I realised the fish gave us diarrhoea
The water has given us stomach illnesses like diarrhoea and we lost our one child

From the questionnaires it was indicated that some 42.60% of the Bekkersdal households would use water for additional activities if it were more readily available (Figure 6.14). Furthermore, as can be noted in Figure 6.15 and Table 6.3 the respondents indicated that they would make use of the Donaldson Dam for the following activities if it were in a better state: drinking (22.02%); irrigation (25.45%); livestock watering (9.11%); religious practices (19.69%); recreation (11.98%); fishing (10.97%); and other activities such as construction-related activities (0.78%).

Table 6.3. Perceptions of some Bekkersdal community respondents regarding the Wonderfonteinspruit (inclusive of the Donaldson Dam) as noted by the fieldworkers.

I'm not going there anymore because people say there is a big snake.

There must be a project to clean the dam so that it can be a safe healthy place that can be used and can create job opportunities. I am scared of that dam like I have been told that there is a big snake that chokes people that go there. I am afraid of the snake even though I really like the natural environment and sometimes feel like going there. Something must be done about the dam because we want to enjoy ourselves there
As an individual it is important for me because it is part of job creation for the unemployed. It is also very good coming to the dam for entertainment for us because we won't go far and spend unnecessary money. Entertainment will be near our homes.
I wish they could renovate Donaldson Dam so that it can generate jobs for the poor.
The municipality promised to clear water debts but they are still receiving statements and have to buy prepaid water.
If our municipality takes care of the Dam there are many things children and others can do like playing, swimming and fishing, but because there is no safety in that dam so we are afraid of doing those things.
Most people say they use to collect water and fish from Donaldson Dam but now the security stops them
Some are very good fisherman and if the security did not stop them and the municipality allowed them some could fish at Donaldson Dam and sell the fish.
Should allow people to fish and swim, but people are also scared of the snake that you can see at night enlightened in the dam.
If the municipality cleaned the dam it can be very good for the community because people especially the youth can play sport and swim and they would stay out of trouble.

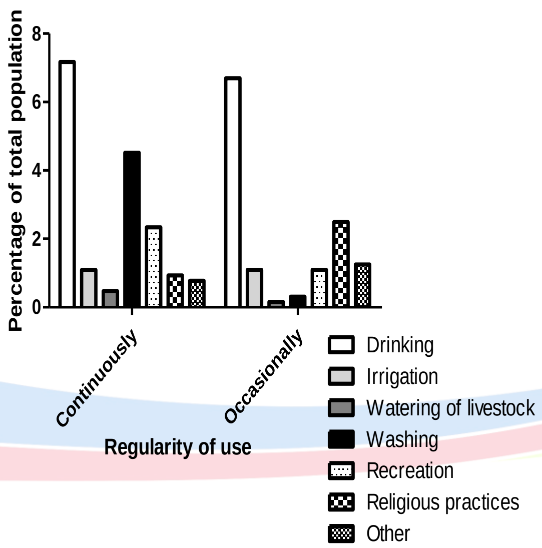


Figure 6.9. Use of the Upper Wonderfonteinspruit (inclusive of the Donaldson Dam) for various activities.

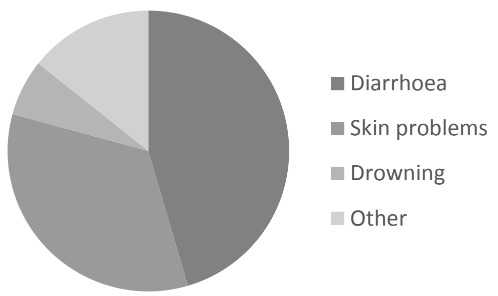


Figure 6.10. Health effects caused by the use of Donaldson Dam water.

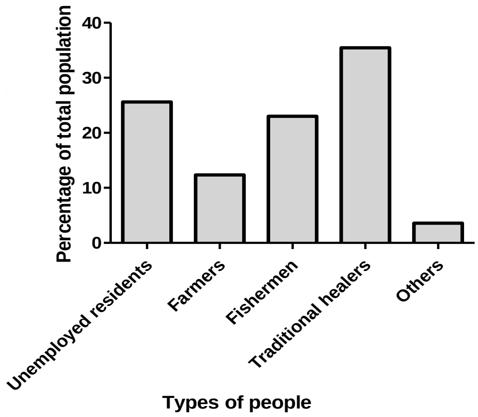


Figure 6.11. Persons identified as most commonly using the Donaldson Dam.

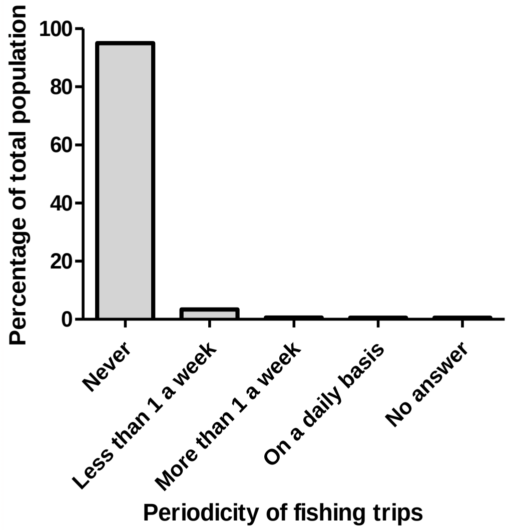


Figure 6.12. Fishing in the Donaldson Dam.

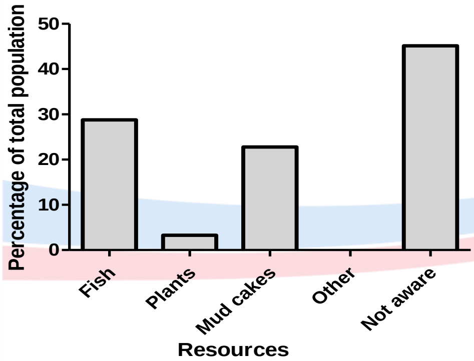


Figure 6.13. Donaldson Dam Resources being sold.

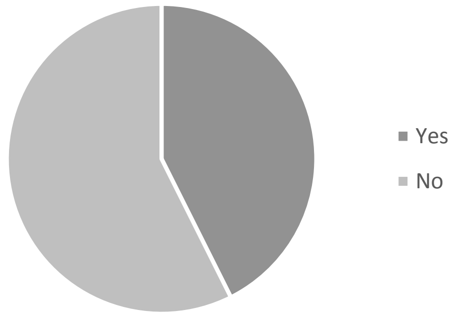


Figure 6.14. Bekkersdal residents would use water for additional activities if it were more readily available.

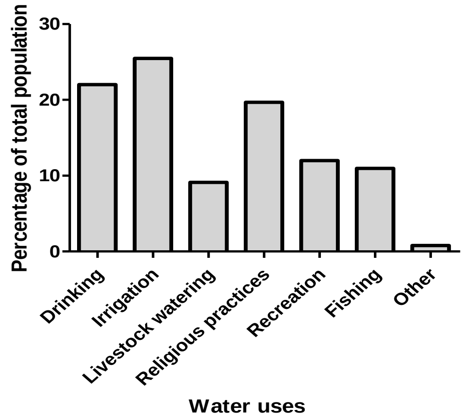


Figure 6.15. Activities the people of Bekkersdal would like to use the Donaldson Dam for in future.

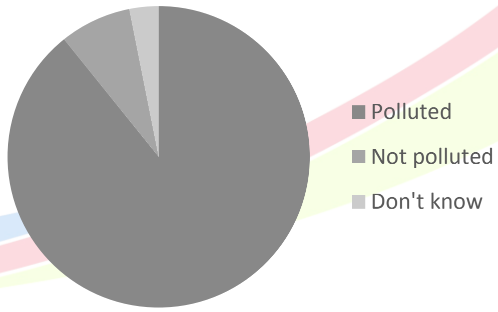


Figure 6.16. State of the Wonderfonteinspruit as viewed by the people of Bekkersdal.

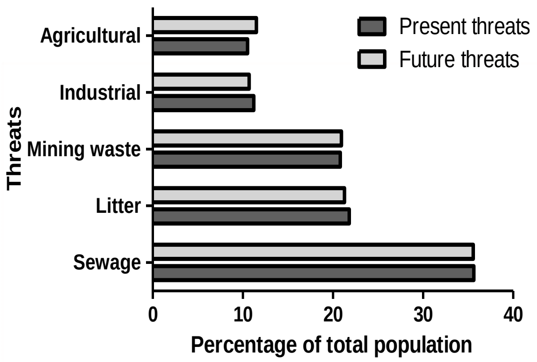


Figure 6.17. Current human impacts on the Wonderfonteinspruit as identified by the people of Bekkersdal.

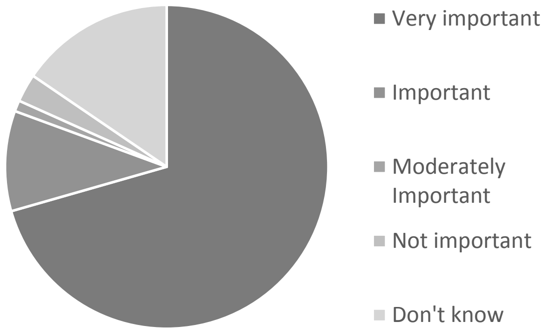


Figure 6.18. Importance of a clean environment for human health and wellbeing as viewed by the people of Bekkersdal.

The majority (89.10%) of Bekkersdal residents indicated that they view the Wonderfonteinspruit as polluted (Figure 6.16) and sewage, litter and mining waste were indicated to be both the greatest current and future threats to the Wonderfonteinspruit (Figure 6.17). A large majority of respondents (70.6%) believed that a healthy environment is very important for human health and wellbeing while 10% believed it to be important. Only 2.82% indicated that the environment is not important for human health and wellbeing as shown in Figure 6.18. As indicated in Figure 6.19, more than half of the respondents care about the state of the Wonderfonteinspruit (57.63%), the Donaldson Dam (70.46%), as well as the environment surrounding the Wonderfonteinspruit and Donaldson Dam (73.78%). In particular, concern about the state and availability of water for present and future generations was shown (91.15%) as well as the quality of water used by the householder and the household members (89.73%). When asked what feelings the households of Bekkersdal have towards the Wonderfonteinspruit including the Donaldson Dam, 54.07% of respondents indicated that they were unaware of it prior to this questionnaire, 10.37% viewed it as unimportant, 9.33% viewed the dam as important, 24.59% indicated an affinity for the river and 1.63% indicated that the river makes them happy (Figure 6.20). An overwhelming number of respondents (87.80%) expressed their willingness to be part of environmental clean-up initiatives in the area of Bekkersdal.

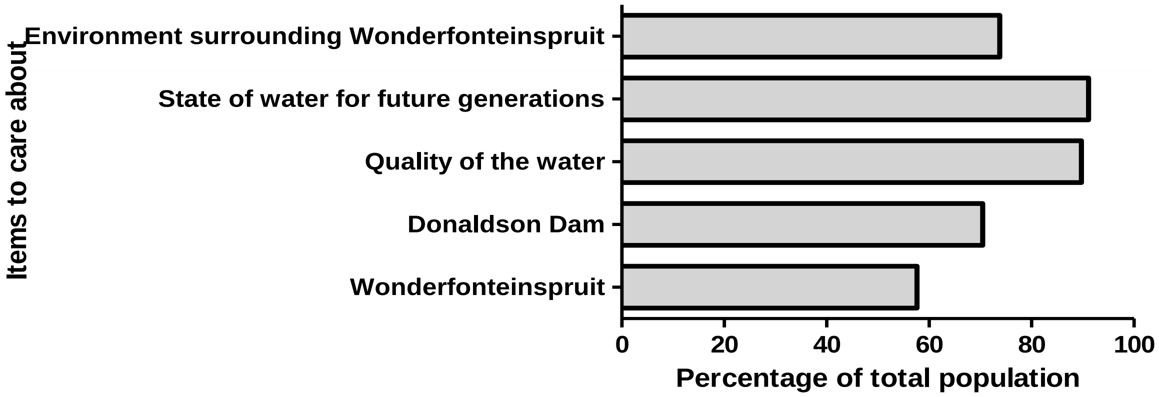


Figure 6.19. What the people of Bekkersdal care most about.

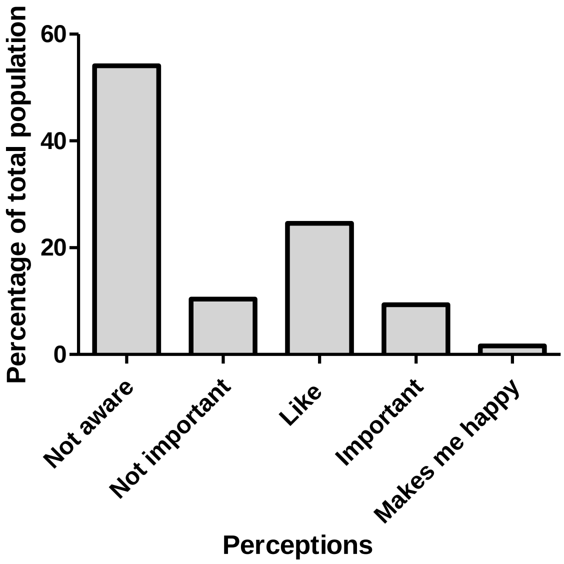


Figure 6.20. Perceptions of the Bekkersdal people regarding Donaldson Dam.

6.4. Discussion

6.4.1. Reliance on municipal water services

The South African constitution along with a plethora of national and international laws and treaties provide for the protection of the right to sufficient water for every South African citizen (RSA 1996; RSA 1997; RSA 1998a; b; Salman and McInerney-Lankford 2004). Water is considered to be central to upholding human rights such as are enshrined in the Universal Declaration of Human Rights, the Declaration on the Right to Development and the International Covenant on Economic, Social and Cultural Rights (Salman and McInerney-Lankford 2004). The United Nations Committee on Economic, Social and Cultural Rights in 2002 issued General Comment No. 15: The Right to Water. It states categorically that all humans have the right to water and that human rights cannot be upheld without access to water (CESCR 2002).

Despite the absolute right to sufficient drinking water and the need for a certain quantity and quality of water to uphold rights such as the right to life or the right to an environment that is not harmful to human health and wellbeing, a link between poverty and water shortage is apparent (Molle and Mollinga 2003; Salman and McInerney-Lankford 2004; Kummu et al. 2010). According to the Bloomberg, International Monetary Fund (updated June 28, 2013) South Africa has the third highest unemployment rate in the world of 25.2%. Some 30.2% of South Africans receive social grants and 45.5% of South African households have at least one member reliant on a social grant (Statistics South Africa 2014; SAinfo 2013). This trend of unemployment and reliance on governmental services is shared by the Bekkersdal community where some 78.20% of the households are unemployed (Figure 6.3). The number of dependents within Bekkersdal is by far the majority making up some 64.73%. Furthermore, it was found that 100% of Bekkersdal households rely on the municipality to provide water as it is their primary water source. Despite the indication given by respondents that some people have no access to water, from the wording of these responses in Table 6.1 and Appendix G it was deducted that this response of “no water” indicates that these respondents experienced times when water was unavailable or that taps were too far away for them to collect water as these residents nonetheless indicated that they use municipal water as their primary source of water. Bekkersdal can be considered an impoverished or indigent community due to the high unemployment rate. According to the National Indigent Policy by Municipalities, indigent households are those who are unable to access or pay for basic services (SAHRC 2014). According to the Free Basic Services (FBS) Policy, indigent households have a right to free water service delivery. Many of the complaints regarding water service delivery in Bekkersdal were directed towards payment issues (25.42%) as can be noted in Figure 6.8 and one of the reasons identified by the respondents for the strikes in 2013 was because the residents were unwilling and unable to pay for metered taps as can be seen in Appendix G. The WLM 2013/14 Annual Report indicates this unwillingness or inability to pay for services as some 80% of all monies owed to the municipality are owed by residents and 90% of the debts are due to non-payment by the townships Simunye and Bekkersdal. Taking into consideration the unemployment rate of 30%; and 26% of households with no income in the Westonaria Local Municipality (WLM 2014) it was unexpected to see the implementation of metered systems in Bekkersdal and understandable that especially the informal community members were unhappy about paying for services due to their financial constraints. The Free Basic Water Policy as stipulated in the Water Services Act of 1997 furthermore places the demand upon the government to provide a minimum of 6 kL per household per month without charging the consumer (RSA 1997). This minimum amount of free basic water has to be provided regardless of an individual being able to provide for the water themselves. However, it must be noted that indigent households must register to benefit from the free service delivery. This has been found by the Centre for Applied Legal Studies to be an inappropriate system (SAHRC 2014). Coupled with the high unemployment rate in Bekkersdal of 78.20% is the high cost of clean water if it has to be provided to 64.73% of dependents (Figure 6.4). According to the Brita Index (25 March, 2014) on the highest cost of safe water per country, South Africa ranks sixth globally.

6.4.2. Issues with water service delivery

The WHO and the United Nations Children's Fund (UNICEF) stipulate that a potable water source should be within a reasonable distance from the household, that is, no more than 200 m in an urban environment (WHO 2000). The World Bank allows for the water source to be within a reasonable distance which was defined as 15 min walking distance from the household within rural areas (Langford and Kok 2005). It is recommended that the definition of a "reasonable distance" should take into consideration the local conditions and most importantly the citizens collecting water should also "not spend a disproportionate time fetching water" (Langford and Kok 2005; Heleba 2009). South Africa's Free Basic Services (FBS) Policy stipulates that the water source should be within a 200 m radius from the household and that a minimum of 6 kL per household per month should be provided (SAHRC 2014). Figure 6.6 indicates that there is a disparity between what the formal residents travelling to a water resource experience compared to that of the informal households. Almost without exception (99.60%) the formal residents, on average, spend less than 5 min to collect water while the majority of the informal residents (38.27%) have to spend more than 20 min to collect water. Furthermore, this disparity is again emphasised by the difficulty involved in collecting water as some 45.15% of the informal households considered collecting water to be difficult while the formal residents once again almost unanimously responded that collecting water was very easy. The differences between the formal and informal residents' responses are to be expected as most formal households have taps within their houses while the informal residents collect water from communal street taps or use the Donaldson Dam.

The water services delivered to the informal settlement thus do not conform to the recommendations provided by the World Bank. To add to this issue, 9.28% of the complaints regarding water services indicated long queues at municipal water taps in which the residents have to wait to collect water (Figure 6.6; Table 6.1). Once again, adding more time to the process of collecting water; some 22.63% of the complaints were regarding the interruption of water services without residents being given prior notice resulting in residents having to wait for hours to collect water as can be seen from the quotes in Table 6.1. While the delay in collecting water may be seen as an inconvenience it becomes a more serious issue if water is limited or inaccessible when needed for fire-fighting purposes as some residents have mentioned (Table 6.1).

6.4.3. Use of the Wonderfonteinspruit (inclusive of Donaldson Dam)

In scientific reports the Wonderfonteinspruit is considered to be a highly polluted and modified system. Despite its degraded condition it is still utilised by both the people of Bekkersdal and as a tourist site for recreational and professional angling (Coetzee 2004; Winde 2009; Hamman 2012; Dennis et al. 2013). Some 10.14% of the Bekkersdal residents make use of the Upper Wonderfonteinspruit (inclusive of the Donaldson Dam) on a regular basis. To clarify; this does not exclude these individuals' use of municipal water as their primary source of water, as they make use of the dam water, as a secondary or supplementary source, for either additional activities or when experiencing the aforementioned issues with municipal water services. Those that have used or continue to use Donaldson Dam water make use of it most often for drinking and laundry purposes as can be seen in Figure 6.9. Since the water is of a questionable quality, it is expected that 11.54% complained about health effects caused by the use of Donaldson Dam water. The most commonly reported problems are diarrhoea and skin problems. Many households commented that the children would swallow the water when swimming and return home with gastrointestinal problems and skin rashes as can be noted in Table 6.2. Along with the dangers associated with the polluted water, such as issues regarding drowning; community views also affect the use of the Donaldson Dam including the use of the dam for recreational purposes. Several residents explained that they were afraid of the large snake living in Donaldson Dam that damages buildings and leads to drowning (Table 6.3). Others explained that their concerns relate to the safety of using the dam and requested both better security and lifeguards.

The existing use of the Donaldson Dam (especially by 15.49% of the youth between five and 20 years old) is alarming. Not only because it once again relates to the right to life but also relates to another fundamental right defined in the South African constitution: the right to an environment that is not harmful to a person's health and wellbeing (RSA 1996). The Stockholm Declaration of 1972 declared principles to ensure the "preservation and enhancement of the human environment" (Sohn 1973). The Declaration states that a person has the right to an environment that allows for dignity, wellbeing and adequate living conditions (UN 1972).

The importance of natural environments for the development of children is another factor of concern if viewing the status of Bekkersdal and which should be seriously investigated. As has been mentioned, the respondents indicated that children make use of the dam for recreation (Table 6.2) and furthermore indicated that they would like to make use of the dam in future if it were safer (Table 6.3). Middleton et al. (2013) stresses the importance in terms of dietary health of having a clean water source easily available for children. Interaction between a child and nature can have a great number of benefits leading to increased cognitive functions and psychological wellbeing; it decreases physical ailments and increases recovery from illnesses, moderates the impact of stressful home environments and life events in distressed households as is often the case in impoverished areas (Wells and Evans 2003), and improves their "biophilia" or love for nature (Sobel 1996). Instilling the values of preserving and protecting the earth's natural resources is no longer in question as it is generally known that the environment is key for both human health and wellbeing (RSA 1996; Frumkin 2001; Stilgoe 2001; van Kamp et al. 2003; WHO 2005) This will allow for the love of nature to develop within the youth of Bekkersdal and can aid in preserving Bekkersdal's natural resources for the future and also even have a favourable impact on the wellbeing of the local youth within the educational environment. By 2013, the area became known for the lowest performance in education in the Gauteng Province (WLM 2013). Furthermore one of the principles of the National Environmental Management Act of 1998 states: "The environment is held in public trust for the people, the beneficial use of environmental resources must serve the public interest and the environment must be protected as the people's common heritage."

Donaldson Dam is one of the few natural features in close proximity to Bekkersdal and thus should play a pivotal role in providing a link to the environment and the people of Bekkersdal. The solution is thus not to limit the exposure of Bekkersdal residents to the Wonderfonteinspruit but rather that it should be remediated especially as this link to nature is vital for the wellbeing and health of children and adults. Some residents were of the opinion that the Donaldson Dam may provide entertainment for the youth thus distracting them from unlawful or dangerous activities (Table 6.3).

One resident from the informal settlement of Bekkersdal expressed the following view:

> *Why should we in Bekkersdal suffer from a shortage of water especially here in the informal area when the dam is so nearby? The municipality must do something about the dam. The taps are far away and some streets don't even have taps. What if it is raining and we cannot collect water. Please I beg those who can afford to help us with water. We cannot live a better and healthy life without water*.

The abovementioned view emphasises the plight of the residents of Bekkersdal especially those living in the informal sections. The people of Bekkersdal not only have a right to a better environment but should also be afforded the opportunity to be able to improve their living conditions by using the Wonderfonteinspruit.

6.4.4. Future water use wants and needs

Respondents participating in the Bekkersdal questionnaire indicated that if water could be made more readily available, 42.60% would use the water for additional activities (Figure 6.14). Figure 6.15 indicates the percentages of water uses which the Bekkersdal residents would utilise from the Wonderfonteinspruit if it were of an acceptable quality. It can be noted that most residents would use the water for irrigation (25.45%), drinking water (22.02%) and religious practices (19.69%). Residents indicated that they would furthermore like to use the dam for recreation (11.98%); however, it should be noted that adults (aged 18 and older) were the target group of this questionnaire and thus it is expected that many individuals of the younger generation would most likely use the dam far more regularly for recreation. This is further supported by the fact that many parents indicated that their children already make use of the Donaldson Dam for recreation (Table 6.2). Some 10.97% of the respondents indicated that they would like to use the dam for fishing and if properly implemented this option could provide opportunities for income generation or a means to feed some households. Livestock watering was another use identified as well as other uses such as using the water for construction purposes.

From Table 6.3 it seems obvious that there is demand within Bekkersdal for water use over and above the water provisions currently available. In addition, the questionnaire survey clearly indicated that the people of Bekkersdal would make use of the Wonderfonteinspruit if it were perceived to be a safer environment. In fact, many views expressed by the Bekkersdal residents indicated their desire to use the dam for various activities as can be seen in Table 6.3. It is therefore essential when considering the importance of the Wonderfonteinspruit to consider its value not only in terms of current use but also in terms of future use. The rights of future generations should not be compromised for the goals of current generations (Weiss 1990; Stein 2005).

6.4.5. Perceptions of the Bekkersdal community toward the Upper Wonderfonteinspruit

Bekkersdal has water resources that are shared between the community members especially within the informal section. These shared resources include the communal municipal taps and the Donaldson Dam (the Upper Wonderfonteinspruit) which are shared between the members of the Bekkersdal community as well as paying visitors to the Donaldson Dam.

It is essential to note that when considering water as a common good, it must be then realised that it is a shared good or shared benefit at a societal level; one that should be maintained and protected by the users in order that all users can reap the same benefits. The NWA of 1998 makes provision for the participation of current and potential water users, local and provincial government as well as groups interested in the environment to form part of catchment management agencies whose primary purpose is to manage water resources. The National Water Act (1998) also provides for the formation of water user associations that may be formed by a group of water users to undertake mutually beneficial activities related to water use. A water user association should seek approval for establishment from the Minister. Furthermore, the Stockholm Declaration (1972) emphasises the responsibility of all to ensure an environment for future generations that is protected and improved (Sohn 1973). Principle 22 of the Rio Declaration on Environment and Development (1992) emphasises the valuable contribution the communities of indigenous people can make in environmental management and development (UN 1992). It is therefore apparent that not only should communities take responsibility for the protection of their natural resources, but also that they should be consulted as to the use and development of the natural resources surrounding the community. The Wonderfonteinspruit (inclusive of the Donaldson Dam) is a prime example of a river that has been exploited for close to 100 years (compare Van Eeden, 1992), developed and changed to meet the needs of industry, but not the needs of the communities living nearby or adjacent to the river (Winde 2010). On the whole, a mining operation benefits a local community such as Bekkersdal; however, these communities are negatively affected when upstream gold mining activities cause pollution of the Wonderfonteinspruit and therefore community members should be consulted when the remediation of the Wonderfonteinspruit takes place, as is undoubtedly necessary considering its highly polluted state (Coetzee 2004; Winde 2009; Hamman 2012; Dennis et al. 2013). The use of a river cannot be limited to a few corporate users.

The responsibility to improve the Wonderfonteinspruit and ensure improved water resources within Bekkersdal is that of the Bekkersdal residents, the municipality and the commercial users of the river. The challenges regarding its use from the community's perspective are highlighted by complaints of theft and destruction of water service infrastructure, and thus the community should take responsibility for this to better protect the resources available to them and use these responsibly. Furthermore, it is clear that many people within Bekkersdal believe the Wonderfonteinspruit to be polluted (89.10%). When asked to rank the impacts on the Wonderfonteinspruit the Bekkersdal respondents indicated that sewage and litter are seen to be the worst pollutants and the worst threats in future to the Wonderfonteinspruit as can be seen in Figure 6.17. It is therefore once again the responsibility of Bekkersdal residents to decrease the amount of litter entering the system. However, sewage treatment and collection as well as litter collection, maintenance of water service infrastructure and the monitoring of South Africa's water systems is the responsibility of the government as detailed in both the Water Services Act of 1997 and the National Water Act of 1998. Finally, according to the National Water Act (1998), abstractors, polluters and other users of the Wonderfonteinspruit have the legal responsibility to ensure that their water use is within the legal limits set by their Water Use Licences.

According to the perspectives provided by the residents of Bekkersdal it would seem apparent that the majority of the households taking part in this survey are interested in improving the state of the Wonderfonteinspruit (inclusive of the Donaldson Dam) and the surrounding environment. The residents indicated that they understand the importance of a healthy natural environment for their good health and wellbeing as can be noted in Figure 6.18. Furthermore, Figure 6.19 indicates that the greater majority of the inhabitants of Bekkersdal care about the Wonderfonteinspruit, the environment surrounding it and the state of water quality for both present and future generations. Finally, some 87.8% of the respondents expressed their willingness to be involved in environmental clean-up initiatives in their area despite the fact that some 54.07% of the respondents were unaware of the existence of the Wonderfonteinspruit and Donaldson Dam prior to this questionnaire being presented to them. Taking into consideration the concern shown by the residents of Bekkersdal it is thus imperative for government and corporate water users of the Wonderfonteinspruit to consult with the community of Bekkersdal as is required by the National Environmental Management Act of 1998 and the National Water Act of 1998. The principle of participation is summarized by Llamas (WDJ, 2003) as including, not avoiding, any individuals, in particular the poor, from taking part in ensuring that their rights are upheld and protected. This sentiment is supported by Bovaird (2007) who emphasises the importance of placing communities centrally in decision-making processes such as service delivery decisions.

6.5. Conclusion

There are limitations with regards to water access within Bekkersdal and some threats to national and international human rights within parts of Bekkersdal. These inadequacies are apparent from both a water service delivery perspective as well as an environmental perspective. The residents at times have to spend more than 20 min to collect water, stand in long queues and experience the closing of municipal taps which is in contravention to the guidelines set by the World Bank (Haleba 2009). If municipal taps are closed without prior notice, the residents are unable to plan for this eventuality and have few options for alternative sources, particularly in view of their impoverished state. This situation would impinge upon the requirement set by the NWA No. 36 of 1998 for 25 L of potable water to be provided per day per person. Furthermore, the environmental state of the Upper Wonderfonteinspruit (inclusive of the Donaldson Dam) poses risks to their health when it is used for activities such as drinking, recreation and doing laundry which threaten their right to health (RSA 1996; Coetzee et al. 2004; Dennis et al. 2013). The degraded condition of the Upper Wonderfonteinspruit also threatens the right to an environment that is not harmful to their health and wellbeing and one that is sustainably developed for both present and future generations (RSA 1996; Winde 2010a; Hamman 2012).

The residents of Bekkersdal have a generally good understanding of the importance of the environment for human health and wellbeing and do perceive the Wonderfonteinspruit to be polluted and dangerous. Nevertheless, there is an overwhelming desire within the respondents to improve their situation with regards to water use and use of the Wonderfonteinspruit and surrounding environment. This finding should not be ignored and overlooked by the relevant organs of state and corporate users of the Wonderfonteinspruit, especially as water is a shared common good, despite the indication that this concept has been neglected within the Wonderfonteinspruit catchment.

7. Linking ecological health to human health

7.1. Introduction

Van Kamp et al. (2003) emphasised the need for a relationship to be formed between the community, the environment and economics to create an acceptable quality of life. With high unemployment rates within Bekkersdal and a degraded environment, the standard for a good quality of life is already diminished. However, developing a natural resource such as the Wonderfonteinspruit and improving the state of water resources within Bekkersdal, such as repairing broken water pipes and implementing the proper treatment and discharge of sewage, can aid in improving the environmental element of this partnership. In addition, it can increase job availability by creating new economic opportunities and improving community cohesion by providing a joint project for community members to be part of. Laurence and Heath (2008) found that providing formal volunteering opportunities is key to improving cohesion within a community.

The solution to the complex problems presented by South Africa’s legacy of mining cannot be solved by simply ceasing all mining activities, for then the South African citizens and government would have to contend with the impacts of mining without having the necessary capacity to implement remediation (WWF 2012; Cronje et al. 2013).

The solution thus lies in cooperative management of impacts, where all interested and affected persons are involved in decision-making processes, especially those aimed at working towards a sustainable remediation strategy. This is emphasised in the MPRDA which requires involvement of interested and affected parties and states in section 3(1): “mineral and petroleum resources are the common heritage of all the people of South Africa” (RSA 2008). Though the legacy left by mining is negative there can be a shift towards a positive outcome if cooperative planning is implemented (Cronje and Chenga 2009; Cronje et al. 2013).

Mine closure practice resulting in the remediation of affected areas was originally established in developed countries and focused on returning the affected area back to its previous natural condition. This is seen to have occurred in countries with long established mining industries and mature economies in the late 1960s and early 1970s (Limpitlaw and Briel 2013). However, developed countries such as Australia, Canada and the United States of America still implement mine-closure strategies without taking social needs into consideration. These processes usually involve stripping mining infrastructure and the restoration of mined land based on the historic pre-mining ecological condition of the land (SER 2004).

In developing countries, where mining areas have created infrastructure and employment in otherwise rural areas, returning the land to the historic natural state would not be the best possible solution due to its social implications. Furthermore, subsequent to the Brundtland Report and the Earth Summit of 1992, the inclusion of cultural and social-economic considerations into mine closure has developed (Limpitlaw and Briel 2013). In terms of South Africa's mine closure laws as well as the inclusion of the Integrated Development Plan (IDP) in the Social and Labour Plan (SLP) of mines in South Africa, the inclusion of social issues is a requirement of mine closure planning. The Mineral and Petroleum Resources Development Act (MPRDA) of 2008 stipulates that the mined land should be rehabilitated to a sustainable land use (with associated resources such as water) predetermined and agreed upon by the interested and affected parties (RSA 2008). In terms of the National Environmental Management Act (NEMA) to which the MPRDA commits, the best practicable environmental option must be followed; this is the option that causes the least damage to the environment at a cost acceptable to society in both the short and long term (RSA 2008; RSA 1998a). Returning mined land to its pre-impacted state may also not be a viable option as a study in the United States of America showed that restored lands provided only between 31-93% of the services provided by the various reference biomes after a decade (Bullock et al. 2011) and thus resulted in a sub-optimal solution (Limpitlaw and Briel 2013). In an area such as the West Rand where gold mining and the associated infrastructure development has occurred for over a century (Coetzee et al., 2006) returning the Wonderfonteinspruit to its original state may not be possible, especially in view of the introduced persistent landscape changes surrounding the river system (Doley and Audet 2013).

Research suggests that an adaptive management approach allowing for alternative and novel ecosystems may provide more realisable and achievable outcomes as well as better opportunities that the pre-mining ecosystem would not have provided (Bullock et al. 2011; Doley and Audet 2013). Nonetheless, as is emphasized by Doley and Audet (2013): the "primary outcomes should always aim to achieve the highest standards of biological conservation and ecosystem stewardship." This approach has to satisfy the condition that all stakeholders are consulted and agree on an end land use; these include the mining company, regulator and the community (Doley and Audet 2013).

The most important step involved, and a step repeated almost continuously throughout the life cycle of any remedial process or project implementation, is monitoring. Many indices and monitoring programmes have been developed; however, these are usually divided between assessments of human or ecological health. The relationship between ecological indices, such as PAI (Chapter 2), MIRAI (Chapter 5) and SPI (Chapter 5), and human health and/or wellbeing (Chapter 6) has not been extensively explored. The aim of this final chapter is to determine the link, if any, that exists between human health and wellbeing as well as the ecological indices that have been applied. Furthermore, the specific wants and needs identified by the Bekkersdal community will be discussed in terms of developing the Wonderfonteinspruit to satisfy these needs and desires. It is hypothesised that perceptions from community members towards the state of the Wonderfonteinspruit will be worse than evidence suggests, that the indices will be useful monitoring tools to determine possible links between detrimental impacts and human health and wellbeing, and that the water from the Wonderfonteinspruit can be used for activities that improve the health and wellbeing of Bekkersdal residents.

7.2. Methods and materials

The suitability of the water quality to human health and wellbeing was assessed in terms of human water use requirements, firstly household activities (drinking quality, drinking aesthetics, food preparation, bathing and laundry), and secondly other human-related uses (i.e. irrigation, livestock watering and industrial activities). The water quality variables that are presented in this chapter are limited to those that exceeded the water quality guidelines or were identified in the previous chapters as possible causes of concern. The following constituents were identified in terms of household water use assessments (DWAF 1998): total coliforms, faecal coliforms, TDS, pH, arsenic, calcium, chloride, iron, total hardness, magnesium, manganese, nitrates, sodium, potassium and sulphate. The total nutrient concentrations were determined from the guideline values given in DWAF (1996a) for ammonium, nitrate and nitrite. In terms of irrigation, livestock watering and industrial processes the following water quality variables were assessed: faecal coliforms, sulphate, TDS, chloride and pH. The suitability of a particular water quality constituent meeting the different human use requirements is reflected in a category allocation (DWAF 1998) ranging from Class 0 (ideal) to IV (dangerous). A rank score ranging between 1 and 5 was allocated to these water quality categories assigned in terms of the DWAF (1998) classification scheme (see Table 7.1).

The ecological indices are categorised using the A-F classification system - see Chapters 3 (PAI) and 5 (BDI, SPI and MIRAI). To allow for the direct comparison of the ecological categories to the water quality use categories mentioned in the previous paragraph, the former were also allocated rank scores ranging between 1 and 5 (Table 7.1).

Table 7.1. Rank scores allocated to the classification system of household water quality (DWAF et al. 1998) and the ecological indices.

Household water quality ranking					
Category	**Rank score**	**Description of water quality**			
0	1	Ideal			
I	2	Good			
II	3	Marginal			
III	4	Poor			
IV	5	Unacceptable			
Ecological index ranking					
Class	**Rank score**	**Description of water quality**			
		PAI	**BDI**	**SPI**	**MIRAI**
A	1	Natural	High	High	Unmodified
B	2	Good	Good	Good	Largely natural
C	3	Fair	Moderate	Moderate	Moderately modified
D	4	Fair	Poor	Poor	Largely modified
E-F	5	Poor	Bad	Bad	Seriously-critically modified

Two sets of spider diagrams were plotted using the rank scores obtained for the biological indices together with the household and other human-use categories (i.e. for irrigation, livestock watering and industrial processes) respectively DWAF (1996c-e). For the purposes of the integration the ranks scores are not reported per site and survey but rather based on the average rank value for the five sites and two surveys combined.

7.3. Results

The relationship between the ranking of pH and TDS for human household use and ecological health is presented in Figure 7.1. The overall ecological health has a rank score of 4, which relates to bad water quality. The TDS concentrations were shown to be high (poor for general human use), whereas the pH was ideal for human use. The rank scores for total coliforms and faecal coliforms indicated that the suitability of the water for human use was just as poor as the ecological health ranks (Figure 7.2). The nutrients were not ideal for human use with ranks for drinking water indicating unacceptable water quality in terms of the aesthetics; however, in terms of health the drinking water quality was marginal, while the ecological health indicated a rank falling between the aesthetic and health drinking water quality (Figure 7.2). The ecological health indicated a poorer rank than was suggested by the ranks for nitrates in terms of human use (Figure 7.2).

All ionic elements had scores below the index scores, however total hardness showed similar scores for household use to index scores (Figure 7.3). All mining metal scores were below the index scores with iron and arsenic showing slight increases for drinking (aesthetics), drinking (health) and food preparation (Figure 7.4). Figure 7.5 indicates that industrial scores for sulphate and TDS were equal to or exceeded the index scores. Irrigation scores were only equal to index scores for TDS but were below index scores for all other water quality constituents. Consistently lower scores than the index scores were observed for livestock watering (cattle and sheep) (Figure 7.5).

From Table 7.2 it can be noted that the overall scores for water use by humans is lower than the scores given by indices. Industrial water use scores followed by drinking (health) water use scores were found to be most similar to the scores indicated by indices.

Table 7.2. Averages of all scores according to water use categories.

Water use category	**Average score for human use**	**PAI**	**BDI**	**SPI**	**MIRAI**
Drinking (health)	2.13	4	4	4	4
Drinking (aesthetics)	1.75	4	4	4	4
Food preparation	2.07	4	4	4	4
Bathing	1.80	4	4	4	4
Laundry	1.93	4	4	4	4
Irrigation	2.00	4	4	4	4
Livestock (sheep)	1.33	4	4	4	4
Livestock (cattle)	1.67	4	4	4	4
Industrial	3.00	4	4	4	4
Overall average	**1.96**	**4**			

Figure 7.1. Comparison of ecological indices rank scores and TDS and pH rank scores for household use. A rank of 1 = ideal and 5 = extremely poor.

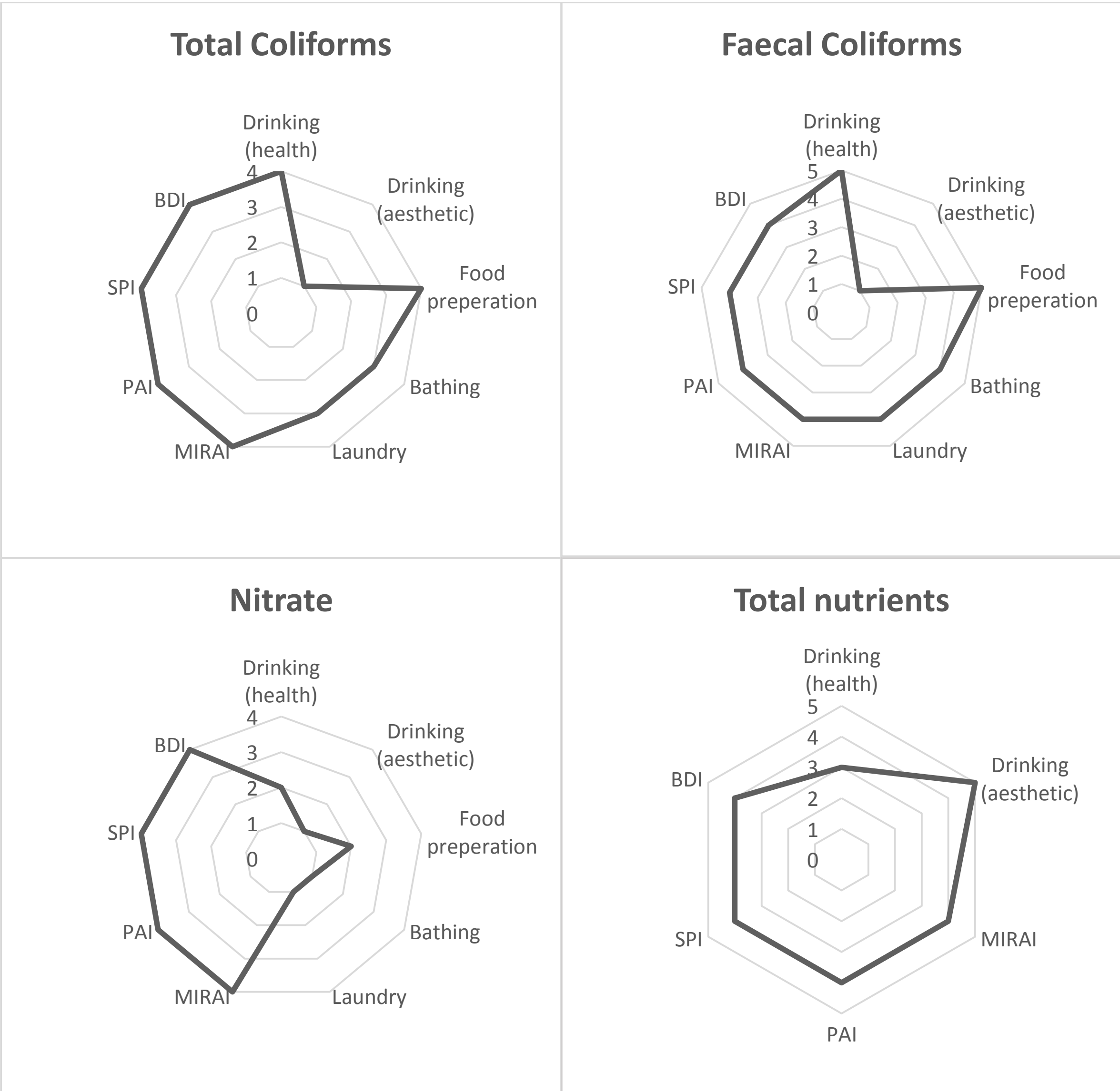


Figure 7.2. Comparison of ecological indices rank scores and coliforms, nitrates and total nutrients rank scores for household use. A rank of 1 = ideal and 5 = extremely poor.

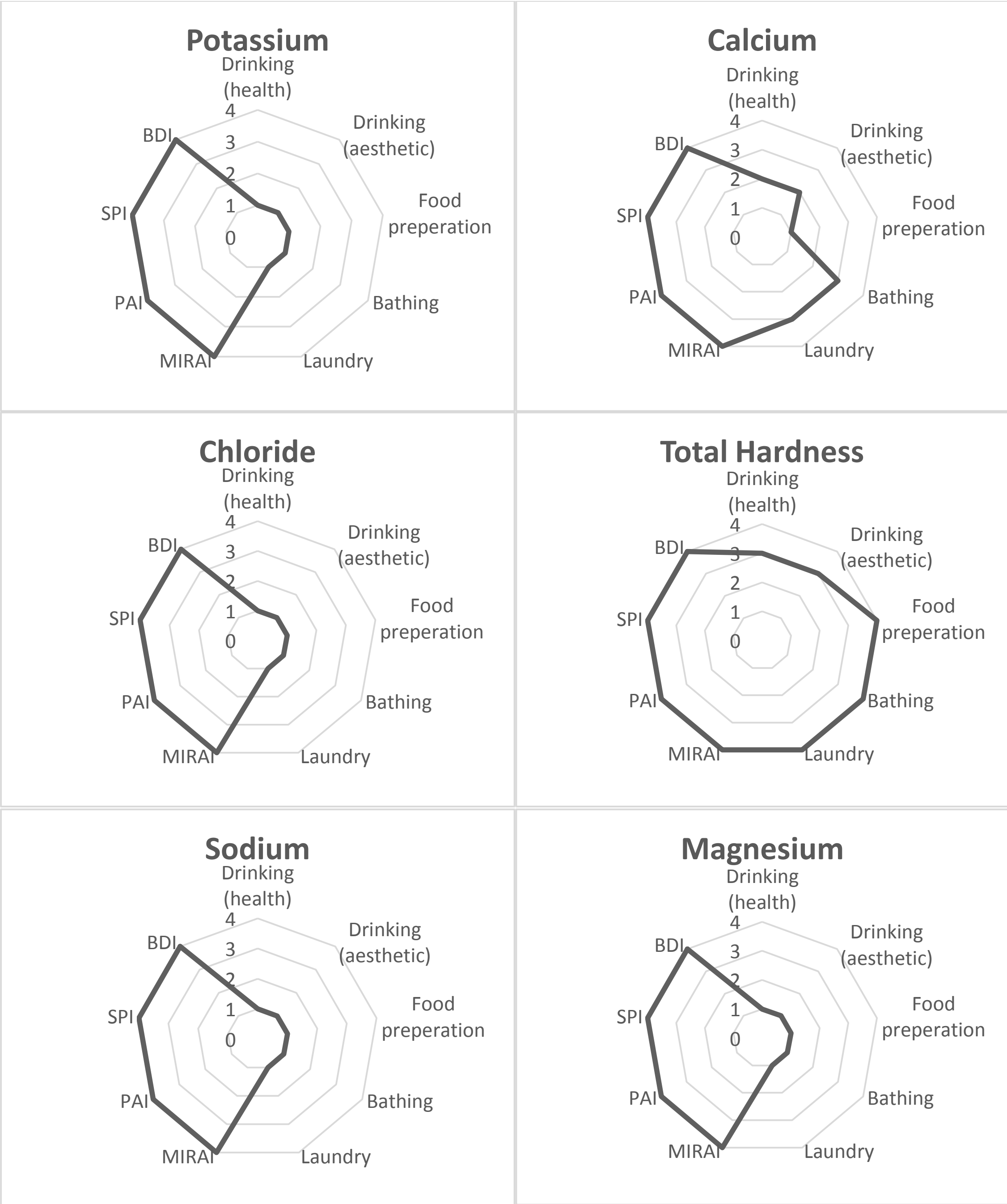


Figure 7.3. Comparison of ecological indices rank scores and major ions rank scores for household use. A rank of 1 = ideal and 5 = extremely poor.

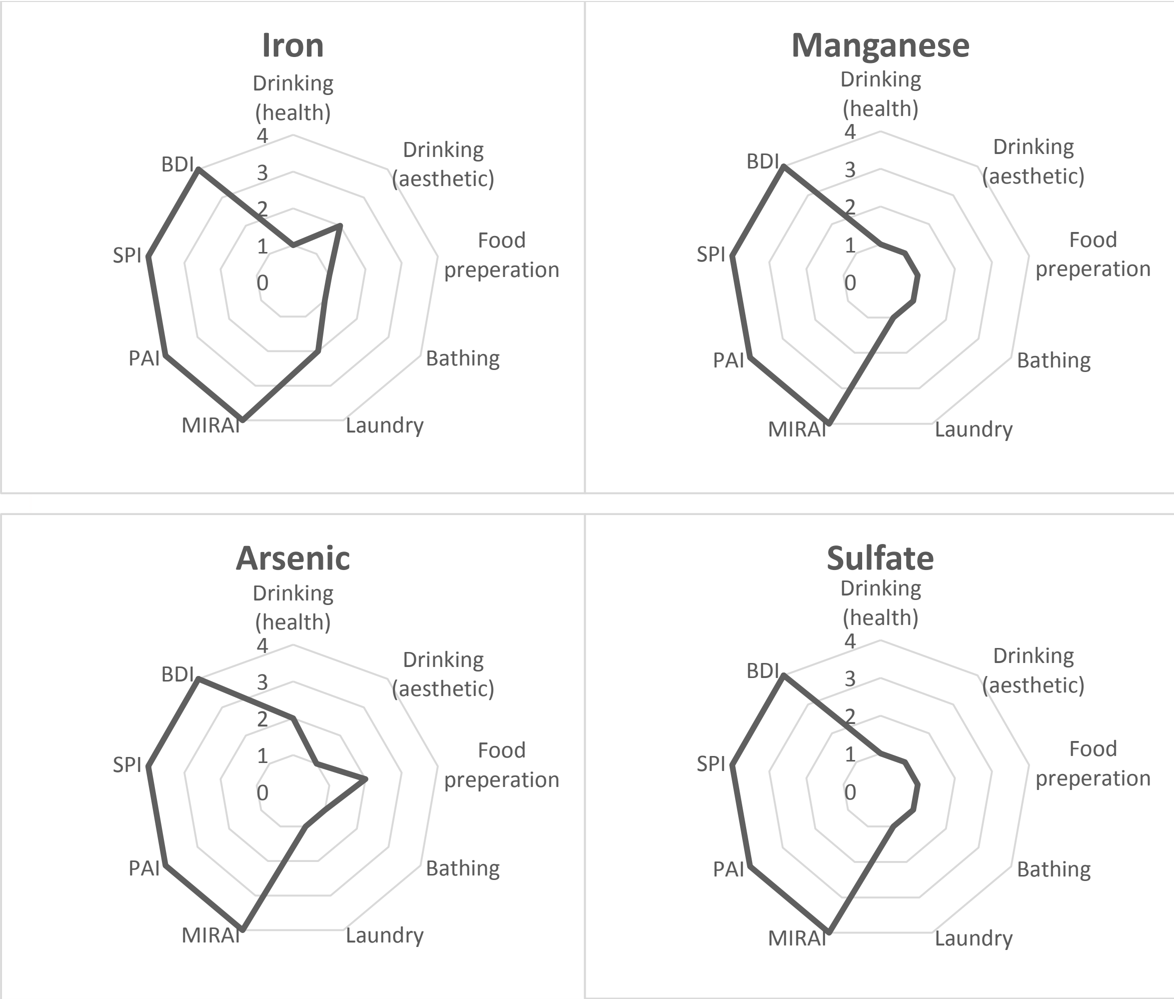


Figure 7.4. Comparison of ecological indices rank scores and mining associated metals and sulfate rank scores for household use. A rank of 1 = ideal and 5 = extremely poor.

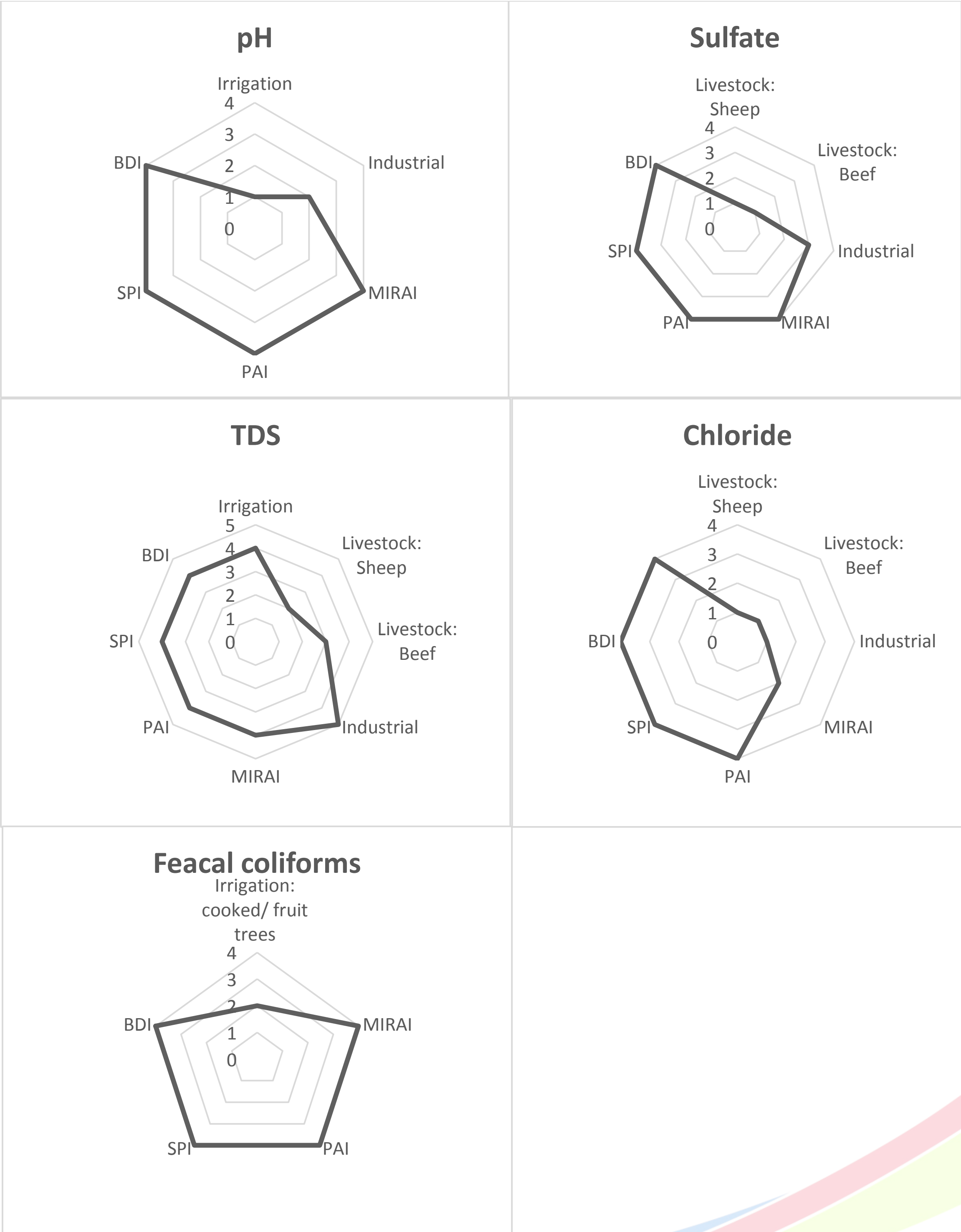


Figure 7.5. Comparison of guideline values for problem water quality variables in terms of irrigation, livestock watering and industrial activities compared to ecological index values. A rank of 1 = ideal and 5 = extremely poor.

7.4. Discussion

7.4.1. Non-metals

The pH, chloride, magnesium, manganese, potassium, sodium and sulphate concentrations in water are acceptable for human use. If this is compared to the indices such as given in Figures 7.1, 7.3 and 7.4 it can be assumed that these constituents did not necessarily contribute to the poor classes indicated by the indices. The factors that have been identified to be most closely associated to the variation within the indexes were nickel, nitrates and nitrites for the diatom species assemblages as well as arsenic and ammonium for macroinvertebrate taxa assemblages. The water quality test results indicated that the ammonium and nitrate concentrations in particular exceeded the TWQR for drinking water (DWAF 1996a). Both these constituents along with nitrites indicate nutrient contamination and may be indicative of sewage inputs.

The association between the indices applied and the total and faecal coliforms as represented in Figure 7.2 indicate that the impacted state of the Wonderfonteinspruit as indicated by the indices is similar to the impacts upon human health. However, the relationship is not direct as elevated coliform counts have not been proven to impact upon macroinvertebrate or diatom assemblages and are also not considered in the PAI. However, these elevated coliform counts can be linked to the high nutrient loads that exceed the TWQR and this association can be seen in Figure 7.2. If the total nutrient scores for drinking water are compared to the classes provided by the indices a similar trend can be observed to that of total and faecal coliforms (Figure 7.2). Donze (2004) found that *E. coli* counts in particular are related to an increase in trophic levels in lakes.

In terms of the regulations for the total faecal coliform counts for irrigation the coliforms counts were found to be below the limit of 1 000 cfu/100 mL for cooked food or fruit trees as has been previously discussed in Chapter 2 (DWAF 1996d). This suggests that the observed data from the indices are more sensitive than those of the criteria for irrigation; however, it is important to note that precautions must be taken for any water used for irrigation exceeding 1 cfu/100 mL (Figure 7.5). Such precautions include: avoid irrigation methods that apply contaminated water directly to crops, such as drip irrigation (if this method is used ensure equipment is regularly disinfected), rinse and cook fresh produce, allow a maximum amount of time between the final irrigation and harvesting of produce (DWAF 1996d). Data given in Figure 7.5 suggest that the sensitivity of industrial processes and irrigation quality are closely represented by the indices applied. In contrast, livestock watering is less sensitive than suggested by the applied indices. There does not appear to be a relationship between chloride, pH and sulphate in terms of industrial activities, irrigation and livestock watering when compared to the values of classes of the indices.

7.4.2. Metals

Figure 7.1 indicates that the TDS in drinking water is unacceptable for drinking and food preparation and less than ideal for other domestic usages. Furthermore, it should be noted that the index values are in line with the values given for domestic use with regards to water usage. TDS is a measure of the dissolved inorganic salts in water and is often closely associated with total hardness. This relationship can be observed in similar plot distributions in Figure 7.1 and Figure 7.4; however, a variation in the severity of impacts between consumption of drinking water as compared to other domestic activities can be observed. Increased TDS is more likely to be detrimental to human health while total hardness is more likely to impact on infrastructure (such as pipes and kettles) (DWAF et al. 1998). This is most likely explained by the fact that total hardness is determined by the combined concentration of calcium and magnesium present in the water; these would only have negative health effects at, on average, much higher concentrations than would be expected for metals such as arsenic, uranium or manganese which would form part of the TDS (DWAF et al. 1998; DWAF 1996a). As mentioned, arsenic and nickel were identified as issues within the macroinvertebrate (Chapter 5) and diatom (Chapter 5) studies, respectively, and therefore warrant closer attention.

Arsenic concentrations were found to be associated with macroinvertebrate species assemblage. Arsenic was also determined to be the main metal affecting edibility of fish, but was not seen as a major issue within the sediment or water quality. According to Figure 7.4 the measured arsenic concentrations in water are less than ideal for domestic use but not lethal; this figure also indicates that the indices implemented are more sensitive than what is required by human communities. The associations between cancers and arsenic may be part of the cause of the abnormal morphology of the gonads of the fish and can be indicative of possible adverse health effects on human populations (Abernathy et al. 1999; Kapaj et al. 2007).

No guideline value for nickel is given in the TWQR for drinking water provided by DWAF (1996a); however, WHO (2011) sets the guideline value at 0.07 mg/L, and all five sites along the Wonderfonteinspruit were found to be compliant with this guideline value. Despite the low acceptable nickel concentration within the water it was identified as causing very high enrichment/contamination within the sediment. Diatom abundances and diversity have been found to increase and to be more closely associated with increased metal concentrations in sediment rather than in water within lakes in Quebec, Canada (Cattaneo et al. 2011).

The intrinsic value of a clean river system should also not be ignored (Frumkin 2001; Maller 2005); without a healthy ecosystem the deterioration of a river system is inevitable which would not only affect the use of the water for recreation by the people of Bekkersdal but also decrease the income generated by tourists to the area. The Donaldson Dam is a popular angling destination that can act as a source of job creation and pride for the Bekkersdal residents. Ecotourism initiatives that are community-based allow communities and not government or private companies to accrue the benefits from these projects, which can be ploughed back into the community and the natural resources surrounding it (Scheyvens 1999). In order for such endeavours to succeed, however, there must be an equitable share of responsibilities and profits which requires responsible and active community participation (Scheyvens 1999).

7.4.3. Indices and use of the Wonderfonteinspruit

The average score for all the water quality parameters that were compared in Table 7.2 gives an indication of the similarity or disparity that exists between the scores in terms of human use versus the water quality as indicated by indices. The average score per use does not provide a detailed account of the risks associated with each water quality parameter. Any average water quality class score exceeding 1, which represents ideal water quality, should be thoroughly investigated for threats to human health and wellbeing.

In general, indices show that impacts are trending higher compared to the standards required by humans; see the average scores per water use given in Table 7.2. Therefore, this suggests that indices such as SPI, BDI and MIRAI can act as early detection methods for possible threats to human health and wellbeing. Furthermore, these indices, in particular MIRAI, can be more cost-effective and less time-consuming than the water quality tests that require experienced technicians and expensive equipment. Such indices also allow for the effect of a number of polluting factors to be assessed over a longer period of time than what a single water or even sediment sample can indicate (Kitner and Poulíčková 2003; Heath et al. 2004; Kleynhans 2008; Thirion 2008; Harding and Taylor 2011).

The indices themselves have various categories that are ranked, rated and weighted in order to determine the overall class for each index; this may also aid in guiding assessors toward possible sources of impacts on human health and wellbeing. The very basis of assessments such as MIRAI, BDI and SPI is that organisms have preferences and tolerances (Thirion 2008; Harding and Taylor 2011). As has been demonstrated in Chapter 5, the specific preferences and tolerances can indicate areas of concern such as for example the large number of the diatom species found to have a preference for eutrophic water (such as indicated by %PTV above 20%) (Harding and Taylor 2011). Other species were found to be tolerant of electrolyte-rich waters, such as *Cyclotella meneghiniana, Nitzschia palea, Gomphonema parvulum* and *Sellaphora seminulum*.

MIRAI indicates the preferences for water quality each family has. The majority of the families found within the Wonderfonteinspruit had no water quality preferences indicating that only those with high tolerances of pollution were present (Thirion 2008).

7.4.4. Perceptions versus results

The perceptions with regards to the state of the Wonderfonteinspruit as discussed in Chapter 6 highlight the understanding the Bekkersdal residents have in terms of the pollution of the Wonderfonteinspruit. Undeniably, the perception of 89.10% of the residents that the Wonderfonteinspruit is polluted has been demonstrated to be accurate. Furthermore, as demonstrated in Chapter 3 and shown in Figure 7.2, the assumption made by the Bekkersdal residents that sewage is the greatest pollutant in terms of human health of the Wonderfonteinspruit proves true. Solid waste and mining pollutants were identified as being the next worst pollutants in the river. The presence of harmful metals in the fish tissue (Chapter 4), water and sediment also indicates that mining and solid waste pollution is a probable and likely source that can affect human health, although the impact thereof might be delayed.

The residents of Bekkersdal expressed concern with regards to the danger and possible health hazards their children might be exposed to when swimming in the Donaldson Dam (Chapter 6). According to the TWQR for faecal coliforms the water within the Donaldson Dam is still acceptable for recreational use; however, it should be noted that potential accidental ingestion of the water can be hazardous to health (DWAF 1996b). Furthermore, swimming in the water in Donaldson Dam may pose other possible health hazards, such as being infected by *Schistosoma* sp. that may be carried in *Bulinus* sp. in the dam (de Kock and Wolmarans 2005). The perceptions of problems associated with bathing in the Wonderfonteinspruit are further supported by the less-than-ideal categories given in Figures 7.2 and 7.3 which demonstrate that calcium, total hardness, total coliforms and faecal coliforms are above the ideal guidelines set for bathing, and are expected to pose at least a slight risk to bathers (DWAF 1998).

7.5. Summary of responsibility for management of the Wonderfonteinspruit

Despite the correct assumptions made by the residents of Bekkersdal, the social motivation to improve the condition of the river does not appear to be present. For example, photographic evidence from numerous newspaper articles and from site visits as demonstrated in Figure 7.6 show the large amount of solid waste dumped into canals that lead into the Wonderfonteinspruit (Olifant and Ngcobo 2013; Hutchings 2014). A need has thus been identified for communities, mining companies and government to work together and cooperate to improve the state of the Wonderfonteinspruit as these impacts on the river system cannot be solved by a single organisation. The key issues and responsible authorities are demonstrated in Table 7.3 for the Upper Wonderfonteinspruit and the Bekkersdal community specifically. The data given in this table illustrate that there are possibilities for remediation strategies that can be implemented independently or jointly by the responsible individuals.

Table 7.3. Pollution types, sources and management examples within the Wonderfonteinspruit.

Pollution type	**Source**	**Possible management strategies**
Sewage	Lack of sufficient sewerage infrastructure	Improvement of sewerage infrastructure by local government
Livestock faecal pollution	Local farmers	Control of discharge from livestock farms; set up of specific watering areas and crossings to allow livestock to cross river without entering the water
Mining waste	Mines located upstream, including any mine dumps, dams and discharge points	Stop mining discharge by reducing point and nonpoint source pollution
Solid waste	Residents of Bekkersdal dumping solid waste inappropriately	Recycling and composting initiatives for each section of block according to the size of the area

The impact of sewage pollution is clear from the total faecal pollution and the discharge of untreated sewage into the river system can be observed; proper management is therefore of utmost importance. A solution that can present economic opportunities for the residents of Bekkersdal in terms of addressing eutrophication from sewage inputs is the growth and harvesting of aquatic plants. Aquatic macrophytes have been long proven to accumulate nutrients (Boyd 1970; Hill 1979). Aquatic macrophytes can also accumulate metals such as copper, iron, manganese, zinc, chromium and lead which can also aid in improving water quality impacts caused by mining pollution (Miretzky et al. 2004). The use of aquatic macrophytes such as water hyacinth (*Eichhornia crassipes*) is often criticised as it can grow and spread rapidly; however, these plants can be harvested and in the case of water hyacinth can be used as fertilizers to generate income (Wolverton and McDonald 1976; Wolverton and McDonald 1978; Wooten and Dodd 1976; Conover et al. 1976; Sircar and Ray 1961). Solid waste also provides economic opportunities in terms of recycling and composting opportunities. This can aid in improving both the water quality and aesthetics of the Donaldson Dam. The Department of Environmental Affairs and Tourism (DEAT) of South Africa have provided guidelines for the recycling of solid waste that can be used by communities (DEAT 2006).

Local government is responsible for the delivery of water and sanitation services and often much hostility is directed toward them if services are not delivered. The evidence for this statement can be seen from the 70.09% of Bekkersdal residents who indicated that they were disgruntled with municipal water services as identified in Chapter 6. The responsibility to provide water services is not solely that of the local government but should be supported by provincial government that is also responsible for monitoring (SAHRC 2014). According to the preamble of the NWA, the National Government has “responsibility for and authority over the nation’s water resources and their use…” Therefore, the National Government has the overall responsibility to ensure that the country’s water resources are properly allocated and managed (SAHRC 2014). Government is further supported by organisations such as: the Department of Cooperative Governance and Traditional Affairs (CoGTA); the South African Local Government Association (SALGA); the Water Research Commission; the Water Institute of Southern Africa; non-governmental organisations (NGOs); the private sector; and water boards (SAHRC 2014).

Mining companies form the second component of those who are responsible for the Wonderfonteinspruit as some of the pollution of the Wonderfonteinspruit is as a result of mining activities that took place historically and has become the liability of present-day mining companies. This begs the question: Who bears the obligation to rehabilitate such areas and to what extent is this liability retrospective? With regards to the historical pollution of the Wonderfonteinspruit, Section 19 of the National Water Act (36 of 1998) and Section 28 of the National Environmental Management Act (107 of 1998) have relevance. The duty to remediate is imposed on “every person” who causes, has caused or may cause significant pollution or degradation of the environment (RSA 1998a). The duty to remediate is also imposed on “successors-in-title” (Section 28(1) of NEMA.) A very similar duty is set out in Section 19 of the NWA and imposes a duty to rehabilitate on owners, persons in control of or persons who occupy the land (RSA 1998b). Both the NEMA and the NWA include historical contamination as one of the triggers for the obligation to rehabilitate and the DWS is given the authority and responsibility to enact these sections (RSA 1998a; RSA 1998b).

Finally, the residents surrounding the Wonderfonteinspruit form the third group of individuals responsible for the Wonderfonteinspruit. Eleanor Roosevelt, Chair of the United Nations Commission in 1948, wrote regarding the Universal Declaration of Human Rights, that: "Without concerted citizen action to uphold them (human rights) close to home, we shall look in vain for progress in the larger world." Though these rights are enshrined and supported by national and international law the recognition of these rights is not always achieved. This becomes especially problematic when citizens are uneducated, marginalised and poor. These citizens are often uninformed or unable to participate meaningfully with decision-making and implementing bodies such as government departments, industry or courts (Moench et al. 2003).

The large percentage of residents (87.8%) who expressed their willingness to be involved in environmental clean-up initiatives suggests that the residents of Bekkersdal would be willing to implement the aforementioned or alternative remediation strategies. However, the knowledge and resources are often lacking within impoverished communities such as Bekkersdal with an unemployment percentage of 78.20%. It is therefore recommended that mining companies whose operations have an impact on the Upper Wonderfonteinspruit as well as the Westonaria Local Municipality participate in empowering residents and promoting community-driven development in the remediation of the Wonderfonteinspruit.

7.6. Conclusion

The results demonstrate that though indices such as PAI, MIRAI, SPI and BDI have been developed to determine the effect of changes in a river system on ecological factors the results of their study can provide useful insight into possible impacts on human health and wellbeing. Furthermore, the hypothesis that the residents of Bekkersdal would perceive the state of the Wonderfonteinspruit as being worse than in reality was not correct; the assumptions made by the residents as to the polluted state and main sources of pollution were correct as it was found that they majority of residents viewed the Wonderfonteinspruit as polluted. The sources of pollutants were also identified by the largest portion of the respondents to be those (mining waste and sewage) that were found to be the greatest sources of pollution in the Wonderfonteinspruit. Finally, the Wonderfonteinspruit water can possibly be used to aid in improving the health and wellbeing of the citizens of Bekkersdal through providing opportunities for economic growth, clean-up initiatives, improved green spaces and community cohesion.

8. Conclusions and recommendations

8.1. Conclusions

Any inquiry into environmental matters is inherently an interdisciplinary study; however, the role of sociology in investigating environmental issues is becoming more and more evident because humans are the cause of many environmental issues but also suffer consequences to their health and wellbeing due to changes in the environment (Dunlap and Marshall 2007). Thus, human interactions with the environment have to be understood in order for environmental concerns to be correctly addressed. The aims, objectives and hypotheses of this dissertation can be divided into three sections: environmental, social and the combined outcome. The aim of the environmental assessment of the Upper Wonderfonteinspruit is to demonstrate the health of the Wonderfonteinspruit using physical, chemical and biological indicators. These findings will then be related to the residents' perceptions of their environment as well as the health status of any current and potential users of the river. It is hypothesised that the physical and chemical results for the Wonderfonteinspruit will indicate unacceptable pollution in terms of utilization of the river water for human activities and that the indices used will give an indication of the polluted state of the Wonderfonteinspruit. The objective of the environmental assessment is to determine the Ecological Category (EC) of the Wonderfonteinspruit using: R-DRAM (Koekemoer and Taylor, 2009); MIRAI (Thirion, 2008); fish HAI (Heath et al. 2004); water quality both *in situ* and *ex situ;* as well as heavy metal analysis of sediment, water and fish tissue.

8.1.1. Environmental outcomes

The objectives and aims in terms of determining the ecological state of the Wonderfonteinspruit were achieved through the use of several indices as well as comparing results for water, sediment and fish tissue quality to other studies and standards. The hypothesis that the quality of water within the Wonderfonteinspruit is impacted by pollutants has been largely accepted; however, it was demonstrated that some water uses can be implemented with little or no change to the water quality of the Wonderfonteinspruit. Furthermore, the hypothesis that the index results will indicate the impacted state of the Wonderfonteinspruit was also accepted for indices applied in terms of water quality, sediment quality as well as macroinvertebrate and diatom community assemblages. However, the fish indices gave little indication as to the polluted state of the Donaldson Dam and the findings that did indicate pollution should be further explored and validated. The examination on the edibility of fish muscle tissue did, however, indicate that the concentration of arsenic in fish muscle tissue is less than ideal and is likely to cause health issues in consumers.

8.1.2. Social outcomes

The social assessment achieved the aims and objectives in terms of determining the use and issues associated with use of both the municipal water supply and the Wonderfonteinspruit. Furthermore, the viewpoint as to the state and the possible remediation and care of the Wonderfonteinspruit (in particular the Donaldson Dam) was determined. It was found that some limitations do exist with regards to the provision of clean water to the people of Bekkersdal by the local municipality and therefore this hypothesis was accepted. In the second hypothesis it was stated that the Wonderfonteinspruit is viewed as unimportant to the residents of Bekkersdal was largely rejected due to the majority (70.46%) of the respondents indicating that they care about the Donaldson Dam and the willingness of some 87.80% of the respondents to participate in environmental clean-up initiatives.

8.1.3. Combined outcomes

The combined outcomes in terms of the aims and objectives were to primarily determine the link between the state of the Wonderfonteinspruit as indicated by ecological indices and the possible link to human health and wellbeing were achieved. The hypothesis that a link exists between the ecological indices and human health and wellbeing was accepted; however, more accurately, it was found that ecological indices act as early warning systems that can indicate possible threats to human health and wellbeing. The secondary aims and objectives in terms of providing comments and solutions on the apportionment of responsibility for the remediation and maintenance of the Wonderfonteinspruit were achieved. The hypothesis that solutions exist that can involve and empower the residents of Bekkersdal was realised; however, the recommendation that further investigation should be implemented should not be neglected before such measures are implemented. Finally, the hypothesis with regards to multiple entities being responsible for the state, remediation and maintenance of the Wonderfonteinspruit was found to be true as government, communities and industry, in particular mining companies, were seen to have a legal and social obligation to the Wonderfonteinspruit.

8.2. Recommendations

In the previous chapters it was indicated that the Wonderfonteinspruit is polluted and degraded with regards to water and sediment; however, this does not make the system unusable. Some possible uses of the Wonderfonteinspruit have been discussed, which include watering of vegetables (to be cooked) and fruit trees as well as the use of aquatic macrophytes for the production of fertiliser. Other uses can also include use of the river water for construction activities (mixing mortar), wash water for vehicles and equipment as well as irrigation for biofuels and ornamental plants. These activities require limited exposure of humans to the water of the Wonderfonteinspruit. Based on the findings presented in this thesis, it is recommended that further investigations be done such that the future wants and need of the residents of Bekkersdal as expressed in Chapter 6 are met. Such that the natural resources within the area are developed in order to expand the possibilities for addressing the serious lack of economic opportunities in Bekkersdal. This can be achieved through the use of the Wonderfonteinspruit as a supplementary water source alongside the provision of the municipal water. In particular, activities other than where there is a risk of ingesting water should be investigated, and awareness creation within the community to improve the knowledge with regards to the Wonderfonteinspruit is strongly recommended. The possible use of indices such as MIRAI, SPI, BDI and PAI to inform communities as to the state of the river and its subsequent possible impacts on human health should also be further investigated, as these indices were identified as useful tools in the previous paragraphs.

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Appendix A: Concentrations (mg/kg) of metals in sediment

	Al	As	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	U	Zn
1 HF	2199.334	5.609	0.125	17.333	50.988	14.347	10445.280	0.183	699.854	25.999	5.485	93.704	40.886
2 HF	3502.337	12.386	0.028	26.163	153.627	30.177	28134.530	0.000	801.870	43.010	10.709	1.418	21.378
3 HF	9504.541	14.803	0.361	49.697	304.945	42.876	46871.850	0.040	4461.150	134.914	23.229	26.993	150.252
4 HF	10458.570	11.092	0.189	25.040	148.733	32.522	27222.450	0.531	3736.927	55.169	44.177	7.083	125.905
5 HF	13490.950	50.362	0.582	218.209	123.944	116.801	32374.250	0.028	2028.169	684.708	38.250	24.386	248.189
1 LF	6562.500	8.693	0.018	20.020	396.875	27.056	43306.450	0.000	1452.621	44.435	9.972	1.571	15.958
2 LF	1939.473	13.141	0.159	27.669	45.817	13.543	14277.100	0.000	994.973	50.835	7.190	7.239	61.251
3 LF	6067.941	9.347	0.178	25.173	202.807	23.362	27542.720	0.000	906.123	68.775	13.629	17.514	76.210
5 LF	16176.470	54.227	0.678	297.923	129.576	138.215	32085.560	0.000	1435.623	982.620	41.125	24.630	279.515

Appendix B: Fish health assessment variables

Fish no.	Gender	Eyes	Skin	Fins	Opercula	Gills	Bile	Mesenteric fat	Liver	Spleen	Hindgut	Kidney	Parasites	Comments
M. sal 1	Male	Normal	Normal	Normal	Normal	Normal	Light straw	>50%	Slightly discoloured	Normal	Normal	Normal	None	Testes with nodules
M. sal 2	Male	Normal	Normal	Normal	Normal	Normal	Light straw	<50%	Slightly discoloured	Normal	Normal	Normal	None	
M. sal 3	Male	Normal	Normal	Normal	Normal	Normal	Light straw	<50%	Slightly discoloured	Normal	Normal	Normal	None	Testes with nodules
M. sal 4	Male	Normal	Normal	Normal	Normal	Normal	Light straw	>50%	Slightly discoloured	Normal	Normal	Normal	None	
M. sal 5	Male	Normal	Normal	Normal	Normal	Normal	Light straw	>50%	Slightly discoloured	Normal	Normal	Normal	None	Testes with nodules; swallowed large hook
M. sal 6	Female	Normal	Normal	Normal	Normal	Normal	Light straw	<50%	Slightly discoloured	Normal	Slight inflamma tion	Normal	None	Liver more red than yellow; eggs
M. sal 7	Female	Normal	Normal	Normal	Normal	Normal	Light straw	<50%	Slightly discoloured	Normal	Slight inflamma tion	Normal	None	Liver more red than yellow; eggs
M. sal 8	Male	Normal	Normal	Normal	Normal	Normal	Light straw	>50%	Slightly discoloured	Normal	Normal	Normal	None	Testes with nodules
M. sal 9	Male	Normal	Normal	Normal	Normal	Normal	Light straw	>50%	Slightly discoloured	Normal	Normal	Normal	None	Testes with nodules; orange object found between muscle and guts

Appendix C: Fish length and mass results

Fish no.	Total body mass (g)	Total body length (mm)	Standard length (mm)	Liver mass (g)	Spleen mass (g)	Gonad mass (g)
M. sal 1	1360	435	375	10.8	0.6	5.153
M. sal 2	700	325	283	4.18	0.21	1.77
M. sal 3	1040	376	316	6.5	0.73	1.69
M. sal 4	1320	394	342	10.15	0.66	2.06
M. sal 5	1220	432	386	10.11	1.33	5.5
M. sal 6	1520	440	389	14.49	0.47	27.96
M. sal 7	1460	458	404	17.16	0.95	47.39
M. sal 8	1360	427	369	4.32	1.6	5.61
M. sal 9	1520	434	389	7.74	1.16	6.7

Appendix D: List of diatom taxa and indication of taxa in Biological Diatom Index (BDI)

Taxon	In BDI
Achnanthidium exiguum (Grunow) Czarnecki	x
Amphora pediculus (Kützing) Grunow	x
Anomoeoneis sphaerophora (Ehrenberg) Pfitzer	x
Aulacoseira granulata (Ehrenberg) Simonsen	x
Amphora veneta Kützing	x
Cyclotella distinguenda Hustedt	x
Cyclostephanos invisitatus (Hohn and Hellerman) Theriot, Stoermer and Håkansson	x
Cyclotella meneghiniana Kützing	x
Craticula molestiformis (Hustedt) Lange-Bertalot	x
Cocconeis placentula var.*euglypta* (Ehrenberg) Grunow	x
Craticula accomoda (Hustedt) D.G. Mann	x
Craticula cuspidata (Kützing) D.G. Mann	x
Cymbella tumida (Brèbisson) Van Heurck	x
Diadesmis confervacea Kützing	x
Diatoma vulgaris Bory	X
Fragilaria capucina Desmazieres	X
Fistulifera saprophila (Lange-Bertalot and Bonik) Lange-Bertalot	X
Gomphonema minusculum Krasske	
Gomphonema parvulum (Kützing) Kützing	X
Hippodonta capitata (Ehrenberg) Lange-Bertalot, Metzeltin and Witkowski	X
Kobayasiella sp.	
Lemnicola hungarica (Grunow) Round and Basson	
Mayamaea atomus var. *permitis* (Hustedt) Lange-Bertalot	X
Navicula arvensis Hustedt var.*maior* Lange-Bertalot	
Nitzschia amphibia Grunow	X
Navicula sp.	
Navicula detenta Hustedt	
Navicula gregaria Donkin	X
Nitzschia frustulum (Kützing) Grunow	X
Nitzschia intermedia Hantzsch	X
Nitzschia linearis (Agardh) W.M.Smith	X
Navicula microrhombus Archibald	
Nitzschia palea (Kützing) W.Smith	X
Navicula riediana Lange-Bertalot and Rumrich	
Navicula tripunctata (O.F.Müller) Bory	X
Pinnularia acrospheria W. Smith	X
Planothidium frequentissimum (Lange-Bertalot) Lange-Bertalot	X
Pseudostaurosira brevistriata (Grunow) D.M. Williams and Round	X

Pinnularia subbrevistriata Krammer	
Rhoicosphenia abbreviata (Agardh) Lange-Bertalot	X
Staurosira construens Ehrenberg	X
Surirella ovalis Brèbisson	X
Surirella papillifera Hustedt	
Staurosirella pinnata (Ehrenberg) D.M. Williams and Round	X
Sellaphora pupula (Kützing) Mereschkowksy	X
Sellaphora seminulum (Grunow) D.G. Mann	X
Tabularia fasciculata (Agardh) D.M. Williams and Round	X
Tryblionella hungarica (Grunow) D.G. Mann	X
Tabularia fasciculata (Agardh)Williams and Round	
Ulnaria ulna (Nitzsch) Compère	X

Appendix E: List of macroinvertebrate taxa

Phylum	Arthropoda			
Subphylum				
Class	Insecta			
Subclass				
	Order	Hemiptera		
	Suborder	Heteroptera		
		Family	Corixidae	
			Genus and species	*Sigara*
		Subfamily	Corixinae	
			Genus and species	*Agraptocorixa*
	Order	Coleoptera		
	Suborder	Adephaga		
		Family	Gyrinidae	
			Genus and species	*Aulonogyrus*
				Orectogyrus
	Order	Ephemeroptera		
		Family	Baetidae	
			Genus and species	*Pseudocloeon or Labiobaetis* *
		Family	Caenidae	
			Genus and species	*Caenis*
	Order	Odonata		
		Family	Libellulidae	
			Genus and species	*Bradinopyga*
	Order	Trichoptera		
		Family	Hydropsychidae	
			Genus and species	*Cheumatopsyche*
	Order	Diptera		
		Family	Muscidae	
			Genus and species	*Limnophora*
		Family	Chironomidae	
		Subfamily	Orthocladiinae	
			Genus and species	*Pseudorthocladius*
		Subfamily	Chironominae	
			Genus and species	*Tanytarsus*
	Suborder	Nematocera		
		Family	Simuliidae	

			Genus (subgenus) and species	*Simulium* (Meilloniellum) *Simulium* (Metomphalus) *Simulium* (Nevermannia) *Simulium* (Pomeroyellum) (larvae) *Simulium* (Pomeroyellum) *alcocki* (pupa)
		Family	Ceratopogonidae	
		Subfamily	Ceratopogoninae	
Subphylum	Crustacea			
Class	Branchiopoda			
	Order	Cladocera		
		Family	Daphniidae	
			Genus and species	*Ceriodaphnia* *Daphnia longispina* *Daphnia pulex*
Class	Malacostraca			
	Order	Decapoda		
	Infraorder	Brachyura		
		Family	Potamonautidae	
			Genus and species	*Potamonautes sidneyi*
Class	Maxillopoda			
	Order	Cyclopoida		
		Family	Cyclopidae	
			Genus and species	*Macrocyclops*
Phylum	Annelida			
Class	Clittellata			
	Order	Oligochaeta		
		Family	Naididae	
			Genus and species	*Tubifex natalensis* *Tubifex*
Subclass	Oligochaeta			
	Order	Lumbriculida		
		Family	Lumbriculidae	

			Genus and species	*Lumbriculus variegatus*
	Order	Tubificida		
		Family	Nadidae	
			Genus and species	*Nais elinguis*
Phylum	Mollusca			
Class	Gastropoda			
	Superfamily	Planorboidea		
		Family	Planorbidae	
			Genus and species	*Ferrissia*
				Bulinus africanus
				Bulinus tropicus
				Burnupia
		Family	Physidae	
			Genus and species	*Physa acuta*
	Superfamily	Lymnaeoidea		
		Family	Lymnaeidae	
			Genus and species	*Lymnaea columnella*
Phylum	Annelida			
Class	Clitellata			
Subclass	Hirudinae			
	Order	Rhynchobdellida		
		Family	Glossiphoniidae	
			Genus and species	*Batracobdelloides tricarinata*
				Marsupiobdella africana
				Placobdelloides multistrata
				Helobdella stagnalis
Phylum	Cnidaria			
Class	Hydrazoa			
	Order	Hydroida		
		Family	Hydridae	
			Genus and species	*Chlorohydra viridissima*
Phylum	Nematoda			
Class	Secernentea			
	Order	Tylenchida		

*Classification uncertain due to issues explained in text

Appendix F: Bekkersdal questionnaire

Questionnaire on:

Water use of the Upper-Wonderfonteinspruit by the people of Bekkersdal

NORTH-WEST UNIVERSITY ®
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT

Dit begin alles hier ™

Introduction

Purpose of questionnaire:

The purpose of this questionnaire is to gather information on the water habits of the Bekkersdal Township (formal and informal). Special focus is placed on the use of the Upper-Wonderfonteinspruit. The information to be collected will focus on:

- Current water usage patterns and habits.
- Knowledge and views community members may have of the Wonderfonteinspruit.
- The future wants and needs of the Bekkersdal community relating to water use.

The answers from this questionnaire will be used to complete a M.Sc. thesis at the North-West University, currently titled: *Determining attainable ecological categories for the Upper-Wonderfonteinspruit Catchment, based on human community requirements: The case of Bekkersdal*. The study forms part of an NRF Community Engagement Project and this project does comply with the ethics mandate of the greater NRF project (see Ethical Clearance: no. FH-BE-2013-0014).

Instructions to participants:

If you agree to voluntarily participate in the questionnaire titled: *Water use of the Upper-Wonderfonteinspruit by the people of Bekkersdal*, you will be invited to share your experience on water views, usages and needs in the vicinity of Bekkersdal, especially with regards to the Upper-Wonderfonteinspruit, as well as other related information on the household you represent.

Instructions to fieldworker assisting participant:

- Make a cross next to the appropriate answer in the box provided or fill out the answer in the space allowed.
- Answer all questions and if anything is unclear to the participant, then encourage them to ask. It is very important that the participants understand the meaning of the questions.
- Ensure that you have received all the pages (covering five sections and 15 pages in total; 4 introductory pages and 11 question pages).

Thank you for your participation.

Risks/discomforts:

There are minimal risks associated with participating in this questionnaire. The only discomfort may arise from the length of time taken to complete this questionnaire, which will be approximately 30 minutes. All information given by you will be held in strict confidence and will be used for the purpose of this study only. No personal identification will be revealed when the information is used. The researcher and the fieldworkers used will consider and respect the community and participants throughout the study.

Benefits:

There will be no direct benefit to you from participating in this study. Your participation will help the researcher in exploring and identifying a data set on the current water use patterns and habits of yourself and the community as well as the present and future needs of the community regarding water availability and usage. Related challenges faced by yourself and community members' regards potable water availability and water quality in general will be determined and future use of water in Bekkersdal. Your participation can however assist in results that can possibly contribute to provide more insight to local leadership and government on the ecohealth and wellbeing patterns regards water usage in the informal and formal parts of the Bekkersdal Township. Suggestions for improved community practices, an increased capacity and leadership for policy change with increased engagement among stakeholders will be key outcomes for this research. The broader project research team will provide the community with the opportunity to attend a meeting(s) before/by 2016 to be informed on the research results, and provide some last input.

Informed consent

Water use in and around the formal and informal settlements of Bekkersdal:

I have been informed that the purpose of the research is to understand my current and future water use habits and patterns in and around the immediate environment of the Bekkersdal formal and informal settlements, as well as my views and knowledge about the water quality of the Wonderfonteinspruit (inclusive of Donaldson Dam). My participation will specifically involve answering five sections of questions related to i) my personal details ii) my current water use, iii) my use of water from the Upper-Wonderfonteinspruit and iv) my impression on the future utility value of this Spruit in particular as well as v) my impressions of the Wonderfonteinspruit's water quality. I have been informed that the interview will take about 30 minutes. I understand that there are no foreseeable risks or discomforts if I agree to participate in the study.

I understand that the results of the study may be published, but that my name or identity will not be revealed. I also understand that the results of the study may be used for secondary studies connected to the NRF IMD Community Engagement project on Bekkersdal, but that my name or identity will not be revealed. The North-West University will maintain confidentiality of all records and materials.

I have been informed that I will not be compensated for my participation. I have been informed that any questions I have concerning this research study or my participation in it before or after my consent will be responded on or answered by the investigator of this study (Simone Liefferink at lialalief@yahoo.com/ 076 209 8493 or Prof Elize S van Eeden at Elize.vanEeden@nwu.ac.za).

I understand that I may remove my consent and stop participation at any time without penalty or loss of benefit to myself. In signing this consent form, I am not waiving any legal claims, rights, or remedies.

I, the undersigned, _________________________________ (full names), have read and understand the above information and by signing this form indicate that I will participate in the research voluntarily.

Participant's signature: _______________________Date: ______________________

Investigator's signature: ______________________Date: ______________________

Section 1: Demographic Details

Household details

Stand number	
Name of ward	
Name of household member providing information	
Contact number	

Does your household fall into the formal or informal area of Bekkersdal?

Formal	
Informal	

How many members are in your household (not including renters)?

How long have you lived in Bekkersdal?

How many of your household members (including yourself) fall into the different age groups (not including renters)?

Age group	Number of household members
0-19	
20-39	
40-69	
≥70	

Section 1: Demographic Details

Are you a South African citizen?

Yes	
No	

What is the employment status of your household members? Please give the number of members that fall into each category.

Employment status	Number of household members
Preschool	
Scholars	
Unemployed	
Employed	
Self-employed	
Part-time work	

What is your home language?

Do you understand English?

Yes	
No	

Section 2: Current Water Use

What is the main source from which you get your water?

Municipal water (from a tap or water tank)	
River (Upper-Wonderfonteinspruit including the Donaldson Dam)	
Other Please specify:	

Please indicate the difficulty involved in getting water. 1 being very easy with minimum effort required and 5 being extremely difficult requiring a maximum amount of effort (takes a lot of physical work and time to collect).

1. Very easy	
2. Easy	
3. Some effort	
4. Difficult	
5. Extremely difficult	

What distance do you have to travel to get water?

Close (Less than 5 minutes)	
Moderate (6-15 minutes)	
Far (more than 20 minutes)	

I have access to water ...

Continuously (have a tap or water tank)	
Daily (I can collect water everyday)	
Only some days of the week	
Intermittently (sometimes I have continuous access, sometimes I have no access)	

Section 2: Current Water Use

What problems have you experienced in the past regards access to water?

Please indicate how often your household uses municipal water (water from a tap or water tank) for:

Water use	Continuously	Occasionally	Never
Consumption - for drinking and cooking			
Irrigation – for watering plants			
Watering of livestock (such as cattle or sheep)			
Washing			
Recreation (such as for relaxing or playing sport in the water)			
Religious practices			
Other Please specify:			
Do not use municipal water			

Section 3: Use of the Wonderfonteinspruit

Does your household use water from the river (Upper-Wonderfonteinspruit and Donaldson Dam)?

Yes	
No	

If yes to Question 3.1 what do you use the river water for? More than 1 answer can be chosen.

Water use	Continuously	Occasionally	Never
Consumption – for drinking and cooking			
Irrigation – for watering plants			
Watering of livestock (such as cattle or sheep)			
Washing			
Recreation (such as for relaxing or playing sport in the water)			
Religious practices			
Other Please specify:			
Do not use river water			

Has the use of water from the Wonderfonteinspruit (including the Donaldson Dam) ever had an effect on your health?

Yes	
No	

Section 3: Use of the Wonderfonteinspruit

If yes to Question 3.2, what health impacts have you experienced?

Who (which age group) in your household most often uses the Wonderfonteinspruit?

5-12 years of age	
13-20 years of age	
21-60 years of age	
>60 years of age	
None	
All ages	

Who, according to your knowledge, within the Bekkersdal community makes use of the Wonderfonteinspruit (including the Donaldson Dam) most regularly?

Unemployed residents	
Farmers	
Fishermen	
Traditional healers	
Other Please specify:	

How often do you catch and/or eat fish from the river (Wonderfonteinspruit and Donaldson Dam)?

Never	
Not often (less than 1 a week)	

Section 3: Use of the Wonderfonteinspruit

Often (more than 1 a week)	
Continuously (on a daily basis)	

Are you aware of the following resources that are being sold from the Wonderfonteinspruit? Please tick all the appropriate answers.

Fish	
Plants	
Mud cakes ('pica')	
Other Please specify	
Not aware of any resources being sold	

Section 4: Future Water Use from the Upper-Wonderfonteinspruit

Would you like to use water for other activities if water was more readily available?

Yes	
No	

If yes to Question 4.1, what would like to use the water for additionally?

For what uses would you like to use the Wonderfonteinspruit (including Donaldson Dam) in future assuming it is clean?

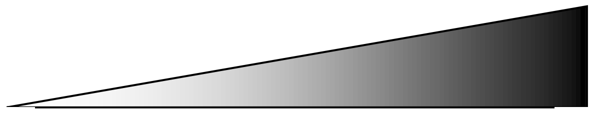
Drinking water quality	
Irrigation quality (can use water to grow fruit and vegetables)	
Livestock watering (can use water for livestock to drink from)	
Religious practices (such as baptisms)	
Recreation (such as for relaxing or playing sport in the water)	
Fishing	
Other	

Section 5: Water Quality Perceptions of the Wonderfonteinspruit

Do you think the Wonderfonteinspruit (including the Donaldson Dam) is polluted?

Yes	
No	

If yes to Question 5.1: What do you think is the biggest current human impact related to the Wonderfonteinspruit? Please circle the appropriate rate next to the source of pollution (1= least concern; 2= 4th greatest impact; 3= 3rd greatest impact; 4= 2nd greatest impact; 5= greatest human impact; 6= becomes the greatest human impact but is only valid if the participant provides an answer for ‘other’).



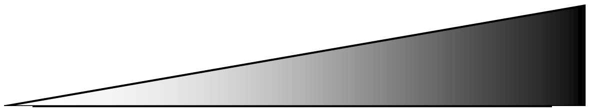
1 — Human impact of least concern

6 — Greatest human impact

Source of pollution	Rating					
Sewage	1	2	3	4	5	6
Litter	1	2	3	4	5	6
Mining waste	1	2	3	4	5	6
Agricultural waste (from farming)	1	2	3	4	5	6
Industrial waste (from big factories)	1	2	3	4	5	6
Other Please Specify:	1	2	3	4	5	6

Section 5: Water Quality Perceptions

What human impact do you think could pose the greatest threat to the health of the Wonderfonteinspruit? Please circle the appropriate rate next to the source of pollution (1= threat of least concern; 2= 4th greatest threat; 3= 3rd greatest threat; 4= 2nd greatest threat; 5= greatest threat; 6= becomes the greatest threat but is only valid if the participant provides an answer for 'other').



Source of pollution	Rating					
Sewage	1	2	3	4	5	6
Litter	1	2	3	4	5	6
Mining waste	1	2	3	4	5	6
Agricultural waste	1	2	3	4	5	6
Industrial waste	1	2	3	4	5	6
Other Please Specify:	1	2	3	4	5	6

Do you think water quality tests using natural components, such as the amount and type of insects and fish, can provide useful information on the quality of water in the Wonderfonteinspruit?

Yes	
No	
c. Don't know?	
If Yes or No please explain your answer:	

Section 5: Water Quality Perceptions

How important do you think it is for the sake of human health and wellbeing to maintain a healthy natural environment?

Very important	
Important	
Moderately important	
Of little importance	
Not important	
Don't know	
Please explain your answer:	

Do you care about…?

The state of the Wonderfonteinspruit	Yes	No
The state of Donaldson Dam	Yes	No
The quality of the water you and your household uses	Yes	No
The state of water quality and availability in Bekkersdal for future generations (e.g. your children and children's children etc.)	Yes	No
The state of the environment surrounding the Wonderfonteinspruit and Donaldson Dam	Yes	No

Please tick the most appropriate statements about your feeling of the Wonderfonteinspruit (including the Donaldson Dam):

I am not aware of the Wonderfonteinspruit at all	
The Wonderfonteinspruit is not important to me, it would not matter if it was there or not	
I like the Wonderfonteinspruit	

Section 5: Water Quality Perceptions

The Wonderfonteinspruit is important to me	
The Wonderfonteinspruit makes me happy	

Would you like to be part of initiatives to improve the state of the natural environment that surrounds you?

Yes	
No	

Field Notes

Appendix G: Several comments regarding water service delivery issues in Bekkersdal

Paying for water services	**Taps are far and too few**	**Water services infrastructure broken**	**Water closed without informing the community**	**Long queues for access to water**	**Burning shacks**	**No water**
In the past few months there was a toy-toy here in Bekkersdal because our municipality want us to pay for water	*I had to travel to collect water and I had a swollen foot*	*Broken taps, in winter we can't get water from the taps*	*The municipality closes the water and do not inform us and we only get water after 5pm, they do not care about us*	*Because the taps are too far and we must queue every day to get water and sometimes municipality closes the water and they don't inform us.*	*Burning of shacks because the water taps are too far away to stop the fires*	*There is no water so we use water from the Donaldson Dam and that causes stomach diseases*
High amounts paid for water and it is uncontrollable	*Many children are very dirty here because their parents or single parent is sick and there is no one to go and fetch water*	*Cutting off street's taps and sold it to scrap yard.*	*The water taps are too far away and we have to queue, we have to wait for 10 hours for water like yesterday when the municipality closed the water without informing us, they do not care about us*	*Have to wait in very long queues for hours to get water and the taps are very far from our houses*	*I saw many shacks burning down because taps are few and distant from many shacks*	*We used the water of Donaldson Dam because the taps were closed*
Last year I	*Our children*	*I experienced*	*When the*	*I experience*	*Most of*	*No water*

experienced protests against the meter system and they broke it and now I'm experiencing wasted water because the water is still running in the street.	*on holidays mostly visit Donaldson Dam and that leads to them getting sick because there are no taps in our yards*	*running and leaking taps that is occurring even now*	*municipality closes the taps they do not inform us, they forget that we have to queue for water and should inform us beforehand so that we can get water*	*long queues for water and the water is no safe because children play and lick the taps*	*the shacks are burning up because of the shortage of taps, even now they are burning up*	*all around informal*
Municipality installed meters without the permission of the community, so we broke the meters and even now there is water running in the street from the broken tap.	*Shortage of taps is a main problem since I've lived here (12 yrs.)*	*I experienced running water from the taps and the streets are full of green water*		*The taps are too far and we must queue for water, the municipality does not care about us*	*Our shacks are burning down because the taps are too far away in order for people to get water to stop the shacks from burning*	*No water in taps*
People toy-toying because they don't want water meters they want free water because they are not working and have no money to buy water.	*The problem is that our taps are too far from us and we must queue for water and the municipality does not care about us because we are living in an informal*	*Our roads are full of mud because the taps are leaking, water is running in the street and that will cause mosquitoes in the summer*				

	settlement					
People were very angry about the meter system and they vandalised the taps	*The problem is when you want water and the taps are broken*	*Water from the taps is running in the street, most are dumping dirty water into the street and the streets become dirty and smell bad, which causes sickness in our community*				