

Nutrient reduction options in Hartbeespoort Dam catchments to lower in-dam eutrophication status

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Dissertation submitted in fulfilment of the requirements for the
degree *Magister Scientiae* in *Environmental Sciences*
(specializing in Hydrology and Geohydrology) at the
Potchefstroom Campus of the North-West University

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November 2015

PREFACE

THIS STUDY IS IN THE FULFILLMENT OF THE DEGREE, MAGISTER SCIENTIAE IN ENVIRONMENTAL SCIENCES, AT THE NORTH WEST UNIVERSITY. THE INTEREST OF THE LOCAL POPULATION AS WELL AS THE RESEARCH BY THE SCIENTIFIC COMMUNITY IN MANAGING THE EUTROPHICATION PROBLEM OF THE HARTBEESPOORT DAM ARE THE MAIN MOTIVATORS TO EMBARK ON AN IN DEPTH STUDY OF THE HISTORY AND CAUSES OF EUTROPHICATION IN THE DAM AND TO ELABORATE ON OPTIONS TO REDUCE PHOSPHATE INFLOW TO THE DAM.

ACKNOWLEDGEMENTS

My Lord and Saviour, Jesus Christ, "in whom are hidden all the treasures of wisdom and knowledge." (Colossians 2:3)

I would like to express my sincere gratitude and appreciation to the following organisations and individuals:

My wife, Annette, for moral support and encouragement as well as editing and special care of the study.

Professor Johan Nel (CEM) inspired me to pursue an academic study of the Hartbeespoort Dam remedial endeavour.

This culminated in my acceptance by Dr Rainier Dennis as a student. I am thankful for the privilege of conducting my study under his guidance.

Mr Petrus Venter of the Department of Water Affairs allowed access to all published data and reports of the Metsi-a-me programme.

Members of HWAG, Rick van Rossum and Dirk Bouwer, who allowed me the opportunity to participate in the formulation of a project plan to implement the Metsi-a-me programme.

Willie Potgieter of Enhanced Engineering Solutions and Dr Zoran Cukic (consultant) for encouragement to apply my long term experience in process engineering and project management at SASOL to assist in problem solving with regard to the Hartbeespoort Dam remediation.

I am also indebted to TUT and Professor Jannie Maree who allowed me mentorship of post graduate students on Hartbeespoort Dam related issues.

Michael de Clercq of University of Ghent, co-operated and shared his research with me on Eco hydraulic modelling.

My sons, Andries and Frikkie, for their support to create an Excel programme of the catchment.

Philine de Clercq for her excellent support with computer related applications.

ABSTARCT

Eutrophication of surface water constitute a major threat to the provision of raw potable and irrigation water in South Africa, being largely dependent on impounded water in order to ensure water supply . South Africa is highly dependent on water stored in dams for socio-economic uses. Some of these dams, including the Hartbeespoort Dam, are experiencing excessive amounts of nutrients which are introduced by raw or partially treated effluents or run-off water from irrigated land that had fertilizer applied. Dams that have been affected by high levels of nutrients in the presence of abundant blue–green algae cause cyanobacterial blooms, which produce cyanotoxins. These cyanotoxins can pose a health-risk to both humans and animals (including aquatic animals) if ingested.

The affected dams are classified as either hypertrophic (excessive levels of nutrients) or eutrophic (high levels of nutrients). Algal and cyanobacterial blooms and particularly surface scums that may result are unsightly and can have unpleasant odours. Eutrophication of water results in various symptomatic changes which can include the increased production of algae and aquatic macrophytes and the deterioration of water quality. The process occurs naturally over geological time, or may be accelerated due to allochothonous anthropogenic impacts, often referred to as “cultural” eutrophication. Phosphorous (P), and to a lesser degree nitrogen, have been identified as the major causes of eutrophication in surface waters. Eutrophication of dams is a major threat throughout South Africa since the early 1970’s.

As a result of the eutrophication of the Hartbeespoort Dam this catchment was identified as a priority area for the implementation of the Waste Discharge Charge System (WDCS) to manage the phosphate load that is discharged from the various sub-catchments to the dam.

The Hartbeespoort Dam has formed the basis of various studies undertaken by the Water Research Commission (WRC). It is factual that eutrophication is especially apparent in the inland areas of South Africa, especially around major urban areas such as the Johannesburg-Pretoria complex (Harding, 2008).

Prominent limnologists recommended that in order to manage the dam effectively the eutrophication capacity for the Hartbeespoort Dam should not be exceeded. The eutrophication capacity refers to the capacity of the dam to assimilate phosphorus loads without trophic status thresholds being exceeded. The trophic status thresholds pertain to the phosphorus loading levels, translated to concentration of in-lake phosphorus that may result in increased frequency of problematic conditions such as algae blooms. The phosphate load entering the Hartbeespoort Dam is entirely due to anthropogenic activities that emanate from the urban areas in the upper reaches of the catchment. A large portion of the load is due to overflowing and leaking sewer systems, which is more difficult to address than the point sources.

Due to this problem with water quality in the Hartbeespoort Dam, the catchment was selected for the research on nutrient reduction options in line with the Waste Discharge Charge System (WDCS) as included in the National Water Act (NWA) of 1998. Water quality standards (DWAf, 1996) in the NWA are related to the South African Water Quality Guidelines (the WQGs) which were published in eight volumes, describing the acceptable level of substances or constituents for the different water users (Barnard, 1999:277).

The objective of this dissertation is to determine the total load of phosphates that is discharged from the four sub-catchments and the area around the Hartbeespoort Dam in order to identify and quantify the different sources as accurately as possible.

The load that enters the Hartbeespoort Dam can be related to the actual nutrient level present in the dam. This can be correlated by models such as the Vollenweider Model. A study by South African scientists was used to verify the relationship.

From literature the threshold level of eutrophication in South African reservoirs have been determined to be 55 µg/ml P. The actual level in the Hartbeespoort Dam is about 250 µg/ml P.

To achieve a level of 55 µg/ml P, the load entering the dam will have to be reduced by about 80%.

This study investigated the level of load reduction that could realistically be achieved through various means. The performance of the relevant waste water treatment works (WWTW) and the non-point source contribution originating from agriculture and informal settlements, as well as storm water was calculated from available databases. Options were identified that could estimate realistic nutrient reduction levels based on current and more advanced technology.

The research also touched on the nutrient reduction theory of using pre-impoundment to perform nutrient reduction coagulation before inflow of water into the Hartbeespoort dam.

The problem of Acid Mine Drainage (AMD) decanting into the catchment is placed within the context of the eutrophication problem in the Hartbeespoort Dam. An intervention is investigated to convey AMD per pipeline to chemically reduce phosphate levels in the Crocodile River. WDCCS and zero phosphate detergents are also discussed to optimise nutrient reduction options in the catchments.

The nutrient reduction strategy is accepted as a long term goal that needs to be integrated with the National Water Resource Strategy.

Key Terms: Eutrophication, pre-impoundment, nutrient reduction, acid mine drainage, waste water treatment.

SAMEVATTING

Eutrofikasie van oppervlakwater is 'n prominente bedreiging in die berging en voorsiening van water vir menslike gebruik en besproeiing van gewasse in dele van Suid-Afrika. Die land is grotendeels afhanklik van opgaardamme wat voorsiening moet maak vir volhoubare beskikbaarheid van water.

Sommige opgaardamme, insluitend die Hartbeespoort Dam (HBPD), ondervind eutrofikasie – probleme as gevolg van oormatige belading met voedingstowwe of nutriënte. Oormatige nutriënte is hoofsaaklik die gevolg van ongereguleerde menslike aktiwiteite wat die natuurlike komponente van eutrofikasie van die eko-sisteem oorskrei. Dit is veral onbehandelde of onvoldoende behandelde riool, asook uitgeloogde kunsmisstowwe wat in riviere beland wat bydra tot eutrofikasie in damme. Die gevolg is dat oorverrykte water aanleiding gee tot buitengewone groei van sekere alge, veral die blou-groen alg, beter gekend as cyanobakterie. Die uitbundige vermeerdering van hierdie bakteriespesie gee aanleiding tot stress weens suurstoftekort met die gevolglike vrystelling van giftowwe soos die cyano-toksiene, wat giftig is vir mens en dier.

Geaffekteerde damme word geklassifiseer volgens die voorkoms van fosfaat (P) of chlorophyll- α . Hipertrofiese damme bevat konsentrasies P so hoog as 250 $\mu\text{g/ml}$. Dit gee gewoonlik aanleiding tot 'n digte versameling cyano-bakterie wat soos 'n mat op die oppervlakte dryf. Meer algemeen gee die verhoogde P aanleiding tot uitbundige groei van makrofiete wat mettertyd die oppervlakte 'n groen skynsel gee en wat slegte reuke afgee in die omgewing. Fosfate is bevind as die beperkende groeimiddel in die HBPD. Aangesien stikstof in 'n mindere mate eutrofikasie veroorsaak, is dit dus belangrik om die teenwoordigheid van fosfate te beperk.

Die prominente posisie van die HBPD het waterbestuurders laat besluit om bekamping van eutrofikasie in die dam as 'n prioriteit te verklaar in die implimentering van die Nasionale Waterbron -bestuurstrategie se besoedelingsvoorkomingsplan deur wetgewing te ontwikkel om besoedelaars te beboet (sogenaamde “Polluter-Pays” beginsel).

Die HBPD was ook die onderwerp van verskeie ondersoeke en verslae wat deur die Water Navorsingskommissie gefasiliteer word, aangesien die besondere ligging van groot stedelike gebiede rondom die ekonomiese dryfkrag in Gauteng bedreig word deur tekort aan geskikte waterbronne.

Prominente limnoloë het aanbeveel dat eutrofikasie beperk kan word as die dam se vermoë om fosfaat te assimileer, voor eutrofikasie handuitruk, nie oorskrei sal word nie. Die drumpel van fosfaatbesoedling is nagevors en die strewe is om die fosfaatinvloei in die dam te beperk, sodat die drumpel nie oorskrei word nie. Die drumpelwaarde is deur navorsers gestel op 55 $\mu\text{g/ml}$ P in

die dam. Dit kan slegs bereik word as die huidige lading van fosfaat na die dam met meer as 75% verminder word, aangesien die huidige vlak van 250 µg/ml reeds genoeg fosfaat bevat om vir 'n lang periode eutrofikasie te laat voortduur.

Die mikpunt van hierdie studie is om vas te stel wat 'n realistiese ladingvermindering moet wees. Die prestasie van die relevante rioolsuiweringaanlegte en die bydrae van die diffuse puntbronne wat uit die landbou en informele nederstettings, sowel as vanaf stormwater afkomstig is, is ontleed om te kan projekteer hoe om realistiese nutriëntvermindering te bereik met die hulp van huidige en gevorderde tegnologie.

Die studie raak ook die teorie van nutriëntvermindering aan, deur 'n voordam te ondersoek wat spontaan nutriënte sal verminder deur koagulasie voor invloed in die HBPD.

Die probleem van suur mynwater wat reeds sedert 2002 in die bo-lope van die Krokodilrivier voorkom, is in konteks geplaas t.o.v. die eutrofikasieprobleem in die HBPD. 'n Voorstel is as potensiële projek ondersoek om suur mynwater per pyplyn te vervoer om fosfate in die Krokodilrivier te laat uitsak as ysterfosfaat. Verder is die “polluter-pays-principle” en zero-fosfaatsepe ook beklemtoon ten einde nutriëntvermindering in die opvanggebied te optimaliseer.

Die veronderstelling is dat die nutriëntverminderingstrategie 'n lang termyn strategie is wat met die Nasionale Waterbronstrategie geïntegreer moet word.

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ABBREVIATIONS

AMD	Acid Mine Drainage
CMA	Catchment Management Agency
CMS	Catchment Management Strategy
CRR	Cumulative Risk Rating
CSIR	Council for Scientific Industrial Research
CWM	Crocodile West Marico
DACET	Department of Agriculture, Conservation, Environment and Tourism
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EWI	Ecological Water Requirement
FSL	Full Supply Level
HBPD	Hartbeespoort Dam
HIF	Hartbeespoort Inhabitants Forum
HWAG	Hartbeespoort Water Action Group
IWRM	Integrated Water Resource Management
IUA	Integrated Unit of Analysis
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MERIS	Medium-Resolution Imaging Spectrometer
NECSA	Nuclear Energy Corporation of South Africa
NEMP	National Eutrophication Monitoring Programme
NIWR	National Institute for Water Research
NWA	National Water Act
NWP	North West Province
NWRS	National Water Resource Strategy
P	Phosphate
PEP	Phosphate Elimination Plant
RQS	Resource Quality Services
SANS	South African National Standards
TP	Total Phosphate
WISA	Water Institute of South Africa
WDCS	Waste Discharge Discharge System (polluter-pays-principle)
WMA	Water Management Area
WR2005	Water Resources 2005
WRC	Water Research Commission
WWTW	Waste Water Treatment Works

1 INTRODUCTION

1.1 Background

Eutrophication of surface water constitute a major threat to the provision of raw potable and irrigation water in South Africa, being largely dependent on impounded water in order to ensure water supply (Harding, 2008). Eutrophication is described (Rossouw et al., 2008:i) as "the enrichment of water with plant nutrients which results in an array of symptomatic changes, namely increased production of algae and aquatic macrophytes, deterioration of water quality and other undesirable changes that interfere with water use". A comprehensive eutrophication research impact assessment has been performed by the Water Research Commission (Frost & Sullivan, 2010). Emphasis has been given in recent research to economic, environmental, social and health impacts. The main driver of eutrophication is the over fertilisation (over enrichment) of water bodies by nutrients (usually phosphorous and nitrogen) that support uncontrolled growth of green plants. Nutrients originating from anthropogenic activities are conveyed through a sewer system and released in effluent from waste water treatment facilities. Problems associated with eutrophication are exacerbated in cases where treated effluents constitute a major proportion of inflows to dams as in the case of the Hartbeespoort Dam (Harding, 2008).

The National Water Act (RSA, 1998) in Section 5(3) directs the Minister of the Department of Water Affairs to establish a National Water Resource Strategy (NWRS) to facilitate the proper management of water resources and to identify water related development opportunities and constraints. The first NWRS notice was gazetted in 2004 to introduce strategies to ensure that basic human needs were protected and socio-economic development would continue with consideration of the environmental reserve to preserve eco-service functions (DWAF, 2004:8). The second NWRS was issued in 2013, after wide public participation, and identifies the importance of water supply as a pivotal factor for economic growth without threatening the integrity of aquatic ecosystems (DWA, 2013:40). The Crocodile-Marico Catchment was highlighted as a priority issue for water resource protection due to the eutrophication concerns in Hartbeespoort Dam and other dams in the catchments that threaten the goal of efficient and effective management of water for sustainable growth and development in the Lephalale area.

The Hartbeespoort Dam Catchment (Upper Crocodile), is considered of strategic importance to augment the supply of the shortfall of water for socio economic development in the North West and Limpopo Provinces, since it links the Vaal River system with the

Crocodile West River system as an inter-basin transfer through supply pipelines of Rand Water (DWA, 2012:iv). The Hartbeespoort Dam catchments, which drains the highly urbanised economic hub of Gauteng, is the main water supply to this Water Management Area (WMA) where eutrophication is a major water quality issue.

According to Ashton *et al.* (2012:24) water quality in the Hartbeespoort Dam was a concern since the 1950's. Already at that stage Dr B. Cholnoky of the NIWR referred to the Hartbeespoort Dam as a maturation pond, implying that the Hartbeespoort Dam could be perceived as a large waste stabilization pond to conclude waste water treatment started in the up-stream sewage treatment plants. Due to deteriorating water quality in impoundments over many years the Council for Scientific Industrial Research (CSIR) in the late 1970's approached eutrophication research by linking nutrient loading from rivers to impoundments, based on the work of Dr D. Toerien of the CSIR (Ashton *et al.*, 2012:26). After 1975 the CSIR instigated several scientific programmes to study the eutrophication problem in the Hartbeespoort Dam. According to Ashton *et al* 2012 the NIWR undertook a detailed limnological study that provided a firm basis for the first successful chemical control programme against water hyacinth at the Hartbeespoort Dam followed by a recommendation to implement a 1 mg/litre phosphorous upper limit as a key part of a special effluent standard for waste water treatment (Ashton *et al.*, 2010:41).

Several scientific reports (Harding *et al*, 2004a/b, Van Ginkel, 2011) have concluded that phosphorus and nitrogen originating from sewage treatment plants in the catchment was the main nutrients involved in eutrophication, with phosphorus the main cause of eutrophication in freshwaters (Harding, 2008). Since 2002, another emerging concern entering the catchment is decanting acid mine drainage from the Western Basin (Krugersdorp area) into the Tweelopiespruit that has become a potential threat for the increased load of sulphate in the Hartbeespoort Dam.

1.2 Reasons for nutrient reduction in the catchment

Nutrient reduction in the catchment of the Hartbeespoort Dam to reduce the eutrophication status in the dam is a demanding challenge for scientists, resource managers and engineers that have been contemplated for the past 30 years.

In the ground-breaking study titled "The limnology of the Hartbeespoort Dam" (NIWR, 1985) the team of scientist revealed fundamental facts about eutrophication in the dam.

The description of the dam and its salient features in the National Institute for Water Research (NIWR) 1985 report was accurate and is still a factual description namely: "The Hartbeespoort Dam is a hypertrophic, warm, monomictic impoundment, with a mean depth of 9.6 m and a surface area of 20 km²". The conclusion was made (NIWR, 1985) that the symptoms of eutrophication, namely algal blooms of *cyanobacteria* (blue green algae), *Microcystis aeruginosa* would proliferate under conditions of high nutrient loading, high incident solar radiation, low wind speeds and warm water in the Hartbeespoort Dam. This has in fact been demonstrated annually between January and April each year as reported in the WRC publication, "Water Wheel" of Jan/Feb 2005 (Dower, 2005:18)). During 2003 the algae bloom occurrence was particularly bad as displayed in Figure 1-1.



Figure 1-1: Dead *cyanobacteria* form blue-green and black-brown crust on the surface which looks and smells - like raw sewage. (Dower, 2005:18).

In a written reply to a question by Mr S. Simmons to the Minister of Water Affairs and Forestry in parliament (National Assembly, 2003)) the minister responded: "Due to the severity and extent of the algal scum that had developed and accumulated at the dam wall since 27 March 2003, emergency clean-up operations of blue-green algae scum at the dam wall was initiated on 10 April 2003 and completed on 23 April 2003."

Intense algae blooms continued to flourish despite the regulation of 1 mg/l phosphate standard introduced in 1985 for treated wastewater effluent. The Crisis control applied by

the Department of Water Affairs and Forestry (DWAF) to remove the hyper scum from the surface of the dam enticed public outcries against smell and threat of *cyanotoxins* in the drinking water prepared from the dam. Local inhabitants of Hartbeespoort and property developers around the Dam were very demanding and the Hartbeespoort Water Action Group (HWAG) confronted the authorities in a constructive way to avoid health and safety threats to all consumers of water around the dam (Dower, 2005:20). Bad publicity through media reports also created the perception that the Hartbeespoort Dam was a large maturation pond that was an extension of the sewage treatment plants in the catchment areas.

This event confirmed the seriousness of the combination of excessive nutrients in the dam in combination with favourable climatic conditions for algae bloom (Owour et al, 2007). In successive seasonal events of algal blooms, special equipment was developed to remove hyper scum from the surface of the dam. Figure 1-2 shows the algae pump barge, which was commissioned in April 2007. Note the protective clothing to prevent exposure of operators against contact with toxic microcystis.



Figure 1-2 an algae harvesting barge removing blue-green algae May 2007 (Photo taken by P Venter in Metsi-a-me project file 2007)

Innovative designs have been developed to remove hyper scum from various points in the dam. Figure 1-3 is a new design operated by employees of Work for Water, who has been trained to recover debris, hyacinths and blue-green algae from the surface of the Hartbeespoort Dam.



Figure 1-3, a new suction devise to remove blue-green algae 2015 (Photo taken by F Botha at Metsi-a-me stakeholder meeting Kurperoord 2015)

The philosophy is that algae and hyacinth harvesting plays an important role to remove phosphorous from the dam after it has been absorbed as nutrient that stimulates growth of the various macrophytes.

Apart from job creation this approach is a positive way of eliminating phosphorous from settling in the sediment from where it may be available for recycling in future.

1.3 Management response to the eutrophication threat in the Hartbeespoort Dam

The Hartbeespoort Dam is typically associated with an increased incidence and frequency of noxious algal development resulting in increased water treatment costs, loss of recreational use and devaluing property value and risks to human and animal health. In the case of the Hartbeespoort Dam the symptoms of eutrophication is most notably excessive aggregations of potentially toxic cyanobacteria that are extremely difficult to manage and often pose long-term problems for affected waters and the provision of potable water. Frequent algal bloom incidents eventually triggered a desperate action plan for the remediation of the Hartbeespoort Dam.

In 1998 DWAF initiated an expert workshop organised by Rand Water, facilitated by Dr R. Walmsley and local stakeholders e.g. Hartbeespoort Municipality representatives to evaluate the water resource management issues for the Hartbeespoort Dam (Walmsley, 1998).

Between 2001 and 2003 a coordinated effort was launched between North West Province, DWAF, consultants, and support by the Finish Government and the local community of Hartbeespoort, to develop a study project with the aim to define an action plan for an

institutional programme to remediate the resource quality of the Hartbeespoort Dam. (Water Wheel November/December 2004).

The study project was managed between the North West Department of Agriculture, Conservation and Environment, (NWDACE) and the Department of Water Affairs (DWA) who entrusted the initiation phase to DH Environmental Consulting. A thorough 2-year study by a competent project team under Dr W. Harding commenced in 2003 on the biological condition of the HBPD (Harding, 2004:6-10). The Hartbeespoort Dam Rehabilitation Study resulted in the North West Environmental Series 5 with a plan called "Hartbeespoort Dam Remediation Plan". D H Environmental Consulting (Harding *et al.*, 2004a) proposed a strategy with several action plans to remediate the Hartbeespoort Dam in various phases. Phase 1 focused on the in dam biological remediation and phase 2 focused on the changes required in the catchment to sustain in dam remediation actions.

The Harties Metsi-a-Me Biological Remediation Programme for the Hartbeespoort Dam was established in 2006 by DWA (Venter, 2012:16) as Project leader with Rand Water as the implementation agent.

Project plans as outlined in "Overview of the programme" (Venter, 2012) are based on the suggested action plan (Harding *et al.*, 2004a) as a comprehensive guideline for the development of the Hartbeespoort Dam biological remediation programme, with due recognition to the findings of the report on "The Limnology of the Hartbeespoort Dam" (NIWR, 1985).

The Harties-Metsi-a-me programme also included as a long-term option, the concept of nutrient reduction in the catchment by introducing the concept of a pre-impoundment to reduce phosphate in the inflow to the dam. The report on "Limnology of the Hartbeespoort Dam" (NIWR, 1985) revealed the large reduction of the inflowing nutrient load between the point of river entry and the main basin of the dam. This observation encouraged an investigation into the concept of pre-impoundment as an option to manage eutrophication in the dam. A simulation study on pre-impoundment as an eutrophication management option was published in 1986 (Twinch & Grobler, 1986). Their conclusion is an important reference in this dissertation, which takes into account further scientific, demographic and legal developments since the middle 1980's.

1.4 Problem statement

Thornton and Harding have labelled eutrophication as tough "wicked problems (that) have multiple resolutions, depending on a variety of factors" (Thornton *et al.*, 2013). The

Hartbeespoort Dam is perceived as a “wicked problem” due to many unsuccessful efforts to resolve this complex problem with its multitude of dependant and independent variables which are expensive and time consuming to manage (Harding, 2015).

"Living with eutrophication in South Africa: a review of realities and challenges" concludes that many of South Africa's rivers, reservoirs and coastal lakes no longer have the resilience to assimilate nutrients or sequester toxicants. If the reservoirs are to fulfil the basic and multiple functions of resource provision, waste assimilation and recreation, then full attention needs to be devoted to the concept of ‘integrated water resource management’ to prevent eutrophication. In South Africa the continuing concerns surrounding eutrophication is described in terms of a “wicked” problem (Thornton *et al.*, 2013).

The Hartbeespoort Dam is one of the most significant dams in the economic hub of the North West Province and the Crocodile (West) Marico (CWM) Water Management Area (WMA) for domestic, agricultural, industrial and recreational purposes. The Hartbeespoort Dam is situated in the upper region of the CWM and is one of the hypertrophic impoundments in South Africa (DWA, 2012).

For many years, the Crocodile River has been pouring an increasing load of phosphorus into the HBPD. Nine waste water treatment works discharge their 720 million litres per day of purified effluent into the Crocodile River and very high loads of waste water effluents, with polluted storm water from the catchment, intensify the occurrence of blue-green algae or cyanobacteria.

The Department of Water Affairs (DWA) implemented the Hartbeespoort Dam Integrated Biological Remediation Programme, Harties Metsi-a-me, in 2005 (Venter, 2012).

The Programme is part of the government's integrated resource management plan that targets growth and development and in turn generates employment. The other main objective is to determine, optimise and manage the physical and biological conditions in the HBPD to ensure optimal diversity through the reduction of algae (blue-green), hyacinth and the undesired fish biomass. The focus is to reduce levels of toxic algae in the dam, to remove hyacinths and to restructure the fish biomass.

The Programme has progressed to the point where implementations of phase1 has been achieved and maintained on an on-going basis. The next phase of the programme will focus on nutrient reduction in the catchment. The problems associated with selecting options for this phase are included in this dissertation.

1.5 Goals of dissertation

The understanding of the impacts of eutrophication and how it can be reduced in the context of the Hartbeespoort Dam is based on the fact that "Eutrophication is the process of excessive nutrient enrichment of waters that typically results in problems associated with macrophytes, algae or problematic cyanobacterial growth" as described in the National Eutrophication Management Programme (NEMP) implementation manual. Cyanobacteria (also known as blue green algae) are more closely related to prokaryotic bacteria than eukaryotic algae and some can produce harmful toxins. A sampling protocol was prepared by Resource Quality Services (RQS) to support the NEMP (DWAF, 2004)

Cultural eutrophication is related to anthropogenic activities - human, social and economic activities (Van Ginkel, 2011).

In theory, this form of eutrophication is controllable, because people can take measures to minimise the impact of their activities. Well known impacts of cultural eutrophication include:

- Accelerated population growth and associated settlement patterns
- Watershed or catchment area alterations, such as dams that are built for water storage to supply increasing population needs
- Increased waste water treatment works discharges
- Increased fertiliser applications to increase food production
- Intensive farming practices that cause increased nutrient polluted return flows
- Poor agricultural practices, for example when farmers plough and cultivate the riparian zones of water resources

Natural eutrophication is caused by the influx of nutrients from natural sources, including the rocks, soil and other natural features within a catchment area. This type of eutrophication is not reversible or controllable, and will therefore continue slowly and inevitably.

The factors driving eutrophication are high nutrient concentration and stagnation for prolonged periods, with suitable temperature, oxygen concentration and proper light regime. These conditions encourage increased primary growth in the form of algae and macrophytes, culminating in severe blooms and eutrophication or, in extreme cases, a hypertrophic state.

Results from an investigation (Owour, *et al.*, 2007) into the environmental factors that affect the occurrence, persistence and bloom formation of phytoplankton species in the

Hartbeespoort Dam, indicate that *Microcystis aeruginosa* consistently dominated the Hartbeespoort Dam at bloom levels during summer months. Cyanobacterial blooms and their effects are symptoms of increasing eutrophication or over-enrichment due to nutrients. Excessive development of certain types of algae disturbs the aquatic ecosystem and becomes a threat for animal and human health, due to formation of cyano toxins (Du Plessis, *et al.*, 2007). The research team Du Plessis (2007:12) concluded that the primary source of excessive concentration of plant nutrients was mainly phosphorous and nitrogen, originating from sewage treatment and agriculture.

The eutrophic state of the water in the Hartbeespoort Dam became a serious concern since the early 1980's due to negative adverse consequences on the primary as well as secondary water use of the dam. The negative impact on the living conditions along the dam as well as the recreational use and tourism is a known fact and it poses a serious threat to one of the most sought after national assets. A large number of studies have been undertaken in the past to investigate the underlying causes of the problem. The literature review provides insight into the work.

The introduction of the 1 mg/l ortho-phosphate standard since 1985 has cost local authorities in the catchment millions of Rands in capital and operating expenses to ensure compliance. Enforcement of the standard is an on-going concern, due to lack of urgency to address non-compliance in terms of permit conditions according to recent Green Drop report (DWA, 2012). Rapid urbanisation and the fact that the catchment drains surface water and sewage treatment effluent from the heartland of the industrial activities of Gauteng with multitude of point as well as diffuse sources of pollution poses a challenge to integrated resource quality management. The outcome of the complex pollution concerns is that the build-up of nutrients in the dam (which act as a nutrient trap) as well as in the sediment build up in the dam is so extensive that it will cause algae blooms for a long term even if the quality of the inflow from point sources complies with the 1 mg/l p standard.

The Harties Mets-a-me programme is a large scale biological remediation programme. As mentioned in the introduction, the report of D H Environmental Consulting (Harding *et al.*, 2004a/b) became a guideline for the remediation programme when the remediation programme was launched in 2006. In stream nutrient inactivation is recommended for Hartbeespoort Dam with dosing proposed within the Crocodile River at the downstream-most weir adjacent to the Pelindaba site.

The late Prof W.A. Pretorius (then a member of the Harties Metsi-a-me remediation team) submitted a proposal for the pre-impoundment and treatment of the inflow from the

Crocodile River to the dam. The concept was directed to the reduction of the phosphate load on the dam to prevent hyper eutrophic conditions developing within the dam resulting in algae blooms specifically the blue-green algae selection with accompanying toxin production and odours.

The programme consists of a number of projects in the dam basin, the upstream catchment and some downstream activities, ranging from enforcement of legislation to developing institutional arrangements and a supporting management plan (Venter, 2013).

The peer review study of the Harties Metsi-a-me programme (Keto, 2013:7) remarks that "the reduction of the external nutrient load is a crucial factor for the successful rehabilitation of the Hartbeespoort Dam (HBPD) and its protection in the future." This finding supports the remark of Harding in 2004 that in order to achieve a phosphate load consistent with a mesotrophic state, about 80% reduction of phosphate load to the HBPD will be required (Harding, 2004). In order to meet the goal, measures should be implemented throughout the catchment at every point source and non-point source including diffuse ones. A barrier between the catchment and the dam consisting of pre-impoundments and flow diversion should be constructed as well as the riparian wetlands upstream.

This dissertation describes the root cause of the freshwater eutrophication within the Hartbeespoort Dam, its origin in the catchments and investigate options to reduce water pollution (nutrient contamination) in the catchments that has contributed to the current hyper eutrophic condition in the Hartbeespoort Dam. The scientific basis supporting the development of N and P reduction options to prevent eutrophication and the proliferation of harmful algal blooms will be considered. The legal background of controlling eutrophication problems will be examined since the South African Water Act (Act 54 of 1956) allowed for the permitting of effluent standards including sewage works. In 1984 the Government Gazette no. 9225 of May 18, introduced a special standard of 1 mg/l Phosphorous for waste water or effluent arising in the catchment area and draining water to the Hartbeespoort Dam (no freshwater Nitrogen standard was included).

The main focus in this dissertation is on phosphorus reduction in aqueous effluent streams. However, in considering ways of controlling phosphorus pollution, particularly for agriculture, it may become necessary in future to consider measures of tackling Nitrogen pollution which are often driven by drinking water resource protection rather than eutrophication.

In particular the dissertation will describe the concept of pre-impoundment near the inlet of the Crocodile River into the dam to safeguard the Hartbeespoort Dam from excessive nutrients load that needs to be controlled to achieve a reduction of the eutrophication problems in the dam.

1.6 Outline of document

Chapters changed – update accordingly

Chapter 2 gives a brief history of the Hartbeespoort Dam in the context of water use and rights that led to the current national water resource strategy (NWRS). The NWRS is the most recent strategy of the Department of Water and Sanitation: "to achieve sustainable, equitable and secure water for a better life and environment for all". An overview of available research in the area of eutrophication management and control will be given. The objective is to link the literature and research to the complexity of solving an eutrophication problem on a scale of a large impoundment such as the Hartbeespoort Dam in a highly urbanised catchment. Discussion of modelling studies to achieve the desired reduction of nutrients in the catchment that will sustainable long term control of eutrophication levels in the dam.

Chapter 3 includes an analysis of the catchment of the Hartbeespoort dam. The sub-catchments are characterised. This analysis includes detail of point sources and non-point sources of nutrient pollution. An analysis is made of flow and load of specifically phosphates that will enter the Hartbeespoort Dam through the inlet streams.

Chapter 4 explains the available datasets that were used to develop the base case scenario with data from data sources for the period October 2006 to June 2011.

Chapter 5 provide the methodology to calculate the Phosphate load in the base case load and identifies the relative contribution of each sub-catchment to the Phosphate load entering the Hartbeespoort Dam on an annual basis. The assessment approach produced a Phosphate base load in the form of an Excel spreadsheet which can be used to evaluate relative contributions and test other options to change Phosphate loads for various options.

Chapter 6 reflects on the reality of the Phosphate load situation as a result of calculated assumptions within the accuracy of methodology used to determine origin and load distribution of Phosphate load in the total catchment. About 47% of Phosphate load originates from point sources and 53% from non-point sources.

Chapter 7 considers the pre-impoundment options to provide a barrier to prevent nutrients from entering the dam. A target is set for nutrient reduction that can achieve long term reduction of phosphate concentration in the dam towards a mesotrophic state. The threat of acid mine drainage in the catchment is investigated. A scenario is considered where acid mine drainage can be used to chemically remove phosphate in the Crocodile River to meet target phosphate level to reduce eutrophication.

Chapter 8 builds on the strategies outlined as nutrient reduction options in the catchment and discusses the way forward to reduce Phosphate load with several options to achieve a significant reduction of in-dam eutrophication status of the Hartbeespoort Dam in future.

Chapter 9 includes conclusions and recommendations for further reduction of nutrients in the catchment of the Hartbeespoort Dam and best practices that can be transferred to similar situations elsewhere.

Chapter 10 includes the reference list.

2 LITERATURE REVIEW

2.1 Historical Context

The Hartbeespoort Dam was constructed between 1921 and 1923 to store water draining from a watershed of approximately 4120 square kilometres in areal extent, mainly to provide water to the large Government irrigation scheme near Brits (Van Vuuren, 2008). The dam wall was raised by 2.44 metres in 1971 to increase the capacity to 195 million m³ at full supply level. The impoundment has an average depth of 9 metres, a maximum depth of 32.5 metres, and a surface area of approximately 20 km². Water from the Hartbeespoort Dam is used mainly for domestic consumption (about 12%) and irrigation (82%) with 6% being released for compensation. There are two outlet control systems, one on each flank, drawing water from about twenty metres below the full supply level of the reservoir and serving canal systems supplying water to one hundred and thirty square kilometres downstream irrigation scheme. Figure 2-1 indicates the position of the Hartbeespoort Dam in the catchment area.

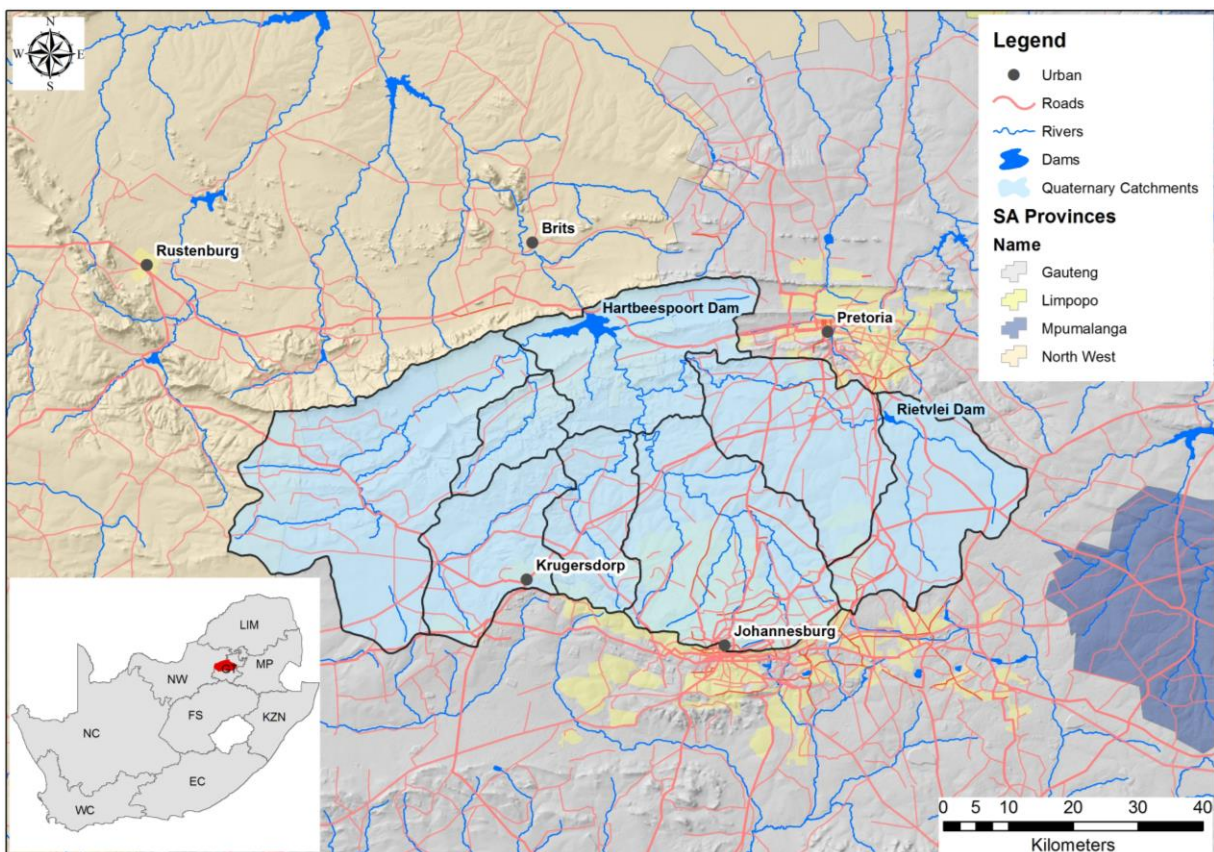


Figure 2-1 Geographical position of the Hartbeespoort Dam and catchment

Land-use within this drainage area is primarily rural agricultural, although the head water portion of the Jukskei River system (A21D & A21E) are highly urbanised north of the city of Johannesburg. Extensive urban development is present along the shore lands of the basin. The typical land uses in the study area is depicted in Figure 2-2.

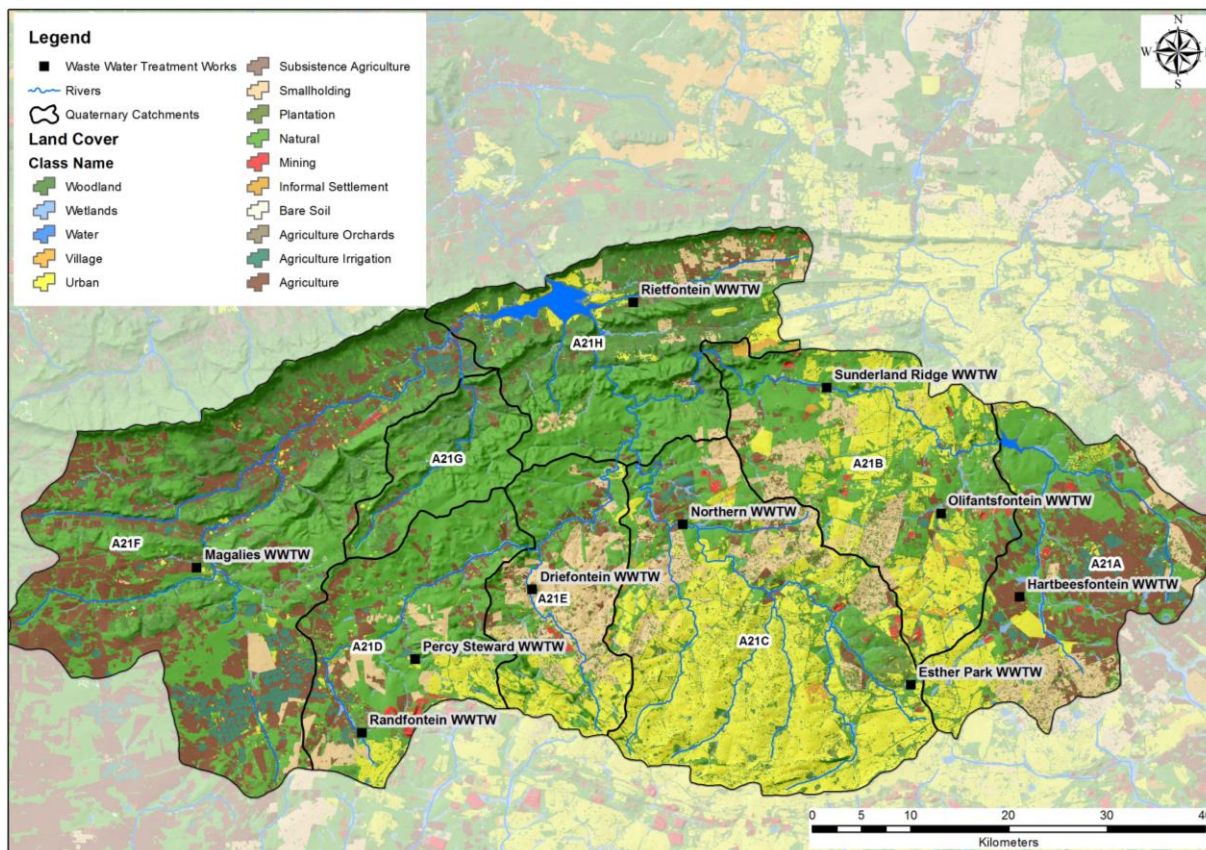


Figure 2-2 Typical catchment land use

The combination of a large water body within an idyllic mountainous setting, attracted city dwellers to the area, which became increasingly important as a regional recreational and tourist centre. The draft Resource Management Plan (RMP) of 2010 describes that socio economic activities and facilities such a fishing, boating, water-skiing, holiday resorts, weekend cottages, conference venues, golf courses, etc., have all developed significantly over the last fifty years (DWA, 2010:28).

The economic significance of the dam is also enabled by the ecosystem services provided by Hartbeespoort Dam, include provisioning (water availability for abstraction), regulatory (waste assimilation), and supporting services (residential, holiday and commercial). The economy with some 5,268 households generating (in 2010 values) a local Gross Domestic Product (GDP) of approximately R1.3 billion per year according to the estimate in the 2010

draft edition (DWA, 2010:28) of the RMP. Of these households, 3,386 households (almost two thirds) are low income households.

Although the main triggers for the RMP and remediation process were not conflict between the various user groups but rather water quality concerns, which are amplified during algae bloom periods when water quality deteriorates and the recreational demand is inhibited.

From the 1970's eutrophication was a concern. The growing concern with water quality in the Hartbeespoort Dam, from an oligotrophic irrigation dam to a hypertrophic impoundment is clearly visible in the aquatic science timeline described in "The Freshwater Science Landscape in South Africa, 1900-2010" (Ashton *et al.*, 2013).

Figure 2-3 indicates the chronology of water legislation in South Africa during the 20th century and highlight milestones of some of the many scientific studies on the impacts and effects of water pollution in the catchment of the Hartbeespoort Dam and other reservoirs. This bear a resemblance to a cause and effect sequence indicating the objectives of the decision making process explored by policy makers (e.g. General Effluent Standards of 1962 as regulated by Water Act, Act 54 of 1956) and scientists (e.g. Foundation for Research Development, CSIR, 1972) to manage some of the consequences of enriched nutrients trapped in the Hartbeespoort Dam (and other reservoirs) over the years.

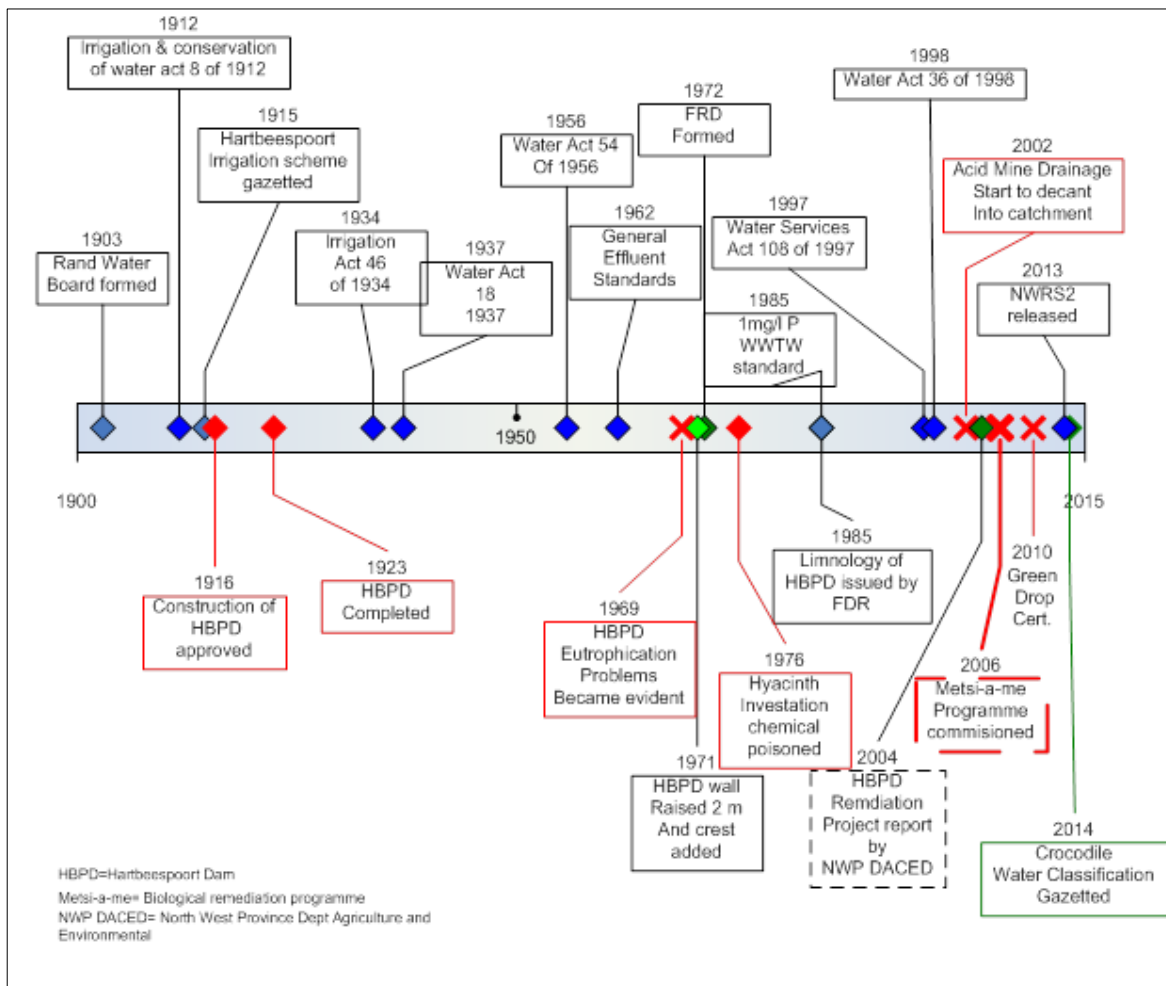


Figure 2-3 Aquatic science landscape time-line showing major events and external forces that influenced eutrophication development in HBPD (adapted from report WRC TT530-12)

2.2 Legal Framework

The 1956 Water Act (Act 54 of 1956) paved the way for a sophisticated system of water quality control in South Africa. The water quality management system developed over the years as water quality issues arose, e.g. rapid industrialisation since 1950 (Sasol, Eskom, Yskor) caused increased stresses on water demand and quality. In 1991 the Department of Water Affairs and Forestry published a policy document: "Water Quality Policies and Strategies in the RSA" (Barnard, 1999). The policy reflects a major change towards water quality management away from the "command-and-control" strategy towards an overarching general management system for the control of both water quality and quantity. A risk management approach developed to avoid anticipated negative consequences when new developments were evaluated in the environmental impact assessment process (EIA regulations were promulgated in 1996).

The National Water Act (NWA) (act 36 of 1998) followed in 1998 and structured the Integrated Water Resource Management (IWRM) concept. The philosophy of the NWA is

based on the principles of IWRM within a South African context. Special provision was made to rectify historical imbalances and ensures the Minister was authorised to “ensure that water is protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner for the benefit of all persons” (RSA, 1998). The entitlement to use water now entails a legal process.

The National Water Act, Act 35 of 1998, was promulgated to provide for the fundamental reform of the law relating to water resources. The National Water Act aims to regulate the relationship between the new laws and reforms that were initiated following the change in government in 1994 and repeals certain laws that can be associated with a lot of the problems of how water was managed up until 1998. In the preamble to the National Water Act of 1998, it is clear that the new Act recognises that the ultimate aim of water resource management is to achieve the sustainable use of water for the benefit of all users. The National Water Act of 1998 can be seen as a milestone in the process of managing the effluent in the catchment of an impoundment such as the Hartbeespoort Dam and a subsequent management of the whole process from the resource to the reuse of the water in a downstream capacity. In the case of the Hartbeespoort Dam, the NWA is very important because it places those items contained in the South African Constitution into perspective with regard to everyone having the right to access of sufficient food and water and that this water must not be harmful to their health or wellbeing. Like in many other cases, the Hartbeespoort Dam is fed by rivers which have been over-used and/or significantly altered to comply with the needs of an ever-growing population. Every day people and organisations have an impact on the quality of the streams and groundwater and the wetlands in the catchment of the Hartbeespoort Dam. The Hartbeespoort Dam is also a strategic function in the catchment of the larger area since it provides the necessary storage capacity to augment any shortages of possible droughts facing the downstream communities in a country where drought is part of the natural cycle. The Hartbeespoort Dam therefore provides an important water supply to areas and communities, which will be under stress from time to time due to access to potable water and for sustained agricultural production.

The NWA made provision for the establishment of a National Water Resource Strategy (NWRS). The first NWRS was published in 2004 and was followed in 2013 by an update.

The NWRS provides a basis for the Catchment Management Strategies (CMS), and is a key enabler of Catchment Management Agencies (CMA). In accordance with Chapter 2, Part 2 of the NWA, the CMA of the Crocodile/Marico Catchment is responsible for the protection, conservation, development and management of the water resources at the

Water Management Area (WMA) level. At this point the process of appointment of a CMA for the Crocodile/Marico Catchment has not progressed to an implementation phase.

2.3 Classification of the Hartbeespoort Dam Catchments

In order to facilitate the process of selecting appropriate strategies for integrated water resource management, the NWA specifies a series of measures, which together are intended to ensure the comprehensive protection of all water resources. These include:

1. A classification system;
2. Classifying each major resource;
3. Determining resource quality objectives;
4. Setting the reserve.

The NWA identified a system for classifying water resources to form the basis for water quality control, as it forms a basis for the establishment of goals relating to the quality of South African water resources (Kleynhans & Louw, 2005).

The Minister has, in terms of section 12 of the NWA, Act 36 of 1998, prescribed a system for classifying water resources by promulgating Regulation 810, Government Gazette 33541 dated September 17, 2010.

The classification study was concluded for the Crocodile/Marico catchment in 2014 and gazetted by the minister in the Government Gazette No 37999 of 19 Sept 2014.

The water resource class of the Upper Crocodile/Hennops/Hartbeespoort is described as Water Resource Class III (Table 2-1) and Ecological Reserve Category D (Table 2-2), as illustrated in table 2.3, where a summary of management class descriptions are presented. Table 2-2 reflects the ecological (reserve) status assigned to specific river health categories. Due to the fact that Gauteng metropolitan areas are located on the watersheds of the Hartbeespoort Dam, it can be expected that it would be regarded as a work horse as the rivers draining away from these industrialise watersheds (Upper Crocodile) have the dual burden of providing water supplies and transporting waste material.

Table 2-1 Management class descriptions

Management Class Descriptions	
Class I	Minimally used Water resource is one which is minimally used and the overall condition of that water resource is minimally altered from its pre-development condition

Class II	Moderately used Water resource is one which is moderately used and the overall condition of that water resource is moderately altered from its pre-development condition
Class III	Heavily used Water resource is one which is heavily used and the overall condition of that water resource is significantly altered from its pre-development condition

Table 2-2 Ecological (reserve) categories (Kleynhans *et al.*, 2005)

Ecological (Reserve) categories	River Health Category	Description
A	Natural	Unmodified natural
B	Good	Largely natural with few modifications
C	Fair	Moderately modified
D	Poor	Largely modified
E	Seriously modified	Seriously modified
F	Critically modified	Critically or extremely modified

2.3.1 Water Resource Classes of the Upper Crocodile/Hennops/Hartbeespoort catchments

The Minister proposed to classify the classes as indicated in

Table 2-3 of each significant resource for the catchments of the Upper Crocodile in the Crocodile (West), Mokolo and Matlabas water management area.

Table 2-3 Water resource classes per integrated unit of analysis and ecological categories per biophysical node (Upper Crocodile portion)

Integrated Unit of Analysis (IUA)	Water Resources Class for IUA	Quaternary catchment	River name	Ecological category to be maintained	Natural MAR (Mm ³ /a)	EWR as % of natural MAR
Upper Crocodile/ Hennops/ Hartbeespoort	III	A21A	Rietvleispruit To Rietvlei Dam	C	4.788	27.83
		A21C	Jukskei River	D	34.4	29.19
		A21D	Blaauwbankspruit	D	-	-
		A21A,B,H	Hennops	D	-	-
		A21H	Swartspruit	D	-	-
Magalies	II	A21F	Magalies below	B	14.7	45.58

			Maloney's Eye			
Crocodile/ Roodekopjes	III	A21J	Crocodile from HBPD to Roodekopjes Dam	D	-	-

From the table it can be concluded that:

- (a) The Upper Crocodile catchment feeding the Hartbeespoort Dam is already over-used.
- (b) The water is polluted with exception of the Magalies River.
- (c) The available water is already taken and the surrounding environment is in a poor state.
- (d) In the Hartbeespoort Dam catchment there are very few water sources that are in a natural state and therefore the rest of the water resources require protection.
- (e) Water in this catchment is not only scarce, but is also augmented by transfers from the Vaal basin through the drinking water supply to the urban areas in the catchment.
- (f) It is thus clear that the level of protection in the catchment of the Hartbeespoort Dam will require a specific strategy to avoid the overall problem of enrichment due to high level of nutrients.

The conclusion from the classification study emphasises the need for an IWRM strategy as has been recommended by several scientific studies since the detailed assessment of eutrophication problems since the 1980's.

2.4 Scientific studies

Since the release of the study on "Limnology of the Hartbeespoort Dam" (NIWR, 1985) nutrient reduction in the catchment of the Hartbeespoort Dam is perceived as one of the most important protecting strategies to safeguard the quality of water in the resource against excessive eutrophication and hypertrophic conditions in a water body (Harding, 2008). The Trophic State boundaries as used by the DWAF Trophic Status Assessment (Van Ginkel et al, 2001) are summarized in Table 2-4:

Table 2-4 Trophic state classification boundaries

TROPHIC STATE CLASSIFICATION BOUNDARIES Per DWAF Guidelines (Van Ginkel et al., 2001)

Variable	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
Total Phosphorus (mg/l)	< 0.015	0.015-0.047	0.048-0.130	>0.130
Median Chlorophyll- α ($\mu\text{g/l}$)	0-10	11-20	21-30	>30
% time Chlorophyll- α >30 ($\mu\text{g/l}$)	0	<8	8-50	>50
Values expressed as annual medians				

As concluded by Harding (2008), “South African impoundments have a threshold of nutrient availability, as total in-lake phosphorus concentration, above which an increased frequency and duration of potentially-problematical algal growth may be experienced. This level has been equated, per the Nutrient Enrichment Assessment Protocol, as approximately 55 $\mu\text{g/l}$ P” (Harding, 2008:19).

The results of a ten-year study entitled “Eutrophication and cyanobacterial blooms in South African inland waters: 10 years of medium-resolution imaging spectrometer (MERIS) observations” have revealed that harmful cyanobacteria are widespread in South Africa’s 50 largest dams, with the Hartbeespoort Dam, in the North West, the Darlington Dam, in the Eastern Cape, and Spitskop Dam, in the Northern Cape, found to be the worst affected by cyanobacterial surface scum. The mean chlorophyll- α value for Hartbeespoort Dam is near 90 $\mu\text{g/l}$, compared to the hypertrophic status of mean chlorophyll- α ($\mu\text{g/l}$) of >30. The Hartbeespoort Dam is representative of a hypertrophic system dominated by frequent and persistent *microcystis aeruginosa* cyanobacterial blooms and surface scum conditions (Matthews, 2015). The study relied on data from time series observations of parameters related to phytoplankton and water clarity derived from the MERIS full-resolution satellite instrument.

The article explained that water rich in cyanobacteria posed a serious health risk and could result in death, if consumed in large quantities. Matthews (2015) cautioned, “Water quality in South Africa is a significant concern. Serious steps need to be taken to reduce the amount of nutrients entering our lakes”.

A great deal of information has been published on the occurrence and distribution of eutrophication and cyanobacteria in South African water bodies (Harding, 2008; Rossouw, 2008; Van Ginkel, 2007 & 2011). These reviews on eutrophication research emphasise in particular, monitoring efforts, that have been driven by the National Eutrophication Monitoring Programme (NEMP), by the Department of Water Affairs (Van Ginkel, 2007 & 2011). These studies indicate that eutrophication and cyanobacterial blooms are widespread and extensive in South African water bodies. Harmful algal blooms (HAB)

can cause poisonings of domestic and wild animals by cyanobacterial toxins are a frequent occurrence (Du Plessis *et al.*, 2007:7).

2.5 Management response to the Hartbeespoort Dam situation

The Department of Water and Sanitation (DWS), together with all citizens of the country are faced with the challenge of protecting water resources on the one hand and the need to utilise water for social and economic development on the other hand. The NWA provides decision-making tools to achieve a balance between protecting and utilising water resources. Typically, a water resource in this case, the catchment of the Hartbeespoort Dam, is a sensitive ecosystem. Ecosystems are made up of water, earth, and energy of the sun, plants, animals and small organisms. If the aquatic environment cannot support the ecosystems, then the overall health (water quality and/or water quantity) of the water resource will decline with the obvious negative consequences of degradation in quality for current and future use. The aim of protecting water resources is to ensure that healthy water is available for current and future human use. This is achieved by leaving enough water of a certain quality in the water resource to maintain the overall ecological functioning of the rivers, wetlands, ground water and estuaries. Protection of the water resource is therefore about the quantity and quality (overall health) of the nation's water resources. A detailed discussion of the catchments of the Hartbeespoort Dam in Chapter 3 will illustrate how the current use of water in the catchment is negatively impacting on the quality and quantity of this resource.

2.5.1 The Hartbeespoort Remediation Programme in environmental management context

2.5.1.1 Background

Nutrient reduction in the catchment of the Hartbeespoort Dam to reduce eutrophication status in the dam is a demanding challenge for scientists, resource managers and engineers that have been contemplated for the past 30 years. In a ground-breaking study titled, "The limnology of the Hartbeespoort Dam" (NIWR, 1985) the team of scientist revealed a fundamental fact about eutrophication in the dam. At the interface between scientific research and management the study of the limnology of the Hartbeespoort Dam in the 1980's revealed the large reduction of the inflowing nutrient load between the point of river entry and the main basin of the dam. This finding stimulated the concept of pre-impoundment in the management of the dam. Their description of the dam and its salient features is accurate and still factual: "The Hartbeespoort Dam is a hypertrophic, warm,

monomythic impoundment, with a mean depth of 9.6 m and a surface area of 20 km² (NIWR, 1985).

The prediction that the blue-green algae, *microcystis aeruginosa*, would proliferate under conditions of high nutrient loading, high incident solar radiation, low wind speeds and warm water has been demonstrated seasonally between January and April each year. In some years, for example 2003, the algae bloom was particularly bad. Crisis control was applied by DWAF to remove the hyper scum from the surface of the dam. Public outcries were very loud.

This event gave an urgent impetus to approve a desperate action plan for the remediation of the Hartbeespoort Dam. North West Province Department of Agriculture, Conservation, Environment and Tourism (NWP DACET) appointed DH Environmental Consulting to prepare a remediation strategy. The terms of reference for the project were to prepare a study namely, "Hartbeespoort Dam Remediation Project (Phase 1)". Bill Harding of DH Consulting in cooperation with co-opted specialists, proposed a detailed business and management action plan (Harding *et al.*, 2004:a), in response to the terms of reference for the project. In Volume 2 of the DH Environmental Consulting remediation project proposal, the synthesis presented in Volume 1 is supported by findings of specific specialist investigations that could guide the implementation of the project (Harding *et al.*, 2004b).

2.5.1.2 Framework within National Water Resource Strategy

The aforementioned report became the blue print for the development of the Hartbeespoort Dam biological remediation programme, also known as "Harties Metsi-a-me" which was started by DWA in 2006 with Rand Water as the implementing agent.

Nutrient reduction in the catchment of the Hartbeespoort Dam clearly falls into the Water Management Strategy section of the NWA. The Act recognises that to achieve sustainability, equity and efficiency, water resources need to be managed in an integrated manner. This is related to the hydrological cycle. The different water resources (rivers, wetlands, groundwater and estuaries) are all linked to each other by the hydrological cycle. Water resources are also affected by the surrounding biophysical environment (people, plants and animals) and human activities that impact on them. IWRM is a process for coordinated planning and management of water, land and environmental resources. It takes into account the amount of available water (surface and groundwater), water use and water quality, environmental and social issues as an integrated or combined whole to ensure sustainable, equitable and efficient use.

The Minister of Water Affairs and Sanitation is responsible for ensuring that a National Water Resource Strategy (NWRS) is established. Furthermore the NWRS binds all water institution and water users. The Minister must update the NWRS at least every five years. The first NWRS was published in 2004 and subsequently the update was published in 2013. The NWRS must address sustainability, equity and efficiency. In the NWRS2 the water quality problem (eutrophication) in the Hartbeespoort Dam is targeted as a strategic focus area (DWA 2013:40).

2.5.1.3 Strategic intent of the case study

The case study of the Hartbeespoort Dam is a typical example of how the available water from the catchment of the Hartbeespoort Dam was included in a detailed study for the supply of the necessary water for economic and social development in the area of Lephalale. The Hartbeespoort Dam became a strategic facility that was the focus point where water was stored and augmented by transfers from the Vaal River basin through the recycle of water that was used by the population in the metropolitan areas and then released into the catchment of the Hartbeespoort Dam to become a sustained flow of water for the growing needs of development in the Lephalale area. This complex integrated planning process requires cooperation and coordination between the various planners and institutions where water related planning takes place and to also take into account the quality of water that would be required for the downstream activities in the Marico/Lephalale catchment areas.

A catchment management strategy requires a comprehensive natural water resource strategy to ensure that the necessary water could be available for the different areas. Unfortunately, the catchment management agency for the catchment of the Hartbeespoort Dam and downstream of the Crocodile/Marico catchment has not yet been officially appointed. This is a very important shortcoming since a lot of strategic decisions have been taken by the Department of Water and Sanitation and will have to be further developed by the catchment management agency that has to implement it in order to make this vision of future water use of water in this catchment a reality.

The purpose of the catchment management strategy is to set principles for allocating water to existing and new water users to provide the framework for managing water resources within the water management area and to ensure that water resources in the water management area are protected, used, developed, conserved, managed and controlled. In the case of the Hartbeespoort Dam, a process was initiated based on the need from the

Provincial authorities of North-West to solve the eutrophication problems in the Hartbeespoort Dam.

2.5.2.4 Vision and programme design

The Harties Metsi-a-me programme was initiated in 2006, following a detailed study of solutions that could help to improve the water quality in the Hartbeespoort Dam. Although this programme is still ongoing, it is only a small part of the total catchment management strategy and since there is no catchment management agency in place at the moment, it is still being sponsored by the North West Provincial Government with a small input from the Department of Water and Sanitation.

Nutrient reduction in the catchment of the resource can be regarded as one of the very important protecting strategies to safeguard the quality of water in the resource. Government is faced with the challenge of protecting water resources on the one hand and the need to utilise water for social and economic development on the other hand. Water in this catchment is not only scarce, but is also augmented by transfers from the Vaal basin through the drinking water supply to the urban areas in the catchment. It is thus clear that the level of protection in the catchment of the Hartbeespoort Dam will require a specific strategy to avoid the overall problem of enrichment due to high level of nutrients. In order to facilitate the process of selecting appropriate strategies, the NWA specifies a series of measures which together are intended to ensure the comprehensive protection of all water resources. These include:

1. A classification system;
2. Classifying each major resource;
3. Determining resource quality objectives;
4. Setting the reserve.

The third and fourth activity in water resource protection is a combined exercise since it must be an integrated approach to provide the necessary outcome to the resource protection.

The vision of the Harties Metsi-a-me programme is the restoration of the Hartbeespoort Dam ecosystem to a level where it will result in increased levels of ecosystem services derived from the HBPD including the quality of potable and irrigation water, fishing, recreational use and ecotourism.

Chapter 4 will explore options to reduce external loading of nutrients in catchments to achieve the set target of in-dam phosphate loading that has to be reduced by about 80% (Van Veelen, 2013).

2.6 Pre-impoundment as an eutrophication management option

The pre-impoundment concept envisaged for eutrophication control in the Hartbeespoort Dam will be considered against the background of some successful pre-impoundment projects in Germany, where pre-impoundments play an important role in protecting water quality in reservoirs intended for drinking water supply.

2.6.1 Literature review of pre-impoundment concepts

The ability of pre-reservoirs to remove nutrients became known during numerous investigations on various existing pre-reservoirs in Germany. Scientist studied natural attenuation of phosphate to protect reservoirs against nutrient overload (Benndorf & Pütz, 1987) as well as chemical removal of phosphate (Clasen & Krämer, 2002).

2.6.2 Pre-impoundments based on natural attenuation of phosphorous

Pre-impoundments are small reservoirs, with a water-retention time of a few days that reduce the phosphorus input in main reservoirs (Pütz & Benndorf, 1998).

Pre-reservoir is normally situated immediately before the larger main reservoirs. "The purpose is to improve the water quality for drinking water purposes (Benndorf & Pütz, 1987). The improvement of the water quality is the result of the following of physicochemical and biochemical processes within the pre-reservoirs:

1. The first stage in the process of nutrient removal in pre-reservoirs involves the biochemical conversion from the dissolved to the particulate form; mainly phytoplankton uptake of orthophosphate in the euphotic zone as illustrated in Figure 2-4.
2. The second stage is the sedimentation of phytoplankton and other particulate matters within the pre-reservoir or in the shallow inlet sections of the main reservoir. This sedimentation process is enhanced by the presence of natural precipitants and flocculants.

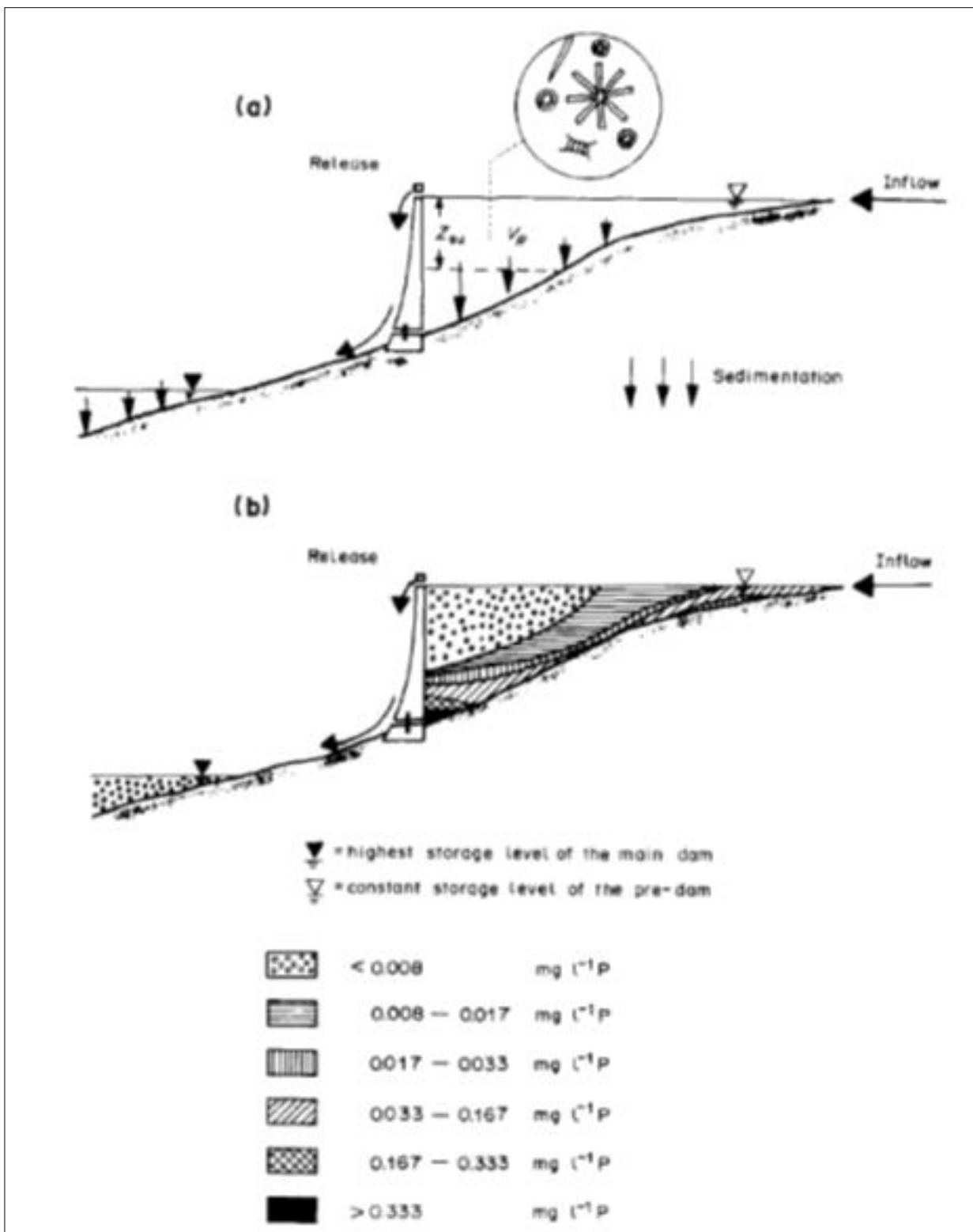


Figure 2-4 Schematic representation of the functioning of a pre-impoundment (Benndorf & Pütz, 1987)

Figure 2-4 (a) depicts the orthophosphate uptake by phytoplankton within euphotic zone and sedimentation in shallow section of the in pre-dam and shallow section of main dam, while Figure 2-4 (b) depicts the typical resultant orthophosphate distribution, slightly altered.

To establish the potential possible process, it is important to determine the geochemical conditions in the drainage area, which can affect nutrient removal by influencing the nature and intensity of the processes involved, in a particular situation (Benndorf & Pütz, 1987):

1. Incorporation of P and N into microbial biomass;
2. Combination of PO_4^{3-} with aluminium compounds;
3. Formation of FePO_4 ;
4. Denitrification.

Chemical binding or adsorption of the orthophosphate in solution, as outlined in point 3 above, can take place largely in the inflowing waters, but the uptake of orthophosphate by the algae is more important in the pre-reservoirs than the competing chemical or physicochemical processes, particularly in the pH range of 6.0 - 8.0. The greater the deviation of the pH from this range, the more likely it is that the orthophosphate will combine with iron, aluminium and manganese (at pH < 6) or calcium (at pH > 8) (Vollenweider, 1976) as illustrated in the phosphate cycle in Figure 2-5.

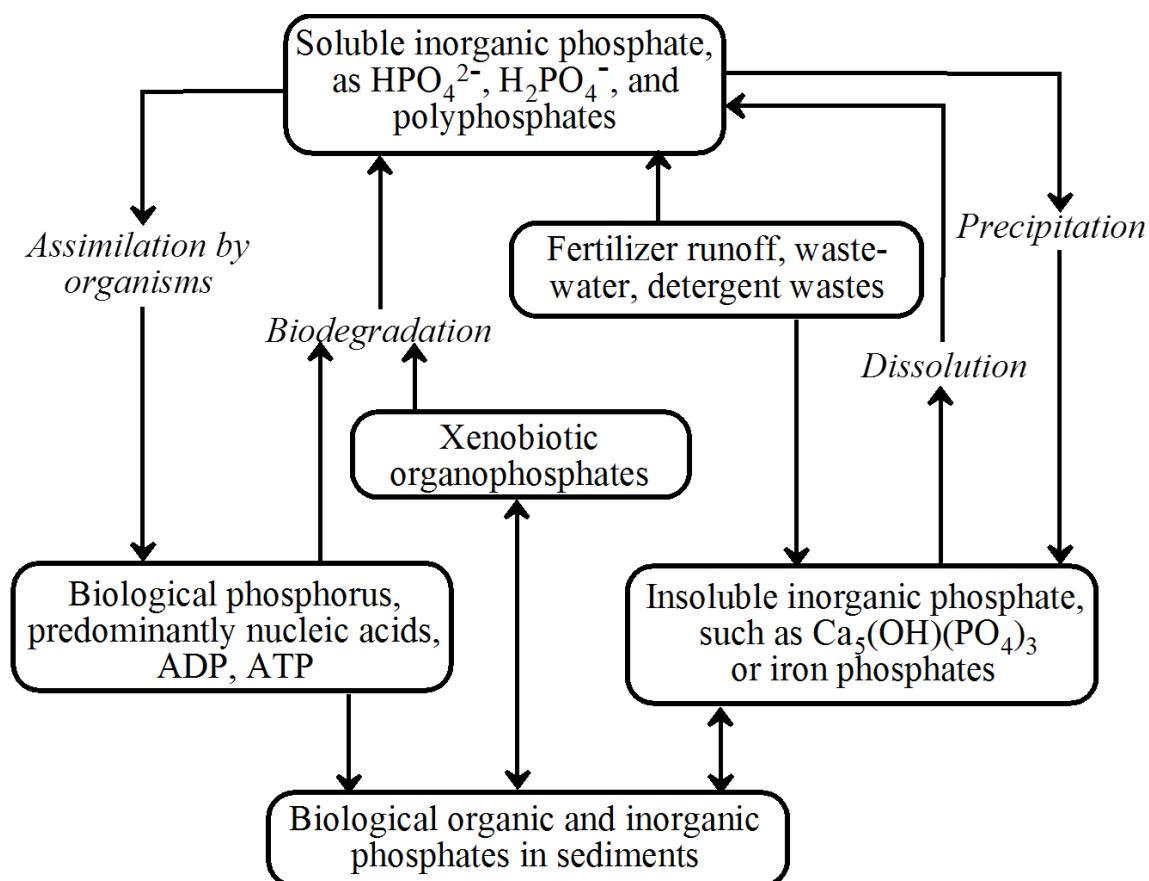


Figure 2-5 the Phosphorous Cycle (Vollenweider, 1975)

The process of phosphorus removal involves the biochemical conversion from the dissolved to the particulate form (mainly phytoplankton) and the sedimentation of this particulate matter is dependent on the input variables light, orthophosphate concentration, temperature of the inflowing water and discharge (discharge determines the retention time of the inflowing water in the "reaction space"). The phytoplankton activity plays the most important role among the various processes. The maximisation of orthophosphate elimination depends on adequate design, construction and operation of pre- reservoirs. The complete calculation procedure for P-elimination in a pre-reservoir is described by Benndorf and Pütz (1987).

The efficiency of pre-reservoirs is limited, because of the lower light intensity and the colder temperature during the winter period. However, discharge is often high during summer rainfall storms. Pre-reservoirs are an important tool for reservoir water-quality management, but they cannot substitute regulatory control and remedial action in the catchment area to reduce nutrients.

The design concept of a pre-impoundment dam is illustrated in Figure 2-6.

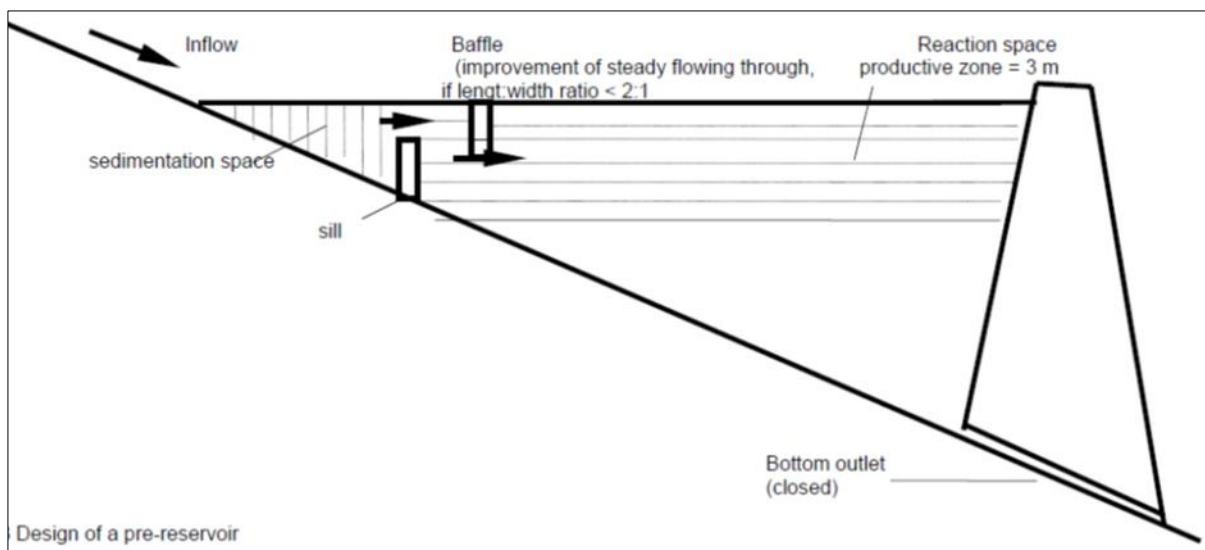


Figure 2-6 Design concept of a pre-impoundment facility (Benndorf & Pütz, 1987):

2.6.3 Example of pre-impoundments in Saxony

An important field of the uses from reservoirs in Germany is the drinking water supply. About seventy reservoirs with a total storage capacity of nearly 1100 Mm³ are used for this purpose. Due to the geography and socio-economic conditions in Saxony, practically all of the catchment areas for these reservoirs are suffering from anthropogenic influences. The water-quality problems in several reservoirs reflect the physical and geochemical structure

of the watershed and are primarily affected by nutrients from both diffuse and point sources. The objectives of the water quality management of reservoirs involve:

- Protection of water quality against deterioration;
- Improvement of water quality as required complying with the standards for the uses.

The Eibenstock-dam (largest drinking water reservoir in Saxony, holding 75 Mm³, with five pre-reservoirs), demonstrates the importance but also the limits of pre-reservoirs. The objective of water quality set for the main reservoir was to achieve mesotrophic to oligotrophic conditions in a recovery process. Productivity is limited by the nutrient phosphorus and the necessary P-load reduction was achieved by the implementation of a masterplan including sewage diversion out of the watershed, upgrading of sewage treatment plants, regulation of agricultural non-point sources and the creation of five pre-reservoirs.

Table 2-5 indicates the annual P elimination of Eibenstock Dam in Saxony with pre-reservoirs during the period 1991-1996. A remarkable total phosphate elimination of 40% and more based on a 7 day retention time was achieved.

Table 2-5 Annual P elimination of Eibenstock Dam in the period 1991-1996 (Pütz & Benndorf, 1998)

Main Reservoir	Pre-reservoir	Retention Time (days)	P Elimination		
			Calculated o-PO ₄ (%)	Observed o-PO ₄ (%)	Observed P _{tot} (%)
Eibenstock	Schönheide	3	36	40	25
Eibenstock	Rohrbach	5	50	42	22
Eibenstock	Rähmerbach	6.3	56	56	40
Eibenstock	Weißbach	7	57	60	42
Eibenstock	Geidenbach	7	57	64	44

2.6.4 Conclusions reached based on several studies (Pütz & Benndorf, 1998).

Pre-impoundments in Germany have an important role to play as a protection for water quality in a drinking water reservoir. The following considerations have been observed by Pütz:

- The phytoplankton activity plays the most important role among the various processes governing the phosphate elimination in pre-reservoirs;

- The maximization of orthophosphate-P elimination depends on adequate design, construction and operation of pre-reservoirs:
 - a relatively low mean depth;
 - a relatively large reaction space, (upper 3 m zone), in relationship to the total volume with a mean retention time of a few days;
 - a constant storage level as a consequence of surface release;
 - an optimum size.
- A simple calculation procedure for the monthly mean removal rates of orthophosphate-P in pre-reservoirs has been developed on the basis of laboratory experiments, the results of which were combined with the probabilistic distribution of the water through flow;
- The efficiency of the pre-reservoirs is limited, because the light-intensity and the temperature in the winter - period are low.

Pre-reservoirs are also an important tool for reservoir water-quality management depending on local conditions. However, it can't be a substitute for remedial action in the catchment area, as the co-operation of agriculture and other diffuse sources of phosphates must be properly regulated (Krämer, 2000).

2.6.5 Phosphorous elimination Wahnbach Reservoir pre-impoundment

The Wahnbach Reservoir was completed in the early 1950's to supply drinking water for Bonn and surroundings. Soon after completion severe eutrophication was observed. After a comprehensive study it was established that phosphorus was the key element of eutrophication and that 30 to 40% of the total Phosphorous (TP) load originated from sewage, while the source of the greater part was agriculture. This led to the development of a multi barrier approach to control nutrients. Scientists designed a pre-impoundment ahead of the main dam with a phosphate elimination plant (PEP) that would treat the normal flow of water in a phosphate elimination plant before allowing it to enter the main reservoir (Bernhardt and Clasen, 1982).

The phosphorus elimination plant came into operation in 1977. The phosphorus concentration of the main tributary, that is 90% of the total water load to the reservoir, is reduced from between 100-150µg/l TP to 3 to 5 µg/l TP in the elimination process (95% reduction). This strategy to remove phosphate through the PEP has decreased the total phosphorous concentration in the Wahnbach Reservoir to between 8 and 10 µg/l. The result is that the eutrophic dam became oligotrophic within 3 years. The blue-green algae which had been predominant disappeared and algal growth has been reduced significantly so that

Secchi-depth of between 10 m and 6 m on an average basis is commonly the case. This was achieved by eliminating phosphorous, without eliminating nitrogen at the same time (annual average N-concentration of all tributaries was 5 mg/l). Different measures in the catchment area, where co-operation with farmers was most important, are combined with the operation of a phosphorus elimination plant, in which the main tributary is treated, and with aeration and bio manipulation in the reservoir (Krämer, 2000). All measures together have led to the present oligotrophic state and the excellent hygienic condition of the reservoir.

The Wahnbach pre-impoundment acts as an in-line flow equalisation dam from where the untreated inflow is pumped to a phosphate elimination plant where FeCl_3 salt is added. Figure 2-7 is a schematic diagram of the Wahnbach Reservoir with pre-impoundment. During abnormal high flow conditions the surplus water overflows from the equalisation ponds into the main reservoir. The Process design of the PEP is indicated in Figure 2-8.

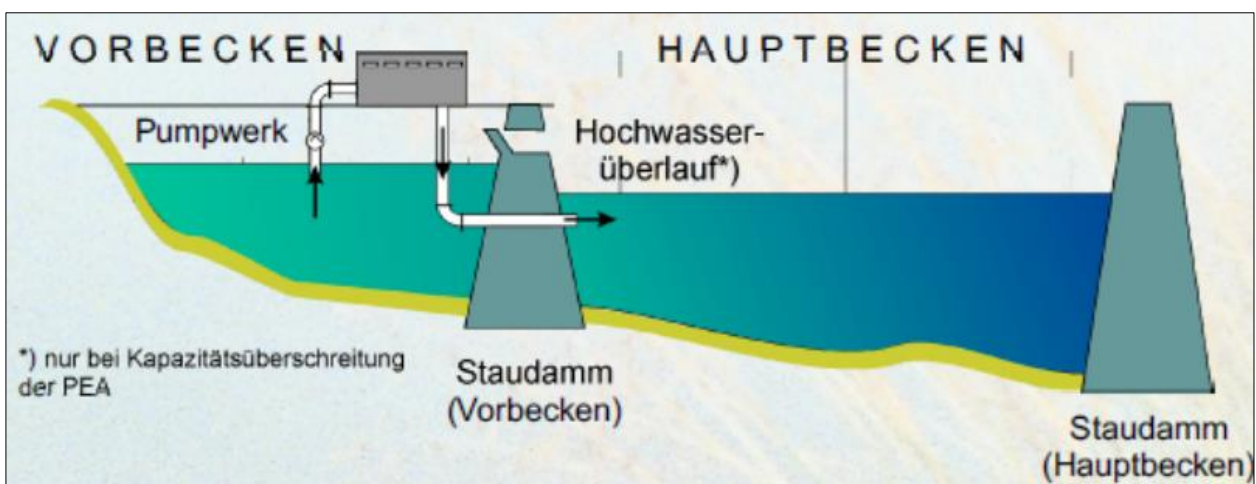


Figure 2-7 Graphical presentation of the Wahnbach Pre-impoundment (Wahnachtalsperrenverband. 2003)

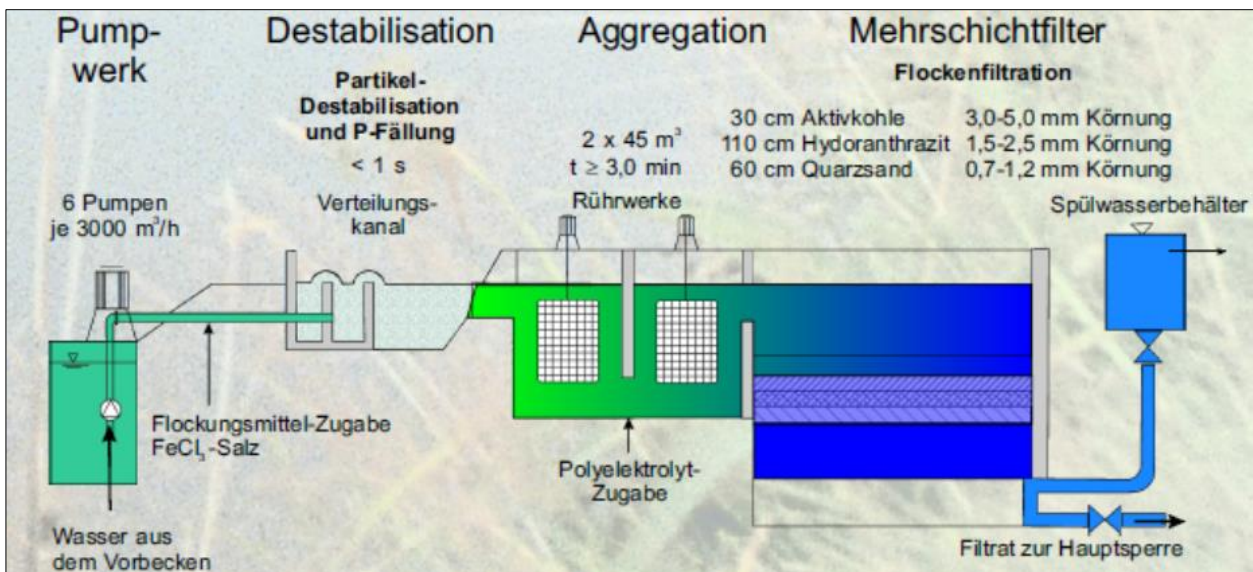


Figure 2-8 Phosphate Elimination Plant at Wahnbach Reservoir pre-impoundment (Wahnachtalsperrenverband. 2003)

The performance of the PEP since the commissioning of the plant has been excellent as can be seen from Figure 2-9, which is a graphical presentation of the phosphate concentration before and after commissioning of the phosphate elimination plant as well as the phosphate load reduction in the catchment due to regulatory control to avoid phosphate loss from agricultural activities (Clasen, J. & Krämer, R. 2002).

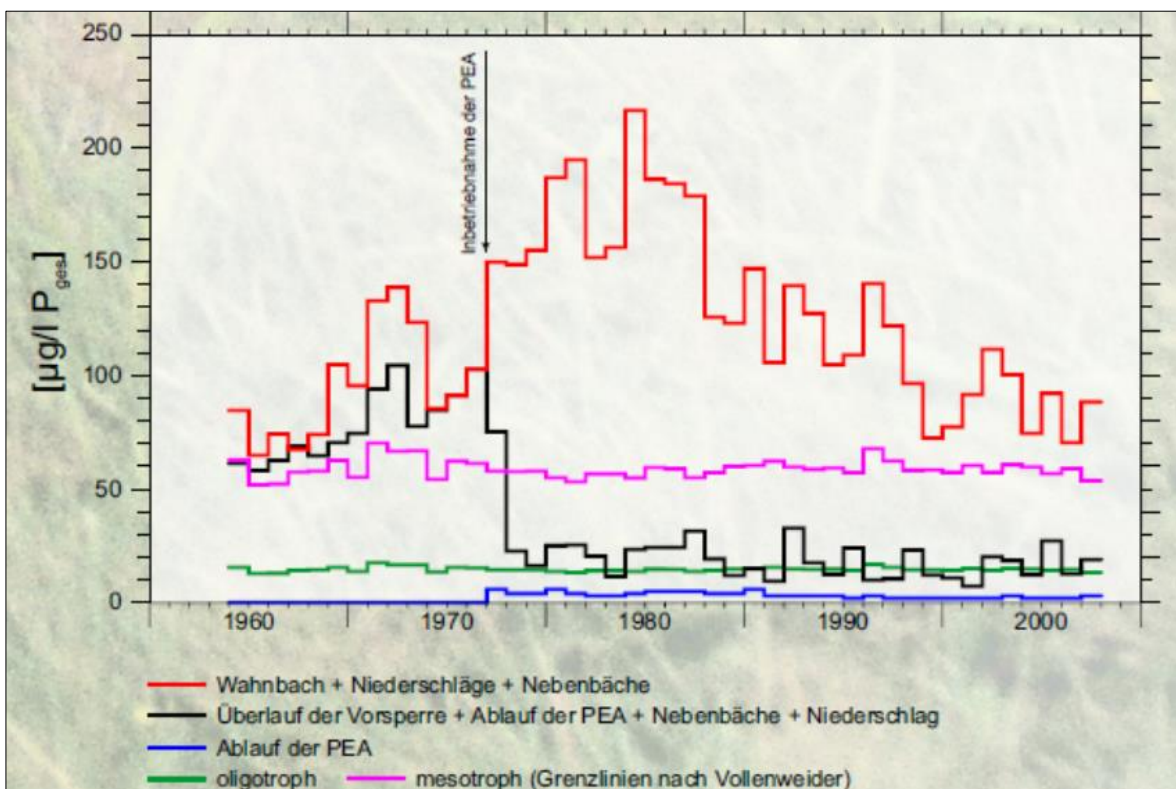


Figure 2-9 History of Phosphate concentration since commissioning of Wahnbach Reservoir (Wahnachtalsperrenverband. 2003)

The quality of treated flow consistently met the target of better than mesotrophic quality despite peak phosphate load in of more than 200 µg/l P during flooding period in 1976 and 1980 respectively due to a consistent phosphate concentration of < 10 µg/l produced in the PEP.

The average discharge of the main tributary amounts to about 86.4 Ml/d and the maximum capacity of the plant is 430 Ml/d. This allows spare capacity to handle seasonal floods that can be as high as 172 Ml/d. Spills of non-treated water may however occur during flood events. For design purposes the mean total phosphate concentration of inflow to the main reservoir was calculated to be between 10 - 25 µg/l TP, which considers all sources which comprise the treated and non-treated water of the main tributary and the minor lateral tributaries and precipitation (Bernhard & Clasen, 1982).

2.7 Pre-impoundment ahead of the Hartbeespoort Dam

2.7.1 Simulation study

The inclusion of a pre-impoundment as an eutrophication management option was considered during the study of the “The Limnology of the Hartbeespoort Dam” (Twinch & Grobler, 1986). This strategy was linked to the Hartbeespoort Dam Ecosystem Study (NIWR, 1985) that envisaged a pre-impoundment of about 10% of the full supply volume of the Hartbeespoort Dam that could result in a 60% P load reduction during average years. In this simulation study the pre-impoundment served as a barrier for point source nutrient removal before the main reservoir.

Three models were utilised to calculate estimated in-lake phosphorous losses by using data from the Hartbeespoort Dam Ecosystem Study (NIWR, 1985). The three models, RIVMOD, VARS, and FIXS (Twinch & Grobler, 1986) used to predict phosphate retention in the simulated pre-impoundments have not been validated in lakes with low water residence times. Further developments and validation of the models are required before they can be generally applied to problems such as the situation in the Crocodile River.

The theoretical phosphorus removal in the models depends on the physical settling of particulate phosphate (mostly inorganic). The consequence of the particulate settling is that the remaining phosphorus would mainly be in soluble form. The predicted removal of phosphorus from solution is dependent on the biological uptake of the soluble phosphate by the macrophytes e.g. during algae (or hyacinths) growth.

Eventually, part of the algal crop dies and settles as phosphorus rich biomass which accounts for the reduction in phosphorus concentration between the inflow and outflow from the pre-impoundment.

The phosphorus removal mechanisms involved in pre-impoundment is thus physical settling of particulate-phosphate and the growth and settlement of algae (biomass assimilation). For the pre-impoundment dam to remain functional, the sediment (both organic and inorganic) must periodically be removed by dredging.

The simulation study (Twinch & Grobler, 1986) highlighted the fact that, under the appropriate circumstances, a pre-impoundment can be highly effective in reducing phosphate loads. More favourable circumstances would include high inflow P concentrations, as well as long residence times. In the case of the Hartbeespoort basin sites on any of the tributaries closer to the sewage treatment plant would be more appropriate than the site adjoining the Hartbeespoort Dam. However, rapid siltation of small impoundments could be a negative consequence that progressively decreases the efficiency of phosphorous retention. Small scale dredging operations may solve this problem. Since pre-impoundments will require reasonable constant water levels to function as reliable nutrient traps, they will provide suitable sites for aqua-cultural practices and recreational boating and angling. However, since efficient phosphorous retention in pre-impoundments is partially due to uptake by macrophytes (algae) (Benndorf & Pütz, 1987) they can be expected to cause severe symptoms of eutrophication, with aesthetic problems.

Based on the simulations it was concluded that phosphorous loads on Hartbeespoort Dam during the period 1980/83 could have been reduced by between 24% and 55% (depending on the model used to estimate phosphorous losses) in the pre-impoundment of 12.8 Mm³. Without a detailed test programme under current conditions, it will be risky to accept the simulation study as a design basis for a pre-impoundment for eutrophication protection of the Hartbeespoort Dam.

3 STUDY AREA

3.1 Introduction

This chapter presents an overview of the catchments of the Hartbeespoort Dam, the hydrology as well as the nutrient pollution and its origins. The purpose is to determine the phosphate load conveyed by different resources in order to establish a database for nutrient reduction options. Phosphorous has been identified as the pivotal nutrient that must be reduced substantially to enable the trophic status in the Hartbeespoort Dam to change to a mesotrophic (<35 µg/l P) level. The pre-impoundment options will be investigated in Chapter 4.

3.2 Description of the Dam

The Hartbeespoort Dam is situated in the North West Province in a valley south of the Magaliesberg Mountain Range. The elevation map of the study area is shown in Figure 3-1.

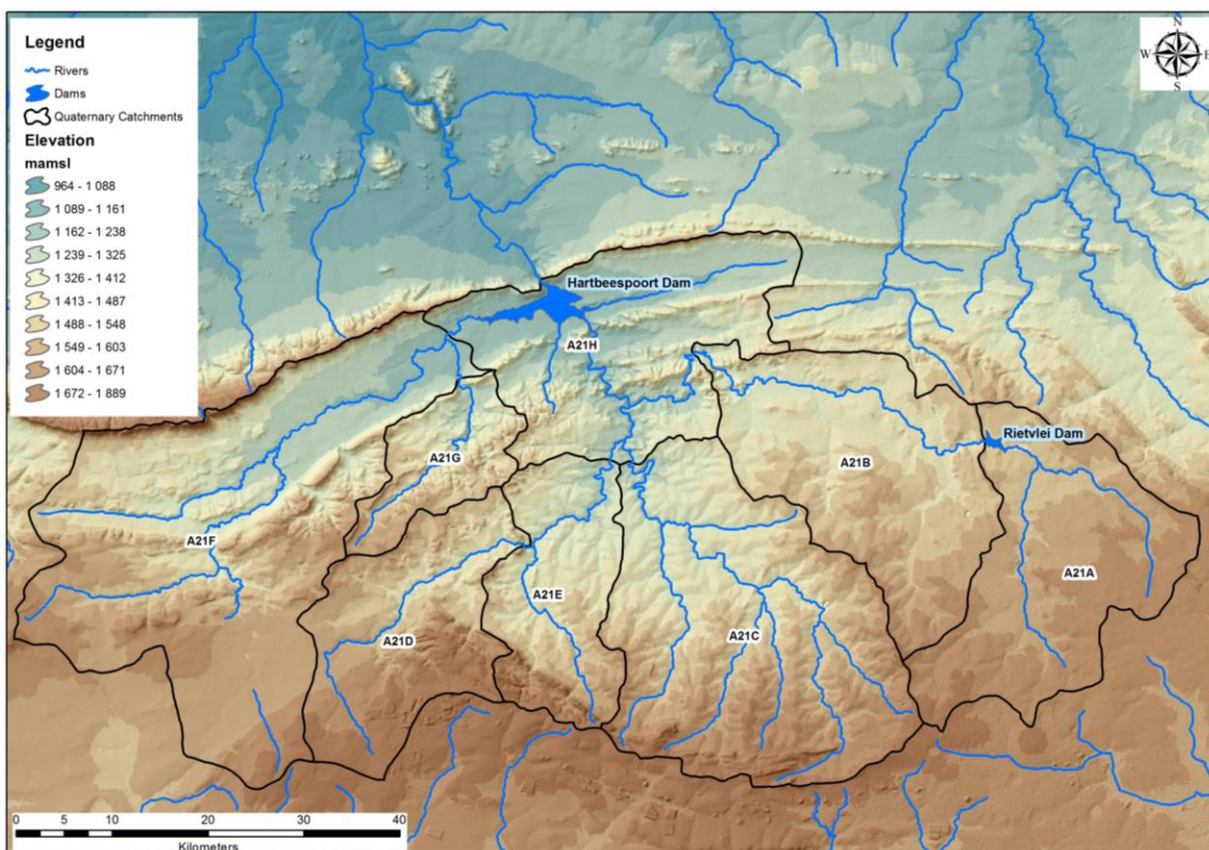


Figure 3-1 Elevation map of the Hartbeespoort catchment area

The Hartbeespoort Dam lies approximately 35 kilometres west of Pretoria and approximately 70 kilometres north-west from Johannesburg (Figure 2-1). The dam was

constructed in 1921 as an irrigation dam. In 1969 the full supply level of the dam was raised by 2.44 m by means of crest gates on the spillway, to increase the gross capacity of the dam from 168 Mm³ to 211 Mm³. (Van Vuuren, 2008). The characteristics of the dam as summarised in the “Taming of the Poort: S.A.’s Water History” (Van Vuuren, 2008) is presented in Table 3-1.

Table 3-1 Characteristics of the Hartbeespoort Dam

CHARACTERISTICS	DATA
Catchment area	4112 Km ²
Mean annual rainfall	670 mm (WR2005)
Mean annual evaporation	1690 mm/a (WR2005)
Surface area	2034 ha
Natural mean annual run-off	163 Mm ³ (WR2005)
Full supply capacity	196 Mm ³
Gross capacity	211 Mm ³
Wall height	59 m
Crest length	140 m
Irrigation area	14000 ha (Brits area)

The Hartbeespoort Dam Irrigation Board supplies irrigation water through a network of canals to farmers, cultivating a wide variety of produce including wheat, lucerne, fruit and flowers. The area used to be a major producer of tobacco, but due to increased quality requirements for the tobacco itself and an ever-increasing chloride concentration in the dam water, tobacco could no longer be produced commercially and has mostly been phased out. Fruit and vegetable growers are very concerned about water quality due to potential cyano toxins that is associated with hypertrophic impoundments that may enter plants through irrigation water and washed products.

The quality of water in the dam has deteriorated consistently over the last 15 years due to gradual increase in pollutants in the dam. This, despite the introduction of the 1 mg/l P standard for effluent from the Waste Water Treatment Works (WWTW) in the catchment of the Hartbeespoort dam in 1989. Scientists and Department of Water Affairs were expecting a general drop in phosphate levels in the reservoir. Monitoring data (Huizenga *et al.*, 2013b) of water quality in the dam reveal that concentration of pollutants have risen steadily over time due to inadequate management and control over sources of pollutants in the catchment (Harding, 2008; Van Ginkel, 2011). Figure 3-2 indicates water quality from the Hartbeespoort Dam (sample point A2R001) for the period January 1999 to December 2011.

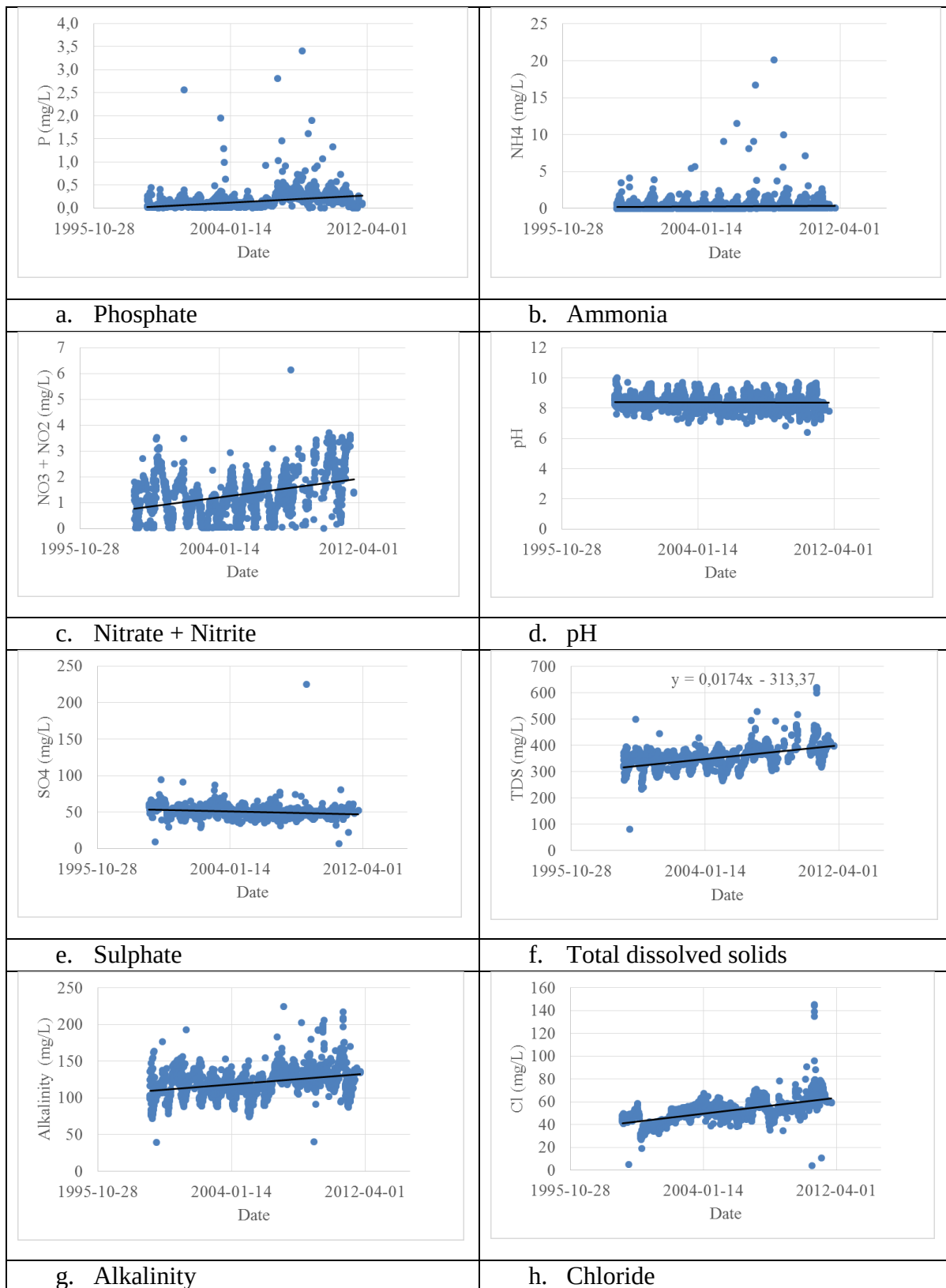


Figure 3-2 Water quality of the outflow from Hartbeespoort Dam (A2R001) (Huizenga *et al.*, 2013)

3.3 Catchment Demarcation

The Hartbeespoort Dam can be divided into five sub – catchments:

- The Magalies River Catchment.
- The Upper Crocodile River Catchment.
- The Jukskei River Catchment.
- Hennops River Catchment
- The Incremental Crocodile River Catchment between the Upper Crocodile River Catchment and the Hartbeespoort Dam (Including the area around the Dam and the Swartspuit).

Figure 3-3 shows location of the Hartbeespoort Dam, the quaternary catchments and associated drainage network.

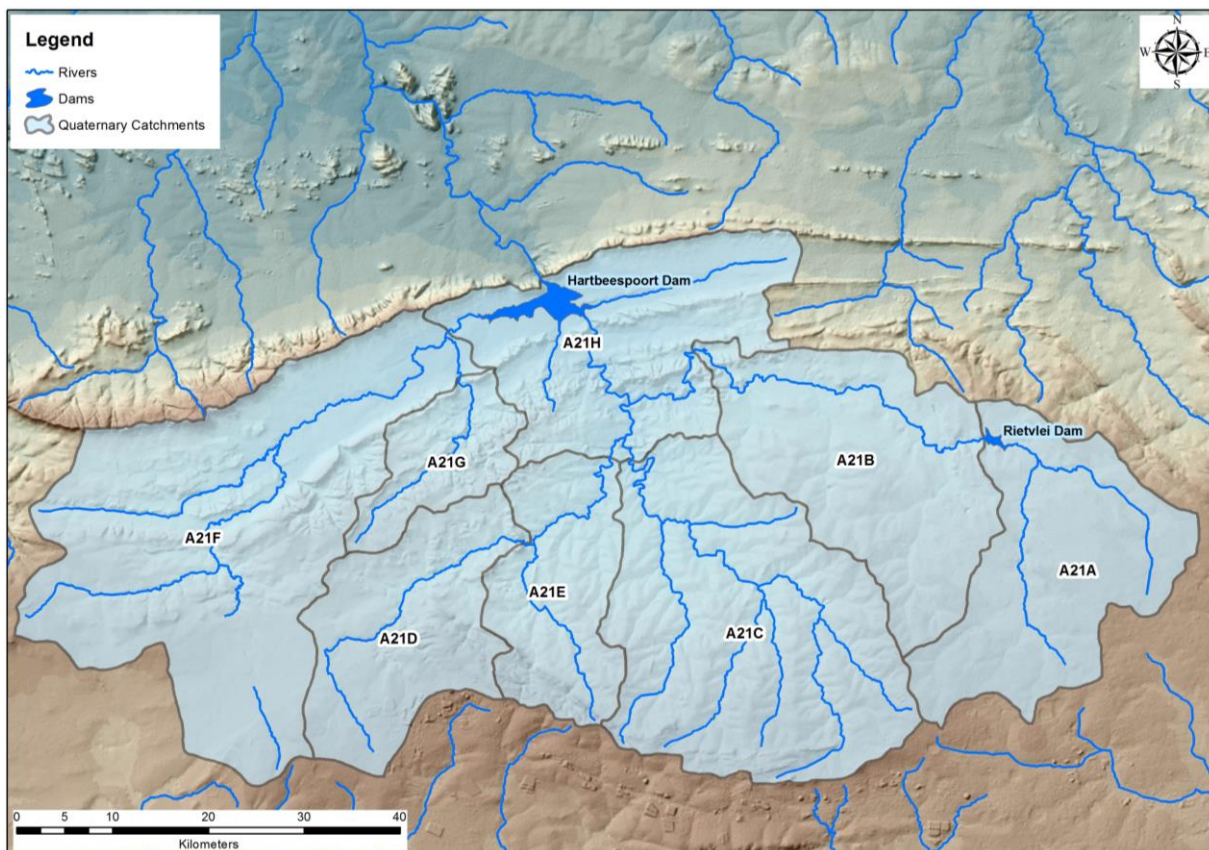


Figure 3-3 Quaternary of the Hartbeespoort Dam

3.4 Description of sub-catchments

3.4.1 The Magalies River Catchment (A21F and A21G)

The Magalies River originates towards the southwest of the town Magaliesburg in the vicinity of the Magaliesberg mountain range. The river meanders through an agricultural

area, with irrigation on the banks of the river. The river has a catchment of 1171 km² with a natural mean annual runoff of 10 Mm³. The main tributary of the Magalies River is the Scheerpoort River. The Magalies River is considered the cleanest sub-catchment of the five, with the only impact coming from agriculture and the Magalies WWTW responsible for treating the sewage generated in the town of Magaliesburg. Rand Water and boreholes are important sources of water for domestic and agricultural activities. The Magalies River catchment is shown in Figure 3-4 and the catchment hydrology parameters is presented in Table 3-2 (WRC, 2011).

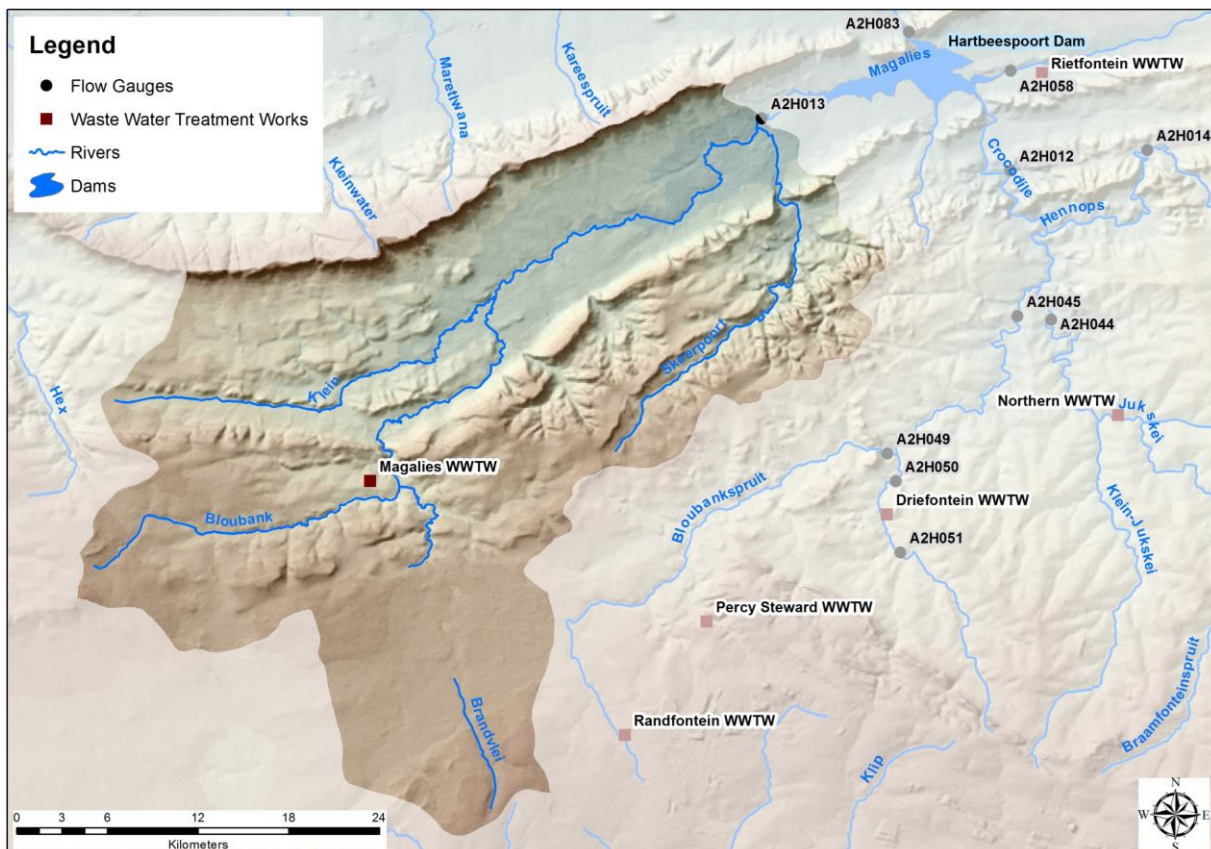


Figure 3-4 Magalies River catchment map

Table 3-2 Magalies River catchment hydrology parameters

Quaternary	Area (km ²)	MAP (mm/a)	MAR (mm/a)	MAE (mm/a)	Base flow (Mm ³ /a)	% No Flow
A21F	1000.2	677.3	25.0	1700	7.28	0
A21G	160.5	694.3	82.4	1700	56.77	0

3.4.2 The Jukskei River Catchment (A21C)

The Jukskei River rises in Johannesburg near the Ellis Park sport stadium. The Jukskei River catchment contains the urban areas of Johannesburg in the south, Midrand in the north, Randburg in the west and Kempton Park in the East. The Jukskei River Catchment covers a surface area of 768 km². The main tributaries of the Jukskei River are the Little Jukskei River, the Braamfontainspruit, the Sandspruit, and the Modderfontainspruit. This area is highly urbanised. A few large industries can be found in the catchment, such as the AECI factory in Modderfontein and the Kelvin Power Station. One of Johannesburg's largest waste water treatment works, the Northern WWTW, discharges to the Jukskei River. The Northern WWTW also provides Kelvin Power Station with water for cooling purposes. This water is then discharged to the Modderfontainspruit. The Jukskei River catchment is shown in Figure 3-5 and the catchment hydrology parameters is presented in Table 3-3 (WRC, 2011).

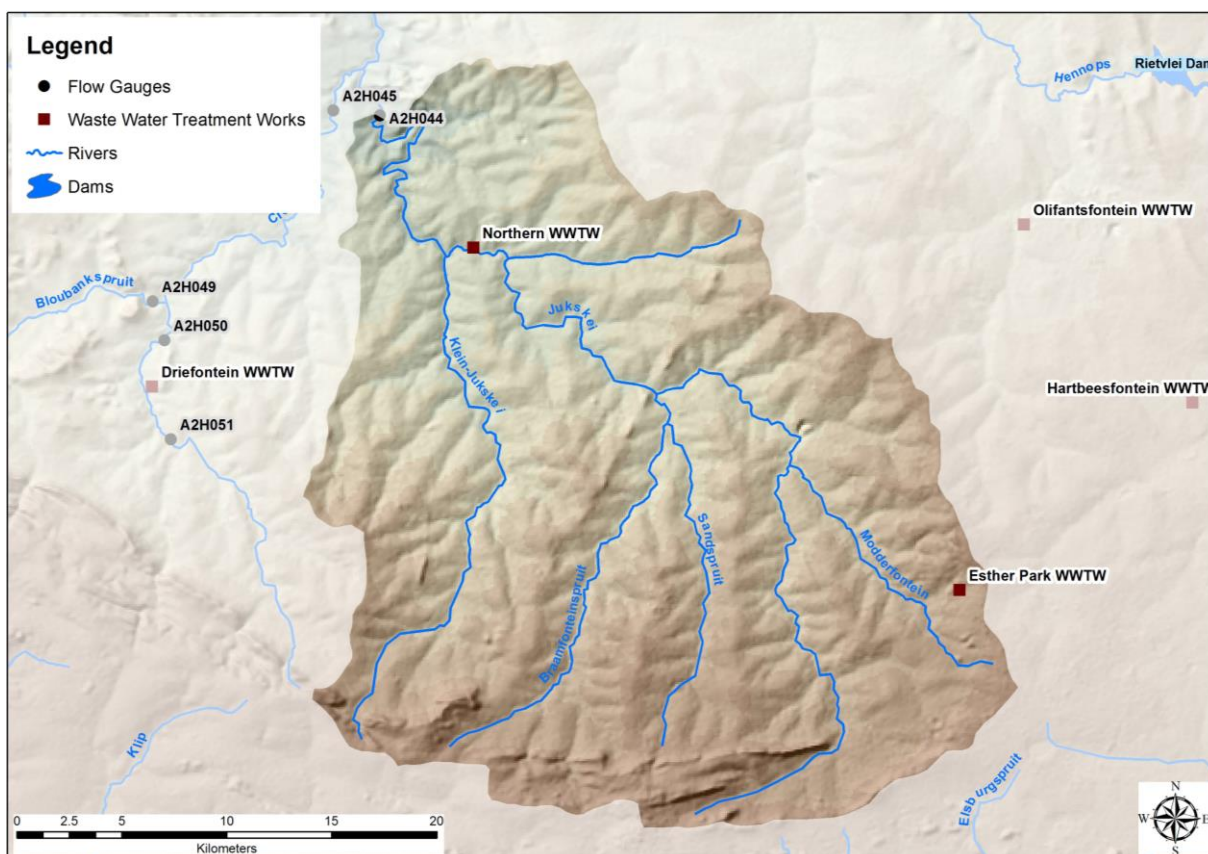


Figure 3-5 Jukskei River catchment map

Table 3-3 Jukskei River catchment hydrology parameters

Quaternary	Area (km ²)	MAP (mm/a)	MAR (mm/a)	MAE (mm/a)	Base flow (Mm ³ /a)	% No Flow
A21C	761	682.2	49	1700	20.27	0

3.4.3 The Hennops River Catchment (A21A and A21B)

The Hennops River originates in the vicinity of Olifantsfontein. The upper reaches of the River flows through an agriculture section where ground water is used for irrigation, Centurion and Pretoria. It has a catchment area of 1010 km² and a mean annual runoff of 28 Mm³. The Rietvlei Dam is situated on the Hennops River and provides Pretoria with potable water. The East Rand Water Treatment Company's Hartbeesfontein WWTW discharges into the Rietvlei Dam catchment. The Hennops River catchment is shown in Figure 3-6 and the catchment hydrology parameters is presented in Table 3-4 (WRC, 2011).

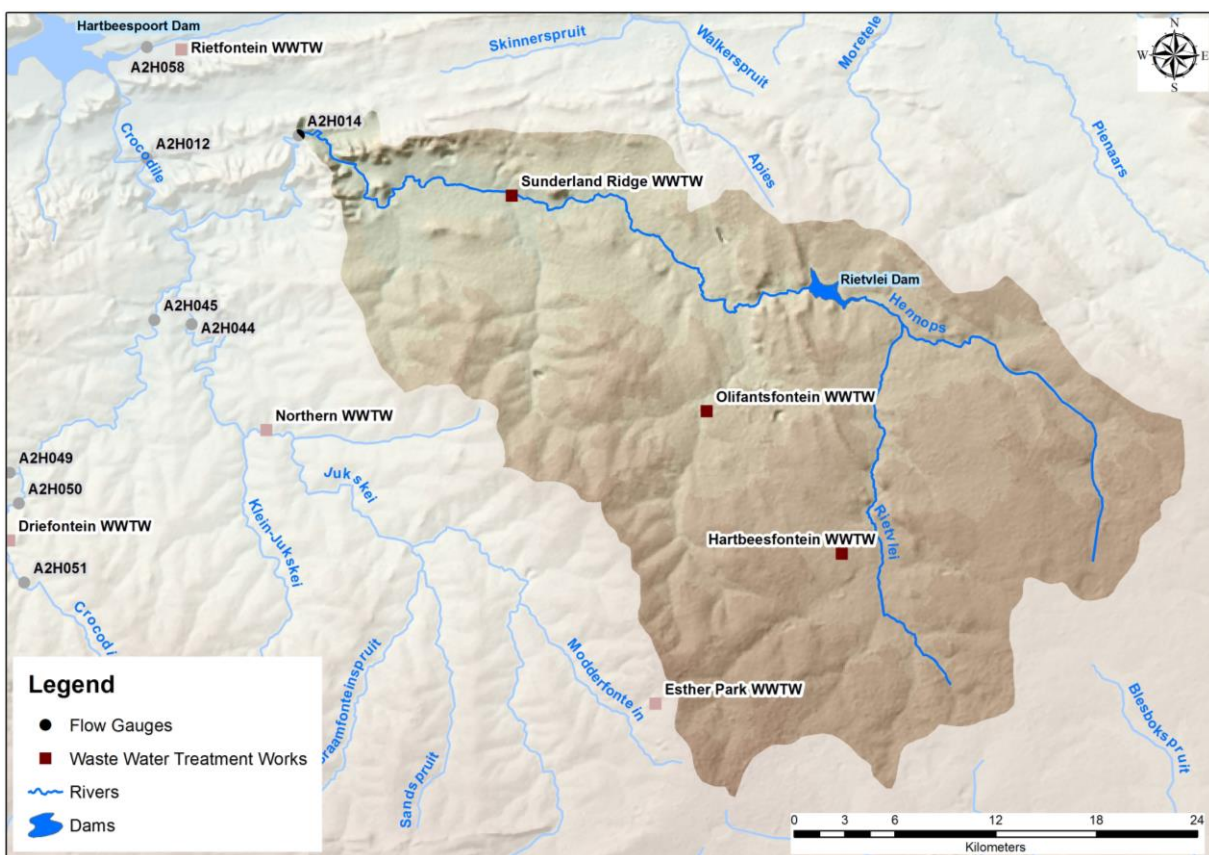


Figure 3-6 Hennops River catchment map

Table 3-4 Hennops River catchment hydrology parameters

Quaternary	Area (km ²)	MAP (mm/a)	MAR (mm/a)	MAE (mm/a)	Base flow (Mm ³ /a)	% No Flow
A21A	482.8	683.5	33.6	1700	14.49	0
A21B	526.5	671.8	19.1	1700	8.30	0

3.4.4 The Crocodile River Catchment (A21D and A21E)

The Crocodile River has its source in the Witwatersrand mountain range at a height of 1700 meters above sea level a catchment area of 653 km² up to the confluence with the Jukskei River and a total catchment of 2551 km² just before the inflow into the Hartbeespoort Dam. The Blaauwbankspruit is the major tributary before the confluence with the Jukskei River. The main tributaries to the Crocodile River are the Jukskei and the Hennops Rivers. The Crocodile River catchment is urbanised and include Roodepoort and Krugersdorp. Small holdings and commercial agricultural activities takes place in the vicinity of the dam. Derelict old gold mines pose a threat to the water quality due to acid mine drainage that is threatening to discharge to the natural environment. The Crocodile River catchment is shown in Figure 3-7 and the catchment hydrology parameters is presented in Table 3-5 (WRC, 2011).

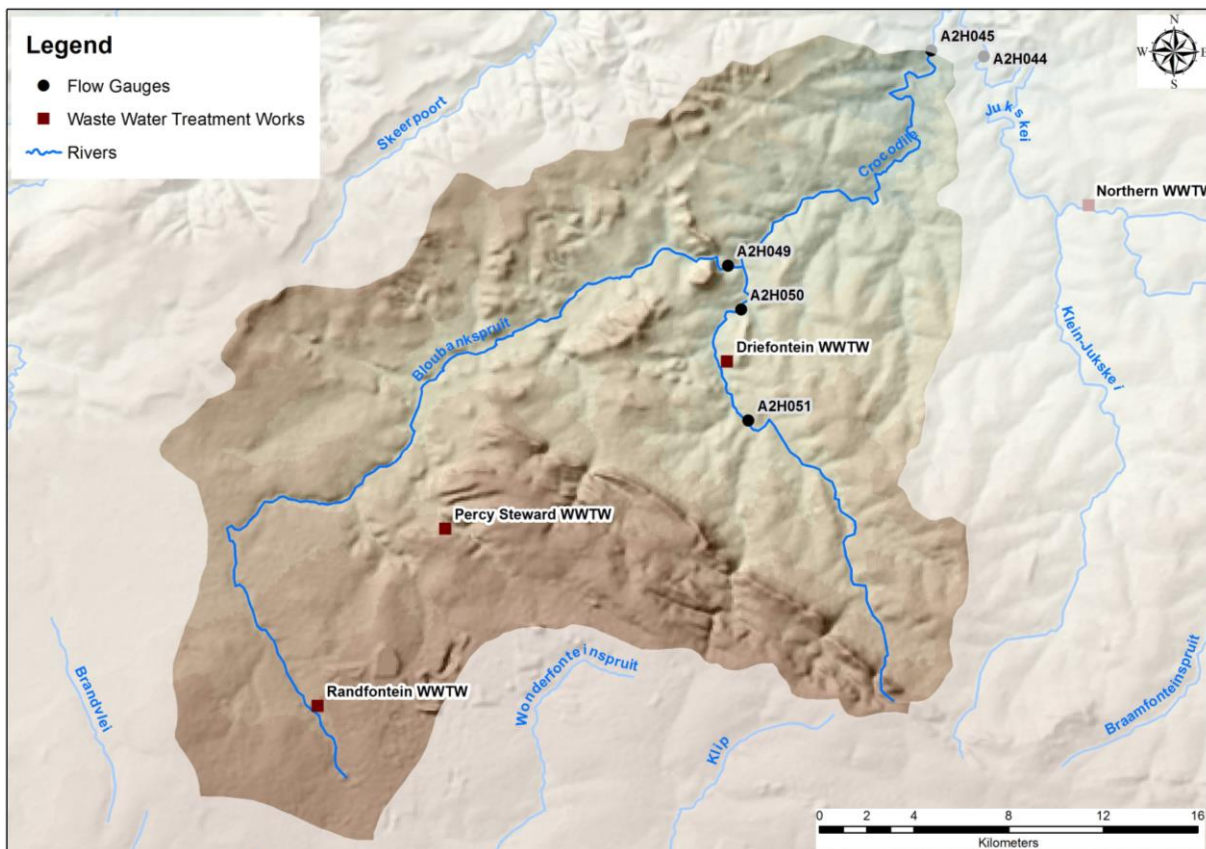


Figure 3-7 Crocodile River catchment map

Table 3-5 Crocodile River catchment hydrology parameters

Quaternary	Area (km ²)	MAP (mm/a)	MAR (mm/a)	MAE (mm/a)	Base flow (Mm ³ /a)	% No Flow
A21D	371.5	713.7	56.3	1700	32.62	0
A21E	289.8	706.4	54.6	1700	21.17	0

3.4.5 Hartbeespoort Dam Catchment (A21H)

The catchment size is approximately 515 km². This includes the dam itself and the Swartspruit. There are three municipalities within the catchment area, namely Local Municipality of Madibeng, Mogale City (West Rand) and City of Tshwane. There are seven continuous flow weirs within the catchment, namely: A2H058 (measuring flow from the Swartspruit); A2H014 (measuring flow from the A21A and A21B sub-catchments); A2H044 (measuring flow from the A21C sub-catchment); A2H045 (measuring the flow from the A21D and A21E sub-catchments); A2H012 situated just in the A21F sub-catchment (measuring flow from the A21F and A21G sub-catchments); dam wall (measuring the flow out of the Hartbeespoort Dam). The mean water qualities and flow leaving the river catchment is indicated by the Kalkheuwel measuring point A2H012, just before the Crocodile River enters the dam and provides an indication of the water quality in the dam the point close to the dam wall. The Hartbeespoort catchment is shown in Figure 3-8 and the catchment hydrology parameters is presented in Table 3-6 (WRC, 2011).

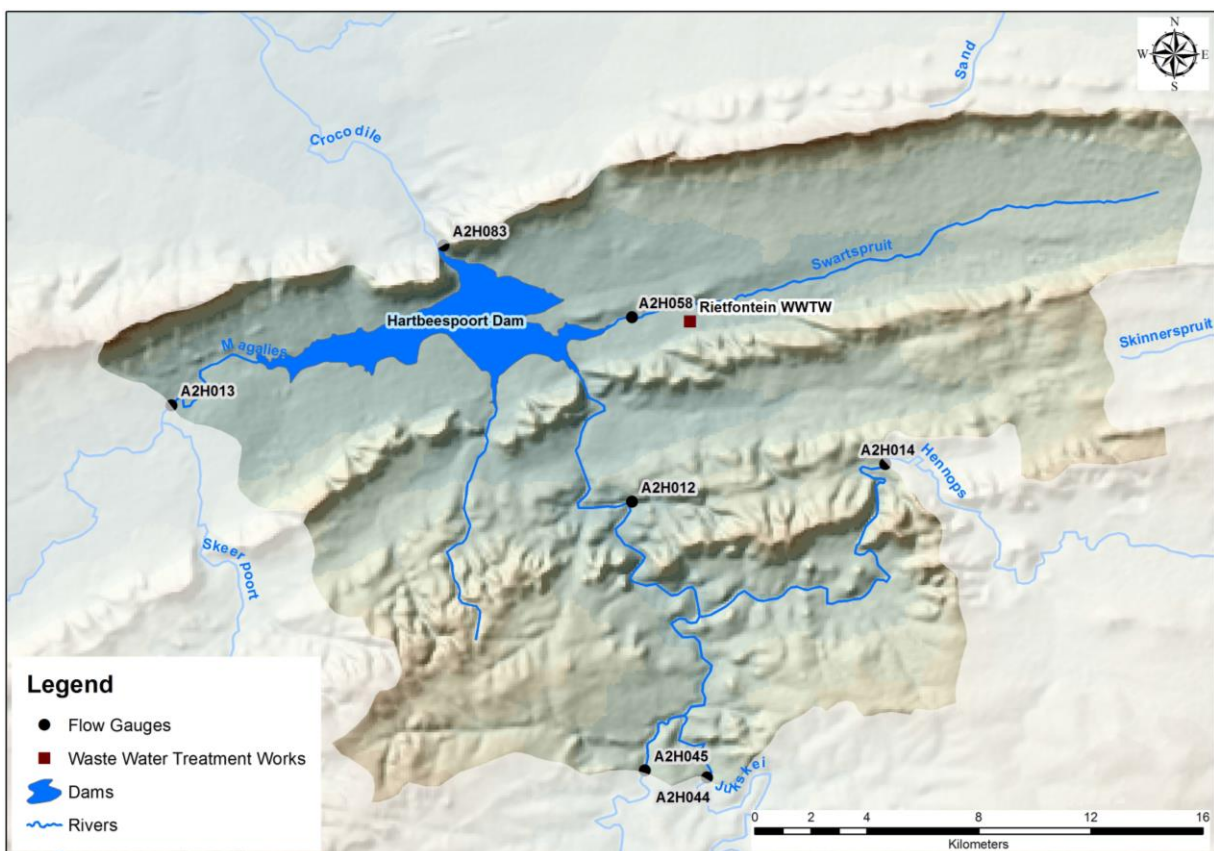


Figure 3-8 Hartbeespoort catchment map

Table 3-6 Hartbeespoort catchment hydrology parameters

Quaternary	Area (km ²)	MAP (mm/a)	MAR (mm/a)	MAE (mm/a)	Base flow (Mm ³ /a)	% No Flow
A21H	513.7	668.2	36.3	1700	4.29	0

3.4.6 System diagram of Hartbeespoort Dam catchment

The system flow diagram in Figure 3-9 provides significant information about the complex network of tributaries draining into the Hartbeespoort Dam. This represent the network of main river systems, waste water treatment plants, acid mine drainage and sampling stations in the catchment.

As described previously, the catchment is highly urbanised with 10 municipal waste water treatment plants discharging the bulk of the flow entering the dam under normal dry weather condition.

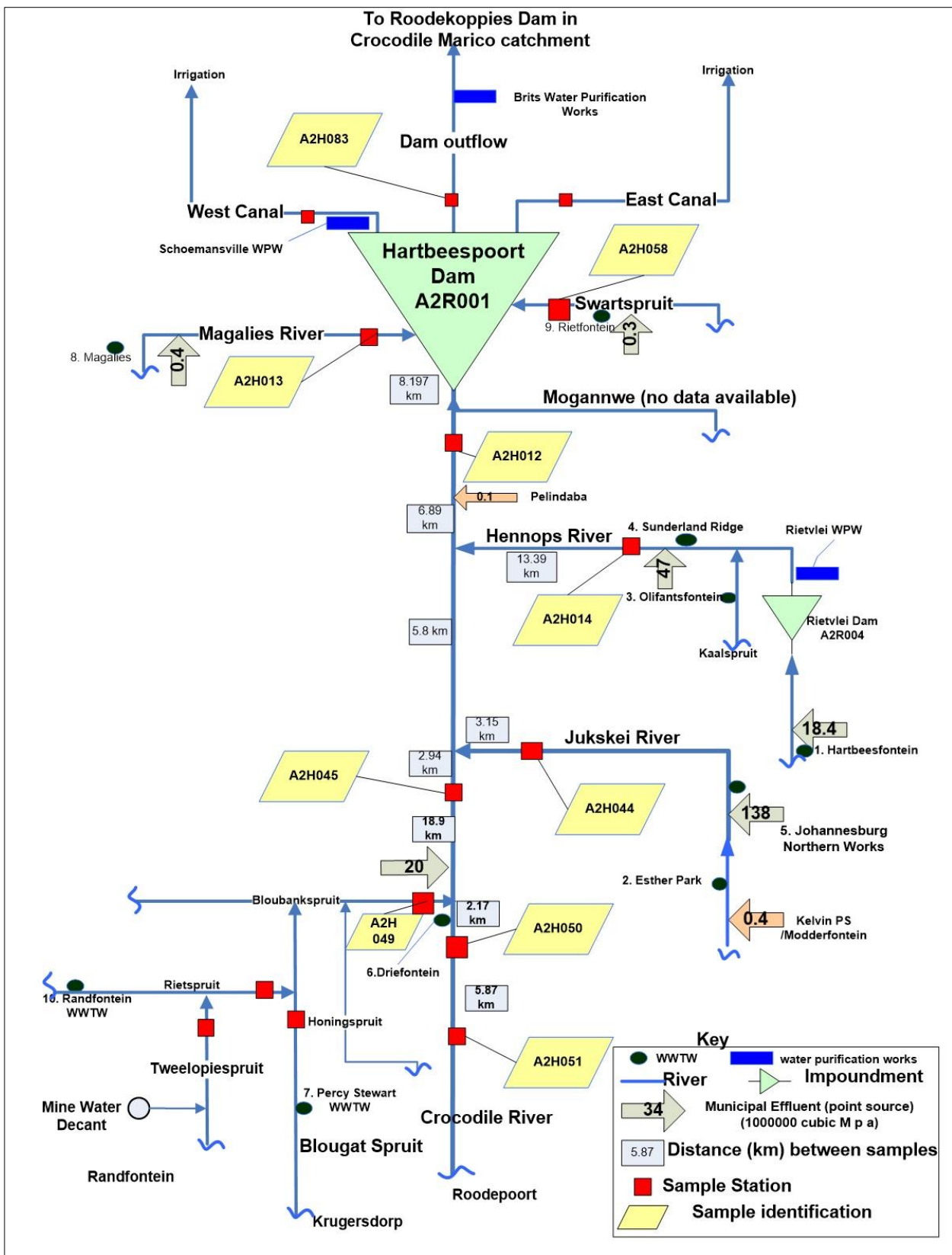


Figure 3-9 System flow diagram

The flow diagram represents the basis for a matrix to model the variables in the catchments to enable calculation of nutrient loads draining towards the Hartbeespoort Dam. The various

sub-catchments contribute the nutrients that could cause the eutrophication phenomena in the Hartbeespoort Dam. The key to investigate sensible options for nutrient reduction in the dam is to understand the flow dynamics of surface water from the catchments to the dam and to analyse the load of phosphates that is transported in association with a wide spectrum of pollutants.

3.4.7 Catchment water quality

The pollution load along the flow path of the Crocodile River was studied during the situation analysis to formulate action plans for the remediation plans as part of the Harties Metsi-a-me programme (Hartbeespoort Dam Bioremediation programme Integrated monitoring programme progress report. 2013) Figure 3-10 illustrates the cumulative load of inorganic chemicals conveyed by in-stream flow by the Crocodile River from its origin to the inflow to the dam.

From the profile of pollutants in the Crocodile River it is evident that major portion of pollution, as measured in the measuring points, show a steep increase in chemical contamination after the Jukskei River and Hennops River join the Upper Crocodile River.

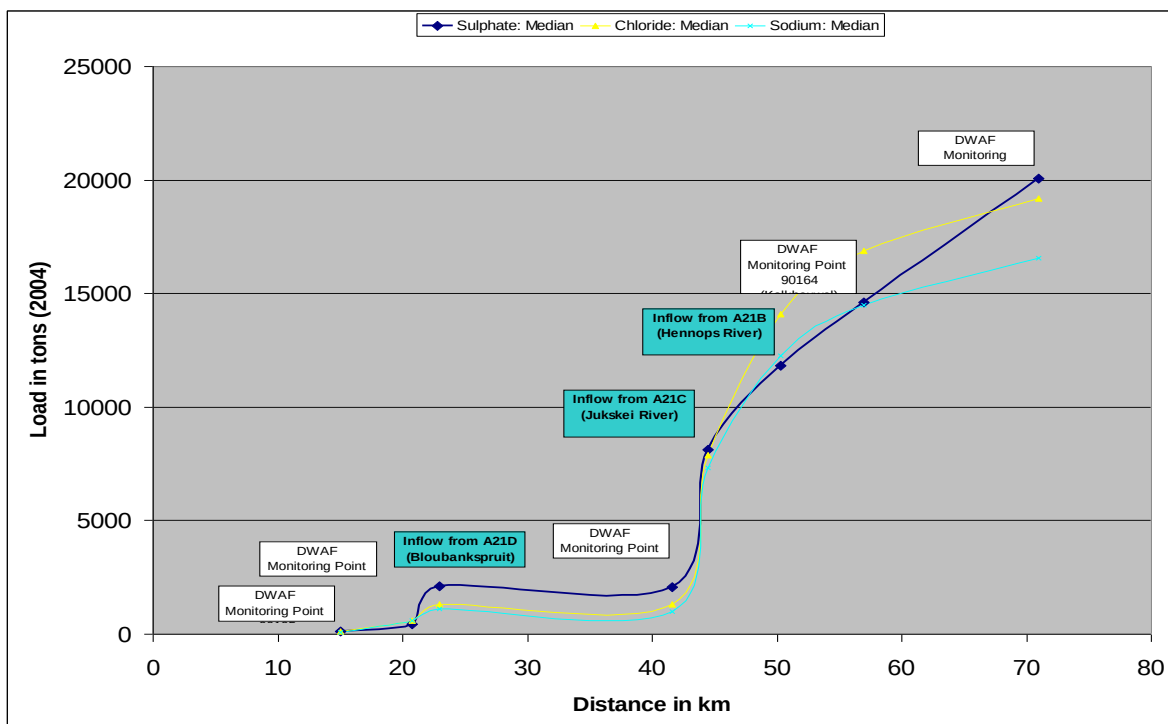


Figure 3-10 Profile of pollution load along the length of the Crocodile River (Integrated Monitoring Programme: Progress Report. 2012)

Macro indicators of water quality are EC and pH. The time series EC and pH as compared to the SANS 241:2005 drinking water guideline is shown in Figure 3-11. Over the time period indicated

only one EC value from A2H012 (flow gauge in Crocodile River before HBPD inflow) reported to the acceptable limit where all other monitoring data showed 100% compliance with the drinking water quality guideline with respect to EC and pH.

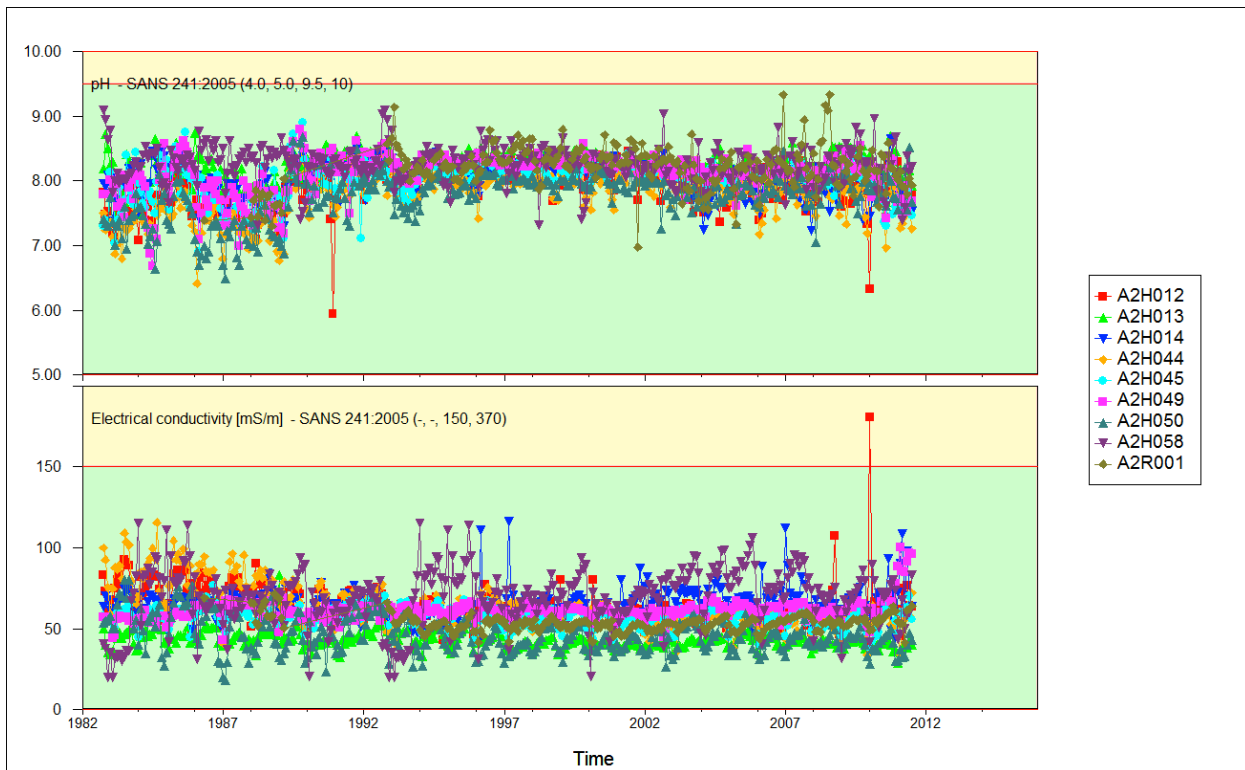


Figure 3-11 Time series EC and pH of all monitoring points

The time series graphs for the major anions and cations are presented in Figure 3-12 and Figure 3-13 respectively. All sites show 100% compliance with the SANS 241:2005 drinking water guideline with the exception of A2H058 (Swartspruit) and A2H014 (Hennops River) which reports to acceptable for a few instances.

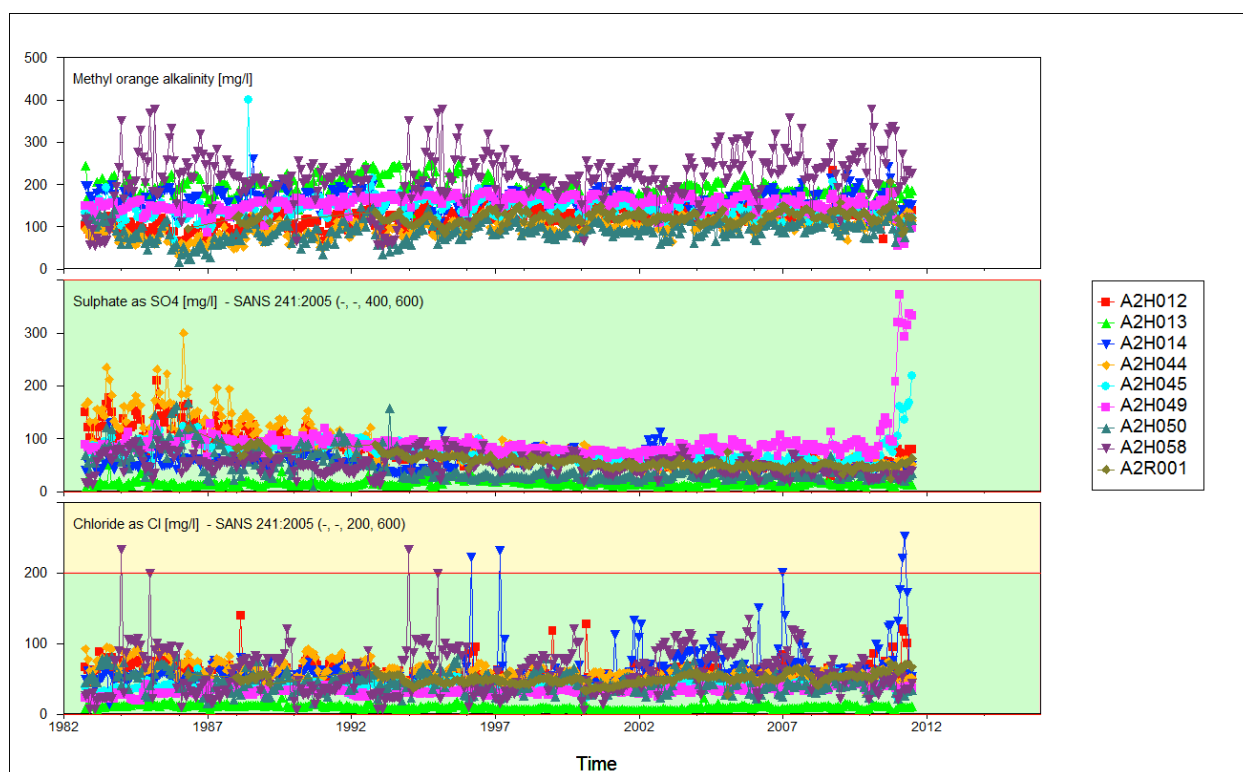


Figure 3-12 Time series data of major anions of monitoring stations

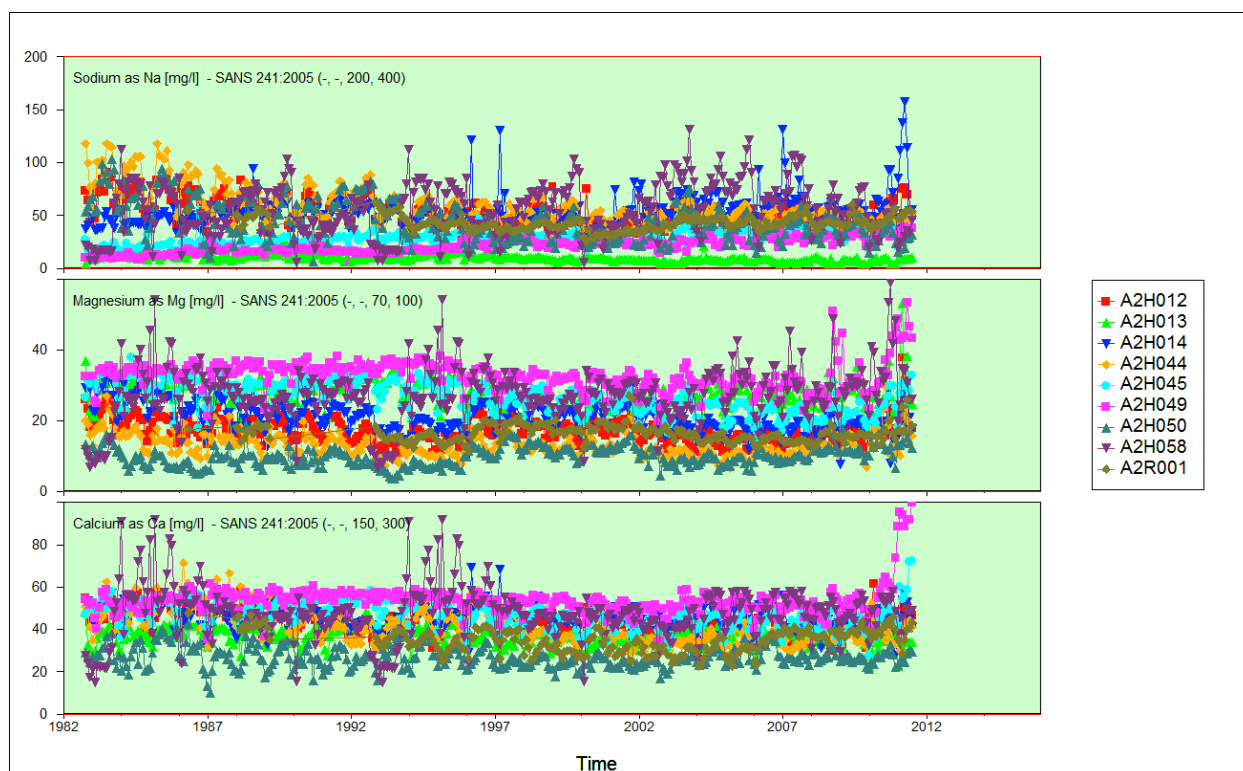


Figure 3-13 Time series data of major cations of monitoring data

The Piper and Expanded Durov diagrams for the monitoring sites within the study area is shown in Figure 3-14 respectively Figure 3-15. An explanation of the aforementioned diagrams is

presented in Appendix A. Recent data from Huizenga *et al.* (2013b) were used to generate the diagrams and the presentation of the full set of data is available in Appendix B.

It is clear from the Piper and Expanded Durov diagrams that A2H013 (Magalies River), A2H058 (Swartspruit) and A2H050 (Crocodile River before the Bloubank tributary) represents a water character consistent with unpolluted water. It is important to note that the aforementioned graphs only relate to water character and not water quality.

The water character of A2H049 (Bloubankspruit) and A2H045 (downstream from Bloubankspruit and Crocodile A2H050) are typical of a water character associated with mining practices.

The remainder of the sites A2H044 (Jukskei River), A2H014 (Hennops River), A2H012 (Crocodile River before entering the HBPD) and A2R001 (HBPD) exhibit a similar character with that of A2H012 and A2R001 being very close as expected.

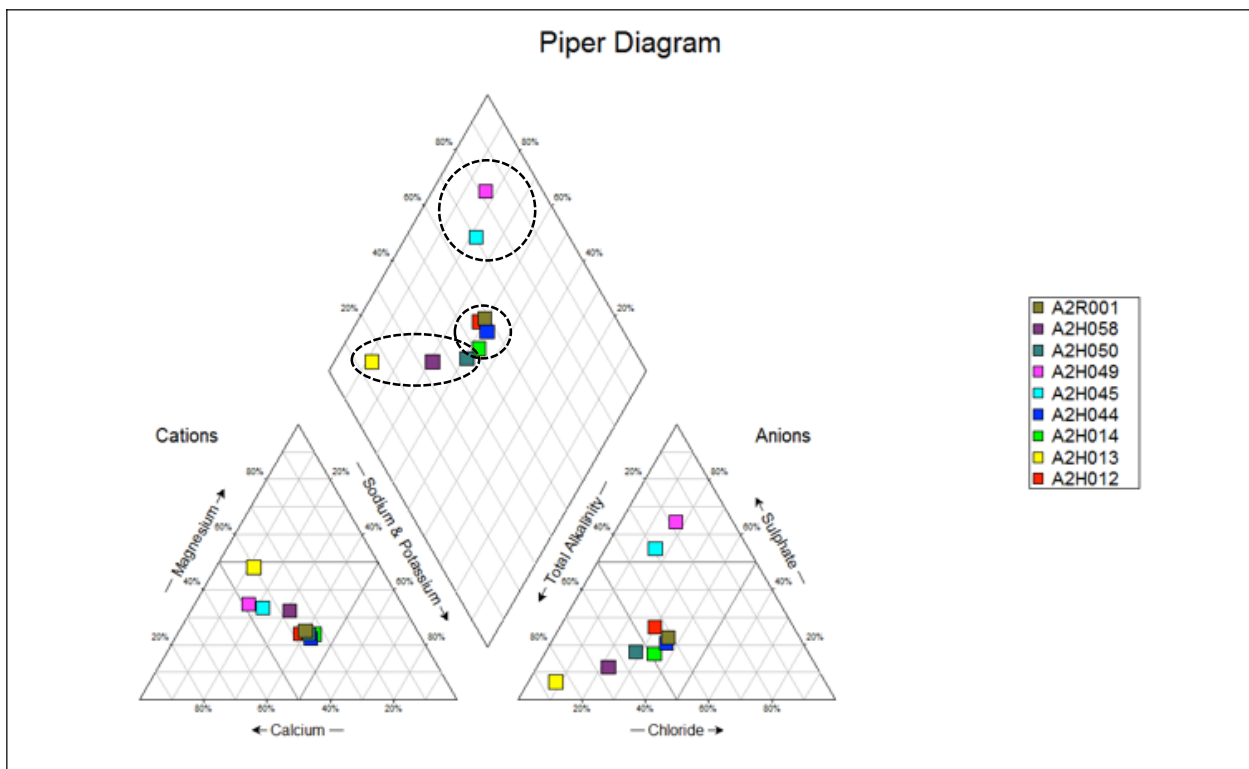


Figure 3-14 Piper diagram for monitoring sites using recent data

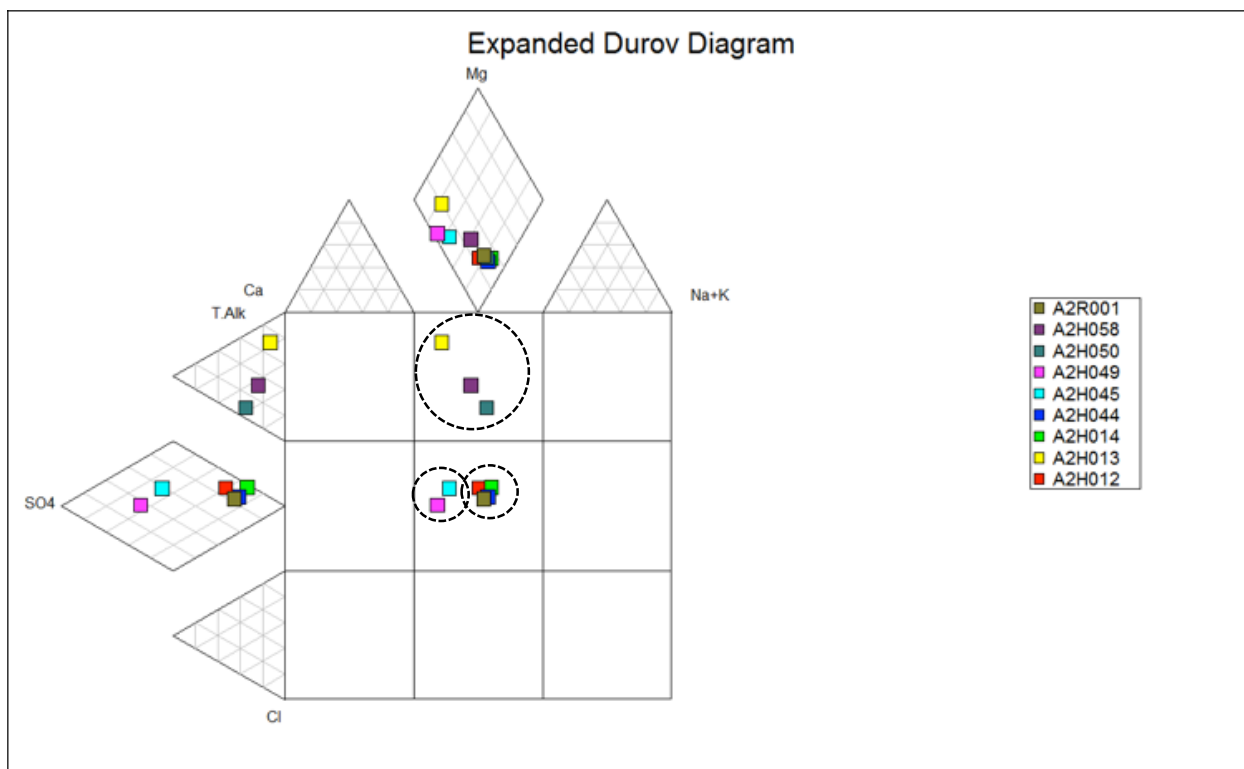


Figure 3-15 Expanded Durov diagram for monitoring sites using recent data

4 AVAILABLE DATASETS

4.1 Availability of data to quantify nutrient load in surface water

Data used for calculation of flow and phosphate loading in catchment have been obtained from official records of Department of Water and Sanitation (DWS) which has been recording hydrological data since the commissioning of the Hartbeespoort Dam.

The DWS conducts an ongoing water quality programme in the Hartbeespoort Dam Catchment. In addition the Harties Metsi-a-me programme implemented specific monitoring programme to study the variables to be able to assess the impact of interventions on eutrophication in the dam. The WRC published a comprehensive set of validated data on rivers and dams in the associated catchments (Huizenga *et al.*, 2013).

For the purpose of this study, data were extracted data from the different sources to represent the base case scenario for development of phosphate load variation scenarios. The base case situation will be instrumental in recognising and evaluating phosphate reduction options that will have a beneficial influence in achieving a reduction in eutrophication level towards a mesotrophic state in the dam.

4.2 Datasets

The monitoring sites considered as well as the WWTW are shown in Figure 3-9. For each site flow and water quality data (PO_4 in particular) are required for modelling purposes.

4.2.1 Base case scenario

The base case scenario has been selected for a period October 2006 to June 2011 when sufficient data were available that could easily be retrieved from Department of Water and Sanitation resource quality monitoring programmes. All the DWA long term monitoring sites include the monitoring of water quantity and water quality such as Electrical Conductivity (EC), salts (e.g. sulphates, magnesium, calcium, potassium and chlorides) and the nutrients (e.g. phosphates (PO_4) ammonia (NH_3) and nitrates (NO_3)). However, for this study the main focus was phosphates and only the relevant data was considered.

4.2.2 Water quality data

Water quality data for the base case were obtained from a comprehensive report published by Water Resource Commission (Huizenga *et al.*, 2013b). The report includes a dataset

based on RQS monitoring data, with the difference that it has been checked for ion-balance errors.

4.2.3 Flow data

Flow data for the base case were obtained from the Hydrological website of DWS: www.dwaf.gov.za/hydrology. The summary of the data quality is shown in Figure 4-1. Patching of data were facilitated by taking an average of the surrounding data.

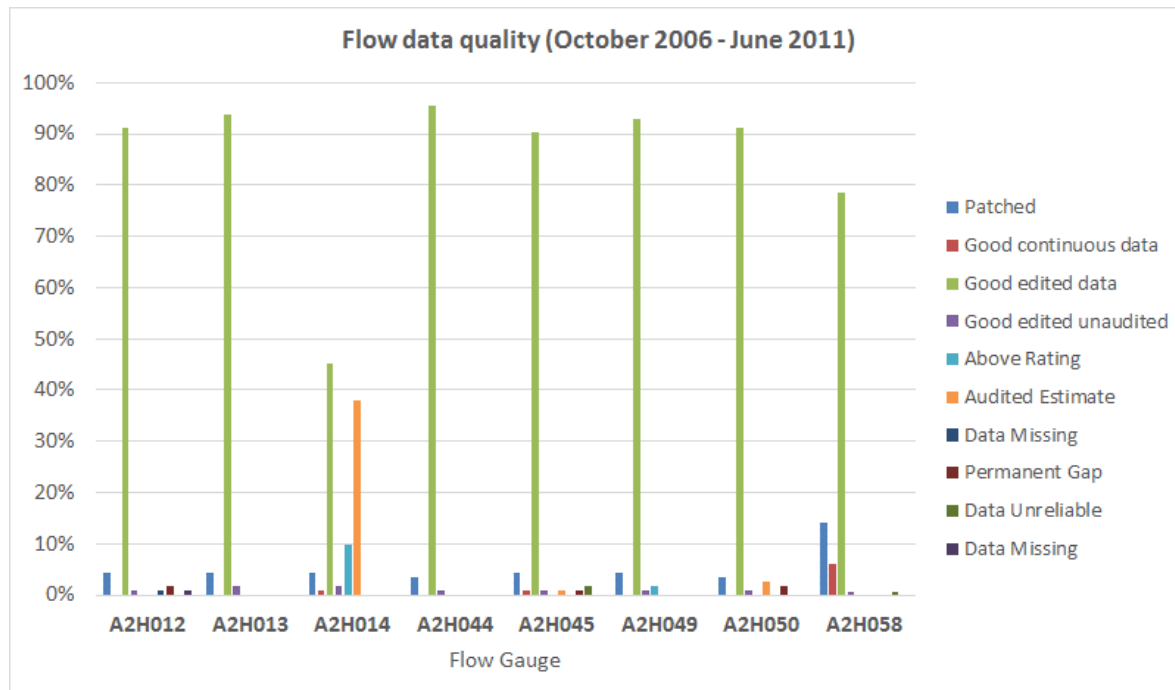


Figure 4-1 Flow data quality for base case

4.2.4 WWTW data

A similar study was done by Van Veelen in 2013 and permission was requested from Ilisio to use their data for the performance of the WWTW as the Green Drop System was only introduced in 2008. The data obtained from the Green Drop System is only available for about 3 years and in some case not available e.g. Rietfontein in the Madibeng area. With the exception of the Magalies, Percy Steward and Randfontein WWTWs, the majority of stations used in this study had sufficient data which is representative of the existing situation.

Table 4-1 Summary of available data from the various sources

Data required	Data source	Flow data	Quality data	No years
DWA data for the dam				
Flow data into the dam	DWA	Oct 2006 – Mar 2012	Oct 2006 – Jul 2011	4 years and 9 months
Flow Data out of the dam	DWA	Oct 2006 – Sept 2011	Not applicable	5 years
Volumes of the dam	DWA	Oct 2006 – Sept 2011	Not applicable	5 years
Vaal dam	DWA	Not applicable	Jan 2006 to Jan 2012	6 years
Data for the river stations before the inflow into the dam from DWA				
Magalies River (A2H013)	DWA	Oct 2006 – Feb 2011	Oct 2006 – Feb 2011	4 years and 4 months
Crocodile River (A2H045)	DWA	Oct 2006 – Mar 2012	Oct 2006 – Mar 2012	4 years and 5 months
Jukskei River (A2H044)	DWA	Oct 2006 – Mar 2012	Oct 2006 - Aug 2011	4 years and 5 months
Hennops River (A2H014)	DWA	Oct 2006 – Mar 2011	Oct 2006 – Mar 2011	4 years and 5 months
Crocodile River (A2H012)	DWA	Oct 2006 – Mar 2012	Oct 2006 – Nov 2011	
Swart Spruit (A2H058)	DWA	Oct 2006 – Jul 2011	Oct 2006 – Jul 2011	4 years and 8 months
Point sources				
Magalies (WWTW)	Mogale City	No data was received	No data was received	0
Randfontein WWTW	Randfontein Municipality	10 Jul 2008 – 23 Aug 2011	10 July 2008 – 23 Aug 2011	3 year and 1 month
Percy Steward WWTW	Mogale City	No data was received	No data was received	0
Driefontein WWTW	Johannesburg Metropolitan Municipality	Jan 2006 – Jun 2012	Jan 2008 – Apr 2012	6 years and 6 months
Northern WWTW	Johannesburg Metropolitan Municipality	Jan 2006 – Jun 2012	Jan 2008 - Apr 2012	6 years and 6 months
Esther Park	ERWAT	Jan 2006 – July 2012	Jan 2006 – July 2012	6 years and 7 months
Sunderland Ridge WWTW	Tshwane Metropolitan Municipality	Jan 2006 - Mar 2012	Jun 2004 - Feb 2012	5 years and 3 months
Hartbeesfontein WWTW	ERWAT	Jan 2006 – Aug 2012	Jan 2006 – Aug 2012	6 years and 8 months
Olifantsfontein WWTW	ERWAT	Jan 2006 – Aug 2012	Jan 2006 – Aug 2012	6 years and 8 months
Kelvin Power Station	Kelvin Power Station	April 2006 – Jan 2012	Jan 2006 – Jan 2012	5 years and 8 months
Green Drop System Data				
Magalies (WWTW)	GDS	No flow is available	5 Jul 2011 – 10 Apr 2012	9 months
Randfontein WWTW	GDS	No flow is available	8 Sept 2010 - 28 Jun 2012	1 year 8 months
Percy Steward WWTW	GDS	No flow is available	01 Jul 2011 – 30 Apr 2012	9 months
Driefontein WWTW	GDS	No flow is available	01 Jul 2009 – 30 Jun 2012	3 years
Northern WWTW	GDS	No flow is available	01 Jul 2009 – 30 Jun 2012	3 years
Esther Park	GDS	No flow is available	01 Jul 2009 – 31 Jul 2012	3 years
Sunderland Ridge WWTW	GDS	No flow is available	01 Jul 2009 – 10 Jul 2012	3 years
Hartbeesfontein WWTW	GDS	No flow is available	01 Jul 2009 – 31 May 2012	2 years and 10 months
Olifantsfontein WWTW	GDS	No flow is available	01 Jul 2009 – 31 May 2012	2 years and 10 months

5 METHODOLOGY

5.1 Introduction

Phosphate is a pivotal variable in the equation to manipulate eutrophication in the dam. Within the accuracy of available data and flow measurements at the various measuring points the average phosphate load of surface water drained from the catchments were calculated based on the system flow diagram indicated in Figure 3-9.

Two modelling methodologies were implemented in the PO₄ calculation:

1. Conservation of mass on monthly time step to establish the diffuse PO₄ load and test validity of the range of WWTW PO₄ values obtained.
2. Situation assessment approach followed by Van Veelen (2013) considering annual averages.

Both the abovementioned models are discussed in more detail in the sections that follow.

5.2 Conservation of mass

5.2.1 Theory

The principal of the conservation of mass is applied to the system to calculate the various loads and concentrations in the system. Consider the conceptual model of a catchment system as depicted in Figure 5-1.

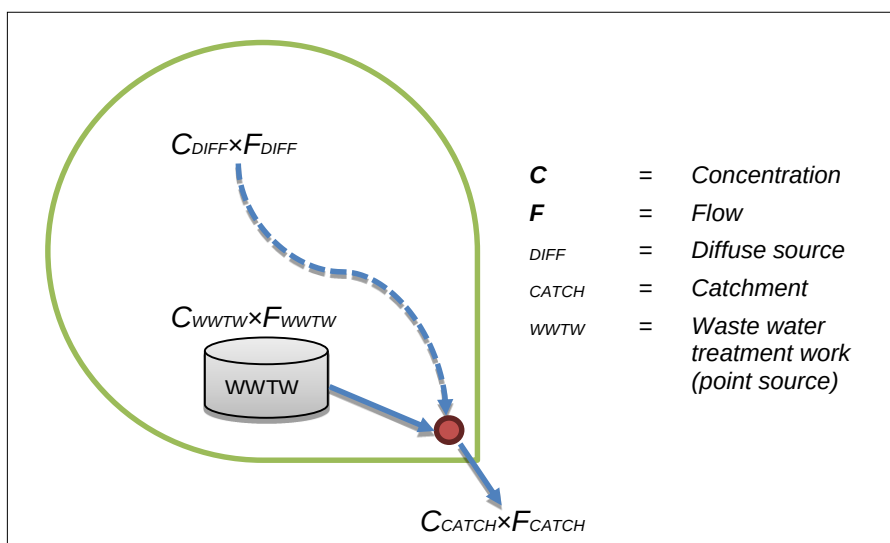


Figure 5-1 Conceptual model of a catchment

The total load for every source is calculated by multiplication of the concentration and flow. Assume the concentration is given in mg/l and the flow in Mm³/month then:

$$C(\text{mg/l}) \times F(\text{Mm}^3/\text{month}) = \frac{\text{mg}}{\text{l}} \times \frac{1,000,000 \text{ m}^3}{\text{month}} \times 1000 = \text{kg/month} \quad (1)$$

The following equations apply to the conservation of mass:

$$F_{\text{CATCH}} = F_{\text{DIFF}} + F_{\text{WWTW}} \quad (2)$$

$$C_{\text{CATCH}} \times F_{\text{CATCH}} = (C_{\text{DIFF}} \times F_{\text{DIFF}}) + (C_{\text{WWTW}} \times F_{\text{WWTW}}) \quad (3)$$

For the purpose of this study diffuse flow of a particular catchment is defined as the total flow minus all point source flows. This implies that the diffuse flow of catchments downstream will include the point source flows of the upstream catchments.

According to the available data, both flow and concentration of the catchment and the WWTW is available allowing for the calculation of the diffuse flow and diffuse concentration by combining Equation 2 and Equation 3:

$$F_{\text{DIFF}} = F_{\text{CATCH}} - F_{\text{WWTW}} \quad (4)$$

$$C_{\text{DIFF}} = \frac{(C_{\text{CATCH}} \times F_{\text{CATCH}}) - (C_{\text{WWTW}} \times F_{\text{WWTW}})}{F_{\text{CATCH}} - F_{\text{WWTW}}} \quad (5)$$

5.2.2 Calibration results

The calibration results for the monthly conservation of mass model based on the system configuration presented in Figure 3-9 is shown in Figure 5-2. Some notes regarding Figure 5-2:

- Model calibration was done on the time period October 2007 to July 2011 which is one year later than the base case scenario as this time period resulted in a much better calibration.
- The red line indicates the measured PO₄ and the green line the calculated PO₄. The blue line on the secondary axis shows the measured flow, with the exception of A2R001 which is a reservoir where no flow is measured and hence the flow was calculated as the sum of A2H012, A2H013 and A2H058.

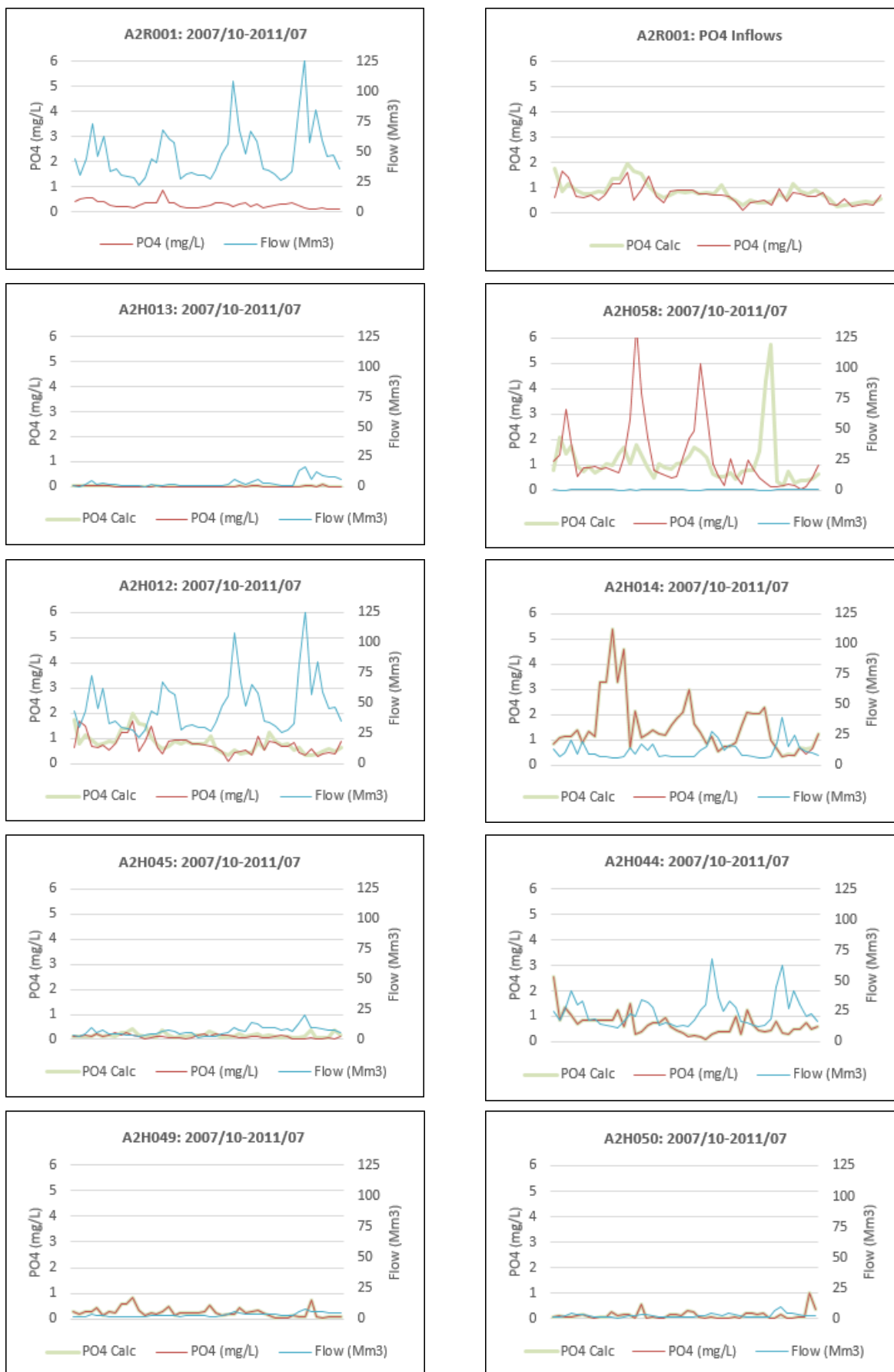


Figure 5-2 Calibration results for monthly conservation of mass model

5.3 Van Veelen (2013) situation assessment approach

The formulas and assumptions as applied to the methodology is summarised in Appendix D. The methodology is an adaptation of the report of Van Veelen (2013) prepared to assess the situation in the Hartbeespoort Dam catchment for purposes of studying the waste discharge charge system (WDCS) in terms of the NWA (Act 36 1998).

The following calculations and assumptions have been incorporated in the model to calculate the phosphate load entering the Hartbeespoort Dam from the catchments:

- i. The total PO_4 load of each catchment is assumed to be represented by the representative gauging station.
- ii. The point source PO_4 load for WWTW is based on information in the Green Drop System reports. Table 5-1 is a summary of the performance of the WWTW.
- iii. The natural PO_4 load for the catchment is based on the run-off due to natural rainfall in the catchment, which will contain a natural level of background phosphorous (Van Veelen, 2013). The natural concentration of PO_4 in a river that has not been impacted upon by any anthropogenic activities is in the order of 0.005 to 0.01 mg/l. For the purposes of this calculation a value of 0.01 mg/l is used. The naturalised mean annual run-off (MAR) for monitoring station A2H013, A2H045, A2H044 and A2H014 was taken from WR2005 tables for the Crocodile West & Marico Water Catchment Area.

Table 5-1 Summary of the WWTW that discharge to the Hartbeespoort Dam (RQS website and Green Drop System)

Works Name	Driefontein WWTW Class A	Northern WWTW Class A	Sunderland Ridge WWTW Class A	Randfontein WWTW Class A	Percy Steward WWTW Class B	Magalies WWTW Class D	Olifantsfontein WWTW Class A	Hartbeesfontein WWTW Class B	Esther Park WWTW Class D	Rietfontein WWTW
Reference Fig xx	6	5	4	10	7	8	3	1	2	9
Water Service Authority	City of Johannesburg Metropolitan Municipality	City of Johannesburg Metropolitan Municipality	City of Tshwane Metropolitan Municipality	Randfontein Local Municipality	Mogale City Local Authority	Mogale City Local Authority	Ekurhuleni Metropolitan Municipality	Ekurhuleni Metropolitan Municipality	Ekurhuleni Metropolitan Municipality	Madibeng Local Authority
Villages Served	Johannesburg	Johannesburg	City of Tshwane	Randfontein	Krugersdorp	Magaliesburg	Tembisa & Kempton Park	Kempton Park	Esther Park	Hartbeespoort
Discharge into	Crocodile River	Jukskei River	Hennops River	Blaauwbank Spruit	Blaauwbank Spruit	Magalies River	Hennops River	Hennops River	Modderfontein Spruit	Swartspruit
Design capacity (Mℓ/d)	35	450	65	20	27	1.1	105	45	0.4	3
Operating capacity (Mℓ/d)	30	390	57.2	13	16.9	0.38	79	58	0.71	2.5
Available Capacity (Mℓ/d)	5	60	65	7	27	1.1	105	45		3
Maximum Discharge volume (Mℓ/d)	35	450	65	37	16	0.3	85	53	0.90	3
Typical Phosphate concentration mg/l Reported for case study period.	$10810 * 0.17 = 1837.7 \text{ kg/a}$	$147621 * 0.3 = 44286 \text{ kg/a}$	$22082 * 1.86 = 41072 \text{ KG/a}$	$3807 * 2.38 = 9061.2 \text{ kg/a}$	$6185 * 1.85 = 11411 \text{ kg/a}$	$139 * 5.98 = 831.7 \text{ kg/a}$	$28601 * 1.41 = 40613 \text{ kg/a}$	$19443 * 0.33 = 5832 \text{ kg/a}$	$205 * 0.96 = 197 \text{ kg/a}$	$2501 * 1.26 = 3152 \text{ kg/a}$
*Target effluent P load at 1 mg/l concentration	1081	14762	2208	3807	6185	13	2860	1944	20	250
Green Drop Compliance	>90%	>90%	<80%	<80%	<80%	<80%	>90%	>80%	>80%	Not implemented

5.3.1 Total diffuse load

Total diffuse phosphate load for a sub-catchment can be determined by subtracting the phosphate load discharged by WWTW in the sub-catchment from the load measured at the applicable measuring station. The phosphate load originating from diffuse sources other than the natural background can be attributed to (Withers & Jarvie, 2008):

- Run-off from hard surfaces.
- Additional runoff from hard surfaces such as roads, paved areas, roofs.
- Run-off from gardens and parks.
- Water supply system leakage.
- Leaking and overflowing sewers.
- Irrigation return flows

5.3.1.1 Additional run-off from hard surfaces such as roads, paved areas, roofs

Run-off from an urban area is more polluted than from natural area, due to hard surfaces e.g. roads, paved areas and roofs allow less infiltration that causes faster concentration of rainwater delivery to the storm water system. Rain water is essentially clean, but not totally free of nutrients and represents a large quantity of water. It was therefore thought sensible to also take this into account as a source of the diffuse load.

Additional run-off was calculated to be 24 Mm³/a in the Water Resource Reconciliation Strategy (DWA, 2008). As this is associated with urban areas, the total quantity was allocated proportionally to each sub-catchment based on the urban area in that catchment and the associated PO₄ concentration for this flow component was taken as 0.01 mg/l.

5.3.1.2 Return flows from gardens and parks

It is assumed that about 60% of water supplied to an urban area eventually becomes sewage flow and urban water supply is often used to irrigate gardens and parks which in turn will increase groundwater recharge and will probably become part of the base flow. For the calculation purposes it is assumed that the recharge will increase by 60 mm/a for the irrigated areas (10% of the rainfall). The gardens and parks have been assumed to constitute roughly 40% of the urban area. Rand Water contains 0.046 mg/l PO₄, but gardens and parks often get fertiliser added which may increase the phosphate level of the base flow up to 0.05 mg/l.

5.3.1.3 Leaking and overflowing sewer networks

Poor infrastructure and maintenance may result in leaks and overflows. The capacity of sewers has in some cases not kept track with increased population and urbanisation. Informal settlements are sometimes also not linked to a formal sewer system. In many municipalities no record is available and one can only make an assumption from local experience in this regard. For the purposes of this study it was calculated as the difference between the total diffuse load and all the other diffuse loads as mentioned above. A PO_4 concentration of 10 mg/l was assumed for the sewer system overflows to calculate the associated flow based. In other words, the sewer system load was divided by 10 mg/l PO_4 to derive the volume. This volume was then added to all the other volumes and compared to the total sub-catchment flow.

5.3.1.4 Leaking potable water supply networks

Rand Water as supplier of drinking water to most of the urban areas in the catchment is very concerned about the problem of aging infrastructure. An assumption was made that the phosphate load due to runoff as a result of leaking water supply is 10% of total supply provided by Rand Water with a PO_4 concentration of 0.046 mg/l.

5.3.1.5 Irrigation return-flow

Irrigation is limited in the Hartbeespoort Dam Catchment in comparison with downstream of the dam. The Reconciliation Strategy for the Crocodile West (DWAF, 2008) indicated that 11 Mm^3/a is returned as irrigation return-flow. In order to determine the load that could be expected from this component the WR2005 information (Middleton & Baily, 2008) was used to determine the irrigation areas in each sub-catchment and the percentage of the catchment that is actually irrigated. Once the volume of the irrigation return flow was determined for each of the sub catchments a PO_4 concentration of 0.01 mg/l was used to determine the load that would be derived from the irrigation in the catchment.

5.3.2 Phosphate load imported from Vaal dam

The WR2005 data (Middleton & Baily, 2008) suggests an inter-basin water transfer of 655 Mm^3/a . About 50% of this water is as a result of flow from the WWTW in the catchment. Some of the balance will reach the Hartbeespoort Dam through pathways discussed above.

5.3.3 Point source pollution

Waste WWTW are well documented sources of phosphates. Biological waste water treatment is commonly used in the WWTW in the catchment of the Hartbeespoort Dam. The

facts about the operation and relative performance of the WWTW's will be analysed in the next paragraph.

5.3.3.1 Effluent derived from WWTW

The WWTW discharging to the Hartbeespoort Dam are summarised in Table 5-1. Point sources such as WWTW's are monitored by Water Service Authorities as part of their Water Use Authorisations which could include a permit or water use licence. Since 2008 the Department of Water and Sanitation has introduced the Green Drop System to monitor the performance of WWTW's for compliance (DWA, 2012). This programme is a bold struggle to reduce phosphates entering the dam. All municipalities in the catchment of the Hartbeespoort Dam have a waste water abatement plan in place, except Randfontein and Madibeng (Rietfontein WWTW). In the 2012 Green Drop progress report (DWA, 2012) the majority of the plants in Table 5-1 have reduced their cumulative risk rating, and thereby negated their impact on the Hartbeespoort Dam.

The cumulative risk rating (CRR) is defined and calculated as follows:

$$CRR = (A \times B) + C + D \quad (6)$$

Where,

- A = Design capacity of plant which also represent the hydraulic loading onto the receiving water body*
- B = Operational flow exceeding, or below capacity*
- C = Number of non-compliance trends in terms of effluent quality as discharged to the receiving water body*
- D = Compliance or non-compliance in term of technical skills*

A CRR value is calculated for each municipal waste water treatment facility as provided in the Green Drop Progress Report. Sunderland Ridge WWTW was rated as the highest risk, while Northern Works WWTW showed the most improved risk abatement performance.

Although WWTW s may comply most of the time with the targets of the Green Drop System, events do occur that put a stress on the phosphate load running into the Jukskei River. The effects of the Green Drop System influence will only be observed in future when all the WWTW have achieved Green Drop status.

Figure 5-3 highlights the achievements of Northern Works WWTW. All of Johannesburg's sewage north of the ridge close to the city's centre is treated by these works situated on the Jukskei River, a tributary of the Crocodile River flowing to the Hartbeespoort Dam.



Figure 5-3 Green Drop Report recognises Northern Works as best provincial performer (DWA Green Drop Report 2009)

5.3.3.2 Private package plants (onsite treatment)

From 2012, private and public packaging plants are also included in the profile of the Green Drop System.

The Green Drop progress report (DWA, 2012) assessed a total of 53 on site package plants in the catchment of the Hartbeespoort Dam. These are considered point sources since they need a DWA permits and licenses. Approximately 43% possessed a valid license in terms of the NWA during the assessment period. The perception was that there is a lack of understanding of the special effluent standard of 1mg/l Phosphorous enforced in the Crocodile River catchment. In this dissertation the contribution of the private package plants have been included in the flow from the WWTW since no reliable data on composition and

flow is available at this stage except from some major facilities such as NECSA, which are properly managed.

5.3.3.3 Informal settlements

Informal settlements do not have package plants and it is assumed that waste water and sewage must be classified as a non-point source that is washed into the rivers after rain storms. This phenomenon is a growing concern due to the effect of urban sprawl continuing un-controlled in many parts of the catchment e.g. Diepsloot and along the Jukskei River in close proximity to Lanseria Airport.

5.3.4 Total Phosphate load model

In order to clarify the logic of the base case phosphate calculation, a diagram was prepared to illustrate the contribution of diffuse and point sources. Figure 5-4 is a schematic diagram illustrating the flow of data to obtain a base case load for a specific selection of independent variables.

A model was created with Microsoft® Excel to calculate the total phosphate load in the sub catchments as per the scheme in Figure 5-4.

Table 5-2 represents the base case calculation based on the Van Veelen (2013) approach. Point source load and diffuse load have been calculated separately using the assumptions described in earlier sections (Appendix D). The relative contribution by each sub-catchment can be surmised. Flow and concentration average values can be varied to calculate potential changes that allows theoretical outcome if the base case includes different efficiency for phosphate removal or if leaking sewer maintenance is improved.

For instance, if the WWTW efficiency improves due to technology upgrade the average contribution from that particular WWTW can be recalculated. The programme is a useful tool to evaluate the impact of special situations that can be manipulated through phosphate load reduction programmes. It can also be used to decide on priorities for management interventions. In Chapter 7 options to reduce phosphate load by introducing chemical treatment in a pre-impoundment option ahead the Dam will be discussed.

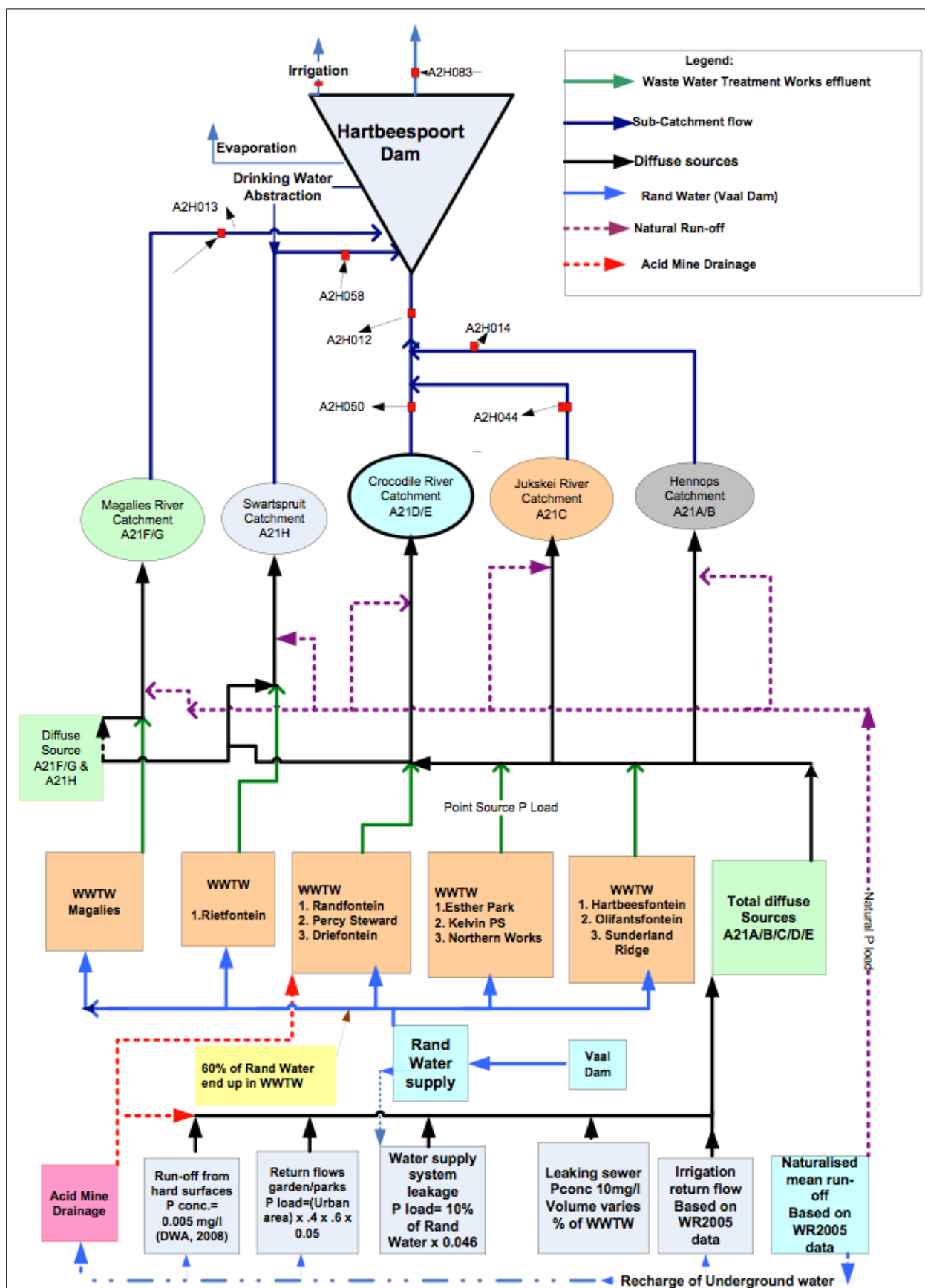


Figure 5-4 Total phosphate calculation diagram

Table 5-2 Phosphate load base case calculation

	P (con.) unit	Magalies		Crocodile		Jukskei		Hennops		Swartspuit + HBPD		TOTAL	
		A21F/G units	Load units	A21D/E units	Load units	A21C units	Load units	A21 A/B units	Load units	A21H units	Load units	units	Load units
Area													
Urban area		1,18 km²		86 km²		426 km²		315 km²		11 km²		828,18 km²	
% of catchment area		0,14% %		10,38% %		51,44% %		38,04% %		1,33% %		101,33%	
% urban area within HBPD catchment		0,029% %		9,95% %		51,59% %		37,07% %		1,41% %		100,049% %	
Total Catchment area Km²(WR2005)		1171 km²	769 kg/a	653 km²		768 km²		1010 km²		515 km²		4117 km²	
Diffuse flow													
Catchment irrigated km²		125,86 km²		27,6 km²		6,6 km²		2,74 km²		9,7 km²		172,5 km²	
% of catchment irrigated		3,06% %		0,67 %		0,16 %		0,07% %		0,24% %			
% irrigation of total catchment		73,0% %		16 %		3,83 %		1,59% %		5,62% %			
Irrigation return flows	0,01 mg/l	8025855 m³/a	80 kg/a	1760000 m³/a	18 kg/a	420870 m³/a	4 kg/a	174725 m³/a	2 kg/a	618551 m³/a	6 kg/a	11,0 M m³/a	110 kg/a
Return flow due to gardens & parks	0,1 mg/l	28094 m³/a	3 kg/a	1901972 m³/a	190 kg/a	10276668 m³/a	1028 kg/a	7355673 m³/a	736 kg/a	279272 m³/a	28 kg/a	19,8 M m³/a	1984 kg/a
Additional urban run-off	0,01 mg/l	33982 m³/a	0 kg/a	2300578 m³/a	23 kg/a	12430401 m³/a	124 kg/a	8897239 m³/a	89 kg/a	337801 m³/a	3 kg/a	24,0 M m³/a	240 kg/a
Leaking potable water supply	0,046 mg/l	70795 m³/a	3 kg/a	4792871 m³/a	220 kg/a	25896669 m³/a	1191 kg/a	18535914 m³/a	853 kg/a	703751 m³/a	32 kg/a	50 M m³/a	2300 kg/a
Leaking overflow sewers	10 mg/l	10 m³/a	0 kg/a	155700 m³/a	1557 kg/a	10740763 m³/a	107408 kg/a	6955094 m³/a	69551 kg/a	25000 m³/a	250 kg/a	18 M m³/a	178766 kg/a
Naturalised MAR m³/a (WR2005)	0,01	38640000 m³/a	386 kg/a	32500000 m³/a	325 kg/a	32420000 m³/a	324 kg/a	24780000 m³/a	248 kg/a			128 M m³/a	1283 kg/a
PO4 load originating from Vaal (kg/a)	0,046 mg/l	1290 m³/a	0,059 kg/a	447750 m³/a	21 kg/a	2321550 m³/a	106,8 kg/a	1668150 m³/a	76,73 kg/a	63450 m³/a	2,9 m³/a	4,5 M m³/a	207 kg/a
Diffuse Load (total)		46,8 Mm³/a	473 kg/a	43,9 Mm³/a	2354 kg/a	94,5 Mm³/a	110186 kg/a	68,4 Mm³/a	71554 kg/a	2,0 Mm³/a	323 kg/a	255,6 Mm³/a	184890 kg/a
Point Source													
Magalies WWTW	5,98 mg/l	139080 m³/a	832 kg/a									0,1 M m³/a	832 kg/a
Percy Steward WWTW	1,85 mg/l			6185400 m³/a	11443 kg/a							6,2 M m³/a	11443 kg/a
Randfontein WWTW	2,38 mg/l			3807246 m³/a	9061 kg/a							3,8 M m³/a	9061 kg/a
Driefontein WWTW	0,17 mg/l			10810307 m³/a	1838 kg/a							10,8 M m³/a	1838 kg/a
Esther Park WWTW	0,96 mg/l					205288 m³/a	197 kg/a					0,2 M m³/a	197 kg/a
Northern Works	0,3 mg/l					147621538 m³/a	44286 kg/a					147,6 M m³/a	44286 kg/a
Kelvin PS	0,93 mg/l					2517711 m³/a	2341 kg/a					2,5 M m³/a	2341 kg/a
Hartbeesfontein WWTW	0,33 mg/l							19443082 m³/a	6416 kg/a			19,4 M m³/a	6416 kg/a
Olifantsfontein WWTW	1,42 mg/l							28601213 m³/a	40614 kg/a			28,6 M m³/a	40614 kg/a
Sunderland Ridge WWTW	1,86 mg/l							22082000 m³/a	41073 kg/a			22,1 M m³/a	41073 kg/a
Rietvlei Dam	0,26 mg/l							14400000 m³/a	3744 kg/a			14,4 M m³/a	3744 kg/a
Rietfontein WWTW	1,26 mg/l									2501583 m³/a	3152 kg/a	2,5 M m³/a	3152 kg/a
Total Point Source load kg/a	0,64 mg/l	0,1 Mm³/a	832 kg/a	20,8 Mm³/a	22342 kg/a	150,3 Mm³/a	46825 kg/a	84,5 Mm³/a	91846 kg/a	2,5 mm m³/a	3152 kg/a	258,3 Mm³/a	164997 kg/a
Total Phosphate inflow to HBPD		46,9 Mm³/a	1305 kg/a	64,7 Mm³/a	24696 kg/a	244,9 Mm³/a	157011 kg/a	152,9 Mm³/a	163401 kg/a	4,5 Mm³/a	3475 kg/a	513,9 Mm³/a	349887 kg/a

6 RESULTS

6.1.1 Overall situation

Table 6-1 contains the results of the base case calculation.

The total calculated load from the HBPD, using the values from Figure 5-2, is 349.8 ton/a. The total phosphate load calculated by the Harties Metsi-a-me programme, using the data for the Crocodile River at A2H012 is 344 ton/a as presented in a phosphate balance. This is about 0.3% less than the calculated sum of the load of the three sub-catchments, and well within an acceptable margin of error. The total current load for all sub-catchments entering the Dam can therefore be assumed to be about 349.8 ton/a as calculated by the base case calculation and is summarised in Table 6-1.

Table 6-1 Summary of phosphate loads emanating from the Hartbeespoort Dam Catchment

Catchment	WWTW		PO ₄ Diffuse Load	PO ₄ Natural load	PO ₄ Total Load	% Contribution
	Name	PO ₄ Load (kg/a)	(kg/a)	(kg/a)	(kg/a)	
Magalies	Magalies	832	86	386	1 305	0.37
Swartspruit+ Lower Crocodile catchment around dam		3152	323		3475	0.99
Upper Crocodile	Randfontein	9 061				
	Percy Steward	11 443				
	Driefontein	1 838				
	Total	22342	2029	325	24696	7.05
Jukskei	Esther Park	197				
	Kelvin P/S	2 341				
	Northern Works	44286				
	Total	46825	109861	325	157011	44.87
Hennops	Hartbeesfontein	6416				
	Olifantsfontein	40614				
	Sunderland Ridge	41073				
	Rietvlei Dam	-3 744	3 609			
	Total	91846	71306	248	163401	46.7
Total for Catchment		165000	183080	1 283	349887	100.00

6.1.2 Load distribution of phosphate between sub-catchments

Figure 6-1 indicates that the most of the load generated in the Hartbeespoort Dam Catchment emanates from two sub-catchments, namely the Jukskei and the Hennops which together represent 92.4% of the load. The other significant sub-catchment is the Upper Crocodile, which contributes 6.69% of the load. Together these three sub-catchments contribute almost 99% of the load.

The Magalies River is the less impacted sub catchment in the HBPD catchment and it is expected that the phosphate load from this catchment should be low. The Magalies WWTW contributes less than 0.55% of the flow to A2H013. Therefore, although the concentration of phosphate in the effluent is high, the contribution is very little.

The Crocodile River catchment contributes 7% to the total load. Decanting of mine water from the Western Basin is included in the flow from the catchment. A detailed analysis is included in the discussion of the use of AMD in a pre-impoundment.

The load emanating from the Jukskei River Catchment represents 44.8% of the load to the Hartbeespoort Dam. The Northern WWTW is the single largest contributor of load to the Jukskei River at A2H044 with approximately 44000 kg/a. However, the load from this area is dominated by diffuse sources. The diffuse load originating from overflowing and leaking sewers is a concern that needs special investigation.

The load from the Hennops River catchment represents 47% of the load entering the Hartbeespoort Dam. The largest contributors to the phosphate load in the catchment are the WWTWs which discharge to the Hennops River. The diffuse phosphate load is made up of the natural background phosphate and the load due to anthropogenic activities such as broken sewage lines, overflowing from pumps stations and runoff from dense settlements such as Tembisa. The broken sewer lines and non-functional sewer network contribute a major portion of the diffuse load in the catchment.

The area directly adjacent to the Hartbeespoort Dam contributes about 3.5% of the phosphate load. There are many private package plants in the area as well as golf courses which may contribute phosphate that has not been accounted for in this study. The inhabitants of the area are more aware of impacts of the over enrichment of the dam as they have experience some of the worst events of eutrophication due to drinking water restrictions and an embargo on water sport.

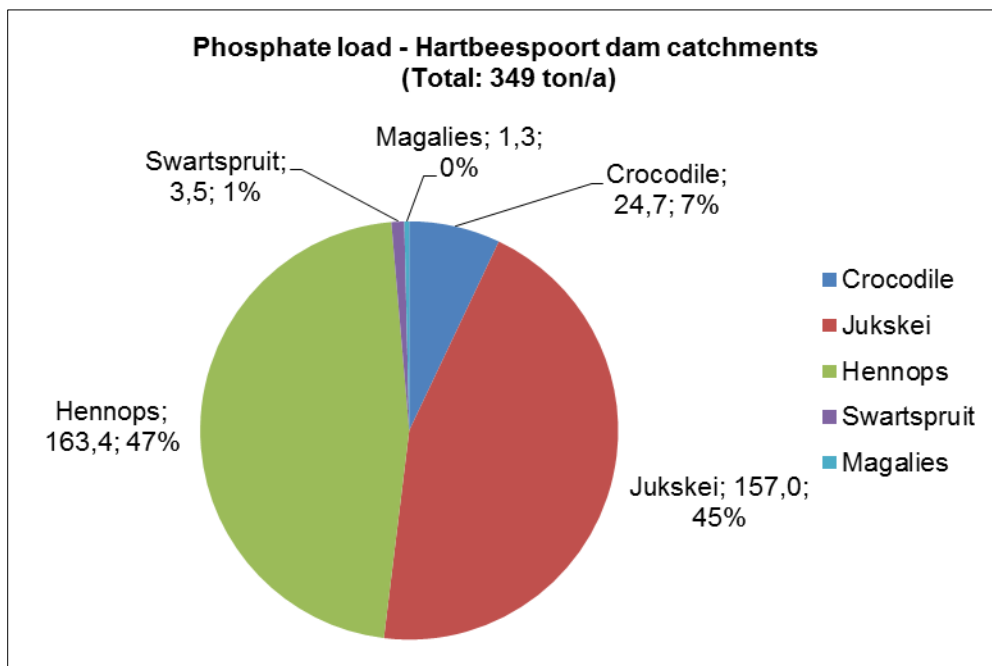


Figure 6-1 Load distribution (%) from the sub-catchments

6.1.3 Load distribution in sub-catchments divided between diffuse sources

Figure 6-2 illustrates the division between the phosphate load of point sources and diffuse sources. The load is almost equally divided between point sources (47.16%) and diffuse sources (52.84%), with the natural background contribution representing a negligible contribution. The contribution from diffuse sources is larger than from the point sources.

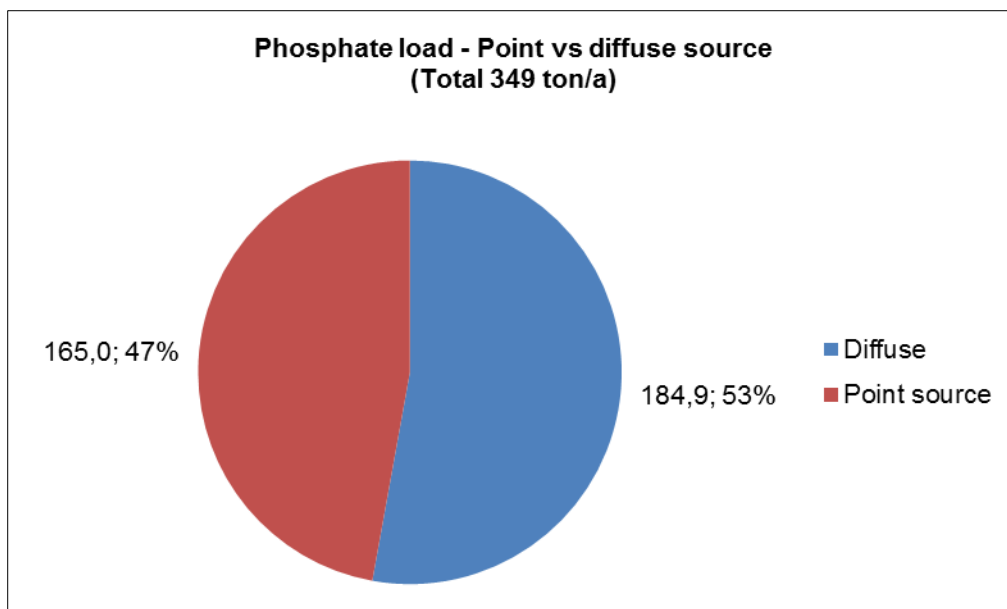


Figure 6-2 Division of phosphate load between point sources and diffuse sources

6.1.4 Phosphate load distribution between diffuse sources in total catchment

The diffuse sources can for all practical purposes be allocated to overflowing and leaking sewers and the contribution from informal settlements that have no sewer connections. These failures of infrastructure or inadequate infrastructure accounts for 99% of the phosphate load of streams entering the natural environment unintendedly. The associated flow is about 7% of the flow discharged by the point sources.

The percentage contribution as illustrated in Table 6-2 is difficult to verify either through the Green Drop System or through any form of monitoring (Van Veelen, 2015). The calculation in the base case is only indicative of what is currently perceived as a failure by local authorities to introduce preventative maintenance practices as opposed to break-down maintenance with constrained budget provisions for contingency plans.

Table 6-2 Diffuse source contributions

Diffuse source	Load (kg/a)	% Contribution
Additional runoff from hard surfaces	240	0.13
Leaking potable water supply	2 300	1.27
Leaking overflow sewers	178 766	98.32
Higher base flow	396	0.22
Irrigation return flow	190	0.10

6.1.5 Phosphate load distribution from point sources

Point sources contribute 165 ton/a to the phosphate load as shown in Table 6-3. Three waste water treatment works, namely Northern Works, Olifantsfontein and Sunderland Ridge together contribute 78.6 % of the point source load.

The majority of WWTW are higher than the 1 mg/l effluent standard for Phosphate. Northern Works stands out as one of the largest point sources but also has the best phosphate reduction record with an average of 0.3 mg/l Phosphate in the effluent. Modern technology and excellent operating management practices are contributing factors Green Drop System compliance still need attention like an all other WWTW's.

Table 6-3 Point source contributions

WWTW	Load (kg/a)	% Contribution
Magalies	832	0.51
Randfontein	9 610	6.93
Percy Steward	11 443	6.9
Driefontein	1 838	1.11
Esther Park	197	0.19
Kelvin P/S	2 341	1.42
Northern Works	44286	26.84
Hartbeesfontein	6416	3.89
Olifantsfontein	40614	24.61
Sunderland Ridge	44817	27.16
Total	164997	100

7 PHOSPHATE REDUCTION OPTIONS

7.1 Hartbeespoort Dam Phosphate balance

The base case study was calculated for a five year window of available data as discussed in previous sections. The situation investigated is an accurate reflection of history. In reality the flow is quite variable as indicated by the graph of average annual flow at Kalkheuwel over an eleven year period, where wet and dry hydrological cycles are as a result of higher mean average rainfall for 2009 and 2010. It is important to notice from Figure 7-1 that the phosphate load also followed the flow tendency, but not completely synchronised. The overall tendency is for an increase in phosphate load into the Dam. This can probably be explained by steady urban sprawl and urbanisation in the catchments which is clearly projected in the DWA reconciliation strategy where downstream needs for additional water will be through inter-basin transfer from the Vaal River through the Hartbeespoort Dam in the form of additional recycle effluent from WWTW. In reality flow is highly variable and unpredictable and there is an upward long-term trend (DWA, 2008).

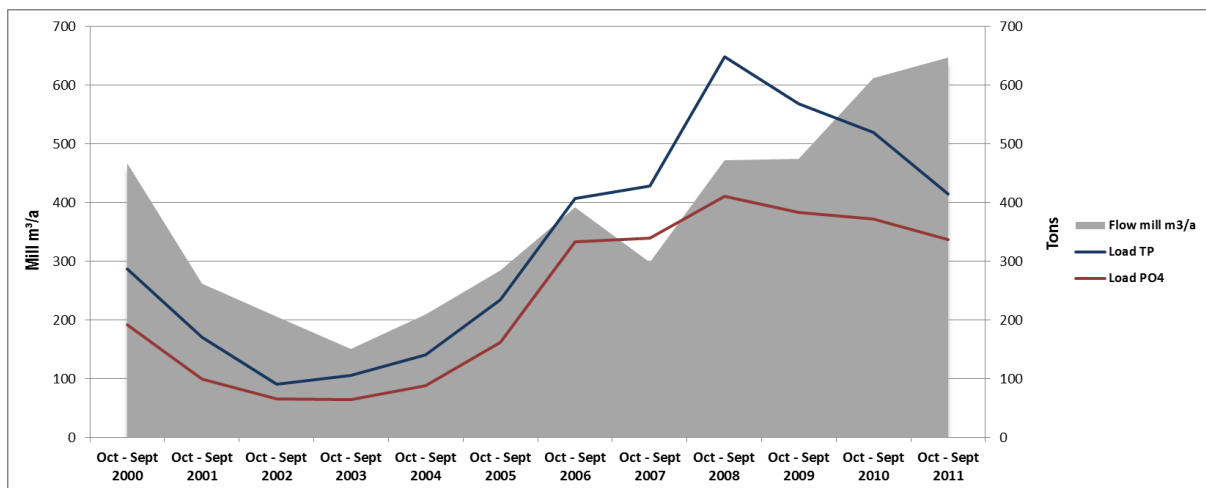


Figure 7-1 Flow at Kalkheuwel as measured at AH2012 with concentration of Total P and PO₄

The Harties Metsi-a-me programme prepared the rate of Phosphates entering the dam. The schematic illustration of a phosphate balance in Figure 7-2 is a summary of the total phosphates entering the dam over a two year period. The conclusion is that Dam acts as a nutrient trap, since about 30% of the phosphates entering the dam is released in the outflow. The 70% remaining in the dam is captured in the sediment from where it is released under favourable conditions to stimulate the growth of algal blooms.

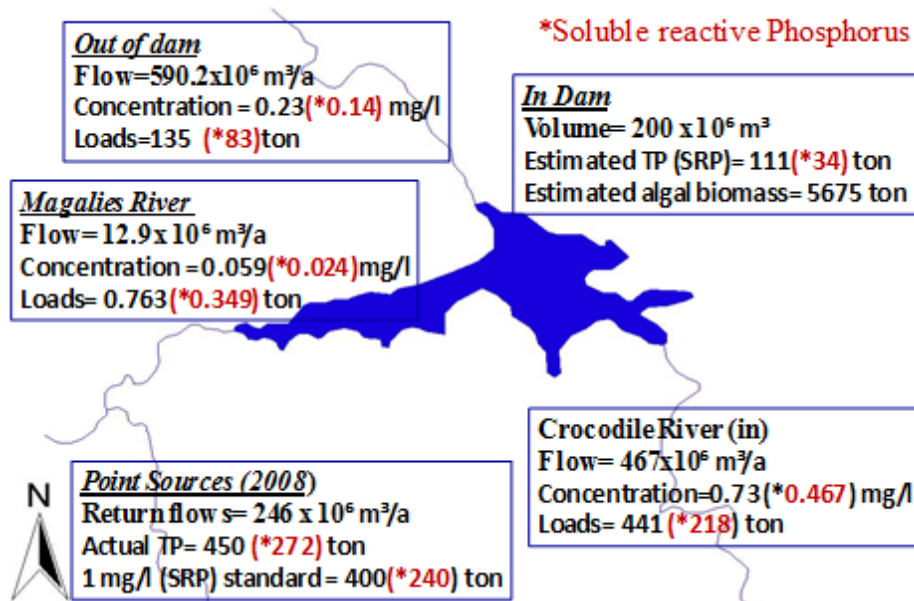


Figure 7-2 Summary of Phosphates entering the dam (WISA 2012 overview Phosphorous balance 2008/9))

To reduce the eutrophication status of the dam is an important objective to be achieved by the responsible authority that needs to appoint a Catchment Management Agency (CMA) as soon as possible.

7.2 Eutrophication capacity threshold

The HBPD catchment has been designated a special catchment in terms of the 1 mg/l phosphorous standard for effluent discharges to achieve the phosphorous load modification as predicted by the scientist in the 1985 study (NIWR, 1985). The objective was to manage the eutrophication level. As discussed in Chapter 2 eutrophication is the enrichment of water with plant nutrients which result in various symptomatic changes which can include the increased production of algae and aquatic macrophytes and the deterioration of water quality (Rossouw *et al.*, 2008).

Harding (2008) determined in order to manage the dam effectively the eutrophication capacity for the Hartbeespoort Dam needs to be determined. The eutrophication capacity refers to the capacity of the dam to assimilate phosphorus loads without trophic status thresholds being exceeded. The trophic status thresholds pertain to the phosphorus loading levels, translated into concentration of in-lake phosphorus, results in an observed increase in the frequency of problematic conditions such as algae blooms.

In the Hartbeespoort Dam the causes of eutrophication can be traced to cultural eutrophication which originate from point sources such as discharges from waste water treatment works and diffuse point sources such as run-off from informal settlements.

Nutrients can also be released from in-lake sources, a process referred to as internal loading. The rate at which nutrients are released from the bottom sediments depend on a number of physical processes such as re-suspension, mixing, bottom feeding fish and chemical process such as low dissolved oxygen concentrations (Harding, et al., 2004a:21).

In 1968 Vollenweider published his generally accepted thesis that the trophic state of a lake is connected to the phosphorous concentration of its water and that this influence exceeds all other eutrophication factors (Schneider *et al.*, 2008). Vollenweider's concept was later adopted, extended and refined by enlarging the data background of regressions derived from statistical analysis of measured data from various lakes. The Organisation for Economic Cooperation and Development (OECD) conducted a comprehensive study on 87 lakes. Based on these data, a classification scheme was established as shown in Figure 7-3 (Schneider *et al.*, 2008).

The threshold defining the boundary between the mesotrophic and eutrophic conditions in South African reservoirs has been determined as 55 µg/l (Harding, 2008) as indicated in Figure 7-3. In order to achieve this condition in the Hartbeespoort Dam, the estimated required load reduction would be >75% of the current aggregate load of 349,000 kg/a. Accordingly, the allowable load compared to the base case scenario, would be about 87,000 kg/a (Harding, 2008:23).

A reduction of >75% is unrealistic in the short to medium term due to the complexity of the potential reactions to a Phosphate modification strategy. A more realistic approach would be to manage the phosphate reduction while monitoring the results of eutrophication level in the dam. It is suggested that an interim target of 85 µg/l PO₄ be set.

Figure 7-3 indicates the OECD probability distribution of the boundaries for different trophic states (Schneider, *et al.*, 2008). In 1968 Vollenweider published his generally accepted thesis that the trophic state of a lake is connected to the phosphorus concentration of its water and that this influence exceeds all other eutrophication factors.

The probability distribution indicates a 50% probability that the hypertrophic state will become eutrophic at a phosphate level of 85 µg/l phosphate. This represents the cut-off between mesotrophic and hypertrophic, and is the median for eutrophic. It cannot be seen as ideal, but would result in some improvement in the dam. This results in an annual PO₄ load of about 110 ton/a, which implies a reduction of 238 ton. Currently the point sources contribute 52.8% (184 ton/a) while the diffuse load contributes 47.2% (165 ton/a).

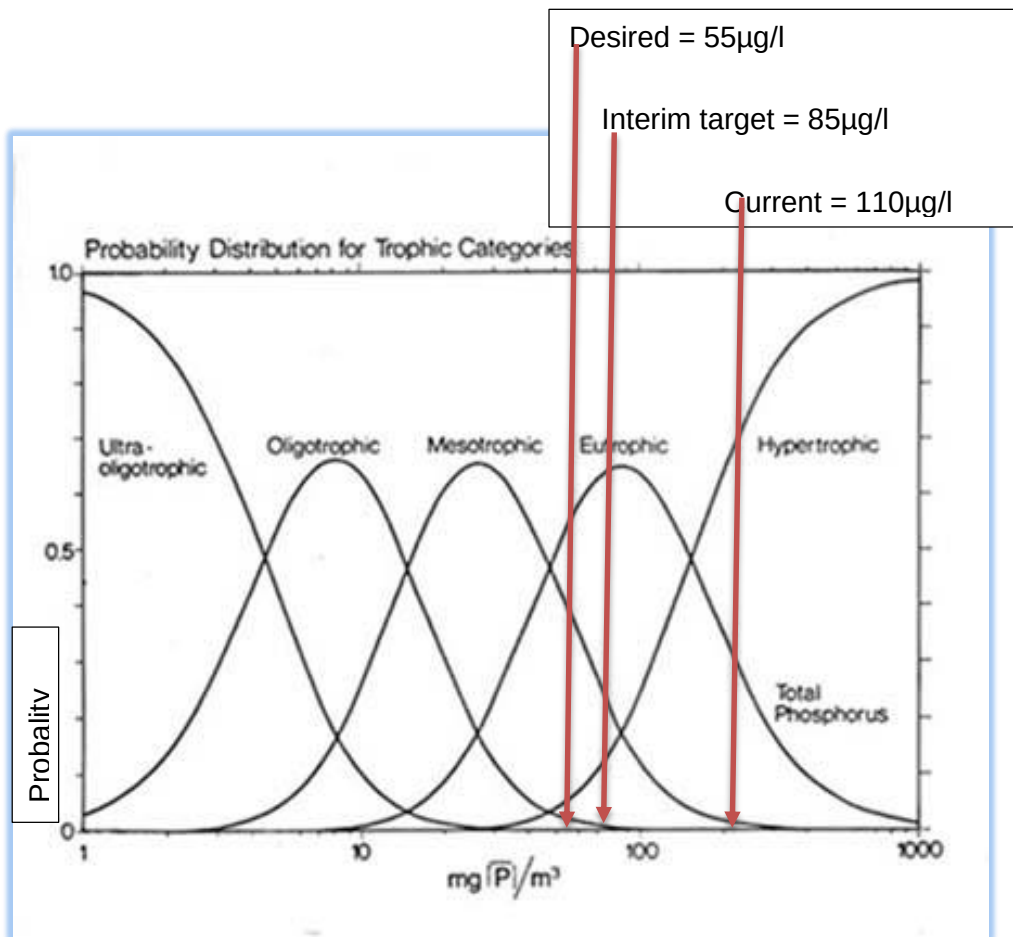


Figure 7-3 Optimal PO_4 concentration imposed on probability-based distribution of trophic status depending on phosphorous concentration (Rossouw *et al.*, 2008)

7.3 Phosphate reduction options

The phosphate load entering the Hartbeespoort Dam is without doubt entirely due to anthropogenic activities and emanates from the urban areas in the catchments. The most significant diffuse load is overflowing and leaking sewer systems, which will be difficult to prevent due to the diversity of situations in aging infrastructure and growing population in the catchment. Two of the point sources, Olifantsfontein and Sunderland Ridge WWTW are operating below what should be achieved and the contribution from these works is disproportional. The biggest flow is from Northern Works, which is adding a dilution factor to the flow. Any malfunction of facilities at Northern Works may have serious consequences for the Hartbeespoort Dam which is already burdened by untreated sewage from diffuse sources.

Phosphorous load modification is the most common method of eutrophication management employed (NIWR, 1985). The current load will have to be reduced by about 80% which means a reduction in total phosphate of about 280 ton/a.

7.4 Acid Mine Drainage

7.4.1 Background

Since August 2002, the first decanting of water from the flooded gold mines of Krugersdorp and Randfontein, collectively referred to as the Western Basin mine void, started to occur (according to an unpublished report in 2007 by African Environmental Development).

The water, decanting from a disused mine shaft, flowed through the Krugersdorp Game Reserve and entered the underlying dolomitic aquifers in the Zwartkrans Compartment.

During this mining process, water was pumped from the mine workings into the streams feeding the dolomitic aquifers via the Tweelopiespruit. This pumping continued until around 1998, when a final decision was made to stop the last pumping operations at Harmony's Central Ventilation Shaft and allow the mine void to flood.

For the next four years the mine void gradually flooded, until 2002 when the water in the mine void finally reached the surface and started to decant into the Tweelopiespruit, upstream from the Krugersdorp Game Reserve as shown in Figure 7-4.



Figure 7-4 Decanting ventilation shaft near Tweelopiespruit

Initially the water decanting from a dolomitic borehole was of a relatively good quality. However the volume decanting from the mine void increased progressively while the quality of the decanting water decreased.

The mine water flowed freely down the Tweelopiespruit till it crossed a geological fault and within a few hundred meters, all the surface flow in the stream is lost into the dolomitic aquifer of the Zwartkrans Compartment.

The Tweelopiespruit forms part of the catchment of the Blaauwbankspruit, which, in turn, is a tributary of the Crocodile River upstream from the Hartbeespoort Dam. This system forms part of quaternary catchment A21D. This catchment has a surface area of 371,584 km², a mean annual precipitation of 713.7 mm/a and a reported mean annual run-off into surface streams of 56.3 mm/a. (WR2005 tables). Figure 7-5 indicate where the catchment area is situated in the Western Basin.

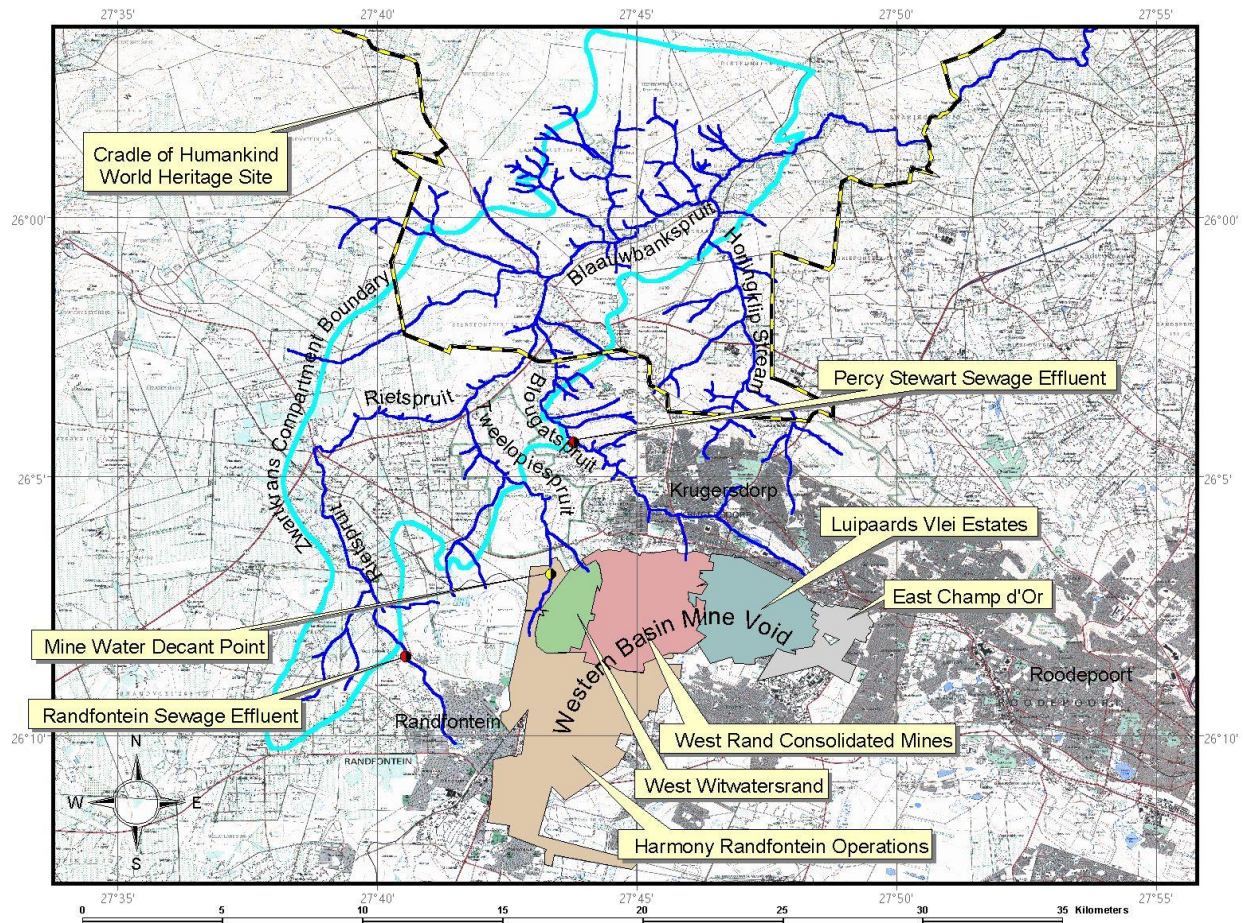


Figure 7-5 Catchment of the Blaauwbankspruit with the approximate extent of the Western Basin (African Environmental Development, 2007)

The initial drainage rate (August 2002) of 4 to 8 ML/d slowly increased to a relatively constant 25 ML/d by mid-2008 as the hydrostatic head in the flooded mine void continued to build. The establishment of containment structures and a high density sludge treatment plant with a capacity of 15 to 20 ML/d attempted to control the Acid Mine Drainage (AMD) by neutralising it as it decanted from various point sources (shafts and boreholes). Although successful in curbing the release of raw mine water into the environment, the treated and neutralised mine water still carried concentrations of sulphate >2500 mg/l and, whilst

maintaining a near-neutral pH in the downstream receiving stream reaches. More recently, such as during the abnormally wet 2009-2010 and 2010-2011 summer seasons, the combined discharge of treated/neutralised and raw mine water has on occasion exceeded 60 Ml/d (Hobbs & Cobbing, 2007), with acidic raw mine water (pH 3) comprising 75% of this volume. The main result of these circumstances has been the manifestation further downstream of acidic surface water (pH 4), threatening the ecological sensitivity of the receiving environment, the Cradle of Humankind World Heritage Site and the Hartbeespoort Dam.

The annual inflow of dissolved phosphate before 2000 was estimated at 20 ton as P, while that associated with incoming sediment, at 180 ton as P. Since then the inflow of phosphate has significantly increased (Maree *et al.*, 2015).

The sulphate concentration in the outflow of the dam has remained constant at 50 mg/l during the period 2002 to 2011, when mine water started to decant in the Western Basin. It is speculated that mine water was probably trapped in an underground karst aquifer and replaced good quality groundwater until the aquifer became saturated during 2014 as indicated by an increase in the sulphate concentrations in the Blaauwbankspruit from 100 to 430 mg/l during November 2014.

7.4.2 Potential use of decanted mine water

Phosphate concentration levels needs to be lowered to 0.05 mg/l or less to control eutrophication. Chemicals such as Fe(III), Fe(II), Aluminium(III) and lime can be used to precipitate phosphate as FePO_4 , $\text{Fe}_3(\text{PO}_4)_2$, AlPO_4 and $\text{Ca}_3(\text{PO}_4)_2$ respectively. Mine water rich in Fe(II) would be the most cost-effective solution. The option to apply decanted mine water to reduce phosphate load in the inflow to the Hartbeespoort Dam needs to be investigated further.

In the case of phosphate removal with iron-rich mine water, originating from the growing AMD issue in the catchment, the following two options can be considered (Maree & Mitchell, 2015):

- (a) In-dam phosphate reduction: Install a floating clarifier in the pre-dam at the mouth of the Crocodile River. The floating clarifier could consist of light-weight geotextile, plastic or steel sheets, suspended from a floating support system. Clarified water would be allowed to flow over the weir of the floating clarifier. Settled Fe_3PO_4 and other

suspended solids will be removed from the floor of the dam via periodic dredging in the vicinity of the floating clarifier.

- (b) In stream phosphate reduction: Dose H_2SO_4 and iron-rich mine water in the Crocodile River downstream from the Northern Works to lower the pH to between 6 - 6,5 and precipitate phosphate as FePO_4 .

The Western Basin AMD decants uncontrolled at a flow rate of 10–60 Ml/d. This water has a pH of 3.2 and contains mainly Fe(II) and free acid.

In 1983, the idea was evaluated to use acid mine water for removal of phosphates from sewage effluent (Van der Merwe et al., 1983:156). The basic concept was successfully tested by treatment of acid mine drainage in the Rondebult sewage purification plant. By extrapolating the concept to a new idea, to use acid mine water to treat effluent from the sewage treatment plants draining into the Crocodile River, an option was envisaged that could perform in-stream chemical fixation of phosphate at a reasonable cost.

Option (a) and (b) are illustrated in a conceptual flow diagram, Figure 7-6 where a pipeline of about 50 km length conveys raw mine water at a rate of between 5-15 M/l per day for treatment of water in Crocodile River near Kalkheuvel.

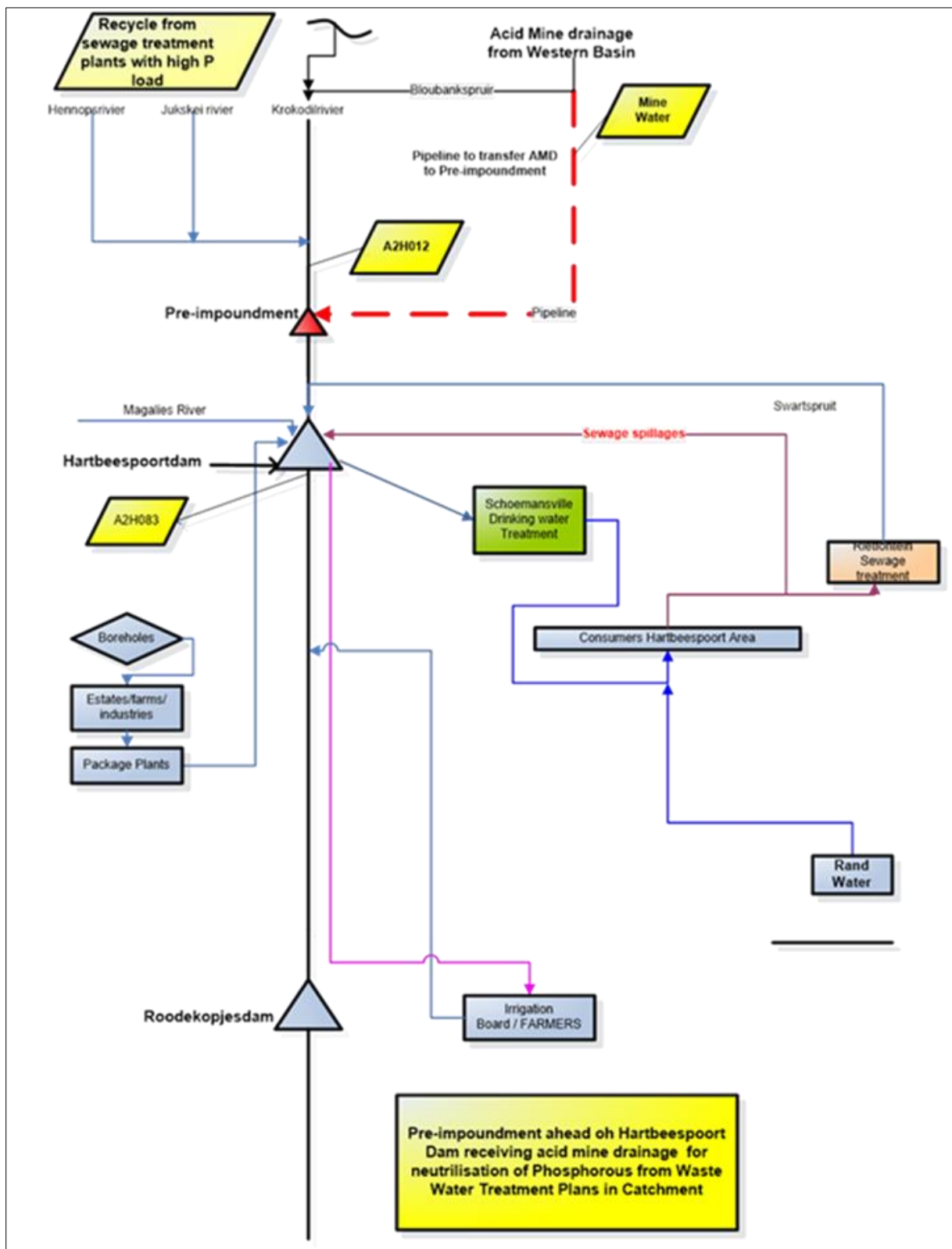


Figure 7-6 Flow diagram indicating acidic mine water flow to Crocodile River

The feed water to the Hartbeespoort Dam amounts to an average of 255 Mm³/a, mainly treated sewage (between 640 and 740 Ml/d). Table 6-1 is the base case to illustrate the calculation of phosphate load originating in the catchments between 2006 and 2011. The annual inflow of dissolved phosphate is estimated at 280 ton/a as ortho-phosphate (SRP), which is about 80% of the total phosphate. The rest is phosphate associated with incoming sediment.

7.4.3 Environmental chemistry for fixating phosphate with mine water

Mine water from the Western Basin, containing 400 mg/l Fe(II), can be pumped to the pre-impoundment ahead of the dam. The FePO₄ reaction must be stimulated by mixing of the reactants with proper aeration, to allow for precipitation of phosphate as FePO₄ and Fe₂(PO₄)₃. The reactor needs to be specially designed for the purpose.

The precipitate can be allowed to settle in the pre-impoundment dam, followed by removal together with sediment in a dredging operation. A pilot dredging test was done as part of Metsi-a-me programme (Cukic & Venter, 2012:42-47) and the concept can potentially be adapted to this proposal.

Mine water has to be piped to the dosing point to prevent iron precipitation, if allowed to flow in an open system together with the flow of treated waste water from the WWTW in the Upper Crocodile system. Alternatively mine water can also be pumped to the various waste water treatment plants in the catchment of the dam as a scenario to compare the relative costs before final design.

Preliminary calculations based on the assumption that Fe(II) is dosed from mine water containing 400 mg/l Fe(II), in between 5-15 Ml/d of mine water, will be required.

At a flow-velocity of 3.3 m/sec, a 150mm diameter pipe will be required to transfer the mine water. The capital cost for transferring mine water from the Western Basin to the dam is estimated at about R4.5 million.

This is a once off cost and provision only needs to be made for piping since water will flow downwards along with existing water ways. The addition of 5 Ml/d mine water to about 640Ml/d inflow into the dam water, will probably result in an increase of sulphate (from the current 60 mg/l to only 86 mg/l), Calcium will probably increase from 38 to 41 mg/l. The increases in other parameters are negligible.

Implementation of a phosphate reduction strategy in pre-impoundment with mine water has not been fully developed yet. The essential points for further study have been identified from a preliminary study (Maree & Mitchell, 2015):

- (a) Phosphate needs to be removed to a concentration less than 0.05 mg/l to control eutrophication (the eutrophication capacity threshold). Chemicals such as Iron (III), Iron (II), Aluminium (III) and lime can be used to precipitate phosphate as FePO_4 , $\text{Fe}_3(\text{PO}_4)_2$, AlPO_4 and $\text{Ca}_3(\text{PO}_4)_2$ respectively. Mine water rich in Fe(II) is potentially a low cost option to reduce phosphate. A cost benefit analysis has to be done in future.
- (b) In order to achieve the necessary transfer of reactants and enable the reaction it will be important to design facilities to transfer mine water by pipeline from the mine water outflow to the Crocodile River with the aim to precipitate phosphate in the feed water to the dam as FePO_4 . Rapid mixing between the feed water of the dam and the iron-rich mine water will be required. (A detailed design needs to be done after further research.)
- (c) Suitable dosing points will be in the Crocodile River downstream of the junction of the Jukskei River and Hennops River at the mouth of the Crocodile River into the Hartbeespoort Dam. The addition of about 5 Ml/d mine water to about 650 Ml/d inflow water at Kalkheuvel must be done through a mixing device to achieve proper contact between reagents and for adjustment of pH to sustain the reaction at the optimal pH range of about pH 6. (Zhang, 2010). Since the sediment contains precipitated FePO_4 , sediment removal through a low cost dredging system, as was tested by the Harties Metsi-a-me programme (Cukic and Venter, 2012:42-47) could be considered. Predicted result is an increase in sulphate in the Hartbeespoort Dam from the current 60mg/l to a slightly higher level of about 80 to 90 mg/l (Maree, 2015).

7.5 Pre-Impoundment

7.5.1 Background

The vision of the Harties Metsi-a-me programme (DWAF, 2007) is the restoration of the Hartbeespoort Dam ecosystem to a level where it will result in increased levels of ecosystem services derived from the HBPD including the quality of potable and irrigation water, fishing, recreational use and ecotourism.

Modelling of phosphate load reduction to attain an in-lake mesotrophic/eutrophic boundary was done by the DH Environmental Consulting model that calculates the time related change of phosphorous concentration in a lake as a result of phosphorous input variation according to Harding (2004a:27-36).

The use of models to predict phosphorous load modifications were also applied in the "Limnological study of the Hartbeespoort Dam" 1985 study (NIWR, 1985). These models have not been subjected to rigorous (load versus response) testing under South African conditions and provide a generalised indication of lake response to nutrient loading. The conclusion from modelling is that long term reduction in external loading necessary was >60% to achieve sustainable and acceptable (algal bloom free) management of the reservoir.

The Metsi-a-me programme has set an objective to limit the available phosphate within the Hartbeespoort Dam to such an extent that eutrophication is manageable: It is envisaged by Venter, (2012:21) that the strategic objective would be achieved by "the reduction of the internal nutrient load through sediment dredging and its beneficiary uses as well as the reduction of the external nutrient load, including improved catchment management and the formation of a barrier between the dam and the catchment". A pre-impoundment intervention is one of the options to achieve the objective as it will provide capacity to remove phosphate ahead of the dam.

The simulation study described in 2.6.1 (Twinch & Grobler, 1986) indicates that a pre-impoundment would be of limited effectiveness due to the heavy load of soluble ortho-phosphate released by waste water treatment plants and that pollution prevention in the catchment was more economical. This assumption may have been overoptimistic judged by the steady increase of phosphate load even after implementation of the 1 mg/l P standard in 1989.

The Harties Metsi-a-me programme considers the reduction of external phosphate load for the Hartbeespoort Dam as an integrated plan of potential projects that need to be prioritised on a cost benefit basis (Cukic & Venter, 2012:42-47).

Due to the complex nature of the independent variables, the main objective is to reduce the phosphate load at the inlet to the dam to prevent hyper-eutrophic conditions developing within the dam, which cyclically result in algae blooms with accompanying toxin production and odours problems.

The most important nutrient reduction options outside the Dam that have been considered as part of the Metsi-a-me programme are the following (Harding, et al., 2004b:36):

- Upgrading of waste water treatment plants.
- The implementation of stricter phosphate discharged standards.
- Stricter control of point source pollution, including industrial effluent.
- Improved control of non-point sources of pollution.
- Improved management of numerous municipal dams and other retention dams that exist within the Crocodile River catchment.
- The revival, restructuring, protection and management of natural treatment systems (wetlands, shoreline and in-stream aquatic ecosystems, etc.) which retain and absorb nutrients.

7.5.2 Pre-impoundment as phosphate reduction option

The ability of water bodies to retain a substantial portion of the incoming phosphorus load is well known (NIWR, 1985). The theoretical possible phosphorus load reduction that could be expected if a pre-impoundment dam with various capacities were to be constructed in the Crocodile River Arm of the Hartbeespoort Dam was calculated to be:

- With no pre-impoundment wall but with main dam at full supply level (FSL) the annual average retention of phosphate in the Crocodile River Arm was about 17 – 28%.
- A pre-impoundment at 5m height at FSL increases the phosphate retention to 31 – 37%
- With increasing pre-impoundment dam wall at 10m height, phosphate retention increased to a maximum of 60 - 63% at FSL+10 m.

This (FSL+10m) pre-impoundment dam will have a volume of $26 \times 10^6 \text{ m}^3$ (about 10% of the full supply volume of the Hartbeespoort Dam), a mean depth of 8.2 m and a surface area of 322 ha, based on existing morphometry of the Crocodile River Arm.

From the above it can be concluded that even the lowest of pre-impoundment dam walls will reduce up to 28% of the phosphorus load (Twinch & Grobler, 1986). This phosphorus reduction is most probably due to the settling of suspended inorganic particulate phosphate, e.g. sand and clay and some phosphate consumed in biochemical reactions (Withers, 2008). The further reduction of phosphate load when the pre-impoundment wall is increased is most probably due to soluble phosphate that is converted to biomass of which a major

fraction eventually settles as an organic sludge, similarly to what is presently be happening in the Hartbeespoort Dam.

Unless the settled material (both the organic sludge and inorganic silt) is periodically removed, this trapped phosphorus will eventually accumulate to such a degree that especially the organic sludge will be flushed into the Hartbeespoort Dam.

If this type of pre-impoundment is considered, periodical emptying and cleaning up will be essential.

By capturing the phosphorus-rich particulates will not only reduce the phosphorus load to the dam, but will also prevent any phosphate-rich inorganic sediment built-up in the Hartbeespoort Dam.

Pre-impoundment as a possible phosphate load reducing option should seriously be considered to achieve at least a 28% reduction (about 90 ton/a) which is about the same as implementing the zero phosphate detergent concept as in 4.4.2 above.

7.6 Potential strategies for phosphate reduction in catchments

7.6.1 Waste discharge charge system

The above mentioned strategic options all have merit and should be mandatory to achieve the resource quality objectives envisaged by the appropriate regulations in the National Water Act, Act 36 of 1998. The NWA established a foundation for the introduction of catchment management agencies.

7.6.1.1 Legal context

In order to determine the basis for management of a catchment a system for classifying water resources was authorised in section 12 to 15 of the NWA. The classification forms the basis for water quality control as it forms a basis for the establishment of clear goals relating to the quality of the South African water resources. Section 19 enables the necessary tool for pollution prevention measures and section 20 contains control measures for managing emergency incidents (Barnard, 1999). Section 19 is based on the pollution prevention measures in the 1956 Water Act.

This act was amended in 1993 by introducing a section that authorised the Minister to take steps to avoid pollution and to demand reimbursement of the expenditure. A novelty was introduced in this section by creating a category of people from whom reimbursement could

be claimed. The polluters who are accountable are people that benefited directly or indirectly from the failure to prevent the pollution. Companies could be made liable for cleaning up of environmental degradation caused by their impecunious (poor) subsidiary companies. Section 19 of the National Water Act 36 of 1998, retains most of the old section 22A of the Water Act 1956 as amended in 1993. This amounts to the “polluter pays” principle, which is known as the Waste Discharge Charge System.

The WDCCS aims to:

- promote the sustainable development and efficient use of water resources
- promote the internalisation of environmental costs by the transgressor
- create financial incentives for dischargers to reduce waste and use water resources in a more optimal way
- recover the costs of mitigating water quality impacts of waste discharge

7.6.1.2 Implementation bottlenecks

Implementing the Waste Discharge Charge System has been studied by industry, consultants and institutions since 1999 without reaching consensus about the way it should be implemented. Pollution control in the Hartbeespoort Dam catchments has been used as a case study by Iliso Consulting for DWA (Van Veelen,2013). Van Veelen, discussed his perception in a personal interview about the WDCCS on 27 May 2014, at the WISA Conference in Nelspruit. It was thought that the National Treasury and Department of Water and Sanitation (DWS) have not agreed on implementation guidelines and a schedule for implementation.

Without debating the administrative detail to enforce the WDCCS it is important to note that the process will facilitate the strict objective to achieve the resource quality objectives as foreseen in the NWRS2. Some points of interest to the catchment of the Hartbeespoort Dam include:

- (a) Charges will be levied based on loads e.g. the flow multiplied by the concentration of a licensed pollution load.
- (b) Waste discharge charges are only applicable for controlled and authorised discharges (for example overloading or failed sewage systems will not be subjected to a charge but should be disincentives through a fine or penalty).
- (c) Charges will only be levied where there is a deviation from permit standards.

- (d) The receiving water quality objective (RQO) will be used as the basis – if the river's RQO is exceeded or threatened by a discharge then it will be charged.
- (e) Only registered users will be charged under the system.
- (f) Roll out of the WDSCS will be tested in priority catchments e.g. Hartbeespoort Dam.

7.6.2 Green drop initiative

The Green Drop initiative that was launched in 2008 by the Department of Water Affairs to provide a continuous assessment of waste water quality and improve poor-performing waste water management services. The most recent Green Drop assessment was released in 2011 and indicated that all of the waste water treatment plants in the catchment of the Hartbeespoort Dam reached Green Drop status by 2011 except the Rietfontein plant in Hartbeespoort Dam that drains into the Swartspruit 1 km from the inlet to the dam.

On paper the perception is created that the Green Drop System is an effective incentive scheme to motivate improved performance of units as well as reducing risks of untreated or insufficiently treated sewage to pollute the natural environment. However, a major concern in South Africa is the aging infrastructure and overload of sewage collection systems. The result is periodic releasing of raw sewage into the country's rivers. (The writer has first-hand experience in this regard with his personal involvement in HWAG and initiatives of the Hartbeespoort Inhabitants Forum to constructively engage with Madibeng Local Authority and the Green Scorpions). The potential load of sewage spills related to leaks is estimated to be 99% of the diffuse phosphate load. This clearly emphasise the importance of infrastructure maintenance of sewage collection systems to reduce diffuse loads.

7.7 In-stream pollution control: External Phosphorous load

7.7.1 Theoretical background

Urbanisation has led to increased phosphate enrichment of surface waters causing a range of environmental, social and economic problems in the catchments associated with eutrophication. Rivers are particularly vulnerable due to their proximity to population centres. Rivers are also the obvious channel for conveyance of diffuse loads.

It was observed (Withers *et al.*, 2008), that phosphate load studies of rivers have shown that phosphate fluxes entering rivers do not correspond with those measured at the reach or catchment outlet and that P tends to be retained within river systems, particularly under low flow periods. The river is the channel conveying pollutants and may be stagnant, slow flowing or fast flowing. This can be interpreted that there is a risk of eutrophication

developing in a river system. Withers *et al.* concluded: “Phosphorus retention in rivers occurs as a result of a combination of biogeochemical and physical processes which temporarily remove and/or transform P during downstream transport allowing opportunity for biotic and abiotic assimilation”. Figure 7-7 is a conceptualised diagram of in-stream processes influencing phosphate concentrations in flowing waters, as postulated by Withers. The key deduction from the study (Withers *et al.*, 2008) is that: “Retention therefore provides two key ecosystem functions: (a) allows nutrient-poor pristine and upland streams to develop and sustain a productive community and (b) buffers the impacts of anthropogenic P inputs on downstream communities during the critical summer period by temporarily removing P (i.e. a damping effect) ”.

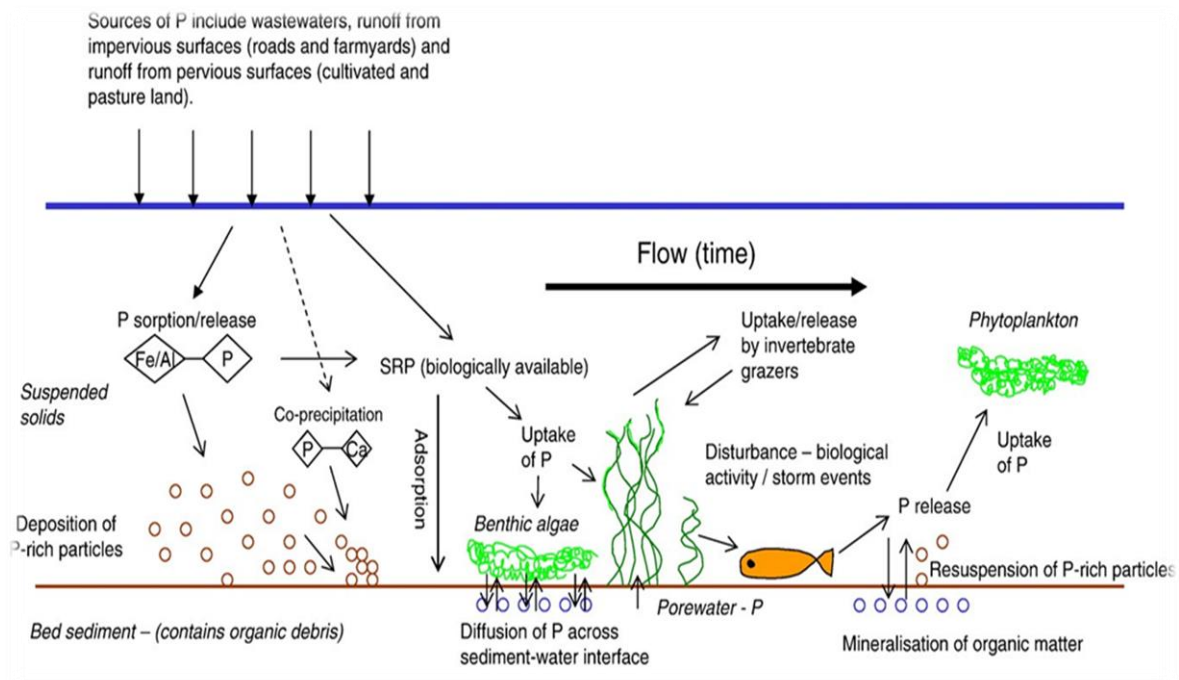


Figure 7-7 Conceptualised diagram of in-stream processes influencing P concentrations (Withers, 2008)

These observations provide a useful insight to what is probably happening with phosphates that enters the natural environment as effluent from a WWTW. The form of phosphate, e.g. soluble reactive phosphate (SRP) and how it reacts in the aquatic environment as presented in Figure 2-5 as the Phosphorous Cycle.

Researchers (Withers *et al.*, 2008) reports that: “50% of the SRP load could be removed during spring in the River Frome, England due to biological uptake”. It can be deduced that in the case of a natural wetlands (which acts like a sponge by holding water and keeping rivers at normal level), the phosphate removal could be more efficient since it is a retention

area where these aquatic chemical processes can occur to complete the phosphate attenuation steps.

The concept of a pre-impoundment can be linked to the concept of in-stream processes influencing the phosphate removal from flowing waters. The pre-impoundment is considered to be a form of in-line flow equalisation.

7.7.2 Strategic focus areas

Chemical removal of part of the phosphorous in the Crocodile River inflow to the dam is a positive approach to ensure that phosphorous is controlled within the constraints of a specific design concept.

There needs to be a barrier between the catchment and the Hartbeespoort Dam where at least 60% or more of the external total phosphate load can be retained and removed.

A combination of two approaches, namely direct influx control and the regulatory process could be an optimal strategy for the long term management of phosphate load to the Hartbeespoort Dam (Harding et al., 2004b:36).

An integral part of this strategy is the formation of a barrier (referred to as the “pre-impoundment” or “pre-dam”) which could reduce that part of external total phosphorous load and sediment load to the dam that cannot be successfully controlled. The philosophy is that such an intervention would be based on engineering principles that are not dependant on human actions, climatic conditions and regulatory control processes.

7.8 Options to reduce part of total external phosphorous load

Chapter 5 provided a useful tool in the sense of phosphate load calculation model in the catchments of the dam. The question is: How can the phosphorus concentration be reduced to change the eutrophication status of the dam to become at least mesotrophic? Options that have been mentioned in scientific studies (Harding et al., 2004b; Van Ginkel, 2011) should be explored.

7.8.1 Stricter phosphorus standard for treated sewage

As indicated earlier, about 47% of total phosphate load entering the dam comes from sewage works. This does not represent sewage leaks which enter from diffuse sources in storm water. The implementation of a stricter phosphate standard would be an obvious strategy. The sensitivity of the phosphate standard could have a multiplying effect as this

could also motivate municipalities to improve infrastructure for sewage collection. The implementation of the WDCS on WWTW in addition to the Green Drop System will be a major breakthrough.

The problem with this approach is however that:

- (a) In the present political climate the existing special phosphorus standard of 1mg/l is very poorly enforced in the catchment area (Green Drop System, 2011). Therefore, the chances that a stricter standard will be enforced are about dubious.
- (b) Up-grading of WWTW to include the latest technology such as Enhanced Biological Phosphorous Removal (EBPR) will be very capital intensive. Several options of EBPR approach has been implemented worldwide and can achieve a phosphorous standard of 0.3 mg/l (Wentzel *et al.*, 2008).
- (c) The maintenance of sewerage systems in some of the major municipalities is very poor (personal observation in Hartbeespoort). Even with the relative small rain storms, many main sewers overflow with the result that raw sewage directly enters the storm water drains. Leaking and overflowing sewers contribute nearly 99% of the diffuse phosphate load in the catchment.
- (d) There still exist plenty of unsewered informal settlements that contribute to pollution of natural run-off.
- (e) Package plants and private sewage treatment facilities in security estates are unknowns which need to be properly managed and controlled.

Unless these problems are addressed, which are unlikely in the near future, the implementation of a stricter phosphate standard would not be a reliable and sustainable solution.

7.8.2 Replacing phosphate in detergents

The implementation of phosphorus-free detergents has been successful in e.g. Finland (Harding *et al.*, 2004a). A recent investigation into the consequences of zero phosphate detergents in South Africa (Quayle *et al.*, 2010) concluded that the impact of zero detergent phosphate on the Hartbeespoort Dam would be a potential reduction of 26% in-dam TP.

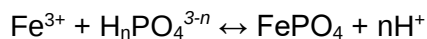
Similarly a reduction in chlorophyll- α concentration due to elimination of detergent phosphate could be as high as 22% in the Hartbeespoort Dam. Water treatment cost savings with the reduction in algal blooms can also be expected although relatively small.

The report further determined that the proportional contribution of detergent phosphates to the total phosphate loading of the Hartbeespoort Dam was 28.1% of the total phosphate loading. The total phosphate load in their assessment namely, 321 ton/a, is close to the 350 ton/annum calculated in Table 6-1 of this study. Their assumption is that a 26% or about 91 ton/a reduction of total phosphate load in the dam could be achieved, once the zero phosphate detergent concept is strictly enforced.

Whether or not phosphorus-free detergents are used, the problem with law enforcement both at the detergent industry and sewage works still exists.

7.8.3 Chemical fixing of all or part of the phosphorus in the Crocodile River

Chemical removal and recovery of phosphorus by ferric chloride or sulphate are widely used in WWTW for phosphate removal from waste water (Storm, 2006) and (Leopold and Freese, 2009:27). The basic reaction is:



Ferric ions combine to form ferric phosphate (Lentech, 2015). The Fe and phosphate react slowly with the natural alkalinity and so a coagulant aid, such as lime, is normally added to raise the pH in order to enhance the coagulation.

The model described in Chapter 5 has been applied to determine a base case scenario of phosphate load distribution in the catchments of the dam. Table 8-1 indicates that 345 ton/a total P is present at Kalkheuwel. Of this 80% or 276 ton/a soluble reactive phosphorous (SRP) is available for reaction in the Crocodile River at Kalkheuwel. It is assumed that the SRP at this point has not been reduced due to any in-stream removal action.

Under ideal conditions, as determined by the appropriate reaction kinetics (Zhang, 2010) it is possible to chemically fix the phosphorus of the total Crocodile River inflow. For an 80% removal efficiency of phosphorus with ferric sulphate (6 mg/l Fe) as flocculent, the estimated cost in 2004 was R6.5 million per annum (Harding *et al.*, 2004b:37-58). This excludes the capital cost for a phosphorus elimination plant (PEP).

Apart from the fact that the dosing of a chemical has the same reliability drawbacks than the operation of a sewage works, it is critical to design a system that will have an appropriate degree of reliability to ensure the protection of a sensitive eco-system once the target eutrophication level has been achieved.

An example of such a process (PEP) is illustrated by the phosphate elimination plant at the Wahnbach Reservoir in Germany (Bernhard & Clasen, 1982; Clasen & Krämer, 2002).

By setting an objective that 100% of ortho-phosphate in the stream should be removed from the Crocodile River by an intervention which still have to be designed, a calculation has been done to determine how much FeCl_3 salt would be required to reach the objective. It is possible to chemically fix the phosphorus of the total Crocodile River inflow.

For an 80% removal efficiency of phosphorus with ferric salt (6 mg Fe/l) as flocculent, the estimated cost in 2004 was R6.5 million per annum (Harding et al. 2004b). In-lake and in-stream phosphorous management attenuation options according to Harding (2004b:37-45). Apart from the fact that the dosing of a chemical treatment process has the same reliability drawbacks than the operation of a sewage works, the question can be asked if it is wise from a water quality point of view to exchange one chemical (phosphorus) for another chemical (chloride or sulphate).

Chemical fixation of phosphorus is a possible option. However due to concerns associated with flocculent availability, reliability of dosing, and costs, chemical fixation should be considered in conjunction with other phosphorus removal methods.

Table 7-1 Calculation of phosphate load at Kalkheuwel that needs to be reduced

	P (con.)	to treatment plant				not treated				TOTAL				
		Crocodile/Jukskei/Hennops				Magalies/Swartspruit/HBPD								
		unit		A21F/G	units	Load	units	A21D/E	units	Load	units	units		Load
Area														
Urban area			827	km²			12,18	km²			839,18	km²		
% of catchment area			98,5%	%			1,5%	%			100,00%			
% urban area within HBPD catchment								%			0,000%	%		
Total Catchment area Km²(WR2005)			2431	km²			1686	km²			4117	km²		
Diffuse flow														
Catchment irrigated km²			36,94	km²			135,56	km²			172,5	km²		
% of catchment irrigated				%				%						
% irrigation of total catchment				%				%						
Irrigation return flows each m³/a	0,01	mg/l	2355595	m³/a	24	kg/a	8644406	m³/a	86	kg/a	11,0	Mm³/a	110	kg/a
Return flow due to gardens & parks	0,1	mg/l	19534313	m³/a	1953	kg/a	307366	m³/a	31	kg/a	19,8	Mm³/a	1984	kg/a
Additional urban run-off m³/a	0,01	mg/l	23628218	m³/a	236	kg/a	371783	m³/a	4	kg/a	24,0	Mm³/a	240	kg/a
Leaking potable water supply	0,046	mg/l	49225454	m³/a	2264	kg/a	774546	m³/a	36	kg/a	50	Mm³/a	2300	kg/a
Leaking overflow sewers	10	mg/l	17851557	m³/a	178516	kg/a	25010	m³/a	250	kg/a	18	Mm³/a	178766	kg/a
Naturalised MAR m³/a (WR2005)	0,01		89700000	m³/a	897	kg/a	38640000	m³/a	386	kg/a	128	Mm³/a	1283	kg/a
PO4 load originating from Vaal (kg/a)	0,046	mg/l	4437450	m³/a	204	kg/a	64740	m³/a	3	kg/a	4,5	Mm³/a	207	kg/a
Diffuse Load (total)			206,7	Mm³/a	184094	kg/a	48,8	Mm³/a	796	kg/a	255,6	Mm³/a	184890	kg/a
Point Source														
Magalies WWTW	5,98	mg/l					139080	m³/a	832	kg/a	0,1	Mm³/a	832	kg/a
Percy Steward WWTW	1,85	mg/l	6185400	m³/a	11443	kg/a					6,2	Mm³/a	11443	kg/a
Randfontein WWTW	2,38	mg/l	3807246	m³/a	9061	kg/a					3,8	Mm³/a	9061	kg/a
Driefontein WWTW	0,17	mg/l	10810307	m³/a	1838	kg/a					10,8	Mm³/a	1838	kg/a
Esther Park WWTW	0,96	mg/l	205288	m³/a	197	kg/a					0,2	Mm³/a	197	kg/a
Northern Works	0,3	mg/l	147621538	m³/a	44286	kg/a					147,6	Mm³/a	44286	kg/a
Kelvin PS	0,93	mg/l	2517711	m³/a	2341	kg/a					2,5	Mm³/a	2341	kg/a
Hartbeesfontein WWTW	0,33	mg/l	19443082	m³/a	6416	kg/a					19,4	Mm³/a	6416	kg/a
Olifantsfontein WWTW	1,42	mg/l	28601213	m³/a	40614	kg/a					28,6	Mm³/a	40614	kg/a
Sunderland Ridge WWTW	1,86	mg/l	22082000	m³/a	41073	kg/a					22,1	Mm³/a	41073	kg/a
Rietvlei Dam	0,26	mg/l	14400000	m³/a	3744	kg/a					14,4	Mm³/a	3744	kg/a
Rietfontein WWTW	1,26	mg/l					2501583	m³/a	3152	kg/a	2,5	Mm³/a	3152	kg/a
Total Point Source load kg/a			255,7	Mm³/a	161013	kg/a	2,6	Mm³/a	3984	kg/a	258,3	Mm³/a	164997	kg/a
Total Phosphate inflow to HBPD			462,4	Mm³/a	345108	kg/a	51,5	Mm³/a	4780	kg/a	513,9	Mm³/a	349887	kg/a

8 THE WAY FORWARD

8.1 Introduction

Strategies to reduce phosphate load in the inflow to the Hartbeespoort Dam is dependent on the hydrology of the catchment and the specific classification of the rivers entering the dam. The rivers in the catchment are in the “D” ecological category with a management class III rating. This means that the system is a workhorse to drain the catchment and convey pollutants downstream (Kleynhans & Louw, 2005).

The literature study (chapter 2-6) introduced the concept of the pre-impoundment as an eutrophication management option. This option has been analysed with variations on the theme above.

The important point is that there need to be a barrier between the catchments and the Dam to prevent unwanted debris, sediment and nutrients to enter the dam. A pre-impoundment before entrance of the Crocodile River into the Dam is the recommended approach to follow.

This was included as a possible strategy as part of Metsi-a-me programme by Charl Claassens of Ilifa Africa Engineers (Pty) Ltd, based on the philosophy proposed by Prof A Pretorius (DWAF. 2010).

The design of a pre-impoundment, incorporating chemical precipitation of Phosphate with injection of iron, has not been explored in this dissertation. This needs to be researched with inclusion of the mine water injection as a chemical fixation intervention to precipitate phosphate. The reaction kinetics and reactor design need to be refined. The preliminary work (Maree & Mitchell, 2015) is a useful contribution that can be studied further.

8.2 Future growth

In future the growing need for water supply to the energy sector in Limpopo and mining developments to recover various minerals will rely on a dependable supply from the Crocodile (West) Marico water management area. Adequate quantities of water can be made available for use if the quality of return flows is of sufficient quality or treated to the desired quality (DWA. 2012:13). This dissertation clearly indicates the deteriorating quality of water in the outflow of the Hartbeespoort Dam (Figure 3-2). The importance of pollution prevention is emphasised, in the NWRS2 (DWA. 2013:44), as opposed to expensive strategies to control the inevitable effects of current pollution practices in this study area. The reuse potential of return flows is however largely dependent on the quality of the return

flow combined with the quality requirements of the users. The four most important water quality problems are salinity, eutrophication, microbial pollution and sediments. This study clearly indicates that pollution reduces the quality and therefore the economic value of the available water in the Hartbeespoort area.

A low cost solution (see interventions in 8.3 below) is required to ensure quality control to avoid eutrophication with accompanying costs to make the water fit for purpose. The most measurable impact in economic terms is the analysis of the costs incurred by municipal and private entities responsible for waste water treatment and potable water purification as indicated in Table 7-2. Technology used to treat relative good quality water less than a decade ago must now be viewed as outdated and inadequate, based on the increased load of nutrients in the intake water to WWTW's. The escalating cost of recent technology upgrades (including ultra violet light systems, reverse osmosis etc.) to continue to produce water of potable quality from growing volume of recycle clearly indicates the financial impact of pollution in the study area. The 2010 investigation by the CSIR on the cost of sewage treatment and potable water associated with increased pollution in the catchments of the Hartbeespoort Dam (Roux, Oelofse & De Lange, 2010) gives a comprehensive overview of the rising costs of both sewage treatment and the production of potable water associated with increasing levels of pollution in the catchments of the Hartbeespoort Dam.

Individual WWTW have varying infrastructure, environmental, and effluent-limit requirements, so treatment costs will certainly vary as shown in Table 8-1.

Table 8-1 Treatment cost for sewage effluent and drinking water (Roux, Oelofse & De Lange, 2010)

Treatment Process	Capital cost for replacement In 2010 money value	Operating Cost In 2010 money value
WWTW	R7million ~ R8 million per MI/day*	R794 /MI* ~ R1500 /MI**
Potable Water Treatment	About R9 million per MI/day	R1030 /MI

Note:*Sunderland Ridge WWTW operating cost for 58MI/day at R794 /MI. Replacement cost R585 million

**Hartbeesfontein WWTW operating cost for 50 MI/day at R1500/MI. Replacement cost R315million.

Future growth in the catchments of the Hartbeespoort Dam will require very expensive capital investment (estimated to be greater than R9 million per MI/day) to achieve effluent standards and to improve Green Drop performance levels to be able to meet the required reduction of nutrient levels entering the Hartbeespoort Dam without further deterioration in in-dam eutrophication status.

8.3 Interventions

It was estimated, based on a table prepared by Harding (Harding et al., 2004b) to chemically fix the phosphorous of the total Crocodile River inflow at a cost of R6.5 million/annum . The assumption was for a 6 mg/l Fe as FeSO_4 salt addition and with 80% conversion efficiency.

In the case where mine water will be used to treat water of the Crocodile River near Kalkheuwel, capital cost for a pipeline and mixing facility have to be calculated. The estimated cost for a pipeline is R4.5 m (Maree, & Mitchell, 2015). The Fe in the acid mine water will be at zero cost. This option will probably be a low cost solution. A proper cost benefit analysis must be done.

The aim will be to share the burden of nutrient removal and the cost. The WDCS is an accepted legal process to internalise the cost of externalities instead of shifting the burden to downstream users. An “all of the above” approach that considers nutrient assimilation alongside point-source treatment, storm water management, and non-point “best management practices” is a pragmatic approach to harness the approach of treating excess nutrients and toxic algal blooms.

Up-grading of technology of WWTW to comply with reduced nutrient load in effluents can be pushed to the limit where nutrient reductions at point sources become increasingly more expensive. Costs of nitrogen removal at WWTW in the Connecticut River Basin have been estimated to increase from \$12 per pound at 8 mg/l total nitrogen discharged to \$14 per pound at 5 mg/l total nitrogen discharged to \$37 per pound at 3 mg/l total nitrogen discharged. It is not unusual for costs to upgrade individual plants to a higher level of nitrogen reduction to run into the tens and hundreds of millions of dollars (Rose *et al.*, 2014).

Wetlands are efficient absorbers of nutrients, especially for nitrogen (important in that nitrogen is more expensive for WWTW to remove than phosphorous). According to Turpie (2010:25) organic pollutants, such as nitrates and phosphates, and inorganic pollutants, such as heavy metals, are diluted, taken up by plants, trapped along sediments or broken down within aquatic systems. The wetlands work by holding water in place and collecting nutrient-rich sediment, which is then absorbed into the roots of its plants. Managed wetlands optimize nutrient uptake by actively managing the volume and timing of the water flow, as well as the type of vegetation that works best. Landowners can be incentivized to construct wetlands, perhaps by using funds obtained from a WDCS levy. This is probably a less expensive solution to meeting nutrient effluent requirements than WWTW upgrades.

Since the eco-systems in the catchments are severely disturbed, it became clear that the available eco-system services such as natural attenuation of waste water will be critical to renovate the situation in the Hartbeespoort Dam. A pre-impoundment may be regarded as an artificial wetland if the in-line flow is slowed down and a retention time in the pond is allowed long enough to let natural attenuation take place (Withers & Jarvie, 2008). The valuable advice of Kevin Westerling, chief editor of “Water Online” for this situation prefers that: “With a little help from water-quality managers, Mother Nature can do the job of remediating impaired or at-risk watersheds, while making them more resilient to nutrient loading.”

8.4 Summary

Strategies to reduce phosphate load in the inflow to the Hartbeespoort Dam is dependent on the hydrology of the catchment and the specific classification of the rivers entering the dam. As discussed in 2.3 of this dissertation, the rivers in the catchment are in the “D” ecological category with a management class III rating. This means that the system is a workhorse to drain the catchment and convey pollutants downstream (Kleynhans & Louw, 2005).

The literature study in chapter 2.7 introduced the concept of the pre-impoundment as an eutrophication management option. This option has been analysed with variations on the theme above.

The important point is that there need to be a barrier between the catchments and the Dam to prevent unwanted debris, sediment and nutrients to enter the dam. A pre-impoundment before entrance of the Crocodile River into the dam is the recommended approach to follow.

The design of a pre-impoundment has not been included in this dissertation. This option needs to be considered with inclusion of the mine water injection as a chemical fixation intervention to precipitate phosphate. The reaction kinetics and reactor design need to be refined. The preliminary work (Maree & Mitchell, 2015) is a useful contribution that can be explored further.

9 CONCLUSIONS AND RECOMMENDATIONS

The Hartbeespoort Dam with its catchments is a case study of an advanced stage of cultural eutrophication. Cultural eutrophication is the process that speeds up natural eutrophication because of human activities such as clearing of land, building of towns and cities, which cause accelerated run-off of storm water carrying debris and more nutrients such as phosphates and nitrates. The pollution is drained to a strategic storage facilitate from where further downstream socio economic development has to be supported

After about 90 years of growth and development in the economical hub of South Africa, the once rural irrigation dam has gradually changed into a large waste stabilisation pond for the recycle from waste water treatment plants. The inter-basin transfer of Vaal Dam water through the waste water treatment facilities in Gauteng leaves a finger print on water quality, which is recycled for further use by other riparian and shoreline users downstream.

The scientific community has been very active in researching the cause and effects of pollution, especially in the Hartbeespoort Dam. The current Harties Metsi-a-me programme is the culmination of many intellectual efforts to proceed with the solution of a “wicked problem”. The success of the programme is dependent on support from all stakeholders, especially the Department of Water and Sanitation.

Despite one of the most advanced legal frameworks for water management, as imbedded in the National Water Act of South Africa, the regulatory control process needs additional capacity to avoid more Hartbeespoort Dam situations to emerge.

The reluctance to implement the intentions of the National Water Resource Strategy is a concern due to the fact that decisive actions to limit pollution by implementing the Waste Discharge Charge System and to appoint the intended Catchment Management Agencies have not yet realised for this particular catchment.

A quote by Leonardo da Vince (15th century renowned intellectual) is an appropriate guideline for approaching the current pollution problems, as was uncovered during research for this dissertation:

"I have been impressed with the urgency of doing. Knowing is not enough; we must apply. Being willing is not enough; we must do."

The three essential growth promoting essentials of algae, which are classified as photo-autotrophic organisms, namely light, carbon dioxide and phosphorus are optimally present

in the Hartbeespoort Dam. Fluctuating temperatures due to seasonal progression also plays a role to inhibit algal blooms to continue in colder winter months. Although any one (or more) of these essential growth promoting essentials can be made growth limiting, it would be the reduction of the phosphorus concentration that will have the greatest impact on hyper eutrophication.

To have a significant impact on the control of eutrophication, the bio-available phosphorus concentration of the inflow (in the Crocodile River) must be lowered from the present average concentration of $\pm 340 \mu\text{g/l}$ to between 30 and 50 $\mu\text{g/l}$. From all the various proposed methods of phosphate reduction which have been considered in this dissertation, it is the chemical fixing of phosphorus that can probably result in a reliable and ensured phosphate removal to any predetermined value.

The approach to the investigation to reduce nutrient levels in the catchments is based on in depth involvement with the Harties Metsi-a-me programme. This provided insight and data to analyse the causes of eutrophic through contact with knowledgeable persons.

A phosphate model was created to describe the sources of the nutrient load into the dam. With the worksheet the available data was researched as a desktop study to calculate phosphate loads in all catchments. Results were compared with other studies of the catchment over many years. The data was found to be accurate enough to assess the origin and distribution of phosphate. With a clear understanding of phosphate loads the concepts of reducing phosphate load was investigated within the framework of legal compliance, technical, environmental and management capacity within the context of the Hartbeespoort Dam catchments. Eutrophication concerns in other countries were researched and the progress with the Wahnbach Reservoir in Germany was visited to explore similarities and best management practices.

A comprehensive literature study was done through the Water Research Commission and the University library systems. As a member of WISA the biennial conference was attended to evaluate the latest technology options in waste water treatment.

Options to reduce nutrients in the catchments required to fundamentally understand the role of nutrients in eutrophication situations, specifically the hypertrophic condition of the dam. Nutrient load reduction became primarily focused on phosphate as the growth limiting factor in the Hartbeespoort Dam. Nitrogen is freely available in the catchment and it will be much more expensive to reduction nitrogen to achieve a similar reduction in eutrophication status of the Hartbeespoort Dam.

The Harties Metsi-a-me programme is a comprehensive integrate resource management approach. Phase one has progressed steadily with the implementation of the Biological Remediation Strategy. Phase two is under consideration and is focused on the reduction of nutrients in the catchments. An “all of the above” approach that considers nutrient assimilation alongside point-source treatment, stormwater management, and non-point Best Management Practices (BMP) is a pragmatic approach to harness the adrenaline of treating excess nutrients and toxic algal blooms.

This dissertation investigated the most important phosphate reduction options that can make a significant contribution to changing the eutrophication status in the dam and recommend the following:

- (a) Implementation of the WDCS is a strong recommendation. However, this is an administrative barrier that is dependent on sound financial management practices. Full implementation of the WDCS system is a moving target. Due to the lack of established catchment management structure (CMA for Limpopo) to provide the institutional support to the Hartbeespoort Dam remediation initiative, the Harties Metsi-a-me programme will remain a long term objective. In this instance functions still to be finalised such as revenue management based on “the-polluter-pays” taxation, debt management and accounting as well as liaison with the National Treasury. This can eventually release funding for capital projects and on-going biological remediation programmes.
- (b) Improved performance of the WWTW is a high priority. The Green Drop System is a laudable initiative. Management training and a preventative maintenance approach will facilitate the optimisation of available technology. New technology should be incorporated when expansion of capacity becomes necessary.
- (c) Zero phosphate detergents can result in about 28% reduction in phosphate load in the dam. This will assist to de-bottleneck phosphate removal capacity in the WWTW. The benefit of reduced phosphate load on the dam will be a bonus which will save capital expenditure in treatment of waste water as well as some reduction in operating cost to treat drinking water if eutrophication status of the Hartbeespoort Dam is reduced.
- (d) Stricter phosphorus standards for point source discharges, use of phosphorus-free detergents, and chemical fixation of phosphorus are all an approach that will

theoretically reduce phosphate load from all potential sources. From the mentioned methods the chemical fixing and precipitation is capable of lowering the phosphorus load to any predetermined level, albeit at a cost. However, because of constant human involvement, this method is subjected to all the problems presently encountered with the compliance of the 1 mg/l phosphorus standard.

- (e) After careful consideration it became clear that, due to the complex nature of the catchment and the multitude of risks that have to be controlled, if a reduction of 80% or 280 ton /annum phosphate has to be achieved a barrier will be the most desirable potential intervention that will protect the dam and contribute to phosphate reduction entering the dam. The recommended barrier should be a pre-impoundment before the main dam where the Crocodile River enters the dam.
- (f) The pre-impoundment option with mine water injection through an innovative mixing process needs to be studied further to clarify uncertainties with regard to specifications, cost and schedule for a potential project. Based on calculations for the removal of phosphates with acid mine water, the phosphate input reduction could be 55% or more (probably closer to 75%).

The viability of this system needs to be investigated further. This study of the concept is to assess the efficacy of using an iron rich wastewater such as AMD to remove the limiting nutrient of phosphate from the incoming source waters to the dam. The aim will be to contribute to the in-dam remediation measures, being implemented by DWS by further reducing incoming nutrient loads, specifically the phosphate component through chemical removal of phosphate from the feed streams, using soluble iron (such as is present in acid mine water). A second component of the research will be to investigate and pilot approaches to sediment removal and thereby address this huge contributor to phosphates that occurs during the summer stratification. The outcomes of this research could support the development of techniques to manage eutrophication problems experience by other SA lakes, e.g. Roodeplaat Dam.

Even if the phosphorus load in the Crocodile River inflow to the dam is reduced to, and maintained at zero, the liberation of phosphorus from the accumulated mass of settled phosphorus (organic and inorganic) present in the dam will have to be addressed on its own if the remediation is to be successful.

In future, the growing need for water supply in the energy sector in Limpopo and mining developments in this area to recover various minerals will rely on a consistent supply from the Crocodile (West) Marico water management area. Substantial quantities of water can be made available for use if the quality of return flows is of sufficient quality, or treated to the desired quality. This investigation clearly indicates the importance of pollution prevention over attempts to control the inevitable effects of current pollution practices in this study area.

10 REFERENCES

Acts see South Africa.

African Environmental Development. 2007. Hydrological/Chemical aspects of the Tweelopie-/Riet-/Blaauwbankspruit, with specific reference to the impact water, decanting from the Western Basin mine void, has on this system. (Unpublished).

Ashton, P.J., Roux, D.J., Breen, C.M., Day, J.A., Mitchell, S.A., Seaman, M.T., Silberbauer, M. 2012. The freshwater science landscape in South Africa, 1900-2010. *Water Research Commission*, TT 530/12.

Barnard Duard 1999, Chapter 24: 'Environmental Law for All', Impact Books, Pretoria.

Benndorf, J. & Pütz, K. 1987a. Control of eutrophication of lakes and reservoirs by means of pre-dams - I. mode of operation and calculation of the nutrient elimination capacity. *Water research*, 21(7):829-838.

Benndorf, J. & Pütz, K. 1987b. Control of eutrophication of lakes and reservoirs by means of pre-dams—validation of the phosphate removal model and size optimization. *Water research*, 21:839-842.

Bernhard, H., & Clasen, L, 1982. Limnological effects of the elimination of phosphorous from Wahnbach Reservoir, *Water Science & Technology*, 14, 4-5, pp 397-406 IWA Publishing 1982.

Clasen, J. & Krämer, R. 2002. Experience with integrated water quality management in the Wahnbach watershed. *Water science and technology*, 46(6):303-309.

Cukic, Z., & Venter, P. 2012. Hartbeespoort Dam remediation sediment removal and management. *Civil Engineering*, 20(7):42-47.

Dower, P. 2005. Would you swim here? *Water Wheel*, 4(1):16-18.

Du Plessis, M.M., Kruskopf, A., Venter, A. & Conradie, K.R. 2007. The role of nutrient utilisation and photosynthetic capacity in micro-algal bloom formation and the production of cyanotoxins. *Water Research Commission*, Report TT1401/2/07.

DWA. 2010. Hartbeespoort Dam Resource Management Plan, 1 st Edition, July 2010. Department of Water Affairs. 2010. Hartbeespoort Dam Resource Management Plan, 1 st Edition. ix = 109 pp.
http://www.harties.org.za/documents/RMP/RMP_Draft20Jul2010Toc.pdf Date of access: 2 Feb. 2016.

DWA. 2013. National Water Resource Strategy 2. *Department: Water Affairs Republic of South Africa National Water Resource strategy June 2013 Second Edition*. www.dwa.gov.za/nwrs2013 Date of access: October 2015.

DWA. 2012. Crocodile West River Reconciliation Strategy 2012. *Department of Water Affairs Republic of South Africa Report number WMA 03/A31/00/6110/4 December 2012*.
https://www.dwa.gov.za/Projects/crocodilemaintenance/Documents/MOCWS%20Reports/CWR_S%20Strategy%202012%20FINAL.pdf Date of access: December 2012.

- DWA. 2012. Green Drop progress report 2012. www.dwa.gov.za/greendrop, Chapter 7, pp.192, Chapter 11, pp.331, Chapter 14, pp.451.
- DWAF. 1996. South African Water Quality Guidelines. Volume 7: Aquatic Ecosystems. *Department of Water Affairs and Forestry, 1996. South African Water Quality Guidelines. Volume 7: Aquatic Ecosystems.*
https://www.dwa.gov.za/iwqs/wq_guide/Pol_saWQguideFRESHAquaticecosystemsvol7.pdf
- DWAF. 2004. Sampling protocol for toxic algae. *Resource Quality Services Department of Water Affairs.*
https://www.dwa.gov.za/iwqs/reports/general/WRQM_Vol03_Sampling_protocol_for_Toxic_Alga_e.pdf
- DWAF. 2004. National Water Resource Strategy. *Department of Water Affairs and Forestry South Africa. National Water Resource Strategy First edition, September 2004.*
www.dwaf.gov.za/Documents/Policies/NWRS/Sep2004/pdf/Chapter1.pdf Date of access: 2 Feb.2016.
- DWAF. 2008. Pre-impoundment and flow diversion for the Hartbeespoort Dam integrated biological remediation programme. Department of Water Affairs and Forestry, South Africa. 2010. Pre-impoundment and flow diversion (Conceptual design report) for the Hartbeespoort Dam Integrated Biological Remediation Programme: Prepared by Ilifa Africa Engineers (Pty) Ltd.
<http://www.harties.org.za/documents/PreImpoundmentDesignReportDraftSept08.pdf>
(Unpublished).
- Frost & Sullivan, 2010. Eutrophication research impact assessment. *WRC report*, no.TT461/10
- Harding, W.R., Thornton, J.A., Steyn, G., Panuska, J. & Morrison, I.R. 2004a. Hartbeespoort Dam Remediation Project (Phase1) Volume I. *DH Environmental Consulting.*
www.harties.org.za/documents/ActionPlanVol1Oct04full.pdf
- Harding, W.R., Thornton, J.A., Steyn, G., Panuska, J. & Morrison, I.R. 2004b. Hartbeespoort Dam Remediation Project (Phase1) Volume II. *DH Environmental Consulting.*
www.harties.org.za/documents/ActionPlanVol2Oct04full.pdf
- Harding, W.R. 2004. Hartbeespoort Dam: An action plan. *Water Wheel* 3(6):6-10.
www.wrc.org.za/Knowledge%20Hub%20Documents/Water%20Wheel/Magazine?WaterWheel_Archive_ww-nov-dec%2004.pdf
- Harding, W.R. 2008. The Determination of Annual Phosphorus Loading Limits for South African Dams: Report to the water research commission. *Water Research Commission Report No 1687/1/08.*
- Harding, W.R., Downing, T.G., van Ginkel, C.E. & Moolman, A.P.M. 2009. An overview of cyanobacterial research and management in South Africa post-2000. *Water SA*, 35(4):479-484.
- Harding, W.R. 2015. Living with eutrophication in South Africa: A review of realities and challenges. *Transactions of the Royal Society of South Africa*, 70(2):155-171.
- Hobbs, P.J. and Cobbing, J., 2007. Hydrological assessment of acid mine drainage impacts in the West Rand Basin, Gauteng Province. Report no. CSIR/NRE/WR/ER/2007/0097/C.CSIR/THRIP. Pretoria. South Africa, pp109.
<http://hdl.handle.net/10204/3348>

- Huizenga, J.M., Silberbauer, M., Dennis, R. & Dennis, I. 2013. An inorganic water chemistry dataset (1972-2011) of rivers, dams and lakes in South Africa. *Water SA*, 39(2):335-339.
- Integrated Monitoring Programme: Progress Report. 2012. Hartbeespoort Dam Bioremediation Programme.
http://www.harties.org.za/documents/ProgressReport/20120423_Consolidated_Monitoring_and_Annual_Progress_report_IM.pdf
- Keto, J., 2013. Hartbeespoort Dam Integrated Biological Remediation Program, Phase 1 Peer review and follow-up report. www.harties.org.za/documents/Peer/PeerReviewLathiMar2013.pdf
- Kleynhans, C.J & Louw, M.D., 2005 River Eco-Classification: "Manual for eco-status determination". *Water Research Commission* report TT 329/08.
- Lentech, BV, Delft. 2015. Phosphorous removal from wastewater:
<http://www.lenttech.com/phosphorous-removal.htm#ixzz3ztR6t9Zf> Date of access 10 Nov. 2015.
- Leopold, P. & Freese, S.D. 2009. A simple guide to chemistry, selection and use of chemicals for water and wastewater treatment. *Water Research Commission* report TT 405/09
- Maree, J.P., Mitchell, S. 2015. Mine water that influence the water quality in the Hartbeespoort Dam. (Unpublished).
- Matthews, M.W. & Bernhard, S. 2015, Eutrophication and cyanobacteria in South Africa's standing water bodies: A view from space: *South African journal of science*, (5):1.
- Middleton, B.J., and Baily, A.K. (2008) "Water Resources of South Africa, 2005 Study (WR2005)". *Water Research Commission*, Report No. TT 381/08, Pretoria, South Africa.
- National Assembly. 2003. Question No 1008. www.harties.org.za/press/q1008NA13Jun03.pdf
- NIWR. 1985. The Limnology of Hartbeespoort Dam, South African National Scientific Programs Report No. 110, *Foundation for Research Development, Council for Scientific and Industrial Research*, Pretoria, 269 pp.
- Owour, K., Okonkwo, J., Van Ginkel, C., Scott, W. 2007. Environmental factors affecting the persistence of toxic phytoplankton in the Hartbeespoort Dam. *Water Research Commission* Report No 1401/3/07.
- Pütz, K. & Benndorf, J. 1998. The importance of pre-reservoirs for the control of eutrophication of reservoirs. *Water science and technology*, 37(2):317-324.
- Quayle, Dickens, L.M., Graham, C.W.S., M., Simpson, D., Goliger, A., Dickens, J.K., Freese, S., Blignaut, J. 2010. Investigation of the positive and negative consequences associated with the introduction of zero-phosphate detergents into South Africa. *Water Research Commission*, Report No. TT 446/10.
- Rose, J, Bruker, S, Tedesco, M, Wikfors, G. 2014. Nitrogen removal, Environmental Science & Technology,
http://www.nmfs.noaa.gov/aquaculture/docs/environment/shellfish_and_nitrogen_removal_rose_etal_2014.pdf

- Rossouw, J.N., Harding, W.R. & Fatoki, O.S. 2008. A guide to catchment scale eutrophication assessments for rivers, reservoirs and lacustrine wetlands. *Water research commission*. Report TT352/08.
- Roux, S., Oelofse, S, and De Lange, W. 2010. The rising costs of both sewage treatment and the production of potable water associated with increasing levels of pollution in a portion of the Crocodile –West Marico water management area. WISA 2010 Biennial Conference ICC Durban, South Africa, 18-22 April 2010, p.18.
- Schneider, Y. Grube, S. & Weiland, M. 2008. Determination and evaluation of the phosphorous load of and artificial shallow lake. *IWA Publishing*, 58(10)1993-2000.
- South Africa. 1998. National Water Act 36 of 1998.
- Storm, P. 2006. Technologies to Remove Phosphorus from Wastewater, Rutgers University report, <http://www.water.rutgers.edu/Projects/trading/p-trt-lit-rev-2a>
- Thornton, J.A., Harding, W.R., Dent, M., Hart, R.C., Lin, H., Rast, C.L., Rast, W., Ryding, S. & Slawski, T.M. 2013. Eutrophication as a 'wicked' problem. *Lakes & reservoirs: Research & management*, 18(4):298-316.
- Turpie, J., Lannas, K., Scovronick, N., Louw, A. 2010. Wetland valuation Vol 1-wetland ecosystem services and their valuation: a review of current understanding and practices. WRC Report TT440/09.
- Twinch A.J. & Grobler D.C. 1986. Pre-impoundment as a eutrophication management option: A simulation study at Hartbeespoort Dam. *Water SA*, 12(1):19-26.
- Van der Merwe, P.H., Maree, J.P. & Basson, N.D. 1983. Using acid mine water for removal of phosphates from sewage effluent. *Water Science & Technology*, 15(2) (155-167).
- Van Ginkel, C.E. 2007. Investigating the applicability of ecological informatics modelling techniques for predicting harmful algal blooms in hypertrophic reservoirs of South Africa *Thesis -PhD North-West University Potchefstroom*
- Van Ginkel, C.E. 2011. Eutrophication: Present reality and future challenges for South Africa. *Water SA*, 37(5).
- Van Veelen, M. 2013. Waste charge discharge system: Situation assessment and RQMP. Iliso. (no. WP10510). (Unpublished)
- Van Vuuren, L. 2008. Taming the Poort: SA's water history, *Water Wheel*, 7(3):19-21.
- Venter, P.S. 2012, Hartbeespoort Dam Remediation Overview of the programme. *Civil Engineering* 20(7) 15-23).
- Venter, P.S. 2012. Hartbeespoort Dam integrated biological remediation programme addressing hypertrophic conditions by enhancing aquatic ecosystem bio-diversity. *Southern African society of aquatic scientists*, 49th Congress (-):45-45.
- Vollenweider, R.A., 1975. Input-output models with special reference to the phosphorous loading concept in limnology. *Schweiz. Z. Hydrol.* 37: 53-83.
- Wahnachtalsperrenverband. 2003. Phosphor-Eliminierungsanlage am Vorbekken der Wahnachtalsperre. *Wasser: 50 Jahre Wahnachtalsperrenverband 1953-2003 Eine Chronik*.

WTV herausgegeben vom Wahnbachsperrenverband Redaktion und Bearbeitung, Siegburg: 114-119.

Walmsley, R. 1998. Proceedings of Hartbeespoort Dam Water Quality Workshop, Proceedings compiled by Rand Water. (Unpublished HWAG notes).

Withers, P.J.A. & Jarvie, H.P. 2008. Delivery and cycling of phosphorus in rivers: A review. *Science of the total environment*, 400(1–3):379-395.

Zhang, T., 2010, Thermodynamic modelling of ferric phosphate precipitation for phosphorous removal and recovery from wastewater, *Journal of Hazardous Materials*, 176:444-450.

APPENDIX A – PIPER AND EXPANDED DUROV DIAGRAM EXPLANATION

Data Interpretation with Piper and Durov Diagrams

Many facilities for the interpretation of water quality monitoring data exist. Some of these are well-known methodologies, such as statistical evaluations, line and bar charts, or plots of borehole and water-level information. Other methodologies are less known. These are, for instance, the so-called specialized chemical diagrams. Of these, only the Piper and Expanded Durov Diagrams will be discussed.

Piper and Expanded Durov Diagrams

The Piper and Expanded Durov Diagrams allow the plotting of eight chemical parameters for a single water sample. Either surface or ground-water chemistries may be plotted.

The procedure is as follows:

- Calculate concentrations for Ca, Mg, Na, K, Cl, SO₄, NO₃, T. Alk. in units of milli-equivalents per litre.
- Calculate relative percentages for the cations and anions.
- Plot the percentages cations in the bottom left triangle.
- Plot the percentages anions in the bottom right triangle.
- Project the two points to the central block on the Piper or Durov Diagrams and make a mark where the two projections cross.

Interpretation is as follows:

- It is a matter of personal preference whether the Piper or Durov Diagrams are used.
- Both diagrams should primarily be used as visual displays, summarizing the chemistry of all samples taken at a site, or at many sites.
- Of particular value is the identification of pollution trends, through the aid of these diagrams. A comparison between plots of successive sampling exercises, will clearly

show whether or not trends in the chemistry of the water are developing. Trends to observe are:

- 1) Sodium enrichment - typical of processes such as waste water discharge, chemical extraction of minerals from ore, dewatering of deep mines, return flow from irrigation or natural deterioration of the ground-water quality by ion exchange within the aquifer.
- 2) Sulphate enrichment - typical of most mining environments.
- 3) Calcium enrichment - typical of lime dosing to neutralize acid water.
- 4) Chloride enrichment - typical of leachate from domestic waste and dewatering of deep mines.

A word of caution though: the ground-water chemistry is one of the most complex natural systems to predict, because of the many natural processes/parameters that could affect it. The following are but a few examples of chemical changes which could occur within an aquifer:

- Dissolution of soluble elements, such as Na, K, Cl and HCO₃.
- Precipitation of oversaturated species.
- Ion exchange and adsorption onto clays, such as Ca-adsorption and Na-release.
- Chemical reaction between two waters mixing.
- Natural decay of substances, such as modern pesticides.
- Bacterial oxidation/reduction, such as pyrite oxidation and sulphate reduction.
- Dispersion of pollutants through the aquifer.
- Convection during flow of pollutants through the aquifer.
- The aquifer hydraulic constants, such as transmissivity, storativity, gradients and boundary conditions.

The specialized diagrams and other techniques for the interpretation of the data, included within WasteBase and WasteManager, should therefore be used with circumspection. The identification of trends should be done by all waste disposal managers. However, if undesirable pollution trends develop, which cannot obviously be linked to operations, it should best be left to the geohydrologist to suggest remedial action.

PIPER DIAGRAM

The chemical composition of ground water reflects the processes which are responsible for the different constituents it contains: Wind blowing over the ocean carries mainly sodium chloride landwards. Oxygen, nitrogen and carbon dioxide dissolve when the humidity in the air condenses. Additional carbon dioxide and humic acids dissolve when water percolates through the soil containing organic matter.

The ground water changes its composition as the water moves through the aquifer. Minerals dissolve and release salts; sulphides may oxidize; cations are exchanged; sulphides and nitrates can be reduced through bacterial action; evaporation leads to concentration; and once the solubility products are exceeded minerals are precipitated. Mixing with water of different origin also influences the composition.

Trilinear diagrams are used for the investigation of ions or groups of ions as a function of the concentration. On these diagrams the milli-equivalent percentages of the major cations and anions are plotted; and it has been found that the point at which an analysis plots is of considerable diagnostical value.

The Piper diagram is a combination of two trilinear diagrams and a central diamond field. In the diamond field the cations Ca^{2+} , Mg^{2+} , $\text{Na}^+ + \text{K}^+$; and the anions SO_4^{2-} , Cl^- and $\text{HCO}_3^- + \text{CO}_3^{2-}$ are represented by a point, in the trilinear diagrams cat- and anions each separately.

To convert the units mg/L normally given in an analysis to milliequivalents the determined quantities must be divided by the molecular weight of the respective ion and its

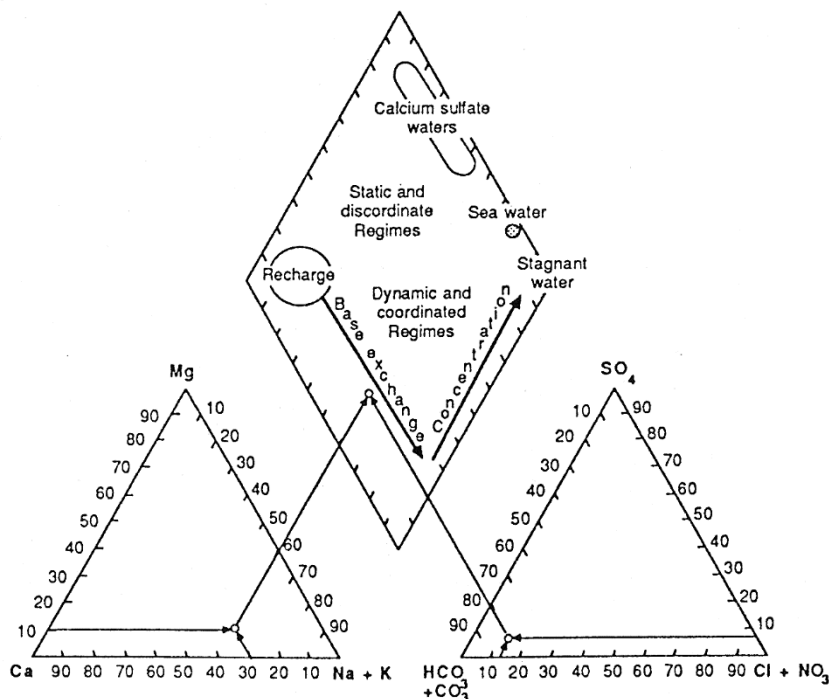
valence. The constants for the conversion of the different ions are:

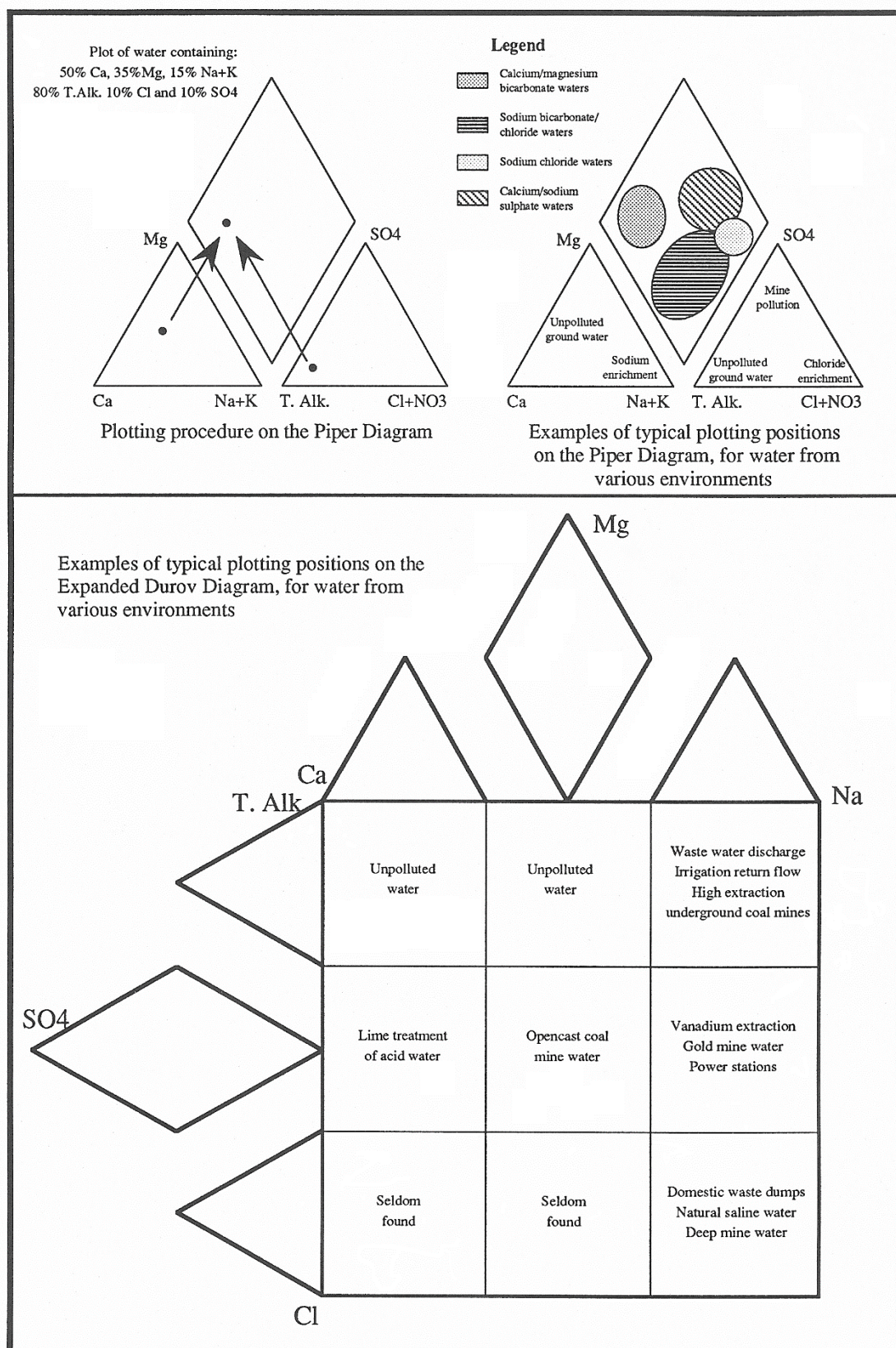
Cations		Anions	
Ca	1/20	HCO_3^-	1/61
Mg	1/12	CO_3^{2-}	1/30
Na	1/23	Cl	1/35.5
K	1/39	NO_3^-	1/62
		SO_4^{2-}	1/48

The percentage milli-equivalents for the different cations are calculated by dividing the respective milli-equivalent values by the sum of the milli-equivalents of the cations. The percentage milli-equivalents for the anions are calculated accordingly.

After the cat- and anions are plotted in the trilinear fields their position is projected in the central diamond field. Based on the position in the diamond field ground water can be divided into four categories, nl.:

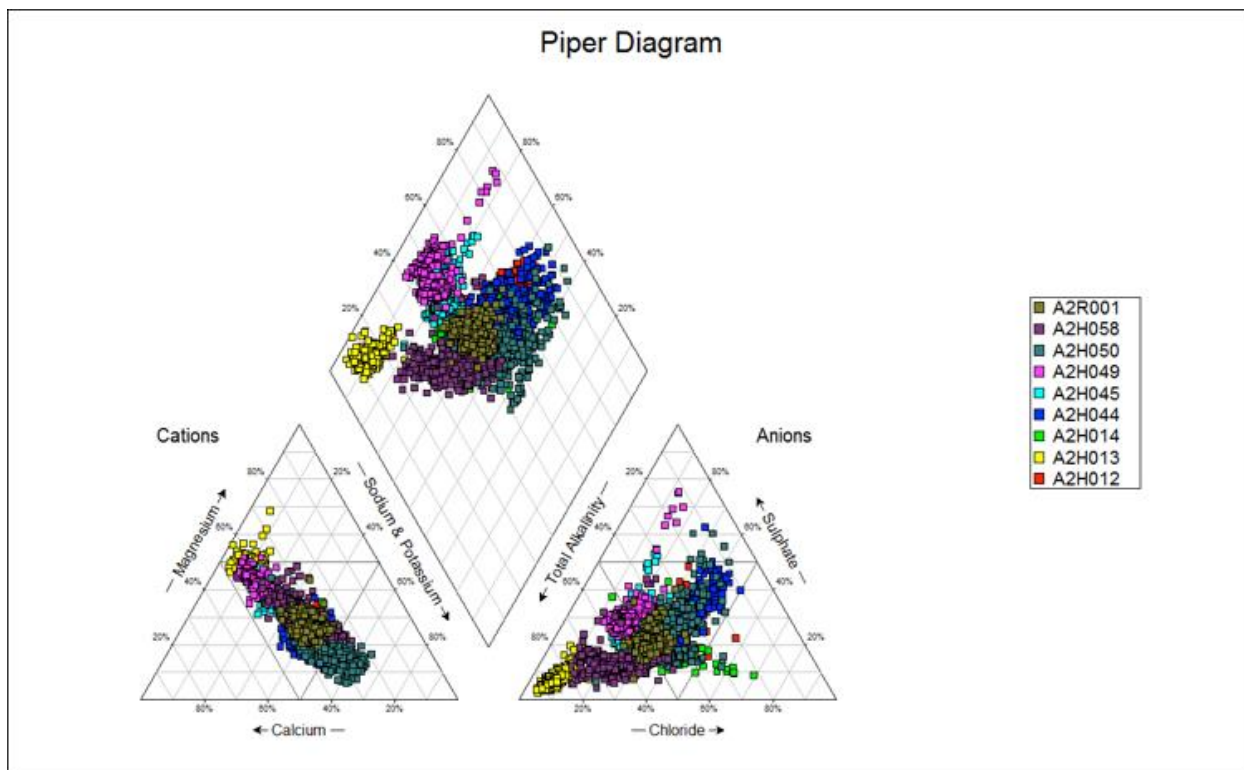
- Recently recharged ground water rich in calcium and/or magnesium and bicarbonate.
- A dynamic regime with water rich in bicarbonate with increasing sodium (and potassium) concentrations.
- "Stagnant" or relatively old ground water at the end of the cycle with high sodium, chloride and/or sulphate values. It plots near the point for sea water.
- Calcium sulfate water as well as other relatively seldom encountered water which plots in the upper half of the diamond field.



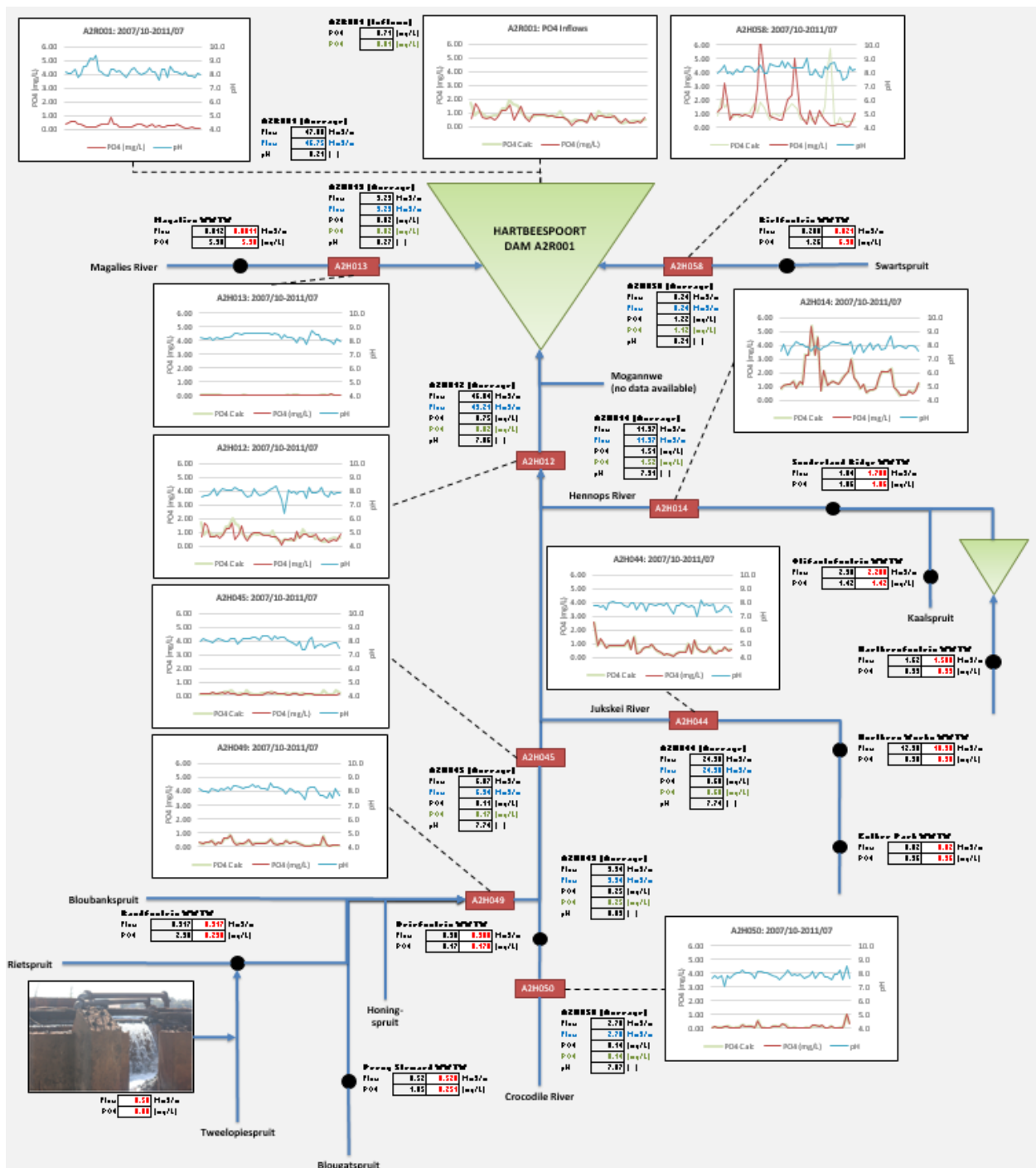


APPENDIX B – TIME SERIES PIPER AND EXPANDED DUROV DIAGRAMS

Hydrological years 1982 - 2011



APPENDIX C – MONTHLY MASS BALANCE MODEL



APPENDIX D – PHOSPAHTE LOAD CALCULATIONS (VAN VEELLEN, 2013)

A. The case study was based on available data for the period 2006 to 2011.

B. Total Phosphate load expressed as Kg/a. Soluble reactive Phosphate is $0.81 \times \text{TP}$

(a) Total Catchment Diffuse load = (Total load at measuring station) - (sum of load discharged by relevant WWTW)

(b) Total Diffuse load = (natural background) + (Anthropogenic activities load)

(c) Natural P load = [naturalised mean run-off (MAR)] $\times$ (natural P 0.01mg/l)

(d) P load from diffuse source = (Diffuse P load) - (natural P load)

(e) P load from Vaal Dam = (total flow discharge from WWTW) $\times$ (P load of Vaal dam)

(f) Anthropogenic P load = (Total diffuse P load) - (natural P load)

(g) Run-off hard surfaces = (24000000 cub m/a) $\times$ (%urban area in total catchment) $\times$ (0.01mg/l P) The 24000000 cub m/a is an average estimated in DWA 2008 reconciliation strategy

(h) Return flow garden, parks = (urban area km² $\times$ 40%) $\times$ (10% of rain fall 600 mm/a) $\times$ 0.05 mg/lP. Average rainfall 600mm/a as per W2005 tables.

(i) Water supply system leakage = (estimate 10% of potable water Rand Water supplied) $\times$ (% urban area of total urban area) $\times$ 0.046 mg/l). Rand Water study estimate.

(k) Leaking sewer P load = [(total diffuse load)(b)] - [(other diffuse load)(g+h+i)] or Volume = [(WWTW load)/10mg/l added to other sub-catchment diffuse volume. The figure is an estimate.

(m) Irrigation return flow = 11000000 m³/a as per WR2005 allocated to %irrigation of total area irrigated $\times$ 0.01 mg/l

(n) Vaaldam import = WWTW effluent flow $\times$ Vaal Dam P concentration/1000
Assume 500×10^6 cubm/annum supplied by Rand Water.

Variables:

1. Dependent variable: Eutrophication in Hartbeespoort Dam due to phosphate load

2. Independent variables:

2.1 Point source phosphate in WWTW effluent. WWTW design and operating efficiency are long term variables.

2.2 Diffuse load phosphate entering Hartbeespoort Dam through catchment's draining.

2.2.1 Anthropogenic P load (consumer behaviour influence Rand Water supply).

2.2.2 Rainfall can vary and will effect irrigation and storm water run-off.

2.2.3 Leaking systems is related to management control of infrastructure all areas.

2.2.4 Urbanisation growth effects hard surface area, garden and parks area and Import Rand Water supply.

3. Intermediate variables:

3.1 Legal and regulatory control

3.2 Waste Discharge Charge System (Polluter pays principle)