REVIEW OF THE HARTBEESPOORT DAM INTEGRATED BIOLOGICAL REMEDIATION PROGRAMME (HARTIES METSI A ME)

Report to the
WATER RESEARCH COMMISISON

by

Dr SA Mitchell[1] & Dr JG Crafford[2]

with contributions from

Dr Martin van Veelen[3], Professor Jannie Maree[4], Ms Elana Reyneke[2]
[1]Eon Consulting
[2]Prime Africa Consultants
[3]Iliso Consulting
[4]Phillert Trust

WRC Report No. KV 357/16
ISBN 978-1-4312-0803-6

July 2016

Obtainable from
Water Research Commission
Private Bag X03
Gezina, Pretoria
0031 SOUTH AFRICA

orders@wrc.org.za or download from www.wrc.org.za

The publication of this report emanates from a project entitled *Review of the Hartbeespoort Dam Integrated Biological Remediation Programme (Harties Metsi a Me)* (WRC Project No K8/1083).

1 Recommendations and overview

1.1 Main Recommendations

The programme needs to be continued and expanded. Certain structural changes to the programme are recommended as follows:

1. The Minister should appoint a broad-based scientific committee to guide the work done within the programme. A part of the mandate of this committee would be to identify priority areas for attention. The full mandate would be decided during the early stages of the committee. A range of hypotheses are presented in this overview which may serve to direct the initial thinking of this committee. More detail is given in the report.
2. Phase 2 of the HDRP needs to focus on the catchment upstream of the dam, specifically on improving the quality of the water flowing into the dam. The waste discharge charge system has been piloted in this catchment and this provides the opportunity to implement the system.
3. Certain of the in-lake activities started in Phase 1 should be continued. But the programme should be broadened to effectively address the quality of the inflowing water in order to reduce the loading of plant nutrients. This will require increased funding. Some Methods and sources of funding are presented in the report.
4. The programme should be set within an adaptive management framework. This will provide the structure for developing the vision and translating it into achievable objectives. It will also provide for a monitoring programme focused on progress towards achieving the required objectives.
5. The social-ecological system (SES) around the dam is dynamic. Changes in the trajectories of aspects within the SES should be anticipated and where necessary incorporated into the adaptive management framework.
6. There should be a thrust of R&D and innovation within the programme. Some possible examples are given in this overview and more n the report.
7. Strategies and associated activities developed during the programme should be transferred to other eutrophic water bodies as appropriate.
8. Most importantly, the revitalization of reservoir limnology as a profession remains paramount. South Africa relies on reservoirs to balance the supply of water with the demand in the face of variable precipitation. The country needs to develop the capacity to manage these reservoirs.
9. It is recommended that the 1 mg/ℓ P standard for effluents discharged into designated sensitive catchments by wastewater treatment works be reviewed in the light of the capabilities of modern technology.
10. It is recommended that a stakeholder forum be established.
11. It is recommended that that a full-time financial officer be appointed and that annual internal audits be conducted.

More recommendations are given in the report.

1.2 Overview

The Hartbeespoort Dam is a complex system that, in practice, integrates the activities in the catchment upstream. These activities include urbanization, industrial developments, mining agriculture and recreation. These activities have been increasing over the 90 year life of the dam.

Hartbeespoort Dam is also the centre of a hub of economic activity both cantered on the dam and including water users downstream.

Dams are built to store water for times when the natural availability is insufficient to supply the need, so the water level is expected to fluctuate. Hartbeespoort Dam has, however, been kept at or close to full supply level since 1996 as a result of the increasing inter-basin transfer (IBT) from the Vaal catchment as Rand Water has supplied an increasing urban and industrial demand in the northern parts of its supply area. This enters the dam as return flows from urban and industrial activities. It follows that the quality of this water is dependent in part on the effectiveness of the wastewater treatment works in treating the effluent. There are, however, two other factors which play a part in the quality of water entering the dam. The first of these is the sheer volume. Between 1985 and 2010/11 the volume of water flowing into the dam annually increased from 233.5 Mm^3 (NIWR, 1985) to 534 Mm^3 (HDRP, 2013a). Even with the high quality effluent from the larger works in the catchment the load of nutrients entering the dam is substantial and increases proportionately with the increase in the IBT. The second factor is the level of maintenance of infrastructure with a substantial contribution of nutrients coming from poorly maintained sewerage infrastructure. The dam is a phosphorous sink and it is estimated that between 1999 and 2012 in excess of 3 000 tons of total phosphorous (TP) has accumulated in the dam (HDRP, 2012a).

1.3 Achievements of Phase 1

Phase 1 of the Hartbeespoort Dam Bio-Remediation Programme (HDRP) started in 2006 and the period of the review ended in 2013 which is a short period in the life of the dam. There have been a number of successes during Phase 1. These include, for instance, the large scale hyacinth and other alien plant removal with the beneficiation of this biomass, the testing of floating reed bed systems which increase the biodiversity and biomass of the open water, a fisheries programme and the clearing of debris from the system. In addition, the zone of sediment in which the P is concentrated has been mapped and pilot-scale dredging has been carried out. A number of jobs have been created.

The lack of scientific rigour in certain of the aspects such as the quantity of P removed by the floating islands, algal harvesting and fishery mean that the results cannot, at this stage, be used for projecting the effectiveness of these activities in managing the eutrophication of the dam. Estimates of this are, however, given in the report.

1.4 Changes foreseen

There are some changes to the system which can be foreseen. Amongst these is the fact that the return flows will continue to increase as a result of the increase in urbanisation. This will, in turn, increase the nutrient load into the system. There are various proposals for polishing the inflowing water to reduce the phosphate concentration beyond current levels. The use of acid mine drainage (AMD) is one option and is discussed briefly below and in detail in the report. Another effect of the increase in urbanization is the increase in hard surfaces which will alter the hydrology of the system. Another change which cannot be avoided is the increase in the AMD decanting into the system. This will need to be managed in a way that does not impact the system, or reduces impacts to a minimum. A far-reaching change which is foreseen is that the water level is going to undergo annual fluctuations once water from the dam is being released to the Lephalale industrial development node. These fluctuations will vary from year to year but will potentially be large. In addition, although the provision of water for irrigation is not expected to increase much, it is anticipated that the provision of water for mining purposes will increase. The DWS has, through the WRCS, gazetted certain environmental quality policy imperatives for the system, and these need to be implemented in future. In addition there are emerging hazards such as climate change which need to be taken into account.

1.5 Questions and hypotheses

Work done during Phase 1 has raised some questions and also led to the development of some hypotheses. These need to be tested.

One question is the fate of the phosphate in the dam. While the annual load of P flowing into the dam was highest between 2007 and 2010, the phosphate concentration in the water declined from 2007/08. This was mirrored by a decline in chlorophyll-a over the same period. The question is, where was the P sequestered?

Two decades of stable lake level has created conditions allowing the establishment of a filamentous algal mat and rooted hydrophytes. The hypotheses are (a) that the establishment of the algal mat and rooted hydrophytes armour the nutrient-rich littoral sediments against resuspension by wave action and (b) these effectively sequester nutrients from the water body, so reducing the likelihood of algal blooms.

The projected lake level fluctuations give rise to questions which have led to the formulation of three hypotheses. The first (a) is that the P in exposed and rewetted sediments will be temporarily immobilized; (b) pollutants in exposed and rewetted sediments will be mobilized and (c) that the drying and rewetting of hyacinth seeds will stimulate their germination.

Over the life of the dam heavy metals and pollutants have accumulated in the sediment. Will the dredging remobilize these?

The NIWR study indicated that the energy pathway in Hartbeespoort Dam had shifted form phytoplankton – zooplankton – fish to phytoplankton – decomposers. Is this still the case?

Other hypotheses are articulated in the report.

1.6 Innovation

There is the opportunity to develop products that will add value.

For instance, the dredged material is already being used as a phosphorous-rich fertilizer in certain specific applications. Can the phosphorous be recovered and developed into a high value commercial product? Options include the recovery of the P either at source at the sewage works or at the dam inflow. The latter would offer the opportunity to recover more P as at the moment approximately ½ the P load into Hartbeespoort Dam is from diffuse sources. The assumption is that the proportion of P from diffuse sources entering other impoundments is similar. The P may be precipitated chemically using an iron salt and then recovered from the precipitated sludge. One option to be tested is to use AMD as the source of iron to precipitate the P. This would be cheaper than setting up a production facility to produce the iron salt for the process. It does, however, need to be tested.

Currently, water hyacinth biomass is being used to make compost. There is opportunity to train people to develop microenterprises producing compost for sale to local estates. Elsewhere in the world water hyacinth biomass is being used as the raw material for products such as high quality furniture, basket-ware, biodegradable plastic or briquettes. The development of similar opportunities for the beneficiation of hyacinth biomass would provide opportunity for cottage industries to develop and provide employment opportunities for more people around this and other dams where hyacinth is a problem.

Similarly, the fishery lends itself to the development of artisanal fisheries on this and other dams.

Is there opportunity for the production of fine chemicals from the algal biomass? For instance, *Spirulina*, a blue-green alga, contains certain fine chemicals valued by the health food market. As another example, Algal or hyacinth biomass may be used as a basis for biofuel production.

There are other avenues of innovation which could be profitably pursued.

Executive summary

The purpose of this review is to assess Phase 1 of the Hartbeespoort Dam Integrated Biological Remediation Programme (HDRP) and to make recommendations for the future Phase II of the programme. The review benchmarks the HDRP against selected national and international benchmarks which are introduced as appropriate through the document.

Hartbeespoort Dam is the hub of the economy in the area, supporting irrigation and mining as well as substantial residential and recreational developments around the Dam. The most important ecosystem service is the provisioning of water, through the storage that the Dam provides. The Dam further plays an important water regulation role. It is common cause that it has a waste assimilation role, as it traps nutrient pollution. A number of ancillary benefits exist, these include fishing for food, habitat for species, and a range of cultural services that include tourism, recreation and aesthetic services.

As with other impoundments downstream from the Gauteng conurbation the dam has become highly eutrophic. Of great concern is the challenge of managing the effluent from the Gauteng. The institutional environment governing the management of effluents is complex and spread across different government structures. This, combined with the expense and difficulty of treating the effluents to a standard that will not impact the receiving environment, is one factor that has led to widespread eutrophication in the impoundments on the rivers draining Gauteng. Harding (2010) estimates conservatively that *35% of South Africa's impounded water resources are seriously impaired (eutrophic to hypertrophic); a further 20-30% are incipiently problematical. All of the major impoundments in the economic heartland of the country, Gauteng, are grossly impaired. The full extent of the problem is unknown as no systematic comprehensive spatial surveys have been conducted.* Matthews (2014) found that 62% of South Africa's largest dams were highly nutrient enriched.

The HDRP was designed to give effect to the recommendations made by the various research initiatives in order to reverse the trend of increasing eutrophication in the impoundment. The intention was, then, to repeat successful initiatives in other eutrophic impoundments and to investigate and implement, if suitable, additional remedial interventions.

During 2003 the North West Department of Conservation and the Environment (DACE) and later Department of Agriculture Conservation, Environment and Tourism (DACET) issued a request for a proposal to develop a management plan for the Hartbeespoort Dam. The action plan, supported by various individual task assessments (Annexures and Appendices) (Harding et al., 2004 a, b), formed the basis of the HDRP. The HDRP is also known as the Harties Metsi a me programme.

Rand Water was appointed by Department of Water and Sanitation (DWS)[1] as the Implementing Agent of the HDRP and the programme lead was assumed by the North West Regional Office of DWS. The HDRP Phase 1 began with a Business Plan dated August 2006 and continued to March 2010. The period between March 2010 and the present has been the Transitional Phase 2. A formal HDRP Phase 2 is planned in the near future.

The HDRP started in the 2006/7 financial year and, to date, has a total expenditure on project, from 19 September 2006 to September 2014, of R158 725 549.67 (excl. VAT).

[1] The Department of Water and Sanitation (DWS) has changed its name from the Department of Water Affairs and Forestry (DWAF) through the Department of Water Affairs (DWA) to DWS. For consistency the Department will be referred to as DWS.

There appears to have been some controversy among various stakeholders about the HDRP, which have led to questions being asked in Parliament regarding the programme (Appendix 3). The topics which received most questions related to acid mine drainage, eutrophication and mitigation of pollution issues and issues around governance, the budget and audits.

In addition, significant changes are expected in the greater Hartbeespoort Dam meta-system in future. The dam level has been stable for almost 2 decades. This has changed the environment from that during the 1980s when the water level was low and fluctuating. The stable lake level has created conditions in which rooted macrophytes (emergent and submerged) may be able to establish. However, it is highly likely that these stable conditions would change in the near future as a result of water transfers to the Lephalale area, increased return flows from waste water treatment works and acid mine drainage.

In 2014, the Acting Director General of the DWS, requested a more detailed independent review of the HDRP to ensure that more focus was given to catchment activities inclusive of detailed action plans (HDRP, 2011).

This review adopted a systematic assessment of the HDRP Phase 1, and a simultaneous recommendation process for Phase 2.

A focused literature review was undertaken to evaluate international and South African literature on lake re-oligotrophication in order to identify key areas for remediation programs for lakes with severe eutrophication problems. This analysis formed and important benchmark against which the HDRP Phase 1 has been reviewed and against which recommendations for Phase 2 have been made. Three messages came through from the review. Firstly, nutrient ingress into the eutrophic water body needs to be controlled. Secondly, a multi-pronged approach is necessary and thirdly, it is not a quick job but takes a long term commitment. A systems ecology approach is needed in order to develop the holistic understanding that is necessary to address eutrophication. The strategy needs to include technical, biological and social components if re-oligotrophication is to be successful. Post-normal science (Funtowicz and Ravetz, 2008) provides a basis for making decisions in a situation where both the stakes and the uncertainties are high. An adaptive management approach provides a framework within which decision makers and managers are able to learn by doing, thus enabling decisions to be taken based on incomplete knowledge which can be checked and refined as the work progresses.

In recognition of the centrality of a systems ecology approach, the review of Phase 1 and the development of recommendations on Phase 2 thus require a fundamental understanding of the socio-ecological meta-system. Chapter 4 sets the socio-economic scene within which the Dam functions. The key ecological parameters within the system are then elucidated and linked to the socio-economic system through the ecosystem services which they provide are described in chapter 5. This demonstrates importance of the Hartbeespoort Dam within the system and identifies the key challenges to which Phase 2 of the HDRP will need to respond.

Chapter 6 identifies key hazards resulting from a variety of future changes which may be expected to occur in the system. The HDRP Phase 2 needs to be able to manage and mitigate these hazards and the risks they pose to ecosystem services.

There has been considerable growth of the conurbation in the catchment and this has affected the Hartbeespoort Dam meta-system in the following ways:

1. Water use from the Dam is expected to increase in future. In particular, there are plans to supply the Lephalale industrial development area through a water transfer in the medium term.
2. The population and the economy of the area is projected to grow which will exacerbate the problem if impacts are not managed. Associated with this, the urban spread has increased the area of hard surfaces, so changing the pattern of runoff, with reduced infiltration to the groundwater and higher flood peaks after rain. Thus, increasing quantities of water have been pumped from the Vaal catchment to supply the needs of the economic and urban growth. This has resulted in increased discharge of effluent into the catchment and translates into an increase of flow into the dam. The urban and industrial growth in the catchment, together with the increase in hard surfaces resulting from urban sprawl, will result in an increase in the nutrient and pollutant load into the system.
3. The mining activity has led to decant of acid mine drainage (AMD) into the system. Projections are that this will increase over time and this AMD will find its way to the Dam.
4. The DWS has, through the WRCS, gazetted certain environmental quality policy imperatives for the system, and these need to be implemented in future.
5. A variety of other emerging hazards, such as climate change effects, sewage spills and sediment deposition also exist.

The HDRP Phase 1 Business Plan (2006-07) has 10 focus areas addressing the dam basin, 5 addressing upstream activities and 1 addressing downstream activities. Chapter 7 addresses specifically the science of the dam basin activities, reviewing the HDRP Phase 1 Business plan and associated documents, in particular the Consolidated Phase 1 report (HDRP, 2012a), against the benchmarks identified. These benchmarks include:

- Systems ecology approach
- Goal setting
- Limit/divert influx of nutrients
    - Phosphate management
- Bio remediation
- Understanding hazards in the system
- Adaptive management approach to managing complex systems
- A focus on the full set of ecosystem services provided by the Dam
- A focus on job creation

A number of biological and physical interventions have been implemented with the aim to improve the dam. The catchment upstream has not been addressed during Phase 1.

The HDRP Phase 1 has achieved many successes. These include, for instance, the large scale hyacinth and other alien plant removal, the testing of floating reedbed systems, a fisheries programme and the clearing of debris from the system. In addition, the zone of sediment in which the P is concentrated has been mapped and pilot-scale zoning has been carried out.

However, there are also a number of key problems with Phase 1. The most fundamental problem is with the vision of the HDRP which states that '*The Future Desired State (FDS) of the dam is a residential dam focused on water based recreation, with clarified equitable public and private access, as well as controlled commercial operations, offered in a safe and healthy environment, from both a physical and environmental perspective*.' This is clearly in conflict with current water policy and water management planning, which puts the emphasis on water equity, and in the Crocodile-West system on water provision to large users in irrigation and the Lephalale area. We strongly recommend that this vision be revised and that the management goals that cascade from this be revised accordingly.

A second weakness of the HDRP Phase 1 is a failure of focusing on managing phosphate. Eutrophication is defined as 'excessive richness of nutrients in a lake or other body of water, frequently due to run-off from the land, which causes a dense growth of plant life'. While both Phosphate and nitrate are causes of nutrient enrichment, phosphate is more important than nitrate in this process. The reason is twofold. Firstly, Phosphate is more difficult to remove during the wastewater treatment process than nitrate and secondly, when excessive phosphate is present in a waterbody, blue-green algae (cyanophytes) are able to dominate the system as these are able to fix atmospheric nitrogen. Management of phosphate in the system is, therefore, the first step in the control of eutrophication.

Another weakness is in technical and financial governance. The monitoring programme seems to be defunct, the technical committee responsible for technical governance of the programme is defunct, and there are numerous problems with the financial management of the programme.

It is recommended that that a full-time financial officer be appointed and that annual internal audits be conducted.

The review of the technical governance proposes that the HDRP Phase 2 adopts an adaptive management approach. This approach is well suited to managing large scale remediation projects in complex systems, and managing the associated risk environment associated with possible future outcomes or hypotheses. Successful adaptive management is based on good science, and relies on the involvement of independent experts as appropriate. In addition, it requires a formal approach to assessing remediation options as well as an appropriate monitoring program to assess whether the goals that have been set are being achieved. Importantly, it provides a system within which it is possible to make decisions based on incomplete data and to refine the decisions based on the results of the monitoring programme.

The backbone of the adaptive management programme is the development of a system conceptual model (SCM). This would be based on what is known about the dam and its meta-system. The SCM will provide the basis for integrating the interactions occurring in the complex socio-ecological system within a framework such as the Anderies Framework. The SCM will identify gaps in current knowledge and provide a basis for prioritising future interventions. It should provide the background to the planning and goal development of the adaptive management, structure. It will also provide the basic structure of an integrated model of the catchment which is needed to guide catchment management.

The technical governance of the HDRP is not adequate. The HRDP was originally intended to be overseen by a technical committee, entitled a Project Management Committee. The most recent set of Minutes of Meeting of this committee that we received was from 2011 and it therefore appears that the technical committee either does not exist or does not meet. It is therefore not clear whether rigorous technical oversight of the programme exists. The fact that the monitoring programme has also stopped since 2011 is an indication that the technical governance of the Project Management Committee was not exercising its oversight role.

It is in the nature of complex system management and multiple stakeholder involvement, that consensus is not easy to achieve. However, the WRC has developed excellent methodology and governance systems for managing science, research and development of complex ecological systems. Thus we strongly recommend that the WRC become involved in the HDRP Phase 2, and play a key role in the design of the SAM approach and the various supporting initiates.

The need for stakeholder collaboration is an integral component of adaptive management. One important aspect of this is that stakeholder satisfaction is an important consideration. Amongst the large water users who are important stakeholders are water service authorities, municipalities, irrigated agriculture and mines. The recommendation is made for the formation of a formally-structured stakeholder forum.

Chapter 10 covers the assessment of the value for money. Comparison of the business plan budgets and actual spending reveals that actual expenditure was consistently far less that the proposed budget amounts, with a total budget of R504 530 307 and actual expenditure for the same period total of R150 186 939.08. This is highly problematic, as it either reflects an opportunistic and unrealistic budget, or a lack of funding commitment. There are also consistently very large discrepancies between detailed budgets and actual expenditure, and some expenditure items are reported against incorrect budget items. Job creation was low, very little non DWS funding was sourced, and several problems where asset management were identified. Moreover, Rand Water in 2009 conducted an internal audit of the HDRP and highlights a number of high risk areas in the HDRP[2]. The internal audit report was limited to transactions that had taken place between 1 April 2008 and 31 March 2009 (Rand Water Internal Audit No. 678/09). In this report 59% of the findings were described as “High Risk” areas. It is not clear whether these audit findings were addressed since 2009.

We make the following key recommendations for HDRP Phase 2:

Change the key emphasis of the HDRP from managing aesthetics to managing nutrient input

The Dam directly and indirectly supports a diverse local economy and provided that the water quality remains useable it will continue to do so. Working into the catchment to clean that up is an imperative, but this review recommends that there is justification in continuing with the in-lake interventions. We see that these need to be planned carefully and with an overall goal in mind. These interventions also need to be accurately monitored to see whether they are helping to achieve the goal or not. The HDRP Phase 1 has focused on aesthetics rather than addressing the increasing ingress of phosphorous into the dam. This has delayed the management decision to address the P load coming into the lake from the catchment, causing the total load into the dam to increase, with the concomitant increase of P stored in the dam. Phase 2 needs to give more attention to reducing the contributions of nutrients and pollutants from the catchment to the dam.

While phosphorous management in the catchment is covered in the business plans, it appears that this was not prioritized. The integrated monitoring report (HDRP, 2013c) worked into the catchment, but the Phase 1 progress report (HDRP, 2012a) shows an almost exclusive focus on the dam aesthetics.

Implement a scientific management approach

There is a need for a system conceptual model that can quantify the physical, chemical and biological relationships of the activities occurring in the catchments and the effect of these on the water quantity and quality of the dam. The development of this model will need to start with existing data and knowledge on the system. It will then be possible to identify the priorities for

---

[2] The appointment letter was signed on the 13th of October 2009 by Mr M (Mike) Ramukumba (who also led the internal audit), Mr Mandla Xulu and Mr Sameer Morar

management. Ideally, it should be developed in such a way that it may be applied to other water bodies as well

The programme has shown an overall lack of scientific rigour. This makes it impossible to assess the actual impact of each of the interventions. It also means that there is no firm ground which can serve to guide decisions on future interventions. A point of departure of this should be to develop an SCM with associated remediation goals, and linked to an appropriate monitoring program.

The assumption that the HDRP is responsible for the current state of the dam should be tested in the light of the overall current state of the dam and from the basis of understanding limnological processes likely to occur under the current status quo of the dam.

There is an acute shortage of limnologists in the country. Capacity building at all levels as well as succession planning need to be worked into the programme to ensure the continuity of the work.

There is little evidence that the body of work that has been done on the dam over the years has been taken into account in the implementation of the HDRP.

Hypotheses which could be investigated

The lake level has been stable for approximately 2 decades. This has created conditions which allow for the establishment of a filamentous algal mat as well as rooted macrophytes which compete for the pool of dissolved nutrients and also reduces the re-suspension of phosphate-rich sediment. The influence of this on the overall nutrient dynamics of the lake has not been ascertained.

Hypothesis 1 is that the establishment of submerged vegetation in the littoral zone reduces the re-suspension of nutrient-rich sediment, so reducing the level on nutrient in the water body.

Hypothesis 2 is that the establishment of submerged vegetation in the littoral zone effectively sequesters nutrients from the water body, so reducing the likelihood of algal blooms.

A question that arises is how is the lake going to respond when the water level is drawn down for extended periods each year, scheduled to begin in 2017, when water from Hartbeespoort is transferred to the Lephalale area? This gives rise to further hypotheses:

- The P in the exposed and re-wetted sediment will be temporarily immobilized;
- The pollutants in the exposed and re-wetted sediment will be mobilized;
- The fluctuation in water level will stimulate germination of hyacinth seeds in the seedbank in the exposed and re-wetted sediment;
- Pollutants (including heavy metals) will be released into the water column by the dredging process;
- While the zones of sediment deposition in the dam will be targeted by the dredging operations, there is a substantial accumulation of P elsewhere in the dam as a result of the rain of dead algae that has occurred over the years. This will be available for release during stratification of the water body.
- The energy pathway shifts from phytoplankton – zooplankton – fish to phytoplankton – decomposers in algal-dominated systems.

Implement an adaptive management approach

Remediation of eutrophic or hypertrophic water bodies is a problem that cannot be solved by a single technology. It requires an approach which integrates a number of technologies both in the catchment and in the water body. Phase 1 implemented a number of interventions, mostly biological, in the dam itself, but the phosphate load into the dam continued to increase at a rate greater than the interventions implemented can cope with. If the problem is to be solved sustainably then it will be necessary to reduce the load of phosphate into the dam. Once this has been achieved the water quality of the dam will improve. This will not be a quick process.

Implement a dedicated monitoring system

The monitoring programme should be planned and implemented within the adaptive management programme and should be designed to address the needs of the HDRP Phase 2. This will ensure that the monitoring programme is given the correct weighting in the programme and it will ensure that records are kept.

Remediation options assessment system required

This should form part of the system conceptual model and should be considered in the adaptive management framework, using rigorous selection techniques. It is common cause that there is no one optimal solution for a large scale remediation problem, and this is especially so for the HDRP. Risk management therefore has a dominant role in adaptive management decision making for managing remediation as it provides a rational framework for evaluating problems and determining the availability of solutions. It is not, however, the only decision criterion. The drivers for a remediation project, the boundaries limiting what can be done on a system, the suitability / feasibility of available remediation options, the views of different stakeholders and the wider effects of the remediation work should all influence the choice of approach. An appraisal of costs versus benefits can be a useful approach to integrating this wide range of considerations.

Establish a technical governance committee

Successful adaptive management is premised on good science, and involving independent experts and thus highly dependent upon good technical governance. In addition, it requires a formal approach to assessing remediation options; as well as an appropriate monitoring program, that follows from the adaptive management approach. It is in the nature of complex system management and multiple stakeholder involvement, that consensus is not easy to achieve. However, the WRC has developed excellent methodology and governance systems for managing science, research and development of complex ecological systems. Thus, we strongly recommend that the WRC become involved in the HDRP Phase 2, and play a key role in the design of the SAM approach and the various supporting initiatives.

Capacity building program required

There is an acute shortage of limnologists in the country, especially those with the expertise to manage eutrophication. There is also an acute shortage of specialists in other disciplines related to impoundment management and the management of the complex socio-ecological systems that have developed in the urban, industrial and other economic hubs in the country.

The focus of the HDRP is on Hartbeespoort Dam, but there are other dams that need the same attention. It is important that HR capacity is developed not only for succession planning but also to address the problem on other dams in South Africa, not all of which are in the Gauteng region.

Job creation program required

A job creation programme needs to be developed. The job creation programme needs to be carefully planned to ensure that it builds capacity while at the same time delivering value for money. Examples of similar programmes may be seen in the 'Working for' programmes. The programmes need to define the different skills required as well as the approximate number of people with each skill. In this way it will be possible to build teams with the correct balance of skills to work on each of the sites where remediation is taking place.

Improve the financial management of the program

The HDRP has not published annual reports with budgets and audited statements against which the business plans may be assessed. In addition, in the absence of any evidence that the internal audit findings were addressed, and in the context of the budgetary and expenditure problems identified, we recommend a significant improvement in the financial management of the HDRP Phase 2. We propose that a full-time financial officer be appointed and that annual internal audits be conducted.

Establish an appropriately constituted stakeholder forum

We propose that a stakeholder forum be established. Membership should be carefully considered within an appropriately structured sub-committees system according to the mandate represented by the stakeholders. This does not mean any stakeholder gets excluded, but rather that there is balance of representation with respect to ecosystem services and system priorities. Moreover, the stakeholder forum must be appropriately constituted. The DEA protocols that exist for constituting and governing environmental management committees provide appropriate precedent for this

Structure of the report

This review was conducted in two ways. Firstly, expert studies were conducted on the following topics:

- Technical comprehensiveness of the HRDP Business Plan for Phase 1
- Monitoring of the HDRP management
- Water quality monitoring programme
- Technical governance of the HDRP
- Review of the Science of Phase 1 with recommendations for Phase 2
- Interested and affected party relations / public engagement
- Value for money
- Roadmap for reducing the phosphorous load from the Hartbeespoort Dam catchment
- The influence of mine water of water quality of the Hartbeespoort Dam

Secondly, the stakeholder engagement process has two initiatives. A number of subject matter experts from different disciplines were interviewed, either face to face or over the telephone on topics related to Hartbeespoort Dam. Insights from these SMEs have been worked into relevant chapters of the report. In addition, a consultation meeting open to the public has been held.

Questions which have been raised in Parliament on the Hartbeespoort Dam and are available from the Parliamentary Monitoring Group (https://pmg.org.za/) and the Metsi-a-Me (http://www.harties.org.za/) websites. The information has also been worked into relevant chapters of the report.

Acronyms

AMD	Acid Mine Drainage
BIC	Bushveld Igneous Complex
BMAA	β-Methylamino-L-alanine
Chl-a	Chlorophyll-a
CMA	Catchment Managements Agency
CSIR	Council for Scientific and Industrial Research
DACE (DACET)	Department of Agriculture, Conservation and the Environment (and Tourism)
DO	Dissolved oxygen
DPSIR	Drivers, Pressures, State, Impact, Response
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Electrical conductivity
ECL	Environmental critical level
EIS	Ecological importance and Sensitivity
EWR	Environmental water requirement
FDS	Future Desired State
GDP	Gross Domestic Product
GVA	Gross Value Added
GWS	Government Water Scheme
HDI	Historically disadvantaged individual
HDRP	Hartbeespoort Dam Remediation Programme
IA	Implementing Agreement
IBT	Inter-basin transfer
ISO	International Organisation for Standardisation
IUA	Integrated Units of Analysis
LEDRG	Lake Ecosystem Dynamics Research Group of the University of Helsinki
LM	Local municipality
MCWAP	Mokolo and Crocodile River Water Augmentation Project
MERIS (FR)	Medium resolution imaging spectrometer (full resolution)
Ml/d	Megalitres per day
MM	Metropolitan municipality
Mm^3/a	Millions of cubic meters per annum

N	Nitrogen
NIWR	National Institute for Water Research
NWA	National Water Act
OECD	Organisation for Economic Co-operation and Development
ORP	Oxidation reduction potential
P	Phosphorous
PES	Present Ecological state
PGM	Platinum Group Metals
REC	Recommended ecological category
RHP	River Health Programme
RMP	Resource Management Plan
RQO	Resource Quality Objectives
RW	Rand Water
SASS	South African Scoring System
SCM	System conceptual model
SES	Social-ecological system
SMME	Small, medium and micro enterprise
SRP	Soluble reactive phosphate
TDS	Total dissolved solids/salinity
TN:TP ratio	Total nitrogen to total phosphorous ratio
TOR	Terms of Reference
TPC	Thresholds of Potential Concern
TSS	Total suspended solids
VAD	Value Added
VIP	Ventilated improved pit latrine
WDCS	Waste Discharge Charge System
WISA	Water Institute of Southern Africa
WMA	Water Management Area
WMS	Water management system
WRC	Water Research Commission
WRCS	Water Resource Classification System
WRPM	Water Resource Planning Model
WTW	Water treatment works
WQ	water quality
WQSU	Water quality sub-unit

WWTW	Wastewater treatment works

Glossary of terms

Anthropogenic	Originating from human activity
Ecostatus	'The totality of the features and characteristics of the river and its riparian areas that bear upon its ability to support an appropriate natural flora and fauna and its capacity to provide a variety of goods and services'.
Ecosystem services	The benefits derived by humans from ecosystems
Epilimnion	The water above the thermocline.
Eutrophic	Excessive richness of nutrients in a lake or other water body. Water in the deeper parts lack oxygen for part of the year.
Hypertrophic	A waterbody which is more nutrient rich than eutrophic
Hypolimnion	The water below the thermocline. This may become anaerobic under nutrient-rich conditions.
Isothermic	Condition prevailing when the water of a lake is the same temperature from top to bottom
Mesotrophic	The nutrient status of a water body which is between oligotrophic and eutrophic
Monomictic	A waterbody that has one period of turnover per year
Oligotrophic	Relatively poor in plant nutrients and containing abundant oxygen in the deeper parts.
Seiche	A temporary disturbance or oscillation in the water level of a lake or partially enclosed body of water, especially one caused by changes in atmospheric pressure
Thermocline	The zone of rapid temperature (and density) change separating the epilimnion and hypolimnion of a body of water, causing stratification of the water body
Turnover	Mixing of the entire water body under isothermic conditions

Acknowledgements

We express out appreciation to the number of people were consulted during the review process for sharing their knowledge and experience with the review team. These people are identified in the following table.

In particular we thank Mr P Venter, the programme manager, for providing us with the material to review.

We thank the Water Research Commission for giving the opportunity to review this programme. In particular Dr Jennifer Molwantwa for guidance and support.

People consulted	How consulted	Expertise / Affiliation
Azui, Ms T	Meeting	Rand Water
Bierman, Mr Bertus	Verbal	Water portfolio, Anglo mining
Botha, Mr F	Verbal and written	Meerhof resident
Brisley, Ms M	Verbal	DWS, ex-North-West region, now Head Office
Coetzee, Ms L	Verbal, Water Wheel, WRC report and other articles	Ex Deputy Director, Bulk water supply, Tshwane MM, ex Rietvlei water works. Worked with the Solar bees
Coleman, Mr T	Verbal	Golders, Experienced in water resource management
Cronjé Mr M	Meeting	
De Jager, Mr M	Verbal	ex Metsi-a-Me monitoring Programme
Ellis, Mr AF	Meeting	Westlake Country and Safari
Ellis, Mr R	Meeting	Ward Councillor (Ward 29)
Esterhuyse, Mr Kerneels	Verbal	Wastewater Treatment, City of Tshwane
Ferrall, Mr P	Written	Consultant
Fourie, Mr	Verbal	Manager, Hartbeespoort Irrigation Scheme
Grosch, Mr C	Meeting	Hartbeespoort Tourism Association
Harding, Dr WR	Verbal, email & publications	Lake management specialist; Wrote the Hartbeespoort Action Plan (Vol 1 & 2) published 2004
Hill, Prof Martin	Verbal	Ex ARC, now Rhodes University, does a lot of work for Working for Water on Biological Control of alien invasive weeds
Holmes, Mr D	Meeting	Caribbean Beach Club
Jooste, Dr S	Verbal	RQIS, DWS
Kellner, Ms A	Meeting	Student

People consulted	How consulted	Expertise / Affiliation
Keto, Mr J	Email – awaiting further correspondence	Bioremediation, Finland
Kruger, Mr J	Verbal	Pecanwood estate and Chairman of the Association of resident Communities
Ledger, Ms G	Verbal and written	Resident of Pecanwood, ex-Metsi-a-me member
Louw, Mr Dries	Verbal	Urban effluent treatment-retired Director and Lab manager of ERWAT
Manus, Ms A	Verbal	Johannesburg Municipality
Mare, Mr J	Verbal	ex Metsi-a-Me monitoring Programme
Martin, Mr R	Verbal	Pretoria resident, Hartbeespoort Dam angler
McKay, Mr G	Verbal and written	Founder and past chair of HWAG, ex-HDRP member
Mdulusi, Ms S	Meeting	Harties Metsi a Me
Molekwa, Mr S	Meeting	Rand Water
Morar, Mr S	Verbal and written	Implementing Agent, Rand water representative
Nel, Mr G	Meeting	The Islands Estate
Pirow, Mr P	Meeting	Necsa (Environmental Management)
Potgieter, Mr T	Meeting	Pecanwood Estate
Sharpe, Ms D	Meeting	The Coves
Siaga, Mr E	Meeting	Harties Metsi a Me
Silberbauer, Dr M	Verbal	RQIS, DWS
Strohmeneer, Mr L	Meeting	Ifafi Aquatic Club
Supple, Mr F	Meeting	Transvaal Yacht Club
Van Ginkel, Dr C	Verbal	Ex-RQIS, DWS (managed the National Eutrophication Monitoring Pgm) and now consultant-involved in Metsi-a-Me
Van Heerden, Ms E	Meeting	Necsa (Environmental Management)
Van Riet, Prof W	Verbal	Hartbeespoort Dam Resident
Van Rossum, Mr R	Verbal	Current Chairman of HWAG
Venter, Mr P	Verbal and written	Programme Manager, HDRP
Wentzel, Mr J		Resident, Hartbeespoort Eastern Foreshore
Wilkinson, Ms M	Verbal and written	Sustento Development Services
Wilsenach, Dr J	Verbal	Wastewater treatment Process engineer, Virtual Consulting. Grew up in, and parents still resident in, Schoemansville

Table of Contents

List of Tables

List of Figures

2 Introduction

2.1 Purpose of this Chapter

The purpose of this review is to assess Phase 1 of the Hartbeespoort Dam Integrated Biological Remediation Programme (HDRP) and to make recommendations for the future Phase II of the programme. The review benchmarks the HDRP against selected national and international benchmarks which are introduced as appropriate through the document.

This Chapter provides the background to the Hartbeespoort Dam Integrated Biological Remediation Programme. The value of Hartbeespoort Dam is described, and is put in the context of the strategy for managing the nation's water resource. Eutrophication, the central problem to be addressed, is explained and the consequences are outlined.

The extent of the eutrophication and its implications to the social-ecological system based on the dam led to a request from the Department of Water and Sanitation (DWS) to the Water Research Commission (WRC) to commission an independent review of the HDRP. Based on this request, the WRC developed the Terms of Reference which is addressed by this report. The standards against which aspects of the HDRP have been benchmarked are listed in this chapter.

2.2 Background to the Review of the Hartbeespoort Dam Integrated Biological Remediation Programme

For historical reasons the conurbation in Gauteng is based on the distribution of mineral wealth. This has attracted people to the employment opportunities as well as the industry to support the development of the mineral wealth. As the mineral wealth is situated on the continental divide the conurbation has developed remote from any water source sufficient to sustain it. Internationally, this is an unusual situation and has led to specific challenges in the management of the water resource. Water needs to be brought from far afield, a challenge solved successfully by engineering solutions.

Of greater concern currently is the challenge of managing the effluent from the conurbation. The institutional environment governing the management of effluents is complex and spread across different government structures. This, combined with the expense and difficulty of treating the effluents to a standard that will not impact the receiving environment, is one factor that has led to widespread eutrophication in the impoundments on the rivers draining Gauteng. Harding (2010) estimates conservatively that *35% of South Africa's impounded water resources are seriously impaired (eutrophic to hypertrophic); a further 20-30% are incipiently problematical. All of the major impoundments in the economic heartland of the country, Gauteng, are grossly impaired. The full extent of the problem is unknown as no systematic comprehensive spatial surveys have been conducted.* The answer to Parliamentary question 2428 of 20 September 2013 on the percentage of dams currently eutrophic is that 5% are currently eutrophic. This is an underestimate. Recent work by Matthews (2014), using remote sensing, found that the majority (62%) of the 50 largest standing water bodies in South Africa were hypertrophic. The answer to Parliamentary question 2002 of 30 July 2010 is probably more accurate than the answer to question 2428 of 20 September 2013 as this answer lists impoundments across the country which are eutrophic or hypertrophic.

The HDRP was designed to give effect to the recommendations made by the various research initiatives in order to reverse the trend of increasing eutrophication in the impoundment. The intention is, then, to repeat successful initiatives in other eutrophic impoundments and to investigate and implement, if suitable, additional remedial interventions.

Eutrophication resulting from excessive nutrient pollution has been a problem in the Hartbeespoort Dam for many decades. The dam is important for water supply and irrigation, and is one of a number of impoundments downstream from the Gauteng conurbation affected by eutrophication, predominantly due to high phosphate levels, from the urban areas upstream. This leads to excessive algal or plant growth, causing taste, odour and sometimes toxic conditions in the water. Many studies have been done on this problem since the early 1960s. NIWR (1985) is a benchmark report. More recent work on this problem in Hartbeespoort Dam and catchment are Owuor et al. (2007), Bornman et al. (2007) and Barnard et al. (2013).

During 2003 the North West Department of Conservation and the Environment (DACE) and later Department of Agriculture Conservation, Environment and Tourism (DACET) issued a request for a proposal to develop a management plan for the Hartbeespoort Dam. The action plan, supported by various individual task assessments (Annexures and Appendices) (Harding et al., 2004 a, b), formed the basis of the HDRP. The HDRP is also known as the *Harties Metsi a me*[3] programme.

Rand Water was appointed by Department of Water and Sanitation (DWS)[4] as the Implementing Agent of the HDRP and the programme lead was assumed by the North West Regional Office of DWS. Phase 1 of the programme was initiated in 2006 and ended with the publication of the Phase 1 Consolidated Progress Report and a number of subsidiary supporting documents published in 2012 and 2013. This was followed by the Transitional Phase.

The HDRP started in the 2006/7 financial year and, to date, has a total expenditure on project, from 19 September 2006 to September 2014, of R158 725 549.67 (excl. VAT).

There appears to have been some controversy among various stakeholders about the HDRP, which have led to questions being asked in Parliament regarding the programme (Appendix 4). The topics which received most questions related to acid mine drainage, eutrophication and mitigation of pollution issues and issues around governance, the budget and audits.

In addition, significant changes are expected in the greater Hartbeespoort Dam meta-system in future. The dam level has been stable for almost 2 decades. This has changed the environment from that during the 1980s when the water level was low and fluctuating. The stable lake level has created conditions in which rooted macrophytes (emergent and submerged) may be able to establish. However, it is highly likely that these stable conditions would change in the near future as a result of water transfers to the Lephalale area, increased return flows from waste water treatment works and acid mine drainage.

In 2014, the Acting Director General of the DWS, requested a more detailed independent review of the HDRP to ensure that more focus was given to catchment activities inclusive of detailed action plans (HDRP, 2011). (See Chapter 2.5, 2.6 and Appendix 1 below for detailed Terms of Reference).

2.3 Why is the Hartbeespoort Dam valuable?

The primary benefit of dams is in its supply of water for productive uses. Growth of populations, agriculture, mining, commercial and industrial economic activity and households rely heavily on South Africa's available water resources as a critical input into livelihoods and economic production. South Africa is a water-scarce country and the pattern of precipitation has a high

[3] Harties Metsi a Me – Harties My water

[4] The Department of Water and Sanitation (DWS) has changed its name from the Department of Water Affairs and Forestry (DWAF) through the Department of Water Affairs (DWA) to DWS. For consistency the Department will be referred to as DWS.

coefficient of variability. In order to deliver water to the various users at the required assurance of supply it is necessary to impound water to ensure that water is available during the drier periods. The country, thus, relies on dams to sustain ecological, agricultural, urban, industrial, mining and all other activities. While the quantity of water impounded is important, the quality of the impounded water is also important in terms of the health of the users, including the environment, and the additional costs of working with poor quality water. Not only is it important that sufficient water is impounded to meet the demand but it is also important that the water impounded is of high enough quality to meet the intended needs.

The Hartbeespoort Dam was originally built to supply the irrigation scheme but the needs have evolved over time. It is particular is valuable for its current and future water supply to household use (via municipalities), irrigation agriculture, mining and recreation, with a number of up-market housing estates having been developed around the impoundment.

The Dam has also contributed to tourism and has increased property prices in residential areas adjacent to the Dam.

The above benefits of the Dam are put at risk due to severe eutrophication.

2.4 Central problem: Eutrophication and its consequences

Eutrophication is the enrichment of fresh water bodies by inorganic nutrients. It may occur naturally, but it is mostly the result of human activity.

The trophic status of a water body is defined by the level of plant nutrients in the water and the quantity of plant growth which these nutrients support (Table 2-1). The main nutrients responsible for eutrophication are phosphates and nitrates, with the phosphates being the main cause.

Table 2-1: The terms describing the trophic level of water bodies.

Trophic status	Description
Oligotrophic	Nutrient-poor water bodies that are generally clear, having a low concentration of plant life.
Mesotrophic	Water bodies having a moderate amount of dissolved nutrients
Eutrophic	Water bodies that are enriched with nutrients, resulting in good plant growth and possible algal blooms.
Hypertrophic	Bodies of water that have been excessively enriched with nutrients. These lakes typically have poor clarity and are subject to devastating algal blooms. Lakes typically reach this condition due to human activities in the lake catchment area.

The following table (Table 2-2) defines the limits set by the OECD and South Africa for Chlorophyll a and phosphate levels in impoundments for the various trophic levels of the impoundment.

Table 2-2: The limits of Chlorophyll a and Total Phosphorous used by the OECD and South Africa to define the trophic levels of water bodies (figures from Harding, 2015).

Trophic Status	Classification criteria			
	International (OECD, 1982)		South African (DWA, 2008)	
Parameter	Chlorophyll a (µg/ℓ)		TP (µg/ℓ)	
	OECD	DWA	OECD	DWA
Oligotrophic	≤ 2.5	≤ 10	≤ 10	≤ 15
Mesotrophic	2.5-8	10-20	10-35	15-47
Eutrophic	8-25	20-30	35-100	48-130
Hypertrophic	≥ 25	≥ 30	≥ 100	≥ 130

As may be seen from Table 2.2 the TP limits set for South African impoundments are substantially higher than those set by the OECD.

The major sources of nutrients are anthropogenic and result from point sources in the form of wastewater treatment works (WWTW) effluent and diffuse sources such as sewage spills and fertiliser runoff. Eutrophication is particularly evident in slow-moving rivers and shallow lakes, such as the dam, where it will cause one or more of the following effects if not controlled:-

- ***Decrease in biodiversity.*** Eutrophication kills the more sensitive species of fauna and flora, decreasing the biodiversity. At the same time, the density (or biomass) of the more resistant species tends to increase to a peak until, in extreme cases, the biomass will decrease. The South African Scoring System (SASS) test is designed to measure the degree of eutrophication of water bodies, rivers in particular. One effect of eutrophication is that it causes the loss of desirable fish species. In addition, direct spills of sewage deplete the oxygen in the water killing the organisms living there.
- ***Excessive growth of algae or plants***. The most common algae in eutrophic systems are the blue-green algae (cyanophytes) (Figure 2-1). Cyanophytes have the competitive advantage in eutrophic systems which have excessive P as they are able to fix atmospheric nitrogen. Nitrogen is the limiting nutrient in Hartbeespoort and other impoundments for two reasons – (a) waste water treatment technology is generally more effective at removing nitrogen than phosphorous and (b) further denitrification occurs in the anoxic hypolimnion of impoundments. Cyanophytes cause bad odour problems and have the capacity to develop toxins. There have been a number of cases of livestock and wildlife deaths in South Africa through ingesting algal toxins. Microsystin, one of the toxins generated by the blue-green alga *Microcystis*, is a small, stable molecule. This renders the water unsafe to drink, and people especially at risk are those who rely on the water directly from the environment for their needs and those who are immune-compromised. Excessive surface plant growth, water hyacinth being the most common in Hartbeespoort Dam, covers the water surface with a dense growth, preventing light from penetrating the water. As it dies the dead material sinks to the bottom and microbial action uses the available oxygen, killing off the other organisms which contribute to the stability of ecosystems.

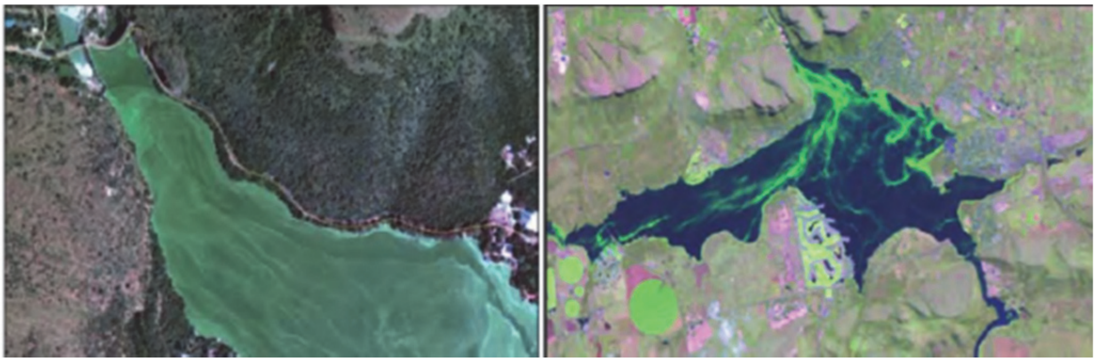


Figure 2-1: The figures show satellite images of algal blooms on Hartbeespoort Dam (taken from HDRP, 2013a)

Problems in treating water for potable or other uses. Algae cause blockages in water treatment works (WTW) systems, and in addition, in order to render water from a source contaminated with blue-green algae safe, it is necessary to use activated carbon. This increases water treatment costs.

- ***Human health risk***. Water from an eutrophic source is not only unhealthy *per se*, but is an indicator of contamination which, if it comes from untreated sewage is likely to harbour disease-causing microbes or, if from some other source, may contain contaminants such as pesticides, heavy metals, trihalomethanes or endocrine disrupting compounds. Prolonged exposure to these may be harmful to both people and ecosystems.
- ***Aesthetic effects (colour, odour, hyacinths etc.) on property value.*** Eutrophication negatively affects the aesthetics of a water body. Not only does the water look unattractive but blue-green algal blooms may cause the water body to smell bad. This effect will not only impair the recreation experience of users, but where residential or business facilities are adjacent to the water the appearance and odour will impact negatively on the value and the experience of using the facility. Dense growths of plants such as hyacinth on the surface affect the aesthetics of a water body through the decrease in the 'sense of place' experienced by users, but also by making the water surface inaccessible for recreation. Ongoing mechanical removal of the hyacinth, as practiced by the HDRP, is necessary to prevent the hyacinth problem from getting out of control, and should be continued.
- ***Risk to irrigation agriculture.*** While high nutrient loads are not a concern to irrigated agriculture, the possibility of certain salts, residual pathogens or cyanobacterial toxins on the irrigated produce are of concern and irrigators address this before marketing their crop.

The above risks result in economic costs. Graham and co-workers (2012) showed that severe eutrophication not only increased costs of water treatment, but also increased the cost to agriculture (livestock health and crop losses), caused a decline in value of property adjacent to the water body and lead to a substantial decline in recreation services through decking aesthetic values of the locality. In general, eutrophication needs to be prevented at source and its effects mitigated as it has a negative impact on the health of the people and the national economy.

2.5 Request for an independent review of the HDRP from the Department of Water and Sanitation to the Water Research Commission

The DWS requested the Water Research Commission (WRC) to conduct an external independent review of the HDRP to assess the processes of the programme since its inception and to advise on the future of the HDRP. The assessment was also required to evaluate the holistic effects of the programme, addressing all components of the programme's activities in the catchment on the water resource.

2.5.1 Challenges

The request to the WRC lists the following challenges:

- The activities of diverse role players (parties / institutions / authorities) in the catchment are impacting on the quality, quantity and the hydrograph of the influent rivers as a result of the on-going rapid development of the catchment.
- The capacity, ability and political will / commitment by municipalities to implement and / or enforce bylaws to ensure improved management practices in their areas of jurisdiction and to adhere to the requirements of DWS.
- The hydraulically complex and dynamic system within the catchment makes it difficult to accurately quantify the impacts of the HDRP.
- There is no integrated predictive model that can quantify the physical, chemical and biological relationships of the activities occurring in the catchments.

2.5.2 Information available on the HDRP

There are a number of reports on the activities of the HDRP which have been written for various audiences such as Parliament (and associated committees), DWS (and associated committees) and to the North West Province DACET. Business Plans have also been developed. These are all available on DVD. There is also a website[5] which houses current information.

2.5.3 Scope of Work (as requested by the DWS)

The full Terms of Reference for the review from the Department of Water and Sanitation to the Water Research Commission are given in Appendix 1, Chapter 13.1. A brief summary is given here.

Ascertain whether the HDRP has achieved the desired outcomes as described in the business plans.

This task includes the administrative and management activities

Outcomes assessment

The effectiveness and efficiency of the HDRP, including, but not limited to, the outcomes, value for money, use of funds and skills

Address the concerns and inputs on different levels and for different stakeholder sectors

Political (e.g. Members of Parliament, provincial and local / regional)

Institutional (emphasis on legal and provincial government departments and DWS.

---

[5] http://www.harties.org.za/

Technical and scientific / academic specialists in water and integrated environmental management fields.

Technical review

Criteria to be agreed on for evaluating the efficacy of the implementation of the business plan, in relation to other (better / improved) alternatives that might ensure improved outcomes within the context of the National Water Act (NWA) and other environmental legislation to address the collective impacts from the catchments.

Assess the appropriateness of the above in terms of local growth and development goals.

Stakeholder engagement

There needs to be an effective stakeholder engagement process

Financial and economic

DWS and Rand Water (RW) have initiated an audit programme. The financial assessment needs to be done within the context of the Implementing Agreement. This should also address the expenditure for external stakeholders.

The potential economic benefits and socio economic growth and development targets of the North West Province, Hartbeespoort Dam Economic Hub, needs to be assessed and evaluated against other alternatives that may also stimulate continuous economic growth and confidence in development and investment.

2.6 The Terms of Reference of the Review

Based on the request from the DWS to the WRC, the WRC developed the Terms of Reference as follows. The full Terms of Reference as issued by the Water Research Commission are given in Appendix 1, Chapter 13.2. Salient aspects are given below.

2.6.1 Aim

To conduct an external independent review or assessment of the Hartbeespoort Dam Integrated Biological Remediation Programme (HDRP) (Harties Metsi a Me – “My Water”) that started in 2006 and to provide recommendations on the future of the HDRP.

2.6.2 Objectives

General:

To evaluate and assess the effect or impact of the HDRP in a holistic manner addressing the impacts received from the catchment activities on the dam in terms of the components associated with the dam. Specifically, to assess the degree to which the HDRP has achieved the outcomes and milestones as described in its business plans: to engage with relevant stakeholders to identify research questions that require further assessment/ investigation: To benchmark, using collectively agreed criteria, the effectiveness and efficiency of the HDRP thus far against possible appropriate alternative approaches. This should include but not be limited to outcomes, value for money and use of skills (see Chapter 1.6.4): To perform a financial assessment in the context of the Implementing Agent Agreement that exists with the DWS. Transparency and availability of expenditure for external stakeholders will be assessed and presented. Assess the HDRP and benchmark against appropriate alternatives, the potential economic benefits and socio-economic growth and development targeted by the Hartbeespoort Dam Economic Hub: And to provide recommendations on the future of the Programme.

2.6.3 Data collection

A colossal volume of documents has been generated during Phase 1. The Review Team, in preliminary discussion on how best to address the requirements of the TOR, has adopted the following approach. The review commenced with an analysis of the Implementing Agreement (IA) between the DWS and Rand Water. This included an assessment of the funds allocated to the programme. Then the Business Plans were examined with reference to the planned work and the outputs from the planned work. The detailed methodology is outlined below.

We conducted a meeting, chaired by the WRC, with DWS and Rand Water staff involved in the HDRP at Kurperoord on the 17th October 2014. At this meeting we received various reports from DWS staff and Rand Water staff. The DWS staff presented us with a CD containing a vast number of documents and, in addition to the public website, arranged access for us to the new site which is under development (http://41.79.107.124/hartiesdev/).

The Rand Water staff presented us with a memory stick containing business plans, financial summaries, and Internal Audit conducted by Rand Water in 2009.

We had a number of stakeholder interactions, in the form of meetings, telephone conversations and email communications with DWS staff, Rand Water staff, domain experts, community representatives and housing estate managers.

From the information obtained above we conducted a rapid assessment of the HDRP. The assessment started with a literature review

2.6.4 Standards against which aspects of the HDRP review have been benchmarked.

The following international and national standards have been used as benchmarks against which the performance of the HDRP has been assessed:-

- International and South African scientific literature on remediation of nutrient enriched lakes: this literature was used to develop an analysis framework against which the HDRP could be assessed (refer to Chapter 3).
- Millennium Ecosystem Assessment (MEA) framework of ecosystem services: this framework was used to assess the benefits of the Dam and contextualize the meta-system within which the Dam functions (refer to Chapter 4)
- The Anderies Framework was used to structure the systems analysis (refer to Appendix 5)
- Comparative risk assessment: this risk assessment approach was used to assess future changes within the meta-system that could put the ecosystem services related to the Dam at risk (refer to Chapter 6).
- Social Adaptive Management – Governance (refer to Chapter 8)
- National Treasury – value for money (refer to Chapter 10)
- Accounting standards (refer to Chapter 10)
- Adaptive Management (as practiced by the US EPA, South Africa (refer to Chapter 8.6)

2.6.5 Conclusions

The DWS requested from the WRC that the following challenges be addressed:

- The impact of the activities of diverse role-players on the quality, quantity and hydrograph of the influent rivers. The various impacts have been addressed in the appropriate chapters of the report.
- The capacity, ability and political will has been addressed in some cases (City of Tshwane, Johannesburg Water).
- The hydraulically complex and dynamic system within the catchment makes it difficult to accurately quantify the impacts of the HDRP. A systems ecology approach has been adopted in the review to provide the methodology to assess this.
- The development of a System Conceptual Model is recommended to provide the integrated predictive model to quantify the complex relationship of the social-ecological system in the catchment (see, for instance, Chapters 8 and 11).

The assessment of the efficiency and effectiveness of the HDRP in the various fields such as the outcomes, value for money, use of funds, use of skills, science of the HDRP, capacity building and other aspects are covered in the appropriate chapters of the document.

The WRC Terms of Reference were addressed as follows:

- The achievement of the outcomes and milestones of the HDRP have been assessed as described in the relevant chapters below.
- A number of stakeholders and subject matter experts (see Appendix 5) were interviewed and their opinions have been worked in to the report in the appropriate places.
- The effectiveness and efficiency of the HDRP thus far have been benchmarked against the standards given in Chapter 2.6.4 above.
- The financial assessment is provided in Chapter 10.
- Appropriate alternatives against which the HDRP may be assessed are discussed in relevant chapters of the document including Appendices 3 and 4.
- Recommendations for the future of the HDRP are given in appropriate chapters.

3 Literature review

3.1 Purpose of this chapter

The purpose of this chapter is to evaluate international and South African literature on lake eutrophication in order to identify key focus areas for remediation programs for lakes with severe eutrophication problems. This analysis forms an important benchmark against which the HDRP Phase 1 is to be reviewed and against which Phase 2 gap analysis is to be conducted.

Recent references have been used as much as possible in order to draw on the most recent findings for guiding the future of the HDRP.

3.2 Overview of international literature on lake eutrophication

Beklioglu et al. (2011), in their review of the eutrophication and restoration of lakes in cold and warm climates note that lakes respond to external forces in a non-linear fashion. The 'alternate stable states' hypothesis asserts that shallow lake ecosystems can exist in more than one stable state. We estimate that Hartbeespoort Dam may be categorized as a shallow lake. One alternative is clear water dominated by submerged plants and the other being turbid water with phytoplankton or other suspended matter dominating. A third state is when the lake is dominated by floating plants. Figure 3-1 illustrates the hypothesis and relates the alternate stable states to total phosphate concentrations.

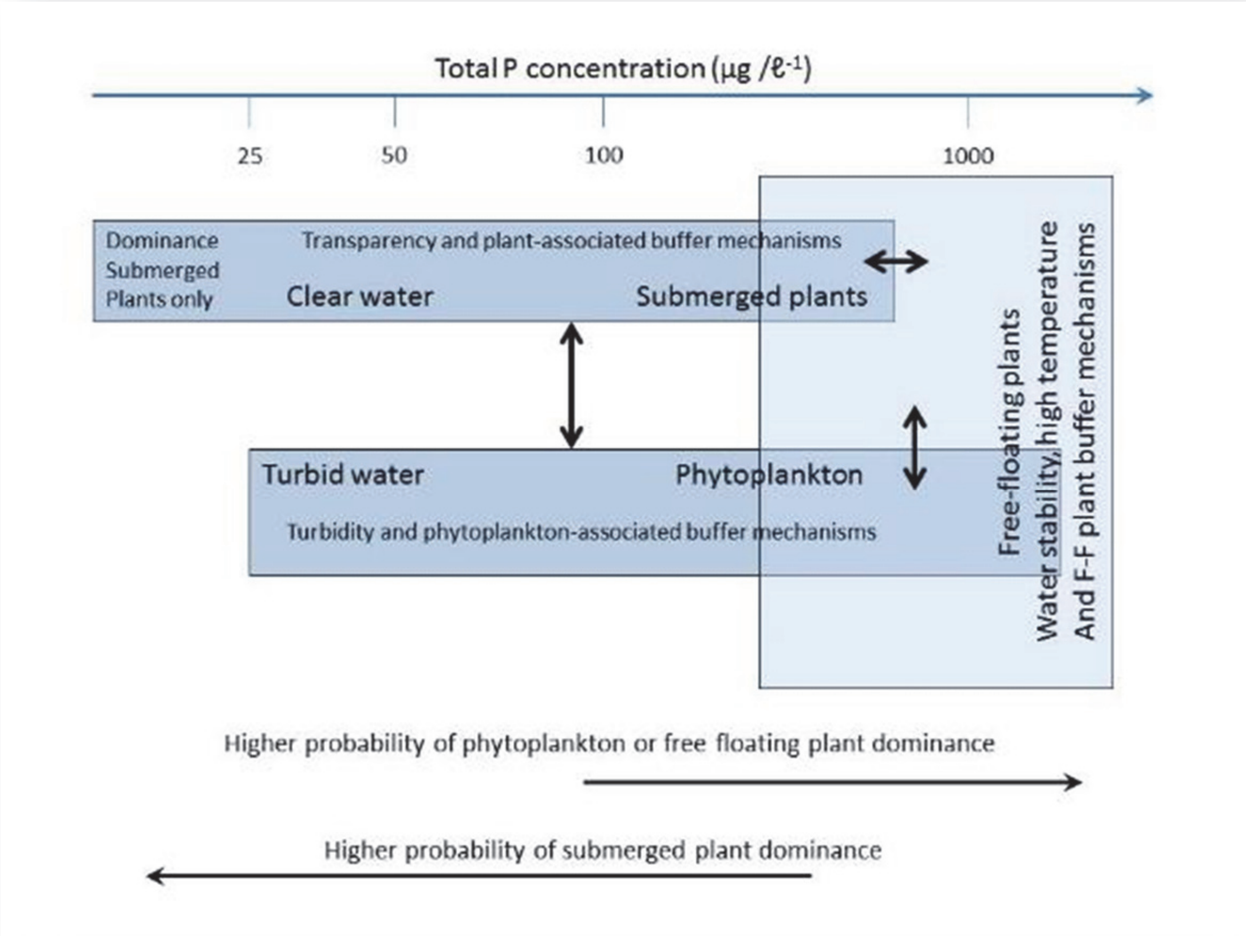


Figure 3-1: General model of the alternative states in shallow lakes over a gradient of nutrients (phosphorus) where the three main alternative states: (redrawn from Beklioglou et al., 2011)

Genkai-Kato and Carpenter (2005) note that lakes may have alternate states (as explained above) due to excessive phosphorous loading. These vary between clear water and turbid with high chlorophyll concentration water (Figure 3-1). Shifts between these states have significant effects on the ecosystem. These shifts may be difficult to reverse and are also difficult to predict as they depend on a variety of factors with lake morphometry, temperature and the dominance of macrophytes having been shown to be important. Genkai-Kato and Carpenter (2005) evaluated these and other factors using an empirically-based mechanistic model. The macrophyte effect of preventing phosphate (P) recycling from sediments was critical to the susceptibility of shallow lakes to regime shift. Warmer temperatures rendered eutrophication more likely and restoration generally less successful due to increased internal P recycling from the sediment. Lakes of intermediate depth are the most susceptible to regime shifts and the least restorable as they are too deep for the sediments to be protected by macrophytes but the P recycling is not mitigated by dilution by water from the hypolimnion during turnover. The results from this work showed interactions between a range of physical, chemical and biotic mechanisms which, between them, may be responsible for the regime shifts.

Lakes are complex systems and the factors researched by Genkai-Kato and Carpenter (2005) need to be included in the system conceptual model to be developed during Phase 2.

Understanding the hydrological regime is an important parameter for modellers and limnologists when making the decision as to which technology or suite of technologies to use. Klapper (2003) states that while priority action in curbing eutrophication and bringing about the restoration of the water resource is to stop the nutrient sources, in-lake technologies are also important, especially in lakes with a long retention time. As a generalization, natural lakes have a much longer retention time than impoundments. Hartbeespoort Dam has a short retention time. Aeration, natural or otherwise, does not provide the complete answer as many pollutants tend to accumulate in the sediment.

Mattson et al. (2004) examine a number of case studies from Massachusetts and review the various techniques used. They note that lake restoration is not a 'one size fits all' process but needs to be assessed on a lake-by-lake basis. Each of the following has a place and the decision as to which to use and should be tested in models to see which is likely to yield the most acceptable results before implementation is started.

They list the following options for controlling unwanted plant or cyanobacterial growth:

- Limit the supply of nutrients, this is the most effective method. There are a number of approaches to this:
  - Limit nutrient input from point sources
  - Manage non-point source of nutrient input (non-point sources are more difficult to control but nevertheless need to be controlled as the contribution may be significant.)
  - Implement hydraulic controls to limit nutrient input (e.g. diversion, dilution, flushing, hypolimnetic withdrawal)
  - Achieve P inactivation through chemical binding
  - Introduce artificial circulation and aeration
  - Do dredging to remove embedded P
  - Implement biological methods such as bacterial additives and the removal of bottom-feeding fish
- Use of biocides or biocontrol agents should also be considered where applicable.

Anneville and Pelletier (2000) note that Lake Geneva became eutrophic through the 1970s. Measures to reduce the P inputs began to be effective in 1981 and from 1981 to 1992 there was a correlation between the late winter concentration of soluble reactive phosphate (SRP) and summer algal biomass and chlorophyll-a. More recently however, there has been an increase in algal biomass and chlorophyll-a while the SRP remained low. This was due to the growth of inedible filamentous algae. These results stress the importance of studies at the appropriate time scales as the recovery of lakes from eutrophication is a long term process.

Tadonléké et al. (2009), working in Lake Geneva, revealed complexities related to the restoration of lakes through the reduction of total P. Initially the decrease in primary production was correlated to the decrease in total P, but after a certain point other factors such as incident light and water column stability increased the primary productivity even though the levels of total P declined, leading to a reduction in transparency. There was an apparent shift in the factors driving primary productivity nearly 20 years after the managed decrease of the total P levels which may be in part attributable to the influence of cladoceran grazing.

The Lake Ecosystem Dynamics Research Group of the University of Helsinki (LEDRG, Undated) note that originally, Lake Vesijärvi, Finland, was a clear-water lake, but anthropogenic eutrophication began already in the first decades of the 20^{th} century due to growing ingress of industrial wastewaters and domestic sewage. In the 1960´s, Lake Vesijärvi had become one of the most eutrophic of the large lakes of Finland. Keto and Tallberg (2000) recorded that Lake Vesijärvi became heavily eutrophied by 1975 when restoration measures were introduced. The sewage loading was diverted from the lake in 1976 and the loading of phosphorus and nitrogen into the basin fell to 8 % of the previous level and the lake started to recover.

In the 1990s, however, massive cyanobacterial blooms (*Oscillatoria agardhii Gomont, Microcystis* spp., and *Aphanizomenon flos-aquae* (L.) Ralfs) occurred again. To restore the lake, biomanipulation through mass removal of planktivorous and benthivorous fish was performed during 1989-1994. More than 1 000 000 kg (1 000 t) of fish was removed. Kairesalo (undated) reported that roach (52%), and smelt (28%) were the two dominant species in the catch. This fish harvest removed 6-8 tonnes of phosphorous, amounting to about 10 mg m^{-3} yr^{-1}. As a result, cyanobacterial blooms disappeared, water clarity increased and submerged macrophytes colonized larger areas. Following predictions by fish population analysis, moderate fish removal was continued.

However, during the 2000s the water quality again declined. The biomass of cyanobacteria has been increasing, although massive blooms have not occurred yet. But large areas of the hypolimnion have become anoxic during summer stratification period. To improve the water quality and reduce internal phosphorus loading, it has been decided that large scale aeration will be implemented.

The secondary decline in water quality after a period of water quality improvement as found in the above studies is from different species of alga which have larger cells and are inedible to the algal-eating zooplankton.

Kutics et al. (2013) note that Lake Balaton, Hungary, a large but very shallow lake suffered severe algal blooms for 3 decades as a result of anthropogenic eutrophication. The lake was restored during the mid-1990s through the reduction of phosphorous and nitrogen influx but subsequent reduced water levels have caused a lack of outflow and this has led to various changes including an increase in the filamentous alga *Cladophora glomerata*, a slight increase in phytoplankton, and an increase in the spread of alien species. The concern is that climate change induced drought conditions may exacerbate this situation.

The International Joint Commission: Canada and United States (2009) takes the weight-of-evidence approach to determining the causes of the resurgence of eutrophication in Lake Erie. This is an approach to examining multiple lines of evidence to reduce uncertainty and to support science-based decision making. This report indicates that eutrophication has a few key indicator variables (excess growth of the filamentous alga *Cladophora glomerata* and cyanobacterial blooms which correlate with SRP levels). They note that analysis of the changes indicate that they are the result of a complex of factors with few direct management actions to address these. Each case should be assessed independently.

Scavia et al. (2014) note that with the implementation of phosphorous load reductions from 1972, Lake Erie responded quickly, showing reduced water column phosphorous, phytoplankton biomass and bottom-water hypoxia. However, since the mid-1990s cyanobacterial blooms have increased with associated bottom-water hypoxia. The advent of low-till agriculture has resulted in an increased load of SRP to the system. It is estimated that to reduce the bottom-water hypoxia to levels observed in the early 1990s will require a load reduction of SRP by 78% of the 2005-2011 average.

Desbarats Lake is a small lake in Ontario with a small community living there. When the lake became eutrophic, a not-for-profit organization was formed to identify the major causes of the eutrophication. Funds were successfully raised to support a limnological evaluation of the lake with a focus on the causes of the cyanobacterial blooms and remedial actions to deal with these. The report by Nürnberg and LaZerte (2013) made the following recommendations:

- Apply best management practices in the catchment
- Ensure septic system compliance
- Ensure environmentally friendly lifestyles
- Continue monitoring
- Review lake and land-use in the catchment
- Prepare a lake shore capacity assessment including a phosphorous budget.

The two overarching activities in the above list are to manage the incoming nutrients and to educate the residents.

3.2.1 Summary of Chapter 3.2

The HDRP is a complex system in which prediction of the outcomes is difficult. International experience indicates that the first step to be taken is to manage the ingress of P into the system. It has been ascertained that there is also P in the sediments. P occurs in various compartment in the dam. It is present in the water body (including the biota), it is concentrated in the old river bed as has been mapped in the project, but also occurs diffused in the sediment across the lake. Managing this will take a variety of appropriate measures. It is recommended that this management is done within an adaptive management framework in which the management of the P in the water column and the various parts of the dam. This would, then, include dedicated monitoring programmes to address the influence of the HDRP on the P concentration in the various compartments in the water body. The monitoring programme would also address the other aspects of concern to Phase 2.

3.3 Overview of selected South African Literature on lake eutrophication

Allanson and Gieskes (1961) state that the high concentration of phosphorous in the Hartbeespoort Dam was '*clear evidence of the extensive degree of eutrophication'* in the dam. They quote from Hutchinson et al. (1933 – reference not seen) who described the dam (a mere 8 years after its construction) as oligotrophic and note that in the intervening quarter century that the state of the dam had changed materially. They found that the main source of the nutrients was from the Jukskei and Crocodile Rivers.

During the early 1980s scientists at the National Institute for Water Research (NIWR) conducted a large multidisciplinary study of the dam (NIWR, 1985). This study took place at a time when the water level was low. They described Hartbeespoort Dam as hypertrophic. They found that the algae (cyanobacteria) formed hyperscums which the wind moved around the lake. The rates of algal production in the dam were the highest measured in the world but the zooplankton population remained small because they were unable to digest the large-sized colonies of Microcystis. The study found that, concomitant with the excessive algal growth, there were also large bacterial populations and that the main energy pathway was through the detrital cycle. The fish production was high but the fish community was dominated by three species, carp and Mozambique tilapia which are detritivores, and catfish which feed mainly on benthic invertebrates. The study stressed the importance of the finding that the main energy pathway is through the detritus cycle and note that this has not been sufficiently studied for understanding the flow of phosphorous into and through the detritus cycle. The large reduction in the nutrient load between the river mouth and the main basin of the dam introduced the concept of a pre-impoundment as an option for nutrient management.

The concept of a pre-impoundment has been considered by the HDRP and would provide a way of preventing the ingress of a certain, as yet undefined, quantity of P from entering the dam. The review, however, presents an alternative to this which could prove more cost-effective and easier to manage. This entails the use of acid mine drainage and is explained in Appendix 4. This study examined several options for managing the eutrophication in the dam and concluded that the only intervention that could be recommended to improve the water quality with any certainty was the reduction in the external load of phosphorous into the dam.

Robarts (1984) noted two categories of factors controlling primary production in Hartbeespoort Dam. The first included nutrient and wind factors where the high nutrient concentrations available ensured that nutrients were not limiting and wind patterns were responsible for spatial and temporal changes to the biomass at a locality. The second category includes the biological, chemical and physical factors that affected the rate of processes. An important factor was the buoyancy mechanism of Microcystis which enabled most of the cells to remain within the photic zone of the dam.

Following the period of low water levels during the time that the NIWR (1985) study was being conducted, there was a period when cyanobacteria did not dominate the algal population as had been the case. Chutter and Rossouw (1992) gave an account of the major physical, chemical and biological changes that had occurred between 1980 and 1990 in Hartbeespoort Dam. From the management point of view two of these changes were of interest. The first was the introduction of the special orthophosphate standard of 1 mg/ℓ for effluents discharged into designated sensitive catchments by wastewater treatment works. The second was the absence of Microcystis during the summers of 1988 to 1990. This disappearance of Microcystis was associated with a change in the total nitrogen to total phosphorous ratio. Consistent with observations in the northern hemisphere this study found that a TN:TP ratio (the ratio of total nitrogen [TN] to total phosphate [TP] higher than 29 favours the faster-growing green algae while at a TN to TP ratio of lower than this N becomes limiting, favouring the blue-green algae which are able to fix atmospheric nitrogen. Green algae do not produce odours and toxins as do the cyanobacteria). Chutter and Rossouw (1992) found that at a TN:TP ratio of >17 resulted in a shift of algal dominance from cyanobacteria to other algae and cyanobacteria comprised a small percentage of the total algae. This study illustrated the effect of decreasing the P content of the water column on the dominance of desirable over undesirable algal species.

Walmsley (2000) reviewed the international scene of eutrophication management. He distilled five key principles on which successful eutrophication management strategies are based, as follows:

- Anthropogenic eutrophication is reversible
- There is no quick fix
- A collaborative approach between government, business and communities is necessary, but government must lead the facilitation role
- Eutrophication needs a suite of interventions (social, economic and technical) if it is to be reversed and
- Transparent research and monitoring activities are prerequisites to the decision-making that is required.

Walmsley then examines the South African situation and concluded that with the new perspectives on waste water and waste management introduced by NWA (1998) and NEMA (1998), a more explicit approach is needed if eutrophication is to be brought under control. These include clearly defined specifications and resource management objectives together with communication on eutrophication management and monitoring and the building of research and management capacity to address the problem. These are summarized at the end of the Chapter.

Harding and Paxton (2001) reviewed the work done on cyanobacteria as well as the causes and occurrence of cyanobacterial toxins with a focus on the South African situation. In their documentation of work up to the time of publication they note that during the summer of 1993-94 Microcystis was once again the dominant algae in Hartbeespoort and the mouse test showed positive for the presence of toxins on a number of occasions.

Rossouw et al. (2008) found that the extent of eutrophication had increased since it was first noted in the 1970s and has been recognised as a priority water quality problem in South Africa. This study delivered three products, a guide to assess eutrophication-related water quality, an internet-based Nutrient Enrichment Assessment Protocol (NEAP) and a course outline and training material for a short course in eutrophication assessment. This study resulted in a number of recommendations on each of the three aspects of the work. Regarding the catchment eutrophication assessment guide the study recommended that the guide be used as a tool to support catchment water quality assessment studies, that eutrophication assessment be integrated with other water quality variables which require investigation and that similar guidelines be developed for other priority water quality problems. They recommended that NEAP be widely used in the country and be further developed. They also recommended that the training material on eutrophication assessment methods be used by lecturers and kept up to date and that the training material be developed to the control and management of eutrophication as well as the use of more sophisticated assessment tools.

Eutrophication assessment needs to be based on the relationship between the level of nutrient loading (particularly P) and the in-lake condition. To this end Harding (2008) determined the threshold of nutrient availability (as TP) above which potentially problematic algal growth maybe experienced. He noted that '*Eutrophication (nutrient enrichment of surface waters) constitutes the greatest single threat to the impoundment of raw potable and irrigation water. In countries such as South Africa, where treated effluents and other wastewaters comprise an often significant proportion of return flows to reservoirs (dams), the problems associated with eutrophication are exacerbated. This problem is especially apparent in the inland areas of South Africa, especially around major urban areas such as the Johannesburg-Pretoria* complex'. He provides the following figure ranking impoundments in terms of their median annual phosphorous (TP) concentration (Figure 3-2).

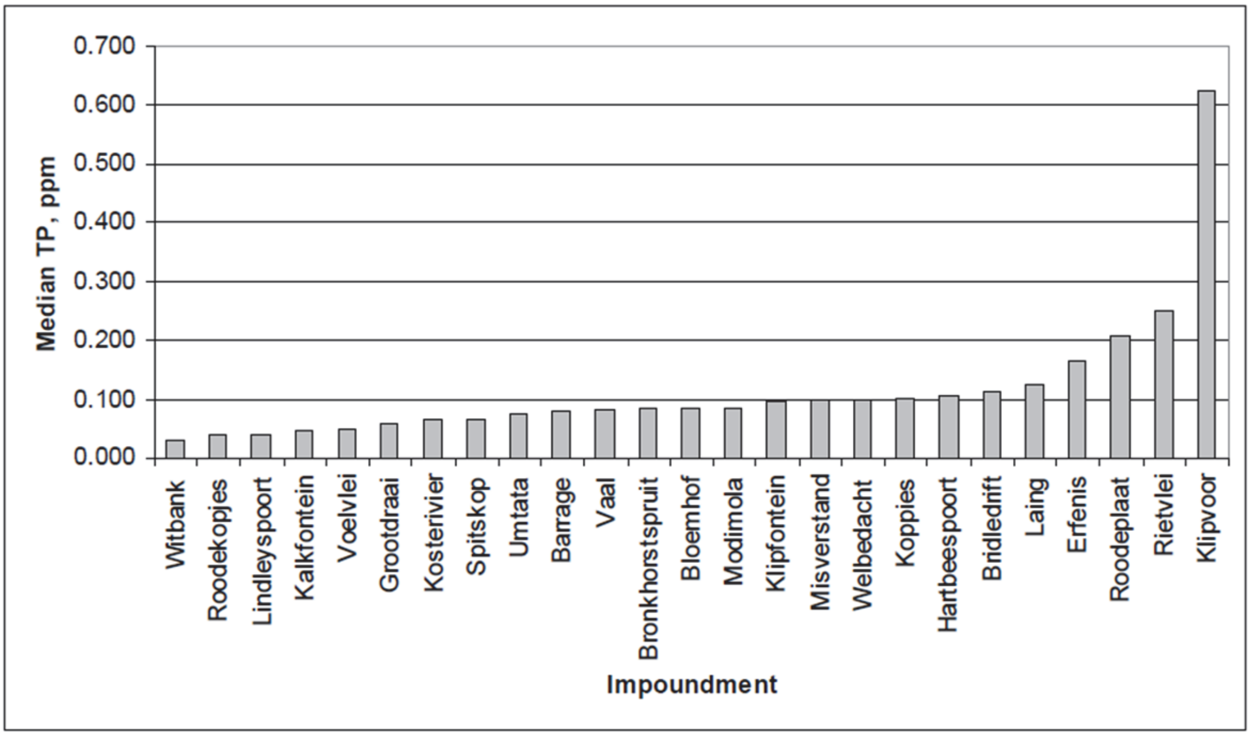


Figure 3-2. Ranking of impoundments (lowest to highest) in terms of median annual concentration of phosphorus (TP) (from Harding, 2008).

Eutrophication has been ongoing in South Africa for 30 years. Harding (2010) observes that the problem is insidious, and may only become apparent sometime after the onset of the pollution. He notes that while the management of water quality is the domain of DWS, responsibility for the problem is much broader than that, including in addition the Departments of Environmental Affairs, Health, Agriculture, Trade and Industry and Tourism as it impacts the health of people, agriculture and the environment. Failing WWTWs are a major source of the nutrients responsible for eutrophication. Harding provides an exhaustive list of factors which have exacerbated the problem, central to which is the lack of human resource capacity at all levels of management to deal with water quality deterioration that has allowed eutrophication to get out of hand.

The concept of foodweb biomanipulation has contributed to the re-oligotrophication of Lake Vesijarvi in Finland (Keto and Tallberg, 2000). Hart (2006) and Hart and Harding (2015) examine the concept for implementation in South African reservoirs. Hart (2006) examined the implementation of ‘top-down’ foodweb biomanipulation in South African reservoirs and concluded that *‘As far as can be generalised, prospects for applying ‘classical’ biomanipulation as a management tool to ameliorate consequences of eutrophication in local reservoirs are weak.’* Hart and Harding (2015) investigated the standing stock of fish in 7 South African reservoirs to assess the prospects of reducing the in-lake of total phosphorous through remedial biomanipulation. They concluded that the **relative** importance of fish in reservoir TP budgets declined progressively with rising trophic status and that ‘bottom-up’ bioremediation accordingly offers little help in the management of nutrient-enriched reservoirs.

The *Water for Growth and Development Report* (Department of Water Affairs, 2009) notes with concern that poor water quality is a threat to the growth of the South African economy. Poorly performing or malfunctioning WWTW is a major cause of the deteriorating water quality in the country and it may be expected to threaten neighbouring countries in the river basins which South

Africa shares with its neighbours. In an effort to reverse the trend of deteriorating water quality in the country, the DWS has introduced the Green Drop programme. This programme aims to improve the performance of WWTWs through providing an incentive to the works in the form of a scoring system which rates the aspects of WWTW performance. Those WWTWs which are performing properly are awarded Green Drop status.

The first Green Drop report published (Department of Water Affairs, 2009) the statement is made that waste water is the first barrier in a multi-barrier system of ensuring safe drinking water quality.

The first round Green Drop assessments was able to report on 449 of the approximately 852 municipal WWTWs (ca. 52.6%) in the country. For various reasons the remaining WWTWs were not able to be assessed. Of those assessed, a mere 7.4% achieved Green Drop Status.

By 2011 the Green Drop initiative had stimulated improvement in the waste water treatment industry. A total of 831 WWTWs were assessed and there was an overall improvement in the performance of the industry, although 55% waste water treatment works require serious, critical and urgent refurbishment.

The Green Drop initiative is achieving success but there remains the need for ongoing attention to the industry. The Upper Crocodile drains an area where the level of capacity to treat wastewater is generally high but the level of urbanization in the catchment is such that the nutrient load brought into the dam is high. This makes it all the more important that the WWTWs in the catchment are well maintained and well run.

Matthews et al. (2010), Matthews (2014) and Matthews and Bernard (2015) have used Medium Resolution Imaging Spectrometer (MERIS) to assess cyanobacterial blooms in inland and near-shore waters. Matthews et al. (2010) investigated the hypertrophic Zeekoevlei on the Cape Flats to assess the optical properties of the lake, to evaluate various atmospheric correction procedures and to compare the performance of empirical and semi-analytical algorithms. This study demonstrated the potential value of simple Top-of-Atmosphere algorithms for hypertrophic systems and recommended that be integrated into future water quality monitoring systems.

Matthews (2014) and Matthews and Bernard (2015) used the MERIS FR (medium resolution imaging spectrometer full resolution) archive to investigate the state of algal blooms in the 50 largest standing water bodies in South Africa. He found the majority (62%) to be hypertrophic. 26 of these water bodies showed cyanobacterial scum to varying extents. He was also able to validate the algorithm demonstrating that eukaryote and cyanobacterial Chl-a can be accurately determined. But the determination of Chl-a in oligotrophic and mesotrophic waters remains challenging due to a variety of reasons. The finding on Hartbeespoort Dam in Matthews and Bernard (2015) is that in terms of the synthesis presented in this paper that the most impacted reservoir in the country is Hartbeespoort Dam.

In 2006 approximately 50% of urban and industrial drainage in urban areas such as Johannesburg and Pretoria was reused. Roux et al. (2010) note that the potential for reuse depends on the quality of the effluent and the quality required by the users. They note, in addition, that technology adequate to treat the water to acceptable standards less than a decade prior to the research is no longer adequate due to the deterioration in water quality and the necessary technology upgrades add to the costs of water treatment. This study clearly showed that pollution prevention is more cost effective than downstream control measures.

The Olifants River in Gauteng, Mpumalanga and Limpopo Provinces is one of the most ‘hard-working’ rivers in South Africa with mining activities which have gone on for over a century and poorly performing WWTWs contributing to the deteriorating water quality. The deaths of large numbers of crocodiles in the system has raised public awareness of the impact of this ongoing lack of attention to the deterioration of water quality in the catchment and its impact on the biodiversity of the area which supports substantial conservation and ecotourism activities (Oberholster, 2009; Ashton, 2010).

Routine water quality sampling at sites in the vicinity of abandoned mines, agriculture, WWTWs and industry in the Olifants River catchment showed that nutrient concentrations were relatively high with a number of sites showing N:P ratios indicative of eutrophic or hypertrophic conditions. Longer term trends shown by DWS data indicate significant positive trends in the SRP with time and increasing sulphate concentrations downstream indicate the cumulative impact of mining in the catchment (Dabrowski and de Klerk, 2013). This study showed that the contribution of metals to the system from active mines was lower than that from abandoned mines and that the contribution of acid water to the river flow in the low flow season was higher than the contribution of neutral water. This raises a warning flag that in time of a drought, the relative contribution of AMD to the total flow will increase with potentially severe impacts on the ecosystems and economic activities downstream, stressing the importance of rehabilitation of mining activities in this and other catchments.

Excessive phosphate loading in the upper Olifants River has led to eutrophication and widespread health risks. Waste water treatment works (WWTW) in the upper Olifants River, Mpumalanga are, by and large, not performing well. Dabrowski (2014) used the soil water assessment tool to identify sources of SRP in order to predict changes in the trophic status of reservoirs receiving the effluent from WWTWs. The model indicated that reduction in the SRP load to 1 mg ℓ^{-1} would bring 2 of the reservoirs into the mesotrophic range, but that further reduction to 0.1 mg ℓ^{-1} would not make a significant difference. This indicates the impact of non-point sources of SRP in the catchment and the importance of addressing these.

3.4 Conclusions from literature: a technical analysis framework

A systems ecology approach is needed in order to develop the holistic understanding that is necessary to address eutrophication. The strategy needs to include technical, biological and social components if re-oligotrophication is to be successful. Post-normal science (Funtowicz and Ravetz. 2008) provides a basis for making decisions in a situation where both the stakes and the uncertainties are high. An adaptive management approach provides a framework within which the players are able to learn by doing, thus enabling decisions to be taken based on incomplete knowledge which can be checked and refined as the work progresses.

The HDRP was founded on almost half a century of research. The action plan (Harding, 2004a, b) was published in 2004. The first business plan for the HDRP Phase 1 was compiled in 2006.

Fundamental to understanding of the state of the Hartbeespoort Dam '*is greater than simply the load of phosphorus reaching the system. The present state of ecosystem health of this impoundment is the sum of nutrient loading over extended periods coupled with the loss of biotic stabilization (plant communities and the role these play in providing biochemical services and supporting zooplankton and juvenile fish populations)*' (Harding et al., 2004b). These authors also found that '*the capacity of the dam to deal with the loads of phosphorus has already been substantially exceeded*'.

Harding et al. (2004b) also state that '*the existence of submerged aquatic plants in lakes and reservoirs is essential to the maintenance of a healthy ecosystem. As nutrient levels rise (eutrophication) aquatic plants disappear and become replaced by dense populations of phytoplankton, often the noxious and undesirable blue-green algal (cyanobacterial) varieties*.' These authors, together with Beklioglu et al. (2011), note that lakes and reservoirs may exist as either a clear water state or an algal-dominated state. They note that '*the following reasons have been identified as the drivers causing a system to move from the clear to the algal-dominated conditions*:

- *loss of submerged macrophytes – either through eutrophication, mechanical damage or deliberate eradication (e.g. the use of aquatic herbicides);*
- *increased water levels (e.g. raising of dam walls) resulting in a loss of shallow areas suitable for the development of aquatic plants;*
- *a high frequency of water level changes preventing development of aquatic macrophytes;*
- *a loss of variability in water levels (over regulation);*
- *an increase in the density of cyprinid fish;*
- *presence of substances lethal to zooplankton;*
- *sustained high levels of available phosphorus (> 100 µg ℓ^{-1} as P)'.*

The lessons learned from this brief literature review are summarised in Tables 3.1 and 3.2.

Table 3-1: Summary of lessons learned from the international literature

Authors	Lake studied	Lessons learnt
Beklioglu et al. (2011)	Review of lake restoration in cold and warm climates	• Lakes respond to external forces in a non-linear fashion • The 'alternate stable states' hypothesis asserts that shallow lakes can exist in more than one stable state

Genkai-Kato and Carpenter (2005)	General Review of excessive P input using an empirically-based model	• Eutrophication more likely with warmer temperatures
		• Lakes of intermediate depth most susceptible to regime shifts and most difficult to restore
		• There are a range of physical, chemical and biotic mechanisms which may be responsible for regime shifts. The most important were found to be:-
		  • Lake morphometry where lakes of intermediate depth are the most susceptible to eutrophication
		  • Temperature where warmer waters are more susceptible to eutrophication than cooler waters
		  • Dominance of macrophytes where dense macrophyte growth protected the sediment from disturbance, so reducing the release of nutrients in the sediment to the water column

Klapper (2003)	Technologies for lake restoration	• Priority-Stop nutrient ingress • In-lake eco-technologies are important in lakes with long residence times. • Aeration / circulation does not provide the complete answer as many pollutants accumulate in the sediment • Important for modellers / hydrologists to understand the hydrological regime when deciding on the suite of technologies to use
Mattson et al. (2004)	Eutrophication and Aquatic Plant Management in Massachusetts: Final Generic	• Understanding the lake ecosystem • Develop a management plan – each water body is unique and needs to be assessed separately • Limit the nutrient influx. Methods recommended for this

Authors	Lake studied	Lessons learnt
	Environmental Impact Report	are the control of Point sources (easiest to locate and manage); Non-point sources (more difficult to control but nevertheless need to be controlled as the contribution may be significant.); Hydraulic controls (e.g. diversion, dilution, flushing, hypolimnetic withdrawal); Phosphorous inactivation through chemical binding; Artificial circulation and aeration; Dredging; •Biological methods such as bacterial additives and the removal of bottom-feeding fish •Biological control of plants
Anneville and Pelletier (2000)	Lake Geneva, Switzerland / France	•SRP reduction implemented and effective from 1981 •1981-1992 – positive correlation between late winter SRP levels and chlorophyll a •Followed by an increase in filamentous (inedible) algae •Stress the importance of studies at the appropriate time scales
Tadonléké et al., 2009	Lake Geneva, Switzerland / France	• Following a period of SRP reduction-induced chlorophyll a decrease, there was an increase in primary production (PP) in spite of decreasing levels of SRP. • This increase in PP was the result of increased light penetration and water column stability and a change in the N:P ratio • Neglecting these factors may make re-oligotrophication more difficult and may lead to wrong management decisions
Lake Ecosystem Dynamics Research Group, University of Helsinki AND Keto and Tallberg (2000)	Lake Vesijarvi, Finland	• Sewage load diverted from the lake in 1976, leading to reduction in nutrient loading which led to a cessation of cyanobacterial blooms • Other species of cyanobacteria bloomed through the 1980s • More than 1 000 t of planktivorous and benthivorous fish removed between 1989 and 1994 (6-8 t P or 10 mg P m^{-3} yr^{-1}) • Cyanobacterial blooms disappeared, water clarity increased and submerged macrophytes colonised large areas. • During 2000s, water quality again decreased – decision to implement large scale aeration.
Kutics et al. (2013)	Lake Balaton, Hungary	• Lake restored through reduction in SRP and N loading • Subsequent reduced water levels and lack of outflow has led to an increase in filamentous and planktonic algae and spread of alien species • Concern that climate change could aggravate the situation
International Joint Commission on water : USA and Canada (2009) and Scavia et al. (2014)	Lake Erie	• Lake Erie initially responded quickly to reduction in nutrient loading, but cyanobacterial blooms have increased as has the associated bottom-water hypoxia. • Eutrophication
Nürnberg and LaZerte (2013)	Lake Desbarats	• Manage the nutrient influx • Educate the people living in the catchment
All the studies		• Re-oligotrophication is a long term process demanding an ongoing commitment.

Table 3-2. Summary of the lessons learned from the South African literature

Authors	Lake studied	Lessons learnt
Allanson and Gieskes (1961)	Hartbeespoort Dam	• Hartbeespoort Dam was oligotrophic when first constructed, but after 25 years it had become eutrophic. • The main source of nutrients were the Jukskei and Crocodile Rivers
NIWR (1985)	Hartbeespoort Dam	• Primary production rates were the highest measured in the world. • Zooplankton population remained small. • The main energy pathway was through the detrital cycle. • Further study is required to understand the flow of phosphorous through the detritus cycle. • The large reduction in nutrients between the river mouth and the main basin prompted the concept of a pre-impoundment as an option for nutrient management. • The study concluded that the only intervention that could be recommended with confidence to improve water quality was the reduction of the external load of phosphorous.
Chutter and Rossouw (1992)	Hartbeespoort Dam	• The TN:TP ratio rose to >17 after the dam filled following a period of low water through the early to mid-1980s. • This resulted in the virtual disappearance of blue-green algae.
Walmsley (2000)	International and South Africa	• Cultural eutrophication is reversible • There is no quick fix • Government must lead a collaborative approach to dealing with eutrophication. • Reversal of eutrophication needs a suite of interventions • Transparent research and monitoring are prerequisites to decision-making • South African legislation and policy need to be more explicit to bring eutrophication under control.
Harding and Paxton (2001)	International review (Hartbeespoort dam comment)	• Note that by 1993 / 94 Microcystis again the dominant algae in Hartbeespoort Dam. • The mouse test showed positive to toxins in the algae on a number of occasions.
Rossouw et al. (2008)	South Africa	• Eutrophication has increased over several decades • Study delivered 3 products:- • Guide to conduct catchment eutrophication studies • Nutrient Enrichment Assessment Protocol to be used country wide and further developed as necessary • Courseware for building capacity in reservoir management.
Harding (2008)	Eutrophic dams in South Africa	• Eutrophication is the single greatest threat to raw, potable and irrigation water • Thresholds of nutrient loading for certain South African dams has been defined • South Africa has a high proportion of return flows in rivers • Eutrophication particularly apparent in the rivers draining Gauteng.
Harding (2010)	Eutrophication crisis in South Africa	• Lack of capacity to deal with the problem • Lack of training courses for eutrophication management • Lack of resolve at decision-makers level to deal firmly with the problem • Lack of communication between WRC and DWS • Focus on symptoms rather than causes of eutrophication
Hart (2006), Hart and Harding (2015) and	Food chain bio-manipulation	• Top down bio-manipulation is less effective in systems with fish originating in a lotic environment than those originating in a lentic environment.

Authors	Lake studied	Lessons learnt
Harding and Hart (2013)		• Bottom up bio-manipulation becomes less effective as the level of nutrient enrichment increases.
Green Drop Initiative	South Africa	• The Green Drop initiative has improved the overall level of waste water treatment in South Africa. • The level of capacity and the refurbishment amongst the WWTWs requires ongoing attention if the desired results are to be achieved.
Matthews et al. (2010)	Zeekoevlei, Western Cape	• MERIS (remote sensing) can be used successfully to monitor cyanobacterial blooms in both fresh- and salt-water environments • Recommends that MERIS be integrated into future national water quality monitoring.
Matthews (2014) and Matthews and Bernard (2015)	50 largest inland water bodies in South Africa	• 62% of these water bodies are hypertrophic • 26 of the 50 water bodies showed scum formation • MERIS can accurately determine eukaryote and cyanobacterial Chl-a • Oligo- and mesotrophic determinations are not possible at the moment. • Hartbeespoort Dam is the most heavily impacted in the country.
Roux et al. (2010)	Water treatment costs	• Water quality has deteriorated to the point where new and costly technologies are necessary to treat the water to acceptable standards • It is more cost-effective to prevent pollution at source than to treat polluted water.
Oberholster, (2009); Ashton, (2010)	Olifants catchment	• The Olifants catchment has over a century of mining activity • The catchment supports large and important conservation and ecotourism activities • Recent crocodile deaths in the catchment have raised the public profile to the loss of biodiversity resulting from the ongoing pollution
Dabrowski and de Klerk (2013)	Olifants catchment	• Nutrient and pollution loads are increasing in the Olifants River • Active mines contribute less than abandoned mines • Proportional contribution of acid flow increases during dry periods • Drought will exacerbate this, with potentially severe impacts to ecosystems and economic activities • Rehabilitation of abandoned mines is critical
Dowbrowski (2014)	Upper Olifants catchment	• Improving the performance of WWTWs in the catchment would reduce trophic levels of reservoirs • Non-point sources of SRP need to be addressed

4 Systems' description of the Dam: Socio-economic context

4.1 Purpose of this Chapter

Chapter 3.4 above concluded that a systems ecology approach is crucial. The review of Phase 1 and the development of recommendations on the future of the HDRP thus require a fundamental understanding of the socio-ecological meta-system. This is also a pre-requisite for assessing the effectiveness of Phase 1 (refer to Chapter 7 below). This chapter also sets the socio-economic scene within which the Dam functions. The key ecological parameters within the system are then elucidated and linked to the socio-economic system through the ecosystem services which they provide.

The chapter demonstrates the importance of the Hartbeespoort Dam within its meta-system and identifies the key challenges to which Phase 2 of the HDRP will need to respond.

This chapter has several focus areas. It provides a spatial, socio-economic setting and demonstrates the benefits of the Dam through the Millennium Ecosystems Assessment's framework of ecosystem services.

It then proceeds to demonstrate how these benefits link to ecological infrastructure and ecological processes.

4.2 Overview

The catchment of the Hartbeespoort Dam drains southern Tshwane, northern and western Johannesburg, northern Ekurhuleni, Mogale City and Randburg. The area is highly urbanised and is home to a variety of industries as well as agriculture. The discharge from the urban areas and industries have, over the years, contributed a substantial pollution load to the Crocodile (West) river since the start of the gold mining industry in the late nineteenth century. Hartbeespoort Dam has been the first major dam on the system for almost 90 years. Figure 4-1 shows the catchment of the Hartbeespoort Dam.

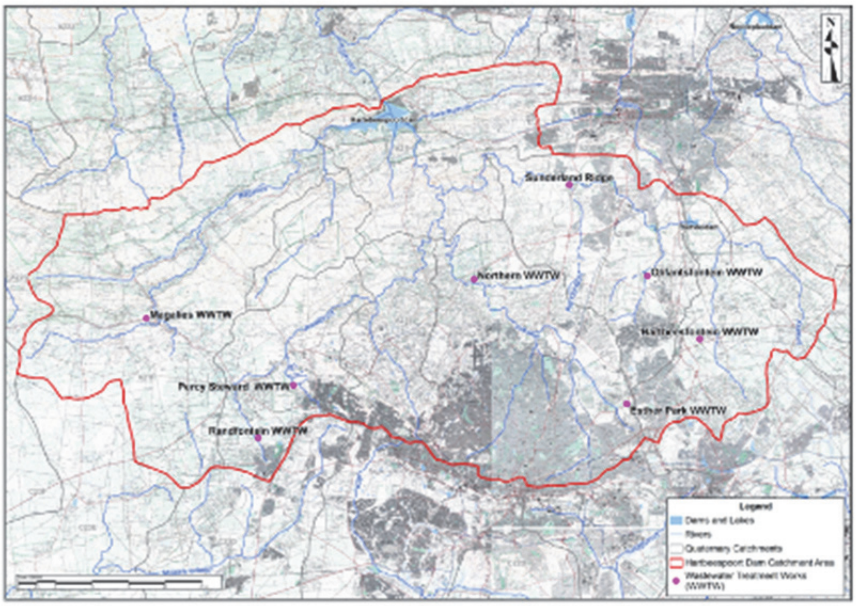


Figure 4-1: The Hartbeespoort Dam catchment showing the main urban areas in grey and with the waste water treatment works marked (from Van Veelen and Hooghiemstra (2013).

The Dam is situated in one of the most economically active areas in South Africa. Not only does it receive return flows from Gauteng, but it also plays a key role in the water economy of the Basin.

The Dam is located in the Limpopo Water Management Area (WMA) (formerly Crocodile (West) Marico WMA.) The two major rivers in the Limpopo WMA are the Crocodile (West) River and the Groot Marico River, which form the south-western part of the Limpopo River basin (Drainage Region A), eventually draining into the Indian Ocean in Mozambique. The Crocodile River contributes to the flow of the Limpopo River, an international river basin shared with Botswana, Zimbabwe and Mozambique.

The Dam is located within tertiary drainage region A21, the Upper Crocodile, with a catchment area of 6,336 km^2 (refer to Figure 4-1). The Pienaars, Apies, Moretele, Hennops, Jukskei, Magalies and Elands rivers are the major tributaries of the Crocodile River which together make up the A20 tertiary drainage catchment, with 39 quaternary catchments.

The DWS Water Resource Classification System (WRCS) study delineated the basin into 13 Integrated Units of Analysis (IUAs), several of which relate directly and indirectly to the Dam.

IUA 1, upstream of the Dam, contains the Metropolitan Municipalities of Tshwane (full), Johannesburg (part) and Ekurhuleni (part) and various other municipalities (Figure 4-1). The IUA constitutes a large portion of South Africa’s commercial, financial, industrial and manufacturing sectors and is an important contributor to National GDP. This IUA relates to the Dam in a number of ways: it produces large volumes of return flow from Waste Water Treatment Works (WWTW) and diffuse sources and it creates a demand for recreation and tourism services.

IUA 2, upstream of the Dam, contains the Magaliesburg conservation area as well as the Cradle of Humankind World Heritage Site. There are also agricultural activities in the IUA that have water requirements, and that produce diffuse return flows. This IUA also produces AMD which finds its way to the Dam.

IUA 3, downstream from the Dam, is an important agricultural irrigation area which is also associated with some recreation and tourism activities along Crocodile River.

IUA 4, around Rustenburg, contains the western limb of the Bushveld Igneous Complex (BIC), the largest platinum group metals (PGM) deposit worldwide. The mining sector in this area has been earmarked for significant future growth and has significant future water requirements.

IUA 13, downstream of the Dam, is primarily agricultural in nature and contains commercial agriculture, dry-land and subsistence agriculture. In addition, the area has large hunting and private conservation areas.

IUA 15 and 16, although in a separate drainage area (A42), will effectively become part of the Dam supply system through the Mokolo and Crocodile River (West): Water Augmentation Project (MCWAP) which will transfer water from the Crocodile River to meet the future water demand of the Lephalale economic development zone. IUA 15 is largely comprised of a mix between conservation, game farming and some irrigation agriculture. IUA 16 contains the town of Lephalale. The area is an important future energy hub and contains the Matimba power station as well as the Medupi power station, which is under construction. The Grootgeluk Coal Mine is in the IUA and several new coalmines have been earmarked for future development.

Together, these IUAs accommodate 5.58 million people (more than 10% of South Africa’s population in 2014). The average population growth rate of between 2001 and 2011 has been 5.8% per year, especially in IUAs 1, 2, 4 and 16, all of which has exceeded a growth rate of 5% per year. Such growth is an indicator of economic opportunity, and thus the role of water in the economy is important to understand. This is investigated in the chapters that follow.

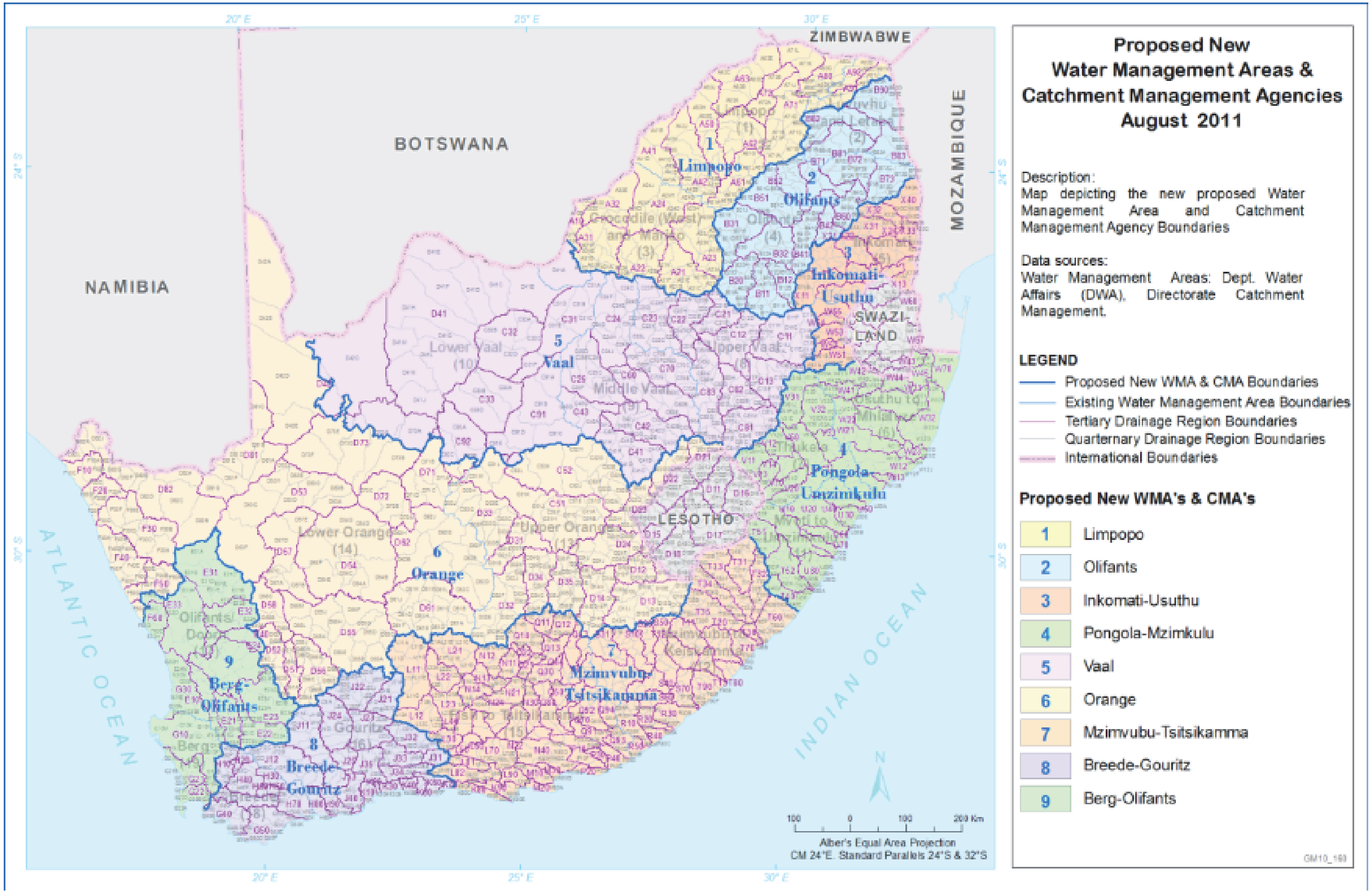


Figure 4-2. The proposed new water management areas for South Africa

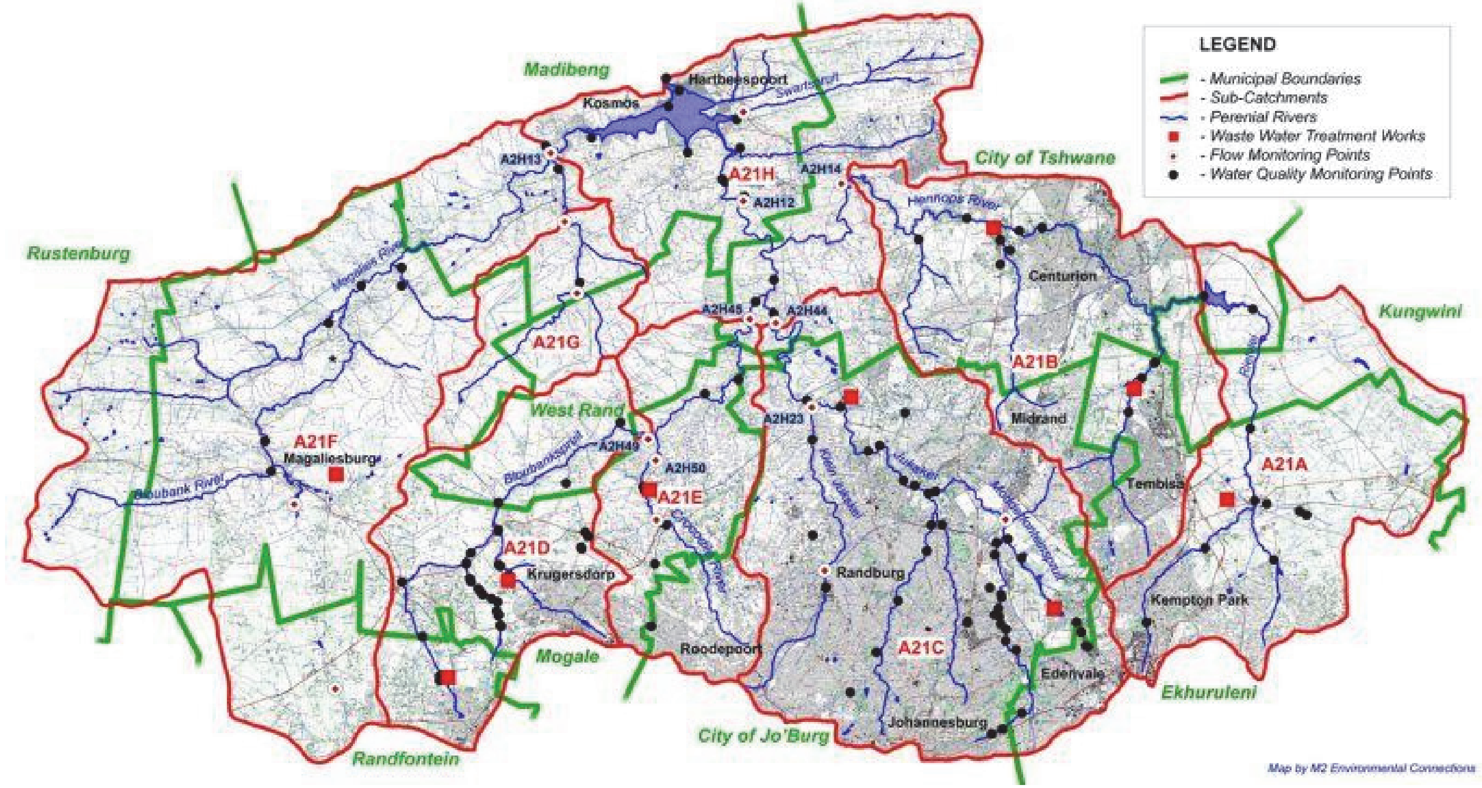


Figure 4-3. The Hartbeespoort Dam catchment, showing the quaternary catchments and municipal boundaries

Table 4-1: IUAs of the Limpopo WMA, directly and indirectly linked to the Hartbeespoort Dam.

IUA	Quaternary catchment	Socio-economic Description	Area (Km^2)	Population (Census 2001)	Population (Census 2011)
1	A21A-E; A21H; A23A; A23B; A23D and A23E	IUA 1 contains the Metropolitan Municipalities of Tshwane (full), Johannesburg (part) and Ekurhuleni (part) and the town of Krugersdorp. The IUA constitutes a large portion of South Africa's commercial, financial, industrial and manufacturing sectors and is an important contributor to National GDP.	5 076	2,945,840	4,660,835
2	A21F and A21G	The IUA contains the Magaliesburg conservation area as well as the Cradle of Humankind World Heritage Site. Both important for tourism and conservation activities. There are also agricultural activities in the IUA.	1 161	9,899	44,565
3	A21J	The area downstream from Hartbeespoort Dam is an important agricultural area and considerable tourism activities exist on the Crocodile River.	1 150	171,775	244,330
4	A21K; A22G; A22H; A22J	Rustenburg is the main town found in this IUA. The western limb of the Bushveld Igneous Complex (BIC), the largest platinum group metals (PGM) deposit worldwide, is found in this IUA. There is also substantial granite mining in the area.	2 533	315,239	471,919
13	A21L: A24A-C and A24G-J	This large IUA is primarily agricultural in nature and contains commercial agriculture, dry-land and subsistence agriculture. In addition, the area has large hunting and private conservation areas.	6 806	65,701	88,962
15	A42A-F	The IUA is largely comprised of a mix between conservation and game farming. The IUA contains some commercial agriculture. Tourism, in the form of hunting and game viewing, is an important sector in this IUA.	4 319	27,240	27,238
16	A42G-J	The IUA contains the town of Lephalale. The area is an important future energy hub and contains the Matimba power station as well as the Medupi power station, which is under construction. The Grootgeluk Coal Mine is in the IUA and several new coalmines have been earmarked for the future.	4 074	27,604	46,276
Total			25 119	3,563,298	5,584,125

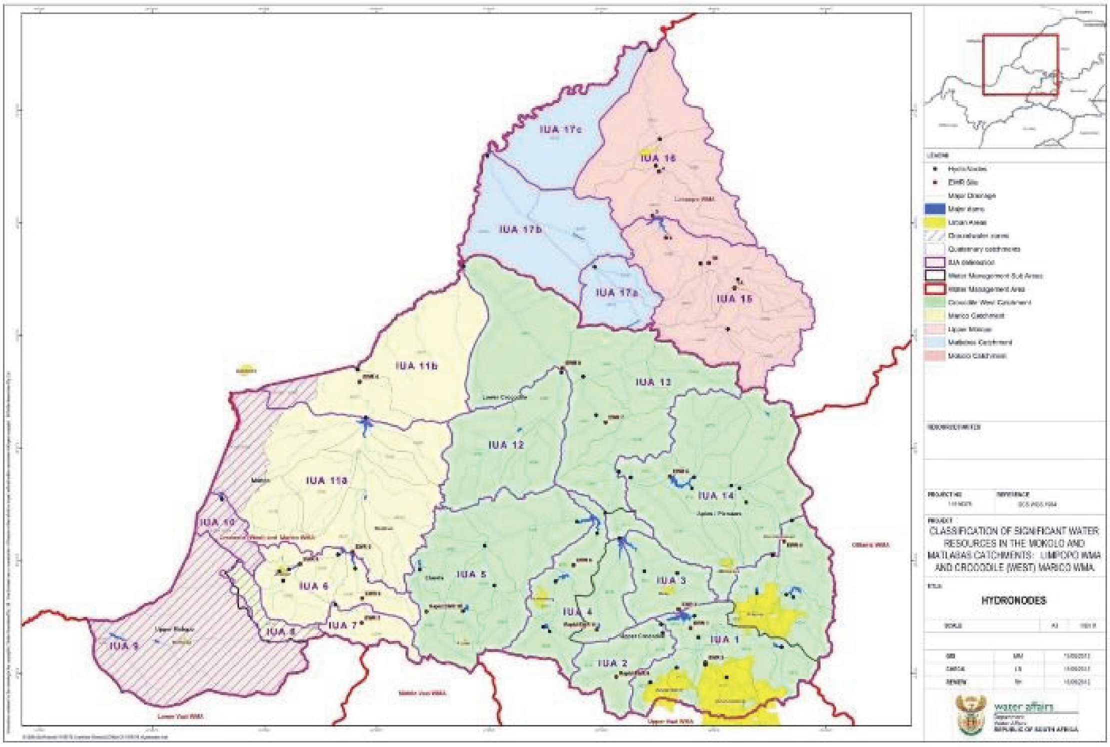


Figure 4-4. Delineation of IUAs related directly and indirectly to the Dam.

4.2.1 The benefits provided by the dam

The beneficiaries within this system derive their benefit from a range of ecosystem services delivered directly and indirectly by the Dam. The Millennium Ecosystem Assessment (MEA), and later, the TEEB (The Economics of Ecosystems and Biodiversity) defines ecosystem services as the benefits that ecosystems provide to human well-being[6].

The table (Table 4-2) below provides a detailed identification and description of key ecosystem services provided. The most important ecosystem service is the provisioning of water, through the storage that the Dam provides. The Dam further plays an important water regulation role. It is common cause that it has a waste assimilation role, as it traps nutrient pollution. A number of ancillary benefits exist, these include fishing for food, habitat for species, and a range of cultural services that include tourism, recreation and aesthetic services.

[6] Adapted from http://www.teebweb.org/resources/ecosystem-services/

Table 4-2. Key ecosystem services provided by Hartbeespoort Dam

Ecosystem service	Definition	Applicability to the Hartbeespoort Dam	Chapter in report
Provisioning services	**These are ecosystem services that describe the material or energy outputs from ecosystems**		
Water		In the case of the Dam, water provisioning is the key ecosystem service provided, is the key purpose of the Dam and has the largest economic impact	Chapter 3.3.2
Food	Ecosystems provide the habitat for growing food.	In the case of the Dam, food comes directly from freshwater fish harvests	Chapter 3.3.3
Raw materials	Ecosystems in general provide a great diversity of materials for construction and fuel including wood, biofuels and plant oils that are directly derived from wild and cultivated plant species.	The Dam do not provide any significant raw materials of this kind.	
Medicinal resources	Ecosystems and biodiversity in general provide many plants used as traditional medicines as well as providing the raw materials for the pharmaceutical industry.	The Dam do not provide any significant raw materials of this kind.	
Regulating services	The services that ecosystems provide by acting as regulators e.g. regulating the quantity and quality of water, air and/or soil or by providing flood and disease control.		
Water regulation	Aquatic ecosystems play a vital role in the hydrological cycle, as they regulate the flow and purification of water.	The Dam plays such a regulatory role and this is described in the system analysis	Chapter 3.6
Waste-water treatment	Ecosystems such as wetlands and lakes filter, treat and sink anthropogenic waste and act as a natural buffer to the surrounding environment. Through the biological activity of microorganisms, most waste is broken down. Thereby pathogens (disease causing microbes) are eliminated, and the level of nutrients and pollution is reduced.	The Dam, by default, serves as a sink into which excess nutrients are deposited. It therefore plays a role in the economy as it is the place where nutrient pollution from the catchment area is "externalised"	Chapter 3.4
Moderation of extreme events	Extreme weather events or natural hazards include floods, storms, tsunamis, avalanches and landslides. Ecosystems and living organisms create buffers against natural disasters, thereby preventing possible damage.	The Dam obviously plays a role in moderating floods	
Local climate and air quality	Forests provide shade whilst forests influence rainfall and water availability both locally and regionally. Trees or other plants also play an important role in regulating air quality by removing pollutants from the atmosphere.	In the case of the Dam, the water body is likely to affect the micro-climate.	
Carbon sequestration and storage	Ecosystems regulate the global climate by storing and sequestering greenhouse gases. As trees and plants	The Dam does not play a significant role of this kind.	

	grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues. In this way forest ecosystems are carbon stores. Biodiversity also plays an important role by improving the capacity of ecosystems to adapt to the effects of climate change.		
Erosion prevention and maintenance of soil fertility	Soil erosion is a key factor in the process of land degradation and desertification. Vegetation cover provides a vital regulating service by preventing soil erosion. Soil fertility is essential for plant growth and agriculture and well-functioning ecosystems supply the soil with nutrients required to support plant growth.	Although the Dam serves as a sink for eroded material from upstream, it does not directly prevent soil erosion.	
Pollination	Insects and wind pollinate plants and trees which is essential for the development of fruits, vegetables and seeds.	The Dam does not play a significant role of this kind.	
Biological control	Ecosystems are important for regulating pests and vector borne diseases that attack plants, animals and people.	The Dam does not play a significant role of this kind.	
Habitats for species	Provide everything that an individual plant or animal needs to survive: food; water; and shelter. Each ecosystem provides different habitats that can be essential for a species' lifecycle. Migratory species including birds, fish, mammals and insects all depend upon different ecosystems during their movements.	The role of the Dam in providing habitat is described in chapter 3.6 below	Chapter 3.6
Maintenance of genetic diversity	Genetic diversity is the variety of genes between and within species populations. Genetic diversity distinguishes different breeds or races from each other thus providing the basis for locally well-adapted cultivars and a gene pool for further developing commercial crops and livestock. Some habitats have an exceptionally high number of species which makes them more genetically diverse than others and are known as 'biodiversity hotspots'.	The Dam is not a biodiversity hotspot.	
Cultural services	Are intangible benefits including recreation, tourism, aesthetic, cultural and spiritual services. Recreation and mental and physical health relate to exercising, playing sports and/or engaging in hobbies in green space that is not only a good form of physical exercise but also lets people relax. The role that green space plays in maintaining mental and physical health is increasingly being recognized, despite difficulties of	All these cultural services are of importance at the Hartbeespoort Dam	Chapter 3.5.3

	measurement. In addition, ecosystems and biodiversity play an important role for many kinds of tourism which in turn provides considerable economic benefits and is a vital source of income for many countries. Aesthetic appreciation and inspiration for culture, art and design are important: language, knowledge and the natural environment have been intimately related throughout human history. Biodiversity, ecosystems and natural landscapes have been the source of inspiration for much of our art, culture and increasingly for science. Spiritual experience and sense of place are important: in many parts of the world natural features such as specific forests, caves or mountains are considered sacred or have a religious meaning. Nature is a common element of all major religions and traditional knowledge, and associated customs are important for creating a sense of belonging.		

4.2.2 Households, their income, employment and access to basic services

Although the Gauteng Province is the wealthiest province in the country, the meta-system is nevertheless characterised by extreme poverty. A key challenge for the HDRP would be to contribute to the creation of significant numbers of jobs which could be sustained after the HDRP is over.

A large number of households within the study area (46%) fall within the Very Poor to Poor household income categories (Table 4.3, 4.4). The trend is repeated across all IUAs, with 83% households in IUA 11b falling within this category. IUA 1 incorporates the urban areas of Johannesburg, Tshwane and Ekurhuleni and 44% of households fall within the lower two categories (Department of Water Affairs, 2012).

Table 4-3. Household income categories for households found within the IUAs directly and indirectly related to the Hartbeespoort Dam within the Limpopo WMA (Source: Census 2011)

IUA	Very Poor (no income- R9,600)	Poor (R9,601- R38,400)	Tolerable (R38,401- R76,800)	Comfortable (R76,801- R153,600)	Wealthy (>R153,601)	Total number of households
1	337 827	394 752	213 734	176 722	513 565	1 636 600
2	3 424	6 907	2 502	1 196	1 744	15 773
3	18 691	29 693	14 948	8 380	10 697	82 409
4	41 650	46 195	40 515	21 579	23 617	173 556
13	5 932	9 385	4 425	3 164	3 358	26 264
15	1 335	2 968	942	549	580	6 374
16	2 676	3 298	2 148	1 807	3 342	13 271

Overall unemployment for the area, as measured by 2011 Census data, is significant (Table 4-4).

Table 4-4. Employment categories within the IUAs directly and indirectly related to the Hartbeespoort Dam within the Limpopo WMA (Source: Census 2011)

IUA	Employed	Unemployed	Discouraged work-seeker	Not economically active
1	2 051 311	491 589	72 656	843 692
2	18 241	4 378	679	8 436
3	84 762	30 489	4 935	50 801
4	175 166	62 835	9 072	98 714
13	30 120	8 400	1 361	23 283
14	313 589	196 641	47 749	310 971
15	8 192	2 796	527	6 039
16	19 918	3 864	559	13 297

The majority of people employed in the study area are employed in the formal sector (75%) while 10% of employed are employed in the informal sector.

Table 4-5. Employment in the formal and informal sectors within the IUAs directly and indirectly related to the Hartbeespoort Dam within the Limpopo WMA (Source: Census 2011)

IUA	In the formal sector	In the informal sector	Private household	Do not know
1	1 603 737	174 014	275 798	50 788
2	10 850	2 920	4 262	589
3	60 923	11 305	11 296	2 523
4	132 098	19 732	21 468	3 850
13	21 688	3 977	4 046	840
15	5 550	1 318	1 272	211
16	15 819	1 653	2 309	337

Employment in the study area is varied and distributed across all of the employment categories. Overall, the community; social and personal services sector provides the most employment in the study area (Table 4-5). IUA 1 has by far the most employed people with the Financial and Community; social and personal services providing a large proportion of all employment in the IUA. IUA 4 is another centre of employment in the study area mainly due to the Mining and Quarrying (IUA 4).

4.2.3 Description of the aquatic ecosystem services economy

4.2.3.1 Water provisioning

The Limpopo WMA is the second most populous WMA in the country, which closely relates to the large proportionate contribution to the national economy (this area generates almost a third of the country's GDP).

The GVA of the Limpopo WMA was estimated by DWS to exceed R660 billion in 2012 with the following contributions from various municipal areas estimated as follows:

- Tshwane = 34,1%
- Johannesburg = 32,0%
- Ekurhuleni = 10,0%
- Other 22,9%

The key economic sectors contributing to GVA were:

- Manufacturing 22,7%
- Government sector 18,7%
- Finance 17,7%
- Transport 15,7%
- Other 25,2%

Economic production activities use water as an input into their production processes. Production outputs are the gross income or turnover of each user activity. The Agriculture, Mining, Electricity and Water, and other sectors are all significant value adding sectors, with significant multiplier effects into the rest of the economy. The GDP (defined here as Value Added (VAD) of economic sectors directly dependent upon Water Use Licenses in the study area in 2011 was R549 billion (Table 4-6). This estimate is based on preliminary analysis conducted at this early stage of the project.

Table 4-6. The GDP, expressed as Value Added (VAD) of the water sector in the in the Limpopo WMA

User Sector	Agriculture		Urban	Rural	Industrial	Mining		Power Generation	Total
	Irrigation	Livestock Farming				Platinum	Other		
Water Requirements	509	12	630	48	212	100	43	41	1 602
VAD/m^3 (R/m^3)	7,24	141,16	17,38	17,38	2 006,63	763,92	639,34	69,90	
VAD estimate (R'million)	2 688	1 694	10 952	834	425 406	76 392	27 491	2 866	549 323

4.2.3.1.1 Water supply infrastructure

The water resources of the WMA are already fully utilised and the importance of the transfers and return flows in the water balance has been emphasised by key DWS studies (Crocodile-West Marico Reconciliation Strategy; Crocodile-West Marico WRCS) especially in light of the continued strong growth projections in the Tshwane-Johannesburg, the Platinum Belt and the Lephalale regions (IUAs 1, 4 and 16).

Due to the extensive developments and high level of human activity in the catchment, water use in the catchment exceeds the water available from the local sources. Most of the water used in the catchment is therefore supplied from the Vaal River system via Rand Water, mainly to serve the metropolitan areas and some mining developments. This results in large quantities of effluent from urban and industrial users, most of which is discharged to the river system after treatment, for re-use downstream. In many of the streams and impoundments, water quality is severely compromised by the proportionately large contribution of return flows.

A complex water infrastructure network exists, with most of the water requirements supplied by two major water boards (Rand Water and Magalies Water) which source water from the Upper Vaal WMA and the Crocodile (West) River catchment. Most of the urban water requirements are supplied from surface water.

The Crocodile River system is regulated by 9 major dams:

- Rietvlei, Hartbeespoort and Roodekopjes in the Upper Crocodile catchment;
- Roodeplaat and Klipvoor dams in the Apies/Pienaar catchment, and
- Olifantshoek, Bospoort, Lindleyspoort and Vaalkop in the Elands River catchment.

No major dams occur in the Lower Crocodile catchment area.

There are some 3,800 minor impoundments in the Crocodile (West) River catchment. (irrigation/municipal/recreation dams) of which 460, with a total storage capacity of ±12 million m^3, are in the Lower Crocodile sub-catchment downstream of the Hartbeespoort Dam.

Rand Water imports water from the Upper Vaal WMA to the Crocodile (West) River catchment for urban, industrial and mining use. Water is also imported to Cullinan from the Olifants River catchment for urban use and for use on the Premier Diamond mine. Magalies Water exports water to supply the requirements of Modimolle (previously known as Nylstroom) in the Limpopo WMA.

There are several inter-quaternary transfers within the Crocodile (West) River catchment. Most of these transfers form part of the Magalies Water supply system, supplying water to urban areas, mines and industries. A number of effluent transfers within the Crocodile (West) River catchment are also present.

There are currently 32 WWTW operational in the Crocodile (West) River catchment. Nine WWTWs discharge into the Crocodile and Magalies tributary streams of the Hartbeespoort Dam. The largest WWTW in South Africa, Johannesburg Northern Works, is located in the Crocodile catchment discharging an average 400 Ml/d to the Jukskei River.

4.2.3.1.2 Urban and rural water requirements

The Gauteng conurbation comprises a population of approximately 14.6 million people, and a well-developed manufacturing and general commercial urban economy.

The Crocodile (West) catchment is one of the most developed catchments in the country. The Crocodile (West) catchment contains the largest urban centres in South Africa. Of particular importance are:

- The north, north east and north-west portions of the Johannesburg metropole in the upper Crocodile River Catchment;

.

- The Midrand area also in the upper Crocodile River Catchment;
- Tshwane Municipality including the city of Pretoria, mainly in the Pienaars River catchment; and
- The Rustenburg area in the Elands River Catchment.

In addition, there are large rural populations with important rural water requirements.

4.2.3.1.3 Irrigation Water Requirements

Irrigation is the single largest water user in the Crocodile River catchment using approximately 376 m^3/annum (DWA 2008). According to DWA (2008) irrigation areas and irrigation water requirements are expected to remain constant and no further irrigation growth is planned for.

The irrigation water requirements, the estimated irrigation area, distribution losses and irrigation return flows are summarised per sub-area in Table 4-7.

Table 4-7. Irrigation water requirements (units: million m^3

Sub catchment	Irrigation Area	Irrigation Requirement	Distribution losses	Total Irrigation Requirement		Irrigation Return Flows
				Volume	1:50 assurance	
Unit	ha	million m^3/annum				million m^3/a
Upper Crocodile	20 260	115	57	172	147	11
Elands	1 514	8	2	10	8	1
Apies-Pienaar	6 164	32	3	36	30	3
Lower Crocodile	28 036	153	76	229	191	15
Total	55 974	308	138	447		

The Hartbeespoort Government Water Scheme (GWS) is situated in the Upper Crocodile sub-catchment, below the Dam, and comprises 15,470 ha (Table 4.8).

Table 4-8: Irrigated areas in the Upper Crocodile in 2004 ([Schoeman and Associates 2005)

Drainage region	Sub region	Irrigated area (ha) 2004
UPPER CROCODILE		
A21A	A21A1	248.9
	A21A2	2 474.9
	Sub total	*2 723.8*
A21B	A21B1	286.4
	A21B2	148.4
	A21B3	53.8
	A21B4	142.0
	Sub total	*630.6*
A21C	A21C1	79.4
	A21C2	164.6
	A21C3	6.7
	A21C4	0.0
	A21C5	107.8
	A21C6	732.3
	Sub total	*1 090.8*
A21D	A21D1	28.2

Drainage region	Sub region	Irrigated area (ha) 2004
	A21D2	4.9
	A21D3	915.6
	Sub total	*948.7*
A21E	A21E1	0.0
	A21E2	15.0
	A21E3	293.0
	Sub total	*308.0*
A21F	A21F1	2.9
	A21F2	1 602.5
	A21F3	2 465.6
	Sub total	*4 071.0*
A21G	A21G1	42.4
	A21G2	539.8
	Sub total	*582.2*
A21H	A21H1	17.1
	A21H2	661.3
	Sub total	*678.3*
A21J	A21J1	946.0
	A21J2	1 047.0
	A21J3	846.5
	A21J4	374.2
	A21J5	741.5
	A21J6	97.4
	Sub total	*4 052.6*
A21K	A21K1	77.7
	A21K2	162.0
	A21K3	1 809.8
	Sub total	*2 049.4*
A21L	A21L	0.0
Hartbeespoort Irrigation Board		*15 470.0*
Total – Upper Crocodile		**32 605.3**

Irrigation is an important economic sector and contributes significantly to the regional GDP of the area (Table 4.6). Pivot irrigation is prevalent throughout the study area and is particularly conspicuous in the lower reaches of the Crocodile River in IUA 13. IUA 15 in the Mokolo catchment is also an important pivot irrigation area.

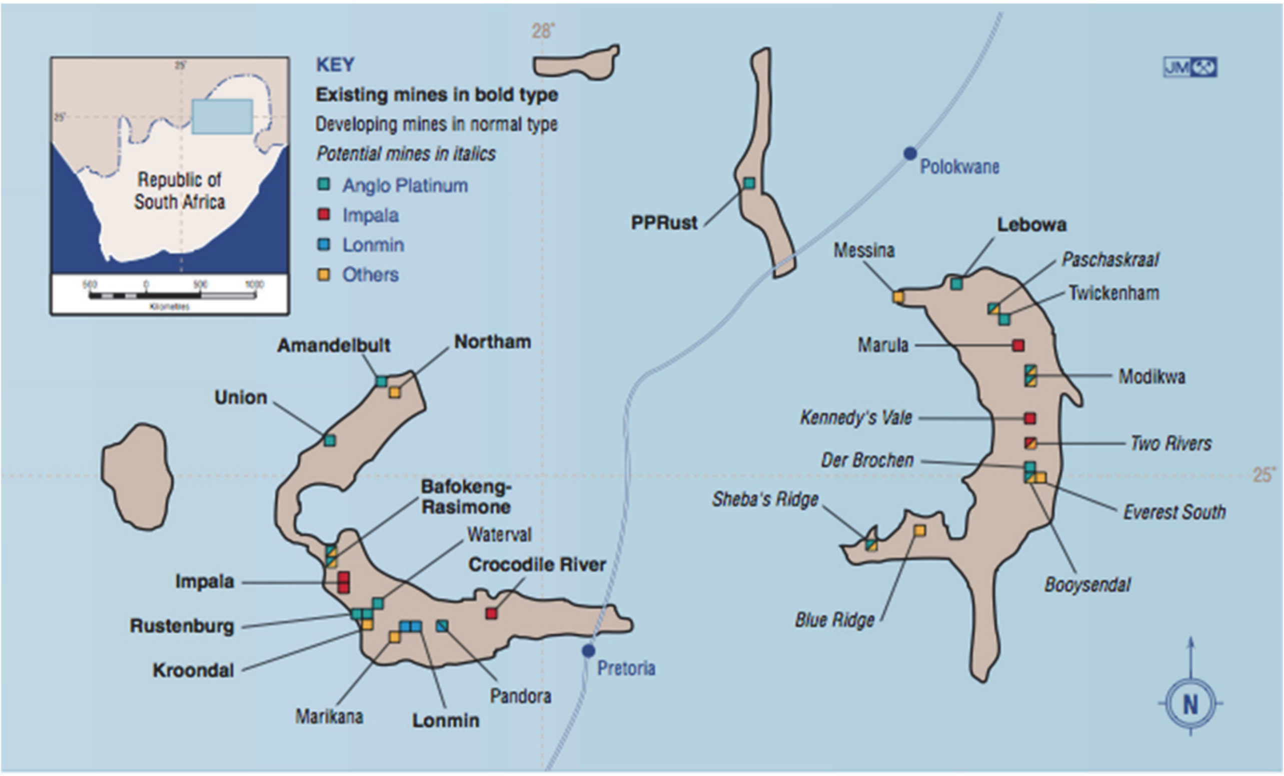


Figure 4-5. General map of the Bushveld Igneous Complex. The western limb is shown to the left of the map (Source: Johnson Matthey 2003)

4.2.3.1.4 Stock Watering

The water requirements for stock watering occur throughout the catchment and the total water requirements are 22 million m^3/annum (DWA 2008).

4.2.3.1.5 Mining

The mining sector is an important contributor to GVA in the study area. Of particular importance is the large number of platinum deposits in the Elands sub-catchment, which are the largest PGM deposits in the world.

The WMA contains a large portion of the Bushveld Igneous Complex, the largest platinum group metals (PGM) deposit worldwide. Thus, below the dam, the Rustenburg area in the Elands River sub-catchment is well known for its extensive platinum mining activities. Mining activities in the study area are dominated by the platinum mining industry, which is centred on the Rustenburg in the Elands catchment. The catchment contains the western chapter of the mineral-rich Bushveld Igneous Complex (BIC) (Figure 4.5).

4.2.3.1.6 Power Generation Water Requirements

There are three relatively small power stations in the Crocodile River catchment: Kelvin in the Upper Crocodile sub-catchment and Pretoria-West and Rooiwal in the Apies-Pienaars sub-catchment. The water requirements of the Kelvin, Pretoria-West and Rooiwal power stations are 11 million m^3/annum, 6 million m^3/annum and 17 million m^3/annum respectively.

Matimba and Medupi (under construction) power stations can be found in the Mokolo catchment. Three new Eskom power stations CF3, CF4 and CF5 are envisaged for the future.

4.2.3.1.7 Manufacturing

The manufacturing sector is an important sector in the study area and remains a critical component of the domestic economy. In Gauteng alone it employs 600,000 people in over 9,000 enterprises. It is therefore one of the biggest employers in the province (Gauteng 2010).

Major manufacturing sectors in the Gauteng portion of the study area includes: manufacture of textiles and clothing; manufacture of petroleum products, chemicals, rubber and plastics; manufacture of metallic products, manufacture of non-metallic products and manufacture of transport equipment (Gauteng 2010).

4.2.4 Fish production for food

During the period covered by the NIWR (1985) study it was estimated that anglers caught an average of 695 t of fish annually. This was estimated to be in excess of the sustainable yield which was estimated at 525 t pa. This fish would have been consumed mainly by the anglers themselves. The foodweb restructuring thrust of the HDRP has caught an average of 47.6 t pa. This is a low estimate of the total production of the dam as anglers will have caught fish and there is known to be illegal netting on the dam. The fish from the foodweb restructuring activities is marketed within the local communities. The assumption is that the illegal catch is also marketed within the local communities. The assumption is that the anglers' catch would be consumed by the anglers themselves. It is postulated that the HDRP Phase 2 could pilot an inland, impoundment-based, fishery which could be implemented in other dams as well. Phase 2 would provide training for people who are prepared to get involved in fisheries for their livelihood.

4.2.5 Cultural services

The Hartbeespoort Dam landscape has significant cultural services through its lifestyle attractions. The dam has thus served as a property development node around which various tourism and recreation activities have developed. Many of the permanent residents in these areas prefer commute to work to destinations in and around Pretoria or Johannesburg on a daily basis, whilst enjoying the country lifestyle benefits provided around the dam. Quantifying the economic value of all the cultural services provided is not a simple task, however, the value of these services are expressed, at least as a proxy value in the property values around the Dam, as influenced by the landscape character.

The European Landscape Convention defines a landscape as ‘‘an area, as perceived by people, whose character is a result of the action and interaction of natural and/or human factors’’. This definition emphasises the complexity of human relationships with particular landscapes and that these relationships are not merely restricted to negative effects to ecosystems or exploitation of natural resources, but it also concerns peoples emotional, intellectual and socio-economic inputs, and the resulting ways in which people contribute to landscape distinctiveness and diversity. Another definition is provided by Berque (1984) who stated that ‘‘landscapes are the biophysical imprint of past generation's activities as well as the matrix for those of the current generation and … for the generations to come’’.

Landscape character can thus be defined in terms of a range of ecosystem services (as envisaged in the Millennium Ecosystem Assessment framework.) These include aesthetic, inspirational, spiritual, sense of place and, where relevant, cultural heritage services.

Aesthetic services refer to those aspects of the ecosystem that give pleasure through beauty. For example, it includes those that underlie the quality of the aggregate viewscape as seen by residents in and visitors to the area. The inspirational service is the degree to which the entity inspires creativity among residents and visitors. This could be reflected, for example, through activities in art, literature and music dependent on the state of the area, but, more generally, inspiration to be more productive in economic activities. The spiritual service refers to the degree to which the area satisfies human needs for religious or other spiritual fulfilment. The notion and value of sense of place has been used in ways that confuse and conflate diverse ecosystem cultural services. Here it means the degree to which people depend on the particular features of the area for their cultural identity. Environmental effects on sense of place may reveal as the potential culture loss in local communities. Cultural heritage services are reflected in the degree to which the cultural heritage within the entity is enjoyed by residents and visitors, independent of sense of place services. This would be reflected in visits to places of special historical or related value, for example (but not for purposes of research or education).

Thus, the cultural ecosystem services, insofar as they are relevant to the Hartbeespoort Dam would be revealed in the value of the landscape that is embedded within property values. The economic technique used in evaluating property price effects is known as hedonic valuation.

In 2010 DWS commissioned such a hedonic valuation study as part of the Reserve determination study for the Crocodile-West Marico. The results showed that a property adjacent to the Dam with no water frontage and no water view had an average value of R6,207 per square meter (/m^2). A water view added approximately R565,000 to the value property of any property. Water frontage added approximately R1,513,000 to the value of any property. These results confirmed that property values are positively affected by proximity to and view of a water body such as the Dam.

5 Systems' description of the Dam: Ecological context

5.1 Purpose of this Chapter

Following on from the socio-economic chapter (Chapter 4 above), this chapter proceeds to demonstrate how these benefits link to ecological infrastructure and ecological processes. It concludes with an understanding of multiple hazards in the system, and it also concludes that a remediation programme should be seen as an opportunity for economic activity.

In the analysis that follows, it is useful to analyse the eutrophication problem of the Dam within the context of a meta-system comprising the Dam's catchment and its downstream and adjacent beneficiaries. In particular, this includes:

- The catchment area comprising several municipalities, containing key rivers, WWTW and acid mine drainage decant points,
- The Dam precinct containing residential areas, water users and recreational users around the Dam,
- The water users downstream within the Crocodile West river system, including principally irrigators and potentially future mining activities,
- The Lephalale industrial development node in the Mokolo system, which will receive water from a transfer from the Dam in the medium term.

The following quote from Williams and Pittock (undated) serve to illustrate the centrality of water to the social-ecological system:

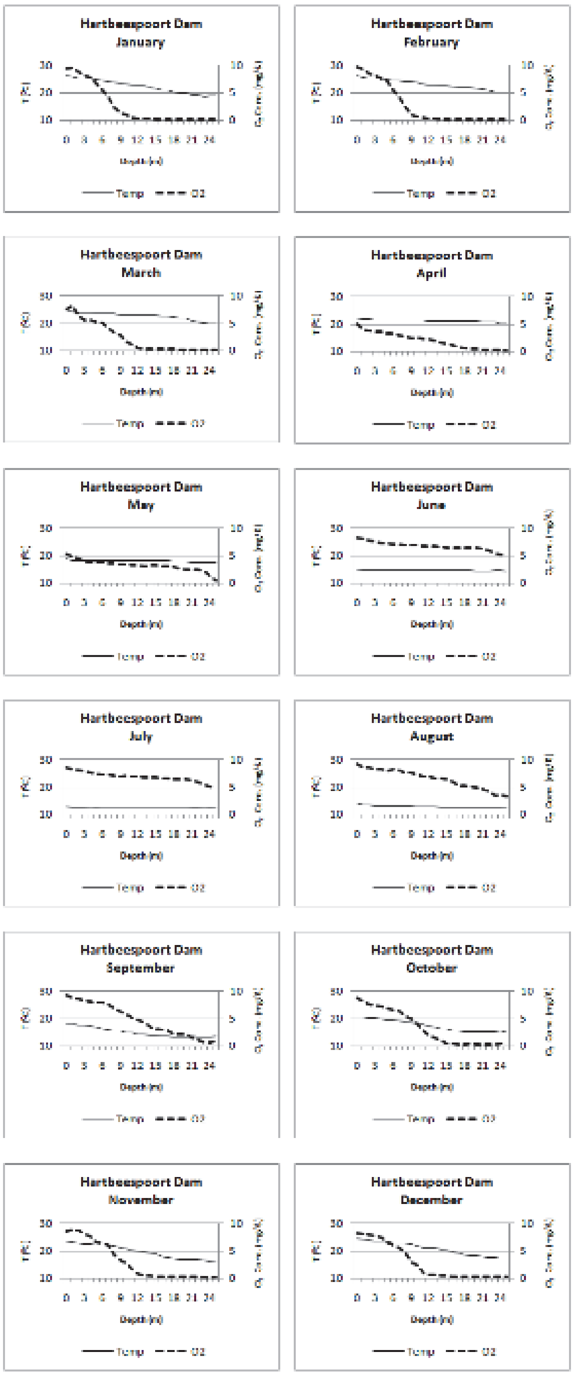
- *In 1911, John Muir observed, 'When we try to pick out anything by itself in nature, we find it hitched to everything else in the Universe.' A century later, a gathering of the World Economic Forum discovered the same phenomenon. Four hundred top decision-makers listed the myriad looming threats to global stability, including famine, terrorism, inequality, disease, poverty, and climate change. Yet when we tried to address each diverse force, we found them all attached to one universal security risk: fresh water.* (Margaret Catley-Carlson, Patron, Global Water Partnership, 2008-2010, Chair of World Economic Forum Global Agenda Council on Water Security) (quoted from Williams and Pittock, undated).

5.2 Limnology

The limnology of the dam will set the background for the understanding of the basic conditions which influence the aspects discussed in this chapter.

Hartbeespoort Dam is a warm monomictic (becomes isothermic and turns over once a year in winter) impoundment (NIWR, 1985). Figure 5.1 gives the median monthly temperature and dissolved oxygen depth profiles for the Lake. During summer the thermocline prevents the epilimnion (warm surface water) and hypolimnion (cooler bottom water) from mixing. The thermocline is not very distinct in the figures as the figures represent the average figures between 1980 and 2012 and for reasons such as the thermocline oscillation with the seiche in the lake (NIWR, 1985; Fig 5.1). What is clear from this figure is that the lake is anoxic below a depth of approximately 12 meters for half the year. Dissolved oxygen is present throughout the water column under the isothermic conditions during the winter turnover. Orthohosphate (SRP) readily combines the metal ions to form largely insoluble compounds under aerobic conditions. Under anoxic conditions, however, the SRP resolubilises and phosphate is released into the hypolimnion. During winter turnover this phosphate is then carried into the surface waters where it provides additional phosphate to support algal blooms (Wetzel, 1983).

The inflow from the Crocodile River is generally colder than the surface waters of the lake (HDRP, 2013 Fig. 12). This causes the water to plunge below the surface to a depth at which the water density of the inflow is similar to the density of the water in the lake. The depth of these density currents and the potential impact of the TDS and TSS on the water body has not been determined. For instance, the depth to which the inflow plunged would determine where the nutrients and pollutants in the inflow would be deposited. The density currents are one of the mechanisms through which sediments and nutrients are distributed through the dam.



The residence time of water in the dam has changed with the increase of water being discharged into the catchment as a result of growth in the upper catchment (Table 3.6).

Chutter and Roussow (1992) refer to microstratification in the surface waters. This refers to thermal differences forming in the surface waters. The microstratification is less stable than that of the main thermocline, being most common during calm, warm weather. This was found to occur at a depth of <2 m. It does, however, keep the algae in the bright light and warmer water near the surface. Microstratification is readily disrupted by wind or cooler weather.

Figure 5-1: Median monthly temperature and oxygen depth profiles in the Hartbeespoort Dam (1980-2012). DWA database was used as source (HDRP, 2013 p.27)

The dam is currently in a plagioclimactic state (Harding, pers comm). A plagioclimactic state may be defined in terms of the intermediate disturbance hypothesis as the stable terminal equilibrium in eutrophic lakes. Wilkinson (1999) refers to the idea of *intermediate disturbance thus: 'One of the best-known consequences of disturbance is reduction in the proportionate abundance of competitively dominant species, as in Connell's (1978) 'intermediate disturbance hypothesis'*.

5.2.1 Water quality

The Crocodile River is, from an ecological perspective, rated as a heavily used river, with PES scores of mostly D's, the lowest acceptable ecological classification under current DWS policy. What this means for Hartbeespoort Dam is that the Crocodile, which contributes the majority of the inflow, has poor quality water. The water quality, both in terms of concentration and load, has a substantial effect of the overall water quality of the dam.

Intermediate Reserve determination studies were undertaken for all of the major catchments during 2008 to 2011. These results are available for Crocodile West and its main tributaries (Pienaars, Elands, Jukskei). Table 5-1 sets out the details of the relevant EWR sites for the Limpopo WMA that were undertaken as part of the Intermediate Reserve determination, and their PES scores.

Table 5-1: Details of EWR sites from intermediate reserve studies

EWR site	River: Site name	Quaternary catchment	PES	Coordinates	Level of determination
Crocodile (West) River system					
EWR 1	Crocodile: Upstream of the Hartbeespoort Dam	A21H	D	E 27.896 S 25.8004	Intermediate
EWR 2	Jukskei: Heron Bridge School	A21C	E	E 27.9621 S 25.9539	Intermediate
EWR 3	Crocodile: Downstream of Hartbeespoort Dam in Mount Amanzi	A21J	C/D	E 27.8431 S 25.7168	Intermediate
EWR 7	Crocodile: Upstream of the confluence with the Bierspruit	A24C	D	E 27.51743 S 24.88661	Intermediate
EWR 8	Crocodile: Downstream of the confluence with the Bierspruit in Ben Alberts Nature Reserve	A24H	C	E 27.32569 S 24.64476	Intermediate

As part of a Reserve Determination process it is necessary to understand the water quality of the system to determine how it would respond to changes.

Water quality is a driver of the overall Ecostatus of rivers. The other drivers are flow and geomorphology. The Crocodile (West) river is highly impacted in terms of water quality. The biggest impacts on water quality in the area are from the large scale water and land users. The urban areas in the south-east of the catchment, with their waste problems impact substantially on the Hartbeespoort Dam. Other contributors to the poor water quality include industries and abandoned and operational mines. The return flows from domestic WWTWs are also a major contributing factor and some local authorities struggle to comply with discharge standards. Fertilizers and pesticides from agricultural activities also have a negative impact. The water quality of the Magalies River is relatively good with localised impacts from land based activities. The dams in the system impact on the water quality in the rivers.

Groundwater quality is generally good, apart from specific rural areas where the groundwater is polluted by poor sanitation facilities.

In addition, treated wastewater return flows from the Upper Vaal WMA play an important role downstream where the water is used in the Crocodile (West) catchment area, making up approximately 27% of available water, in excess of 356 million m^3/a. The quantities are increasing and while serving as a potential source of water for future development, there is likely to be a cumulative impact on the water quality.

The water quality issues within the Crocodile (West) WMA are largely related to nutrients and acid mine drainage (AMD) associated with the Hartbeespoort Dam. The elevated nutrient levels in the dam largely originate from point and non-point sources in the Hennops, Jukskei, Magalies and Crocodile rivers. The AMD concerns are largely associated with the Hennops and Jukskei rivers.

EWR sites 1 and 3 can be used to assess the water quality associated with the Hartbeespoort Dam. EWR 1 (A2H012 water quality monitoring point) is situated upstream of the dam in the Crocodile River and EWR 3 (A2H083 water quality monitoring point) is downstream of the dam in the Crocodile River. EWR 1 was identified to be moderately sensitive with a PES and REC of a D category. The average phosphorous concentration is 0,56 mg/L and the average TDS concentration is 400,08 mg/L. EWR 3 is high in sensitivity with a PES of C/D and a REC of C/D with an average phosphorous concentration of 0,14 mg/L and an average TDS concentration of 346,32 mg/L. From the comparison between the water quality data at the inflow and outflow of the Hartbeespoort Dam it can be assumed that, due to various chemical and physical processes, phosphorous levels decrease significantly with TDS concentrations also decreasing.

The Western Basin AMD samples on average have TDS concentrations of 3850 mg/L. AMD management to minimise the impacts on the water resource include decant prevention and management, ingress control and water quality management. Various treatment scenarios were considered, as discussed below (DWA, 2013; Inter-Ministerial Committee, 2010).

The quantity of AMD is expressed as total dissolved solids (TDS). The main sources of AMD originate from the mining activities within the Hennops and Jukskei River –sub-catchments. However, with the confluence of these tributaries with the Crocodile River, significant dilution narrows the range of impacts associated with AMD. The average annual TDS concentration of the tributaries is between 350-450 mg/L (Golder Associates, 2013).

The scenarios considered for AMD management in the Hartbeespoort Dam catchment are:

- Neutralise AMD to 2776 mg/L resulting in

- 15% salinity increase in the Hartbeespoort Dam corresponding to
    - 50 000 tons/a salinity load and 50 mg/L TDS concentration increase in the long term
- Neutralise AMD to 100 mg/L resulting in
    - 4-5% increase in salinity levels in the dam
    - Significant reduction in impacts

With the implementation of the WDCS and the implementation of AMD management solutions, the impacts of AMD on the Crocodile River catchment downstream of the Hartbeespoort Dam may be negligible.

The Resource Quality Objectives (RQO) for TDS, as set for the Olifants WMA, is:

- Ideal range 220 mg/L
- Acceptable 350 mg/L
- Tolerable 800 mg/L

According to the Olifants River Ecological Water Requirements Assessment, the TDS concentrations for the different water quality categories, are:

- A 195 mg/L
- B 295 mg/L
- C 520 mg/L
- D 780 mg/L

Water quality in the Lower Crocodile River is deteriorating. Salts and nutrients are high. There are also increased levels of toxicants in the middle reaches of the river. Urbanisations, industrial diffuse sources and high agricultural return flows are the major impacting activities.

Present Ecological State assessments for water quality are shown below per Water Quality Sub-Unit. Current status is shown in the Table 5-2, as well as the water quality state used to design quality ecospecs. It is important to note that an extrapolation technique has been used for the determination of water quality at some sites.

Table 5-2. Water quality, PES and REC per sub-unit of the Crocodile (West) WMA.

Water Quality Sub-Unit and EWR site	PES: Water Quality	Recommended water quality category of the overall REC (Quality ecospecs)
WQSU 1	D	D
WQSU 2: EWR 2	D/E	D
WQSU 3 EWR 1	D/E	D/E
WQSU 4: Rapid EWR	B	B

Water Quality Sub-Unit and EWR site	PES: Water Quality	Recommended water quality category of the overall REC (Quality ecospecs)
WQSU 5: EWR 3	D/E	D
WQSU 6: Rapid EWR	B/C	B/C
WQSU 7	B/C	B/C
WQSU 8	C	C
WQSU 9: EWR 6	D	D
WQSU 10: Rapid EWR	C	C
WQSU 11	C/D	C/D
WQSU 12	C	C
WQSU 13	C/D	C/D
WQSU 14	C/D	C/D
WQSU 15: EWR 4	B/C	B/C
WQSU 16	B/C	C
WQSU 17: EWR 5	C	C
WQSU 18	B/C	B/C
WQSU 19	B/C	B/C
WQSU 20	B/C	B/C
WQSU 21: EWR 7	D	D
WQSU 22	C	C
WQSU 23	C	C
WQSU 24: EWR 8	D	D

5.2.2 Stable lake level

The stable lake level provides conditions suitable for the development of vegetation in the littoral zone. Fluctuations in lake level, particularly when low levels may last longer than a year, leaves the vegetation high and dry and typical littoral vegetation is not able to survive these conditions. Figure 5-2 shows the fluctuations of the water level in the dam over the past 3 decades. As may be seen, the dam has been at or close to full supply level for the last 2 decades. This has provided stable conditions in the dam.

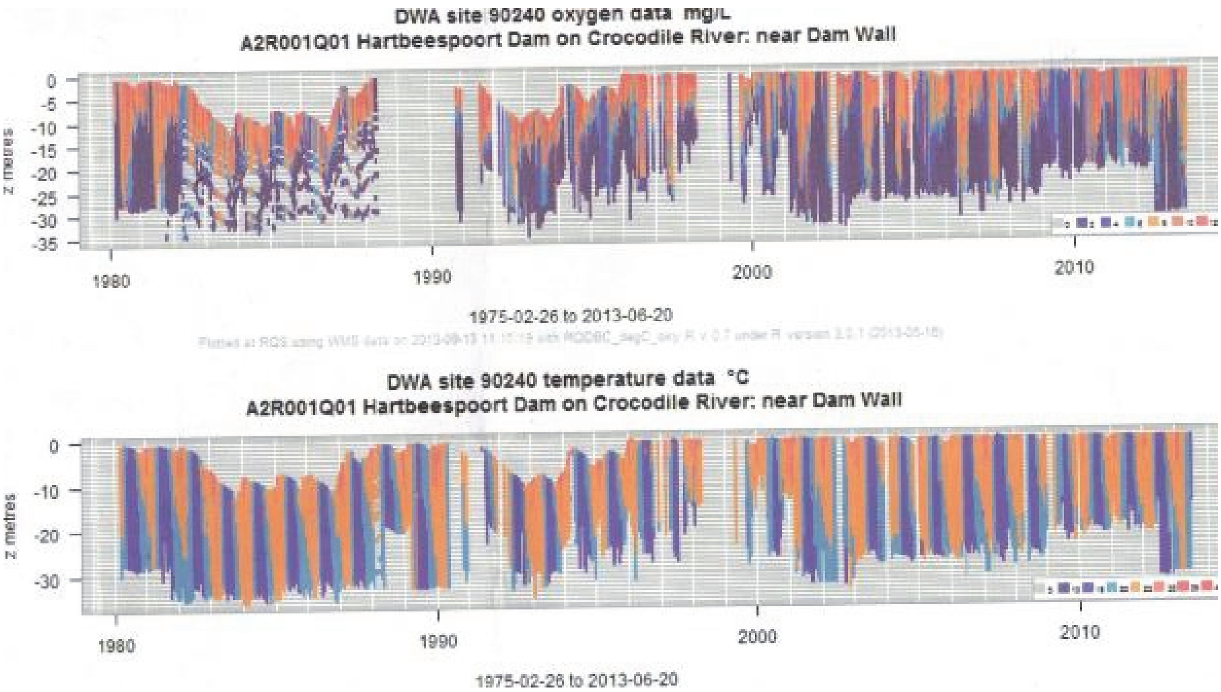


Figure 5-2: The dissolved oxygen and temperature figures for the DWS monitoring site 90240 (near the Hartbeespoort Dam wall) (Charts plotted at RQS using WMS data).

The data for the DWS water monitoring site 90240 (Figure 5-2) from 1975 to 1980 are largely lacking and so have been omitted from Figure 5.2. In addition to the vertical profiles of dissolved oxygen and temperature, these charts also show the lake level fluctuations. Note the relatively low lake levels during the period of the CSIR study (NIWR, 1985) and the almost constant full supply level from 1996 to the present (Charts plotted at RQS using WMS data).

Characteristically, an impoundment which is subject to large annual fluctuations has poor development of the littoral vegetation, both above the full supply level of the impoundment as well as in the shallow, submerged areas. The long period of stable lake levels has created conditions in which the littoral vegetation has been able to develop. A result of the planned change in the management regime of the lake level, however, may change this as the littoral will be subjected to periods of desiccation.

5.2.3 Hydrology and Hydraulics

The increased inflow into the dam has reduced the residence time of water in the dam from an average of 304 days (NIWR, 1985) to 95 days (HDRP, 2013a) (Table 5-3). This has come about as a result of the increase in the volume of water pumped across from the Vaal catchment to cater for the increased population living in the catchment of the Hartbeespoort Dam. In effect, this increase reflects the increased discharge from WWTWs and so bears a load of nutrients and pollutants.

The hydrology reflected in the HDRP reports is the annual inflow. However, the monitoring reports indicate that the floods following rainfall events carry a proportionately higher concentration of nutrients and pollutants than the lower flows. An understanding of the level to which the cooler inflow plunges in the dam will indicate where the sediment load with associated nutrients and pollutants will be deposited.

Table 5-3: The decrease in residence time (in days) of water in Hartbeespoort Dam with the increasing interbasin transfer from the Vaal.

	Million cubic meters	Source	Mean Residence time (Days)
Hartbeespoort Dam capacity	194.626	DWA (1986)	
Inflow 1985	233.5	NIWR (1985)	304
Inflow 2010/11	534	HDRP (2013a)	95

The hydraulics of the lake have not been elucidated but are important in developing an understanding of the currents in the lake from the wind-induced currents. These currents deposit the sediment and the associated adsorbed compounds as well as distributing the nutrient-rich 'plankton rain'.

The hydraulics within the dam will determine where suspended material is deposited, where the 'planktonic rain' will fall, so to some extent determining the distribution of nutrients within the dam basin. The hydraulics will also determine the density currents of the inflowing water.

5.2.4 Nutrient regime

3.4 Integrated Monitoring Program – PEP A4 [CE5.1]
5.4 Phosphate Reduction at Source and Compliance – PEP C3 [CS1.1]

This discussion will be limited to the macronutrients, phosphorous and nitrogen.

The total nitrogen to total phosphorous ratio plays a role in determining the dominant algal species. Chutter and Rossouw (1992) found that when the N:P ratio was lower than 17 then cyanobacteria dominated, but when the TN:TP ratio was over 17 then green algae dominated. Cyanobacteria are able to fix atmospheric nitrogen and so able to take advantage of higher levels of P in the water. In the treatment of urban wastewater N is easier to remove than P. This tends to result in effluent discharges which are relatively richer in P than N, so selecting for cyanobacteria. In addition, the process of denitrification occurs in the anoxic zones of the lake (NIWR, 1985).

Chutter and Rossouw (1992) quote Smith (1986) as saying that cyanobacterial biomass is always <10% at a TN:TP ratio of >29, with other algae predominating. This change took place in Hartbeespoort, however, at the lower TN:TP ratio of 17 during the late 1980s.

Soluble reactive phosphate (SRP or ortho-phosphate) has been identified as the nutrient responsible for eutrophication. During the course of the HDRP the total load of SRP coming into the lake has been increasing (Figure 5-3).

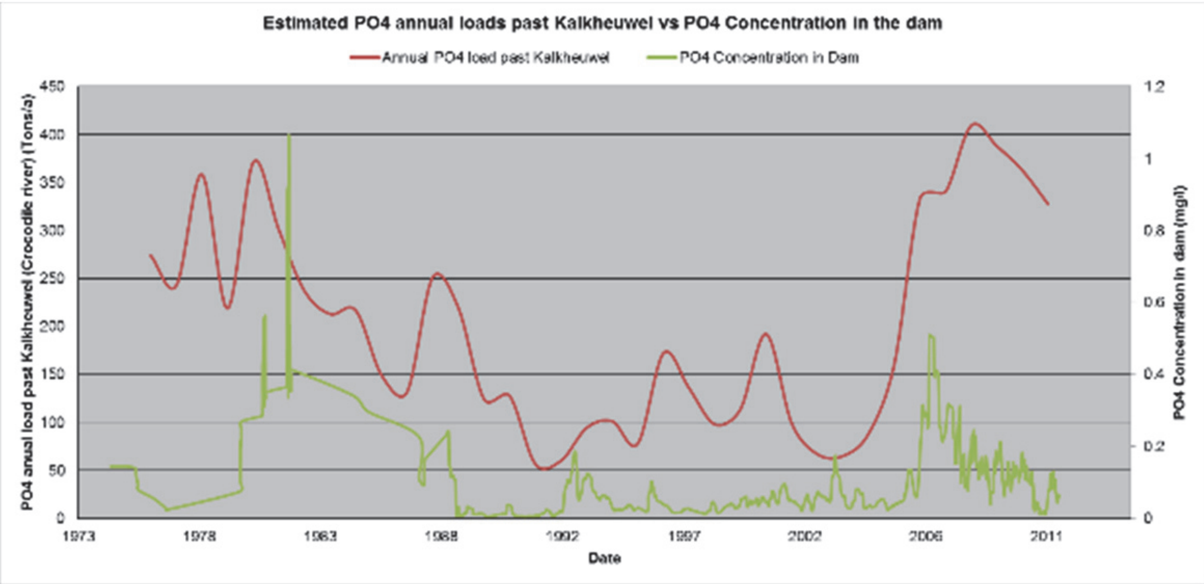


Figure 5-3: SRP concentrations in the dam as well as SRP loads past Kalkheuwel (HDRP, 2013a, p 50)

The figures indicate that the SRP load increased to over 400 t p/a during the HDRP, but that the SRP concentration in the water body decreased at this time.

Using data generated from the DWS monitoring programme, the potential (estimated) phosphorous load accumulating in the lake has been calculated and is given in Table 5-4. It is apparent from this table that the total load of phosphorous in the lake is large. The figures given do not take into account any P accumulated prior to 1999 so should be considered as conservative estimates.

Table 5-4. Inflow, accumulation and outflow of phosphorus loads in the dam (taken from HDRP, 2012a Table 8.2 page 52)

Hydrological year	Inflow (Crocodile and Magalies rivers, Swart Spruit)			Outflow (Crocodile river DS, East and West Canals)			Potential accumulation in dam since 1999	
(Oct-Sept)	Flow (mil m^3/a)	SRP (tons/a)	TP (tons/a)	Flow (mil m^3/a)	SRP (tons/a)	TP (tons/a)	SRP (Tons)	TP (Tons)
Pre 1999	Not calculated						0.0	0.0
1999-2000	577.6	202.0	305.5	652.6	53.3	96.6	148.7	208.9
2000-2001	312.0	104.3	179.6	402.2	49.9	67.0	203.1	321.6
2001-2002	241.3	70.2	97.0	335.1	32.9	53.6	240.4	364.9
2002-2003	167.2	67.1	108.9	219.6	31.9	52.4	275.5	421.4
2003-2004	220.3	89.6	142.9	294.1	25.8	54.9	339.3	509.4
2004-2005	293.9	162.4	238.0	288.9	26.8	43.9	474.9	703.5
2005-2006	414.0	339.6	419.7	371.9	41.8	76.5	772.7	1046.7
2006-2007	303.7	342.1	430.9	296.8	98.1	131.3	1016.6	1346.3
2007-2008	495.9	414.5	658.6	492.9	174.4	241.3	1256.7	1763.6
2008-2009	489.1	389.4	577.3	445.8	176.1	244.6	1470.0	2096.3
2009-2010	648.0	375.9	531.4	618.8	175.7	220.6	1670.2	2407.1
2010-2011	740.7	340.5	422.0	750.7	138.0	180.8	1872.7	2648.3
2011-2012	534.0	417.5	516.6	518.2	113.02	152.5	2177.2	3012.4

5.2.5 Water inflow and phosphate load

The annual volume of water flowing into the dam has been increasing over the course of the HDRP. This is largely as a result of the inter-basin transfer of water from the Vaal system increasing the volume of effluent discharged into the Hartbeespoort catchment. Table 5-4 gives the annual inflow of surface water into the Lake for the hydrological years 1999 to 2011 with a preliminary estimate for the year 2011-2012. These three rivers account for 99% of the flow under current conditions. The table also gives the load of total phosphorous into the lake for the same period which is discussed below. It is apparent from this table that the annual flow into the lake has been increasing. This shows a substantial increase over the annual inflow given in NIWR (1985) which was a total of 233.5 million m^3 per annum (made up of 224 million m^3 per annum of inflow and 9.5 million m^3 per annum of precipitation).

The annual inflow into Hartbeespoort Dam for the hydrological years 1999 to 2011 with the estimate of the annual flow for the year 2011-2012 based on incomplete data (Table 5-5). The load of total phosphorous is discussed below (figures from HDRP, 2013a p. xv).

Table 5-5. The annual inflow and total Phosphorous load entering Hartbeespoort Dam (HDRP, 2013a, pg xv

Hydrological year	Inflow (Crocodile and Magalies rivers and Swartspruit)	
(Oct-Sept)	Inflow (mil m^3/a)	TP (tons/a)
1999-2000	577.6	305.5
2000-2001	312.0	179.6
2001-2002	241.3	97.0
2002-2003	167.2	108.9
2003-2004	220.3	142.9
2004-2005	293.9	238.0
2005-2006	414.0	419.7
2006-2007	303.7	430.9
2007-2008	495.9	658.6
2008-2009	489.1	577.3
2009-2010	648.0	531.4
2010-2011	740.7	422.0
2011-2012 [7]	~ 530	~ 485.5

5.2.6 Phosphorous build-up in the lake

There has been a trend of increasing inflow into the dam since 1999 (Figure 5-3) and earlier as a result of the increasing volume of water supplied by Rand Water to the Crocodile (West) catchment which leads to an increase in effluent discharged into the Hartbeespoort Dam catchment. This has resulted in an increase of the P load into the dam (Tables 5-4 and 5-5). The dam is a sink for P, with the result that a substantial proportion of the P which enters the dam remains in the dam.

The estimate of P which has accumulated in the dam since 1999 is 3 012.4 tonnes.

At the same time that the load of SRP into the dam was increasing, the concentration of SRP in the water column was decreasing (Figure 5-3). The reasons for this were not investigated.

Ashton (pers. comm.), during his work on Hartbeespoort Dam while at the CSIR, found SRP at 600 mg ℓ^{-1} at depths of up to 50 cm below the surface of the sediment. This SRP was mobile and in the laboratory, repeated replacement of the water above the sediment column with distilled water showed that this SRP migrated upwards through the sediment column and into the water column for an extended period. This bears out the statement made by Harding et al. (2004b) that '*the capacity of the dam to deal with the loads of phosphorus has already been substantially exceeded*'.

[7] Roughly calculated by Dr. Z. Cukic from incomplete data

Van Veelen and Hooghiemstra (2013), in their report on the implementation of the waste discharge charge system using the Hartbeespoort catchment as the case study area, quantified the sources of the Phosphorous that flow into the dam (Table 5.6) (see also Appendix 3).

Table 5-6: The sources of the phosphorous load entering Hartbeespoort Dam (from Van Veelen and Hooghiemstra (2013).

Catchment	Waste Water Treatment Works		Diffuse Load	Natural load	Total Load	% Contri-bution
	Name	Load (kg/a P)	(kg/a P)	(kg/a P)	(kg/a P)	
Magalies	Magalies	830	84	386	1 300	0.37
Swartspruit			2 757		2 757	0.79
Upper Crocodile	Randfontein	9 610				
	Percy Steward	11 389				
	Driefontein	1 854				
	Total	22 853	1 837	325	25 015	7.17
Jukskei	Esther Park	166				
	Kelvin P/S	2 500				
	Northern Works	42 142				
	Total	44 808	108 830	324	153 962	44.15
Hennops	Hartbeesfontein	5 969				
	Olifantsfontein	42 243				
	Sunderland Ridge	48 753				
	Rietvlei Dam	-3 606	3 609			
	Total	93 359	70 570	248	164 177	47.08
Lower Crocodile Increment catchment estimate					1 500	0.43
Total for Catchment		161 850	184 077	1 284	348 711	100.00

This study showed that 91% of the P load came from the Hennops and Jukskei Rivers with the upper Crocodile contributing 7.2% of the load. Three waste water treatment works (Northern Works, Olifantsfontein and Sunderland Ridge) contribute 80% of the point source load. The other important fact that this study showed was that the diffuse sources contributed 52.8% of the total load entering the dam. The break-down of the diffuse sources (Table 5-7) revealed that >98% of the diffuse load came from leaking or overflowing sewers.

Table 5-7. Breakdown of the contributions of diffuse sources to the total diffuse source load.

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	178 516	98.28
Higher base flow	396	0.22
Irrigation return flow	190	0.10

Van Veelen and Hooghiemstra (2013) recommend a reduction in the P load of 81% to achieve the threshold boundary between mesotrophic and eutrophic conditions in the dam (Figure 5-4). This load reduction is not achievable in the short term

Van Veelen describes the interventions needed to achieve the reduction in the P load in Appendix 3 of this report.

The figure below (Figure 5-4) is based on the OECD (1982) categorisation of trophic levels. The arrows represent the P levels as they are currently (present) and the interim and desired levels as rated as achievable by Van Veelen and Hooghiemstra (2013) given the interventions which can be achieved in the catchment. These interventions would, over time, change the state of the dam from hypertrophic to borderline mesotrophic / eutrophic. This process will, however, take time.

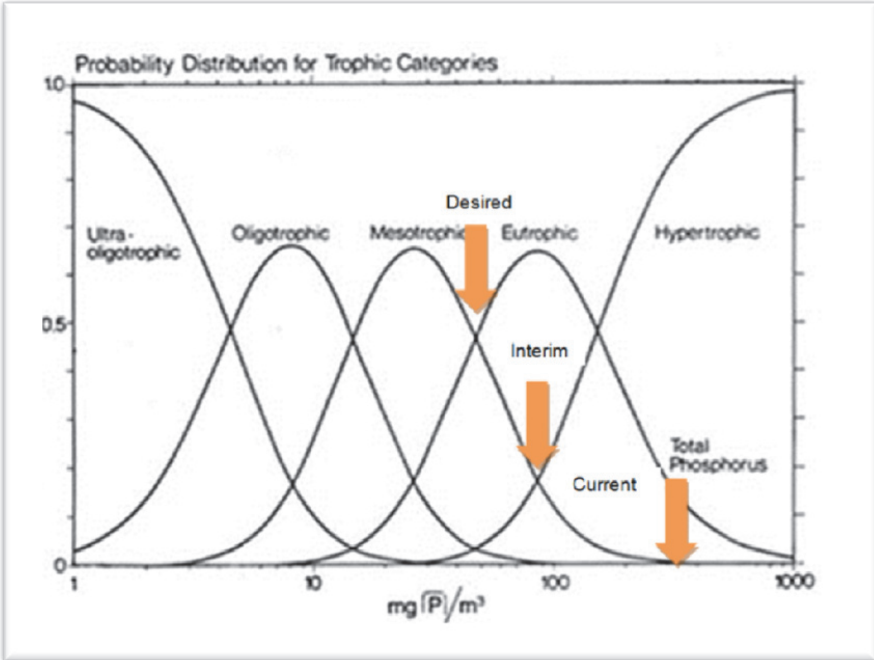


Figure 5-4: Categorisation of trophic levels (OECD, 1982). The arrows indicate the reduction in trophic status of Hartbeespoort Dam that are achievable following the interventions recommended by van Veelen and Hooghiemstra (2013).

5.2.7 The influence of macrophytes on nutrients in the water column

Rooted macrophytes, both submerged and emergent, offer a degree of protection to the littoral zone from wind and wave-induced turbulence. This turbulence can resuspend sediments which, in eutrophic water bodies, contain phosphate. This phosphate may then be carried in the water currents to other areas of the lake. Both Beklioglu et al. (2011) and Genkai-Kato and Carpenter (2005) note the role of rooted macrophytes play in promoting stability in lakes. Beklioglu et al. (2011) (Figure 3-1) note that the dominance of rooted macrophytes is responsible for the clear water steady state in lakes.

5.2.8 Algae

The algae, or indeed other vegetation, will sequester phosphate. As a result, the biomass of algae or other vegetation has a certain phosphate content which may be removed with the harvest of the vegetation.

NIWR (1985) estimated algal productivity in two ways, through the measurement of Chlorophyll a and determining species composition and volume. Chutter and Rossouw (1992) found little difference in the Chlorophyll a concentration between the times when cyanobacteria or chlorophytes dominated the phytoplankton.

NIWR (1985) found that the Chlorophyll a concentrations varied over 3 orders of magnitude to a high of 321 mg m^{-3} (µg ℓ^{-1}) in the top 5 m of the pelagic areas of the lake during the period 1983 to 1984. Chutter and Rossouw (1992) Found a similar magnitude of variation in Chlorophyll a concentrations, but with a high of 1150 µg ℓ$^{-1}$.

The HDRP took chlorophyll a as an indicator of primary production (HDRP, 2013b p 28) show a similar variation in the chlorophyll a concentrations. The Figures 5-5 and 5-6 also show an increasing trend up to 2007 followed by a declining trend in the concentration between 2008 and 2011.

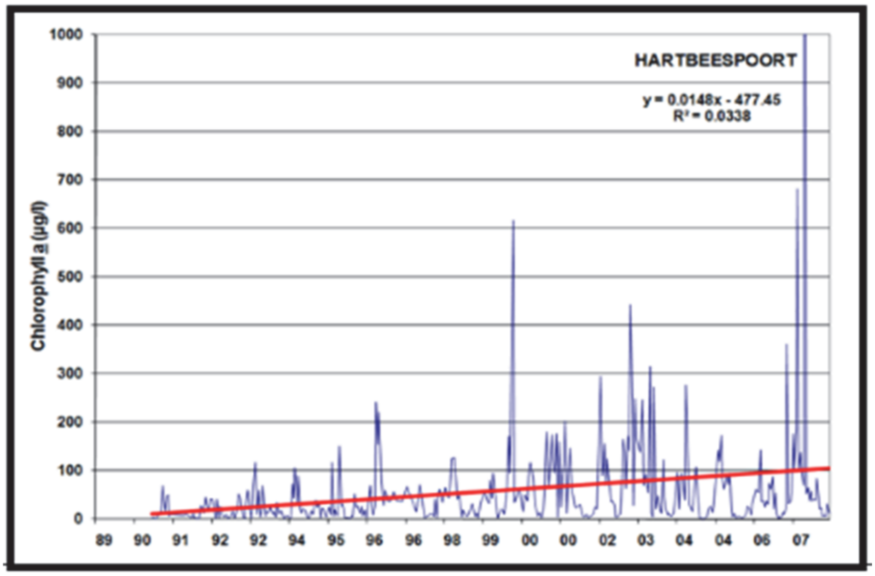


Figure 5-5: Chlorophyll a trend in the Hartbeespoort Dam (1989 to 2007). The DWA WMS database was used as source (Van Ginkel 2013; Fig. 2.3 p 28 in HDRP, 2013).

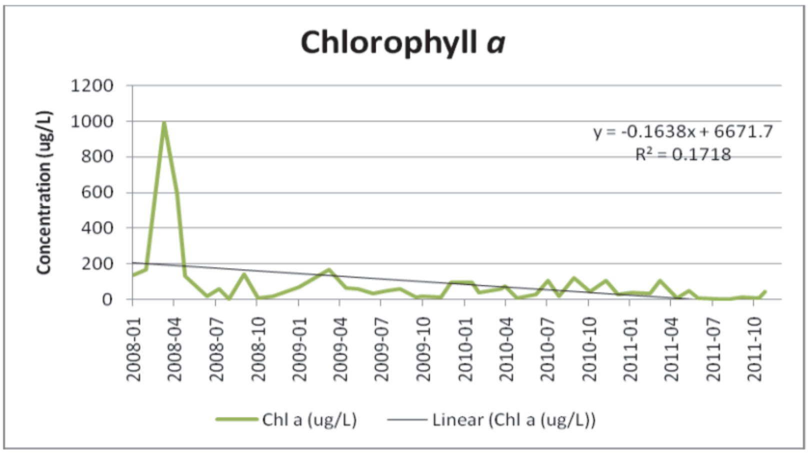


Figure 5-6: Chlorophyll a concentrations over the period 2008 to 2011 (HDRP, 2013a Fig 14 p xix).

The measurements of algal biomass taken during the HDRP are not directly comparable to those given in NIWR (1985) and Chutter and Rossouw (1992). While both these 2 papers specifically note the occurrence of the different groups of algae (green, blue-green, etc.), this distinction is not made in HDRP (2013b).

The effect of the microstratification on the vertical distribution of algae is that, when microstratification is present, the algae will be maintained in the surface layers. During periods of epilimnetic instability induced by, for instance, windy or cooler conditions the algae will be distributed more evenly through the depth of the epilimnion.

5.2.9 Possible explanation of the shift from turbid water to clear water state

The first floating islands were launched in late 2008. As indicated in Chapter 7.4.1 an estimate of the quantity of P removed by activities of the programme indicates that it is substantially less than in estimated P accumulating in the dam. This needs to be researched.

The possible reason for the observed decline in Chl-a after peaks in 2007 and early 2008 is that the stable water level in the dam for the previous decade created conditions conducive to the establishment of filamentous algae and rooted macrophytes (*Potamogeton* sp). As illustrated in Figure 3-1 above, a shift in the primary production between phytoplankton and submerged plants will lead to a shift from the turbid water state to the clear water state. This coincided with both the establishment of filamentous algae and rooted macrophytes in the dam and the onset of HDRP activities. Neither of these activities were sufficiently well documented to be able to say which may have been responsible for the shift.

The assumption is that the armouring of the sediment in the shallow water (Genkai-Kato and Carpenter, 2005) combined with the sequestration of P by the filamentous algae and the rooted plants (both submerged and emergent) would have been an important factor responsible for this change.

5.2.10 AMD Decant

The DWS Reconciliation Strategy assessed various AMD scenarios using the Water Resources Planning Model (WRPM) (Table 5-8). The focus of the analyses was on the impact on salinity (TDS), by the various possible longer term solution options. The analysis assessed the salinity impact at key locations down the river, below the different possible decant or return of treated decant locations, down to Hartbeespoort Dam.

Scenarios 3 and 4 assumed a spatial resolution within the WRPM configuration that could differentiate between the location below the dolomites and that of Percy Stewart. Currently the WRPM set-up has the return flows from Percy Stewart joining the river in between the dolomite compartments (of which there are three). As such, scenario 3 and 4 were lumped together with the AMD returned to the River below the lowest dolomite compartment (Table 5.8)[8].

---

[8] As a note, the dolomite compartments were included in the WRPM, during the salinity calibration task using recorded streamflow salinity downstream. The downstream record did not show the increase in salinity expected due to the AMD decant which begun in the early 2000s. The dolomite compartments were intercepting and somewhat attenuating the salinity of the AMD decant. For this purpose, three dolomite compartments were added to the WRPM, and used the process of mixing in the model used to simulate the attenuation effect of these dolomites. The size of these compartments in the WRPM has not yet been calibrated, and currently are 50 million m^3 each. The inclusion of these dolomite

Scenarios 3 and 4 assumed a spatial resolution within the WRPM configuration that could differentiate between the location below the dolomites and that of Percy Stewart. Currently the WRPM set-up has the return flows from Percy Stewart joining the river in between the dolomite compartments (of which there are three). As such, scenario 3 and 4 were lumped together with the AMD returned to the River below the lowest dolomite compartment (Table 5-8).

Table 5-8: AMD scenarios as assessed in the DWS Reconciliation strategy

Scenario	**Quantity (Ml/d)/(Mm^3/a)**	**TDS (mg/l)**	**Timing**
1. Immediate solution, discharge neutralised water into Tweelopiespruit upstream of Krugersdorp Game Reserve (upstream of dolomite)	21.2 / 7.7	2776	2013-->>
2. Mintails option, as for Scen 1 for 2013, then	21.2 / 7.7 33.1 / 12.1 21.2 / 7.7	2776	2013 2014-2018 2019-->>
3. For Scen 2 but with discharge downstream of dolomite			
4. As for Scen 3 but with discharge into tributary just downstream of Percy Steward WWTW.			
5. Pilot plants then LTS – discharge downstream of dolomites. (Higher discharge till WL down to ECL)	21.2 / 7.7 33.1 / 12.1 33.1 / 12.1 21.2 / 7.7	2776 2776 2776 1000	2013 2014-2015 2016-2017 2018-->>
6. Desalinate and Reuse: As for Scenario 5, then treated water reused (not discharged to river)	21.2 / 7.7 33.1 / 12.1 33.1 / 12.1 0	2776 2776 2776 0	2013 2014-2015 2016-2017 2018-->>

The WRPM was run using the historic streamflow sequence and the flow and TDS concentration at key points along the river reach down to Hartbeespoort Dam output. This was done for each scenario, together with the necessary changes in the AMD decant location, volume and salinity.

compartments, and the number and sizing of these was conducted by Dr. Chris Herold, in an iterative manner, for the purposes of calibrating the WQT model with limited data and time.

The catchment development level that was used for the assessment of these scenarios was the dynamic projected future developments in the catchment, as per the reconciliation Strategy scenario presented at the 5th Strategy Steering Committee Meeting.

Monthly time series of flows and TDS concentration for the period from 2013 to 2042 were output and will be provided electronically as Appendix A to the WRPM document. For the purposes of interpretation of the results, annual load and average TDS values were plotted.

As the decant of AMD in the western basin has been occurring from the early 2000s, the dolomites are already likely to have a higher salinity level. This was evident by the end conditions estimated for 2004 during the WQT model calibration. An initial run was conducted to estimate the increase in salinity levels for a period of about 8 years in order to better capture the continued effect of the AMD decant between the end of 2004 and the start of 2013. The end 2004 salinity levels in the dolomites from the WQT model calibration were used as starting points. The initial 8 year simulation showed TDS values increasing to about 2000, 1100 and 700 mg/L for the three dolomite compartments, with the highest values for the most upstream compartments. These TDS values were then used as estimated 2013 starting values for the scenario analyses.

Interpretation of Results

The following conclusions are drawn from the plotted annual results and trends observed:

Upper Tweelopiespruit: Channel number 1155 was chosen to represent the river below the current AMD decant point. Scenarios 1 and 2 show very high TDS of around 2500 mg/L for the river immediately below the current decant point. This is similar to the decant TDS of 2776 mg/L, which suggests limited dilution by the river at this point. The base scenario with no AMD projects an average annual TDS concentration of around 250 to 300 mg/L, although the confidence on this figure is low due to insufficient resolution in the model to capture detailed localized land-use impacts within this small catchment. There is a noticeable difference in the load into the river between scenario 1 and 2 during the short term period with higher volumes associated with the mintails option (Table 5-8). These results are as expected. All other scenarios return AMD downstream of the dolomites.

Dolomites: Before presenting the results, it must be re-iterated that the simulation of the dolomites is at a low confidence level and should be taken as indicative of possible trends, rather than as absolute. The simulated TDS concentrations in the three dolomite compartments for scenarios 1 and 2 is shown together with scenario 0 (no further AMD decant from 2013 as a base reference) (Figures 5-7, 5-8 and 5-9).

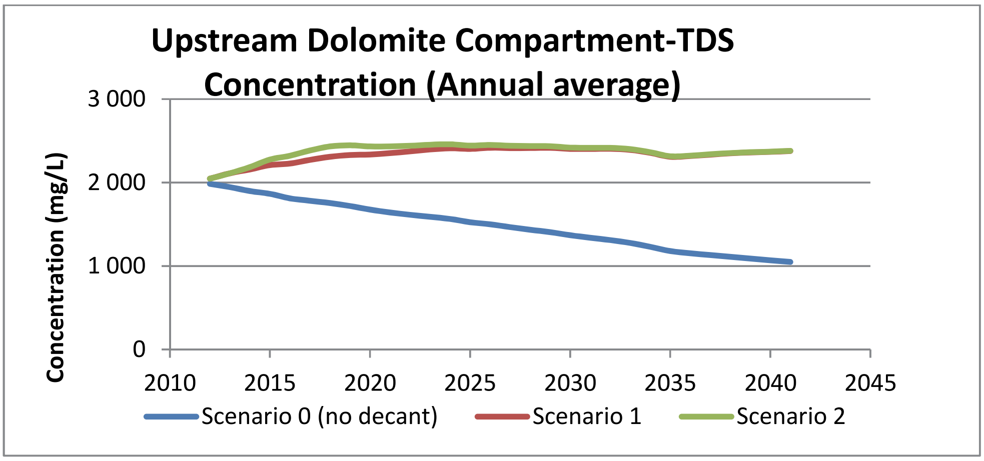


Figure 5-7: TDS concentrations in the upstream dolomite compartment for Scenarios 0, 1 and 2

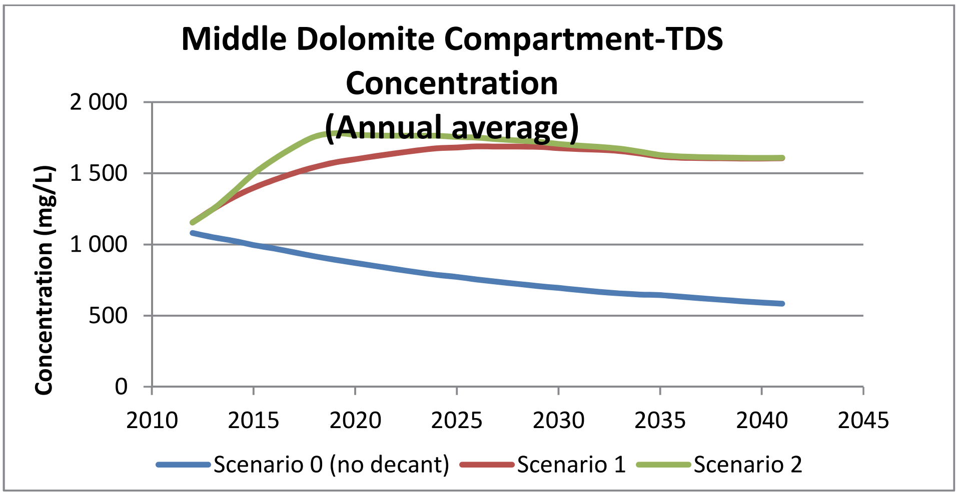


Figure 5-8. TDS concentrations in the middle dolomite compartment for Scenarios 0, 1 and 2

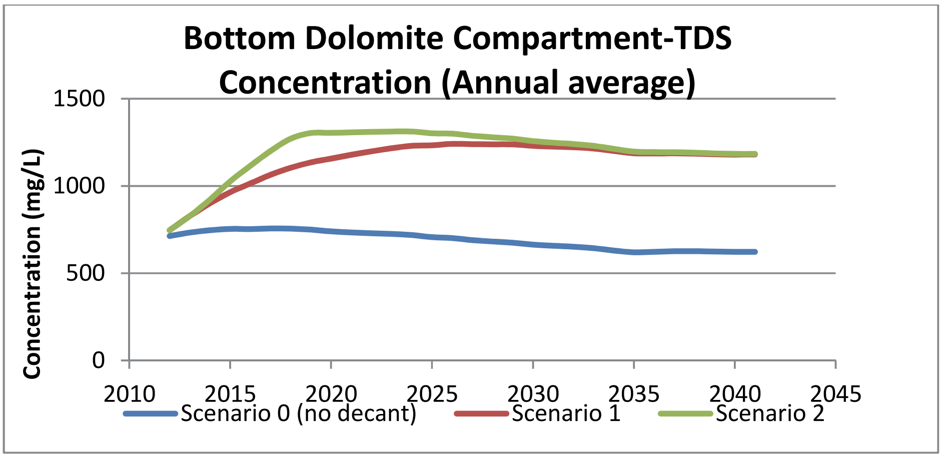


Figure 5-9. TDS concentrations in the bottom dolomite compartment for Scenarios 0, 1 and 2

The results show that the salinity in the dolomites increases significantly over time for scenarios 1 and 2 which continue to return neutralised AMD to the river above the dolomites. The salinity increase is progressively lagged for the downstream aquifers. The simulated salinity in the three dolomite compartments increases up to around 2020, and thereafter appears to stabilise. The longer term TDS concentration flowing out of the lowest dolomite compartment appears to be around 1200 mg/L. Again, this should be only taken as indicative of the trend. If the option of returning neutralized AMD above the dolomites is to be pursued then further work in understanding and defining the dolomites and groundwater extraction will be required.

River stretch below the dolomites: The results obtained for all the scenarios for the river stretch downstream of the dolomites to the junction with the first significant tributary are shown in Figure 5-10.

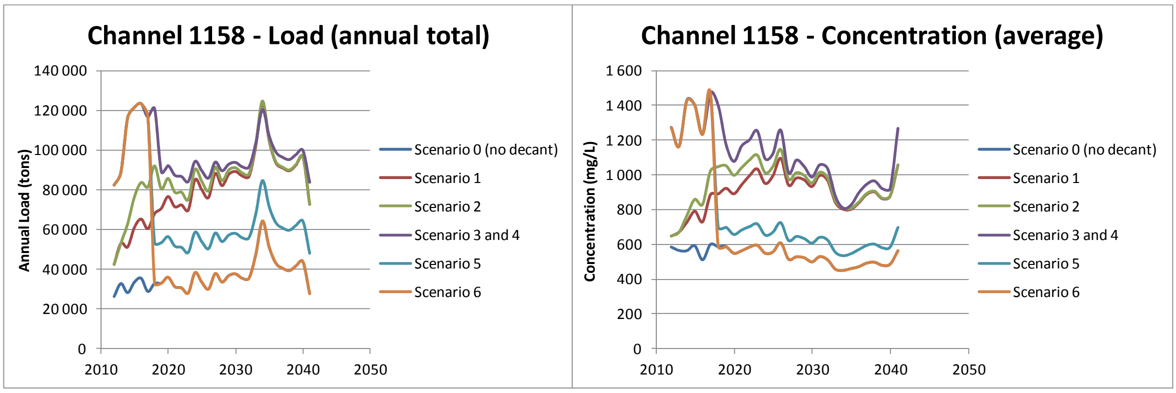


Figure 5-10. The simulated load and TDS concentration in the rivers downstream of the dolomites for the various scenarios modelled.

As can be seen there are significant differences in the loads and TDS concentration levels between the scenarios for this stretch of river. Although there are varied short term differences, the six scenarios tend to cluster into three distinct patterns over the long term. The scenarios (1, 2 and 3) that continue to return neutralized AMD of 2776 mg/L, appear to result in a longer term average annual TDS concentration of around 900 to 1000 mg/L. Scenario 5 which entails reducing the AMD decant down to 1000 mg/L, results in annual average TDS levels in this stretch of river of around 600 to 650 mg/L. Scenarios 0 and 6 which have zero AMD returned to the river from 2013 and 2018 respectively both resulted in longer term average annual TDS concentrations of around 500 mg/L.

Crocodile River downstream of confluence with the Jukskei and Hennops: The simulated load and TDS concentration results for the river after the confluence with both the Jukskei and Hennops tributaries are shown in Figure 5-11. These results are also representative of this Crocodile River flowing into Hartbeespoort Dam. The results show a significant dilution of the Crocodile River with AMD decant, and a narrowing of the range impacts for the different scenarios. Although the average annual TDS values are lower, the trends remain similar to those observed upstream. Scenarios 1, 2 and 3 having similar average annual TDS concentrations of around 400 to 450 mg/L, and scenario 5, 6 and 0 being around 350 to 400 mg/L. The longer term impact of the scenarios with continued return of neutralized AMD of 2776 mg/L, is an increase of approximately 50 000 tons/a in load and 50 mg/L in TDS concentration. This amounts to about a 15% increase in load and TDS concentration entering Hartbeespoort Dam. The impact of scenario 5 (1000 mg/L long term AMD) is relatively small, and only increases average annual load and TDS concentration by about 4 to 5 %.

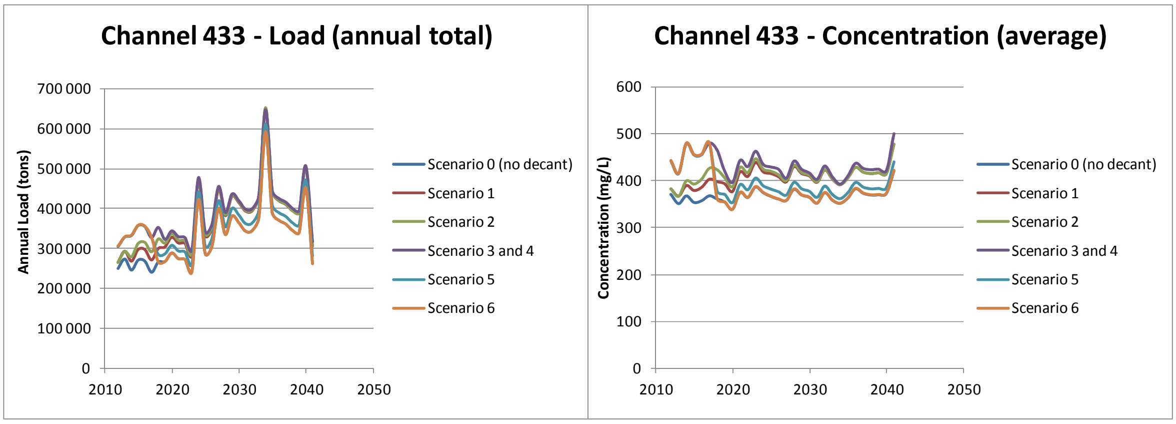


Figure 5-11. The simulated load and TDS concentration in the Crocodile River downstream of the confluence of the Jukskei and Hennops Rivers for the various scenarios modelled.

Hartbeespoort Dam: The TDS concentrations for Hartbeespoort Dam are very similar to the trends of the inflows into the Dam, as to be expected.

The results show significant increases in salinity load and concentration levels in river stretches immediate downstream of the possible decant/return flow points. These impacts decrease with distance downstream with the confluence of tributaries of the Crocodile River. The net impact of the different scenarios shows about a 15 % increase in salinity into Hartbeespoort Dam for scenarios which neutralize the AMD to 2776 mg/L and only about a 4 to 5% increase in salinity into Hartbeespoort Dam for the scenario with longer term neutralized AMD of 1000 mg/L. As there is currently no specific blending rule or other similar water quality related operating rule in the Crocodile (West) River catchment, these potential impacts related to the long term solution options are not quantifiable from a water quantity impact. The acceptability of these impacts will need to be confirmed using the resource quality objective guidelines. In addition, more information on the dolomites is needed to increase the confidence in the results for the scenarios that return AMD above the dolomites, particularly over the short term.

5.2.11 Invasive plants

Two of the attributes that make plants invasive are that they have ruderal (weedy) characteristics and, when alien, have no natural enemies to keep them in check. The hyacinth is such a plant with the additional characteristic that it is very vigorous. Floating aquatic plants show the additional undesirable characteristics of shading the water column below them, so preventing primary production in the shaded area, and when the coverage is extensive they hinder the exchange of oxygen between the air and water. This can lead to anoxic conditions beneath them which in turn will exclude organisms requiring aerobic conditions from living in these areas.

Invasive plants may be controlled chemically, mechanically or biologically. The chemical control of floating mats is considered undesirable as the biomass sinks to the bottom of the water body where it decomposes. The decomposition process depletes the oxygen in the water column and also releases the nutrients sequestered by the plants back into the environment. It may, however, be the best method to clear an extensive infestation. Mechanical control is generally expensive and needs a long term commitment to prevent the plant growth from getting out of hand. Biological control is the most cost effective but under certain conditions may not be sufficient to exercise complete control.

The hyacinth infestation on Hartbeespoort Dam is a case where the biological control agents are not able to exercise complete control although a variety of control agents have been released on the hyacinth. The reasons for this are:

1/ that the high nutrient levels available in the water column promote rapid growth and

2/ the foliage above the water dies back in the winter with growth resuming in the spring. It is only when growth resumes in the spring that the population of the control agents can begin to build up, thus the hyacinth has a period of growth which is not controlled by the agents.

5.3 Conclusions

5.3.1 Varied benefits and many beneficiaries

The Dam plays a key role in the water economy of Gauteng and in the socio-economic prosperity of various beneficiaries. In addition to the ecosystem services of water supply discussed in Chapter 4 as well as the cultural services provided by the dam itself (see 5.3.5 below), this role is projected to increase with the supply of water to the Lephalale industrial development node. Eutrophication puts these benefits at risk.

5.3.2 Understanding hazards in the system

The system is dynamic with complex interactions between the components of the socio-ecological system. These interactions may not always be easily predictable but the hazards presented by the individual components, some of which are discussed in the following chapter, may be identified. Identifying the hazards permits their management to be incorporated into the adaptive management process.

5.3.3 Phosphorous management is the beginning of eutrophication management

Phosphorous management, while both fundamental and essential, is just one facet of the eutrophication challenge and as P is 'managed', nitrogen, micronutrient availability and foodweb interactions start to come into play-as does the changing toxicity of cyanobacteria and/or the role of organism-influenced nutrient recycling.

5.3.4 Adaptive management approach to managing complex systems

By definition, questions arising in complex systems generally have more than a single correct answer. This can present planners and managers with a conundrum as the different answers may lead to different outcomes.

Using the adaptive management approach provides the framework within which the progress of a particular approach may be checked to see if it is leading to the desired outcome. If it is not, then the procedure has the flexibility to adjust the process to achieve the desired goals.

5.3.5 A focus on the full set of ecosystem services provided by the Dam

The dam currently provides a range of ecosystem services to the socio-ecological system. The range, extent and quality of these ecosystem services depends on the management of the dam and its catchment and may be varied depending on the management decisions taken. Not all ecosystem services are compatible with one another and so the full range of ecosystem services needs to be considered when planning or making decisions on the management of the Hartbeespoort Dam meta-system.

5.3.6 A focus on job creation

Current government policy is to create jobs. The HDRP offers a wide scope of options for this. In addition to the jobs at the level of labourers, there is a need for the development of the skills necessary for the planning and management of a large and complex programme such as the HDRP. Re-oligotrophication demands a long term commitment and so succession planning is necessary, and this will require the development of specific skills.

6 Future changes and hazards in the Hartbeespoort Dam meta-system

6.1 Purpose of this Chapter

This chapter identifies key hazards to the system resulting from a variety of future changes expected in the system. The HDRP Phase 2 needs to be able to manage and mitigate these hazards and the risks they pose to ecosystem services.

There has been considerable growth of the conurbation in the catchment and this has affected the Hartbeespoort Dam meta-system in the following ways:

- Water use from the Dam is expected to increase in future. In particular, the Dam is expected to supply the Lephalale industrial development node through a water transfer in the medium term (refer to Chapter 5).
- Both the population and the economy of the area are projected to grow which will exacerbate the problem if impacts are not managed. Associated with this, the urban spread has increased the area of hard surfaces, so changing the pattern of runoff, with reduced infiltration to the groundwater and higher flood peaks after rain. Thus, increasing quantities of water have been pumped from the Vaal catchment to supply the needs of the economic and urban growth. This has resulted in increased discharge of effluent into the catchment and translates into an increase in flow into the dam. It also results in an increase in the nutrient and pollutant load into the system (refer to Chapter 5.2.3).
- The mining activity has led to decant of acid mine drainage (AMD) into the system. Projections are that this will increase over time and this AMD will find its way to the Dam (refer to Chapter 5.2.10).
- The DWS has, through the WRCS, gazetted certain environmental quality policy imperatives for the system, and these need to be implemented in future (refer to Chapter 6.5).
- A variety of other emerging hazards, such as climate change effects, sewage spills and sediment deposition also exist (refer to Chapter 6.6).

6.2 Future water use in the Crocodile (West) River

The Crocodile (West) DWS water resource classification gazette (DWS, 2014) in September 2015 classed IUA I as a Class III, which is a heavily used system, with most of the monitoring sites as a Category D. The exception is the EWR 1 Site at the outflow of IUA below the Dam, which is gazetted as a category C/D.

This Class is based on key future water use scenarios associated with the future development of the water economy. During the classification process the analysis for the Hartbeespoort Dam system was characterised by a future scenario that desired the implementation of ecological categories recommended by aquatic ecology advisors and by the future water use requirements of the Crocodile (West) Reconciliation study (Table 4.1).

Accordingly, future water use and river flows in the Crocodile West are driven by:

- Future urban expansion in Gauteng, leading to significantly increased return flows;
- Additional future mining activities in the Rustenburg area, primarily related to platinum mining;
- Future water use requirements around Lephalale, which would necessitate the transfer of water from the Crocodile directly to Lephalale.

The principal additional water demand is expected to come from domestic use, for which a 31% increase (or 211 million m^3) in water demand is expected by 2030 (or 1.6% per year growth in water demand). Growth in the mining sector demand is expected to be 11% by 2013 (or 10 million m^3).

There is enough water from the available supply sources to meet the demand. Water supply, as set out in the Reconciliation Strategy for the Crocodile-West River (DWA 2012), does not constrain the future growth and development of the economy, with the exception of agriculture. There are numerous reasons for this. Firstly, the future urban expansion of the Gauteng region is expected to produce increased volumes of urban runoff via municipal waste water treatment works (WWTW). Effluent from these works will flow into the Crocodile River and its tributaries and contribute to the yield of the system. Secondly, there exist a number of large dams in the Crocodile-West River for which the operating rules can be optimised to increase the yield of the system. These dams, principally Hartbeespoort Dam, Roodeplaat Dam and Rietvlei Dam, contain surplus water. Thirdly, there exists a future option for additional water transfers into the Crocodile West River, from the Vaal River.

The exception is agriculture, and irrigation agriculture in particular. The DWA Reconciliation Strategy maintains a constant supply and of irrigation water for agriculture, thus, although no reduction to this sector is foreseen, and thus no reduction in agricultural activity result from water supply constraints, there are no additional future supplies of water available for agriculture (DWA 2012).

Key findings of the Limpopo WMA classification study included:

- There is enough water from the available supply sources to meet the future demand.
- The Recommended ecological category (REC) for the Crocodile-West River is achievable.
- From 2018, dam-related aquatic ecosystem services at the Hartbeespoort Dam, Roodeplaat Dam and Rietvlei Dam could be negatively affected (depending on the rate of development and water demand at Lephalale) due to dam drawdowns during the dry winter season.
- The costs of water supply may be affected through measures implemented through DWS's AMD (Acid Mine Drainage) and WDCS (Waste Discharge Charge System) initiatives.

As a result, no trade-offs are required between water users and neither are any negative long term impacts on growth of the water economy expected. However, a potential negative economic impacts of concern is that at some time in the future, most likely from 2018 onwards, the augmentation of the water supply system through using the surplus water stored in dams, would start reducing dam water levels in especially the Hartbeespoort Dam, Roodeplaat Dam and Rietvlei Dam during the dry winter seasons. Figures 6.1, 6.2 and 6.3 provide profiles of expected patterns of water level drawdown in these dams. These dams have various aquatic ecosystem services associated with them which may or may not be affected. These services include recreation and tourism; and aesthetic services. These negative effects are mitigated to some extent by the fact that dam drawdown would likely be limited to the cold winter months when dam-related recreation activities are generally low.

The preliminary findings for the implementation of the WDCS in the Hartbeespoort Dam catchment include an interim phosphorous concentration of 0,085 mg/L in the dam and a final phosphorous concentration of 0,055 mg/L in the dam, corresponding to a phosphorous load reduction of 81% from 348,000 kg/a to 68,000 kg/a.

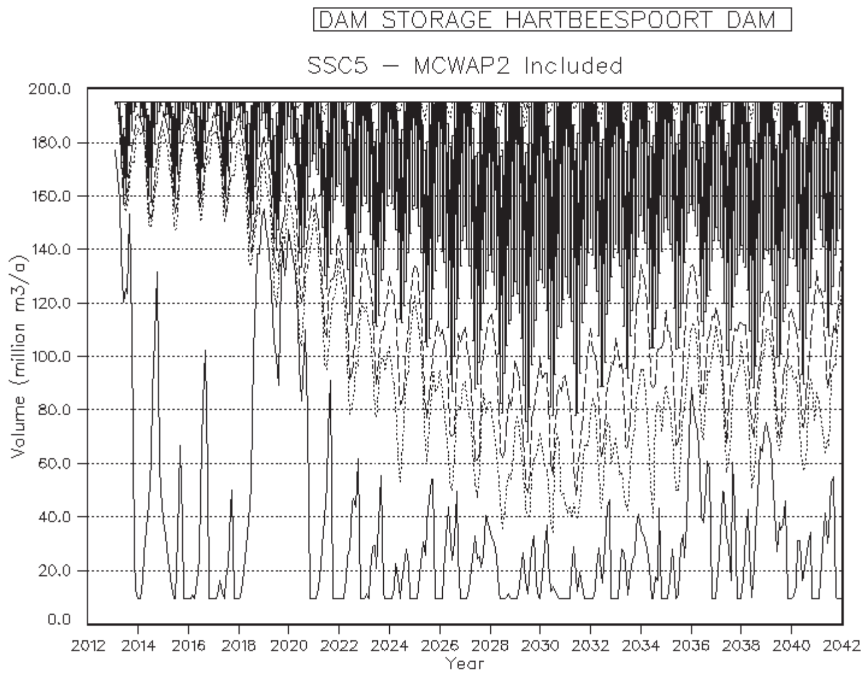


Figure 6-1: Dam draw-down levels in the Hartbeespoort Dam. Source: DWA Update on the Crocodile-West Reconciliation Strategy, June 2013.

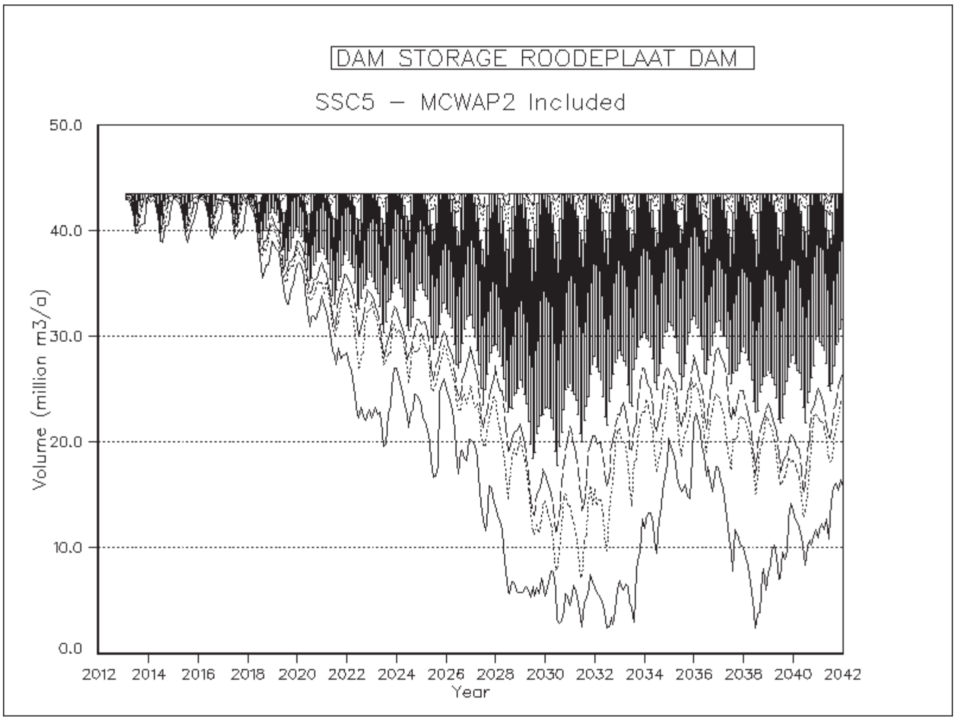


Figure 6-2. Dam draw-down levels in the Roodeplaat Dam. Source: DWA Update on the Crocodile-West Reconciliation Strategy, June 2013

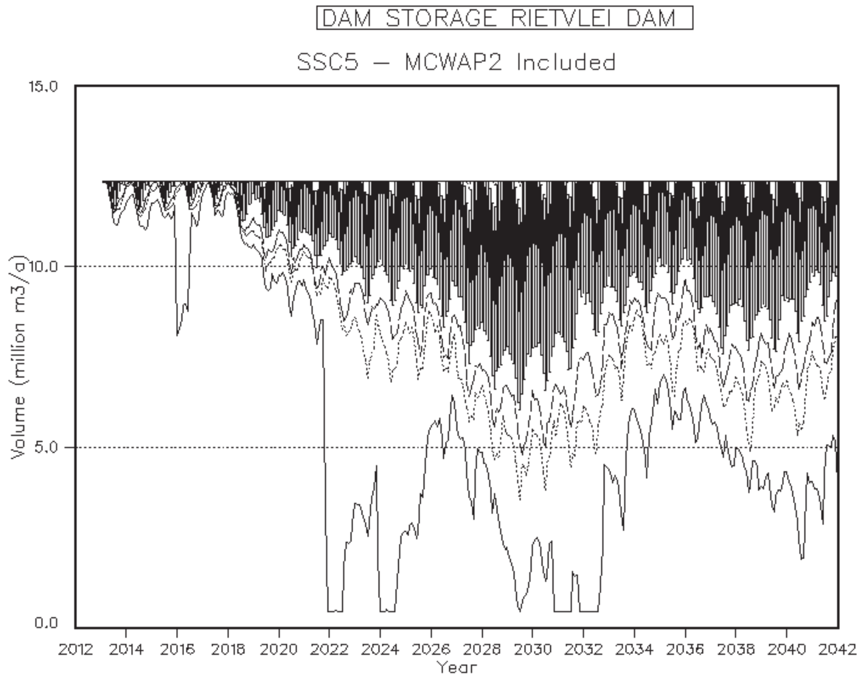


Figure 6-3. Dam draw-down levels in the Rietvlei Dam. Source: DWA Update on the Crocodile-West Reconciliation Strategy, June 2013

Table 6-1. Summary of economic impacts of the Crocodile-West Scenarios, expressed in R'million. All results are expressed in 2012 prices. The results show the combined impact of the scenarios on the full study area. In the Gazetted scenario, the economy grows and there is no net loss of river and wetland ecosystem services.

Zone	Description	Sector	Baseline (2012) R'million	Future water use in 2030 R'million
Limpopo WMA study area	Sectoral Output	Agriculture	31,199	42,170
	Sectoral Output	Mining	228,349	263,485
	Sectoral Output	Manufacturing	1,389,014	1,809,877
	Sectoral Output	Utilities	45,507	59,546
	Sectoral Output	Other commerce	817,829	1,054,344
	Value Added	All sectors	663,150	848,976
	Value Added	All sectors	43.3%	127.41%
	Ecosystem services			4,309
Gauteng	Value Added contribution	All sectors	584,687	757,149
North-West	Value Added contribution	All sectors	74,459	87,254
Limpopo	Value Added contribution	All sectors	4,004	4,572

6.3 Return flows

Urban return flows are of key concern and need to be managed, both as a valuable water resource and as a pollution source. A significant portion of the urban water supply to the large Metros in the southern part of the Crocodile (West) catchment is transferred into the catchment by Rand Water. This supply includes the City of Johannesburg MM, the City of Tshwane MM, Rustenburg, Ekurhuleni MM, Mogale City LM, Randfontein LM, and Kungwini LM. The current volume is in the order of 520 million m^3/a. The projected volume of water transferred into the catchment depends on the total growth of domestic water requirements, and how much of this supply is met from local sources, and how much is to be met by Rand Water. The projected transfer in from the Vaal for domestic supply is shown in Table 6-2. Return flows make up a significant portion of the available water in the catchment. Projected Return flow volumes in the catchment based on the revised domestic water requirements are presented in Table 6-3 [DWS Reconciliation study].

Table 6-2. Projected water future transfer volumes into the Crocodile (West) River catchment from the Vaal by Rand Water for domestic water supply

Projected transfers into the Crocodile (million m^3/a)	2010	2015	2020	2025	2030	2035	2040
Rand Water Supply	523	524	577	624	686	725	765

Table 6-3. Volume of effluent returned to the Crocodile West River from WWTWs

Volume returned to River System (million m^3/a)	2010	2015	2020	2025	2030	2035	2040
Rand Water Supply	313	321	352	376	408	428	449

6.4 AMD decant

Acid mine drainage (AMD) is a problem worldwide where mines have exposed rocks containing metal sulphides to the air. And the problem of the oxidation of metal sulphide to sulphate may continue for very long periods. There are mines dating back to Roman times in the UK which are still producing AMD after 1 500 years (Ground Truth Trekking).

Pollution by AMD takes the form of metal toxicity, sedimentation, acidity and salinization. The complexity of AMD makes the impact on riverine ecosystems difficult to quantify and predict (Gray, 1997). Figure 6-4 lists the major effects of AMD on river ecosystems. In addition, there are impacts on human and animal health and economic activities such as irrigated agriculture.

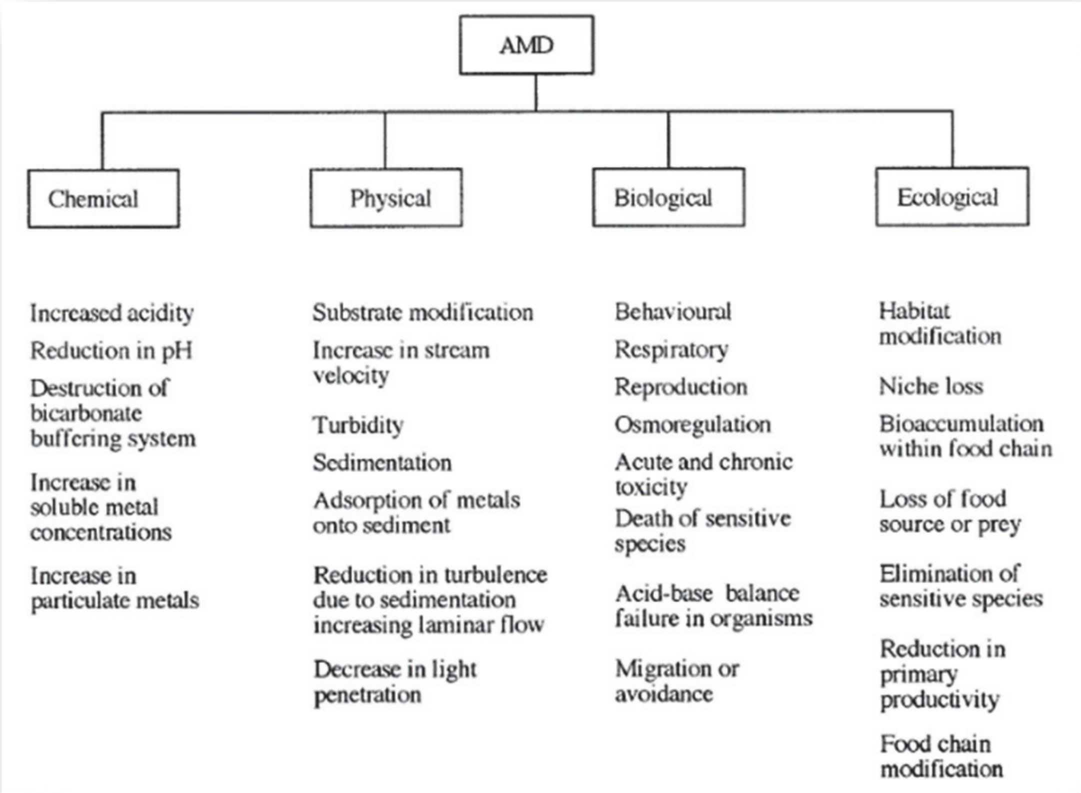


Figure 6-4. The major effects of AMD on a lotic (river) system (from Gray, 1997)

AMD causes high stress in ecosystems. Many organisms cannot tolerate the low pH caused by AMD. Jennings et al. (2008) working with fish in Pennsylvania found that 68 species of fish occurred in rivers with a pH of >6.4, 38 species occurred in rivers with a pH of 5.6-6.4. Only 10 species were found in rivers with a pH of 4.5-5.5 and fish were absent from waters with a pH <4.5.

Historically the costs of AMD treatment have been borne by government but currently mining companies are required to set funds aside to rehabilitate the problem. Treatment of AMD requires a long term commitment and is expensive. As a result the costs are normally borne as lost ecosystem services (Ground Truth Trekking).

Acid mine drainage. The hazard is the ingress of AMD into the dam via the inflowing rivers. The risk is rated as very high (likelihood – almost certain, Consequence – Major).

6.5 Water quality related recommendations from the WRCS process

This Chapter details the Ecological Specifications (ecospecs) for the maintenance of the Water Quality Reserve for each EWR site. These are the values of water quality parameters (usually maximum concentrations) that should not be exceeded in order to meet the water quality component of the Recommended Ecological Category (REC).

The Present Ecological State for water quality (WQ PES), the Overall PES, the Ecological Importance and Sensitivity (EIS), and the Recommended Ecological Category

(REC) for EWR sites at which an Intermediate Reserve determination was done are given in Table 6-4. EIS is high for all the EWR sites and thus the overall REC is equal to the overall PES i.e. the recommendation is that all sites be maintained in the current ecostatus. In order to achieve this, it is necessary for water quality also to be maintained at the current (or better) level of impacts. There are many point and diffuse sources of pollution into the Jukskei and the upper Crocodile Rivers and water quality is highly impacted (D/E category).

The system is driven by the inputs from the Johannesburg Northern Sewage Works (via the Jukskei River) and the Sunderland Ridge (Centurion) Sewage Works (via the Hennops River) and industrial discharges. This has contributed to the high nutrient and salt levels. There are also diffuse inputs from un-serviced areas which result in high litter levels and high microbiological contamination. The increased nutrient concentrations have resulted in a eutrophication problem in Hartbeespoort Dam. Metal contamination has occurred in the past and could occur again from industry. The hazard is that this may be retained in the dam.

There is sustained high flow through the site due to releases from Hartbeespoort Dam.

The PES WQ at EWR sites in this area are all in a "D/E" category.

Table 6-4. Summary of the output of the Crocodile (West) River system and the REC for water quality

Site (River)	EWR no.	EWR site and WQSU	Overall PES	WQ PES	EIS	Overall REC	REC for water quality
Upper Crocodile	1	Upstream of the Hartbeespoort Dam WQSU 3	D	D/E	C	D	D/E
Jukskei	2	Heron Bridge School WQSU 2	E	D/E	C	D	D
Upper Crocodile	3	Downstream of Hartbeespoort Dam in Mount Amanzi WQSU 5	C/D	D/E	B	C/D	D
Pienaars	4	Downstream of Roodeplaat Dam WQSU 15	C	B/C	B	C	B/C
Pienaars	5	Downstream of the Klipvoor Dam in Borakalalo National Park WQSU 17	D	C	B	D	C
Hex	6	Upstream of Vaalkop Dam WQSU 9	D	D	C	D	D
Lower	7	Upstream of the	D	D	C	D	D

Site (River)	EWR no.	EWR site and WQSU	Overall PES	WQ PES	EIS	Overall REC	REC for water quality
Crocodile		confluence with the Bierspruit WQSU 21					
Lower Crocodile	8	Downstream of the confluence with the Bierspruit in Ben Alberts Nature Reserve WQSU 24	C	D	C	C	D
Maloney's Eye	9	Upstream of Maloney's Eye WQSU 4	B	B	A	B	B
Elands	10	Highveld WQSU 10	B		B	B/C	
Sterkstroom	11	Upstream Buffelspoort Dam WQSU 6	C		B	C	

6.6 Emerging hazards associated with the Hartbeespoort Dam meta-system

The future water requirements for the Hartbeespoort Dam system, forecast by the DWS Reconciliation study, took into account climatic variability. As a result, the outputs of the work amplified the dry years as irrigation requirements are likely to be higher due to an anticipated decrease in precipitation and an increase in hot conditions. This results in higher water requirements during dry periods.

Hartbeespoort Dam was originally built to support the irrigation scheme which remains its primary purpose. It is also used for domestic consumption by Magalies Water. The wall was completed in 1923 (NIWR, 1985, http://hdl.handle.net/10204/2425) and raised by the addition of radial crown sluices (crest gates) in 1970, raising the full supply level by 2.44 m (Kormorant, 17 April 2012). Hartbeespoort Dam is a prime recreation destination for the population of Johannesburg and Pretoria, and a number of people live in the surrounding area both in the towns and upmarket estates that have been developed round the dam.

The first study of the limnology of the impoundment was undertaken 5 years after its construction by Hutchinson et al. in 1933 who described the dam as oligotrophic on the basis of the chemistry and biology (Allanson and Gieskes, 1961). Cholnoky (1958) described Hartbeespoort Dam as 'an oxidation pond for the effluents from Johannesburg' And Allanson and Gieskes (1961) described the state of the dam 25 years after the Hutchinson et al. study as 'very eutrophic'. During the large multidisciplinary study of the NIWR (1985) the impoundment was described as hypertrophic with the highest measured algal production rates in the world. The source of the nutrients is the conurbation of the Johannesburg and Pretoria area.

The eutrophication of Hartbeespoort and other dams downstream of large urban areas led to the promulgation of the effluent ortho-phosphate (as P) standard of 1 mg ℓ^{-1} in sensitive catchments, implemented in 1985. This level was selected for two reasons, 1) it was expected to significantly reduce the ortho-P (SRP) load in natural waters and 2) it was considered to be technically achievable at reasonable cost (DWA, 1986). The model developed by the NIWR (1985) predicted that the 1 mg ℓ^{-1} standard would not prevent the eutrophication of impoundments downstream of urban areas. Currently, there are a number of WWTWs in the catchment discharging, between them, over 700 Megalitres per day into the rivers feeding the dam, and the total annual load of phosphate entering the dam is over 280 tonnes (Morar, 2010).

Eutrophication. The hazard is the ingress of nutrients into the dam via the inflowing rivers. The risk is rated as very high (likelihood – almost certain, Consequence – Major).

Urban, agricultural and industrial effluents may contain a variety of pollutants such as EDCs or PAHs. One type of pollutant which is formed during the effluent disinfection process when chlorine is used as the disinfectant is trihalomethanes (THM). THMs occur when naturally-occurring organic and inorganic materials in the water react with the disinfectants. Commonly used halogens for disinfection are chlorine and bromine compounds. Exposure to high levels of THMs in drinking water may cause kidney, liver or central nervous system problems and may increase the risk of cancer (US EPA, undated).

The hazard is the formation of THMs during the disinfection process of drinking water or during the process of disinfection of final effluent at a waste water treatment works (likelihood – almost certain, Consequence – Moderate).

Another hazard is the sediment. There are known to be heavy metals in the sediment (Chapter 7.3.3) which will be mobilized by dredging. It is likely that there are other pollutants which will also be mobilized trough dredging such as endocrine disrupting compounds and polycyclic aromatic hydrocarbons. This will need to be investigated.

Sediments (pollutants). The hazard is the presence of pollutants from sediments. The likelihood of occurrence of heavy metals in the sediments is almost certain. The likelihood of the occurrence of polycyclic aromatic hydrocarbons and endocrine disrupting compounds in the sediments is almost certain, although these have not been analysed for. If these pollutants are released into the water column as a result of the disturbance of the sediments then the consequence of these to human health is major.

While the sediments remain undisturbed, however, the likelihood of these substances being released into the water column is very unlikely. The risk of them being there to the system is, thus, reduced to medium.

Sediments (phosphate). The sediments contain substantial levels of phosphate. The likelihood of the phosphate being released into the water column under anoxic conditions is almost certain. The consequence of this is moderate, giving a high level of risk.

Disturbance of the sediments will cause the release of greater quantities of phosphate than would occur under undisturbed conditions, potentially presenting a severe risk. (likelihood – uncertain, Consequence – major).

The Hartbeespoort Dam Integrated Bio-remediation Programme was initiated in 2005 to address the very high level of eutrophication of Hartbeespoort Dam.

The change in the management of Hartbeespoort Dam with the implementation of the MCWAP is likely to cause dam water level to fluctuate. Fluctuation in the water level will expose sediments that contain nutrients and pollutants. One possible effect of fluctuating water levels is that the phosphate will be temporarily immobilised, reducing the release of the nutrient into the water column for a period. Another possible effect of fluctuating water levels is that the drying out and subsequent re-wetting of the sediment will mobilise pollutants. The hazard presented by these possible effects is estimated as follows:

1/ Temporary immobilisation of the phosphate. The factors involved here are the frequency of fluctuation and the extent of the sediment exposed to drying conditions. The likelihood of there being phosphate in the sediment remains almost certain. The reduction in phosphate released into the water column will depend on the extent of the sediment exposed during the cycle of fluctuation. There will, however, always be some sediment that is not exposed, so the consequence may be reduced from moderate (likelihood – uncertain, Consequence – major).

2/ Mobilisation of pollutants during re-wetting of sediment. If pollutants are mobilised during the re-wetting of sediments, then the risk is estimated as follows – Likelihood – almost certain, consequence severe due to the increased levels of pollutants in the water column. The risk to human and environmental health is severe as a result (likelihood – uncertain, Consequence – moderate to major).

3/ Vegetation in the littoral zone. A characteristic of water bodies that experience wide fluctuations in water level is that vegetation is unable to establish in the littoral zone. While the water level remains stable, vegetation will establish in this zone, but if the water level fluctuates then vegetation may not survive (likelihood under conditions of fluctuating water level – almost certain, Consequence – major – is likely to wipe out marginal vegetation).

Acid mine drainage. There are potential future costs associated with the treatment of AMD and nutrient loads in the Crocodile West River. These costs would result from DWS's AMD treatment initiatives and DWS's WDCS (Waste Discharge Charge System) initiatives.

DWS envisaged two sub-scenarios related to AMD treatment. In the first, AMD is to be neutralised to 2776 mg/L resulting in 15% salinity increase in the Hartbeespoort Dam. This would correspond to 50 000 tons/a salinity load and 50 mg/L TDS concentration increase in the long term. In second scenario, AMD is to be neutralised to 100 mg/L resulting in 4-5% increase in salinity levels in the dam and significant reduction in impacts.

Spills. Spills may be of nutrient-rich effluent such as untreated sewage or of pollutants. The discharge of untreated effluent presents an additional hazard to the increase in nutrient levels in that it will shock the system through raising the chemical oxygen demand of the water, so lowering the dissolved oxygen concentration, often to a point that will kill fish and other organisms in the system (Figure 6.5). Spills of pollutants will damage the environment depending on the toxicity and quantity of pollutant spilled (likelihood – unpredictable, Consequence – minor to major depending of the spill).

Figure 6-5: Fishkill caused by the discharge of untreated sewage.

7 Review of HDRP Phase 1

7.1 Purpose of this Chapter

The HDRP Phase 1 Business Plan (2006-07) has 10 focus areas addressing the dam basin, 5 addressing upstream activities and 1 addressing downstream activities. This chapter addresses specifically the science of the dam basin activities, reviewing the HDRP Phase 1 Business plan and associated documents against the benchmarks identified in the chapters above. The benchmarks include:

- Systems ecology approach (not specifically addressed, covered by 6.3.7-6.3.11)
- Goal setting (6.3.1; 6.3.2)
- Limit/divert influx of nutrients (6.3.3; 6.4; 6.4.1)
    - Phosphorous management
- Bio remediation (6.3.7-6.3.11)
- Understanding hazards in the system (not specifically covered)
- Adaptive management approach to managing complex systems (not covered)
- A focus on the full set of ecosystem services provided by the Dam (not covered)
- A focus on job creation (6.3.9)

7.2 Definition of HDRP Phases

Phase 1 began with the Business Plan dated August 2006 and continued to March 2010. The period between March 2010 and the present has been the Transitional Phase 2. The Phase 1 Consolidated Progress Report (HDRP, 2012a) covers the period reviewed. This report includes results for some of the PEPs (for instance fish and biomass removal) up to 2012. These results have been included in the review process. The suite of supporting reports have also been reviewed.

A considerable number of interventions have been implemented in the impoundment during phase 1 of the programme and the review of these form part of this Chapter.

7.3 Overview of and recommendations on HDRP Phase 1

This review is based on the information supplied by the programme manager, drawing on a limited quantity of other work where relevant, *to evaluate and assess the effect or impact of the HDRP* (from the Terms of Reference). The reader is referred to the HDRP reports, mainly the following, for more detail:-

- Hartbeespoort Dam Remediation Project Business Plan – August 2006.
- Hartbeespoort Dam Remediation Programme, utilizing Integrated Biological Processes and Programmes Addendum to Business Plan. July 2007.
- Hartbeespoort Dam Remediation Programme: (Utilising integrated biological processes and programme) Addendum to Business Plan. 2008/2009.
- Harties Metsi-a-Me Remediation Project: Project Execution Plan: A0, Programme integration and Documentation, April 2008.

- Harties Metsi-a-Me Remediation Project: Project Execution Plan: B1, Development and implementation of the RMP. 2007
- Harties Metsi-a-Me Remediation Project: Project Execution Plan: B4.3 Establish shoreline vegetation – Development and management. 2007
- Harties Metsi-a-Me Remediation Project: Project Execution Plan: B 4.4, Floating Wetlands – Development and management. 2007.
- Harties Metsi-a-Me Remediation Project: Project Execution Plan: B5Investigation and removal (disposal0 of sediment. 2007
- Harties Metsi-a-Me Remediation Project: Project Execution Plan: C1, Pre-impoundment, river diversion and treatment of inflowing water. 2009
- Hartbeespoort Dam Integrated biological remediation programme: Phase II Business Plan: Full Scale Implementation and Extension
- Hartbeespoort Dam Integrated biological remediation programme: Consolidated progress report: Phase 1. December 2012.
- Hartbeespoort Dam Integrated Biological Remediation Programme: Integrated Monitoring-Phase I Consolidated Progress Report: March 2013.
- Hartbeespoort Dam Integrated Biological Remediation Programme: Sediment management progress report: Phase 1, December 2012.
- Foodweb monitoring progress report: Phase 1, October 2012.
- Foodweb restructuring: fish community study and progress for Hartbeespoort Dam 2004-2013 to indicate trends in the fish population in response to biomanipulation.
- Hartbeespoort Dam Integrated biological remediation programme: Foodweb monitoring progress report: phase 1, October 2012
- Fish health and edibility of two freshwater fish species in selected dams in the North West Province.
- Hartbeespoort Dam Integrated Biological Remediation Programme: Consolidated Progress Report: Phase II, March 2014.
- Civil Engineering August 2012 Vol 20 (7) 9-63.
- Resource Management Plan: 1st Edition, July 2010.
- Harties, metsi a me Integrated Biological Remediation Programme Communication Strategy for Communication, Education and Awareness (A3.1) and the Information and Knowledge Centre (A3.2)
- Strategy Document For The Harties Metsi-A-Me Programme PEP 4.5 Aquatic Weed Control Roodeplaat Dam
- Strategy Document For The Harties Metsi-A-Me Programme PEP 4.3 Shoreline Vegetation Version 2 2009-2010
- Hyacinth And Algae Removal Strategy For The Hartbeespoort Dam Integrated Biological Remediation Programme First Draft July 2009
- Vermiculture Strategy For The Hartbeespoort Dam Integrated Biological Remediation Programme First Draft July 2009
- Strategy Document For The Harties Metsi-A-Me Programme PEP B4.4 Floating wetlands Version 2 2009-1010
- Implementing agent agreement between DWAF and Rand Water, 2007.

- Implementing agent agreement between DWA, 2012.
- Foodweb restructuring

The textbox beneath each heading gives the paragraph in the 2008/2009 Business plan to which the chapter relates. The code in [square brackets] gives the new PEP number from the Phase II Business Plan.

7.3.1 Future Desired State of the Dam and Vision of the HDRP

The desired future state of the RMP (Paragraph 4.2.1.2, Page 48) is articulated as '*The Future Desired State (FDS) of the dam is a residential dam focused on water based recreation, with clarified equitable public and private access, as well as controlled commercial operations, offered in a safe and healthy environment, from both a physical and environmental perspective*.'

The vision is articulated as follows: '*It is envisaged that DWA facilitates a programme aimed at restoring, protecting and managing the resource quality of the Hartbeespoort Dam thus ensuring clean and safe water which can support sustainable economic development and provide tangible benefits to the region and its people.*'

The wording of the vision suggests that DWS was not part of the formulation of the vision and so the Department possibly needs to be brought into the process more closely. This document will contribute to the catchment management strategy of the as-yet-to-be-constituted CMA and so needs to be made available early in the process.

This desired future state addresses the needs of the communities around the dam but does not address the needs of the irrigation schemes and other water users downstream nor the needs of the water treatment works that have difficulty treating the water from time to time to a quality that is useable in the households around the dam. The dam was constructed to provide water for irrigation and currently irrigated agriculture remains the biggest user of the water from the dam. Representatives from irrigated agriculture need to make input into the generation of the desired future state.

The RMP was originally scheduled for revision in 2015 and the revision should address this change in management.

7.3.2 Resource Management Plan

4.1 Institutional Development-Develop A Resource Management Plan (RMP) – PEP B1 [OM1.1] 4.3 Support To Recreational Activities And Metsi-A-Me (PEP B3) [PC3.1] 4.4 Control And Enforcement Of Recreational Activities (PEP B3.1)

The RMP is a planning tool which sets out the objectives, plans and institutional arrangements relating to the protection, use, development, conservation, management and control of Hartbeespoort Dam. The Resource Management Plan (RMP) was developed with a substantial stakeholder input. The following is quoted directly from the introduction to the Resource Management Plan- '*The participation process for the RMP commenced during the project announcement meeting on 12 September 2007 followed by various Technical Task Team, Task Coordination and Feedback meetings held with stakeholders. In March and April of 2009, stakeholders had opportunity to review and comment on the draft document prepared based on their inputs, needs and requirements and in November 2009, the process concluded with a project closure and feedback session on the revised and final document (refer Figure 4 [in the RMP]). A more detailed record of the public participation process is contained in Appendix 1 – minutes of meetings and an Issues and Response Report.'*

The final draft RMP was submitted to DWS in 2010 but has not yet been signed off and released for implementation. Evidently parts of the RMP have been implemented in spite of the plan not being signed off.

Recommendations for Phase 2

The Resource Management Plan needs to be reviewed in the light of changes that have occurred or have been planned since 2010 and to ensure that the interests of downstream users are taken into account.

7.3.3 Sediment management – Dredging

4.12 Sediment management and removal-B5 [OM5]

The areas of sediment deposition have been mapped. Options for beneficiation of the sediments, once removed from the impoundment, have been shown to be viable. The necessary environmental authorisations have been obtained. Pilot scale dredging has been carried out and shown to be feasible.

Dredging is essential if the lake is to be restored, but there are questions to be addressed if the outcome is to achieve the desired effect. Dredging will stir up the sediment and for the safety of water users it is necessary to know what this will do to the quality of the water in the dam.

Wittmann and Förstner (1976) found significant levels of heavy metal accumulation in the sediments of the Jukskei and Hennops Rivers from industrial sources in the upper catchments. The same cocktail of heavy metals was present in the dam sediments Of particular concern were the concentrations of mercury, lead, cadmium and zinc although other heavy metals were also present in substantial quantities.

At this time some industries were discharging effluents directly into the environment. The City of Johannesburg had a clean-up during the early 1990s when wastes from, for instance, metal plating industries were collected from the premises and treated separately. But it is likely that at least some of these heavy metals are still in the sediment. Wittmann and Förstner (1976) note that heavy metals in the bottom sediments are "immobilised" and rendered less harmful than when they are in the solubilised state, but they may be brought into solution at any time by a change in conditions. They list four chemical processes which can remobilise heavy metals as follows:

- Increased salinity
- Decrease in pH
- Change in redox (ORP) conditions such as may be bought about by input of nutrients (nitrogen, phosphorous).
- Increasing input of natural or synthetic complexing agents such as organic matter or detergents.

Although these are rendered less harmful when in the sediment, they can be resolubilised under the correct conditions such as described briefly above. Some of these conditions are likely to occur in Hartbeespoort Dam and could re-solubilise heavy metals which are stirred up during the dredging process. In addition, there are pollutants which we were not aware of until more recently, for example endocrine disrupting compounds and polycyclic aromatic hydrocarbons. These will need to be tested for. One question here is 'Will there be the need of additional water treatment requirements for water use during the dredging operations in order to ensure the safety of water users?'

Another question that arises is 'how much of the phosphorous in the sediment can realistically be removed by the dredging operations?' As mentioned above (Phosphorous built-up in the lake), Ashton (pers. com.) found SRP to be mobile in the sediment to a depth of 60 cm. This will almost certainly still be the case, but needs to be verified in the laboratory. This will indicate to what depth the sediment should be dredged.

Ashton (pers. com.) also indicated that P is immobilized when oxidized and that the low lake levels during 1982-1985 exposed sediment to the air, oxidizing the P. When the lake filled again the P remained immobilized for a period. This may indicate that the P in the sediment that will be exposed on an annual basis by the drawdown of the dam may be immobilized in the sediment. The annual drawdown may, in fact, become a management strategy for SRP in the water column, as the P in the exposed sediment may be immobilised on an annual basis, reducing the quantity of P available to move into the water column.

7.3.3.1 Recommendations

The quantity and distribution of P in the sediment which dredging will or will not remove needs to be estimated in order to get an estimate of the potential effectiveness of the operation.

The quantity of pollutants which are likely to be remobilised to the water column during the dredging process should be estimated. During the time of Wittmann and Förstner (1976) there was no knowledge of, for instance, endocrine disrupting compounds but the presence of these and selected refractory organic compounds needs to be ascertained.

The possibility of immobilizing P in the area of the lake which will be subject to an annual drawdown should be investigated.

It is recommended that the dredging operation should proceed with caution as there is the possibility of unexpected consequences.

7.3.4 Algae removal

4.6 Biomass Management – Algae Removal (PEP B4.0) [OM3.1]

Algal 'soup' is pumped from the lake and treated through the vermiculture composting process.

The dry / wet mass of algal cells in the 'soup' is not given so it is not possible to calculate the total mass of algae removed. A total of 31 587 m^3 of this 'soup' was processed between 2007 and 2013, an average of 5264.5 m^3 yr^{-1}. (HDRP, 2012a; Executive summary; page not numbered). Without these figures the benefit to the lake management may only be estimated.

NIWR (1985) estimated that a daily removal of all algal scums would give an annual yield of 4 000 tonnes of fresh algal biomass. At a P content of 1% of dry mass and dry mass about 6% of wet mass, the P removed would be about 24 t per annum. The report concluded that the removal of scums was aesthetic but would not make significant change to the nutrient loading of the lake.

7.3.4.1 Recommendations for Phase 2

The presence of dense algal blooms is a symptom of eutrophication, not a cause. It will be more sustainable to address the cause (see Paragraph 8.6.4). This review recommends that the pumping of algae is discontinued in future phases of the HDRP.

The worm cultures to which the algae was fed underwent mass emigrations from time to time. While the reason for this was not recorded there may be 2 possible reasons for the behaviour. The first is that the cultures were allowed to get too wet. Personal experience has shown that worms exhibit this behaviour when the cultures are made too wet. The second is that the algae were toxic. This latter factor should be investigated.

Various strains of *Microcystis* have been shown in the laboratory to have a doubling time of between 1.5 and 5.2 days (Wilson et al., 2006, Sangolkar et al., 2009). What this means practically is that the entire algal biomass would have to be removed from the dam each week if this intervention is to manage the algal growth. As noted above, NIWR (1985) concluded that this was aesthetic but would not make a significant difference to the nutrient loading of the dam.

There has been some progress on using certain cyanobacteria for biofuel. This may be worth investigating during Phase 2.

7.3.5 Hyacinth and other invasive plant removal

4.7 Biomass Management – Hyacinths And Floating Debris (PEP B4.1) [OM3.1]

Biological control agents have been on the hyacinth in the catchment of the Hartbeespoort Dam for some time, but when in a nutrient rich environment the hyacinth grows strongly and the biological control agents do not keep up with the growth. This is exacerbated by the fact that frost kills off the leaves while the roots below the water surface survive, so growth resumes with the onset of warmer weather. The biological control agents, however, need to breed up once the leaf growth resumes, so the hyacinth has an earlier start than the biological control agents and tends to maintain this lead through the growing season in Hartbeespoort. These agents do exert a moderating effect, though (Byrne et al., 2010).

Mechanical control is necessary to maintain the hyacinth at a manageable level and it is the hyacinth removed by mechanical means that is composted by the vermiculture process. A total of 64 tonnes wet mass of hyacinth was harvested and treated through the vermiculture composting process.

An estimate of the cost of hyacinth removal by the private sector (housing estates around the dam) is an additional R1 million per year.

Large scale chemical control of hyacinth should be avoided if possible as the dead biomass sinks to the bottom and the decomposition process reduces the level of dissolved oxygen in the water column as well as returning the nutrients to the water column or sediment.

Salvinia minuta (water spangles) was first noticed in the dam in latter part of 2011 by Dr Carina Cilliers. This South American fern was possibly distributed through the ornamental fish trade and has proved invasive in the southern states of the USA. It is likely to prove invasive in South Africa. Currently, a biological control agent which has shown promise in Florida is being investigated by the Department of Entomology, Rhodes University.

Although it is not yet a problem, this alien invasive plant has the potential to develop into a nuisance in a similar way as the Kariba Weed (*Salvinia molesta*) did on Lake Kariba.

7.3.5.1 Recommendations for Phase 2

The mechanical control of hyacinth needs to continue to prevent it from getting out of hand which it will do if not controlled.

The spread of *S. minuta* needs to be noted and if it shows signs of becoming invasive then action needs to be taken.

7.3.6 Vermiculture

5.6 Establish Vermiculture To Support Aquaculture – PEP C5 [ICC5.1]
5.9 Vermiculture To Support Waste Minimisation – PEP C7.2 [OM3.1]

Harvested algae and hyacinth was composted by means of vermiculture. Figures for the conversion of algae and hyacinth to usable products through the vermiculture process are not available.

31 587 m^3 of algal 'soup' and 64 tonnes of hyacinth were harvested and put through the vermiculture process and this produced 'about 280 tons of compost and vermicast. 90 labourers were involved (HDRP, 2012a).

In HDRP (2012a) there is a report of a mass emigration of worms from the worm farms from time to time. The cause of this mass emigration is not given and needs to be investigated to enable effective management of the process.

7.3.6.1 Recommendations for Phase 2

Vermiculture has proved an effective way to compost the biomass removed from the lake. However, the reason behind the periodic mass emigration of the worms needs to be understood so that losses from this source can be reduced.

Accurate record keeping of the feeding and maintenance regime of the worm farm together with accurate record keeping of the state of the food fed and moisture regime of the medium will provide insight into the cause of the loss through emigration and so indicate how it may be prevented.

The operation should be carefully costed and a decision made as to whether this could be privatized. The reasoning behind this is that each of the estates also remove hyacinth, and so there is space for itinerant entrepreneurial vermiculturists to tend operations around the dam. The compost produced in this way may be used on the estate or sold.

7.3.6.2 Debris Removal

4.7 Biomass Management – Hyacinths And Floating Debris (PEP B4.1) [OM3.1}

4.8 Biomass Management – Incoming Litter Trap And Debris Removal (PEP B4.2) [CS3.1]

5.8 Waste Minimisation & Recycling – PEP C7.1 [CE4.1]

The inflowing rivers, particularly the Crocodile, carry a lot of debris into the lake. Between 2007 and 2013 a total of 2 461 tonnes of debris were removed (average 410 $t\ yr^{-1}$).

Removal of the debris and litter that is brought into the dam by the inflowing rivers is an important aspect of improving the aesthetics of the dam.

7.3.6.3 Recommendations for Phase 2

This activity could be escalated to capturing the debris and litter at source. This will entail locating the most important areas of debris and litter generation and installing litter traps there. Tending these would require cooperation from the relevant municipal cleansing departments.

7.3.7 Foodweb restructuring

4.13 Foodweb Restructuring And Monitoring – PEP B6 & B6.1 [OM2.1]

One proposal made for the management of the algal blooms by Harding et al. (2004b) was that the coarse fish populations (zooplankton eaters) should be controlled to encourage the increase of the larger species of zooplankton grazers of planktonic microalgae, the larger species being better able to grasp and consume the algal cells and colonies. This is termed the '**top down'** pressure on the foodweb. This recommendation was based on the removal of selected fish species from Lake Vesijarvi in Finland in order to relieve predation on the larger algae-eating zooplankton. Foodweb manipulation was one of a suite of interventions implemented to remediate Lake Vesijarvi. The fish targeted for control in Hartbeespoort Dam to achieve this are the common carp (*Cyprinus carpio*) and the catfish (*Clarias gariepinus*). A third species, the canary kurper (*Chetia flaviventris*) was also targeted.

Hart (2006), in his paper, assessed the prospects of managing the food web through biomanipulation in South African reservoirs by considering successive stages in the generalized foodweb structure. He found that a range of limitations were likely to apply to this approach if implemented as it is employed elsewhere.

Subsequent investigation of the effectiveness of this approach was tested by Harding et al. (2012) in Rietvlei Dam (in the Hartbeespoort Dam catchment) on the same suite of fish species using stable isotope analysis. It was found that all three of the species investigated were predominantly benthic (bottom) feeders, indicating that removal of these species of fish would exercise little control over the zooplankton grazers.

The question then arose 'what is the contribution of carp and catfish to the '**bottom up**' pressure on algal growth caused by excessive nutrient availability?' (the resuspension of bottom mud with associated nutrients through the foraging activity of the fish). Hart (2006) and Hart and Harding (2015) used literature-derived conversion functions to estimate the pool sizes of total phosphorus sequestered in fish biomass, recycled through fish excretion, and released from sediments through carp and catfish bioturbation. They found that the quantity of total phosphorous sequestered or mobilized by the fish was small compared to the quantity in the dam and concluded that there is no objective scientific basis to justify food web management as a 'bottom-up' (resource limitation) strategy to tangibly reduce the quantity of within-reservoir phosphorus stocks and their internal recycling in nutrient-polluted reservoirs.

The following comments should also be borne in mind when assessing the potential effectiveness of foodweb manipulation through the removal of fish.

1. The canary kurper, *showed a strong preference for zoobenthos. Detritus was also identified in the gut to a lesser extent* (HDRP, 2012c, p 6-8). This fish is, however, classed as one of the three species that need to be removed in the biomanipulation programme (HDRP, 2012a; page 10).

2. The importance of the decomposers. The detritus cycle has not been addressed in the foodweb work. The following paragraph has been taken from NIWR (1985; page 109).

   Detritus is non-living particulate organic matter derived from dead plants or animals and from animal faeces. Detritus and dissolved organic matter are the energy base for the third major functional group of living organisms, the decomposers, which are bacteria and other micro-organisms. They mineralize or break down detritus and so provide the second important link between the biotic and abiotic components of the ecosystem. Many detritivores derive their nutrition from the decomposers in the detritus (rather) than directly from the detritus itself

To quote further from NIWR (1985), the importance of the various functional groups changes with the chemical nature of lakes. In oligotrophic lakes the food web is dominated by the phytoplankton-zooplankton-fish chain. But in eutrophic systems the phytoplankton becomes dominated by less palatable species, decreasing the importance of the direct link to zooplankton. The dominant pathway for energy flow, it would appear, is through the detrivores.

During mid to late summer, when the cyanophyte blooms are breaking down, the zooplankton is dominated by small caldocerans such as *Bosmina*. It is possible that these are feeding on the bacteria which are decomposing the cyanobacteria (Van Ginkel, pers. comm.). This assumption, if correct, would weaken the phytoplankton-zooplankton-fish link on which the foodweb manipulation is based for Hartbeespoort Dam. This remains to be investigated.

The mass of fish removed from the lake by the foodweb restructuring process is given in Table 7-1.

Table 7-1: The catch of the target species of fish taken by the foodweb restructuring process (in kilograms) during the HDRP (HDRP, 2012a).

Foodweb Restructuring Progress				
YEAR	**Catfish**	**Carp**	**Bi-Catch**	**Total**
Feb 2008 - Dec 2009	37527.25	24361.59	3915.31	65804.15
2010-2011 (April 10 – Mar 11)	9159.30	14416.70	89.30	23665.30
2011-2012 (April 11 – Mar 12)	34991.10	45856.20	76.50	80923.80
2012-2013 (to end June 2012)	2208.00	17819.00	1.50	20028.50
Total	83885.65	102453.49	4082.61	190421.75

The total catch from the lake is not recorded in Table 7-1 for two reasons. Firstly, anglers will also have caught fish and this figure is not recorded. Secondly, there is known to be illegal gill netting on the dam and it would not be possible to monitor this. The figures in Table 7-1 are, thus, an underestimate of the mass of fish removed from the lake.

In the absence of firm data one might assume that the ratio of catfish to carp to other fish in the illegal gillnetting catch would be similar to that of the official programme. The ratio of different species caught by anglers might be different as anglers will target the more desirable species. The model developed by NIWR (1985) estimated the maximum sustainable yield from the dam under the conditions prevailing at the time was 525 tonnes per year. The estimated mean catch by anglers at that time was 695 tonnes per year (Table 7-2). Following these estimates, the fish were being overexploited by anglers. NIWR put the high catches down to the fact that the lake level was low at the time, making the fish more accessible to anglers.

The relative abundance of the sought-after species would appear to have changed in the intervening three decades, with catfish now dominating the catch. The following paragraphs (in italics) have been copied from HDRP (2013b). For the purpose of this review the discussion has been limited to the three large and important species, namely carp, catfish and Mozambique tilapia.

There has been a general decline in ***carp*** *numbers since 2004. There seems to be a general increase in carp size, although high numbers were recorded for this species in the 20-30cm length range during 2013. Small specimens (<20cm) were not sampled during 2012/2013, and this may be due to an increased impact from predation by largemouth bass, which seems to be recovering in the dam. Large specimens are present in the dam and it seems that larger specimens are also being caught more frequently by the fishery with the fish electro-shocker. Large specimens were also sampled with the 170 mm mesh gill nets during the 2012-2013 survey.*

There has been an increase in ***catfish*** *contribution to the total numbers sampled since 2004. The average length recorded for catfish indicates that there has been a general decline in catfish size, as more specimens in the 20 to 30cm length range were recorded. The occurrence of increased numbers of smaller specimens may be an indication of the pressure now being exerted on the catfish via the fishery. Large specimens are however still present and were also sampled in high numbers. The difference from other years is that there is now an increased number of smaller specimens of catfish (<45cm) in the dam.*

The length frequency trend for the ***Mozambique tilapia*** *shows a definite increase in average length and an increase in numbers of specimens in the 20-25cm length range. Small specimens are still present in high numbers, but an increase in different length cohorts (especially in larger length ranges) indicate to a healthier less stunted population of Mozambique tilapia. Large specimens are present and are also being caught by the fishery more frequently. Large specimens for this species were sampled in the in the 45cm length class during 2012/2013*.

It would appear from these statements that the success of carp recruitment and possibly Mozambique tilapia are down and that that the success of catfish recruitment has increased.

The mean annual catch of the foodweb restructuring process, at 47.6 t, is substantially lower than the mean annual anglers' catch of the early 1980s (Table 7-2). Cochrane (pers. comm.), who developed the fish production model for the research reported by NIWR said that his model showed that there would be an increasing production with increasing nutrient enrichment up to a point, above which the fishery production would decrease. This may be illustrated graphically by a generalised illustration of the intermediate disturbance hypothesis (Figure 7.1) in which ongoing disturbance reduces biodiversity.

Table 7-2: The mean annual catch of fish (in tonnes) taken by anglers from Hartbeespoort between March 1982 and April 1984, together with the estimated maximum sustainable yield, was as follows:

	C. carpio (carp)	*O. mossambicus* (Mozambique tilapia)	*C. gariepinus* (catfish)	Total
Mean annual yield (t)	449	144	102	695
Maximum sustainable yield (t) (calculated)	375	120	30	525

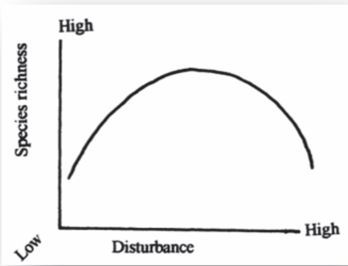


Figure 7-1. A generalised version of the hump-backed graphical model of the intermediate disturbance hypothesis (from Wilkinson, 1999)

The concept of restructuring the foodweb is to decrease the predation on zooplankton (top down approach), so that the grazing pressure of zooplankton on phytoplankton would increase and so exert a control on the phytoplankton biomass. This strategy was successful on Lake Vesijärvi in Finland where the fish were originally from a lentic (still water) environment. The fish in the lakes under consideration evolved in a lotic (running water) environment and so are not predominantly plankton feeders. Recent research by Harding and Hart (2013) using stable isotopes has shown that carp and catfish do not, in fact, eat predominantly zooplankton. Catfish are opportunistic feeders and will take zooplankton when the organisms are available but their diet is predominantly benthos-derived.

There is controversy around the effectiveness of the foodweb restructuring aspects of the HDRP (HDRP, 2012b, pp vi-xiii). This review recommends that a well-designed scientific investigation be instituted to lay this controversy to rest. This investigation should use the stable isotope method used by Harding and Hart (2013) in order for the results of the two studies to be comparable to one another.

There is, however, opportunity for commercial fisheries in the dams draining the Gauteng conurbation. NIWR (1985) recommended that there should be no commercial fishery in Hartbeespoort as the harvest by anglers exceeded the maximum sustainable yield. But there are a number of other dams which could support commercial fisheries and the fish yield from Hartbeespoort should be re-examined.

7.3.7.1 Fish edibility

The safety of the fish from Hartbeespoort for human consumption has been investigated. 'All the Hazard Quotients and risks of developing cancer are low with the exception of chromium which is an over prediction based on the VI versus III speciation, thus no predicted adverse health effects are anticipated based on consumption of fish on a daily basis' (HDRP, 2012b).

7.3.7.2 Fishery yield

The figures given in HDRP 2012b, c and 2013b indicate 2 potential changes from the fish yield as reported in NIWR (1985). One change may be that carp may no longer be much more numerous than catfish and the other is that the catch by the foodweb manipulation team is considerably lower than that recorded for anglers in 1985. There are various possible reasons for this. One is that angling effort may be more targeted and intense than the recent netting effort. Or there may be a difference in the methods by which samples were taken. Another reason may be that the figures indicate a change in the fish community in the lake.

7.3.7.3 Recommendations for Phase 2

The fishery

The fishery provides opportunity for people to generate livelihoods, not only in Hartbeespoort Dam but in other dams as well. Phase 2 could offer training for people who are keen to fish either at a commercial or subsistence level on the dams around Gauteng. At the same time it should also provide information on the permitting requirements of people who are going to become fishermen.

Foodweb restructuring

The reasoning behind the fishing for foodweb restructuring needs to be reviewed. The concept of restructuring the foodweb to decrease the predation on zooplankton, so that the grazing pressure of zooplankton on phytoplankton would increase and so exert a control on the phytoplankton biomass was developed for lentic waters with fish species evolved to live in these waters. This strategy was successful on Lake Vesijärvi in Finland where the fish were originally from a lentic environment. The fish in the lakes under consideration evolved in a lotic environment and so are not predominantly plankton feeders. Recent research (Harding and Hart, 2013) using stable isotopes has shown that carp and catfish do not, in fact, eat predominantly zooplankton. Catfish, an opportunistic feeder, will take zooplankton when the organisms are available but their diet is predominantly benthos-derived.

The 3rd target species, the canary kurper, showed a strong preference for zoobenthos. Detritus was also identified in the gut to a lesser extent (HDRP, 2012c, p 6-8).

This review recommends that the analyses using stable isotopes, as used by Harding and Hart (2013), be done on a representative sample of fish from Hartbeespoort to lay this controversy to rest. Scientists familiar with the method should be consulted as to the value of analysing samples taken during the different seasons of the year.

7.3.8 Macrophytes

4.9 Biomass Management-Shoreline Vegetation – PEP B4.3 [OM3.1]
4.10 Biomass Management – Establishment Of Floating Wetlands – PEP B4.4 [OM4.1]

Emergent macrophytes have been the subject of development, with interventions being implemented in the littoral zone as well as floating wetlands. Submerged macrophytes began to appear in the littoral following the implementation of the programme to establish emergent macrophytes. Their appearance was preceded by the appearance of the filamentous alga identified as *Spirogyra*. Beklioglu et al. (2011) and Genkai-Kato and Carpenter (2005) report that the macrophyte effect of preventing P recycling from sediments was critical to the susceptibility of shallow lakes to regime shift. The filamentous alga is likely to have the same effect.

4 800 m^2 of wetlands have been developed behind berms which have been constructed to stabilise the littoral zone in certain areas of the lake.

The first floating wetlands were developed in late 2008 and by August 2010 a number of the floating wetlands had been launched.

Wetlands have been established both on selected areas of the littoral and as floating islands. Nine thousand m^2 (0.9 ha) of shoreline has been vegetated. The reported number of floating wetlands launched is uncertain. Wetlands have been established both on selected areas of the littoral and as floating islands. The design of a further 42 ha of wetlands at Ifafi has been completed and is included in the Resource Management Plan.

7.3.8.1 Recommendations

As far as possible, plant species which are able to survive periods of desiccation should be selected for planting on berms as many aquatic plants will not survive through prolonged periods of water level fluctuation.

7.3.9 Floating wetlands construction

The reported number of floating wetlands launched is uncertain. In the answer to Parliamentary Question No. 2135 to the Minister (13 August 2010) the number is given as 357 while in HDRP (2012a) the figure given is ‘>280’. The design of a further 42 ha of wetlands at Ifafi has been completed and is included in the Resource Management Plan.

The size of the floating wetlands is not given in the report, but the answer to Parliamentary Question No. 2135 to the Minister (13 August 2010) indicates that the floating wetlands units are 16 m^2. This means that the total area of floating wetlands launched currently stands at either or 5 712 m^2 (0.57 ha) or 4 480 m^2 (0.448 ha) assuming all the floating wetlands are the same size. Figure 7-2 shows a recent view from the wall of some floating wetlands and an algal bloom.

Figure 7-2: Recent view (April 2016) from the wall showing floating wetlands and algal bloom

The longevity of the floating wetlands and their ability to withstand strong winds and storms is not yet available (HDRP, 2012a). As a result, the cost effectiveness of this design cannot be estimated. It is accepted that it is government policy to create jobs.

The floating wetlands have been shown to provide a rich habitat for zooplankton. They will also provide habitat both protection and food source for small fish. The assumption is that the submerged part of the floating wetlands will, in addition, provide substrate for microbial activity which will add to the value of the habitat created by contributing to the nutrient cycling of the wetlands and by providing additional food for the macroinvertebrates and fish.

Operational best practice guidelines have been developed for the establishment of macrophytes on the littoral zone and on floating islands. These will prove invaluable in the roll out of the HDRP to other eutrophic impoundments in the country.

7.3.9.1 Recommendations

The role of the wetlands (both littoral and floating) and the management practice to be followed for the nutrient cycling in the lake should be determined during Phase 2. This will define the contribution of these to the health of the lake.

An aspect that needs further investigation is the effectiveness of the floating island wetlands in sequestering nutrients. This investigation should be conducted with the same rigour as reported by Stewart et al. (2008) and this work may be used for comparison.

We recommend that the cost effectiveness of the islands (cost, longevity, ability to sequester nutrients, employment creation) be calculated.

7.3.10 Submerged macrophytes

4.9 Biomass Management-Shoreline Vegetation – PEP B4.3 [OM4.1]

The submerged macrophytes *Potamogeton pectinatus* (fennel-leaved pondweed) and *Potamogeton crispus* (curled pondweed) are present in the littoral zone. The following paragraphs are copied from HDRP (2012c).

An aquatic vegetation survey was conducted during September 2011 and certain aspects recorded. Bottom coverage was found to be good around the dam up to depths of 3 m, sometimes forming a wide rim in the littoral zone stretching up to 20 m into the dam. The species composition consisted mainly of Spirogyra sp. and P. pectinatus. P. crispus were found at few sites, but provides a good indication that the plants are diversifying.

During April 2012 another aquatic vegetation survey was conducted. Previously densely vegetated areas were mostly barren and only few plants were sampled in some areas. Plant die-off was recorded following or in response to dense algal growth during late summer and early autumn. Some dense aquatic vegetation was however recorded at Meerhof.

The following observation was also made:-*A plant succession is currently occurring with colonization of previously barren areas by Spirogyra sp., now being followed by the true aquatic plants Potamogeton pectinatus (fennel-leaved pondweed) and Potamogeton crispus (curled pondweed) which will become dominant over time and utilise more nutrients leaving less nutrients available for blue-green algae (HDRP, 2013a, p 3.13).*

The extended period of stable lake level will have provided conditions which allow for the colonisation of the shallow areas by rooted macrophytes. These will provide an additional habitat for fauna as well as an additional pathway in the nutrient cycle. In addition, the macrophyte effect, reported by Genkai-Kato and Carpenter (2005), will prevent, or reduce in the early stages of colonisation, the recycle of P from the sediments.

7.3.10.1 Recommendations for Phase 2

Wetlands have been established both on the littoral as well as floating islands. During an extended time of the impoundment being at full supply level the littoral vegetation has had the opportunity to establish. The planned transfer of water to the Waterberg, scheduled to begin in 2017, may mean that the littoral will be dry for a period annually. Will the vegetation that has established be able to withstand the dry periods?

The floating islands will need to be over a sufficient water depth so that they will not rest on the sediment during low water. If they do, it is likely that the vegetation will root in the sediment and will then not float when the water level rises again. The site selected for the islands will need to take this into account.

Was the identity of the filamentous alga *Spirogyra* confirmed? *Cladophora* is the dominant filamentous alga elsewhere in the system, particularly in the irrigation canals.

7.3.11 Macro-invertebrates

4.13 Foodweb Restructuring And Monitoring – PEP B6 & B6.1 [OM2.1]

For the purpose of assessing the macro-invertebrates the HDRP divided the lake into 3 biotopes, the floating wetland islands, the littoral and the benthos. Of these, the floating islands provide a stable habitat that supports both greater diversity as well as greater numbers of organisms than the other biotopes.

The benthic biotope was the least stable, with the taxa present being tolerant of poor to moderate water quality conditions.

Figure 7-3 shows the number of species present at the limnetic site amongst and remote from the floating wetlands. The additional habitat provided by the floating wetlands increases both the biodiversity and the total number of the limnetic macro-invertebrates.

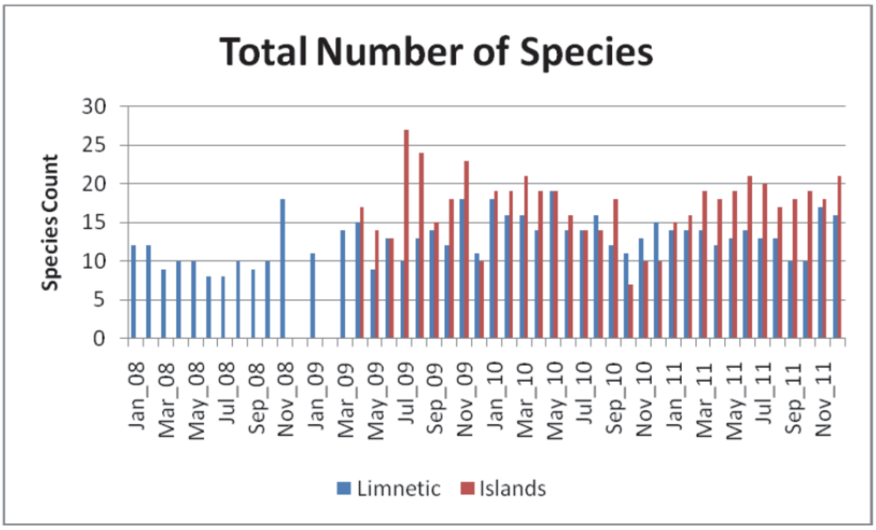


Figure 7-3. A comparison of the total number of different zooplankton species between the limnetic sites and the Floating Wetlands sites in the Hartbeespoort Dam, for the period January 2008 to December 2011.

7.3.12 Effectiveness of managing Dam aesthetics

The aesthetics of the dam have improved since the start of the HDRP. The lake is currently in a clear water state, with better aesthetic appearance than it has had since 1975 (pers. comm., Prof W van Riet, 2014). The assumption has been that this is attributable to the HDRP. While this has been the focus of the dam basin activities there have been other factors involved which will have played an important role in this change.

From 2008, the same year in which the first floating islands were launched, the concentration of SRP in the water column decreased dramatically. At the same time the Chlorophyll-a levels began to decrease. The stable lake level has allowed the development of submerged marginal vegetation, principally filamentous algae and *Potamogeton* species. It is noted in the Consolidated Progress Report that these will sequester increasing amounts of nutrients, leaving less for the algae. The existence of rooted macrophytes is not secure, as reported in HDRP (2102c), where it is noted that *Plant die-off was recorded following or in response to dense algal growth during late summer and early autumn.*

Eutrophic lakes may exist in alternate stable states, clear water dominated by submerged plants or turbid water dominated by algae. These states are difficult to predict and difficult to reverse (Genkai-Kato and Carpenter, 2005; Beklioglu et al., 2011) but have significantly different effects on the lake ecosystem.

7.3.12.1 Recommendation

The effect of projected changes on the alternate clear water / turbid water state of the dam be investigated.

7.4 Effectiveness of phosphate removal

7.4.1 Estimate of P removal by the HDRP interventions

5.4 Phosphate Reduction At Source And Compliance – PEP C3 [CS1.1]

A theoretical estimate of the biomass removed through the interventions of the HDRP (Table 7-3) indicates that a proportion of the incoming P load was removed by the fishery and algal pumping operations. Additional P would have been removed through the hyacinth removal as well as by the anglers' catch, for instance.

The quantity P removed by these interventions, however, is only a proportion of the total mass of P which remains in the dam.

Table 7-3 provides a theoretical estimate of the amount of phosphorous removed by the HDRP. The figures used in the estimations have been obtained from the literature. These figures are an estimate and should not be seen as hard and fast figures of phosphorous removal. The actual content of each component of the biomass removed needs to be determined using standard techniques. It does, however, give an estimate of phosphorous removal which is in the right order of magnitude. The annual fish catch has been obtained by taking the average annual catch for each species from Table 7-3 (average total catch – 47.6 t. p. a. wet mass). This paragraph should be read in conjunction with the chapter on **foodweb restructuring** (Chapter 7.3.7).

Table 7-3. Theoretical estimates of annual phosphorous removal by the HDRP.

	% Phosphorous	kg P per ton dry mass	t biomass/yr. wet mass (Mean /yr.) (ave. from Table on Page 5 of HDRP, 2014)	t biomass/yr. (dry mass at 22% of wet mass) (from Hart & Harding, 2015)	Tonnes P removed / year
Carp[1]	1.5% dry mass	15	25.6	5.632	0.084
Catfish[2]	3% dry mass	30	20.97	4.6134	0.138
By-catch[3]	3% dry mass	30	1.02	0.2244	0.0067
Algae[4]	1% dry mass		4000		24
Hyacinth[5]	0.4% of dry mass				10 (maximum – estimated)
Total Phosphorous removed (estimate)					**34.229**

[1] Sterner RW and NB George, 2000. Carbon, nitrogen, and phosphorus stoichiometry of cyprinid fishes, Ecology, 81(1), pp. 127-140.

[2] Estimated from: Dantas MC and J. L. Attayde, 2007. Nitrogen and phosphorus content of some temperate and tropical freshwater fishes. Journal of Fish biology. Published online. In this case predatory fish have a higher P-content than non-predatory fish. This may be an over estimate.

[3] Estimated from: Dantas MC and J. L. Attayde, 2007. Nitrogen and phosphorus content of some temperate and tropical freshwater fishes. Journal of Fish biology. Published online. In this case predatory fish have a higher P-content than non-predatory fish. This is almost certainly an over estimate.

[4] In the absence of precise figures for the wet or dry mass of algae removed I have taken NIWR (1985) figure of harvesting algal scums which would give an annual yield of 4 000 tonnes of fresh algal biomass. Phosphorous content of the algae is 1% of dry mass and dry mass about 6% of wet mass. 4 000 tonnes of algal biomass (wet mass) would contain about 24 t Phosphorous per annum (figure from NIWR, 1985).

[5]The figure removed is given in cubic metres so the mass is uncertain. Phosphorous content from FAO (1979) and Haller and Sutton (undated).

The floating wetlands will also sequester nutrients as anticipated in the Addendum to the Business Plan 2008-2009 (Page 4-21). This will require suitable management if it is to be realized.

7.4.1.1 Recommendations for Phase 2

The complete TP and SRP budgets need to be clarified.

During Phase 2 there should be a focus on management and reduction of the incoming P load from the catchment.

The N:P ratio in the water body should be calculated as this plays a role in determining the type of algae which may be expected to occur in the dam.

A team of suitably qualified experts needs to be tasked with developing the roadmap for eutrophication management.

7.5 Conclusions to Chapter 7

A number of in-lake interventions to address the hypertrophic conditions of the dam have been implemented during Phase 1 of the programme. However, on review of the overall situation it becomes apparent that the level of phosphorous enrichment is very high and phosphorous is accumulating in the dam at a rate in excess of the removal through these interventions. A desktop estimate of the amount of phosphorous removed by the interventions is that that the mean rate of accumulation in the dam is approaching an order of magnitude greater than that removed through the interventions. The biological interventions already implemented need to be supported by technical and chemical interventions combined with behavioural changes such as the political will to apply regulations, by-laws, etc. by authorities responsible for the catchments. This review, therefore, recommends that Phase 2 focuses primarily on the catchment. The analysis of the sources of pollution in the catchment given by van Veelen (2013) gives clear direction as to where the priority interventions should be addressed. The chapters in this report by Van Veelen (Appendix 3) and Maree (Appendix 4) provide guidelines on how this may be achieved.

8 Technical governance of the HRDP

8.1 Purpose of this Chapter

This chapter proposes a technical governance framework for HDRP Phase 2. In the management of complex systems of this nature technical governance is a key success factor. The HRDP was originally intended to be overseen by a technical committee, entitled a Project Management Committee. The most recent set of Minutes of Meeting of this committee that we received was from 2011. It is therefore not clear whether rigorous technical oversight of the HDRP Phase 1 programme currently exists.

8.2 HDRP Phase 2 to adopt an adaptive management approach

Governance of the HRDP has its roots in strategic environmental management. This creates a foundation for incorporating complex socio-ecological system considerations into management and decision-making and to build consensus on management priorities and remediation outcomes (OECD, 2012).

Within the SEA context, adaptive management seeks to aggressively use management interventions as a tool to strategically probe the functioning of a complex socio-ecological system. In adaptive management, interventions are designed to test key hypotheses about the functioning of the ecosystem. This approach is completely different from a typical management approach which uses the best available knowledge to generate a risk-averse, 'best guess' management strategies. Interest in the concept of adaptive management has developed in response to perceived limitations of traditional natural resources management approaches. Those limitations have included a limited ability of organizations and policies to cope with environmental changes and surprises, incomplete application of ecosystem science principles to management decisions, and a limited ability to resolve science-policy incoherence in large ecosystems, including river systems, in a timely fashion. Adaptive management identifies uncertainties, and then establishes methodologies to test hypotheses concerning those uncertainties. It uses management as a tool not only to change the system, but as a tool to learn about the system. It is concerned with the need to learn and the cost of ignorance, while traditional management is focused on the need to preserve and the cost of knowledge[9].

Adaptive management is thus a common sense strategy for addressing the reality of a changing and uncertain environment.

Recognition of the need to adjust management strategies can derive from several broad sources.

First, various hazards could affect the operations and impacts of the HDRP. These hazards have been discussed in detail in Chapter 6 above.

---

[9] http://www.resalliance.org/index.php/adaptive_management

Second, scientific advances could provide better understanding of the complex linkages between human activities and environmental impacts. Thus a scientific and expert-driven approach to the HDRP is required (refer to chapter 8.4 below).

Thirdly, technological advances could provide better ways of managing the causes and symptoms of phosphate pollution.

Fourthly, shifts in social objectives and preferences may challenge conventional operations schemes, and thus appropriate stakeholder forums are required to provide input into the adaptive management system.

Adaptive management applications are eminently applicable to environmental or ecosystem restoration projects like the HDRP. Adaptive management is particularly suited to large, complex ecosystem restoration projects, which entail large degrees of risk and uncertainty, multiple, and changing objectives, and phased components. Adaptive management can be especially important in multi-phase activities, as it can promote adaptation of ends and means based on lessons learned that lead to model improvements to support future decisions.

8.3 A risk management approach

[Extracted from: Nathanail et al. (2002).]

Adaptive management requires adoption of a holistic approach to remediation management with system investigation, risk assessment and risk management activities taking place in an iterative manner. At the heart of any system management work must be the derivation of a system conceptual model (SCM) that integrates what is already known about the HDRP system, and identifies both what still needs to be discovered, and how that information should be used. The SCM would set out the critical phosphate pollutant linkages of concern for a particular remediation problem, and further develop hypotheses related to current and emerging hazards. The SCM therefore provides a model for understanding how to manage system drivers, and from this point appropriate remediation techniques for specific and set risk management goals can be chosen. The SCM should be established at the earliest possible stage of information gathering, and then continuously extended and adapted as more monitoring and scientific information become available and as various remediation activities proceed.

8.4 Science management and independent experts should be enlisted to provide advice on adaptive management initiatives

There is a need to enlist independent experts in the population of the adaptive management framework. The reason for this is that the results of modelling exercises or economic or environmental investigations do not always provide findings with which all scientists and other interested parties agree on. This lack of agreement can hinder the learning-by-doing offered by the adaptive management framework. Independent review can also indicate where there may be gaps in the assessment. Independent review does not, however, eliminate uncertainties endemic to many operating environments. Independent experts can validate underlying assumptions, logic, planning methods and can help in resolving science-based disputes. Adaptive management will not, however, free agencies and decision makers from using their judgment in the face of uncertainties.

The WRC has excellent water ecosystem science governance best practices in place, and these are extremely useful and relevant to the HDRP Phase 2. This structure starts with project leadership is required to assume basic science management responsibilities:

- To design appropriate projects around scientific research questions and to set appropriate objectives for these projects;
- To plan and direct the execution of the project's duration and the approved budget;
- To appoint an appropriate research team;
- To generate and archive the following important documentation:
    - Minutes of Reference Group meetings
    - Work programmes, progress reports, a final reports,
    - Disseminate findings on completion of the deliverable.
- Keep track of relevant project expenditure and obtain consent for any budgetary reallocations involving capital funds.

The WRC advises that a project Reference Group is required to provide the research team with guidance and to assist in monitoring progress and evaluating deliverables. The Reference Group is required to act in an independent, external advisory capacity, as envisaged by the adaptive management approach.

Although the Reference Group cannot alter the aims of the project, changes in approach could be recommended within the budgetary constraints of the project.

8.5 Options assessment

It is common cause that there is no one optimal solution for a large scale remediation problem, and this is especially so for the HDRP. Risk management therefore has a dominant role in adaptive management decision making for managing remediation as it provides a rationale framework for evaluating problems and determining the availability of solutions. It is not, however, the only decision criterion. The drivers for a remediation project, the boundaries limiting what can be done on a system, the suitability / feasibility of available remediation options, the views of different stakeholders and the wider effects of the remediation work should all influence the choice of approach. An appraisal of costs versus benefits can be a useful approach to integrating this wide range of considerations.

Selection of remedial approach is likely to proceed in a stepwise fashion, with general information being used to arrive at a short list, and then detailed desk studies, and possibly treatability studies, undertaken to support a final selection. The broad classes of decision making influences described in this outline have not been prioritised. In practice some criteria may be seen as more important than others, and weighted accordingly. However, this depends greatly on the regulatory, policy and economic context for the system being considered, so no general rules can be offered here.

A suitable remediation technology is one which would meet the technical and environmental criteria for addressing a particular remediation goal.

Determining suitability is likely to proceed in a stepwise fashion. As far as possible lower cost information should be used, and expensive investigations applied only where strictly necessary. Established performance information and process descriptions are likely to be used to gain a general view of suitability, to arrive at a shortlist of possible remedial approaches. However, it may be necessary to carry out laboratory or pilot scale treatability studies for complex treatment approaches, or where system specific effects are likely to have a large bearing in likely performance of a remediation system.

8.5.1 Costs and Benefits

The options assessment should fundamentally apply a cost-benefit analysis (CBA) approach. The aim of the CBA would be to compare the net effectiveness of diverse remediation options such as the effect on human health, the environment, the land use, and issues of stakeholder concern and acceptability.

As noted above, the options assessment framework comprises a number of steps, each of which approaches the assessment of cost and benefits in the same manner, but which consider impacts in increasing level of details.

There are five steps of key relevance. The main steps are:

- Step I: Screening;
- Step II: Qualitative Analysis;
- Step III: Combined Cost-Effectiveness Analysis (CEA) and Multi-Criteria Analysis (MCA);
- Step IV: Cost-Benefit Analysis (CBA)
- Step V: Sensitivity Analysis and Selection of Preferred Option

Step I and II involve the identification of impacts, with Step II including a simple CEA.

The initial screening stage is used to examine the characteristics of the remediation problem and associated solutions to determine what might be appropriate for particular system, and hence further assessment requirements. Generally, as the complexity of system conditions and potential remediation techniques increases, so will the need for more detailed assessment.

Step II would involve estimating the potential impacts of remedial option without the need to estimate its significance.

Step III and IV examine the significance of impacts in more detail through the use of scoring and weighting and monetary valuation. Step V involves undertaking sensitivity analysis which then leads to selection of the preferred option, or may result in a review of constraints.

The decision to take a Step III and/or Step IV approach is taken following completion of the Step II assessment. It is based on whether the impacts predicted to occur can be values or not. In many cases, it will be possible to combine Step IV (CBA- where impacts are relatively straightforward to value) with Step III (CEA/MCA) for those which cannot be (robustly) valued.

8.6 The monitoring programme

Good information is a pre-requisite for decision making. Environmental risks are the reason that remediation work is being considered, hence the importance of risk assessment as a decision making discipline and the system conceptual model for integrating the information available. Industry and government agencies in several countries are now promoting a more integrated and iterative approach where system investigation, risk assessment, namely selection and remediation overlap in a way that is synergistic.

8.6.1 Background

3.4 Integrated Monitoring Programme – PEP A4 [CE5.1]

According to the successive Business Plans, Menco took over the integrated water quality monitoring from several other people after the programme had been running for 2 or 3 years. Amongst the early tasks was the need to integrate all the various monitoring programmes operating in the upper Crocodile catchment and then to plan the integrated monitoring programme. There were some hitches at this time. One of them was that the water analysis laboratory at the RQIS underwent extensive refurbishment between 2008 and 2010. This reduced the capability of the laboratory substantially. As a result, the unanalysed samples were preserved and stored for future analysis or analysed by a sub-contracted laboratory. After the laboratory became fully functional again in early 2010 the backlog took a long time to clear. As a result, certain gaps exist in the data with total phosphorous being an important determinant for which the data are incomplete. This was identified as a gap in the Phase 1 report (HDRP, 2013a). Another hitch was that the planning of the integrated monitoring programme was thwarted for administrative reasons.

The monitoring programme collected a great deal of valuable data which gives a picture of water quality in the catchment and in the dam. This has been reported in detail in HDRP (2013a) and the raw data are available.

It is not clear how these data were used to guide the management decisions in the programme.

8.6.2 Design of a Monitoring Programme

Without freshwater of adequate quantity and quality sustainable development will not be possible. Uncontrolled human activity will lead to one or more problems such as pollution, nutrient enrichment, microbial contamination or alteration of the hydrograph (which will affect such issues as the exchange rate of a water body), all of which threaten human health and tend to lead to depletion of biodiversity. A monitoring programme should be designed to detect unwanted changes to the resource in time for remedial action to be taken.

The International Organisation for Standardisation (ISO) defines water quality monitoring as "the programmed process of sampling, measurement and subsequent recording or signalling, or both, of various water characteristics, often with the aim of assessing conformity to specified objectives". Monitoring provides the basis on which water quality management decisions are based. Bartram and Ballance (1996) define three types of water quality monitoring as follows:

- **Monitoring** is the long-term, standardised measurement and observation of the aquatic environment in order to define status and trends.
- **Surveys** are finite duration, intensive programmes to measure and observe the quality of the aquatic environment for a specific purpose.
- **Surveillance** is continuous, specific measurement and observation for the purpose of water quality management and operational activities.

The purpose for which the water quality data is being collected will determine which one of the three types of monitoring is appropriate and so set the scene for planning the monitoring programme. The following points are important steps in the formulation of a successful monitoring programme:

- Describing water resources and identifying actual and emerging problems of water pollution.
- Formulating plans and setting priorities for water quality management.
- Developing and implementing water quality management programmes.
- Evaluating the effectiveness of management actions.

The monitoring programme needs to be reviewed at intervals to ensure that it is (a) delivering the required information and (b) to discern whether it has identified gaps in the management programme based on the monitoring that needs to be addressed.

An important aspect of monitoring, particularly monitoring for management, is that the data are used. To this end the incorporation of a monitoring programme in an adaptive management framework will provide the feedback necessary to ensure that the monitoring programme remains focused on the question being addressed (see, for instance, Biggs and Rogers, 2003).

The complete assessment of aquatic environmental quality requires the measurement of parameters from the following disciplines:

- chemical analyses of water, particulate matter and aquatic organisms (such as planktonic algae and selected parts of organisms such as fish muscle),
- biological tests, such as toxicity tests and measurements of enzyme activities,
- descriptions of aquatic organisms, including their occurrence, density, biomass, physiology and diversity (from which, for example, a biotic index may be developed or microbiological characteristics determined), and
- physical measurements of water temperature, pH, conductivity, light penetration, particle size of suspended and deposited material, dimensions of the water body, flow.

The actual parameters measured will depend of the specific characteristics of the water body to be monitored, but consideration should be given to each of the disciplines mentioned above when planning the monitoring programme.

While river flow is unidirectional and mixing is largely limited to vertical mixing, the water body of an impoundment may mix both vertically and laterally and the design of a monitoring programme will need to take this into account.

8.6.3 Design of the adaptive management framework and monitoring programme

The purpose of the monitoring programme is to support and help to focus the management actions. This means that the programme should be embedded in the management system. The system recommended is the adaptive management system which provides the framework for 'learning by doing'. This ensures that the monitoring programme will be correctly focused and cost-effective.

8.6.3.1 Populating the adaptive management framework

The adaptive management framework is illustrated in Figure 8.1.

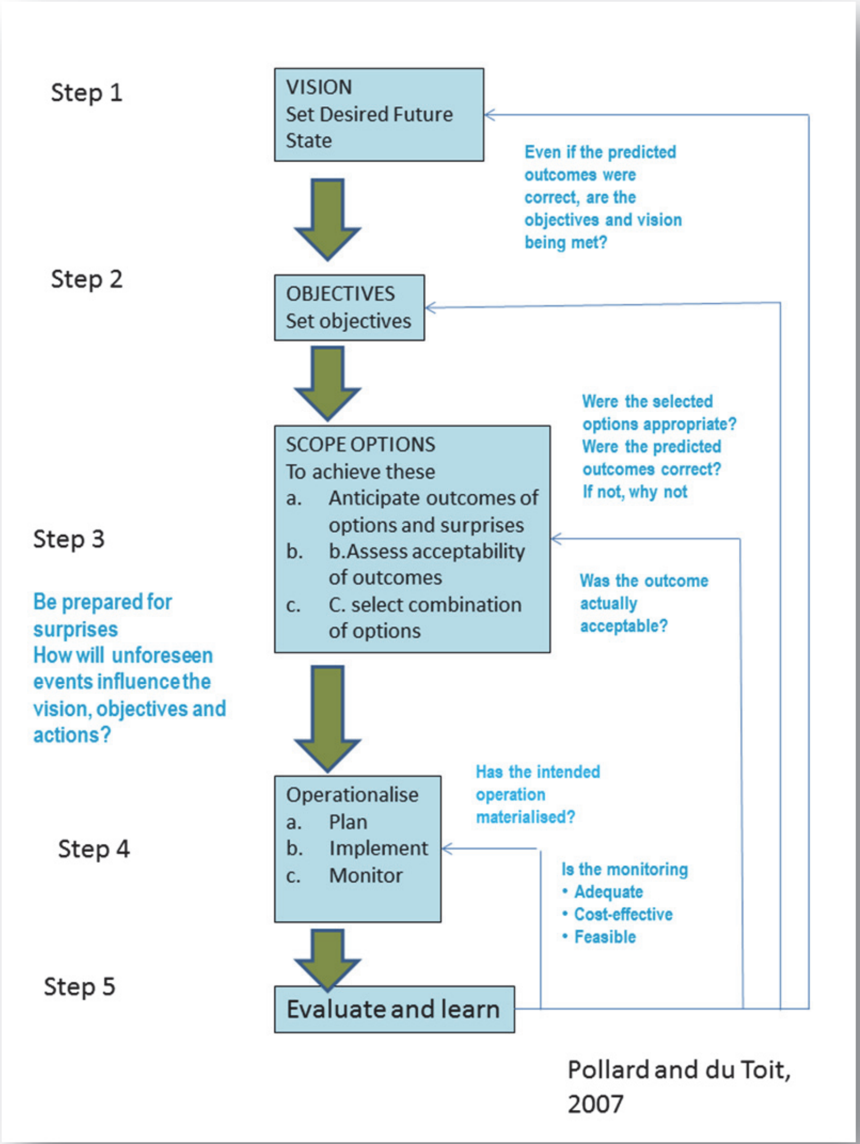


Figure 8-1. The steps of the adaptive management framework

It is recommended that the process described by Pollard and du Toit (2007) is followed when developing the adaptive management framework for Phase 2 of the HDRP. This document is available at

ftp://ftp.sanparks.org/Kruger/IUCN_Rivers/pollard&dutoit(2005).pdf

The example provided by Pollard and du Toit (2007) is developed for the Kruger National Park and provides insight into the process (see also Biggs and Rogers, 2003).

Most environmental problems involve multiple interest groups and present as complex situations. This should be recognized when developing the adaptive management framework and consensus needs to be sought from the relevant interest groups.

The effectiveness of the monitoring programme should be assessed at least annually by answering the questions against the feedback arrows in the figure, or more frequently if it becomes apparent that it is not addressing the needs adequately. The time scale for the routine reassessment of the vision, objectives and options may be longer but should not exceed 5 years.

8.6.4 The monitoring programme

The monitoring programme will address step 4c of the adaptive management process. The development of the adaptive management framework ensures that the monitoring programme will be focused on the needs of the programme.

The DPSIR framework (Figure 8-2) provides an effective method to select the appropriate indices to monitor. The DPSIR (Drivers, Pressures, State, Impact, Response) framework provides a simple method for separating the causes of a problem from the impacts. With this understanding it is possible to identify the causes behind the observed impacts (symptoms) of a particular state and so aim remedial interventions at the source of the problem to be addressed.

A simplistic example from the situation in Hartbeespoort Dam may be that excessive growth of algae or hyacinth is observed (State) which causes problems with the treatment of water and a loss of biodiversity (Impacts). This is caused by an excessive nutrient load into the dam (Pressure). The nutrient load originates from point and non-point sources in the catchment (Drivers). With this understanding it can be appreciated that treating the excessive growth of algae or hyacinth alone will not provide a permanent solution although it may well be necessary in the short to medium term as part of the suite of interventions in the initial clean-up.

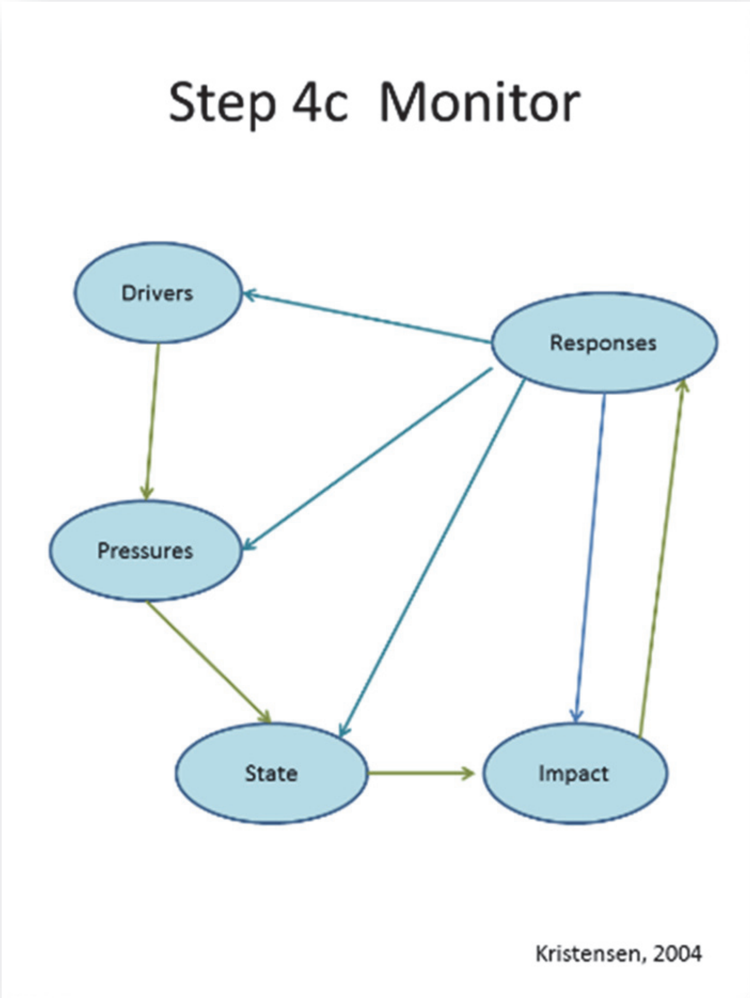


Figure 8-2: The DPSIR Framework

Indicators should be developed which give insight into the changes in the system which may be brought about by the interventions of the adaptive management process. Using the DPSIR framework it is possible to link the causal chains of drivers through impacts and so to select indicators from the 'state' or 'impact' which will assess the effect of an intervention on the 'driver'.

There is an extensive literature on the development of cost-effective indicators which will give guidance to planners.

It is important that the programme managers be aware of new developments for monitoring. An example of a recent development is the use of remote sensing for the monitoring of algal blooms developed by Matthews (2014). The use of this method should be investigated as a means for routine monitoring not only Hartbeespoort Dam but other water bodies in South Africa.

8.6.5 Surveillance monitoring

Surveillance monitoring should be undertaken for cyanobacterial toxins and other metabolites such as BMAA. These have been shown to have deleterious effects on human health and the WTW need to know when these are in the water and to implement measures to remove them as far as possible.

8.7 Conclusions

The technical governance of the HDRP is not adequate. The HRDP was originally intended to be overseen by a technical committee, entitled a Project Management Committee. The most recent set of Minutes of Meeting of this committee that we received was from 2011 and it therefore appears that the technical committee either does not exist or does not meet. It is therefore not clear whether rigorous technical oversight of the programme exists. The fact that the monitoring programme has also stopped since 2011 is an indication of the current state of technical governance of the HDRP.

This chapter concludes that the HDRP Phase 2 should adopt an adaptive management approach. This approach is extremely well suited to managing large scale remediation projects in complex systems, and managing the associated risk environment associated with possible future outcomes or hypotheses. Successful adaptive management is premised on good science, and involving independent experts and thus highly dependent upon good technical governance. In addition, it requires a formal approach to assessing remediation options; as well as an appropriate monitoring program, that follows from the adaptive management approach.

It is in the nature of complex system management and multiple stakeholder involvement, that consensus is not easy to achieve. However, the WRC has developed excellent methodology and governance systems for managing science, research and development of complex ecological systems. Thus we strongly recommend that the WRC become involved in the HDRP Phase 2, and play a key role in the design of the SAM approach and the various supporting initiatives.

9 Liaison with stakeholders

9.1 Purpose of this Chapter

This chapter addresses the need for stakeholder collaboration as an integral component of adaptive management. Stakeholder satisfaction is also an important aspect of the liaison with stakeholders. Amongst the large water users who are important stakeholders are water service authorities, municipalities, irrigated agriculture and mines. The recommendation is made for the formation of a formally-structured stakeholder forum.

9.2 Stakeholder collaboration is an integral component in the adaptive management

Large, multipurpose projects affect many stakeholders that have different, often conflicting, expectations. Differences between stakeholders are inherent and inevitable in nearly all resource management settings.

Adaptive management does not aim to eliminate such differences, but rather to provide an orderly approach for identifying and discussing differences. If stakeholders are willing to negotiate and seek common ground, adaptive management can provide a process for collaborative discussions and learning, both among stakeholders and among stakeholders and scientists. Thus, properly executed, adaptive management can provide a process for resolving disputes, as well as social learning of environmental, economic, and other systems.

There is a need to engage and strengthen local communities and other civil society structures involved in the HDRP, more so than currently exists.

9.3 Stakeholder satisfaction

Effective adaptive management requires the participation of multiple state agencies, including DWS, relevant provincial departments, the relevant municipalities, and the relevant public entities (e.g. WRC and research providers).

The stakeholders at the core of the decision making process for system remediation are typically the system owner and the polluter, stakeholders affected by pollution (water users and other ecosystem service beneficiaries) and the regulator (i.e. DWS). In addition, other stakeholders can also be influential such as:

- System users, workers (possibly unions), visitors,
- Financial community (banks, founders, lenders, insurers),
- Campaigning organisations and local pressure groups,
- Other technical specialists and researchers.

Stakeholders are expected to have their own perspectives, priorities, concerns and ambitions regarding the Dam. The most appropriate remedial actions would have to offer a weighted balance between meeting priorities and needs.

9.4 Municipalities

Hartbeespoort Dam is in the upper catchment of the Crocodile (West) River and drains Johannesburg's northern catchment as well as southern Tshwane. This presents a number of challenges, amongst which are:

- The fact that there are different institutions and authorities impacting on the water resources in ways that affect the quality, quantity and the runoff rate of water.
- The capacity, ability and political will to implement or enforce their by-laws and the effluent standards of the Department of Water and Sanitation.
- The difficulty to accurately quantify impacts of the HDRP within the hydraulically complex and changing upstream catchment.
- The lack of an integrated model to effectively integrate the physical, chemical and biological relationships, so assisting prediction of effects.

The report on the waste discharge charge system (van Veelen, 2013) gives a thorough picture of the sources of P pollution in the catchment. The two main point sources are from the Ekurhuleni and Tshwane municipalities and the main non-point source is from poor management of the sewer systems in the catchment (overflows from non-functional pump stations and blocked sewers).

In response to Parliamentary question No 223 of 28 February 2014, Analysis of inorganic variables of water drawn from the Crocodile by the Brits water treatment plant show most of the variables to be within the specified ranges. One of the samples for NO_3-NO_2 was very high (302 mg/ℓ-maximum safe level of adults – 20 mg/ℓ; for children 10 mg/ℓ) and one of the samples showed very low pH (2.8-Severe danger of health effects due to dissolved toxic metal ions. Water tastes sour). Otherwise the parameters given were within specification. Microbiological quality was not given (DWAF, 1996).

What was not monitored was the presence or absence of cyanobacterial metabolites and toxins. Exposure to these has been shown to have deleterious effects on human health.

9.5 Irrigation board

The Hartbeespoort Irrigation Scheme manager reported that he does not attend any meetings apart from those with the DWS as farmers are sensitive about communication with the media. The high level of nutrients is not a problem to the farmers on the irrigation scheme. Other aspects of the water quality are, however, a problem from three different causes.

Firstly, the algal and microbiological quality of the water is such that the farmers irrigate the crops destined for fresh produce (tomatoes, lettuce, spinach, etc.) with borehole water for at least a week before harvest in order to clear any residue of dam water from the crop, The large retail outlets for fresh produce are very sensitive about the quality of the produce which goes onto their shelves and if the quality is not good enough they will stop taking the crop. This would be a severe loss to the local economy, both in terms of income into the community as well as in terms of the number of people employed in the area.

Secondly, the excessive levels of Mg and Na in the water cause certain soils to form a hard crust when they dry out. The black soils (60% of the Hartbeespoort irrigation scheme) are not a problem but the red and the sandy soils are. Crops such as maize and soya beans are left on the land to dry out before harvest. While this is not a problem with maize, the hard crust makes the efficient harvesting of soya beans a problem, and the crop may be damaged in the process, reducing the return to the farmer. This problem extends down the river and has been reported by farmers from the Thabazimbi District (see also http://www.advancednutrients.co.za/news2.html).

Thirdly, there is a vigorous growth of the filamentous alga *Cladophora* in the canals. In the irrigation canals these filaments may grow to several metres long and they restrict the water flow during the summer when the water demand by the farmers is highest. At the time of the interview the canals could only deliver water at 30% below their design capacity which constrains the capacity of the farmers to use their farms to their full potential.

Each of these three impacts of the water quality has implications for the farmers. Tobacco used to be grown on this irrigation scheme, but can no longer be grown as a result of the salinity, particularly the chloride levels. Smoking tobacco that has been irrigated with water with a high chloride content gives the smoker the taste of chlorine which is unpleasant and unacceptable (Barry Blair, retired director, Kutsaga tobacco research station, Zimbabwe; pers. comm.).

9.6 Mining

We interviewed the person in charge of water for Anglo American. Currently, Anglo's platinum mines in the area are on the market but Anglo will keep the smelters.

Currently, Anglo American mines are using potable water from the Rand Water supply to Rustenburg for their operations. Anglo has approached DWS to give the mines a direct pipeline from the river but have not received a response from DWS, effectively excluding them from the use of river water. Also currently, there are communities in the Rustenburg area which are without water for up to 3 days per week. Provision of the requested pipeline from the river would free up the potable water supply from Rand Water for provision to these communities. Due to the recent history of the area the platinum mining industry cannot afford to build the pipeline itself and will probably not be able to afford the cost for some time into the future.

The water quality from the dam *per se* is not expected to be a problem although they would need to test the water in the process. One imperative is that the water has no suspended solids. All algae and inorganic TSS would need to be removed before the water could be used in the process. They would employ DAF technology to do this.

9.7 Conclusions

We propose that a stakeholder forum be established. Membership should be carefully considered within an appropriately structured sub-committees system according to the mandate represented by the stakeholders. This does not mean any stakeholder gets excluded, but rather that there is balance of representation with respect to ecosystem services and system priorities.

Moreover, the stakeholder forum must be appropriately constituted. The DEA protocols that exist for constituting and governing environmental management committees provide appropriate precedent for this.

10 Value for money assessment

10.1 Purpose of this Chapter

The Value for Money (VFM) case of the HRDP is assessed in this chapter, but also elsewhere in this report, in a number of ways. In order to explain this, it is important to first define the VFM concept.

National Treasury maintains that proper and successful government procurement has to adhere to certain core principles of behaviour, which are termed the Five Pillars of Procurement. National Treasury specifically refers to these as “pillars” because “if any one of them is broken the procurement system falls down”. The Five Pillars are:

- Value for Money
- Open and Effective Competition
- Ethics and Fair Dealing
- Accountability and Reporting
- Equity.

National Treasury provides Guidelines to address these Five Pillars and prescribe a minimum set of standards for each. The Guidelines are supplemented by individual Accounting Officer's Procurement Procedures issued under the general authority contained in the Public *Finance Management Act, 1999.*

Value for Money is an essential test against which Rand Water and DWS have to justify procurement outcomes. Best value for money means the best available outcomes when all relevant costs and benefits over the procurement cycle are considered. The Guidelines recognise that price alone is often not a reliable indicator and the lowest price is not necessarily equivalent to best Value for Money.

The procurement function itself must also provide value for money and must be carried out in a cost-effective way. Procurement organisations, whether centrally located or devolved to individual departments, should:

- avoid any unnecessary costs and delays for themselves or suppliers;
- monitor the supply arrangements and reconsider them if they cease to provide the expected benefits; and
- ensure continuous improvement in the efficiency of internal processes and systems.

The National Treasury VFM definition is essentially limited to the procurement function itself, whereas the common definition of VFM suggests a wider scope. For this reason it is also valuable to consider VFM definition applied in literature[10], where VFM is a concept used to assess whether or not an organisation or program has obtained the maximum benefit from the goods and services it both acquires and provides, within the resources available to it. This definition expands the scope of VFM beyond the procurement process to include effectiveness, achieving program goals. Judging effectiveness of the

[10] http://www.admin.cam.ac.uk/offices/secretariat/vfm/guide.html

HDRP is a largely a technical matter, and has been dealt with in chapter 7 above. In addition, clarification of objectives, detailed planning, openness and transparency of process, compliance with statutes and regulations, and risk assessment in all management processes are of importance. Much of these aspects have been dealt with throughout various chapters of this report, and thus the VFM assessment is not limited to this chapter only.

This chapter is limited to a VFM assessment of the budgets and expenditure of the HDRP. We received detailed financial statements from Rand Water, covering the life-cycle of the project. This provided the basis for the analysis to follow.

10.2 Overview of expenditure against business plan

Detailed financial reconciliation was done on all business plans and actual expenditure incurred against the progress report dated December 2012.

Comparison of the business plan budgets and actual spending reveals that actual expenditure was far less that the proposed budget amounts, with a total budget of R504 530 307 and actual expenditure for the same period total of R150 186 939.08.

The history of expenditure (Figure 10-1) shows a rapid increase from the 2006/2007 to the 2008/2009 financial years. Only in 2008/2009 financial year the actual spending increased dramatically, with the most expenditure incurred in 2013/2014 financial year that totals to R28 331 664.83.

There are some differences between actual spending and the progress report amounts; this is due to the progress report timeframe ending December 2012 and actual expenses timeframe ending 2013/2014 financial year. But it can be concluded that actual spending and progress report information are the same (see Table 10-1).

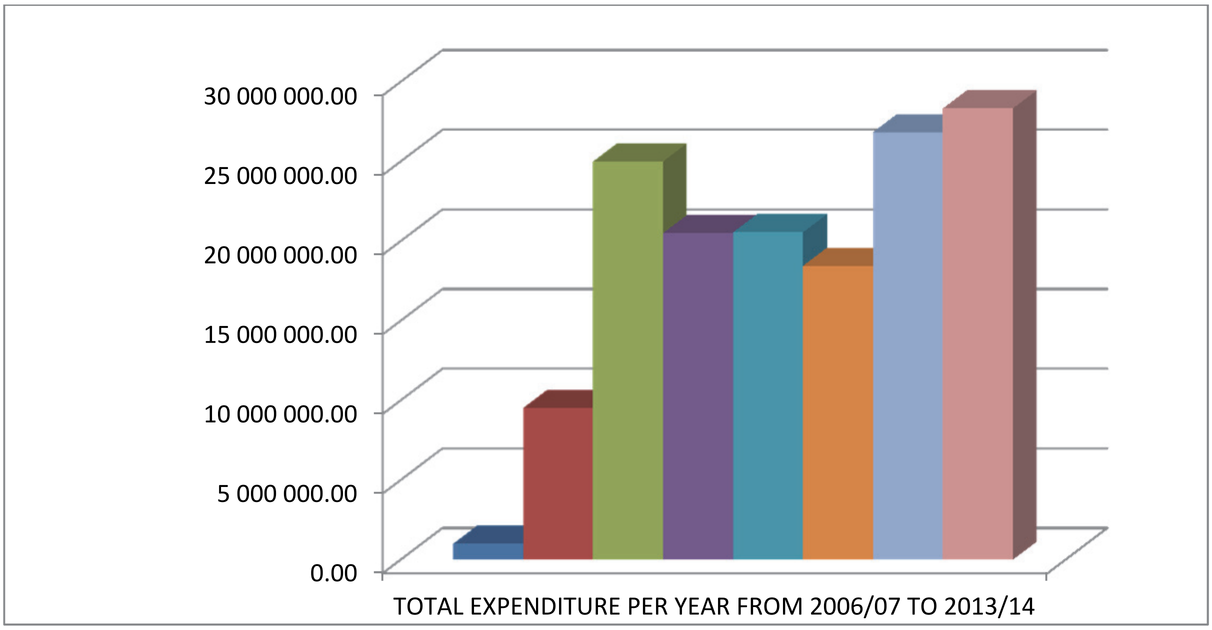


Figure 10-1. Total actual annual expenditure over the life cycle of the project.

(Each bar of Figure 10-1 represents expenditure for the year in question.)

10.3 Analysis of expenditure against business plan

A detailed analysis of the actual expenditure against the business plan reveals a number of key matters.

Firstly, there is consistently a very large discrepancy between budget and actual expenditure.

Secondly, some expenditure items are reported against incorrect budget items. This is not helpful for achieving effectiveness in VFM terms. The program has an extremely large overhead component, and this needs to be better balanced in Phase 2. In addition, a number of key budget items were under-expended upon, and needs to receive priority in Phase 2.

By far the largest expenditure was on Biomass and Debris Harvesting, i.e. focusing on the aesthetic component of remediation.

According to the progress report (December 2012), the harvesting of the biomass and debris was done manually and this amount included removal of algae. Total expenditure during amounted to R45 692 874.19. This makes up 30% of total expenditure for the period.

The expenditure pattern for this item followed a similar escalation trend to that of the overall expenditure, starting slowly with the highest amount spent in 2013/2014 financial year amounting to R8 916 367.33 (Figure 10-2).

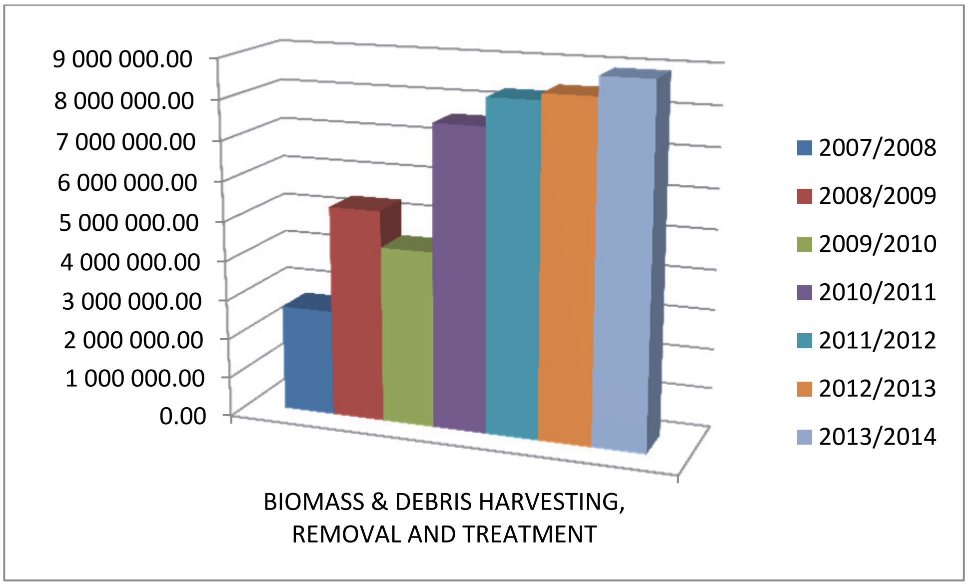


Figure 10-2. Biomass and debris harvesting actual annual expenditure over the life cycle of the project.

Analysing the total expenditure excluding Biomass and Debris Harvesting, an important trend in the expenditure becomes evident. Year on year, the administration costs far exceed the operational costs, indicating a high focus on aesthetic interventions combined with large overhead costs. For the entire Phase 1 period administration costs amounted to R71 096 831.05 and operational expenditure amounted to R33 397 233.84. This essentially means that administration costs make up 68% of total expenditure over the period (Figure 10-3).

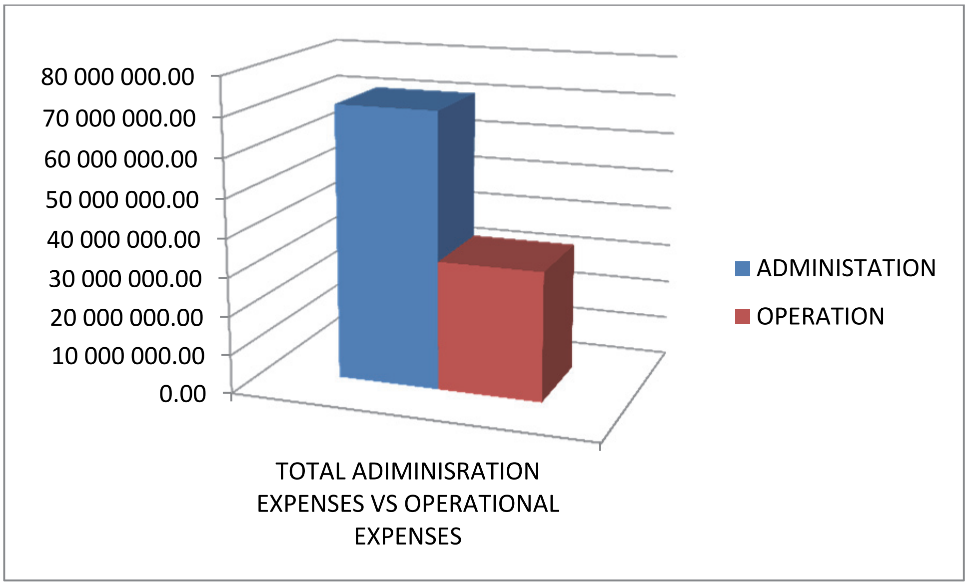


Figure 10-3. Administration versus operational expenditure

Table 10-1 below sets out a detailed comparison of expenditure and budgeted amounts, per item code, as listed in the business plans and progress report dated December 2012.

The following key observations are of interest and are discussed below.

Firstly there are a few budgeted items against which no expenses were incurred. For instance, in the proposed business plans and budget, Control and Removal of Algae was budgeted for an amount of R9 400 000 with no expenditure incurred. Similarly, a Shoreline Vegetation budget of R4 025 000 exists against which no expenditure was incurred. However, the progress report (December 2012) states as follows: "*Biomass (algae and hyacinths) together with litter and debris removal is an on-going activity to address the immediate symptoms of eutrophication, ….*" *which means that the expenditure is allocated with the "Biomass" budget item and "A total of 8 530 m^2 of shoreline remediation was conducted at Kurperoord, Ifafi and Kommandonek through the construction of a jetty filtration berm as well as low water mark berm construction with different stabilisation methodologies plus vegetation with different shoreline and wetland species.*" This means that this expense is listed in another budget item.

The business plan budgeted for a number of "Information communication and knowledge centres" but these have not yet been established. These are listed below:

- Fish & Foodweb restructuring knowledge hub
- Shoreline & Floating wetlands knowledge hub
- Sustainable development knowledge hub
- Waste minimisation knowledge hub

- Aquaculture knowledge hub

Other important budgeted amounts that have been under-expended upon include:

- Waste minimisation and recycling, budgeted R4 384 000.00 and spent R88 920.50.
- Storm water management & rainwater harvesting, budgeted R1 176 000.00 and spent Nil.
- Nutrient management, budgeted R645 070.00 and spent R50 138.00.
- Waste Discharge Charge System Implementation budgeted, R2 261 000.00 and spent R1 200.00.

Table 10-1. Comparison of budget and actual expenditure.

DESCRIPTION	BUDGET (R)	ACTUAL (R)	PROGRESS REPORT (R)
Development of business plan	780 000.00		
PROGRAMME CO-ORDINATION			
Project Coordinating office	8 691 395.00	4 799 918.39	
Support to IGF & Magalies-Cradle Biosphere	209 000.00		
DWA REGIONAL OFFICE SUPPORT			
Office support	14 330 000.00	1 842 975.31	
Steering Committee & Development of IGF	1 150 700.00	350 998.66	
Documentation and Reporting	3 398 000.00	1 641 717.75	
Internal Audit		284 342.40	
Travel		384 719.89	
Refreshments		22 583.51	
Conference		28 435.86	
Ablution Block Refurbishment		241 794.00	
Stationary		3 403.39	
Promotional Gifts		22 560.00	
Time allocation		221 920.00	
RAND WATER IMPLEMENTATION			
Rand Water Implementation & Contingencies	11 828 655.00	3 224 654.86	
Office support		7 769 626.84	
SHEQ Compliance	8 340 000.00	724 190.09	724 190.09
Policy and Legal Issues	1 957 500.00	414 260.23	414 260.23
Bhika Incorporated-Legal consulting		404 638.02	
Assets	791 000.00	3 063 520.03	
Engineering Services	2 540 777.50	933 044.57	933 044.57
Research & Development	2 930 950.00	145 879.41	
Change management order		501 169.00	
Eco Tourism Africa Trust-Consulting Fees		304 852.77	
Zitholele Consulting-Consulting Fees		371 921.56	
Fund raising and managing			
PROGRAMME CONTROL SUB PROGRAMMES			
Office support	14 758 468.00		
TRANSFORMATION COMMUNITY DEVELOPMENT			
Training, Capacity Building and Skills Transfer	968 520.00	10 567.50	
SMME Development	994 000.00		
SUPPORT SUB PROGRAMMES			
Communication and Awareness	16 099 070.00	4 370 771.21	
Information Management	15 506 575.00	13 747 204.90	12 874 212.98
OPERATION AND MANAGEMENT SUB PROGRAMMES			
Develop Resource Management Plan RMP	2 550 000.00	3 879 978.33	3 879 978.33
Foodweb monitoring	14 143 400.00	5 368 854.27	4 475 024.21
SMME Fish Harvesting & Scientific removal	15 644 000.00	5 817 105.97	2 126 292.15
Madibeng Conservancy Holdings Fish harvest company		275 406.67	
Fish Health and Edibility	1 241 000.00	1 036 368.20	749 004.20
Biomass & Debris Harvesting, Removal and Treatment	31 905 000.00	45 692 874.42	28 000 000.00
Biomass Establishment	13 853 500.00	11 893 814.19	6 467 193.60
Sediment Management	59 912 670.00	7 100 555.73	
ICC operations	12 914 445.00	4 124 889.97	
Control and removal of algae	9 400 000.00		
Private and Corporate Support and Participation	2 461 000.00	2 686 140.57	2 003 205.92
Sample analysis		94 219.00	
Shoreline vegetation	4 025 000.00		

DESCRIPTION	BUDGET (R)	ACTUAL (R)	PROGRESS REPORT (R)
INFORMATION COMMUNICATION & KNOWLEDGE CENTRES			
Information and communication centre	62 969 000.00	4 276 750.42	2 688 945.87
Fish & Foodweb Restructuring knowledge hub	150 000.00		
Shoreline & Floating wetlands knowledge hub	12 599 000.00		
Sustainable development knowledge hub	6 531 000.00		
Waste minimisation knowledge hub	320 000.00		
Recreational Access and Use Management	23 064 349.00	462 689.11	462 689.11
Ifafi Wetland knowledge hub	1 282 000.00	234 639.65	
Aquaculture knowledge hub	8 499 000.00		
Vermiculture knowledge hub	1 611 000.00	647 369.92	
COMPLIANCE AND ENFORCEMENT			
Water Use Authorisations from Dam Basin and Catchment	5 302 900.00	2 368 825.32	2 368 825.32
Operational Best Practices		1 509 637.41	1 509 637.41
WUA for HBPD Catchment	7 057 900.00	679 814.18	
WUA for Croc (West) Marico Catchment	8 196 900.00	575 541.65	
Water Use Efficiency	350 000.00		
Waste Minimisation & Recycling	4 384 000.00	88 920.50	
Wetlands and instream habitat	4 623 750.00	1 420 716.91	
Stormwater Management & rainwater Harvesting	1 176 000.00		
Integrated Monitoring Programme	13 606 950.00	3 074 664.53	3 074 664.53
Waste Discharge Charge System Implementation	2 261 000.00	1 200.00	
CATCHMENT STRATEGIES			
Nutrient Management	645 070.00	50 138.00	
Pre-impoundment, river diversion and treatment	14 599 000.00	459 452.62	
Instream and Stormwater Litter Trap	4 612 000.00	251 308.10	
Downstream Eutrophication Control	1 135 000.00		
Artlure-Fishing in support to WfGD	1 416 000.00	165 669.38	
Aquaculture Hub	44 813 862.50	117 723.91	
TOTAL	504 530 307.00	150 186 939.08	72 751 168.52
Contingencies allowance	9 731 174.95		
	514 261 481.95		

10.4 Job creation

National Treasury's general procurement guidelines state about "equity" that "*This fifth pillar is vital to public sector procurement in South Africa. It ensures that government is committed to economic growth by implementing measures to support industry generally, and specially to advance the development of Small, Medium and Micro Enterprises and Historically Disadvantaged Individuals*." In accordance with the Reconstruction and Development Programme, SMMEs and HDIs need to play a bigger role in the economy. Greater participation in the economy and more diversified representation of blacks and gender in ownership is essential."

The HDRP has a commendable provision for this under the heading "Transformation community development", the total amount budgeted was R1 962 520. The Transformation community development heading has been proposed in the business plan and budget since the 2010/2011 financial year.

The following expenses are listed:

- “Training Capacity Building and Skills Transfer” amount to R10 567.50 spent for the period
- “SMME development” Nil spent for the period.
- Under the heading “Operation and Management Sub Programmes”, another SMME development item was included in the proposed business plans and budget since 2010/2011 financial year: “SMME Fish Harvesting & Scientific removal” total expenditure for the period: R5 817 105.97.
- An additional payment to “Madibeng Conservancy Holdings Fish harvest company” was listed on the detailed expenditure report amounting to R275 406.67. It is not clear why this amount was not included in the heading expense.

In the December 2012 report mention was made to Metsi a Me Work Creation:

2007/2008: Full Time 40; Temporary 20

2008/2009: Full Time 60; Temporary 30

2009/2010: Full Time 75; Temporary 20

2010/2011: Full Time 90; Temporary 15

2011/2012: Full Time 87; Temporary 20

2012/2013: Full Time 85; Temporary 33

2008/09: All; Roodeplaat Dam 90.

It is not clear whether job creation targets had been set nor whether they were met.

Moreover, the levels of job creation is extremely low for a programme of this large budget.

We propose that the job creation aspect of the HDRP is planned and implemented in more detail in Phase 2.

10.5 Asset management

The progress report (December 2012) states: “*All assets which have been procured through the Harties Metsi a Me programme have been photographed, tagged, and included in the asset database for the programme. Approximately 2 255 various types of assets have been identified and captured in this manner. The information on the database includes, the type of asset, its reference number in terms of the asset register, date of purchase, invoice number, value of asset, supplier, responsible person, location, and replacement value*.”

In spite of this we found discrepancies in the financial statements, for instance, there is a Solarbee bought for R1 811 663.96 in the 2008/2009 financial year, which is apparently not listed as an asset. Many similar other examples exist in the financial statements.

10.6 External fund raising

Business plan 2006/2007 envisaged that "Funding is the key performance indicator in this project and a dedicated activity must be undertaken to raise funds for this project." It proposed that a task team of interested people be established to conduct the fund raising. The progress report (December 2012) states that the following donations and other income received:

- City of Lahti (North South Cooperation) = R133 000
- Elands platinum mine (committed amount R915 000.00) = R315 000
- Old Mutual = R21 000
- Fish Sales = R334 000

These amounts are very low and we recommend that the external fund raising effort be significantly improved.

10.7 Rand Water Internal Audit 2009

Rand Water conducted an internal audit of the HDRP and highlights a number of high risk areas in the HDRP[11]. The internal audit report was limited to transactions that had taken place between 1 April 2008 and 31 March 2009 (Rand Water Internal Audit No. 678/09).

The findings of the audit report were presented in November 2009**.** In this report 59% of the findings were described as "High Risk" areas. It is not clear whether these audit findings were addressed since 2009. DWS commissioned a forensic audit, reportedly by Gobodo Forensic Investigative Accounting, but this document was not made available for this Review.

Key high risk findings by the Internal Auditors were as follows:

1. Department of Water Affairs (sponsor) is assuming the duties of the implementing agent (Rand Water).

   This is contrary to the Implementing agent agreement of 2012 which states:

- Implementing Agent (Rand Water) accepts responsibility for coordinating and managing the implementation of the activities.
- Implementing Agent will keep records of all matters.
- Implementing Agent will appoint contractors, consultants and service providers.
- Implementing Agent shall pay contractors, consultants or service providers from the budget.

2. Inadequate procurement process of project. There was no evidence of Project Coordinating Office approval of quotations.
3. No contracts for all the service providers. No specified responsibilities, fees, payment of business expenses and intellectual property ownership were agreed upon.

---

[11] The appointment letter was signed on the 13th of October 2009 by Mr M (Mike) Ramukumba (who also led the internal audit), Mr Mandla Xulu and Mr Sameer Morar

4. Inadequate approval of invoices by the Project Coordinating Office. Some invoices were approved without proper supporting documents attached.
5. Expenses exceeding budget estimates: In terms of clause 5.3 of the implementing agent agreement, the implementing agent shall not incur expenses exceeding the budget estimates contained within the approved Business Plan unless prior written approval has been obtained from the Department. Furthermore clause 5.9 states that prior written consent shall be obtained from the Department for all decisions that have financial implications and which have not been implicitly contemplated.
6. Lack of evidence of review and approval of invoices by Project Co-ordinating Office. Infringement of Public Finance Management Act. Sec 57 (c).
7. Lack of evidence of pre-approval of overtime. Infringement of Basic Conditions of Employment Act. Sec 10.
8. Over-reliance on progress report submitted by service providers. No evidence could be found that site visits were conducted to verify progress.
9. Inadequate and incomplete fixed assets register.
10. Inadequate procedure to evaluate performance of service providers. No evidence could be found that service providers' performance is evaluated.

10.8 Conclusions

In the absence of any evidence that the internal audit findings were addressed, and in the context of the budgetary and expenditure problems identified, we recommend a significant improvement in the financial management of the HDRP Phase 2. We propose that a full-time financial officer be appointed and that annual internal audits be conducted.

11 Gap analysis, conclusions and recommendations

11.1 Purpose of this Chapter

The purpose of this chapter is to identify gaps in Phase 1 which should be addressed during Phase 2. There is a need to expand the emphasis from managing the in-dam impacts to managing the influx of nutrients (11.3). There is a need to implement a scientific approach to the management. This should be guided through the development of a system conceptual model that can quantify the physical, chemical and biological relationships of the activities occurring in the catchments and the effect of these on the water quantity and quality of the dam (11.3). Management of the HDRP, when guided by the above model, should demonstrate increased scientific rigour. There is an acute shortage of limnologists in the country (11.9). Over the years there has been a great deal of work done on Hartbeespoort Dam but there is little evidence of this having been taken into account (11.4). Some hypotheses for investigation during Phase 2 are proposed (11.4). The structuring of Phase 2 of the HDRP within the adaptive management framework is recommended (11.5). The monitoring programme should be integral to the adaptive management approach to ensure that the monitoring is focused on the aims of the programme (11.6). An assessment of remediation options needs to be conducted in a structured way in order to implement the most cost-effective options to address the problems (11.7). Capacity building at all levels as well as succession planning need to be worked into the programme to ensure the continuity of the work (11.9 and 11.10). The job creation programme needs to be carefully planned to ensure that it builds capacity while at the same time delivering value for money (11.10). Financial management needs to be improved (11.11). Certain options for innovation are proposed (11.12). This list is not exhaustive.

11.2 Change the key emphasis of the HDRP from managing aesthetics to managing nutrient input

The Dam directly and indirectly supports a diverse local economy and provided that the water quality remains useable it will continue to do so.

Working into the catchment to clean that up is an imperative, but this review recommends that there is justification in continuing with the in-lake interventions. We see that these need to be planned carefully and with an overall goal in mind. These interventions also need to be accurately monitored to see whether they are helping to achieve the goal or not.

The HDRP has focused on aesthetics rather than addressing the increasing ingress of phosphorous into the dam. This is reflected in the vision of the Resource Management Plan.

This has delayed the management decision to address the P load coming into the lake from the catchment, causing the total load into the dam to increase, with the concomitant increase of P stored in the dam.

Phase 2 needs to give more attention to reducing the contributions of nutrients and pollutants from the catchment to the state of the dam.

The focus on the catchment has been addressed in successive business plans but not implemented.

It is essential that Phase 2 focuses on the catchment. There are a number of direct interventions which could be implemented in the catchment in addition to those proposed by van Veelen and Maree (2013 and Appendix 3 and Appendix 4 of this report). Mitchell et al. (2014) and Dr Wilsenach, Dr Jooste and Dr Silberbauer (pers. comm.) all propose upgrading the ecological infrastructure along the water courses in the catchment to provide additional passive treatment capacity for removing nutrients and pollutants. This is being investigated on the Berg River in the Western Cape as a means of improving the quality of the agricultural exports from the region (Dr Wilsenach, pers. comm.).

11.3 Implement a scientific management approach

11.3.1 System conceptual model

There is a need for an system conceptual model that can quantify the physical, chemical and biological relationships of the activities occurring in the catchments and the effect of these on the water quantity and quality of the dam. The development of this model will need to start with existing data and knowledge on the system. It will then be possible to identify the priorities for management. Ideally, it should be developed in such a way that it may be applied to other water bodies as well.

11.3.2 General

- The programme has shown an overall lack of scientific rigour. This makes it impossible to assess the actual impact of each of the interventions. It also means that there is no firm ground which can serve to guide decisions on future interventions. A point of departure of this should be to develop an SCM with associated remediation goals, and linked to and appropriate monitoring program.
- The assumption that the HDRP is responsible for the current state of the dam should be tested in the light of the overall current state of the dam and from the basis of understanding limnological processes likely to occur under the current status quo of the dam.
- Acute shortage of Limnologists-in spite of the application for funding to train limnologists having been put forward.

Over the years there has been a substantial amount of work done on Hartbeespoort Dam and its catchment. Hutchinson et al. (cited in Allanson and Gieskes, 1961) found the lake to be oligotrophic 5 years after construction. By 1959 Cholnoky (cited in Allanson and Gieskes, 1961) described the lake as an oxidation pond for the effluents from Johannesburg. Since then there have been a number of studies funded by the WRC and others with those of the NIWR (1985, for instance) being an important one. The focus of most has been the water quality. Examples of recent studies are Van Veelen (2002), Harding (2004 a, b) and Matowanyika (2010), each of whom worked on the Jukskei River or Impoundment. More recently Van Veelen and Hooghiemstra (2013) have investigated the implementation of the waste discharge charge system in the Hartbeespoort Dam catchment. So there is an extensive literature on the water quality and its remediation on Hartbeespoort Dam.

Research and the implementation of DWS policy and planning on Hartbeespoort Dam and the catchment is ongoing. For instance, Harding and Hart (2013) reported on research examining the top down (fish predation on zooplankton) biomanipulation of lacustrine systems using stable isotopes with Rietvlei Dam as the case study. The species of fish examined were catfish (*Clarias gariepinus*), carp (*Cyprinus carpio*) and canary kurper (*Chetia flaviventris*). While changes in phytoplankton δ^{13} C values were broadly tracked by the zooplankton, the δ^{15} N values differed widely from the zooplankton and indicated that the fish relied mainly on food of benthic origin.

This change in understanding has not been incorporated into the HDRP. The HDRP has had the opportunity to conduct the same analyses in Hartbeespoort but have not done so. Instead there is a debate on the topic as seen in HDRP (2012b, pp vi-xiii). This debate is not going to resolve the issue. Resolution of the issue will come from doing the same analyses as done by Harding and Hart (2013).

There have been no peer reviewed papers from the HDRP. It may be expected that a programme of this size and nature would yield peer reviewed publications (Keto, 2013). Peer reviewed publications provide a reliable measure of the quality of the work undertaken during the programme and also provide the scientific basis for planning and developing interventions for management. The data bank developed during the HDRP may provide the basis for some publications in the future, but someone would need to spend time analysing these data.

There is little evidence that the body of work that has been done on the dam over the years has been taken into account in the implementation of the HDRP.

While phosphorous management in the catchment is covered in the business plans, it appears that this was not prioritized. The integrated monitoring report (HDRP, 2013c) worked into the catchment, but the Phase 1 progress report (HDRP, 2012a) shows an almost exclusive focus on the dam.

Questions that arise which should be addressed during Phase 2 are:

- How is the expected fluctuation in the lake level going to affect the current operating rules of the dam?
- What effect will the fluctuating water levels have on the littoral zone in respect of:-
  - What is the predicted effect on water quality of the drying and rewetting of the sediment? This will require laboratory investigations.
  - How extensive is the seed bank of hyacinth and how will the drying and flooding of the dam affect the seed bank?
  - What effect will the fluctuating water levels have on the vegetation that has established on the littoral zone?
  - What effect will the fluctuating water levels have on the yield of fish from the lake?

- How will the planned water level fluctuation affect the recreational use of the dam, and what, if any, communication with stakeholders will be necessary?

Assumptions, where they are made, need to be explicit. They need to be understood by the people making them and explained so that the audience / readership may assess their validity. They also need to be tested in the most effective way possible using available knowledge.

An underlying assumption through the reports which is largely unquestioned is that the remediation programme is responsible for all the changes that have occurred recently in the lake. Only in the integrated monitoring report (HDRP, 2013a) is this referred to as a possibility that needs to be tested.

For instance, in response to Parliamentary Question 2978 of 26 October 2012, it was reported that 'efforts made by the Department together with Rand Water have improved the water quality of the Hartbeespoort Dam since 2008 after the implementation of the Integrated Biological Remediation Programme (also known as the Harties metsi a Me Programme). This is according to the monitoring results which were obtained through the Integrated Monitoring Programme conducted since the past four years.' While the water quality has improved, the assumption that the HDRP was solely responsible for this improvement remains to be tested. There are other factors at work which could have brought about, or at least contributed to, the observed changes.

11.4 Hypotheses which could be investigated

11.4.1 Stable lake level

The lake level has been stable for approximately 2 decades. This has created conditions which allow for the establishment of a filamentous algal mat as well as rooted macrophytes which compete for the pool of dissolved nutrients and also mitigate against the re-suspension of phosphate-rich sediment. The influence of this on the overall nutrient dynamics of the lake has not been ascertained.

Hypothesis 1 is that the establishment of submerged vegetation in the littoral zone mitigates against the re-suspension of nutrient-rich sediment, so reducing the level on nutrient in the water body.

Hypothesis 2 is that the establishment of submerged vegetation in the littoral zone effectively sequesters nutrients from the water body, so reducing the **likelihood** of algal blooms.

11.4.2 Projected lake level fluctuation

A question that arises is how is the lake going to respond when the water level is drawn down for extended periods each year, scheduled to begin in 2017, when water from Hartbeespoort is transferred to the Lephalale area?

Hypothesis: the P in the exposed and re-wetted sediment will be temporarily immobilized;

Hypothesis: The pollutants in the exposed and re-wetted sediment will be mobilized;

Hypothesis: the fluctuation in water level will stimulate germination of hyacinth seeds in the seedbank in the exposed and re-wetted sediment;

11.4.3 Dredging

Hypothesis: Pollutants (including heavy metals) will be released into the water column by the dredging process;

Hypothesis: While the zones of sediment deposition in the dam will be targeted by the dredging operations, there is a substantial accumulation of P elsewhere in the dam as a result of the rain of dead algae that has occurred over the years. This will be available for release during stratification of the water body.

11.4.4 Energy pathway

Hypothesis: The energy pathway shifts from phytoplankton – zooplankton – fish to phytoplankton – decomposers in algal-dominated systems.

11.5 Implement an adaptive management approach

Remediation of eutrophic or hypertrophic water bodies is a problem that cannot be solved by a single technology. It requires an approach which integrates a number of technologies both in the catchment and in the water body. Phase 1 implemented a number of interventions, mostly biological, in the dam itself, but the phosphorous load into the dam continued to increase at a rate greater than the interventions implemented can cope with.

If the problem is to be solved sustainably then it will be necessary to reduce the load of phosphorous into the dam. Once this has been achieved the water quality of the dam will improve. This will not be a quick process.

11.6 Implement a dedicated monitoring system

The monitoring programme should be planned and implemented within the adaptive management programme and should be designed to address the needs of the HDRP Phase 2. This will ensure that the monitoring programme is given the correct weighting in the programme and it will ensure that records are kept.

11.7 Remediation options assessment system required

This should form part of the system conceptual model and should be considered in the adaptive management framework, using rigorous selection techniques. It is common cause that there is no one optimal solution for a large scale remediation problem, and this is especially so for the HDRP. Risk management therefore has a dominant role in adaptive management decision making for managing remediation as it provides a rational framework for evaluating problems and determining the availability of solutions. It is not, however, the only decision criterion. The drivers for a remediation project, the boundaries limiting what can be done on a system, the suitability / feasibility of available remediation options, the views of different stakeholders and the wider effects of the remediation work should all influence the choice of approach. An appraisal of costs versus benefits can be a useful approach to integrating this wide range of considerations.

11.8 Establish a technical governance committee

Successful adaptive management is premised on good science, and involving independent experts and thus highly dependent upon good technical governance. In addition, it requires a formal approach to assessing remediation options; as well as an appropriate monitoring program, that follows from the adaptive management approach. It is in the nature of complex system management and multiple stakeholder involvement, that consensus is not easy to achieve. However, the WRC has developed excellent methodology and governance systems for managing science, research and development of complex ecological systems. Thus we strongly recommend that the WRC become involved in the HDRP Phase 2, and play a key role in the design of the SAM approach and the various supporting initiatives.

11.9 Capacity building program required

There is an acute shortage of limnologists in the country, especially those with the expertise to manage eutrophication. There is also a need for specialists in other disciplines related to impoundment management and the management of the complex socio-ecological systems that have developed in the urban, industrial and other economic hubs in the country.

The focus of the HDRP is on Hartbeespoort Dam, but there are other dams that need the same attention. It is important that HR capacity is developed not only for succession planning but also to address the problem on other dams in South Africa, not all of which are in the Gauteng region.

11.10 Job creation program required

A job creation programme needs to be developed. Examples of similar programmes may be seen in the ‘Working for’ programmes. The programmes need to define the different skills required as well as the approximate number of people with each skill. In this way it will be possible to build teams with the correct balance of skills to work on each of the sites where remediation is taking place.

11.11 Improve the financial management of the program

The project has not published annual reports with budgets and audited statements against which the business plans may be assessed. In addition, in the absence of any evidence that the internal audit findings were addressed, and in the context of the budgetary and expenditure problems identified, we recommend a significant improvement in the financial management of the HDRP Phase 2. We propose that a full-time financial officer be appointed and that annual internal audits be conducted.

Establish an appropriately constituted stakeholder forum

We propose that a stakeholder forum be established. Membership should be carefully considered within an appropriately structured sub-committees system according to the mandate represented by the stakeholders. This does not mean any stakeholder gets excluded, but rather that there is balance of representation with respect to ecosystem services and system priorities. Moreover, the stakeholder forum must be appropriately constituted. The DEA protocols that exist for constituting and governing environmental management committees provide appropriate precedent for this.

11.12 Innovation

There is the opportunity to develop products that will add value.

For instance, the dredged material is already being used as a phosphorous-rich fertilizer in certain specific applications. Can the phosphorous be recovered and developed into a high value commercial product? One option may be to recover the P either at source at the sewage works or at the dam inflow. The latter would offer the opportunity to recover more P as at the moment approximately ½ the P load into Hartbeespoort Dam is from diffuse sources. The assumption is that the proportion of P from diffuse sources entering other impoundments is similar. The P may be precipitated chemically using an iron salt and then recovered from the precipitated sludge. One option to be tested is to use AMD as the source of iron to precipitate the P. This would be cheaper than setting up a production facility to produce the iron salt for the process. It does, however, need to be tested.

Currently water hyacinth biomass is being used to make compost. There is opportunity to train people to develop microenterprises producing compost for sale to local estates. Elsewhere in the world water hyacinth biomass is being used as the raw material for products such as high quality furniture, basket-ware, biodegradable plastic or briquettes. The development of similar opportunities for the beneficiation of hyacinth biomass would provide opportunity for cottage industries to develop and provide employment opportunities for more people around this and other dams where hyacinth is a problem.

Similarly, the fishery lends itself to the development of artisanal fisheries on this and other dams.

Is there opportunity for the production of fine chemicals from the algal biomass? For instance, *Spirulina*, a blue-green alga, contains certain fine chemicals valued by the health food market. As another example, Algal or hyacinth biomass may be used for biofuel.

There are other avenues of innovation which could be profitable pursued.

12 References

Anderies J, Janssen M and Ostrom E. 2004. A framework to analyse the robustness of social-ecological systems from an institutional perspective. Ecology and Society 9(1):18 [online]URL: http://www.ecologyandsociety.org/vol9/iss1/art18

Allanson BR and JMTM Gieskes, 1961. An Introduction to the Limnology of Hartbeespoort Dam with Special Reference to the Effect of Industrial and Domestic Pollution. Hydrobiologia 18: 77-94.

Anneville O and JP Pelletier, 2000. Recovery of Lake Geneva from eutrophication: quantitative response of phytoplankton. Arch. Hydrobiol. 148 (4) 607-624.

Ashton, PJ., 2010. Demise of the Nile crocodile (Crocodylus niloticus) as a keystone species for aquatic ecosystem conservation in South Africa: the case of the Olifants River. Aquatic Conservation: Marine and Freshwater Ecosystems, Vol 20(5), pp 489-493

Bal, M, undated. Understanding Mansagar Lake Governance using Social-Ecological Systems (SES) Framework. PhD Scholar, FSW-IHS, Erasmus University, Rotterdam, The Netherlands

Barnard S, CE van Ginkel, LZ Coetzee and S Booyens, 2013. Implementation of the rule based agent for *Microcystis* in Rietvlei Dam. WRC report No. 1962/1/13.

Beklioglu M, M Meerfhoff, M Søndergaard and E Jeppesen, 2011. Eutrophication and Restoration of Shallow Lakes from a Cold Temperate to a Warm Mediterranean and a (Sub)Tropical Climate. Chapter 4 in AA. Ansari, SS Gill, GR Lanza and W Rast (Eds.). Eutrophication: Causes, Consequences and Control. Springer Science 401 pages.

Biggs HC and KH Rogers, 2003. An adaptive system to link science, monitoring and management in practice. Chapter 4 in The Kruger Experience: ecology and management of savannah heterogeneity. Pages 59-82. Island Press. 520 pages.

Bornman RMS; Van Vuren JHJ; Bouwman HH; de Jager TC; Genthe BB; Barnhoorn IEJ, 2007. Endocrine disruptive activity and the potential health risk in the Rietvlei nature reserve. WRC Report No, 1505/3/07. Published by the Water Research Commission, Pretoria.

Byrne M; Hill JM; Robertson M; King A; Katembo N; Wilson J; Brudvig R; Fisher J; Jadhav A, 2010. Development of an integrated management plan for water hyacinth control, combining biological control, herbicidal control and nutrient control, tailored to the climatic regions of South Africa. WRC report TT 454-10

Chutter. F M & J N Rossouw (1992). The management of phosphate concentrations and algae in Hartbeespoort Dam. WRC Report No 289/1/91. xii + 37 pp.

Dabrowski, J.M. 2014. Applying SWAT to predict ortho-phosphate loads and trophic status in four reservoirs in the upper Olifants catchment, South Africa. Hydrology and Earth System Sciences, vol. 18, pp 2629-2643

Dabrowski, J.M and De Klerk, L.P. 2013. An assessment of the impact of different land use activities on water quality in the upper Olifants River catchment. Water SA, vol. 39(2), pp 231-244

Department of Water Affairs, South Africa, August 2012. **CLASSIFICATION OF SIGNIFICANT WATER RESOURCES IN THE MOKOLO AND MATLABAS CATCHMENTS: LIMPOPO WATER MANAGEMENT AREA (WMA) AND CROCODILE (WEST) AND MARICO WMA: WP 10506:** Integrated Units of Analysis (IUA) Delineation Report. Report No: *RDM/WMA1,3/00/CON/CLA/0212*

Directorate Water Resource Classification.

DWA, 1986. Management of the water resources of the Republic of South Africa. Published by the Department of Water Affairs, Pretoria.

DWAF, 1996. South African Water Quality Guidelines: Volume 1 Domestic Use. 2nd Edition. Department of Water Affairs and Forestry.

DWA. 2009. *Water for Growth and Development (Version 7)*. Pretoria: Department of Water Affairs and Forestry.

DWA, 2013. "Assessment of the Water quantity and Quality of the Witwatersrand Mine Voids",

DWS, 2014. DWS, National Water Act, 1998. Proposed classes of water resources for the catchments of the Crocodile (West), Marico, Mokolo and Matlabas. Government Gazette, 19 September 2014 No. 37999. Notice 818 OF 2014.

Earle A, G Lungu and D Malzbender, 2008. Mapping of Integrity and Accountability in Water Activities and Relevant Capacities in the SADC-Region. Report commissioned by UNDP Water Governance Facility at SIWI, WaterNet and Cap-Net Stockholm,

Funtowicz S and Ravetz J. 2008. Post-Normal Science. Encyclopaedia of Earth. http://www.eoearth.org/article/Post-Normal_Science

Genkai-Kato M and SR Carpenter 2005. Eutrophication due to phosphorus recycling in relation to lake morphometry, temperature, and macrophytes. Ecology 86:210-219.

Graham M, J Blignaut, L de Villiers, D Mostert, X Sibande, S Gebremedhin, W Harding, N Rossouw, S Freese, S Ferrer and M Browne, 2012. Development of a generic model to assess the costs associated with eutrophication. WRC Report No. 1568/1/12

Gray NF, 1997. Environmental impact and remediation of acid mine drainage: a management problem. Environmental Geology 30 (1/2) March 1997

Ground truth trekking (viewed May 2015) http://www.groundtruthtrekking.org/Issues/MetalsMining/AcidMineDrainage.html

Golder Associates, 2013. Western Basin AMD Decant/ Treatment Scenarios", WRPM Analysis, Golder Associates

HARDING WR and HART RC (2013) Foodweb structure in the hypertrophic Rietvlei Dam based on stable isotope analysis: Specific and general implications for reservoir biomanipulation. *Water SA* **39** 615-616.

Harding WR, JA Thornton, G Steyn, J Panuska and IR Morrison, 2004a. Hartbeespoort Dam Remediation Project (Phase 1) Volume I Action Plan. Department of Agriculture, Conservation, Environment and Tourism, North West Province.

Harding WR, JA Thornton, G Steyn, J Panuska and IR Morrison, 2004b. Hartbeespoort Dam Remediation Project (Phase 1) Volume 2 Action Plan. Department of Agriculture, Conservation, Environment and Tourism, North West Province. Harding WR, RC Hart and LG Muller, 2012. Elucidation of foodweb interactions in South African Reservoirs using stable isotopes. WRC Report No. 1918/1/12.

Harding WR, 2008. The determination of annual phosphorous loading limits for South Africa dams. WRC report No. 1687/1/08

Harding WR, 2010. Eutrophication of impounded water resources in South Africa: descent into crisis. Paper presented at the WRC-convened workshop on water resources and water quality entitled "Water quality : are we serious enough? the need for a change". WISA Conference, Durban.

Harding WR, 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.

Harding WR and B Paxton, 2001. Cyanobacteria in South Africa: a review. WRC Report No. TT 153/2001.

Hart RC, 2006. Food web (bio-)manipulation of South African reservoirs – viable eutrophication management prospect or illusory pipe dream? A reflective commentary and position paper. Water SA 32 (4) 567-575.

Hart RC and WR Harding (2015). The role of fish in phosphorus budget dynamics of some SA reservoirs and the effectiveness of 'bottom up' biomanipulation in reducing phosphorus in nutrient-polluted systems. Water SA 41 (4): 432-440.

HDRP, 2011. Phase II Business Plan: full Scale Implementation and Extension

HDRP, 2012a. Hartbeespoort Dam Integrated biological remediation programme: Consolidated progress report: Phase 1. December 2012.

HDRP, 2012b. Fish health and edibility of two freshwater fish species in selected dams in the North West Province.

HDRP, 2012c. Foodweb monitoring progress report: Phase 1, October 2012.

HDRP, 2013a. Hartbeespoort Dam Integrated Biological Remediation Programme: Integrated Monitoring-Phase I Consolidated Progress Report: March 2013.

HDRP, 2013b. Foodweb restructuring: fish community study and progress for Hartbeespoort Dam 2004-2013 to indicate trends in the fish population in response to biomanipulation.

HDRP, 2014. Hartbeespoort Dam Integrated Biological Remediation Programme: Consolidated Progress Report: Phase II, March 2014

Interministerial committee, 2010. Mine Water Management in the Witwatersrand Coal Fields with Special Emphasis on Acid Mine Drainage. Report to the Inter-Ministerial Committee on Acid Mine Drainage, 2010

International Joint Commission: Canada and United States, 2009. Work Group Report on Eutrophication: Great Lakes Water Quality Agreement Priorities 2007-09 Series.

Jennings, S.R., Neuman, D.R. and Blicker, P.S. (2008). "Acid Mine Drainage and Effects on Fish Health and Ecology: A Review". Reclamation Research Group Publication, Bozeman, MT.

Kairesalo T, undated. Successful biomanipulation of Lake Vesijärvi: have cyanobacterial blooms been vanguished? http://www.nessling.fi/symposiot/Symposio1/kairesal.htm

Keto J, 2013. Hartbeespoort Dam Integrated Biological Remediation Program, Phase I Peer Review and Follow-up Report. Published by LADEC. 20 pages.

Keto J and P Talberg, 2000. The recovery of Lake Vesijärvi, a lake in southern Finland: water quality and phytoplankton interpretations. Boreal Environment Research 5: 15-26.

Klapper H, 2003. Technologies for lake restoration. Papers from Bolsena Conference (2002). Residence time in lakes: Science, Management, Education. J. Limnol., 62(Suppl. 1): 73-90, 2003.

Kristensen, P (2004). The DPSIR Framework: Paper presented at the 27-29 September 2004 workshop on a comprehensive / detailed assessment of the vulnerability of water resources to environmental change in Africa using river basin approach. UNEP Headquarters, Nairobi, Kenya.

Kutics, Karoly; Molnar, Gabor, 2013. Could climate change cancel out the results of water quality control measures at Lake Balaton? EGU General Assembly 2013, held 7-12 April, 2013 in Vienna, Austria (abstract only)

Matowanyika W, 2010. Impact of Alexandra township on the water quality of the Jukskei river. MSc thesis, University of the Witwatersrand.

Matthews MW, 2014. Eutrophication and cyanobacterial blooms in South African inland waters: 10 years of MERIS observations. Remote Sensing of Environment 155 (2014) 161-177

Matthews, M.W., Bernard, S., &Winter, K. (2010, Sep.). Remote sensing of cyanobacteria dominant algal blooms and water quality parameters in Zeekoevlei, a small hypertrophic lake, using MERIS. Remote Sensing of Environment, 11(49), 2070-2087 (URL http://linkinghub.elsevier.com/retrieve/pii/S0034425710001264).

Matthews MW, and Bernard S, 2015. Eutrophication and cyanobacteria in South Africa's standing water bodies: A view from space. S Afr J Sci. 2015;111(5/6), 8 pages. http://dx.doi.org/10.17159/sajs.2015/20140193

Mattson MD, PJ Godfrey, RA Barletta and A Aiello, 2004. Eutrophication and aquatic plant management in Massachusetts: Final generic Environmental Impact report. The Department of Environmental Protection and the Department of Conservation and

Recreation Executive Office of Environmental Affairs Commonwealth of Massachusetts. 514 pages

NIWR, 1985. The Limnology of Hartbeespoort Dam. South African National Scientific Programmes Report No. 110.

Mitchell SA, MP de Wit, JN Blignaut, D Crookes, 2014. Waste water treatment plants: the financing mechanisms associated with achieving green drop rating. WRC Report No. 2085/1/14

Nathanail, J. Bardos, P. & Nathanail, P. (2002) Remediation Management Ready Reference. EPP Publications/ Land Quality Press. Available from: EPP Publications, 52 Kings Road, Richmond, Surrey TW10 6EP, UK. E-mail enquiries@epppublications.com. ISBN 1900995069. Web link: http://www.epppublications.com. http://www.eugris.info/FurtherDescription.asp?Ca=2&Cy=0&T=Selection%20of%20remediation%20options&e=44

Nürnberg G, B LaZerte, 2013. Water Quality and Remediation Options for Desbarats Lake, Johnson Township. Prepared for the Central Algoma Freshwater Coalition Bruce Mines, Ontario

Oberholster, PJ. 2009. Impact on ecotourism by water pollution in the Olifants River catchment, South Africa. SIL News, Vol.55, pp 8-9

Odada EO, Daniel O. Olago, Kassim Kulindwa, Micheni Ntiba and Shem Wandiga, 2004. Mitigation of environmental problems in Lake Victoria, East Africa: Causal Chain and policy options analyses. Ambio Vol. 33 No. 1-2.

OECD, 2008. Eutrophication of Waters (OECD) Monitoring, Assessment and Control. Research of the Organization for Economic Co-Operation and Development (OECD). Soil & Water Conservation Society of Metro Halifax (SWCSMH)

OECD, 2012. Strategic environmental assessment in development practice: A review of recent experience. OECD Publishing, Paris, France (2012) 126 pp. [DOI: http://dx.doi.org/10.1787/9789264166745-en; ISBN 978-92-64-16673-8]

Owuor K; Okonkwo J; Van Ginkel C; Scott W, 2007. Environmental factors affecting the persistence of toxic phytoplankton in the Hartbeespoort dam. WRC Report No, 1401/3/07. Published by the Water Research Commission, Pretoria

Robarts RD (1984) Factors controlling primary production in a hypertrophic lake (Hartbeespoort Dam, South Africa). *J. Plankton Res*. 6 91-105.

Rossouw JN, WR Harding and OS Fatoki, 2008. A guide to catchment-scale eutrophication assessment for rivers, reservoirs and lacustrine wetlands. WRC report No. TT 352/08

Roux, SP, Oelofse, S, and De Lange W. 2010. 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 and Exhibition ICC Durban, South Africa, 18-22 April 2010, pp 18

Sangolkar LN, SS. Maske, PL. Muthal, SM Kashyap, T Chakrabarti, 2009. Isolation and characterization of microcystin producing Microcystis from a Central Indian water bloom. Harmful Algae **8**: 674-684

Scavia D,JD Allan, KK Arend, S Bartell, D Beletsky, NS Bosch, SB Brandt, RD Briland, I Daloğlu, JV DePinto, DM Dolan, MA Evans, TM Farmer, D Goto, H Han, TO H, R Knight, SA Ludsin, D Mason, AM Michalak, RP Richards, JJ Roberts, DK Rucinski, E Rutherford, DJ Schwab, TM Sesterhenn, H Zhang and Y Zhou, 2014. REVIEW: Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. Journal of Great Lakes Research 40: 226-246.

Stewart FM, T Mulholland, AB Cunningham, BG Kania and MT Osterlund, 2008. Floating islands as an alternative to constructed wetlands for the treatment of excess nutrients from agricultural and municipal wastes – results of laboratory-scale tests. Land contamination and reclamation 16 (1), 25-33.

Tadonléké RD, J Lazzarotto, O Anneville and J-C DRUART, 2009. Phytoplankton productivity increased in Lake Geneva despite phosphorus loading reduction. Journal of Plankton Research 31: 1179-1194.

The Lake Ecosystem Dynamics Research Group of the University of Helsinki (undated). http://www.helsinki.fi/lakedynamics/research/vesijarvi.htm

US Army Corps of Engineers. Adaptive Management for Water Resources Project Planning.

US EPA, undated, Basic Information about Disinfection Byproducts in Drinking Water: Total Trihalomethanes, Haloacetic Acids, Bromate, and Chlorite. http://water.epa.gov/drink/contaminants/basicinformation/disinfectionbyproducts.cfm

Van Veelen M and C Hooghiemstra, 2013. Implementation of the Waste Discharge Charge System: Crocodile River Situation Assessment And Resource Quality Management Plan Report. DWA Project Number: WP 10510

Van Zweiten, 2008. Eutrophication or exploitation as a threat for fisheries? Ecosystem change in Lake Victoria. http://content.alterra.wur.nl/webdocs/internet/corporate/prodpubl_eng/african_waterweek/Eutrophication_exploitation.pdf

Walmsley (2000) Perspectives on eutrophication of surface waters: policy / research needs in South Africa: a review and discussion document. WRC report KV 129/00.

Wetzel, RG, 1983. Limnology (Second Edition). CBS College Publishing. 767 pages.

Wilkinson, David M. (1999). "The Disturbing History of Intermediate Disturbance". *Oikos* **84** (1): 145-7

Williams J and J Pittock. The water, food and energy nexus. Australian National University. http://www.wrc.org.za/FreshWater/Documents/09H30%20Williams%20Tues%20Monks%20Cowl.pdf

Wilson AE, WA Wilson and ME Hay, 2006. Intraspecific Variation in Growth and Morphology of the Bloom-Forming Cyanobacterium *Microcystis aeruginosa*. Applied And Environmental Microbiology 72 (11) 7386-7389.

Wittmann GTW and U Förstner, 1976. Metal enrichment od sediments in inland waters – The Jukskei and Hennops River drainage systems. Water SA 2 (2) 67-72.

13 Appendix 1: Terms of Reference

13.1 Terms of Reference from DWS to the WRC

water & sanitation

Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA

Enquiries:	Anil Singh Chadwick Lobakeng
Telephone:	012 336 7531 018 387 9500
Reference:	16/3/4/1

Chief Executive Officer
Water Research Commission
Private Bag X03
GEZINA
0031

REQUEST FOR A PROPOSAL TO CONDUCT AN INTERNATIONAL SCIENTIFIC SPECIALIST REVIEW ON THE HARTBEESPOORT DAM INTEGRATED BIOLOGICAL REMEIDATION PROGRAMME (HARTIES METSI A ME) (HDRP)

The Water Research Commission are hereby requested to conduct an external independent review to assess the successes of the Hartbeespoort dam Integrated Biological Remediation Programme thus far since the inception, and to advise on the future of the HDRP. The assessment must also evaluate the effect of the HDRP in a holistically manner also addressing the impacts received from catchment activities on the dam in terms of all components of the Water Resourse.

Attached (**Annexure I**) is the terms of reference and the draft Implementing Agent Agreement for your attention. You are requested to provide a cost estimate to complete the final Review Report by the end of February 2015, and to start with immediate effect after the signing of the Implementing Agent Agreement.

Should you have any further requests in this regard, please do not hesitate to contact North West Regional manager Mr Chadwick Lobakeng or Wendy Ralekoa North West Director Institutional Support at the above telephone numbers.

CD: NW

Yours sincerely

Petrus
082 807 6098
venterp@dwa.gov.za

Mr Trevor Balzer
DIRECTOR-GENERAL (Acting)

DATE: 7/09/2014

ANNEXURE I

water affairs
Department:
Water Affairs
REPUBLIC OF SOUTH AFRICA

TERMS OF REFERENCE

FOR

APPOINTMENT OF WATER RESEARCH COMMISSION (WRC) AS IMPLEMENTING AGENT (IA) TO REVIEW THE HARTBEESPOORT DAM INTEGRATED BIOLOGICAL REMEDIATION PROGRAMME (HARTIES METSI AME)

PROVINCE : NORTH WEST

DIRECTORATE : INSTITUTIONAL ESTABLISHMENT

DECEMBER 2012

1. PURPOSE

The purpose of this Terms of Reference (ToR) is to appoint Water Research Commission (WRC) to support Department of Water Affairs (DWA) with the review processes of the Hartbeespoort Dam Integrated Biological Remediation Programme (HDRP), also known as the Harties Metsi a me.

2. BACKGROUND

The Harties Metsi a Me Programme commenced mid 2006 after the appointment of Rand Water as the Implementing Agent. The inception phase included the parallel development of a business plan (finalised and signed in October 2007), and the phased implementation of critical activities which culminated in the starting of the fish removal in February 2008. The business plan included a strong research and development component, while the pilot programme implementation was launched concurrently.

The basis of the Harties Metsi a me programme is modelled on the foodweb remediation of Finland's Lake Vesijarvi, a body of water that once suffered from similar eutrophication symptoms (about 30 years ago) like Hartbeespoort Dam, but showed improvements within 5 to 8 years after initiation of the fish removal activities coupled with the reduction of point source pollution. Today Lake Vesijarvi is in a much better condition after these activities were sustained for about 30 years. The gradually increasing impacts that have plagued the Hartbeespoort dam since it has been constructed in 1923 has exponentially increased since the late sixties. After it was ruled by the Director General of the Department of Water Affairs (DWA) in May 2007, DWA became the leader of the Remediation Programme with North West Department of Agriculture, Conservation, Environment and Rural Development (NWDACERD) oversight as chairperson of the Hartbeespoort Dam Steering Committee (HDSC).

The programme has proceeded rapidly with its extensive integrated model that essentially consisted of two phases. The **First Phase** focuses on several intervention points in the undesired food web, starting with the removal of the sediment feeding Carp (exotic) and Barbel; establishing / remediating shoreline and wetland conditions in the dam; and the introduction of biological and mechanical harvesting and processing of algae and hyacinths (which further required the concurrent removal of litter and debris). In boarder terms this involves the restructuring of the fish population from non-desirable bottom feeders like the Catfish and Carp species (which also have high larvae and egg producing properties feeding on zooplancton) towards more indigenous diversity with the Blue Kurper (*Mozambique tilapia*) dominating the system, as it was the case about 3 decades ago. The progress has been monitored by two ecological surveys that show indications that the fish composition and ecosystem in the dam has already changed since the implementation of this programme, with a more intensive on-going monitoring program related to the entire food web that is needed to support the desired restructuring. Parallel with the Sub-programme Dam Basin activities, cross cutting and catchment activities were started to address catchment impacts (compliance and enforcement & sediment management strategy to reduce the external and internal nutrient load) and communication and awareness to facilitate long-term behaviour changes. To legally enable these activities, a Resource Management Plan with local rules was developed in 2008/9 through an intensive stakeholder engagement process, with on-going involvement ever since. Phase 1 has been extended since April 2010 to July 2012 in anticipation for National Treasury to approve long term funding to enable the full scale implementation. Due to the national and international recession that prevailed during this time, such funding did not come forth, and an EEE Review (Effective, Efficient and Economic) of the HDRP was instructed by DWA's Bid Adjudication Committee in August 2012 before the full scale implementation and extension according the Phase II Business Plan can proceed.

The **Second Phase** which has officially started in September 2012 intends to intensify the dam basin activities to full scale implementation and prioritised extension to other dams. The full scale implementation is also extended to focus on the broader catchment impacts, which includes much needed and improved storm water management, erosion/sedimentation control, protection and remediation of wetlands and in-stream river habitats, as well as the more stringent load standards through improved compliance and enforcement (implementation of the Waste Discharge Charge System - WDCS). DWA is developing a catchment management strategy (for piloting within the Hartbeespoort dam catchment) to address these impacts and to manage the catchment in a more integrated manner, which also includes the development of Resource Quality Objectives (RQO), Operational Best Practices (OBP's) parallel with the implementation of the Waste Discharge Charge System.

3. CHALLENGES

Listed hereunder are some of the challenges, which will impact on the enhancement and full scale implementation of the HDRP activities:

- Different parties/institutions/authorities are impacting on the upstream water resources including quality, quantity and quick run off from rapidly increasing hard surfaces resulting from the high development rate;
- Municipalities capacity, ability and political will / commitments to implement and/or enforce bylaws to ensure improved land management practices, and their own adherence to effluent standards of DWA;
- Difficulty to accurately quantify impacts of the HDRP within the physical and hydraulically complex and dynamic system, and increasing impacts coming from the upstream catchment.

- Lack of an integrated model talking to the physical, chemical and biological relationships to quantify and balance all different variables in terms of predictability.

4. ACHIEVEMENTS TO DATE

The outcomes and deliverables of the programme were covered at different levels of detail and extent in Progress Reports to serve various targeted audiences. These progress reports included summarised reports accompanied with consolidated presentations to Parliament, Portfolio and Select committees, DWA Executive and Functional Management committees (Exco, Manco, FMC); Quarterly reports to North West Province (Exco and Steering Committee), Annual Reports, and the consolidated Phase I progress reports.The latter mentioned reports are included in the latest Harties DVD (amongst many supporting information):

1. Consolidated Progress Report: Phase I, December 2012
2. Integrated Monitoring Progress Report: Phase I, November 2012
3. Biological Monitoring Progress Report: Phase I, October 2012

These and other reports read together with the Business Plan (BP), Addendums to the BP and Strategies will serve as a departure point and basis for the Review Panel to orientate them on the HDRP and be able to conclude accordingly. Other supporting information is the Harties website, Factsheets, Flyers, publications and communication materials developed by the HDRP.

5. SCOPE OF WORK

The scope of work to be addressed in the review of the HDRP (Harties Metsi a me programme), need to cover the following aspects:

1. Inception Report

1.1 Ascertain whether the HDRP has achieved the desired outcomes and milestones as described in the Business Plan/s. The IA will develop a work program and a methodology with respect to development of the evaluation criteria and benchmarking to implement the assessment and review.

1.2 Amongst others this task entails administrative activities and management of the project over the project period, which includes regular progress reports, budget updates, etc.

2 Outcomes Assessment

2.1 The effectiveness and efficiency of the HDRP needs to be benchmarked in terms of the appropriateness of the Plan (NW Environmental Series 5, and supporting documents) as intended within the scope of the Business Plan, and the

4

improvement and extension thereof. This includes the outcomes, the value for money / use of funds and skills, amongst other, attached to the programme.

2.2 The outcome of the review will have to address concerns and inputs on different levels and for different stakeholder sectors:

2.2.1 Political, including but not be limited to Members of Parliament (MP), Provincial and Local / Regional;

2.2.2 Institutional, with the main emphasis on legal and provincial government departments and key stakeholders (DWA amongst others).

2.2.3 Technical and Scientific / Academic Specialists in the water and integrated environmental management field, including international expertise with experience with related test cases.

3 Technical review

3.1 Criteria needs to be develop and collectively agreed upon for benchmarking to evaluate, test and determine the effectiveness and efficiency of the implemented Business Plan, in relation with any other better / improved alternatives that might ensure better / more appropriate outcomes and results within the context of the National Water Act (NWA) and other related environmental legislation to ensure an improved and more holistic and integrated approach to address the problems and collective impacts in the dam and upper catchment.

3.2 Appropriateness of alternatives in terms of National, Provincial and Local growth and development goals (Improved water resource quality, economic growth, work creation, poverty alleviation, etc.)

4 Stakeholder engagement

4.1 Stakeholder engagement needs to be conducted to incorporate the above parties, and need be done collectively or separately in a workshop / conference / symposium environment to ensure the most interactive and objective outcome of the review

5 Financial and economic

5.1 Financial and corporate aspects within DWA and related managers need to be evaluated and benchmarked. This is in line with the request and action already conducted by DWA and RW to initiate a proper audit of the programme. The financial assessment need to be done in the protocol, context and environment of the Implementing Agent Agreement that exists within DWA. Transparency and availability of expenditure for external stakeholders need to be assessed and presented appropriately.

5.2 The potential economic benefits and socio-economic growth and development targeted by NW Province in the Hartbeespoort dam Economic Hub need to be assessed and benchmarked to evaluate other possible alternatives that might also ensure continuous economic growth and stimulate confidence in local and regional development and investment.

Although the review will require in-depth engagement with the HDRP and associated managers and service providers, appropriate actions must be taken to ensure the objectivity of the review report by ensuring the use of qualified independent specialists / individuals not directly involved within the HDRP and the development of the Remediation Plan since 2004, or with vested interest and personal agendas.

The conceptual structure and budget for the Programme Review can be summarised as follows (to be expanded and finalise in the inception report):

Task	Output	Estimated Time Frame (months)	Estimated Budget
1. Inception Report	Details of Approach to the Programme Review covering all aspects (Technical, Financial, social & legislative)	1	R50 000.
2. Outcomes assessment of the Harties Business Plan and execution thereof.	Reviewed BP with priorities, including Upstream Catchment activities	1	R100 000.
3. Technical and Scientific review	Achievement of Programme Milestones to be highlighted as per BP and associated impacts on the dam	1	R150 000.
4. Stakeholder engagement workshop/s	Document concerns inputs and outcomes / recommendations from different stakeholder sectors		R 100 000
5. Financial and Economic analysis	Validity and Accuracy of Programme costs.	1	R50 000.
6. Final Review Report	Consolidated Report of all project activities to be reviewed and signed by CD: NW Region	1	R50 000.
TOTAL		**5 (months)**	**R500 000**

6 PROJECT ARRANGEMENTS

6.1 Project approach and structure

In order to provide for the dynamic nature of this type of work, the performance management will be based on an outcomes basis, as outlined above. The project will be managed on an activity basis. An activity can be defined as any task or action falling within the scope of the contract, executed by a resource with the approval of the Project Manager.

6.2 Project management

The **Department: Water Affairs** will act as the **Client** for the proposed project. The Director: Institutional Establishment of DWA, Ms. W. Ralekoa will manage the project (Project Manager). A Project Management Team (PMT) will be established, consisting of the relevant Directorates from DWA Regional office & DWA National Office and other sector Department to assist in the management of the project. A Steering Committee will be established in the WMA consisting of different stakeholders in order to assist with project implement & monitoring. The IA and duly appointed PSP will assist the client in administering and managing all the necessary work to comply with this brief, including those aspects of the study that may be undertaken by DWA.

7. PROJECT MANAGEMENT BY THE PSP

The PSP will ensure that the project is implemented according to what is stipulated in the implementation plan and to employ other expertise if the need arises in any field. The PSP will also be responsible for the detailed planning, monitoring and controlling of the activities carried out under this assignment. The PSP must therefore have a Project Leader with proven relevant management skills and experience on the team. The management function entails performing a variety of activities that are described hereunder.

7.1 Monitoring

The PSP's Project Leader shall collect record and transport information concerning all aspects of the assignment that the Client wishes to know. In order to achieve this, the PSP must design a performance monitoring and information gathering system based on the key performance indicators for the project. The monitoring system must concentrate primarily on measuring various facets of outputs. The PSP must indicate the type of information that will have to be collected in order to evaluate progress against the set of goals stated in the Implementation Plan.

7.2 Project control

The PSP must indicate based on the monitoring system the basic structure of the process of control for performance with respect to quality, time and cost. The structure must indicate at what points in the module, what is to be controlled, how it will be measured, how much deviation from the work plan will be tolerated before remedial action is taken and what kinds of management interventions should be used.

7.3 Day to day co-ordination of all activities

In order to achieve the project management objectives, the PSP shall be responsible for day to day monitoring and co-ordination of all the activities undertaken under this assignment. This involves the following.

- Monitoring progress on each of the tasks being executed against the baseline
- Review actual outcome against the planned outcome and taking corrective action in time
- Analyzing the impact of deviations from the original Project Plan and/or budget and assessing what must be done, at what cost and when to get back on course. The PSP shall be required to prepare a revised inception report if these deviations are significant.
- Giving advice on any changes to the process and progamme that need to be made to avoid delaying the project.
- Controlling costs and performing quality audits of the various tasks

To achieve the above the PSP shall prepare periodic progress and financial reports and submit these to the Client in a format prescribed by the Client. PMT meetings with the Client will be held monthly.

8. INFORMATION TO BE PROVIDED IN THE PROPOSAL

8.1 Extent of proposals

The text of the Proposal, including a Work Programme Schedule and a detailed Schedule of Resources versus Costs should be to the point and not longer than 15 A4 pages (excluding CVs) at a font-size of 10 and 1.5 line spacing. The proposal shall be structured as follows:

8.2 Background and Introduction

The PSP shall outline in this section a background to the project and any information deemed necessary.

8.3 Proposed Approach and Methodology

The proposed methodology should be clearly outlined in the proposal. The PSP is encouraged to use this Section in the Proposal to present innovative approached or other special features of the of the PSP's response to the ToR.

8.4 Project team and summary of capacity, capability and experience

The Proposal must present the key Components of the Project Team in the form of an Organogram. The proposal must also contain explicit information about the relevant capacity, capability and experience of Key Personnel, with particular reference to

- Experience with the programme coordination
- Experience in and in depth knowledge of historical or current water resource capacity building efforts in the Project Area
- The roles of each individual Key Personnel in the project
- Experience of working in multi-disciplinary teams in the water resources sector
- Abbreviated CVs of all key personnel included in the study team must form attachment to the Proposal. CVs must be presented in font size 1.5 line spacing and must not be longer than 2 pages.

8.5 Participation by HDIs

The participation of HDIs (historically disadvantaged individuals) in the project is strongly recommended. The definition of an HDI follows that of PPPF Act in which DWA's current Policy is aligning. Proposals must be explicit about the following:

- Percentage HDI ownership of each participating firm in Association or Joint Venture formed for the project
- The roles of HDIs in Key Personnel and Technical Support positions
- The composition of HDI that participate in Association or Joint Venture formed for the Project
- The percentage ownership for Joint Venture or Associations is calculated as a weight average percentage based on the participating rate
- In the case of collaboration among different PSPs the proposal shall be accompanied by a suitably worded letter from each participating firm confirming their participation in the Association or Joint Venture, signed by a Principal of each participating firm.

8.6 Work Program

A detailed Work Program, broken down to individual tasks and indicating the contributions by all Project Personnel, shall be presented. The Work Program must indicate all Project milestones and targets dates for deliverables.

8.7 Project budget

The project budget shall represent the full resourcing both professional fee (time and cost based) and disbursements associated with each major component and each primary task in the project, as well as the timing of the costs involved. The resourcing must provide details of employment of all project personnel on a primary task basis. The hourly fee rates of all project personnel must be stated. The project budget must include VAT at 14%

8.8 TAX clearance certificate

No contract may be awarded to a person who has failed to submit an original Tax Clearance Certificate from the South African Revenue Services (SARS) certifying the taxes of that person to be in order or those suitable arrangements have been made with SARS. The PSP will be required to attach the original of the tax clearance certificate.

9. RETENTION OF THE PSP CONTRACT

It is DWA practice to impose a retention amount equal to 10% of the approved contract amount where the suite of draft reports or final reports have not been submitted or approved by the employer. The retention clause comes into effect near the end of the Project, reference to the appropriate clause in the contract document needs to be made and it is mentioned here to assist with the planning of cash flow for the Project.

10. PROJECT DURATION

This assignment is expected to run for a period of 5 (five) months from the date of inception.

11. PROJECT BUDGET

The estimated amount for the project is **R500 000.00** for 2012/2013 financial year and the funds are likely to be rolled over to 2013/2014 financial year.

The PSP must provide detailed budget expenditure linked to various project outputs, deliverables and activities as described in the terms of reference. Budget should clearly reflect VAT inclusive and exclusive. The PSP should clearly budget amounts to deliverables for the purposes of claims and invoices. Disbursements should be indicated separately where necessary. The PSP should accept that payments of invoices should be done in accordance with the Departments financial and procurements policies available on request from the relevant directorates.

12. CONTACT PERSON IN DWA

The Terms of reference and the proposed invitation are being administered by the Chief Directorate: North West Region, Institutional Establishment Directorate. The Contact Person for enquiries about the project is Ms W Ralekoa: 018 387 9500.

13.2 Water Research Commission Terms of reference

Water Research Commission
Marumati Building,
491 18th Avenue, Rietfontein, Pretoria

Private Bag X03, Gezina, 0031, South Africa

Tel: +27 (0)12 330 0340
Fax: +27 (0)12 331 2565
Email: info@wrc.org.za
Web: www.wrc.org.za

WATER RESEARCH COMMISSION

TERMS OF REFERENCE FOR A SOLICITED WRC PROJECT

KEY STRATEGIC AREA	**KSA1 Water Resource Management**
THRUST	**3: Water Quality Management**
PROGRAMME	**3: Impacts on and of water quality**
TITLE	**Review of the Hartbeespoort Dam Integrated Biological Remediation Programme (*Harties Metsi a Me*)**

The aims and objectives of the proposed study are based on the request for proposal and the draft Implementing Agent Agreement received from the DWS.

Aim:
To conduct an external independent review or assessment of the Hartbeespoort Dam Integrated Biological Remediation Programme (HDRP) (*Harties Metsi a Me - "My Water"*) that started in 2006 and to provide recommendations on the future of the HDRP.

Objectives:
General:

To evaluate and assess the effect or impact of the HDRP in a holistic manner addressing the impacts received from the catchment activities on the dam in terms of all the components associated with the dam.

Specific:
1. Assess the degree to which the HDRP has achieved the outcomes and milestones as described in its business plans.
2. Engage with relevant stakeholders to identify research questions that require further assessment/ investigation.
3. Benchmark, using collectively agreed criteria, the effectiveness and efficiency of the HDRP thus far against possible appropriate alternative approaches. This should include but not be limited to outcomes, value for money and use of skills.
4. Perform a financial assessment in the context of the Implementing Agent Agreement that exists with the Department of Water Affairs (DWA). Transparency and availability of expenditure for external stakeholders will be assessed and presented.
5. Assess the HDRP and benchmark against appropriate alternatives, the potential economic benefits and socio-economic growth and development targeted by the Hartbeespoort Dam Economic Hub.
6. Provide recommendations on the future of the programme.

Supporting sustainable development through research funding, knowledge creation and dissemination

Rationale:

The Hartbeespoort Dam in the North West Province has long been experiencing eutrophication problems. An Integrated Biological Remediation Programme was initiated in 2006. Phase 1 entailed various activities in and around the dam and enforcement of better water and land-use management practices in the upper catchment. These activities ranged from restructuring the fish population to catchment-wide compliance and enforcement strategies, as well as communication and awareness creation to facilitate long-term behavioural change. An Effective, Efficient and Economic (EEE) review of the HDRP was instructed by the DWA Bid Adjudication Committee in August 2012 before Phase Two could proceed. This Terms of Reference directly addresses this instruction.

The review is also necessary because the social ecological system in the catchment, and in and around the dam in particular, is complex. This is also why the development and use of "collectively agreed criteria" has been included in the specific objectives of the review.

Challenges include the following:

- The wide variety of organisations, institutions, and authorities that impact on the resource quality, both upstream and in the dam.
- The degree to which municipalities are able and/or willing to implement and enforce bylaws to ensure improved land management practices.
- The difficulties associated with quantifying the impacts of the HDRP.
- The lack of an integrated model of the catchment and dam.

General Methodology:

A three phase approach is proposed for the WRC as an Implementing Agent (IA) of the Independent External Review of the Hartebeespoort Dam Integrated Biological Remediation Program (HDRP).

Phase 1: High Level Review of the HDRP Literature and Stakeholder Engagement

This phase of the project will entail the appointment of a specialist project manager (may be an institution/ person) that will conduct the initial high level review of what is available based on the business plans, the interventions and the associated outcomes. Due to the volume of work available, the high level review will result in a draft report that will be used for stakeholder engagement.

The stakeholder engagement should be in the form of a two to three day workshop where the research questions entailed in the volume of work which require answers can be teased out and identified.

The above process should be concluded within a period of two months and the comments from the stakeholder engagement should be incorporated in the draft report.

The cost of Phase 1 is envisaged at R 200 000.00

Phase 2: Short term research projects to address the research questions

This phase will entail the identification of the research teams that can conduct the short term projects (two to five) identified through the stakeholder engagement process. The researchers will form the panel of experts and support the Project Manager in the review of the identified aspects/ research question with the focus on the return on investment in terms of the technical, socio- and economic aspects of the entire project. These assessments should also be carried out simultaneously by each of the experts over a two month timeframe. Up to five research questions can be identified. Future research and further work should also be recommended from this phase.

The proposed cost for Phase 2 R 500 000.00.

Phase 3: Project Finalization

This phase will entail the consolidation of the short term projects' findings into the draft final report. All the information will be synthesized and consolidated into the final report and a Ministerial Brief will also be developed which will highlight the future of the HDRP.
It is proposed that this phase be concluded in 1 month at R 100 000.00.

Deliverables:
The work plan indicating deliverables, duration and the cost is summarised in the table below.

Report	Description	Duration (months)	Cost (R)
Inception	Details of the high level review by an appointed project manager in a holistic manner. 1. Produce a draft report for stakeholder engagement; 2. Undertake stakeholder engagement to identify the research questions and assessments/ investigations to follow.	2	R 200 000.00
Draft final	Simultaneous technical investigations by the panel of experts. 1. Identify and appoint panel of experts to undertake the investigations research questions identified in Phase 1; 2. Undertake the specialist investigations and produce reports	3	R 500 000.00

Report	Description	Duration (months)	Cost (R)
	as input to the final report.		
Final	Consolidation of all information into a final report and the synthesis of the information into a Ministerial Brief.	1	R 100 000

Impact Area: **Sustainable Solutions**

Time Frame: **6 months**

Total Funds Available: **R 800 000**

14 Appendix 2: Review of the HDRP by J Keto, Finland

In 2013 Keto, the retired director of the Lake Vesijärvi Remediation Project, Finland, presented an overview of the HDRP activities (Keto, 2013[12]). A brief summary of the 3 day site visit is presented here.

Keto reviewed the following documents and interviewed the following people:

Documents reviewed:

- Business Plan 2010-2015, Draft June 2009, Final November 2011
- Foodweb Monitoring Progress Report: Phase I, October 2012
- Integrated Monitoring Progress Report: Phase I, November 2012
- Fish Health and Edibility Progress Report, November 2012
- Sediment Management Progress Report: Phase I, December 2012
- Consolidated Progress Report: Phase I, December 2012
- Electronic data on Harties Metsi a Me DVD, November 2012
- Harties Metsi a Me web pages http://www.harties.org.za/
- SAICE Civil Engineering, August 2012 Vol. 20 No 7, 9-55. ISSN 1021-2000

People interviewed:

- P Venter
- S Moraar
- Dr Z Cukic
- Dr J Koekemoer

Programme personnel including management staff, monitoring team, management fishing team, information communication team and workers busy with various project activities.

He makes the comment that this review was limited by time and funds, and that a more comprehensive review should be conducted.

A summary of the main recommendations are as follows:

- The rate of harvesting and processing of biomass should be increased.
- Shredding hyacinth prior to vermiculture would enhance the process.
- The reduction of the external nutrient load is a crucial factor for the successful rehabilitation of Hartbeespoort Dam and its protection in the future.
  - The release of hypolimnetic water through the bottom sluices of the dam has a positive impact on the nutrient balance.
- Strict pollution control should be implemented throughout the catchment, addressing point and non-point sources.
- A pre-impoundment and flow diversion should be constructed.
- The programme should be continued. Mr Keto estimates a period of 10-15 years to solve the eutrophication in Hartbeespoort Dam.

---

[12] http://www.harties.org.za/documents/Peer/PeerReviewLahtiMar2013.pdf, 20 pages

- Increased biodiversity increases ecosystem resilience and is a method for adapting to global change. This should be pursued.
- Bio-manipulation is preferred to chemical dosing or artificial aeration as it is more cost-effective.
- Both the internal and external phosphorous loading should be addressed if the target P load is to be achieved.
- Riparian wetlands and instream habitats upstream of the dam should be developed in order to provide additional reduction of sediment and nutrient load to the dam.
- The programme should be recognised as a national effort in pollution control.
- Mitigation of eutrophication is a long term commitment.
- South Africa's standard of 1 mg/l P is more liberal than European standards. A standard of 0.2 mg/l P is promulgated for sensitive catchments in Finland and modern technology can remove P to 0.1 mg/l.
    - The implementation of a stricter phosphate standard is recommended for the Hartbeespoort Dam catchment.
- Transparent and accurate information and communication are very important issues in lake management.
- The research component in the programme is not as visible as expected from the outcomes of the programme. A programme such as this should lead to publications and possibly even a book.
- An international workshop on the programme would allow an exchange of knowledge and provide an international peer review of the programme.

15 Appendix 3: Nutrient management: High Level Roadmap for Required Actions

Hartbeespoort Dam Rehabilitation

High Level Roadmap for Required Actions

Dr M van Veelen

ILISO Consulting

Acknowledgement

The information that is used in this report was derived from the work that was done for the Department of Water Supply (previously the Department of Water Affairs) as part of the ***Implementation of the Waste Discharge Charge System (Project Number: WP 10510)*** in 2013. Although some minor aspects of the current situation may have changed since then, the data and information used in this report are still substantially relevant.

Hartbeespoort Dam Rehabilitation

High Level Roadmap for Required Actions

Executive Summary

ILISO Consulting were appointed by EON Consulting to produce a high level road map to guide the planning of reducing the pollution load in terms of phosphate loading in the Hartbeespoort Dam catchment.

The Hartbeespoort Dam is well known for its poor water quality due to nutrient enrichment and the resultant frequent algae blooms. The dam is classified as a hypertrophic dam which means that the dam is enriched by phosphates and nitrogen resulting in algal scums. The high algal concentrations also result in problems when treating the water for domestic use, leading to increased costs, aesthetic problems (mostly smells) and a threat to human health in the form of trihalomethanes that may form as part of the disinfection process. The driving force is the very high phosphate concentration.

Most of the load generated in the Hartbeespoort Dam Catchment emanates from two sub-catchments, namely the Jukskei and the Hennops which together represent 91% of the load. The other significant sub-catchment is the Upper Crocodile, which contributes 7.2% of the load. Together these three sub-catchments contribute almost 99% of the load.

The load is almost equally divided between point sources and diffuse sources, with the natural background contribution representing a negligible contribution. The contribution from diffuse sources (53%) is larger than from the point sources (47%). The diffuse sources can for all practical purposes be allocated to overflowing and leaking sewers, as this accounts for 99% of the diffuse load. The associated flow is about 7% of the flow discharged by the point sources.

Three waste water treatment works, namely Northern Works, Olifantsfontein and Sunderland Ridge together contribute 80% of the point source load.

Table 15-1: Point Source Load Contributions

WWTW	Load (kg/a)	%
Magalies	830	0.5
Randfontein	9 610	5.8
Percy Steward	11 389	6.9

WWTW	Load (kg/a)	%
Driefontein	1 854	1.1
Esther Park	166	0.1
Kelvin P/S	2 502	1.5
Northern Works	42 142	25.5
Hartbeesfontein	5 969	3.6
Olifantsfontein	42 243	25.5
Sunderland Ridge	48 753	29.5
Total	**165 458**	**100**

The threshold defining the boundary between the mesotrophic and eutrophic conditions in South African reservoirs has been determined as 55 µg per litre (Figure 15-7). In order to achieve this condition in the Hartbeespoort Dam, the estimated required load reduction would be eighty-one percent (81%) of the current aggregate load of 348 000 kg per annum, and the allowable load would be 68 000 kg per annum.

A reduction of 80% is not achievable in the short to medium term and it is proposed that an interim target of 85 µg/ℓ PO_4 be set. 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.

The interim target represents an annual load of 110 tonne P per annum, which requires a reduction of 238 tonne. Currently the point sources contribute 173 tonnes per annum while the diffuse load contributes 184 tonnes per annum. The proposed reduction targets are shown in the table below.

Table 15-2: Reduction Targets for Point and Diffuse Sources

Description	Unit	Point Sources	Non-point Sources	TOTAL
Current load	tons	165	184	349
Interim Target Load	tons	90	130	220
Percentage reduction	%	55	71	63

The required management actions can to all intents and purposes be divided into two categories. The first category consists of actions to reduce the load, while the second consists of in-lake management options to mitigate the effect of the high nutrient loading.

Reducing the load should focus on the one hand on point source management actions, and on the second hand on the sewer systems. The required management actions are summarised in the table that follows.

Table 15-3: Required Interventions.

Intervention	Description	Capital Cost (R million)	Running Cost (R million/a)	Responsibility
1A	Upgrade Olifantsfontein to 1 mg/L phosphate discharge	1 050		Ekurhuleni
1B	Improve discharge standard for phosphate to 0.3 mg/L	275		DWS
1C	Improve discharge standard for phosphate to 0.15 mg/L	760		DWS
1D	Implementation of the required improvement to the WWTWs	-	-	Local Authorities
2A	Integrated Monitoring and Regulatory System	5	0.7	DWS
2B	Rehabilitation of failing pump stations	275	-	Local Authorities
2C	Refurbishment of sewers	800		Local Authorities
2D	General Sewer Monitoring	500		Local Authorities
3A	Hartbeespoort Dam Biological Remediation		30	CMA

The upgradings and improvements to the WWTWs and the sewer systems will require a substantial amount of capital. The local authorities can however access a number of grants for funding, but should do so as soon as possible.

The in-lake mitigation actions should be funded from the Waste Discharge Charge System.

Hartbeespoort Dam Rehabilitation

High Level Roadmap for Required Actions

Table of Contents

Hartbeespoort Dam Rehabilitation
High Level Roadmap for Required Actions

15.1 Introduction

ILISO Consulting were appointed by EON Consulting to produce a high level road map to guide the planning of reducing the pollution load in terms of phosphate loading in the Hartbeespoort Dam catchment. This report describes the sources of phosphates in the different sub-catchments, the current situation, the management objectives that have been adopted and the required actions. A first order costing for the implementation of the management actions is also provided.

15.2 Study Area

The Hartbeespoort Dam is located in the upper reaches of the Crocodile River (West) catchment. The dam was originally constructed for irrigation purposes, but at present a substantial quantity of water is released and used for domestic purposes further downstream. 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, and
- The Incremental Crocodile River Catchment between the Upper Crocodile River Catchment and the Hartbeespoort Dam (Including the area around the Dam and the Swartspruit).

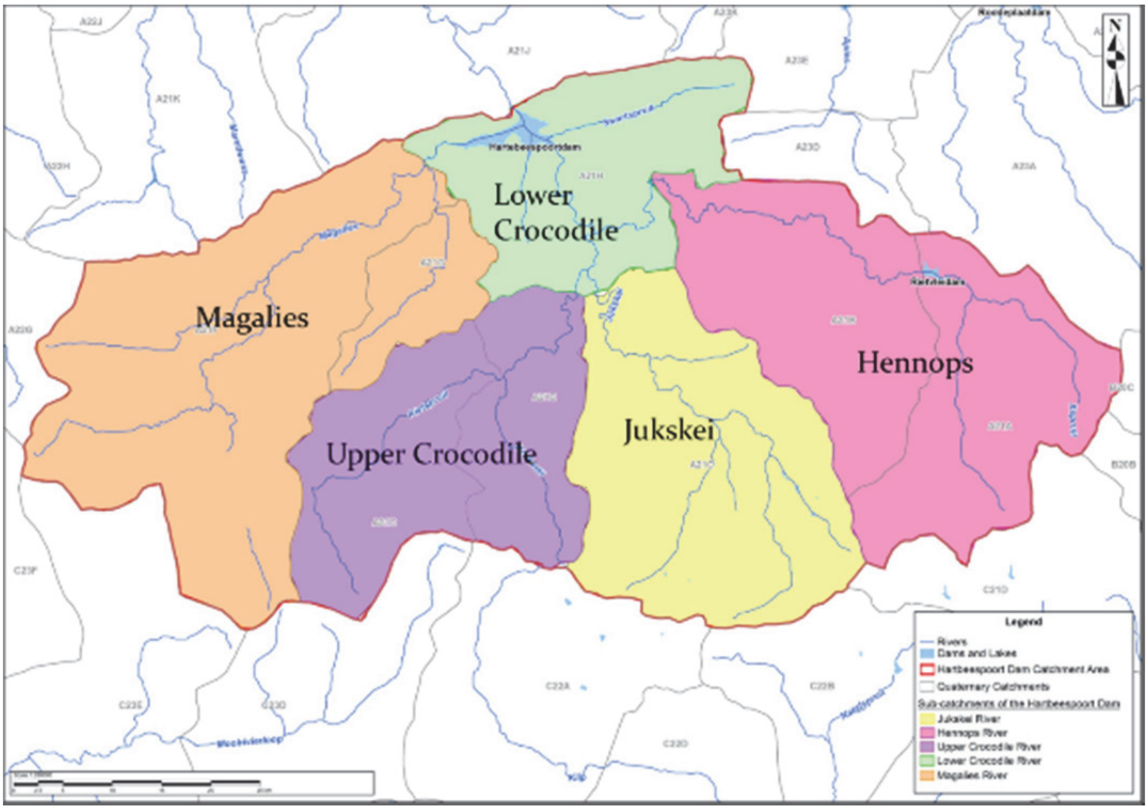


Figure 15-1: Hartbeespoort Dam location and sub-catchments

The main attributes of the dam are shown in **Table 15-4**

Table 15-4: Hartbeespoort Dam attributes

Catchment area	4 112 km^2
Mean Annual Rainfall	670 mm
Mean Annual evaporation	1 690 (S) 1 246 (D)
Surface area	2 034 ha
Natural Mean Annual Runoff	163 million m^3
Full Supply Capacity	196 million m^3
Firm Yield (1990)	159 million m^3
Wall height	95 m
Crest length	101 m

The current run-off into the dam is 542.5 million m^3/annum. This means that, where the dam was originally a 1.2 MAR dam, it is now a 0.36 MAR dam. In practice this means that the dam turns over on average 2.8 times per year. The additional inflow is due to:

- Leaking and overflowing sewer networks,
- Return flows from waste water treatment works,
- Additional rainfall runoff from hard surfaces such as roads, paved areas, roofs,
- Return flows from irrigated gardens and parks,
- Leaking potable water supply networks, and
- Irrigation return flows.

15.3 Current situation

The Hartbeespoort Dam is well known for its poor water quality due to nutrient enrichment and the resultant frequent algae blooms. The dam is classified as a hypertrophic dam which means that the dam is enriched by phosphates and nitrogen resulting in algal scums. The high algal concentrations also result in problems when treating the water for domestic use, leading to increased costs, aesthetic problems (mostly smells) and a threat to human health in the form of trihalomethanes that may form as part of the disinfection process. The driving force is the very high phosphate concentration.

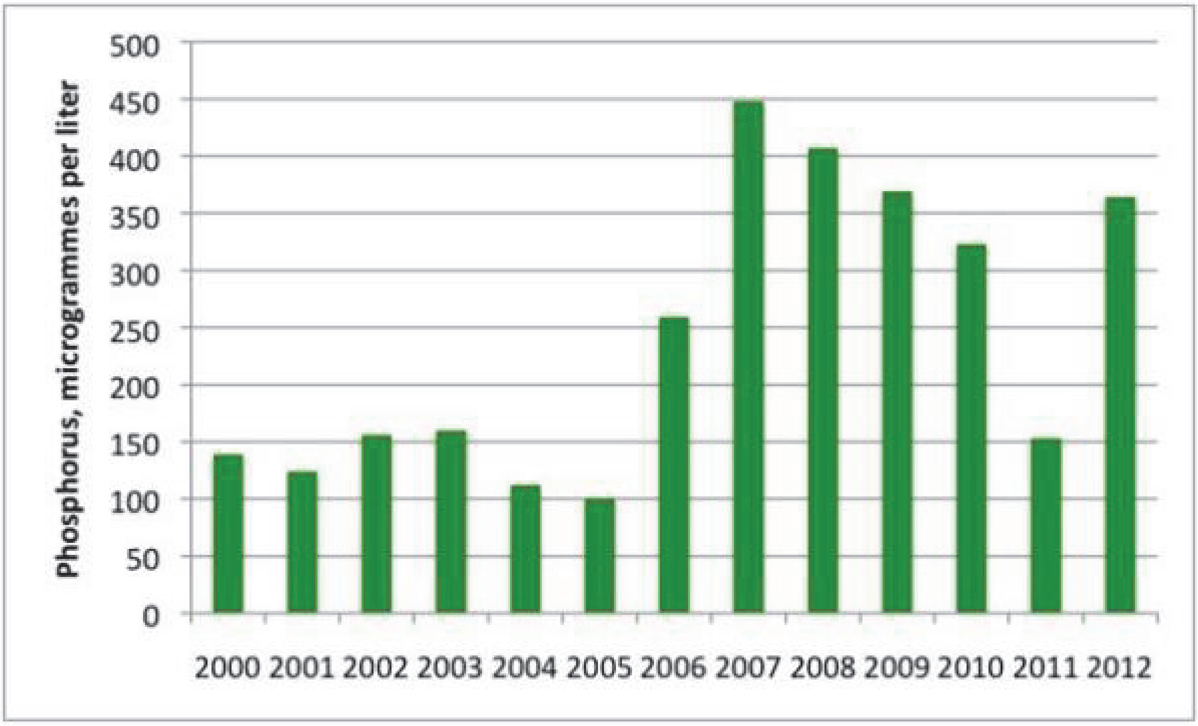


Figure 15-2: PO4 at Dam Wall

The reason for the increase in concentration at the dam wall (as measured) since 2006 is not known, but is probably due to a combination of conditions and circumstances. The current (2012) contributions to the load from the catchment is analysed below.

15.4 Load contributions

The load contributions per catchment and per primary source are shown in **Table 15-5**.

Table 15-5: Summary of phosphate loads emanating from the Hartbeespoort Dam Catchment

Sub-Catchment	Waste Water Treatment Works		Diffuse Load	Natural load	Total Load	% Contribution
	Name	Load (kg/a P)	(kg/a P)	(kg/a P)	(kg/a P)	
Magalies	Magalies	**830**	**84**	**386**	**1 300**	**0.37**
Swartspruit			**2 757**		**2 757**	**0.79**
Upper Crocodile	Randfontein	9 610				
	Percy Steward	11 389				
	Driefontein	1 854				
	Total	**22 853**	**1 837**	**325**	**25 015**	**7.17**
Jukskei	Esther Park	166				
	Kelvin P/S	2 500				
	Northern Works	42 142				
	Total	**44 808**	**108 830**	**324**	**153 962**	**44.15**
Hennops	Hartbeesfontein	5 969				
	Olifantsfontein	42 243				
	Sunderland Ridge	48 753				
	Rietvlei Dam	-3 606	3 609			
	Total	**93 359**	**70 570**	**248**	**164 177**	**47.08**

Sub-Catchment	Waste Water Treatment Works		Diffuse Load	Natural load	Total Load	% Contribution
Lower Crocodile Increment catchment (estimate)					1 500	0.43
Total for Catchment		**161 850**	**184 077**	**1 284**	**348 711**	**100.00**

Most of the load generated in the Hartbeespoort Dam Catchment emanates from two sub-catchments, namely the Jukskei and the Hennops, which together represent 91% of the load. The other significant sub-catchment is the Upper Crocodile, which contributes 7.2% of the load. Together these three sub-catchments contribute almost 99% of the load.

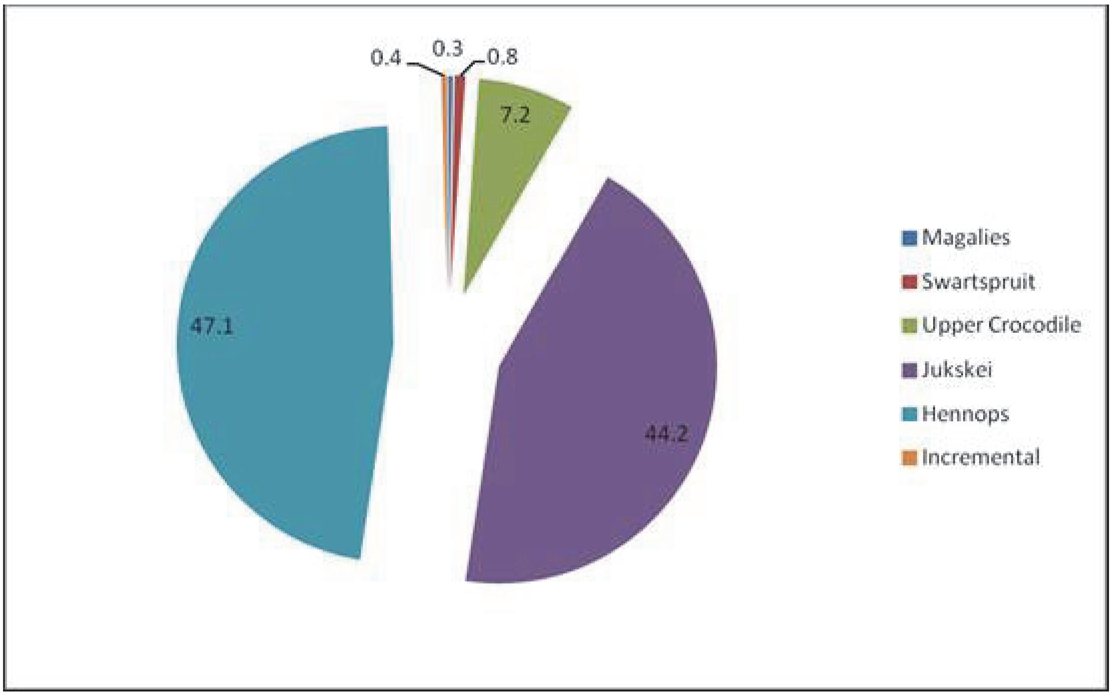


Figure 15-3: Load distribution (%) from the sub-catchments

The load is almost equally divided between point sources and diffuse sources, with the natural background contribution representing a negligible contribution. The contribution from diffuse sources is larger than from the point sources.

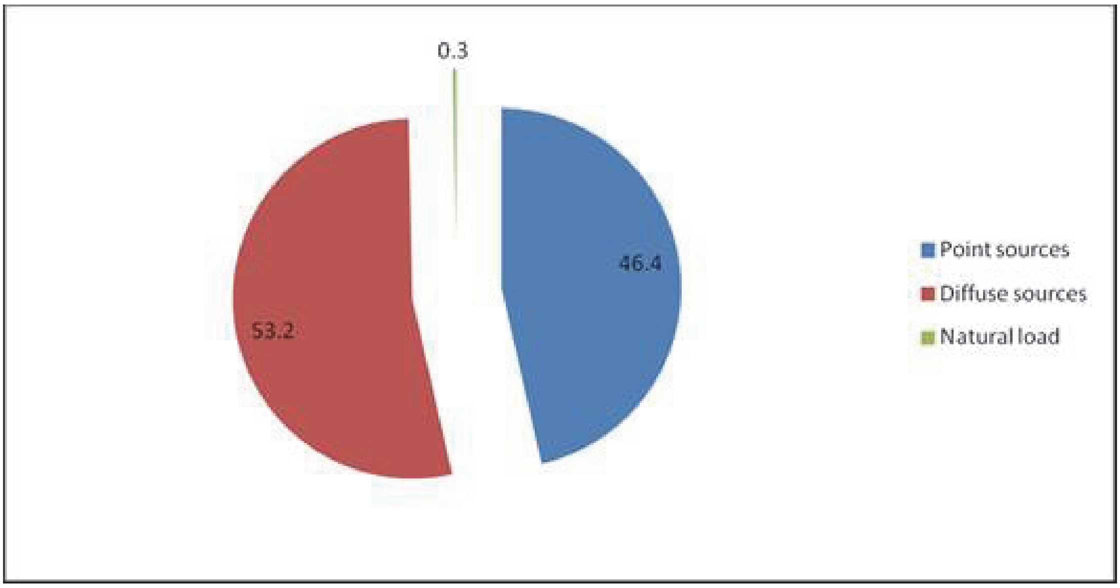


Figure 15-4: Load distribution (%) per category

The diffuse sources can for all practical purposes be allocated to overflowing and leaking sewers, as this accounts for 99% of the load. The associated flow is about 7% of the flow discharged by the point sources.

Table 15-6: 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	178 516	98.28
Higher base flow	396	0.22
Irrigation return flows	190	0.10

Three waste water treatment works, namely Northern Works, Olifantsfontein and Sunderland Ridge together contribute 80% of the point source load.

Table 15-7: Point source contributions

WWTW	Load (kg/a)	%
Magalies	830	0.5

WWTW	Load (kg/a)	%
Randfontein	9 610	5.8
Percy Steward	11 389	6.9
Driefontein	1 854	1.1
Esther Park	166	0.1
Kelvin P/S	2 502	1.5
Northern Works	42 142	25.5
Hartbeesfontein	5 969	3.6
Olifantsfontein	42 243	25.5
Sunderland Ridge	48 753	29.5
Total	**165 458**	**100**

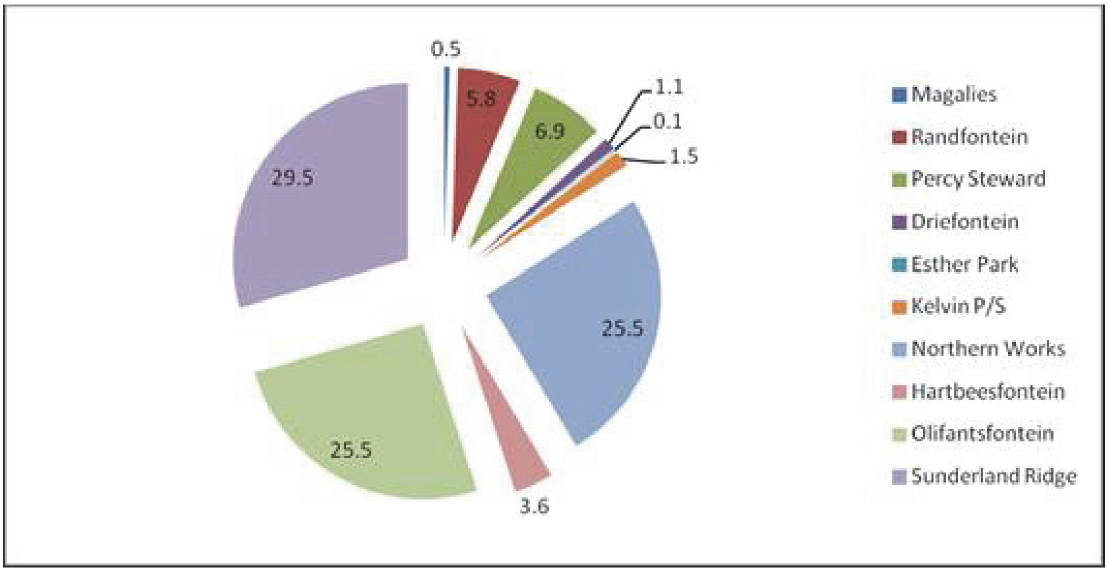


Figure 15-5: Point Source Contributions

15.5 Management Objectives

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). The process occurs naturally over geological time, or may be accelerated due to allochothonous anthropogenic impacts often referred to as "cultural" eutrophication. Phosphorous, 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 1070s. As a result of the eutrophication of the Hartbeespoort Dam this catchment was identified as a priority area for the implementation of the Waste Charge Discharge System 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. Harding (2008) states 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) 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 to concentration of in lake phosphorus result in an observed increase in the frequency of problematic conditions such as algae blooms.

The trophic states are defined in Rossouw *et al.* (2008) as:

- Oligotrophic indicates the presence of low levels of nutrient levels which results

- in no water quality problems,
- Mesotrophic indicates intermediate levels of nutrients, emerging signs of water quality problems,
- Eutrophic indicates high levels of nutrients and an increasing frequency of water quality problems, and
- Hypertrophic indicating excessive levels where plant production is governed by physical factors and water quality problems are almost continues.

Water quality problems may include the spread of hyacinth and the increasing incidence of cyanobacterial blooms. Therefore should this rate of phosphorus loading be known this will allow the setting of limits on nutrient discharges on a sub-catchment level in order to reach the desired in-lake condition.

According to the OECD(1982) lake management problems can be related to trophic categories by considering the degree of impairment of use connected with each trophic category. For most water-use aspects impairment is minimal for oligotrophic lakes and highest for eutrophic and hypertrophic lakes while mesotrophic lakes occupy an intermediate position.

Table 15-8: Trophic characterisation of lakes impairment of various uses (OECD, 1982)

Limnological characterisation	Oligotrophic	Mesotrophic	Eutrophic
General level of production	Low	Medium	High
Biomass	Low	Medium	High
Green and/or blue-green algae fractions	Low	Variable	High
Hypolimnetic oxygen content	Low	Variable	Low
Impairment of multipurpose use of lake	Little	variable	great

The OECD determined that the probability distribution of the boundaries for the different trophic state as reflected in **Figure 15-6** and this system reflects a prediction that is close to reality.

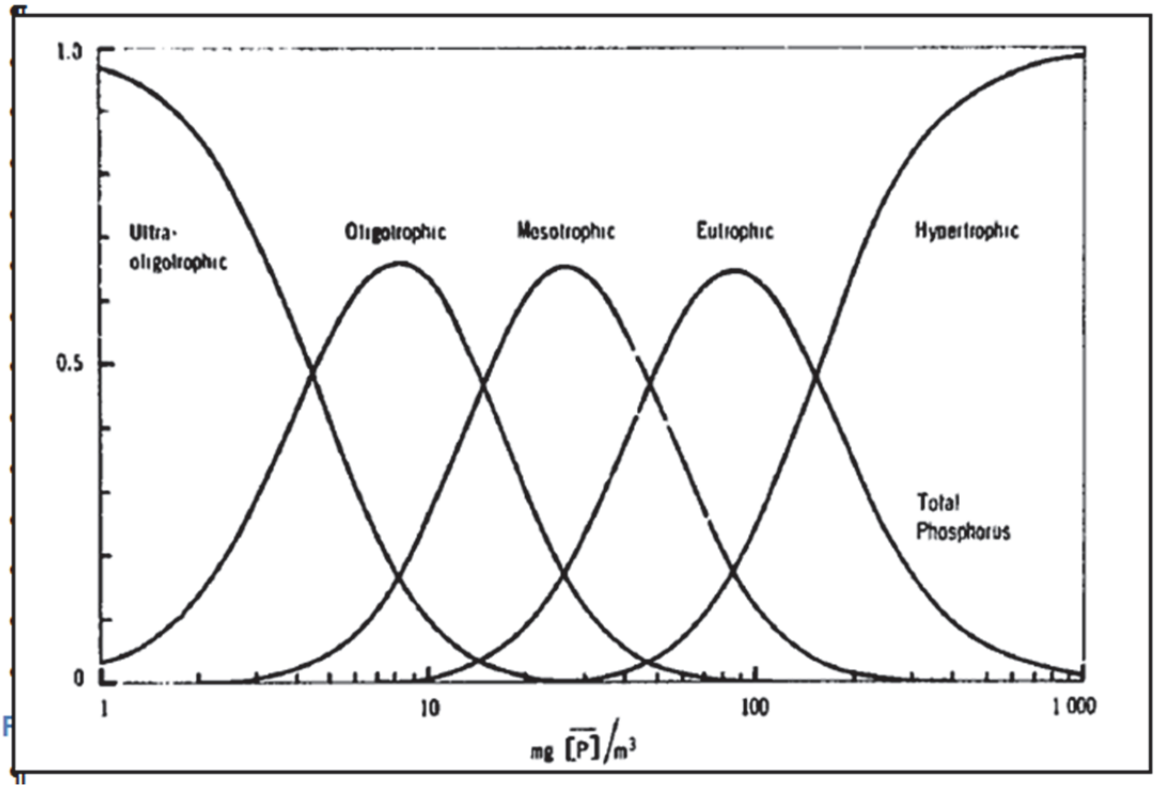


Figure 15-6: Probability distribution for trophic categories

With minor alterations these have been adopted for the South African context. The Department of Water Affairs has set or is using the Trophic State boundaries set out in **Table 15-9**.

Table 15-9: Trophic state classification boundaries (per DWA guidelines) (Harding, 2008) (Values expressed as annual medians)

Variable	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
Total Phosphorous (mg/ℓ)	<0.15	0.015-0.047	0.048-0.130	> 0.130
Median Chlorophyll –a (µg/ℓ)	0-10	11-20	21-30	>30
% time chlorophyll –a >30 µg/ℓ	0	<8	8-50	>50

The threshold defining the boundary between the mesotrophic and eutrophic conditions in South African reservoirs has been determined as 55 µg per litre (Rossouw et al., 2008) as indicated in Figure 15-7. In order to achieve this condition in Hartbeespoort Dam, the estimated required load reduction would be eighty-one percent (81%) of the current aggregate load of 348 000 kg per annum. Accordingly, the allowable load would be 68 000 kg per annum (Harding 2012).

A reduction of 80% is not achievable in the short to medium term and it is proposed that an interim target of 85 µg/ℓ PO_4 be set. 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.

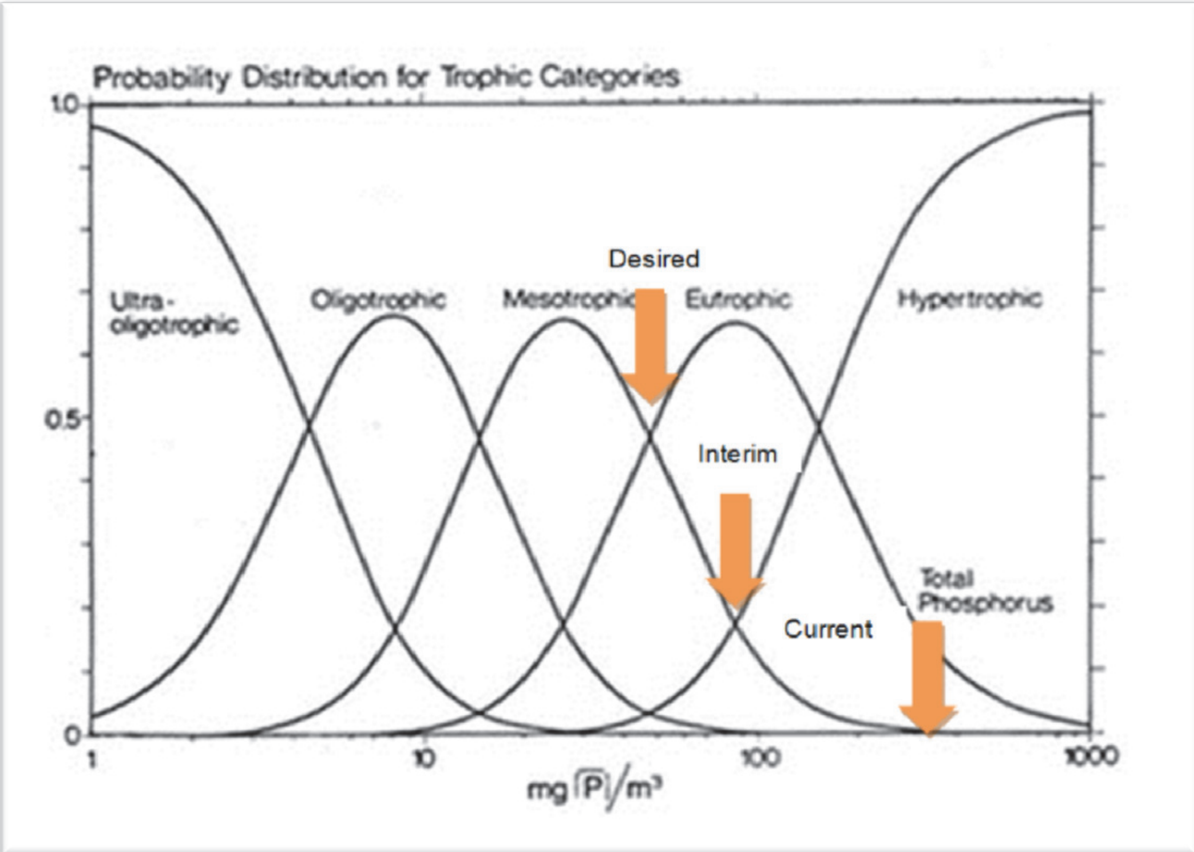


Figure 15-7: Optimal PO4 concentration

The interim target represents an annual load of 110 tonne P per annum, which requires a reduction of 238 tonne. Currently the point sources contribute 173 tonnes per annum while the diffuse load contributes 184 tonnes per annum. The proposed reduction targets are shown in the table below.

Table 15-10: Phosphate reduction targets for point and non-point sources

Description	Unit	Point Sources	Non-point Sources	TOTAL
Current load	tons	165	184	349
Interim target (85µg/L)				
Load	tons	90	130	220
Percentage reduction	%	55	71	63

The reduction in the diffuse load was set in order to achieve the overall load reduction and is not based on any modelling.

The point source contribution can be reduced by the target reduction if all discharges complied with a 0.3 mg/l standard (as currently achieved by the Northern Works WWT). If all works were to comply with the existing 1 mg/l standard, this would already result in a 31% reduction in load from the point sources. A later standard of 0.15 mg/l would reduce the point source load by 78%, but this will require further research and development to achieve.

Table 15-11: Point Source load reduction objectives

WWTW	Current	1 mg/L	0.3 mg/L	0.15 mg/L
Magalies WWTW	830	139	42	21
Randfontein WWTW	9610	3807	1142	571
Percy Steward WWTW	11389	6185	1856	928
Driefontein WWTW	1854	1854	1854	1622
Esther Park WWTW	166	166	62	31
Northern Works WWTW	42142	42142	42142	22143
Kelvin Power Station	2502	2502	755	378
Hartbeesfontein WWTW	5969	5969	5833	2916
Olifantsfontein WWTW	42243	28601	8580	4290
Sunderlandridge	48753	22083	6625	3312
TOTAL	165458	113448	68891	36211
Load reduction		52010	96568	129247
% Reduction		**31**	**58**	**78**

15.6 Required Management Actions

The required management actions can to all intents and purposes be divided into two categories. The first category consists of actions to reduce the load, while the second consists of in-lake management options to mitigate the effect of the high nutrient loading.

Reducing the load should focus on the one hand on point source management actions, and on the second hand on the sewer systems. The required management actions are discussed briefly below.

15.6.1 Load reduction

15.6.1.1 Point Sources

The required actions are as follows:

- Upgrading and refurbishing all existing dysfunctional WWTWs.
- Reducing the current discharge standard from 1 mg/L to 0.3 mg/L for all Waste Water Treatment Works over an achievable period of 3 to 5 years.

This will create the legal framework within which to enforce improved performance at the WWTWs.

- Implementing the changes and improvements that are required at the various WWTWs to achieve the required 0.3 mg/L standard. This will greatly reduce the load going into the resource.

15.6.1.2 Intervention 1A: Upgrade Olifantsfontein to 1 mg/L phosphate discharge

Four WWTWs have been discharging above the existing 1 mg/L standard for phosphate. However, Randburg and Tshwane are currently upgrading their WWTWs. The unit cost for these upgrades was used as estimates for upgrading Olifantsfontein WWTW to the 1 mg/L discharge standard. The cost for the upgrade involves high capital costs estimated at R10 million/ML/day. The overall cost for upgrading the Olifantsfontein is therefore estimated at about R1 050 million. The additional operational costs for the upgrade have been assumed to be negligible, as improved systems tend to be less expensive to operate.

Cost: R1 050 million

Potential Load Reduction: 52 tons PO_4

15.6.1.3 Intervention 1B: Improve discharge standard for phosphate to 0.3 mg/L

This involves improving the discharge standard for phosphate for all WWTWs, besides Driefontein and Northern Works, to 0.3 mg/L; the two WWTWs mentioned already meet the discharge standard of 0.3 mg/L. The costs for the improving the process to biological treatment are estimated at R1million/ML/day, with a reduction in on-going costs associated with chemical savings. The overall cost for improving the phosphate discharge standard to 0.3 mg/L is therefore estimated to be a once-off cost of about R275 million, and would be expected to be implemented over a period of 5 to 10 years.

Cost: R275million

Potential Load Reduction: 42 tons PO_4

15.6.1.4 Intervention 1C: Improve discharge standard for phosphate to 0.15 mg/L

In order to achieve the ultimate goal for load reduction, the discharge standard for phosphate for all WWTWs will have to be reduced to 0.15 mg/L. It should be noted that some WWTWs already achieve this standard, albeit not consistently. The cost for the improved treatment is estimated at R1million/ML/day. The overall cost for improving the phosphate discharge standard to 0.15 mg/L is therefore R760 million, and is only expected to be implemented after 10 years if the total point load continues to increase in the catchment due to population and economic growth.

Cost: R760million

Potential Load Reduction: 33 tons PO_4

15.6.1.5 Intervention 1D: Implementation of the required improvement to the WWTWs

The implementation of the required upgrades and improvements to the WWTWs is the responsibility of the different local authorities. The main challenge here is to obtain the necessary funding to pay for professional services and the physical work. An estimation of the costs involved is given in **Table 15-12**. Please note that these costs are also included in Interventions 1A, B and C.

Table 15-12: Calculated costs for upgrading and improving WWTWs in Hartbeespoort Dam Catchment

WWTW	Owner	Design Capacity (ML/day)	Cost (R million)			
			Upgrade to 1 mg/L	Improvement to 0.3 mg/L	Improvement to 0.15 mg/L	Total
Driefontein	CJMM	35			35	35
Northern Works	CJMM	450			450	450
Sunderland Ridge	CTMM	65		65	65	130
Randfontein	MCLA	20		20	20	40
Percy Stewart	MCLA	37		37	37	74
Magalies	MCLA	3		3	3	6
Olifantsfontein	EMM	105	1050	105	105	1260
Hartbeesfontein	EMM	45		45	45	90
Total			**1050**	**275**	**760**	**2085**

15.6.1.5.1 Diffuse Sources

15.6.1.5.2 Intervention 2A: Integrated Monitoring and Regulatory System

Improving monitoring systems, with increased monitoring sites, increased sampling and an improved regulatory capacity through the appointment of pollution control officers in order to correctly attribute the loads from the non-point sources in the area will be fundamental to be able to manage and control diffuse source discharges. At present there is no legislation that allows for compliance monitoring and enforcement of diffuse sources, and this will have to be put in place first.

While significant development has occurred in the Hartbeespoort Dam Catchment, the number of monitoring points has remained stagnant or decreased. The current National Monitoring Programme does not provide sufficient data to assess:

- Nutrient and sediment inflow into the dam during stormflow conditions
- Chemical and physical water parameters in the dam during biological surveys
- Nutrient and sediment outflows from the dam during times that the sluices are open
- Changes in dam dynamics short and long term periods at different levels
- Actual sources and their types contributing to the non-point load.

The last point is probably the single most important deficiency in the monitoring system. Although water quality samples are collected, there is no associated flow measurement, which renders the determination of loads impossible.

The costs involved in increasing the number of monitoring sites in the catchments is not only limited to the capital costs of actually implementing of the monitoring site, but also includes costs associated with regular maintenance, human resources to monitor, collection and analysis of the data that stems from the monitoring site.

A similar monitoring scheme was established in the Jukskei sub-catchment. Based on those costs, the estimated capital costs for implementing further monitoring sites in the Hartbeespoort catchment will be R5 million, with an annual cost of R700 000 to employ a pollution officer in the catchment to collect the data and have it analysed.

Cost: R5million (capital) & R0.7million/a (operational)

Potential Load Reduction: none

15.6.1.5.3 Option 2B: Rehabilitation of failing pump stations

Approximately 98% of the non-point phosphate load entering the catchment is estimated to be from overflowing, leaking or failing sewers, with the remaining load stemming from urban washoff, water supply leakage and increased urban/peri-urban baseflow. The sewage pump stations, in particular, have failed frequently since the rolling brown outs due to load shedding by Eskom in the late 1990s. This resulted in the blockages in the pumps. The cost for rehabilitating the pump stations are estimated at R275million. Should these pumps be rehabilitated, it is estimated that an additional 40% of the load would be removed from the system, although this will increase the influent load to the waste water treatment works. The identification and prioritisation of these pumps should also be included in Management Action 1A.

Cost: R275million

Potential Load Reduction: 70 tons PO_4

15.6.1.5.4 Option 2C: Refurbishment of sewers

An additional phosphate load is being discharged to the resource due to the under-capacity and poor design of the current sewer system in the catchment and requires the fixing. The main sewer lines in the catchment of the Hartbeespoort Dam closely follow the rivers and streams in order to make use of the topography to convey sewage under gravity. This means that any leakage or overflow from the system ends up almost directly into the rivers and streams. The capacity of sewer systems has not always kept pace with urban densification (flats built on stands originally intended for houses, subdivision of large stands into smaller properties) and storm water ingress into the sewer system is an ever present problem.

The true extent of the contribution from sewer systems to the diffuse load can only be surmised at this point in time. The monitoring programme would assist greatly in getting more accurate data and consequently, having focussed interventions to mitigate the impact from the overflowing sewers. In addition, improved urban design and by-laws should also be considered in the management of this problem to stop the flow of raw sewage directly into the water resources.

It is unknown as to the cost of the interventions or the potential load reduction and these should be clarified in the rehabilitation plan. A ball park figure for the cost is estimated around R800million.

Cost: unknown (estimate R 800 million)

Potential Load Reduction: unknown

15.6.1.5.5 Option 2D: General Sewer Monitoring

Much of the phosphate load entering the dam can be reduced by ensuring that the sewers are maintained in a workable condition, including an efficient monitoring and response system by the municipalities. It is unknown as to the cost of the interventions or the potential load reduction and should be clarified in the refurbishment plan, but the cost could potentially be over R500million.

Cost: Unknown (estimate R 500 million)

Potential Load Reduction: unknown

15.6.2 In-Lake Mitigation

15.6.2.1 Intervention 3A: Hartbeespoort Dam Biological Remediation

Work is currently being conducted under the Hartbeespoort Dam Biological Remediation programme. The program involves the physical removal of hyacinths, litter, debris, unwanted fish and sediments. The programme also looks at floating wetlands and shoreline rehabilitation, eco-system restructuring and on-going management to limit the impacts in the catchment. The estimated costs to conduct all these measures are estimated at R30million/yr. Although the mitigation measures do not necessarily reduce a significant portion of the phosphate load from the dam, the programme limits the impact experienced by the users, which can be equated to an “equivalent” load reduction to lower hypertrophic conditions.

This intervention should be funded from the Waste Discharge Charge System.

Cost: R30 million/a

Potential Load Reduction: estimated at 34 equivalent tons/a PO_4

15.7 Sources of Funding

It is highly unlikely that the local authorities will find the funding for all the required actions on their own budgets. However, a number of grants are available as possible sources of financing the work.

Regional Bulk Infrastructure Grants

The National Treasury through the annual Division of Revenue Act (DORA) allocates the Regional Bulk Infrastructure Grant (RBIG) to DWA (Vote 38). RBIG is a conditional grant in terms of Schedule 6B of the DORA and is an allocation-in-kind to municipalities for designated special programmes.

Municipal Infrastructure Grant

The National Treasury is responsible for allocating the Municipal Infrastructure Grant (MIG) to CoGTA in terms of Schedule 5B the Division of Revenue Act (DORA). In terms of the 2013 DORA, MIG is a specific purpose conditional grant, the purpose of which is “to provide specific capital finance for basic municipal infrastructure backlogs for poor households, micro enterprises and social institutions servicing poor communities.”

Municipal Water Infrastructure Grant

The National Treasury is responsible for allocating the Municipal Water Infrastructure Grant (MWIG) to the DWA, through the DORA (Vote 38). The strategic goal of MWIG is to assist Water Services Authorities (WSAs) to provide water supply services to consumers currently without services, particularly those in rural areas. The purpose of the MWIG is “to facilitate the planning, acceleration and implementation of various projects that will ensure water supply to communities identified as not receiving a basic water supply service.”

Rural Household infrastructure Grant

The National Treasury is responsible for allocating the Rural Household Infrastructure Grant (RHIG) to the Department of Human Settlements. This grant was introduced as a catalyst to support the 2014 target of providing universal access to water and sanitation by 2014. The purpose of RHIG is “to provide specific capital funding for the reduction of rural water and sanitation backlogs and to target existing households where bulk-dependent services are not viable”.

In order to access funding to the different grants, the local authorities will have to prepare the necessary applications in the format that is required. This is required urgently, as budget cycles tend to be long.

15.8 Conclusion

The required actions can be summarised as shown below.

Table 15-13: Summary of Interventions

Intervention	Description	Capital Cost (R million)	Running Cost (R million/a)	Responsibility
1A	Upgrade Olifantsfontein to 1 mg/L phosphate discharge	1 050		Ekurhuleni
1B	Improve discharge standard for phosphate to 0.3 mg/L	275		DWS
1C	Improve discharge standard for phosphate to 0.15 mg/L	760		DWS
1D	Implementation of the required improvement to the WWTWs	-	-	Local Authorities
2A	Integrated Monitoring and Regulatory System	5	0.7	DWS
2B	Rehabilitation of failing pump stations	275	-	Local Authorities
2C	Refurbishment of sewers	800		Local Authorities
2D	General Sewer Monitoring	500		Local Authorities
3A	Hartbeespoort Dam Biological Remediation		30	CMA

15.9 References

Department of Water Affairs 2008, The Development of a Reconciliation Strategy for the Crocodile (West) Water Supply System, DWA Report P WMA 03/000/00/3608

Department of Water Affairs, Implementation of the Waste Discharge Charge System, Monitoring and Evaluation framework, 2013

Harding WR 2008 Determination of Annual Phosphorous Loading Limits for South African Dams. Water Research Commission 1687/1/08

Harding WR 2012 Hartbeespoort Dam: Modelling of nutrient (Phosphorous) load reduction necessary to attain the in lake mesotrophic/ eutrophic boundary

Rossouw JN, Harding WR and Fatoki OS 2008: A Guide to Catchment Scale Eutrophication Assessments for Rivers, Reservoirs and Lacustrine Wetlands Water Research Commission 1643/08.

16 Appendix 4. Acid Mine Drainage in the Hartbeespoort Catchment

Prof. JP Maree

Mine Water That Influences the Water Quality in the Hartbeespoort Dam

by

J P Maree (Phillert Trust)

Pretoria

16.1 Background

16.1.1 Hartbeespoort Dam

Several large dams are currently heavily eutrophied (e.g., Rietvlei Dam, Roodeplaat Dam, and Vaal Barrage). The Hartbeespoort Dam has a surface area of 20 km^2, a capacity of 195 000 000 m^3 and a mean depth of 9.6 m. The dams mentioned receive effluent from waste water treatment works in cities, diffuse runoff from squatter camps, dissolved fertilizer nutrients in runoff from agriculture, and industrial effluents. The Hartbeespoort Dam is one example. It is linked to the Vaal River as some its feed water is channelled via the Rand Water distribution system, south of Johannesburg, and its associated sewage treatment plants, to the Crocodile and Magalies Rivers, that feed its catchment (Figure 16-1). The mean depth is 9.6 m and maximum depth 32.5 m. (NIWR, 1985).

It is estimated that sewage treatment plants currently discharge a total of 650 Ml/d of treated sewage into the Hartbeespoort Dam catchment. Other effluents that are impounded by the Dam are from informal settlement areas, agricultural runoff, storm water from industrial sites, e.g. Modderfontein Factory and NECSA and mine water since 2002, when mine water started to decant at 18 Winze in the Western Basin. A consequence of receiving sewage, industrial effluents and storm water is that these carry dissolved nutrients in the form of phosphate and nitrogen that stimulate plant growth. The surfeit of nutrients results in periodic die-off of algae and water hyacinth resulting in odour problems. There are occasional toxic algal (cyanobacterial) blooms. The impoundment is a phosphate sink resulting in increasing enrichment of the water.

Venter (2004) estimated that the water body contains 25 t of phosphate and the sediment in the Dam, 140 t. The inflow of dissolved phosphate was estimated at 20 t /annum while that associated with incoming sediment, at 180 t/annum. Phosphate in sediment can also be released which indicates that incoming phosphate from sewage treatment plants is not the only problem requiring strict control. A solution to eutrophication would be complete removal of nutrients from sewage treatment plant effluent and phosphate from non-point sources, such as squatter camp run-off. This approach cannot provide a practical solution as phosphate levels need to be as low is 0.05 mg/l before eutrophication can be controlled. Due to the shortage of skilled labour in South Africa and the poor performance of municipalities, services are not properly maintained and contribute further to eutrophication of dams. Waters from eutrophic dams contain cyanobacteria (Oberholster & Ashton, 2008) and sediment creates favourable conditions for growth. The frequent collapse of municipal sewage and water treatment services necessitates treatment of polluted water in dams in addition to the measure of treatment that takes place in sewage treatment plants.

Hartbeespoort Dam water is used for irrigation of 160 km^2 of farmland on which a variety of crops are produced. The water is also used for drinking in the towns of Hartbeespoort, Schoemansville, Kosmos and Ifafi, as industrial water and for aquaculture. In addition, the Dam is popular for angling, water sport and recreation activities.

16.1.2 Mine water

Acid mine drainage (AMD) has for many years been a major environmental challenge associated with the mining industry, especially in the Western, Central and Eastern mining basins of Gauteng. In 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 Fe(II), free acid, manganese and uranium. It is detrimental to the environment and the health of humans and animals, is unsuitable for irrigation and threatens the stability of the dolomitic rock at the Cradle of Humankind World Heritage Site. The immediate construction of a neutralisation plant is required for removal of free acid, metals and uranium, and for partial sulphate removal. Similar situations exist in the Central Basin near Boksburg and in the Eastern Basin near Springs. In the Central Basin the water was currently at a depth of 540 m and is rising at an average daily rate of 0.7 m. It is anticipated that decanting of acid mine water, at an expected rate of 60 Mℓ/d, may start soon. The quality of this water is also acidic and saline, similar to the AMD decanting from the Western Basin.

Mine water from the Western Basin (Figure 16-2) may contribute to poor water quality in the Hartbeespoort Dam. Mine water has decanted continuously since September 2002, often exceeding the capacity of the infrastructure put in place to manage it and flowing without treatment into the Tweelopie Spruit, which feeds into the Crocodile River system. This acid mine water may impact on the receiving environment, notably the Cradle of Humankind World Heritage Site. During a high-rainfall season (January-April 2010) the decant volume peaked at 60 Ml/d. Under low-rainfall conditions, the decant volume ranges between 18-24 Ml/d of which around 18 Ml/d is treated by one of the local mining companies. The resulting water is high in salts and has an acidic pH of around 3.8, which does not comply with the discharge standard contained in directives issued by the Department of Water and Sanitation. Although mine water pumping and treatment infrastructure exists in the Western Basin, the technology applied is inadequate in terms of the desired final water quality and the ability to manage the water levels to prevent surface decant. Neutralized mine water typically contains 2 500 mg/l sulphate.

Currently the volumes of water entering the Krugersdorp Game Reserve, provided by Sibanye Gold in February 2015, are as follows:

Treated water discharged	20 Ml/d
Untreated water discharged	12 Ml/d
Total	32 Ml/d

The Expert Team of the Inter-Ministerial Committee on Acid Mine Drainage investigated the matter in 2010 and recommended specific actions to further manage and control the AMD associated with mining on the Witwatersrand (Expert Team, 2011), as follows: (i) installation of pumping facilities in each of the mining basins to maintain the water level below the Environmental Critical Level (ECL); (ii) construction of measures to reduce the water ingress and recharge to the underground mine workings; (iii) treatment of the excess mine water; (iv) comprehensive monitoring; (v) investigation of and addressing other sources of AMD; (vi) investigation of and research to find long-term sustainable solutions; (vii) investigation of the feasibility of implementing an environmental levy on operating mines to fund environmental rehabilitation; and (viii) ongoing assessment and research.

The Department of Water and Sanitation (DWS) has appointed the Trans-Caledon Tunnel Authority (TCTA) to implement the selected recommendations of the Inter-Ministerial Committee on Acid Mine Water (Creamer, 2012). In June 2011, after a tender process, BKS and Golder Associates were appointed to develop a short-term plan to address the immediate concerns of the AMD problem. An urgent task was to neutralise the water decanting in the Western, Central and Eastern Basins (Creamer, 2012). Owing to the huge threat posed by AMD, it was decided by the TCTA to employ proven technology that uses limestone treatment for neutralisation of free acid, followed by additional lime treatment for removal of iron(II) and other heavy metals (van Niekerk, 2011 – pers. comm.). This approach has been applied widely for treatment of AMD (Aubé, 2004). This treatment process (referred to as the 'high density sludge (HDS)' process) consists of a pH correction/sludge conditioning stage, a neutralisation/aeration stage, and a solid/liquid separation stage (Osuchowski, 1992). A due diligence study of the Witwatersrand mining basins estimated the capital cost of AMD neutralisation plants for the three basins at R924 m. As only R255 m. was approved for this project by Cabinet (Creamer, 2012), ways of making up the shortfall of R669 m. need to be identified or, alternatively, options for reducing the high capital cost need to be investigated and applied.

16.1.3 Harties Metsi a Me initiatives

Various biological remediation initiatives have been launched by the Harties Metsi-a-Me Programme to control the eutrophication in the dam, such as(i) floating wetlands; (ii) fish management; (iii) sediment removal and (iv) biomass harvesting (see the review of the HDRP above).

16.2 Objectives

The purpose of this investigation was to determine:

Whether acid mine water contributes to salinisation of the dam water and how it can be prevented;

Can acid mine water be utilized to control eutrophication?

Propose cost-effective ways for removal of sludge and sediment in the dam, and

Design a floating water treatment plant

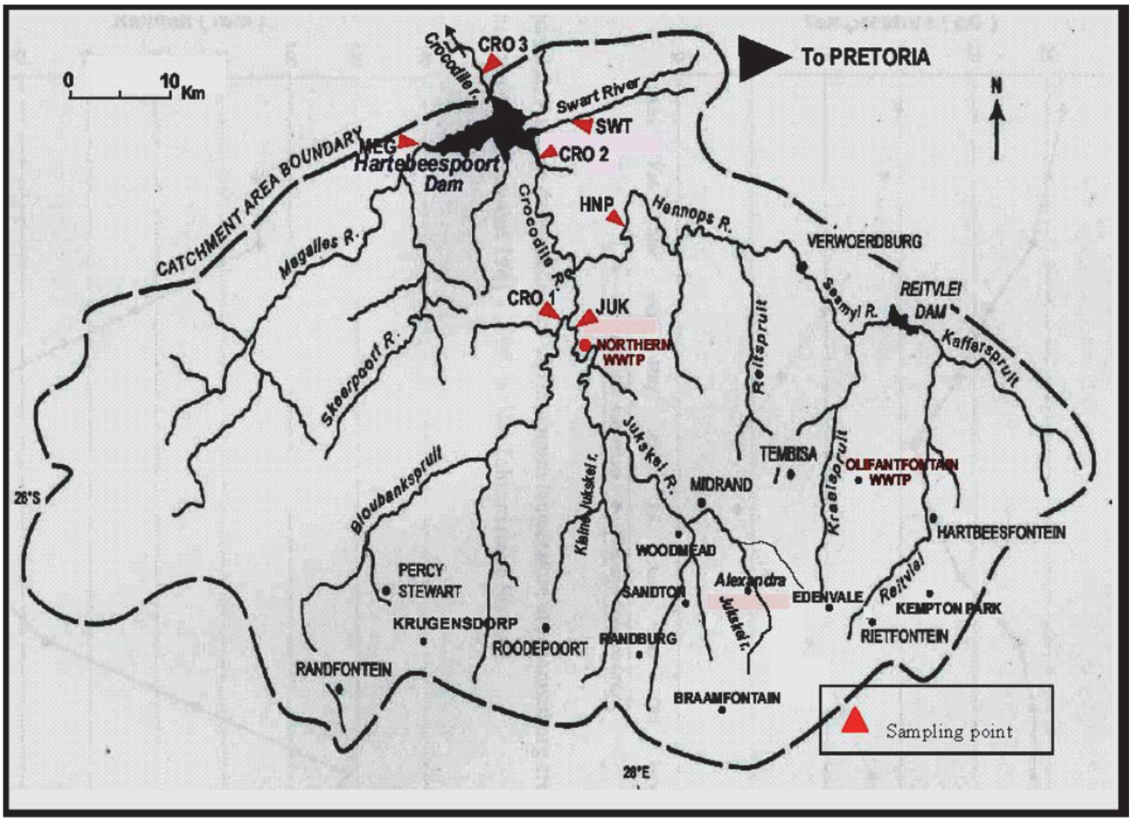


Figure 16-1: The regional setup (A) and the river networks (B) at the HBP Dam Catchment (Dudula,2007)

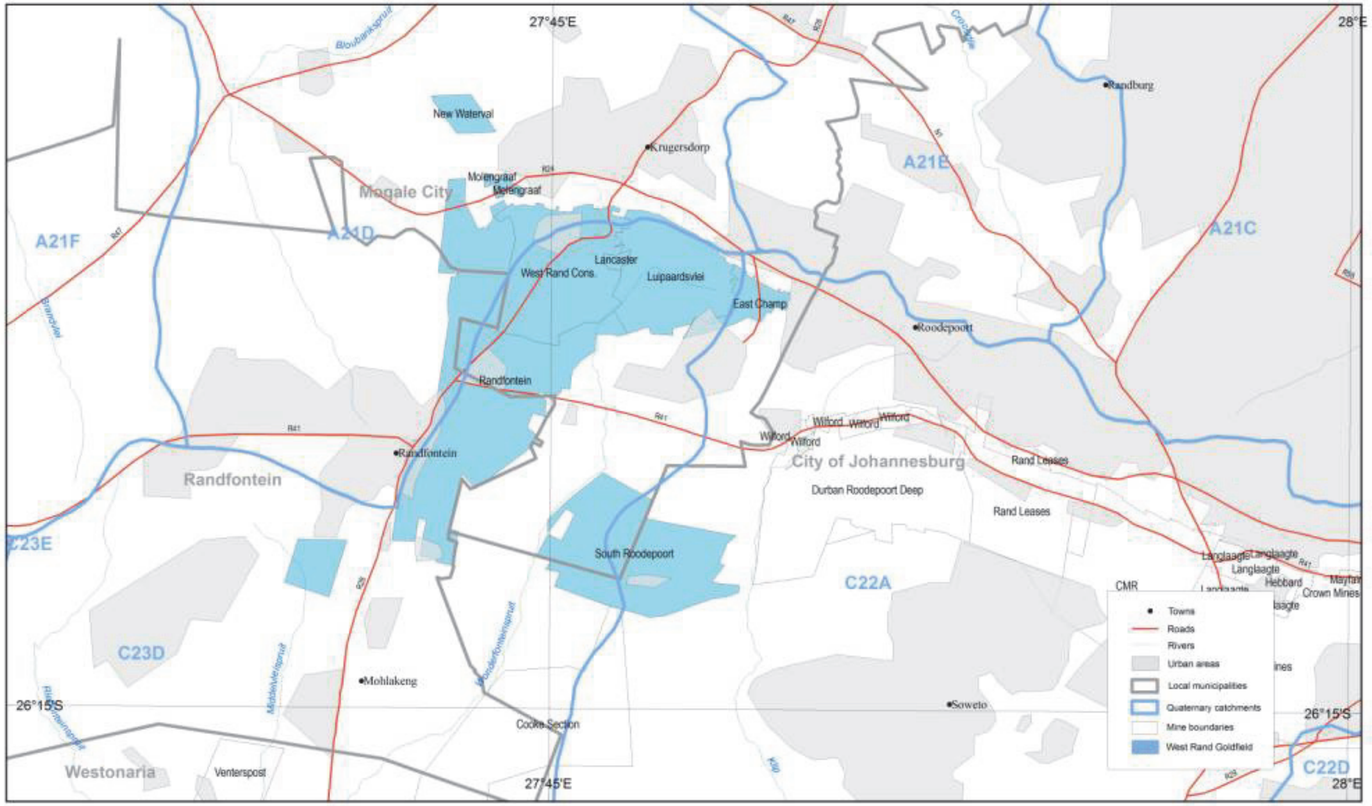


Figure 16-2: Locations of mines in the Western Basin (Expert Team of the Inter-Ministerial Committee, under coordination

16.2.1 EFFECT OF MINE WATER ON HARTBEESPOORT DAM WATER

16.2.1.1 Period 1999 to 2011

The various feed stream volume to the dam amounts to 650 Ml/d. Mining activities in the Western Basin releases between 20-30 Ml/d via the Tweelopiespruit and Bloubankspruit into the Crocodile River. The 20 Ml/d neutralized water has a sulphate concentration of 2 500 mg/l and the 10 Ml/d un-neutralized water, a sulphate concentration of 3 500 mg/l. If mine water enters the Hartbeespoort Dam, it is expected that it would have a negative impact on the quality of the water in the dam with respect to sulphate, due to its high sulphate concentration compared to the other feed streams. Figures 16-3 and 16-4 show the behaviour of various parameters during the period 12 January 1999-14 December 2011. It was noted that sulphate concentration has remained constant at 50 mg/l (HDRP, 2013a). Calcium has increased from 25 to 40 mg/l. Phosphate has increased from 0,1 to 0,2 mg/l (as P) and nitrate + nitrite from 0,8 to 1,9 mg/l (as N). Phosphate should be less than 0,05 mg/l to prevent eutrophication. From this it appears that mine water does not find its way into the Hartbeespoort Dam. Even the analytical results from Sample Point A2H045 (CRO1, the last sampling point in Bloubankspruit, before it joins the Jukskei River) do not show high sulphate concentrations as would be expected if mine water is present. The highest sulphate concentrations measured during 2010 were 100 mg/l. At the end of 2010 an increase in sulphate concentration was observed. It is important that the data for the period 2011-2014 be added to the results reported in Figure 16-3, 16-4 and 16-5.

Hobbs and Cobbing (2007) confirmed that phosphate in the Dam was due to the inflow of treated sewage from various water treatment plants and informal settlements. No mention was made of pollution in the dam due to mine water from the Western Basin via the Tweelopie and Bloubankspruit. Van der Walt (2015, pers. comm.) mentioned the possibility that mine water flows back into the mining void somewhere in the Bloubankspruit. This point needs further investigation. If mine water returns to the void, it needs to be determined where this takes place. More water samples should be collected from surface and groundwater in the area of the Bloubankspruit with the aim to put systems in place at the most appropriate places to minimize environmental pollution.

16.2.1.2 Period after 2011

Hobbs (2014) did a study on the impact of mine water on surface and ground water in the area of the Cradle of Humankind for the period until 2014. His study area is shown in Figure 16-6 which included the Tweelopie Spruit where mine water from the Sibanye Gold neutralization plant passes sampling point F11S12, Bloubankspruit (sampling point BRd), Bloubankspruit sampling points BB@M, BB@PL and ASH049, before entering the Crocodile River). The following observations were made:

Figure 16-7 shows that the sulphate content in the Hippo Dam (between Sibanye Gold neutralization plant and Tweelopiespruit) varied between 2 000-3 000 mg/l for the period 2004-2014. At F11S12 the sulphate concentration was slightly lower – around 2000 mg/l. These results were in line with what is expected from neutralized mine water.

Figure 16-8 shows samples from the Bloubankspruit system and how the sulphate concentration decreased from 3200 mg/l (32 meq/l) at F11S11 to 600 mg/l (6 meq/l) at

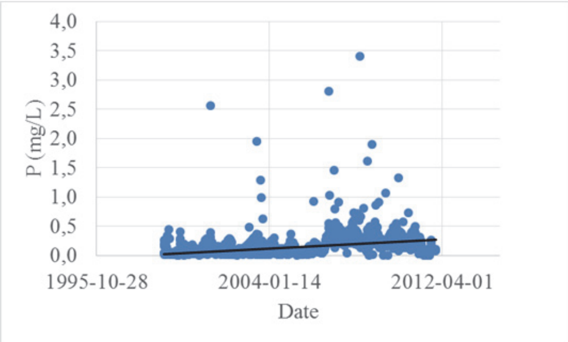
BB@M to 200 mg/l (2 meq/l) at BB@PL. The results reflected the strong mine water impact at station F11S12, at the lower end of the Tweelopie Spruit (Figure 16-6) to a typical CaMg-HCO_3 dolomitic character represented by the Kromdraai Spring ground water. This pattern was explained by mine water flowing into the underground karst aquifer and getting replaced with good quality Kromdraai Spring groundwater. Figure 16-9 shows the SO_4 load in mine water lost to groundwater during the period of September 2009-September 2014. A gradual decrease in the SO_4 load was observed. This was ascribed to the aquifer having become saturated with mine water. Mine water that enters the karst aquifer will appear on surface a few years later.

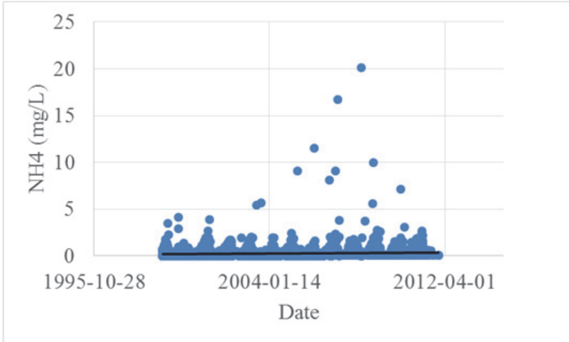
Figure 16-10 shows the SO_4 concentration in the surface water passing station A2H049. The SO_4 concentration was constant between 70-100 mg/l during the period 2002 when decant started) until February 2010. Since February 2010, when the volume of decant started to increase, the SO_4 increased to 200 mg/l during February 2014 and to 430 mg/l during August 2014. This clearly showed that sulphate levels in the Hartbeespoort Dam will start to increase as the aquifers between the Western Basin and the Dam become saturated with mine water. It is calculated in Table 16-1 that when 25 Ml/d of the 650 Ml/d feed water to the Dam is replaced with mine water that contains 2 500 mg/l SO_4, instead of the current 50 mg/l, the SO_4 concentration in the outflow of the Dam will increase from 50-200 mg/l. Since the aquifer is rich in limestone/dolomite deposits, it can be assumed that no acid mine water will enter the Dam. The water will always be neutralized while flowing through the karst aquifer, resulting in water with a typical sulphate concentration of 2 500 mg/l and a pH of 7.

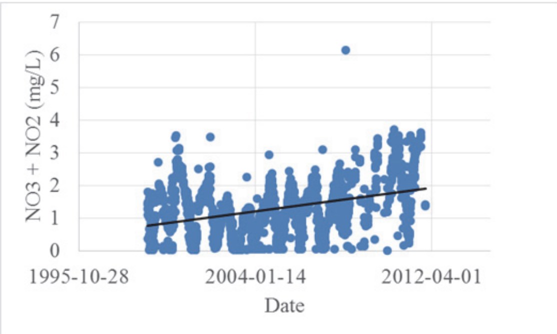
From the above analyses of the impact of mine water on the Hartbeespoort Dam it is clear that the ideal solution for the Hartbeespoort Dam should meet the following criteria:

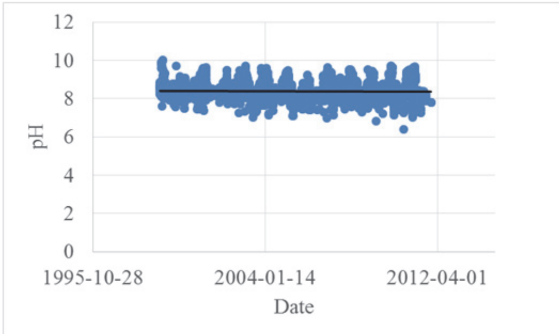
Phosphate in dam water needs to be controlled to below 0,05 mg/l to limit eutrophication.

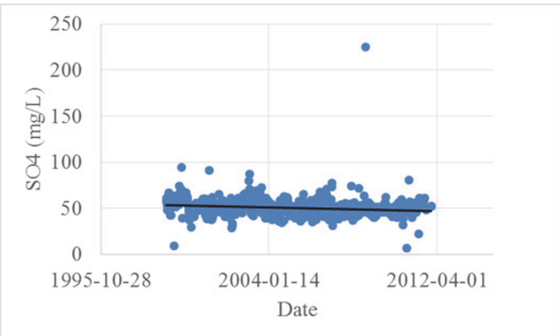
Mine water will impact on the salinity of the dam water and needs to be used / processed separately in the most cost-effective way.

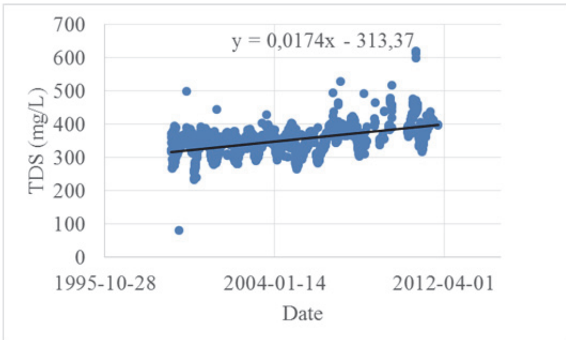
<table>
<tr>
<td>


</td>
<td>


</td>
</tr>
<tr><td>Phosphate</td><td>Ammonia</td></tr>
<tr>
<td>


</td>
<td>


</td>
</tr>
<tr><td>Nitrate + Nitrite</td><td>pH</td></tr>
<tr>
<td>


</td>
<td>


</td>
</tr>
<tr><td>Sulphate</td><td>Total dissolved solids</td></tr>
</table>

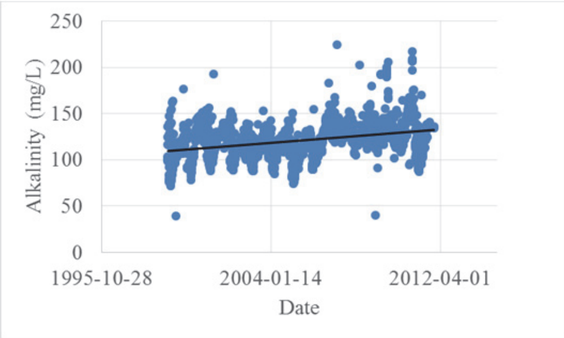
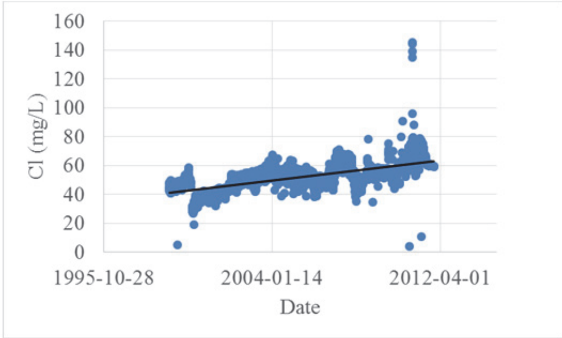
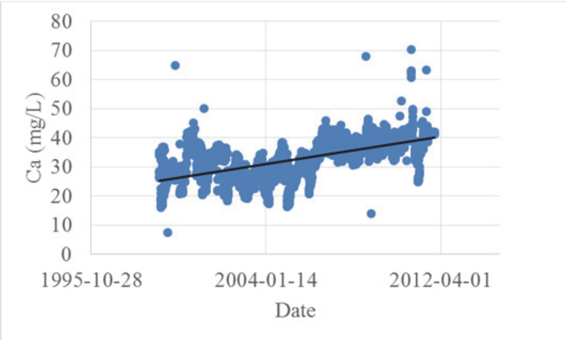
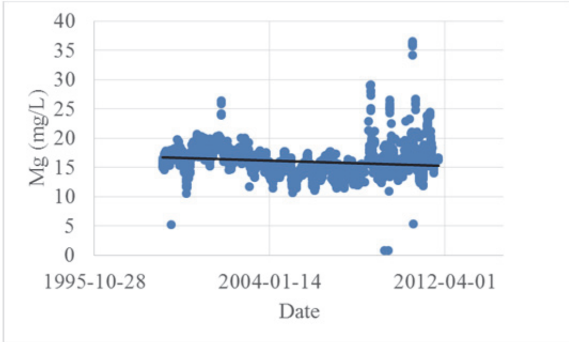
	
Alkalinity	Chloride

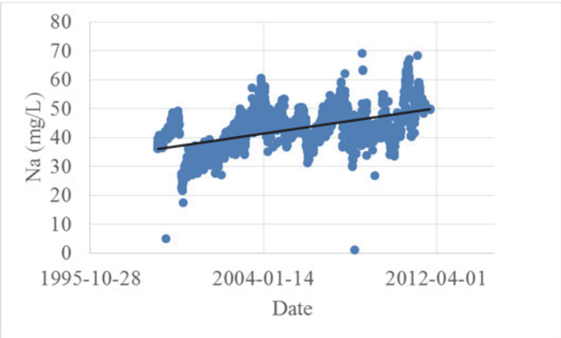
Figure 16-3: Water quality of the outflow from Hartbeespoort Dam (Sample Point: A2R001) during the period 12 January 1999 to14 December 2011 (Huizenga et al., 2013)



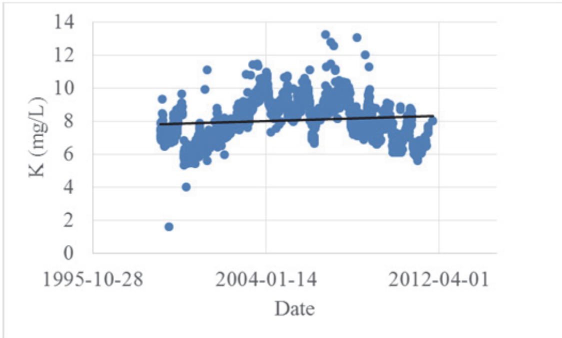
Calcium



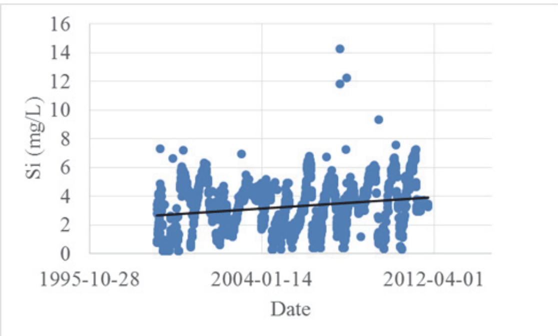
Magnesium



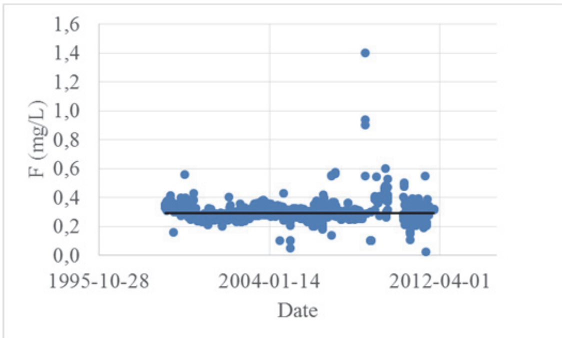
Sodium



Potassium

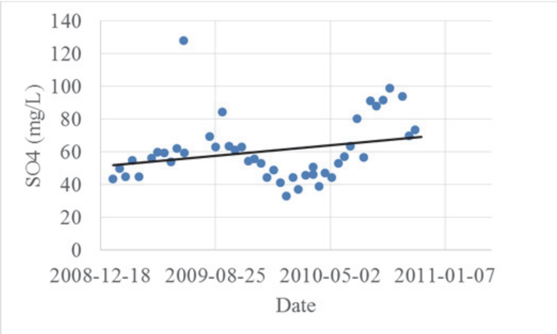


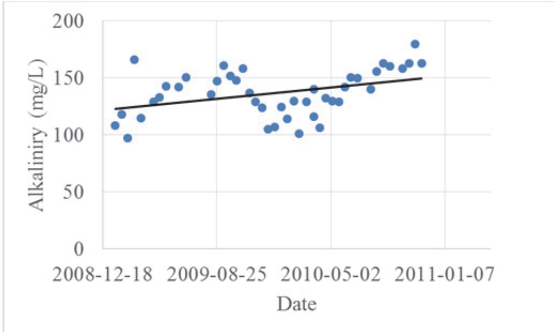
Silica



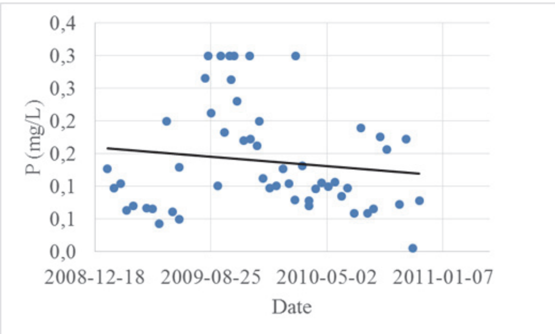
Fluoride

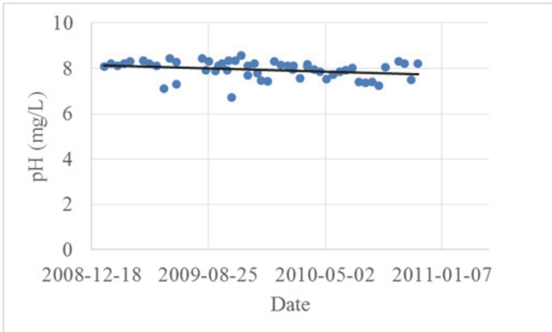
Figure 16-4: Water quality of the outflow from Hartbeespoort Dam (Sample Point: A2R001) during the period 12 January 1999 to 14 December 2011 (Huizenga et al., 2013)





SO_4	Alk





P	pH

Figure 16-5: Water quality of the outflow from Hartbeespoort Dam (Sample Point: A2H045) during the period 14 January 2009 to 12 January 2010 (HDRP Monitoring Data)

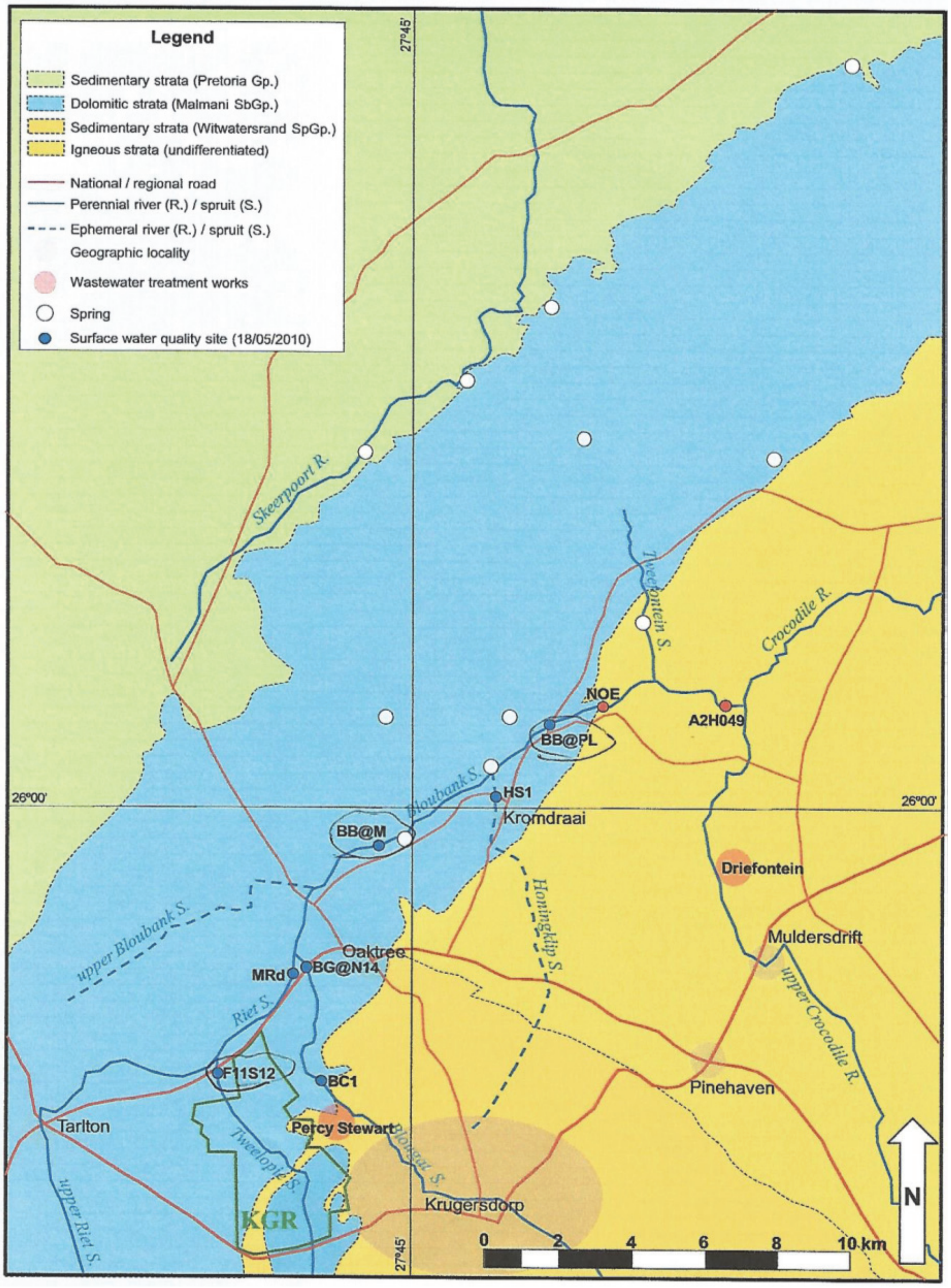


Figure 16-6: Surface water quality sampling sites (Hobbs, 2014)

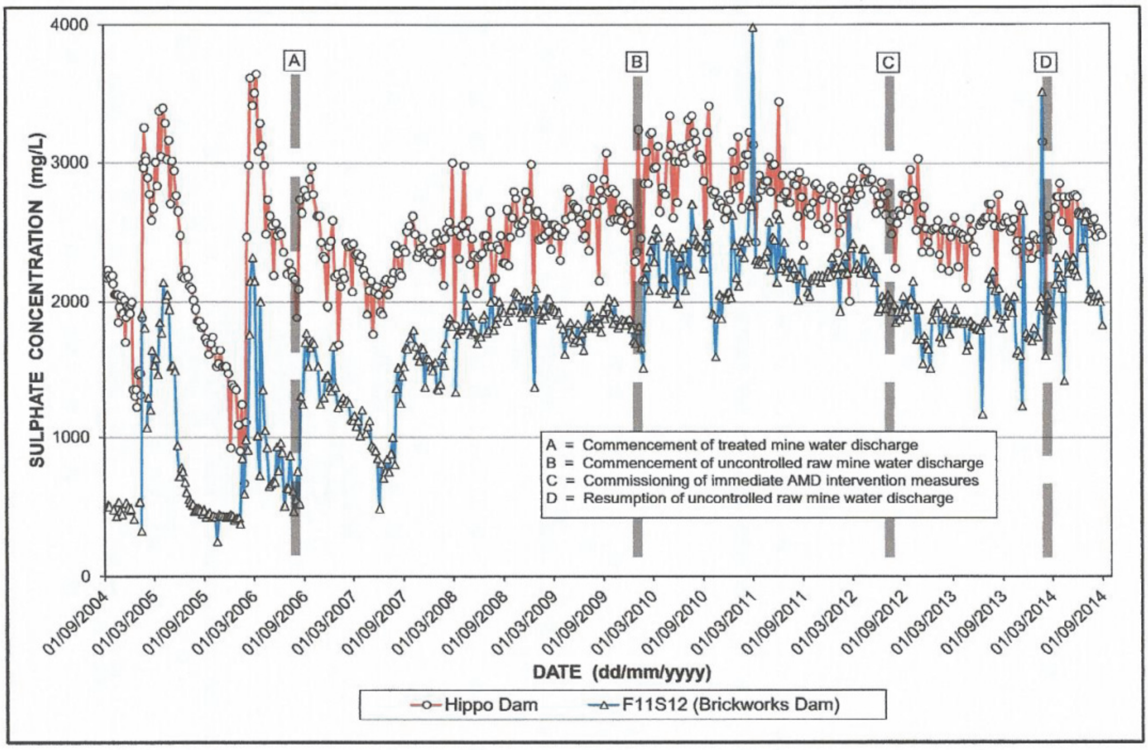


Figure 16-7: Pattern of sulphate values in the Tweelopie Spruit during the period September 2004 to September 2014

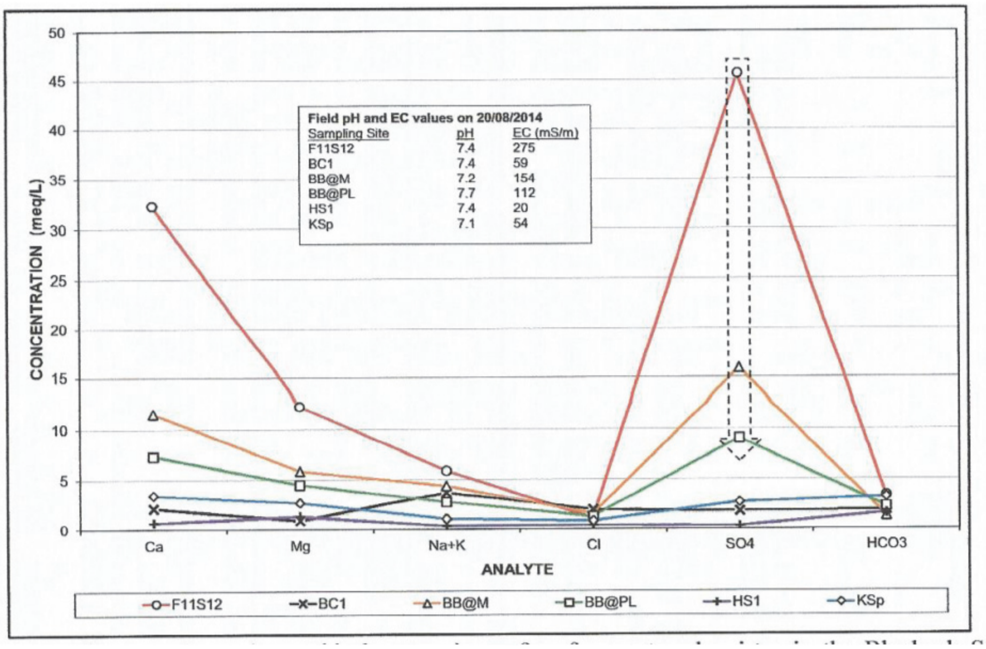


Figure 16-8: Synoptic graphical comparison of surface water chemistry in the Bloubankspruit system on 20/08/2014; see Figure 15-6 for station localities

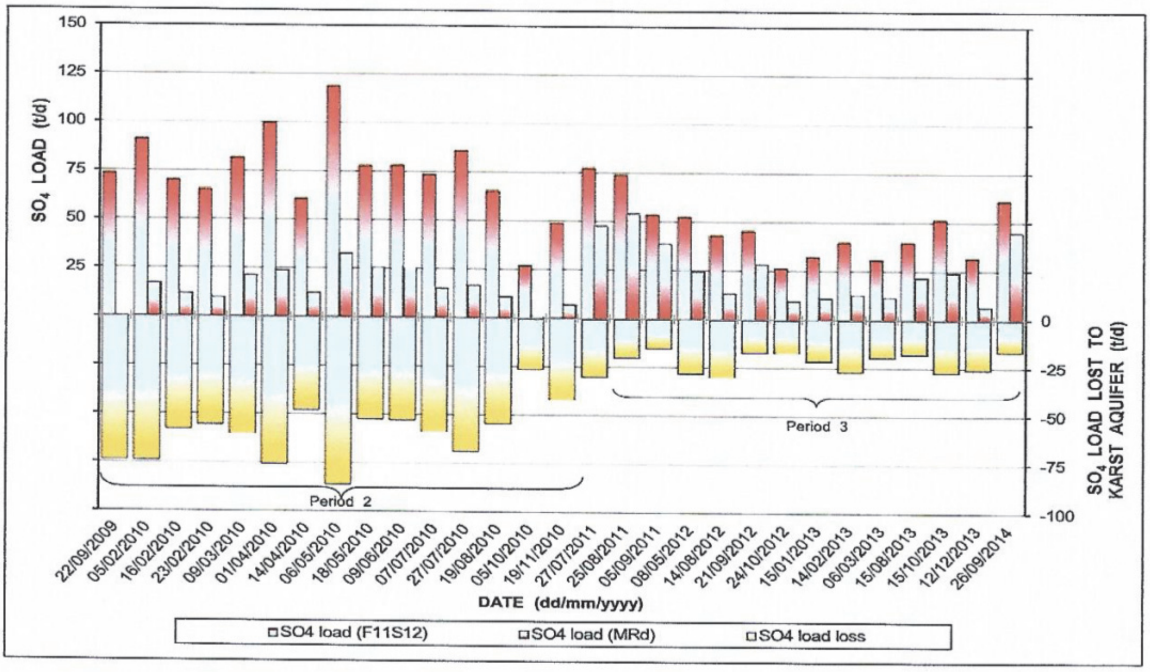


Figure 16-9: Graph of surface water SO4 load lost to groundwater in the lower reaches of the Riet Spruit

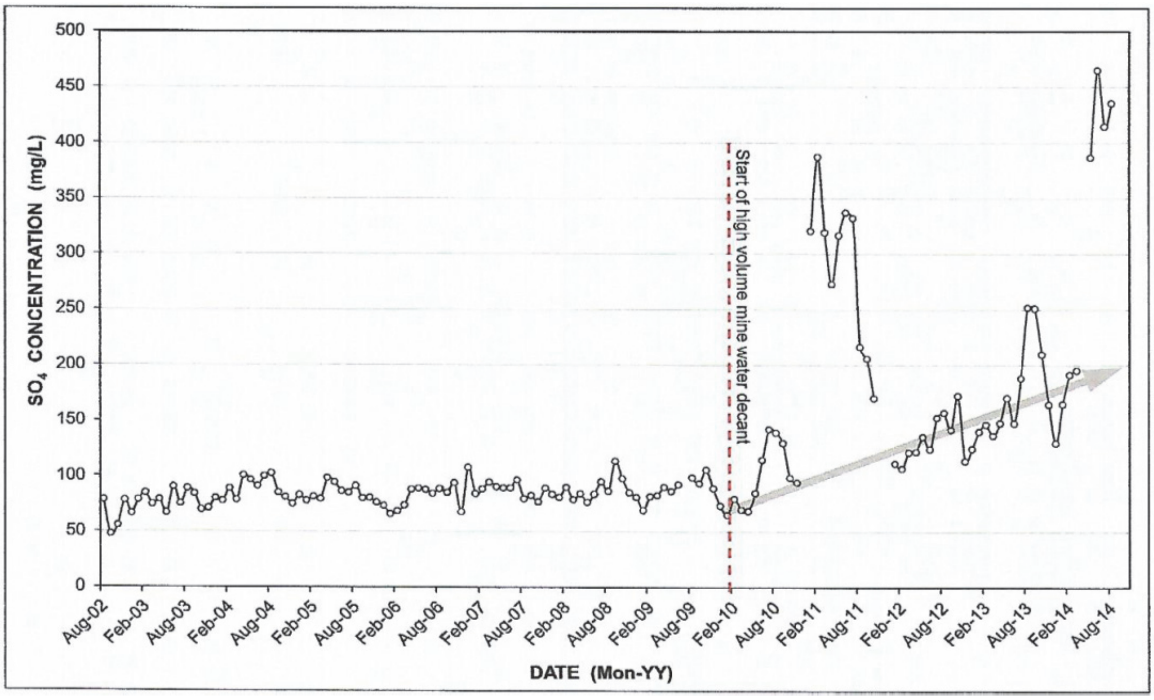


Figure 16-10: Pattern and trend in the SO_4 concentration at station A2h049 since the start of mine water decant in the Western Basin

Table 16-1: Chemical composition of Hartbeespoort Dam outflow currently

Parameter	Western Basin (neutralised)	Hartbeespoort dam outflow currently (CRO3)	Hartbeespoort dam outflow in future (CRO3)
Mine water flow (Ml/d)	25		
Dam outflow (Ml/d)	0	625	650
pH	3	8,6	
Total Acidity	0	0	-
Iron(II)	0	0	0,00
Iron(III)	0	0	-
Aluminium	0	0	-
Manganese	0	0	-
Magnesium	150	15	20,19
Sodium	50	47	47,12
Potassium	0	7	6,73
Ammonia (NH4)		0,3	0,29
Sulphate	2 497	60	153,73
Chloride	30	58	56,92
Nitrate (NO3)		0,4	0,38
P-tot		0,19	0,18
Alkalinity	100	120	119,23
Calcium	780	38	66,54
Free acid	55	0	2,11
TDS (mg/l)	3 661,91	345,89	384,37
Fe utilization efficiency (%)		0	
Fe dosed (t/d)		0	
Cations (+) (meq/l)	54,62	5,36	7,25
Anions (-) (meq/l)	54,86	5,28	7,19

16.2.1.3 Comments on Harties Metsi a Me program

No attention is given to the future effect that mine water will have on the quality of Hartbeespoort Dam water.

16.3 Phosphate Removal With Iron

Phosphate requires to be removed down to less than 0,05 mg/l to control eutrophication. Chemicals such as iron(III), iron(II), aluminium(III) and lime can be used to precipitate phosphate as $FePO_4$, $Fe_3(PO_4)_2$, $AlPO_4$ and $Ca_3(PO_4)_2$, respectively. Figure 16-11 shows the solubility of $FePO_4$, $Fe_3(PO_4)_2$ and $AlPO_4$ (as P) as a function of pH. Fe(II) can remove phosphate in a narrow range around pH 8, compared to the pH range, 4-6, for Fe(III) (Gasshemi and Recht, 1971; Van der Merwe et al., 1983). If iron(II) is available, it can also be easily oxidised to Fe(III) in the presence of air as indicated by the rapid rate of iron(II)-oxidation at pH values of 7.2 and higher (Figure 16-12).

Since Fe(III) effects better phosphate removal than Fe(II), the kinetics of iron(II) oxidation need to be considered. The rate of Fe(II)-oxidation (Stumm and Lee, 1961) is given by:

$-d[Fe(II)]/dt = k.[Fe(II)].[OH-]^2.[O_2]$

[ ] = concentration in mol/l

The value of k at 20,5°C in a bicarbonate buffer system is 1 x 10^{16} mol^3/min.

From this equation it is clear that the rate of Fe(II)-oxidation is greatly dependant on the pH of the solution as well as the concentrations of Fe(II) and oxygen. Consequently, in the presence of 0,5 mg/l oxygen, the half-life of Fe(II) is 7,5 hours at pH 7,0 and only 4,5 min at pH 8,0. The corresponding half-life values for a dissolved oxygen concentration of 5 mg/l are 45 min and 0,5 min respectively. Figure 16-11 shows the Fe(II)-oxidation rate as a function of pH.

Various iron sources can be used for phosphate removal: (i) $FeCl_3$, commercially available as a 43% solution, (ii) iron(II) rich mine water, and (iii) electrolytic generation from steel electrodes.

$FeCl_3$

For treatment of 0,19 mg/l P, with an iron dosage of 3,05 mg/l Fe(III), for treatment of 650 Ml/d, 1,98 t/d of FeCl3 (as 100%), will be required. At a price of R6 000/t (100% FeCl3) the cost will amount to R12,7 million per year (Table 16-2).

Table 16-2: Cost of $FeCl_3$ when used for phosphate removal

Parameter		Value
Phophate (mg/l)		0,19
Utilization efficiency (%)		11,12
FeCl3 dosage (as 100%) (mg/l)		8,94
Price (R/t)		6000
Flow (Ml/d)		650
$FeCl_3$ cost (R/a)		12 720 795

16.3.1.1 Mine water

Mine water rich in Fe(II) would be an attractive alternative to the use of the above mentioned chemicals. Mine water from the Western Basin, containing 400 mg/l Fe(II), can be pumped to the three inlets of the Dam (Magalies, Crocodile and Swart Rivers), mixed together with aeration, to allow for precipitation of phosphate as $FePO_4$ and $Fe_2(PO_4)_3$. The precipitate can be allowed to settle in the dam, followed by removal together with sediment in a dredging operation (see next chapter on Dredging). Mine water has to be piped to the dosing point to prevent iron precipitation if allowed to flow in an open system. Such mine water can also be pumped to the various wastewater treatment plants in the catchment of the dam. If 3,05 mg/l Fe(II) (utilization efficiency of 11,12%) is dosed from mine water containing 400 mg/l Fe(II), 5,0 Ml/d of mine water will be required (Table 16-3). At a flow-velocity of 3,3 m/sec, a 150 mm diam. pipe will be required. The capital cost for transferring mine water from the Western Basin to the Dam is estimated at R4,5 million (Table 16-4). 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 640 Ml/d Dam water will result in an increase from the current 60 mg/l to only 86 mg/l sulphate. The calcium will increase from 38-41 mg/l (Table 16-3). The increases in other parameters are negligible.

16.3.1.2 Electrolytic phosphate removal

Phosphate can also be removed as $FePO_4$ by producing Fe^{2+} electrolytically from iron electrodes. The benefit of this approach is that no anion such as sulphate or chloride is added to the water. The disadvantage is the cost of the sacrificial steel electrodes and the cost of electricity. The power cost for the removal of 0,19 mg/l P from 650 Ml/d feed water to the dam is estimated at R1,9 million/a and the iron cost at R4,3 million/a; a total of R6,2 million/a (Table 16-5). The iron utilization efficiency, in the case of mine water, was taken as 11,12%.

Figure 16-11 shows that the optimum pH range for phosphate removal is between 3,8 and 6,5, with the best at pH 3,8. Beaker studies will be required to confirm the iron dosages required for removal of phosphate from 0,19 mg/l down to 0,05 mg/l. OLI software shows what Fe(III) dosage would be required when the pH of the feed water is reduced with H_2SO_4 to lower pH values prior to iron dosage. Table 16-6 shows that at pH 3,8, a Fe(III) dosage of 0,56 mg/l is required to remove phosphate from 0,19 mg/l to 0,03 mg/l. At pH 6,5 the Fe(III) dosage is still low, namely 1,14 mg/l. A H_2SO_4 dosage of 2,9 mg/l will be required to lower the pH of the Dam water from 7,5 to 6,5 (Table 16-6 and Figure 16-13).

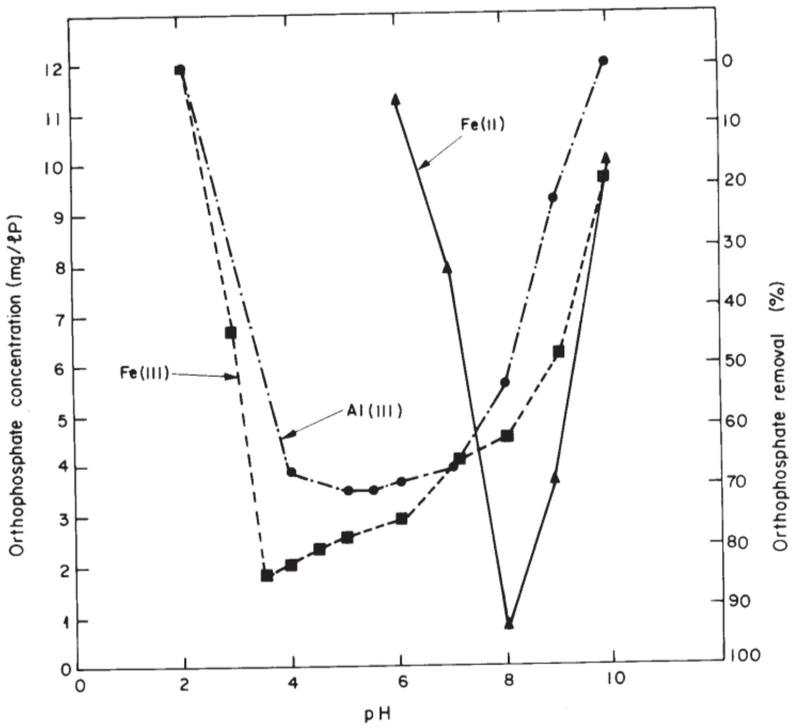


Figure 16-11: Precipitation of orthophosphate with Fe(II), Fe(III) and Al(III) at a cation to orthophosphate equivalent ratio of 1,0 Original orthophosphate concentration = 12 mg/l P (from Na_2HPO_4)

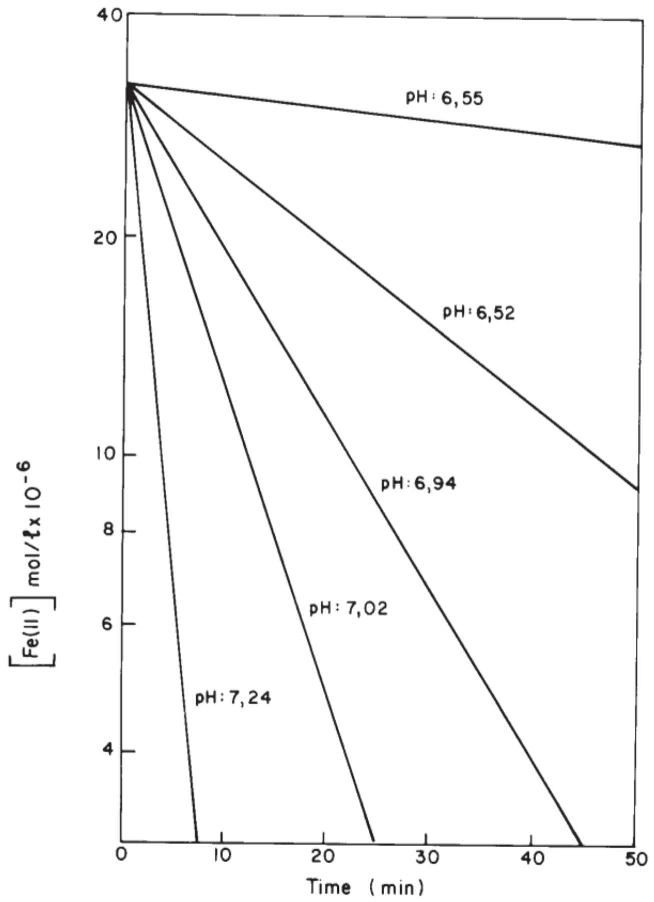


Figure 16-12: Oxidation rate of Fe(II) as a function of pH (Temp = 20,5°C)

Table 16-3: Chemical composition of Dam water before and after mine water

Parameter	Western Basin	Hartbeespoort dam outflow currently (CRO3)	Hartbeespoort dam outflow + 5 Ml/d mine water (CRO3)
Mine water flow (Ml/d)			5
Dam outflow (Ml/d)		650	655
pH	2,8	8,6	
Total Acidity	1 800		13,74
Iron(II)	400	0	3,05
Iron(III)	50	0	0,38
Aluminium	50	0	0,38
Manganese	70	0	0,53
Magnesium	150	15	16,03
Sodium	50	47	47,02
Potassium		7	6,95
Ammonia (NH4)		0,3	0,30
Sulphate	3 500	60	86,26
Chloride	30	58	57,79
Nitrate (NO3)		0,4	0,40
P-tot		0,19	0,19
Alkalinity	0	120	119,08
Calcium	415,00	38,00	40,88
Free acid	671,73	-	5,13
TDS (mg/l)	5 386,73	345,89	384,37
Fe utilization efficiency (%)			11,12
Fe dosed (t/d)			2,00
Cations (+) (meq/l)	72,42	5,36	5,87
Anions (-) (meq/l)	73,76	5,28	5,81

Table 16-4: Capital and running cost to pump mine water to the Dam for phosphate removal.

Item	Amount (R)
Pipe line (30km @ R100/m)	3 000 000
Construction	1 500 000
Total	4 500 000

Table 16-5: Estimated cost for electrolytic phosphate removal

Parameter		Value
j (Fe^0 --> $Fe2^+$)		3
Potential (V)		3
Mol mass of Fe		55,85
Energy W (kWh/kg Fe)*		4,32
Phosphate concentration (mg/l P)		0,19
Fe utilization (%)		11,12
Fe needed (mg/l Fe)		3,05
Fe needed (kg/m3)		0,003053
Energy needed (kW/m3)		0,01319
Eelctricity cost (R/kWh)		0,60
Electricity cost (R/m3)		0,01
Flow (Ml/d)		650
Electricity cost (R/a)		1 877 545
Iron needed (t/d)		1,98
Iron price (R/t)		6000
Iron cost (R/a)		4 346 565
Iron and Electricity cost (R/a)		6 224 110
*mj/M = It/F or		
mj/M =Vit/VF =Wt/VF		
W = mjVF/(Mt)		

Table 16-6: Effect of H_2SO_4 dosage on Fe(III) dosage needed for phosphate removal

H_2SO_4 dosage	Fe(III) dosage	Initial P	Final P	Initial pH	Final pH	Fe(III)/P
mg/l	mg/l	mg/l	mg/l			mol/mol
0,00	1,82	0,19	0,03	7,5	4,5	5,33
0,49	1,76	0,19	0,03	7,2	4,5	5,13
0,98	1,67	0,19	0,03	6,7	4,5	4,89
2,94	1,14	0,19	0,03	6,5	4,5	3,34
9,80	0,56	0,19	0,03	3,8	4	1,65

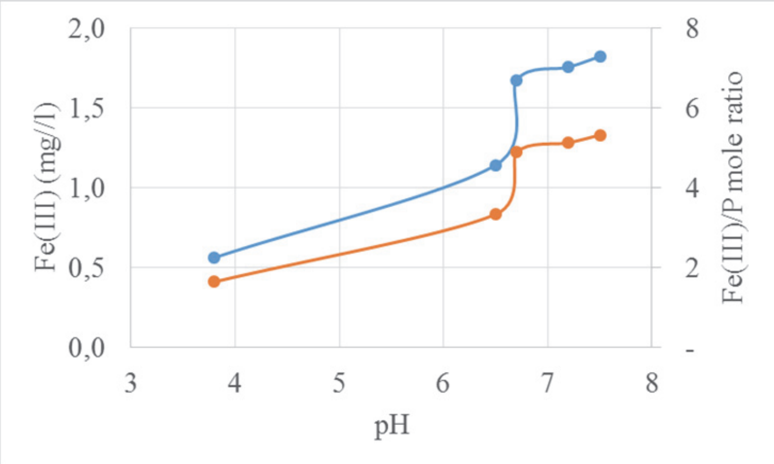


Figure 16-13: Fe(III) dosage required for P removal (0,19 mg/l to 0,03 mg/l) over the pH range 3,8 to 7,6.

16.3.1.3 Comments on Harties Metsi a Me program

Phosphate levels in the dam need to be reduced from 0,2 mg/l down to less than 0,05 mg/l (Venter; 2004). The current program on how to control eutrophication in the dam focuses on harvesting of algae and other water plants. The fact that the dam water body contains 0,2 mg/l phosphate (total of 20 t P), together with the phosphate laden inflow water and the already sedimented 180 t (estimated now at TP of >3 000 tonnes, HDRP, 2013a) of phosphate (as P), is an indication that these methods are inadequate. Further drastic methods need to be implemented.

Chemical phosphate removal is recommended and the above Chapter shows that mine water rich in iron would be the most cost-effective solution. Floating phosphate removal plants can be constructed near the three inlets to the dam: Crocodile River, Magalies River and Swart Spruit. A pipeline (150 m diam.) needs to be laid to transfer acid mine water directly from the decant point at 18 Winze, to the Crocodile River inlet. The pipeline can run via Tweelopie Spruit → Bloubankspruit → Crocodile River to the dam. From the Crocodile River inlet iron containing mine water can be pumped via pipelines laid at the bottom of the lake to the two phosphate removal plants at the inlets of the Magalies River and the Swart Spruit. The benefits of this approach are: (i) No chemical cost (ii); minimum pumping cost since mine water will flow by gravity from 18 Winze to the Dam; (iii) no civil construction at high cost. (See Chapter 8 for more detail on Floating Water Treatment plants). Alternatively, this concept of phosphate removal with iron-rich mine water can first be demonstrated at Percy Stewart Waste Water Treatment Works near Krugersdorp (6 km away from 18 Winze) or at Northern Waste Water Treatment Plant (20 km away from 18 Winze)

As suggested by the Harties Metsi a Me Programme, a second important requirement is sediment removal since a large quantity of phosphate is trapped there.

16.4 Mine Water Treatment / Utilisation

16.4.1 Eutrophication

Eutrophication and salinisation of surface water needs to be controlled at minimum cost. The options are as follows:

Option A – Phosphate removal. If the iron in neutralised mine water is used for phosphate removal, the sulphate concentration in the outflow of the Dam will increase from the current 60 mg/l to 86 mg/l (Table 16-3). The once-off capital cost for a pipeline is estimated at R4.5 million.

In Chapter 5 it was recommended that a small stream of iron-rich mine water be piped to the Crocodile River Mouth on the Hartbeespoort Dam 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 suitable dosing point will be:

Option A1. In the Crocodile River after the junction of the Bloubankspruit and the Jukskei River. At this point 90% of the feed to the Dam will be treated and will include the 450 Ml/d from the Northern Works, 24 Ml/d from Percy Stewart and 19,5 Ml/d from Randfontein. Mine water will need to be piped over a distance of 20 km.

Option A2. Mouth of the Crocodile River. Here more phosphate will be removed but mine water will need to be piped over a distance of 50 km.

Table 16-7 shows the dimensions of a reactor needed for rapid mixing of the mine water with the P-rich feed water to the Dam. The electricity cost is estimated at R2 million /a for treatment of 550 Ml/d or R0,01/m^3.

If the plant is at the in the Hartbeespoort Dam at the mouth of the Crocodile River, the mixers could be mounted on floating devices. This way civil works could be avoided since only partition structures need to be provided between the mixing zone inside the reactor and the Dam water outside the reactor.

Table 16-7: Plant required for P removal

Parameter	Value
Flow (Ml/d)	550
Flow (m3/h)	22 917
Reaction time (min)	10
Reactor volume (m3)	3 819
Height (m)	4
Width (m)	4
Length (m)	239
Velocity in channes (m/sec)	0,40
Distance between mixer (m)	4
No of mixers	60
Energy input (kW/m3)	0,1
Volume per mixer (m3)	64
Energy per mixer (kW)	6,4
Energy needed (kW)	382
Electricity cost (R/kWh)	0,60
Electricity cost (R/h)	229,17
Electricity cost (R/m3)	0,01
Electricity cost (R/a)	2 007 500

Desalination

Option B-Desalination. If all 25 Ml/d mine water is passed through the dam, the sulphate concentration will increase from 60 mg/l to 153 mg/l. The Inter-Ministerial Committee on Acid Mine Water (Expert Team, 2010) recommended that mine water needs to be desalinated in the medium to long term to protect surface water. The typical capital cost for a reverse osmosis plant amounts to R20 million/(Ml/d) and the running cost at R15/m^3. The capital cost of a 25 Ml/d plant will amount to R500 million and the running cost to R136 875 000/a. This is extremely costly and deals with only 3,9% of the flow through the dam. Alternative cheaper options need to be considered such as forced evaporation or evapotranspiration. Valuable work was done by the Harties Metsi a Me on floating wetlands as a way to extract phosphate from Dam water. Floating wetlands might even be more suitable for evaporation of a large portion of mine water in dedicated ponds for neutralized mine water before it is mixed with better quality surface water. Although the use of floating wetlands is a possible method to accelerate evaporation, two other methods will be appraised in the next chapter, namely (i) forced evaporation and (ii) irrigation to produce bamboo.

Option C – Forced evaporation. Mine water from the Western Basin represents only 3,9% of the flow through the Dam (25 Ml/d out 650 Ml/d). Evaporation will be a more cost effective solution to ensure low TDS water in the Dam. The capital cost for evaporation is estimated at R2,5 million/(Ml/d) and the electricity cost is estimated at R1,50/m^3 (Nel, 2015). It would be possible to evaporate 80% of the mine water. The remaining 20% can be treated with Desalination/Brine treatment is proposed under Option B.

Option D – Irrigation. Makgae et al. (2013) and previously Du Plessis (1983) and Annandale et al. (2011) proposed irrigation as a way to reduce the volume of mine water that has to be treated and to keep the mine water away from the better quality surface water. Through irrigation, 80% of the mine water can be evaporated, resulting in the precipitation of gypsum in the soil. Irrigation will result in food production and job creation. The water will mostly be evaporated and beneficially utilized through irrigation. Leachate could be intercepted and treated with freeze desalination as a further option, if deemed necessary. Profits to be generated from the farming activities will depend on the cropping system selected, market forces, and overheads allocated to the farming operation. Conservatively, depending on cropping system selected and market forces, a profit of around ZAR5 000 per ha is quite feasible.

Table 16-8 shows that a profit of ZAR5 000/ha amounts to an income of ZAR6,1 million per year for a 25 Mℓ/d treatment facility or R0,67/m^3. The main benefit associated with irrigation, is that of job creation and the relative savings when compared to existing alternative desalination technologies. This makes this a viable option even if no direct farming profit is generated. The following waste products or re-usable products will be produced:

Gypsum will be precipitated in the soil during irrigation. Much research has been carried out where it has been demonstrated that many crops can be produced successfully using gypsiferous water.

Salt will leach through the soil to already polluted groundwater, or be collected by means of a drainage system. If the leachate is collected and processed by freeze desalination, separate recovery of the various compounds will be possible at a later stage.

The capital cost for irrigation and leachate treatment is estimated at R180 million for a 25 Mℓ/d plant, and makes provision for:

ZAR30,4 million for the centre pivots. The figure was calculated from: R25 000/ha; a flow of 25 Mℓ/d; irrigation or 750 mm/year; requiring an area of 1217 ha.

ZAR13,5 million for farming equipment and soil conservation works on newly developed irrigation fields.

If leachate (20%) is collected via a drainage system it can be treated with freeze desalination. The capital cost of such a system is estimated at R30 million per Mℓ/d and the running cost at R15/m^3.

Comparison of various options

Table 16-6, Chapter 4, shows that phosphate removal with iron-rich mine water (Option 1) has a low cost. The capital cost amounts to R8,5 million and the total running and capital redemption cost to R0,22/m^3. Complete desalination of mine water is the most expensive. The capital cost amounts to R750 million for a 25 Ml/d plant and the total running and capital redemption cost to R24,52/m^3. Option 3 (Forced evaporation combined with desalination of the 20% brine) and Option 4 (Evaporation via irrigation combined with desalination of the 20% brine) are more affordable solutions to prevent salinisation of Dam water. For both these Options the capital cost amounts to about R200 million and the total running and capital redemption cost to R6,00/m^3.

Table 16-8: Cost of various mine water treatment options to minimize eutrophication or salinisation of dam water

Parameter	Eutrophication	Prevent salination of surface water		
	1	2	3	4
	Phosphate removal	Desalination (RO)	Forced evaporation	Irrigation
Flow (Ml/d)	25	25	25	25
Capital cost (R)	**8 500 000**	**750 000 000**	**212 500 000**	**193 916 667**
Pipeline (150 mm dia; 20 km; R100/m) (Table 4)	4 500 000			
Mixing system (Estimate)	4 000 000			
Reverse osmosis plant (R20m/(Ml/d))		500 000 000		
Brine treatment (R10m/(Ml/d))		250 000 000		
Pump, Fan, Water jets R2,5m/(Ml/d); 80%)			62 500 000	
Desalination/Brine treatment (R30m/(Ml/d); 20%)			150 000 000	150 000 000
Farm equipment				13 500 000
Irrigation (mm/a)				750
Input cost (R/ha)				25 000
Income (R/ha)				30 000
Profit (R/ha)				5 000
Area (ha)				1 216,7
Input cost (R)				30 416 667
Profit (R/year)				6 083 333
Capital redemption (10%, 20 y) (R/m)	-82 027	-7 237 662	-2 050 671	-1 871 338
Running cost (R/a)	**1 000 000**	**136 875 000**	**33 762 500**	**31 375 000**
Mainatenance, Electricity	1 000 000			
Mainatenance, Electricity (R15/m3)		136 875 000		
Mainatenance, Electricity (R0,70/m3)			6 387 500	
Mainatenance, Electricity (20%; R15/m3)				4 000 000
Mainatenance, Electricity (20%; R15/m3)			27 375 000	27 375 000
Capital redemption (10%, 20 y) (R/m3)	0,11	9,52	2,70	2,46
Running cost (R/m3)	0,11	15,00	3,70	3,44
Running + Capital Redemption Cost (R/m3)	0,22	24,52	6,40	5,90
Profit (R/m3)				0,67
Net cost (R/m3)	**0,22**	**24,52**	**6,40**	**5,23**
Net cost (R/a)	**2 000 000**	**223 800 000**	**58 400 000**	**47 800 000**

Note: Yellow marked figures were estimated. Civil engineering input needed to estimate total cost for all four options

16.4.1.1 Comments on Harties Metsi a Me program

Much activity is taking place on bioremediation methods such as plant harvesting and management of the fish population. These methods need to be further supported with chemical and physical treatment methods as recommended above. The methods to be added include: (i) Phosphate removal with iron. Iron rich mine water can be used as it is available at low cost; (ii) Treating mine water, other than the small stream that is needed for phosphate removal, separately. Methods to consider here are evaporation, irrigation or desalination/brine treatment.

16.5 Environmental Critical Level (ECL)

16.5.1 Views on ECL level

Mine water typically contains four main components: free acid, iron(II), several heavy metals and salts (Maree, 2012). The formation of AMD can be attributed to the convergence of the following events: (i) dissolution of limestone/dolomite up to its solubility level in natural, ingress water; (ii) pyrite oxidation by bacterial action as a result of oxygen-rich ingress water running through broken pyrite-containing rock within the mine environment and producing acidity, Fe(II), sulphates and other salts; (iii) partial neutralisation of free acid due to natural alkalinity contained in the mined and broken rock media; and (iv) reciprocating contact of pyrites-rich rock with water and oxygen when the water level fluctuates as a result of water being pumped out at a constant rate, whilst the water recharge varies with seasonal rainfall.

In the recommendations of the Expert Team (2011) special attention was given to the Environmental Critical Level (ECL). For the Western Basin the Expert Team of the Inter-Ministerial Committee on Acid Mine Drainage were tasked with investigating the matter in 2010. They recommended specific actions to further manage and control the AMD associated with the Witwatersrand mining activities (Expert Team, 2011), as follows: (i) installation of pumping facilities in each of the mining basins to maintain the water level below the Environmental Critical Level (ECL); (ii) construction of measures to reduce the water ingress and recharge to the underground mine workings; (iii) treatment of the excess mine water; (iv) comprehensive monitoring; (v) investigation of and addressing other sources of AMD; (vi) investigation of and research to find long-term sustainable solutions; (vii) investigation of the feasibility of implementing an environmental levy on operating mines to fund environmental rehabilitation; and (viii) ongoing assessment and research.

Two views can be considered on whether mine water needs to be pumped out.

In View 1 mine water can be pumped out to maintain the water level below a selected ECL (Provide Ref). In this way water is not permitted to rise above the level where it makes contact with and dissolves limestone/dolomite. This practice also offers benefits such as preventing groundwater pollution, preventing damage to building foundations and providing flow-equalisation storage in sub-surface mining voids to allow a constant feed-rate to the treatment plant. A negative outcome of this approach is that as natural ingress water follows the same channels on its way to the underground mine water body, it will dissolve the dolomite/limestone rock and can result in sinkhole formation, i.e., when pockets of limestone-containing rock get dissolved over time in water that is under-saturated with $CaCO_3$.

In View 2 mine water is allowed to decant naturally (Van Tonder, Steyl). This view is based on the fact that no oxidation of pyrites takes place when the rock is submerged and oxygen is excluded. This practice will also reduce limestone dissolution by ingress water. If water is allowed to decant, surface storage facilities (e.g. ponds) need to be constructed to allow constant feed to the water treatment plants. This option would result in less acidity and less Fe(II) in the AMD than provided by the pumping option. The negative impacts of having AMD at shallower depths will need to be managed.

It can be argued that both views have a place, depending on the application. In order to choose between Views 1 and 2, it was necessary to quantify the impact of the two views on the different situations prevailing in the Western, Central and Eastern Basins. Maree (2012) showed that the capital cost, for AMD pump stations in the three basins to maintain the recommended ECL levels of 150 m (below decant level) for the Western Basin, 200 m (below decant level) for the Central Basin and 400 m (below decant level) for the Eastern Basin, will amount to R211.4 million. The electrical power cost was estimated at R57.8 million/a. By raising the ECL to a higher level of 30 m below decant level, the capital cost will be decreased to R20.5 million and the power cost to R5.6 million/a. The cost to compensate for pollution of groundwater by providing piped municipal water, from Rand Water, to local groundwater users will be much less than the cost of pumping high volumes of water against a high pressure head. These figures need to be confirmed in order to ascertain whether Views 1 and 2 are able to and need be applied.

Pumping cost

In the case of future mining taking place, water should be pumped out to dewater the mine to a level below mining operations. If further mining is not planned to take place in a specific basin, the following factors need to be considered in respect of pumping: (i) cost of pumping; (ii) dissolution of limestone/dolomite due to ingress water; (iii) dissolution of limestone/dolomite rock due to reaction with acid water; (iv) pollution of ground water; and (v) damage to building foundations.

Table 16-9 shows that the capital cost for pumps in the Western Basin will amount to R13,6 million at a depth of 150 m versus R2,3 million at a depth of 30 m. The corresponding electricity cost at a price of R0,60/kWh will amount to R4,48 million/a at 150 m depth and R0,74 million at 30 m depth. The cost to compensate for pollution of groundwater by providing piped municipal water from Rand Water to local groundwater users will be much less than the cost of pumping high volumes of water against a high pressure head. These figures need to be confirmed in order to ascertain where Views 1 and 2 are able to and need to be applied. A depth of 30 m was selected for to make provision for water storage. If water is allowed to decant additional provision need to be made for storage areas for a period of 30 days so that water treatment plants can treat water at a fixed feed rate.

It is recommended that the need to pump out water to below the ECL be re-considered in the light of the following arguments:

Iron(II), the main component in acid mine water, does not react with $CaCO_3$ under reducing conditions.

Free acid in mine water that does react with $CaCO_3$ under reducing conditions, and is already partially neutralized in the Western Basin (58%) (Table 16-10). The amount of $CaCO_3$ that will dissolve if contacted with mine water with a free acidity value of 500 mg/l (0.5 kg $CaCO_3/m^3$ acid mine water) is also negligible with the mass of limestone in contact with 1 m^3 of water. If limestone has a void/solid ratio of 0.3 and a density of 1.4 kg/dm^3, it is calculated that 1 m^3 of water will be in contact with 4.7 t $CaCO_3$ (1 / 0.3 x 1.4). The maximum mass of $CaCO_3$ that will react with the free acid amounts to only 0.01% i.e. [0.5 kg acid (as $CaCO_3$) in water /4700 kg $CaCO_3$] x 100.

By allowing mine water to rise to only a few metres below the decant level will reduce the mass of $CaCO_3$ dissolution as a result of ingress water.

Mine water that is currently pumped out at Shaft 8, Sibanye Gold, is neutralized, released into the Tweelopie Spruit and then seeps into the aquifer at the Bloubankspruit, re-appear in the Kromdraai Spring area. There is no merit in trying to protect the ground water in the area of Shaft 8 by pumping water out at high cost to a depth of 150 m, and then to allow it to return to the groundwater at ground level at some 20 km north-north-east. In fact, by pumping water out to a depth of 150 m, more acid formation is stimulated, since acid mine water is formed while it gravitates down to the water level. By allowing the water level to rise to a depth of 30 m, less acid formation will take place due to less contact time and due to less pyrites material in contact with ingress water.

The only concerns that need to be addressed if mine water is allowed to rise to a level near the decant level are: (i) pollution of ground water, (ii) damage to foundations if contacted with acid water, and (iii) the threat posed to the Cradle of Humankind. These issues can be dealt with at a much lower cost than complete dewatering of mines. Rand Water, with a large pipeline network in Gauteng, can provide water to such affected groundwater users. The cost of such water should be carried by the mines or the State. The benefit is that the cost of such water would only be a small fraction of the cost of complete dewatering of the mines to the ECL level. Places where foundations are threatened by rising levels of acid mine water can be protected by injecting clean water into the basements of such buildings and to the outside of the foundations. By having the clean water level in contact with the foundations at a higher level than that of the acid mine water, damage to foundations will be eliminated. Acid water that may threaten the fossils in the Cradle of Humankind should be carefully monitored. It is fortunate that, since 2002 when water started to decant in the Western Basin, no damage has occurred to that heritage site.

It is proposed that mine water levels be pumped down to a level of 30 m below the decant point, just sufficient to provide adequate storage capacity for flow equalization between wet and dry seasons. Savings made this way in overall pumping of mine water should be used to subsidize pumping operations needed where future mining will take place or at tourist sites such as Cradle of Humankind.

Table 16-9: Pumping cost of 25 Ml/d as a function of depth

Parameter	Depth (m)	
Head, h (m)	150	30
Flow (Ml/d)	25	25
Electricity cost:		
Pump efficiency (%)	0,5	0,6
Energy to lift water (kJ)	3 065 625	510 938
Power, P_h (kW)	852	142
Power cost (R/kWh)	0,60	0,60
Electricity cost (R/m^3)	0,49	0,08
Electricity cost (R/a)	4 475 813	745 969
Capital cost:		
Pump cost (R/kW)	16 000	16 000
Pump capital cost (R)	13 625 000	2 270 833
Equalization pond cost:	40 095 873	-

Ph = q ρ g h / (3.6 x 106)

where

Ph = power (kW); q = flow capacity (m^3/h); ρ = density of fluid (kg/m^3); g = gravity (9.81 m/s^2); h = differential head (m)

Table 16-10: Chemical composition of Western Basin water before treatment

Parameter		Western Basin (95th Percentile)
		Feed
Flow (Ml/d)		
Dosage (mg/l 100% CaCO3)		
Mol mass		
Purity (%)		
Utiliztion (%)		
Dosage (mg/l)		
Price (R/t)		
Cost (R/m3)		
Cost (R/m3)		
Cost (R/month)		
Cost ratio		
Total Acidity ($H^+ + Fe^{2+} + Fe^{3+}$)[1]		2 400,0
Total iron ($Fe^{2+} + Fe^{3+}$)		725
TDS (given)		6733
pH		2,9
Alkalinity	mg/l as CaCO3	
Sulphate	mg/l as SO4	4800
Chloride	mg/l as Cl	37
Sodium	mg/l as Na	50
Potassium	mg/l K	
Magnesium	mg/l as Mg	147
Free acidity	mg/l as CaCO3	979
Aluminium	mg/l as Al	6
Iron(II)	mg/l as Fe	625
Iron(III)	mg/l as Fe	100
Manganese	mg/l as Mn	228
Nickel	mg/l as Ni	11
Uranium	mg/l U	0,1
Calcium calc	mg/l as Ca	602
TDS (calc)	mg/l	5 995
Cations (+)		101,0
Anions (-)		101,0
Cations - Ca (+)		70,9
Original Total Acidity[2]	mg/l as CaCO3	5 000,0
Original Free Acidity[3]	mg/l as CaCO4	2 500,0
Acidity neutralized[4]	mg/l as CaCO3	2 109,6
Acidity neutralized[5]	%	60,84

Notes:

1. Total Fe split into Fe2+ and Fe3+
2. Original Total Acidity due to FeS2 oxidation = 100/96 x [SO_4]
3. Origina Free Acidity = 0.5 x Original Total Acidity
4. Free Acidity neutralized due to natural attenuation = ([Original Free Acidity]-[Free Acidity])/[Original Free Acidity] x 100
5. Ca calculated to allow ionic balance

16.5.1.1 Comments on Harties Metsi a Me program

Since mine water was not a problem for the Hartbeespoort Dam until the present, no attention was given to the effect of the depth of the ECL of mine water treatment sites. Since the ECL level influences the amount of acid that is generated, the Programme should advocate shallower rather than deeper ECL levels. Shallower ECL levels will result in less acid generation, lower cost for neutralization and lesser salt concentrations to migrate into the karst aquifer at Bloubank Spruit, and later to the Hartbeespoort Dam.

16.6 Sludge and Sediment Removal

16.6.1 Progress

Cucik and Venter (2010) have clearly characterised the sediment in the Dam and formulated a programme on how to remove and process the sediment. About 40-45 x 106 m^3 of sediments associated with nutrients (phosphorus, nitrogen, carbon) have accumulated in the HBPD over more than 85 years of its operation. The sediments are distributed over 25% of the Dam area, settled in natural valleys present before damming of the river. The sediment results in a loss of 21% of the initial Dam storage capacity and results in a continuous release of nutrients causing severe eutrophication. The top layer of the Dam sediment (volume, ~ 5.5 x 106 m^3) that interacts with the overlying water contains about 2000 tons of phosphorous trapped in particles and attached to the surfaces of particles. A small but very active part of the dam sediment is a buoyant, gelatinous layer (termed the “jelly” layer”) rich in organic carbon, nitrogen and phosphorous that is located in the Dam wall zone (indicated in light green in Figure 16-14).

Figure 16-14: Spatial distribution of sediments within the HBPD

Additionally, 1.25-1.5 x 106 m^3 of sediments occur as a build-up in the Crocodile River inlet zone. The Harties Programme focuses on the removal of top-layer and “jelly” layer sediments, currently built-up in the Crocodile River inlet zone and river mouth, and future incoming sediments associated with nutrients, as well as the processing of these materials for beneficial uses.

In the study much attention has been given to: (i) Characterizing of the Active Sediment Layer (Tables 16-11 – 16-13; Figures 16-15 – 16-19); (ii) Developing criteria for dredging; (iii) Considering the potential for beneficial uses; and (iv) providing elements for (a) Environmental Risk Assessments and (b) Cost-Benefit Analyses.

The focus of the Harties Programme is to: (i) Move top sediments from the aquatic environment where they produce harmful effects, to terrestrial environments where they could provide benefits; (ii) avoid classical disposal of dredged materials and rather use them as valuable environmental media or raw material for construction material manufacturing. Using the coarser sediment for construction materials manufacturing can generate considerable cost recovery; (iii) motivate and mobilize stakeholders for development of the dredging operations, dredged materials processing, power plant construction, railway reviving, etc.; and (iv) job creation, by creating new jobs based on sediment removal and processing. Table 16-11 lists the sediment volumes in the Dam.

Table 16-11: Sediment volumes in the Dam

ZONE	Total Area (ha)	Area covered by sediments (ha)	Total Volume of sediments (000 m^3)	Total Volume of ASL* (000 m^3)
Dam Wall	150	45 - 55	5 250 - 6 750	450 - 550
Main Basin (Crocodile Mouth)	1060 (50 - 60)	350 - 450 (30 - 35)	28 000 - 32 000 (2.25 - 2.75)	3 500 - 4 500 (300 - 350)
Megalies Basin (Megalies Mouth)	850 (50)	55 - 60 (35 - 40)	2 000 - 2 500 (1 500 - 1 800)	550 - 600 (350 - 450)
TOTALS	2 060	525 - 655	35 250 - 41 250	4 500 - 5 650
'Jelly" Layer	60 - 70		1 000 - 1 500	N/A

* **ASL** - Active Sediment Layer

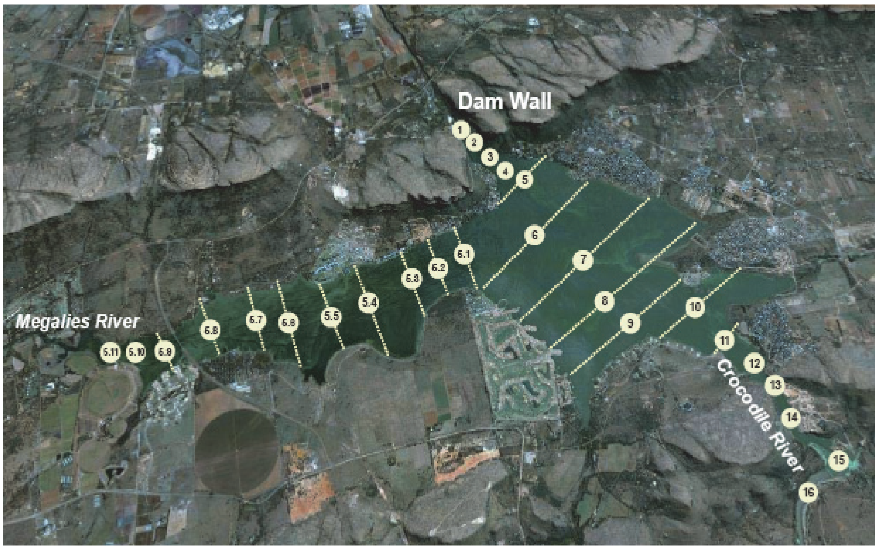
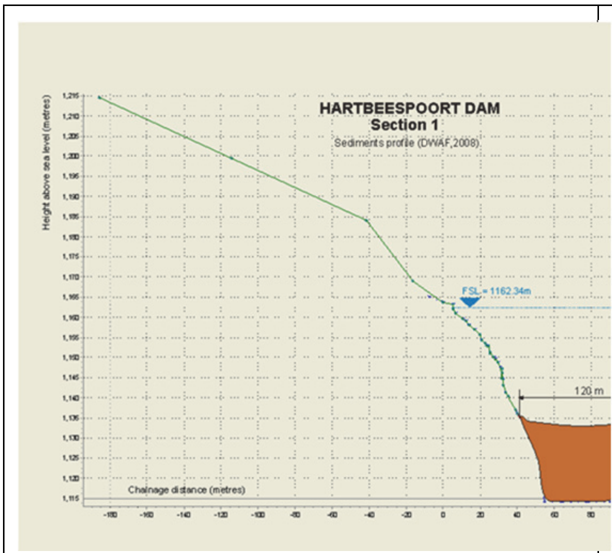
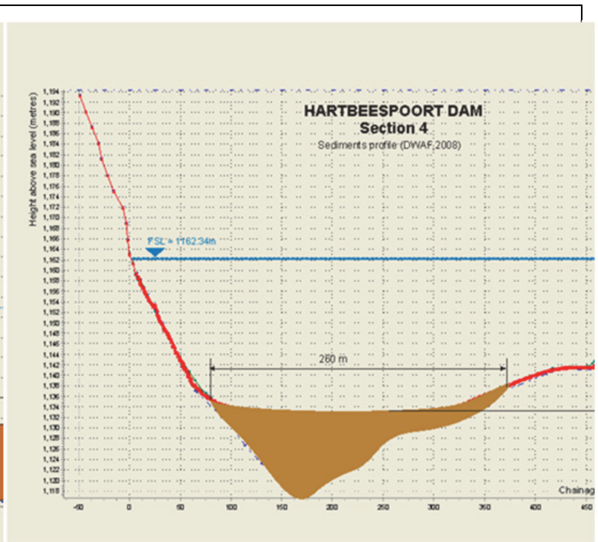


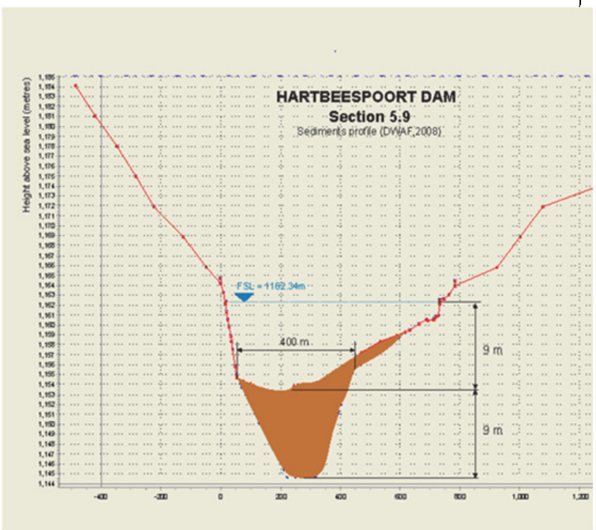
Figure 16-15: Mapping of Hartbeespoort Dam bottom with respect to key lateral sediment sections surveyed (DWAF, 2008)



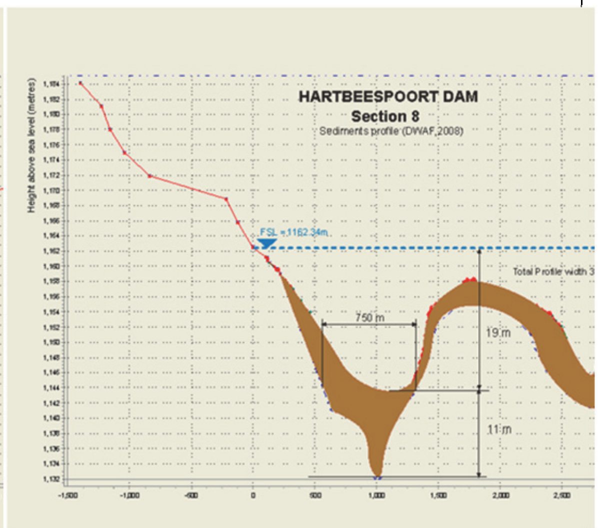
Section 1



Section 4

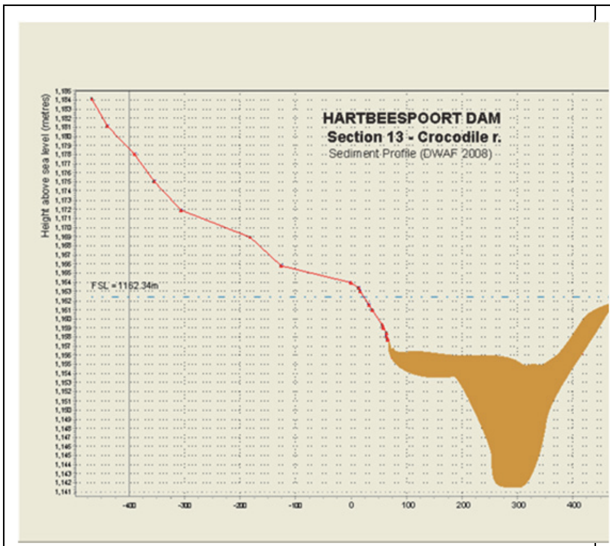


Section 5.9

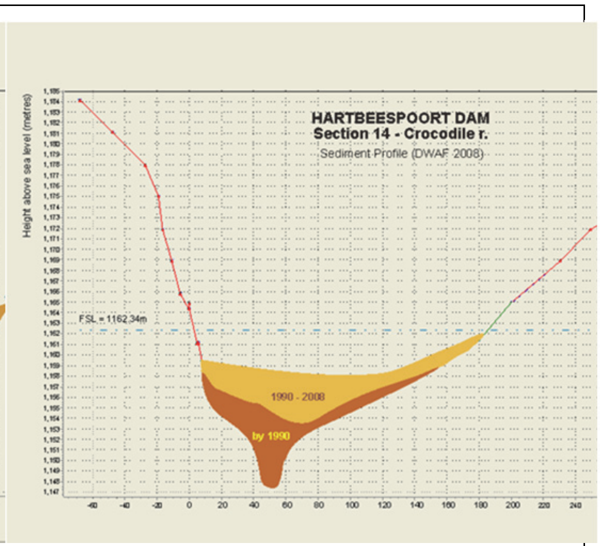


Section 8

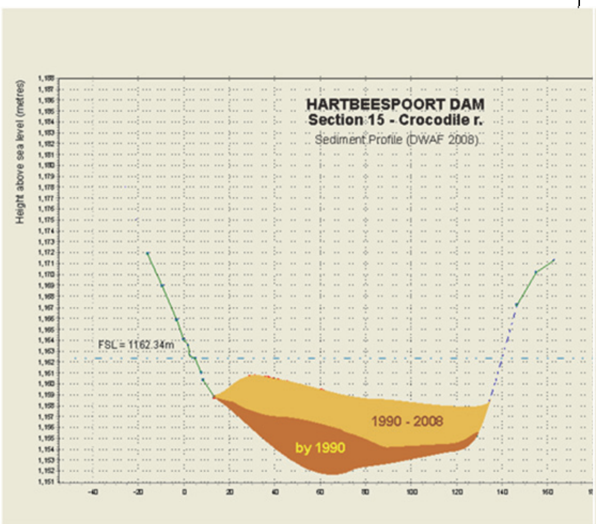
Figure 16-16: Sediment contours in the Dam



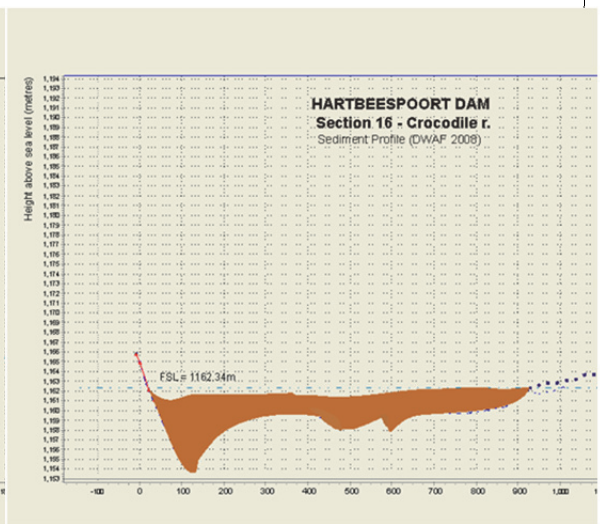
Section 13



Section 14



Section 15



Section 16

Figure 16-17: Sediment contours in the Dam

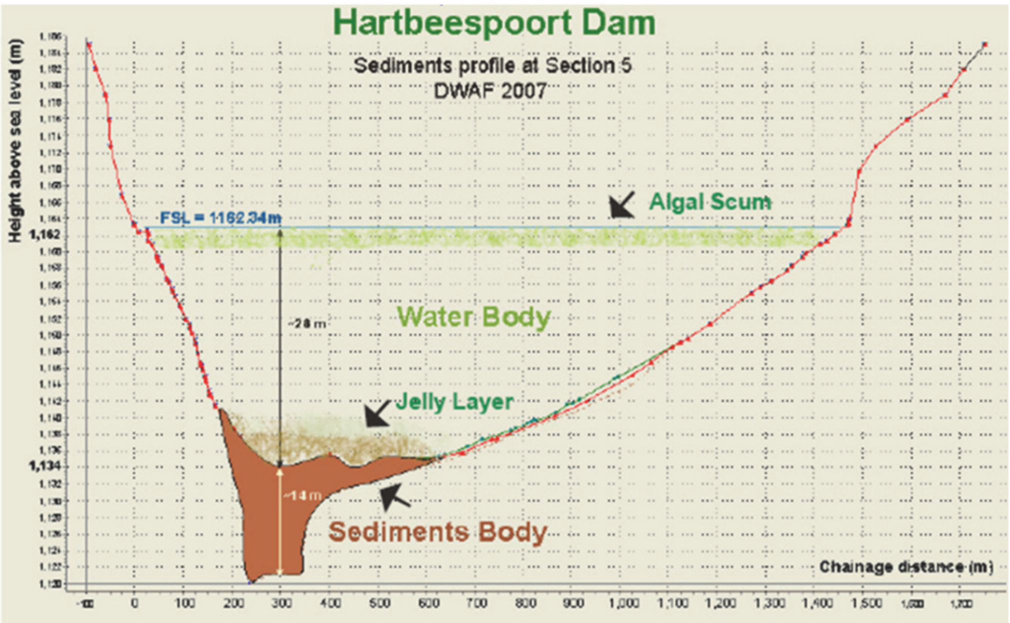


Figure 16-18: Sediment contours in the Dam (Section 5 – Dam wall)

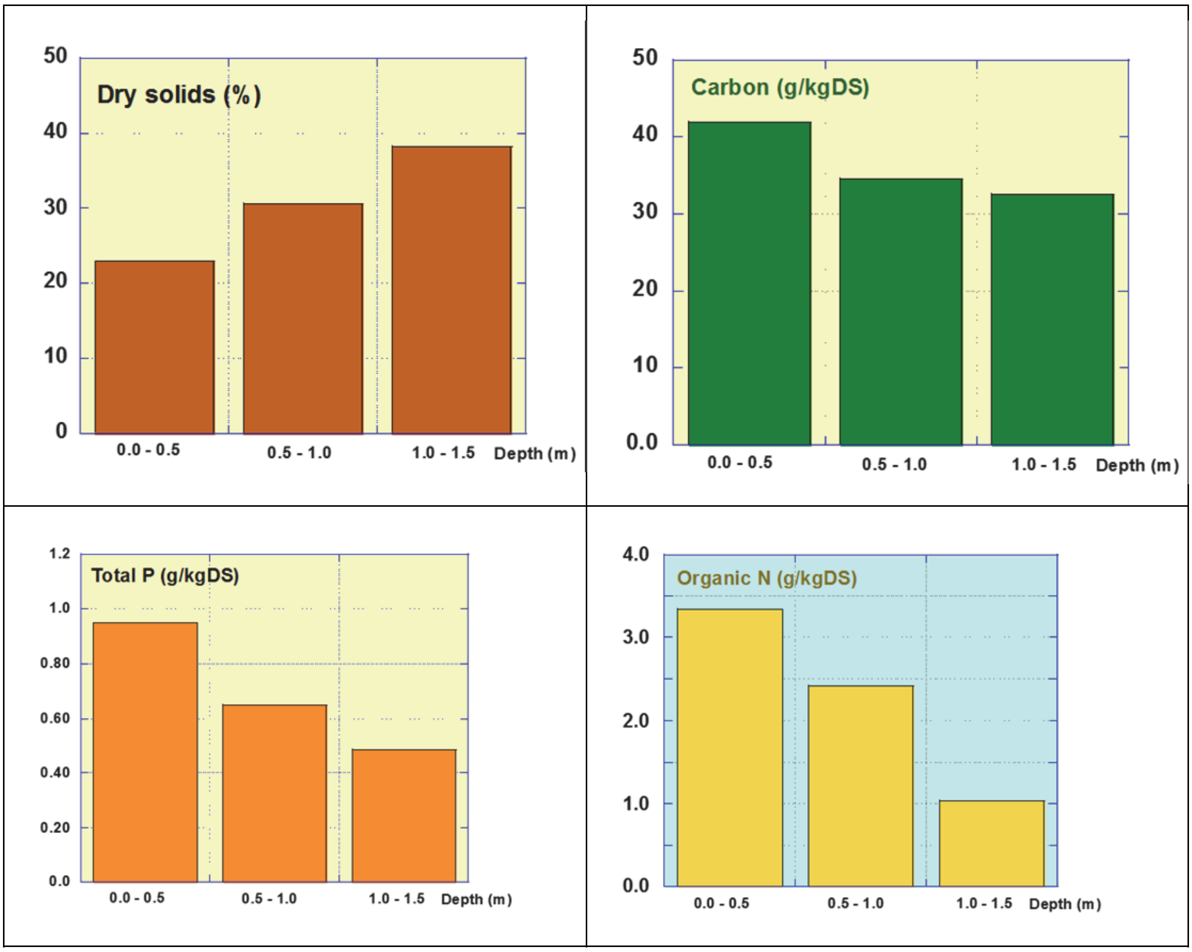


Figure 16-19: Concentration stratification

Table 16-12: Sediment Characteristics (Cores, ~ 1.5 m)

Parameter	Content
Dry solids	25%-55% (mostly 30-35%)
Density *	1.18-1.45 t/m^3
P content	0.45-0.95 g P / kg DS
N content	2-4 g N / kg DS
C content	30-45 g C / kg DS

* Jelly Layer density = 1.11 t/m^3

Note: Significant difference between sediments in Magalies basin and Main basin

Table 16-13: Major components trapped in Sediments (Total)

Parameter	Total Sediment	Jelly layer**
Dry Solids	14 500 000-17 000 000 t	166 000-277 000 t
Nitrogen	20 000-35 000 t N	565-780 t N
Phosphorous	4 600-5 200 t P	35-49 t P
Org. Carbon	150 000-250 000 t C	10 400-14 500 t C

* Active Layer ~ 1 m

** Notes on Jelly layer:

Discovered in Dam Wall Zone.

Rich in organics and nutrients.

Composed of fine clay particles and detritus.

Continuously receives dead biomass.

Bio-reactions driven by biodegradable organic carbon & C transforming to inorganic and gaseous products.

Liberates P originating from dead tissue.

Ready exchange of matter with overlying water.

16.6.2 Future program (Cukic, 2012)

The aims of the programme are the following: (i) Reduction of current internal nutrient load (nutrient recycling) for lowering of Dam trophic levels, (ii) Reduction of current influx of sediment and associated nutrient by the improvement of settling efficiency and sediment retention capacity of Crocodile Inlet zone and river mouth, (iii) Reduction of future influx of sediment and associated nutrients to the Dam by in-stream intervention (conditionally termed as the pre-impoundment). (iv) Beneficial uses of extracted sediments while creating new jobs and recovering a substantial part of sediment dredging and processing costs, (v) Carry out all operations on an environmentally safe, technically feasible, financially reasonable, and socially adoptable manner.

The set objectives are: (i) Dredging of nutrient laden Dam top sediment layer (Dam wall zone, Main Basin, Magalies River mouth) for the reduction of Dam internal nutrient load. (ii) Dredging of sediment built-up in Crocodile river Inlet zone for recovery of its settling efficiency / retention capacity (iii) Partial dredging of Crocodile River mouth for the improvement of its settling efficiency / retention capacity (iv) Processing of dredged materials for separation of solid and liquid phase (vi) Processing of separated solids for producing of valuable materials for agricultural use and for manufacturing of marketable products (sand, bricks, blocks, aggregate, etc.) for the construction industry, in order to provide cost recovery (vii) Separated water make up and reuse in agriculture and industry (viii) Carry out all operation on an environmentally safe manner and with no pressure on surrounds (ix) Job creation and establishment of SMME based on dredging itself and dredged materials processing

Several operations will take place in sediment removal and management;

Dredging / Extraction of sediments now and in the future

Transportation of dredged / extracted materials

Processing of dredged / extracted materials including;

Separation of liquid and solid phase.

Dewatering of solids.

Make up of separated liquid phase for reuse / safe discharge.

Processing of solids for manufacturing of environmentally valuable and marketable products

Job creation through establishing SMMEs.

Dredging / Extraction of sediments

• The extraction of ~ 4.5 x 106 m^3 top, nutrient rich sediments within the Dam main basin including "jelly" layer, should be done for the reduction of Dam internal nutrient load. Deep water sediment extraction of top sediments would be applied in this operation.

• The dredging of ~ 1.5 x 106 m^3 of sediments from the Crocodile River mouth should be done in order to remove nutrient rich top sediments as well as to recover and to improve the settling efficiency of this zone. Combined deep water sediment extraction of top sediments and shallow water dredging would be applied in this operation.

• The dredging of ~1.25 x 103 m^3 sediments from the Crocodile River inlet zone and river mouth by appropriate dredging techniques, for the recovery of their lost settling efficiency and sediment retention capacity. The purchase of modern multipurpose dredging equipment similar to one depicted in Figure 16-20 and establishment of the dredging team within the Harties metsi a me Programme is considered vital to assist dredging as well as the shoreline / wetlands remediation and biomass harvesting and removal.

Dredging

Deep water dredging

Figure 16-20: The dredging equipment to be purchased

The volumes of sediments to be dredged / extracted from above indicated zones are presented in Table 16-14.

Table 16-14: The volumes of sediments to be dredged / extracted

Area	Type	Volume (000 m^3)
Dam wall zone & Northern Dam Basin	Jelly layer	500
	Top layer	1 - 1,500
Central / Southern Dam basin	Top layer	2 - 2,500
Crocodile r. mouth	Top layer & a part of consolidated sedim.	1,500
Crocodile r. Inlet zone	All sediments	1,250
Megalies r. mouth	Top layer	300 - 500
Total		6,550 -7,750

Various places were identified to which dredged/extracted material will be transported. Various products were also identified to be produced from the sediment, such as bricks.

16.6.2.1 Comments on the Harties Metsi a Me program

Sediment removal

The dredging initiative needs to be supported and should also include sludge removal to be produced when iron-rich mine water is used for phosphate removal. Much work has been done by the Metsi-a-me programme on dredging to remove sediment from the Dam. The sediment has been characterised and quantified. It was determined what value added products can be generated from the sediment. In order to make the required progress, it is recommended that much focus be placed on one single aspect, namely the development of a low-cost dredging system. Research Organizations and Engineering Companies should be invited to submit proposals in this regard. A period of one year should be allowed to design, construct and demonstrate such systems. The units should be of a capacity small enough so that no EIA approval needs to be obtained by each of participants. This approach is recommended before large systems are purchased as shown in Figure 16-20.

Areas that need attention are:

Design and construction of a low cost dredging unit that can be evaluated. The approach by the dredging project leader: "Motivate and mobilize stakeholders for development (dredging operation, dredged materials processing, power plant construction, railway reviving, etc.) and job creation", is strongly recommended.

Implement a pilot facility in the mouth of the Crocodile River which will allow bulk sampling over a period of one year.

Provide materials for the pilot block making project.

Investigate the physical characteristics of the sediments from different zones.

Identify methods of sediment processing that will allow: (i) better water/sludge separation characteristics (ii) improved water quality that will be returned to the dam or used for other purposes, and (iii) sediment with a higher market value.

Determine the suitability of the sediment for soil conditioning (e.g. for slimes dam rehabilitation or agriculture).

Identify alternative methods of sediment removal (i.e. optimum dredging methodologies for both the shallow and the deep zones).

Tshwane University of Technology, in collaboration with its industrial partners, is interested in designing, constructing and evaluating a sludge dredging system on pilot scale. This work will supplement the work of Cukic and Venter (2010) and Elvin and Cukic (2010). The project will also be carried out with their collaboration. Sediment removal and processing consists of the following activities:

Dredging of the sediment layer. Sediment is sucked from the bottom and deposited on a barge or directly on dry land.

Water is separated from the sediments and returned to the dam.

The solids are processed for either disposal or beneficial use.

16.6.2.2 Recommendation

Various methodologies for loosening the sediments may be applied to the suction mouth of the dredging unit. These may be a simple vacuum, a vacuum with a cutting head, or a vacuum with a water jet. The TUT pilot plant (Figure 16-21) aims to equip the suction mouth with a high pressure water jet that loosens the sediment layer. The suction stream will have a flow-rate of at least twice the flow-rate of the water jet to ensure that all the loosened sediment enters the suction pipe. The variations that will be applied will be in terms of water jet flow rates (from 0 to 50% of the suction flow). Should additional variations be required, these modifications will be applied at a later stage (e.g. cutting head, air stream). A backhoe type dredger may be tested on the near-surface sand banks.

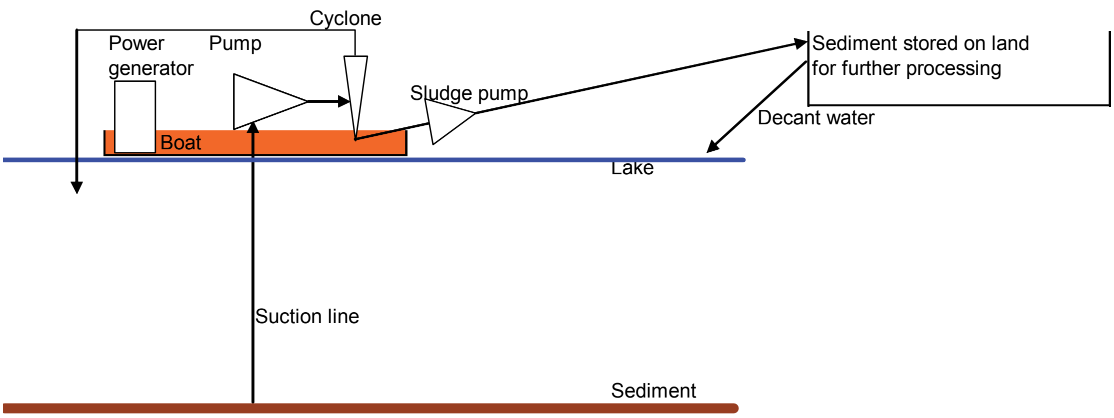


Figure 16-21: Pilot plant for small-scale sediment removal.

Table 16-15 shows the design of the dredging unit for the pilot-scale programme. The pilot-scale unit will dredge up to 5 t/d of sediment. The unit will consist of the following items:

Water jet (4 m^3/h pump; 16 mm diam. water-jet pipe).

Suction device (17 m^3/h; 38 mm diam. suction pipe).

Floating platform to support pumps.

Pipeline to land (110 mm diameter) or to temporary floating tank to transport the sediment.

Sediment handling facility.

Table 16-15: Equipment needed for pilot-plant

Parameter	Pilot
Pump/Sediment ratio	4
Spray/Suction ratio	0,25
Spray pump (m3/h)	4
Velocity (m/sec)	4
Dia of spray pipe (mm)	19
Suction flow (m3/h)	17
Velocity (m/sec)	4
Dia of suction pipe (mm)	38
Settling rate (m/h)	0,10
Settling area (m2)	166,7
Clarifier dia for pilot (1m/h) (m)	14,57
Sludge for pilot (m3/d)	25

Table 16-16 shows the equipment required by the pilot facility and the estimated cost.

Sediment will be removed from the Crocodile River before its enters the dam, with the option of also carrying out two short term dredging tests at the inlet cone of the Crocodile River to the dam and at the dam wall.

Table 16-16: Design of pilot- and full-scale plants

Parameter	Pilot	Main basin	Dam wall
Sediment volume (m3)	30 000 000	30 000 000	6 000 000
Sediment area (m2)	400	400	50
Treatment period (24h/d; 7 d/w) (days)	1 000	1 000	1 000
Pump/Sediment ratio	4	4	4
Spray/Suction ratio	0.25	0.25	0.25
Spray pump (m3/h)	4	42	42
Velocity (m/sec)	6	6	6
Dia of spray pipe (mm)	16	50	50
No of ponds	300	30	6
Sediment volume /pond) (m3)	100 000	1 000 000	1 000 000
Suction flow (m3/h)	17	167	167
Velocity (m/sec)	2	2	2
Dia of suction pipe (mm)	54	172	172
Clarifier dia for pilot (1m/h) (m)	5	15	15
Clarifier dia for full-scale (1m/h) (m)	80	80	
Pond Area (m2)	300	300	20
Sludge for pilot (t/d)	40	400	400
Sludge for full-scale (t/d)	60 000 000	60 000 000	12 000 000

16.7 Water Treatment Plant

Feed water to the Hartbeespoort Dam deteriorates with time due to a drop in the quality of wastewater treatment plant effluents, increased numbers of informal settlements in the catchment of the Dam, and run-off from agricultural activities. In-situ treatment of Dam water should be investigated with the aim to avoid the cost of conventional treatment plants, and to produce water of better quality. This can be achieved by making use of a floating treatment plant that will offer the benefit that no structural systems would be required, only partition walls between the water to be treated and the treated water outside the floating plant. A conventional treatment plant, large enough to treat the full 650 Ml/d influent to the Dam, will be impracticably large and unaffordable.

In the case of phosphate removal with iron-rich mine water, the following approach can be followed:

a. 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 $FePO_4$.

b. Install a floating clarifier in the 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 $FePO_4$ and other suspended solids will be removed from the floor of the dam via periodic dredging in the vicinity of the floating clarifier.

16.8 Conclusions

The feed water to the Dam amounts of 650 Ml/d of mainly treated sewage. The water body and sediment contain a large quantity of sediment.

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.

The sulphate concentration in the outflow of the Dam has remained constant at 50 mg/l during the period 2002, when mine water started to decant in the Western Basin, to 2011, as mine water was trapped in an underground karst aquifer and replaced good quality Kromdraai Spring groundwater.

The aquifer became saturated during 2014 as indicated by an increase in the sulphate concentrations in the Bloubankspruit from 100 to 430 mg/l during November 2014.

Phosphate needs to be removed down to less than 0,05 mg/l to control eutrophication. Chemicals such as iron(III), iron(II), aluminium(III) and lime can be used to precipitate phosphate as $FePO_4$, $Fe_3(PO_4)_2$, $AlPO_4$ and $Ca_3(PO_4)_2$ respectively. Mine water rich in Fe(II) would be the most cost-effective solution. The addition of 5 Ml/d mine water is to 640 Ml/d Dam water will result in an increase from the current 60 mg/l to 86 mg/l of SO_4^{2-}

Salinisation of the Dam can be prevented through evaporation of mine water that is not needed for phosphate removal. Forced evaporation can be applied or water can be evaporated via use for irrigation. Brine or leachate can be treated with freeze desalination for recovery of products and clean water.

The environmental critical level (ECL) of 150 m in the Western Basin needs to be revised as, (i) more acid is generated when ingress water gravitates to lower levels over broken rock in an oxygen atmosphere, and (ii) the mine water flows via an underground aquifer for some distance before it again appears on the surface. The purpose of a shallower ECL level is to reduce the cost of pumping.

Since the sediment contains 120 of phosphate, sediment removal through dredging is essential. In order to make rapid progress, it is recommended that focus be placed on one single aspect, namely, the development of a low-cost dredging system. Research Organizations and Engineering Companies should be invited to submit proposals in this regard.

Mine water needs to be piped to the Crocodile River Mouth in the Hartbeespoort Dam 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. Suitable dosing points will be: (i) In the Crocodile River downstream of the junction of the Bloubankspruit and the Jukskei River, or (ii) at the mouth of the Crocodile River.

16.9 Recommendations

Use iron containing mine water for phosphate removal to below 0,05 mg/l from feeds of Dam water and from Dam water itself.

Construct a plant for mixing 5 Ml/d mine water with 650 Ml/d feed water.

Design and construct a dredging system for removal of $FePO_4$ sludge and sediment from the floor of the Dam.

Negotiate with the authorities to raise the ECL level from 150 m to 30 m, below the surface, with the aim to reduce formation of acid mine water.

Minimize salinisation of the dam water through evaporation of mine water.

16.10 References

Annandale, JG, Beletse, YG, Stirzaker, RJ and Bristow, KL (2011) Managing poor quality coal-mine water: Is irrigation part of the solution? In: Observations on Environmental Change in South Africa, Larry Zietsman, (ed.) Sun Press, pp. 174-177.

CREAMER, T (2012) TCTA again warns of funding shortfall for acid water projects, Mining Weekly, 19 January, 2012.

Cucik, Z and Venter, P (2010) Characterization and managing of Hartbeespoort Dam internal nutrient load (Sediments). Proceedings of the WISA Biennial Conference, Durban International Conference Centre, 18-22 April.

Cucik, Z (2012) Harties Metsi a Me Hartbeespoort Dam Bioremediation Programme, Sediment removal and management approach, goals, objectives, strategy, http://www.harties.org.za/documents/SedimentRemovalManagementStrategy2012.pdf

Dudula, MZ (2007) A situation analysis of the water quality in the Hartbeespoort Dam catchment: Nutrients and other pollutants assessment on rivers entering the dam. A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering. Johannesburg.

Du Plessis, HM (1983) Using lime treated acid mine water for irrigation. Water Science & Technology 15, 145-154.

DWAF, (2008) Department of Spatial & Land Information Management; Report on the Survey of Hartbeespoort Dam Sediments (Draft).

Elvin, A and Cukic, Z (2010) Characterization of Hartbeespoort Dam sediment body. Proceedings of the WISA Conference, Durban International Conference Centre, 18-22 April.

Expert Team, of the Inter-Ministerial Committee, under the Coordination of the Council for Geoscience (2010). Mine water management in the Witwatersrand Goldfields, with special emphasis on acid mine drainage. Report to the Inter-Ministerial Committee on Acid Mine Drainage, 21 October, 2010.

Ghassemi, M and Recht, HL (1971) Phosphate precipitation with ferrous iron, Water Pollution Control Research, Series 17010 EKI 09/71.

Hobbs, PJ and Cobbing, J (2007) A hydrogeological assessment of acid mine drainage impacts in the West Rand Basin, Gauteng Province. Report no. CSIR/NRE/WR/ ER/ 2007/0097/C. Council for Scientific and Industrial Research, Pretoria.

Hobbs PJ (2014) Project Title: Surface water and groundwater resources monitoring, Cradle of Work Heritage Site, Gauteng Province, Gauteng Province, South Africa. Report Title: Water Resources status report for the period April to September 2014, Report No: CSIR/NRE/WR/ER/2014/0063/A, GWDMS No. & Library 244845 in PTA GENERAL, November.

Huizenga, JM, Dennis, R, Dennis, I and Silberbauer, M (2013) National data set (1972-2011) of rivers, dams and lakes in South Africa, Inorganic. Water Chemistry, 39(2)

Makgae, M, Maree, JP, Annandale, J (2013) Neutralized mine water for irrigation – cost and feasibility study, – In: Brown, A.; Figueroa, L. & Wolkersdorfer, Chr: Reliable Mine Water Technology (Vol I) pp. 507-513; Denver, Colorado, USA (Publication Printers).

Maree, JP (2012) Mine water – Pump or decant? Internal report, Tshwane University of Technology.

Nel A, (2015) FlowCentric, Personal communication.

Oberholster, PJ and Ashton, P J (2008) State of the Nation Report. An overview of the current status of water quality and Eutrophication in South African rivers and reservoirs, March, 2008.

Osuchiwski, R (1992) Advanced treatment of acid mine water. Technology SA April 1992, 9-11.

Stumm, W and Lee, GF (1961) Oxygenation of ferrous iron. Industrial & Engineering Chemistry, 53 (2) 143-146.

Van der Merwe, PH, Maree JP and Basson, ND (1983) Using acid mine water for removal of phosphates from sewage effluent, Water Science & Technology, 15(2), 155-167

Van Niekerk, A (2011) Golder Associates, Personal communication.

Van der Walt (2015) Sibanye Gold, Personal communication, 16 February.

Van der Walt (2015) Personal communication, 23 February.

Venter, PJ (2004) New hope for troubled waters: The Hartbeespoort Dam Test Case, Eutrophication management, Water Wheel, Jan/Feb, 2004.

17 Appendix 5. Overview: the Anderies Framework

The Anderies framework provides a structured method for reviewing the various aspect of the SES. The framework is illustrated in Figure 17.1.

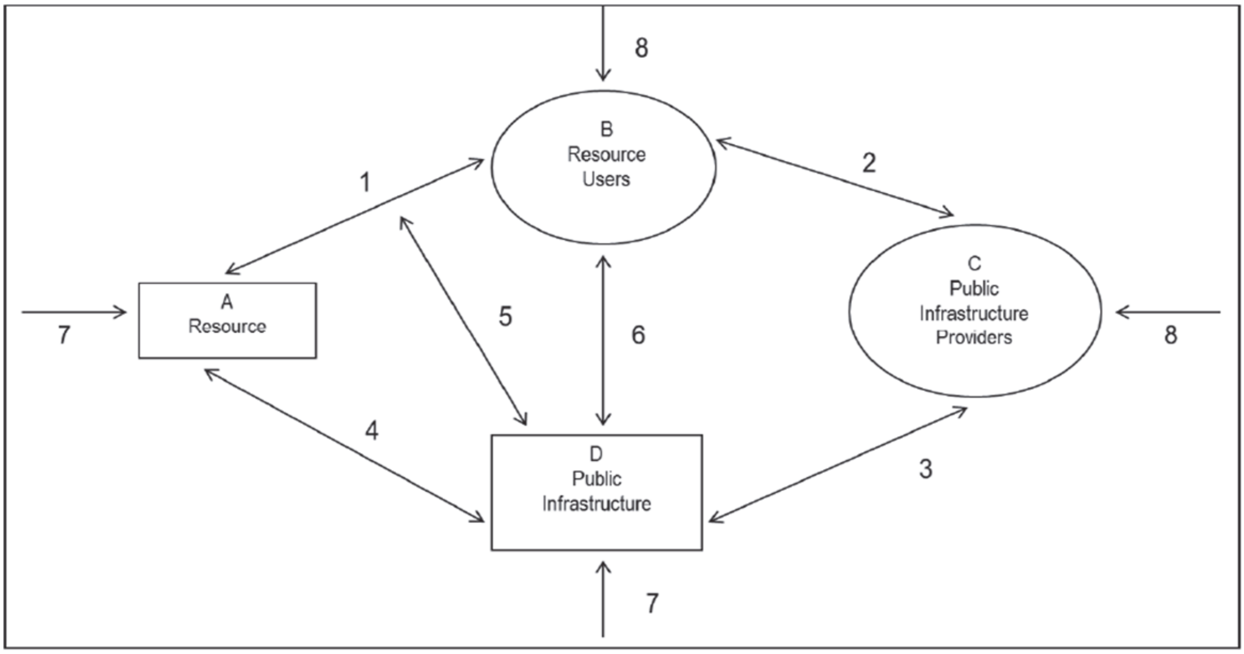


Figure 17-1: The Anderies Framework, illustrating the interactions between the entities of the social-ecological system (from Anderies et al., 2004).

In Table 17-1 we explain the components involved in social ecological systems and in Table 17-2 the links between the entities.

Table 17-1: The entities involved in social ecological systems (from Anderies et al., 2004).

Entities	Examples	Potential problems
A. Resource	Water source Fishery	Uncertainty Complexity / Uncertainty
B. Resource users	Farmers using irrigation Fishers harvesting form inshore fishery	Stealing water, getting a free ride on maintenance Overharvesting
C. Public infrastructure providers	Executive and council of local users. Association Government bureau	Internal conflict or indecision about which policies to adopt Information loss
D. Public infrastructure (Physical)	Engineering works	Wear out over time
D. Public infrastructure (Social-institutional rules)	laws, conventions etc.	Memory loss over time, deliberate cheating
External environment	Weather, economy, political system	Sudden changes as well as slow changes that are not noticed.

Table 17-2. The links between the entities of a social-ecological system (from Anderies et al., 2004).

Link	Examples	Potential Problems
(1) Between resource and resource users	Availability of water at time of need/availability of fish	Too much or too little water / too many uneconomic fish-too many valued fish
(2) Between users and public infrastructure providers	Voting for providers Contributing resources Recommending policies Monitoring performance of providers	Indeterminacy / lack of Participation Free riding Rent seeking Lack of information / free riding
(3) Between public infrastructure providers and public infrastructure	Building initial structure Regular maintenance Monitoring and enforcing rules	Overcapitalization or undercapitalization Shirking disrupting temporal and spatial patterns of resource use
(4) Between public infrastructure and resource	Impact of infrastructure on the resource level	Ineffective
(5) Between public infrastructure and resource dynamics	Impact of infrastructure on the feedback structure of the resource-harvest dynamics	Ineffective, unintended consequences
(6) Between resource users and public infrastructure	Coproduction of infrastructure itself, maintenance of works, monitoring and sanctioning	No incentives / free riding
(7) External forces on resource and infrastructure	Severe weather, earthquake, landslide, new roads	Forces a change of state in the resource and destroys infrastructure
(8) External forces on social actors	Major changes in political system, migration, commodity prices, and regulation	Conflict, uncertainty, migration, greatly increased demand