IMPLEMENTATION OF THE RULE BASED AGENT FOR *MICROCYSTIS* IN RIETVLEI DAM

Report

to the Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

In a study done by Van Ginkel (2008) an early warning/prediction tool (a real-time rule-based agent) for *Microcystis aeruginosa* blooms was developed and validated by means of a merged limnological time-series dataset of the hypertrophic reservoirs Hartbeespoort, Rietvlei and Roodeplaat dams using hybrid evolutionary algorithms (HEA). This rule set was then tested on data from two other hypertrophic dams, Bon Accord and Klipvoor dams that had not been used in the training data set. The agent proved to be generic for the five warm, temperate and hypertrophic reservoirs, four of which were monomictic and one dimictic. Thus, it can be potentially applied for the prediction of outbreaks of *Microcystis* blooms by many South African water treatment works (WTW). Although this model has already been validated conceptually, there is a need for the model to be validated operationally and the data to be used should be statistically validated for it to be acceptable as a prediction tool. In this study, the prediction tool (CEGAP), for *Microcystis aeruginosa,* was validated operationally using data obtained from the Rietvlei Dam WTW. However, due to the recent deployment of the SolarBees, data from Bronkhorstspruit Dam was also used for further validation.

In the Rietvlei Dam WTW long distance circulators (SolarBees) are used as advanced treatment options. The application of these circulators is based on the principle of habitat disturbance by means of continuously circulating the dam's epilimnion where maximum algal growth takes place. The Rietvlei Dam currently contains a total of sixteen SolarBee units, representing full-scale SolarBee implementation according to the size of Rietvlei Dam. This provided an opportunity to test the robustness of the CEGAP prediction tool being applied in case of advanced water treatment procedures. The main aim of this study is to use data collected prior to, as well as after the deployment of the SolarBees to implement the model and assess its applicability and robustness as an early warning/prediction tool for algal blooms.

The prediction tool (CEGAP) has been prepared in a ready-to-use Excel (2007) format and can be used by local water resource managers to predict blooms up to 28 days forward. With the aid of this predicting tool the proper drinking water treatment procedures can be incorporated in advance, in order to ensure the production of safe drinking water. Thereby, managing the risk imposed by the cyanobacterial blooms in the water resource, on drinking water facilities and the health of recreational users.

AIMS

The following were the aims of the project:

1. To compile a recent ecological overview of the water quality of the Rietvlei Dam and to describe the process configuration and advanced treatment options already employed to produce potable water.
2. To investigate the effect of habitat disturbance created by long distance circulation of the SolarBees on the development of cyanobacterial blooms and water quality.

3. To implement the prediction tool CEGAP and evaluate its performance as an early warning/prediction tool for water treatment works' managers.

METHODOLOGY

A brief ecological overview was firstly done in order to characterise the water quality in the Rietvlei Dam and to compare the current ecological status to the previous status before the deployment of the SolarBees. This is an important step in the later evaluation of the model, since the concepts that the model is based on might have changed significantly at Rietvlei Dam. Monitoring of the dam and the water quality is performed by the Department of Water Affairs at Resource Quality Services as part of the National Eutrophication Monitoring Program (NEMP). Samples are taken at the dam wall on a bi-weekly basis. Multivariate statistical analyses for the ecological overview were performed using Canoco version 4.5 and STATISTICA version 10 was used for the descriptive statistics.

In order to determine the effect of habitat disturbance, created by long distance circulation of the SolarBees, on the water quality of the Rietvlei Dam, the data obtained from Resource Quality Services were compared using the Kruskal-Wallis ANOVA (for comparing multiple independent samples of non-parametric data) in STATSTICA version 10. For further comparison the Self Organised Mapping method was employed. Self-Organised Map (SOM) is an unsupervised neural network method which has properties of both vector quantisation and vector projection algorithms. The primary application for Self Organised Map (SOM) modelling is clustering and data segmentation. SOM modelling can be used to investigate before and after situations.

Finally the model was implemented using the data obtained for the Rietvlei Dam. The observed values of the physical-chemical and biological variables necessary for the model were entered into the model in its Excel 2007 format. The rule based agent then forecasted the algal biovolume (cm^3/m^3). The observed data (Real time: RT) for algal biovolume together with the forecasted data (RTF; 14 and 28 days forward) for algal biovolume were then compared to evaluate the model's performance. Data collected for the Bronkhorstspruit Dam, by Resource Quality Services Laboratories at Roodeplaat, was also used to further investigate the performance of the prediction tool CEGAP in order to establish the confidence in its outputs and to discover strengths and limitations in the model. Performance of the model, in both these dams, was measured according to three different criteria, namely: (1) direct comparison of the observed and predicted values; (2) by calculating the difference in the observed versus predicted values using the RMSE and, (3) visual inspection of the time series. The statistical analyses were done using STATISTICA version 10, during which the following tests were performed:

1. Descriptive statistics for the direct value comparison
2. Kolmogorov – Smirnov and Lilliefors test for normality, which indicated that the data mostly did not meet the assumption for normality.
3. Pearson Product-Moment Correlation Coefficient was used to obtain the R value.
4. The Goodness of fit was used to obtain the RMSE

RESULTS AND DISCUSSION

Rietvlei Dam could still be classified as a eutrophied impoundment with high levels of PO_4, TN and chlorophyll *a*. The data obtained from two sampling groups, pre and post SolarBees, was used to describe the water quality before and after installation of the SolarBees. The complete dataset, which corresponds to 44 variables and 62 sampling times (62 samplings pre SolarBees and 61 samplings post SolarBees) were used. Electrical conductivity (EC) and all the salts measured that would contribute to EC (Ca, Mg, K, Na, SO_4 and Si) showed a significant decrease post the installation of the SolarBees. Both PO_4 and NH_4 levels decreased from an average of 0.37 mg/ℓ to 0.11 mg/ℓ and 0.39 mg/ℓ to 0.14 mg/ℓ, respectively. A significant decrease in temperature was also evident for measurements at all depths.

The mass occurrences of *Microcytis aeruginosa* declined significantly after the installation of SolarBees and instead huge blooms of *Ceratium hirundinella* were observed. This significant change in the biovolume of a nuisance species as well as the change in algal species dominance suggests that the SolarBee application in the Rietvlei Dam may have caused this particular change. The principle of the long distance circulators implementation is that of habitat disturbance. This form of bio-manipulation selects against the harmful cyanobacteria whilst favouring edible green and beneficial algae which enhance complex aquatic food webs. A total of 16 long distance circulators (LDCs) or SolarBees were installed in Rietvlei Dam from July 2008 to 2009. The SolarBees strongly suppressed the bloom formation of *Microcystis sp*, but did not eliminate Cyanophyceae from the water body. There was a significant difference observed in the water temperature, from surface temperature up to a depth of 9 m, pre and post the deployment of the SolarBees, which may have contributed to the decrease in *Microcystis sp*. growth.

Most notably was a significant decrease in the levels of PO_4 after the installation of the SolarBees, even though no significant difference in PO_4 at the inflow to the dam during these time periods was observed. The success of the SolarBees in creating changes in the water column was attributed to all or a combination of the following; energy loss due to continuous circulation, continuous aerated water flow into the shallower riparian zone and continuous laminar flow which may impact on the buoyancy regulation of the cyanobacteria.

Despite the observed changes it was decided to still evaluate the early warning/prediction tool evaluated for real-time (RTF), 14-days forward, and 28-days forward forecasting, against real-time data collected by the Department of Water Affairs at Rietvlei Dam. Due to the significant influences the SolarBees had on the water quality and algal bloom formation in Rietvlei Dam, the early warning tool was also evaluated using real-time data collected by the Department of Water Affairs at Bronkhorstspruit Dam, which does not have any SolarBees but is in the same geographical area and temperature range as the Rietvlei Dam.

The predictions for *Ceratium* were successful. Both the models for RTF and 14 days forward were able to predict the individual bloom events with a reasonable degree of accuracy however; they did not manage to predict the magnitude of the events. The prediction tool could be successfully applied to the data obtained for *Microcystis sp.* after the full installation of the SolarBees. The model predicted *Microcystis* blooms both timely and accurately especially after the deployment of the SolarBees. It was noted that the mean biovolumes predicted for *Microcystis* and *Ceratium* in Bronkhorstspruit Dam were exactly the same. The model thus most probably predicts the bloom event and does not discriminate between the species since it does contain chlorophyll *a* as a variable in the calculation. This would then explain why the model could predict *Ceratium* blooms so well in the Bronkhorstspruit Dam but not *Microcystis* (that rarely forms blooms in the Bronkhorstspruit Dam).

CONCLUSIONS

The early warning/prediction tool CEGAP was able to predict both *Microcystis* and *Ceratium* biovolumes well up to 14 days forward in both Rietvlei Dam and Bronkhorstspruit Dam. The RMSE for *Microcystis* prediction 14 days forward in Rietvlei Dam was 1.033. It is robust enough to predict a bloom of either one of these algae and performed well despite the major ecological changes introduced in Rietvlei Dam.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. The prediction tool predicts the events of expected algal blooms of *Microcystis aeruginosa* and *Ceratium hirundinella* accurately, but do not predict the extent of the blooms accurately. Further model development for predicting *Microcystis aeruginosa* and *Ceratium hirundinella* more accurately can be done by using the biovolume of both species in the development of predictive algorithms for both bloom-forming species.
2. The model can be implemented for real-time forecasting by reservoir managers at other plants where the in-take water contain as dominant species one or both of *Microcystis aeruginosa* and *Ceratium hirundinella*.
3. The methodology can assist national water management in setting different scenarios.
4. Develop capacity in South Africa to use the Hybrid Evolutionary Algorithm (HEA) RULE set development in all research spheres, as the method is applicable to any type of numerical data.
5. As a Super Computer are available at the University of the Western Cape, which is necessary to conduct these model development studies, the Department of Water Affairs may investigate the availability to Departmental model development, also for other research work on water quality.
6. Investigate the cause and effects for changing the composition of the phytoplankton introduced by long distance circulation.

INFORMATION AND KNOWLEDGE DISSEMINATION

Conferences Attended

1. Coetzee, L.Z., Van Ginkel, C.E. and Barnard, S. Habitat disturbance for the prevention of harmful algal Blooms. The XXXI Conference of the Societas Internationalis Limnologia, Cape Town South Africa, August 2010. Paper.

2. Van Ginkel, C. E.; Barnard, S and Coetzee, L.Z. Habitat disturbance for the reduction of harmful algal blooms in Rietvlei Dam, South Africa. The XI International Conference on Toxic Cyanobacteria, August 2013, Pilanesberg, South Africa. Paper

Papers published

Van Ginkel, C. E.; Barnard, S and Coetzee, L.Z. Habitat disturbance for the reduction of harmful algal blooms in Rietvlei Dam, South Africa. Submitted.

PROJECT CAPACITY DEVELOPMENT

Mrs Coetzee, manager at the Rietvlei Water Treatment Works, initially would have used the data generated from this research as part of her PhD studies. Mrs Coetzee, however, resigned as a researcher and PhD student for personal reasons but remained involved in the project as a steering committee member. Ms Simone Booyens from the NWU, Potchefstroom continued with part of the research as fulfilment to obtain her BSc Hons degree. She obtained her degree *cum laude* in 2013.

ACKNOWLEDGEMENTS

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Reference Group	Affiliation
Dr Kevin Murray	WRC Chairperson (Primary)
Dr Nonhlanhla Kalebaila	WRC Chairperson (Secondary)
Dr Sebastiaan Jooste	Department of Water Affairs (RQS)
Mrs Leanne Coetzee	CSV Water
Mr Jurgo van Wyk	Department of Water Affairs

CONTENTS

LIST OF FIGURES

LIST OF TABLES

BHSP	Bronkhorstspruit Dam
Ca	Calcium
CCA	Canonical Correlation Analysis
CHLA	Chlorophyll a
DIN	Dissolved inorganic nitrogen (NO3 + NO2 + NH4 -N)
DIP	Dissolved inorganic phosphorous (measured as PO4-P)
DWA	Department of Water Affairs
EC	Electrical conductivity
HEA	Hybrid Evolutionary Algorithms
K	Potassium
LDCs	Long distance circulators
Mg	Magnesium
NH_4	Ammonium
PCA	Principle Component Analysis
pH	indicates acidity: numerically equal to the negative logarithm of H+ concentration expressed in molarity
PO_4	Phosphate
R	Correlation coefficient
RSME	Root Mean Square Error
RV	Rietvlei Dam
Secchi	Secchi disc reading
SO_4	Sulphate
SOM	Self-Organizing Map
TN	Total nitrogen (KN + NO2 + NO3)
TP	Total phosphorous
Tsurf	Surface temperature
WTW	Water Treatment Works
WWTW	Wastewater Treatment Works

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Freshwater is South Africa's most valuable natural resource. About sixty percent of the available water is used for agriculture and about 11.5% for urban and domestic uses (Rand Water, 2013). A typical South African household uses about 250 litres of water a day. The typical South African household consisting of 3 children and two parents would use on average 37500 litres of water a month, all of which has to be supplied by the local water treatment works (WTW) or municipality (Cape water solutions, 2013).

South African freshwater resources are under constant pressure of pollution originating from various sectors especially agriculture, mining, industries as well as domestic uses. Pollution contributes significantly to the process of eutrophication, the presence of high concentrations of organic and inorganic compounds, which enhance algal blooms. It leads to changes in the phytoplankton composition, often shifting the dominance toward cyanobacteria and other species forming algal blooms. Algal blooms have become a global problem and also occur widely in South African water sources (Harding and Paxton, 2001; Downing and Van Ginkel, 2003). Some of the bloom-forming species are potentially toxic and as a result pose a serious health risk to humans and animals alike. In South Africa, blooms, especially *Microcystis aeruginosa* blooms, can cause the release of high concentrations of toxins into the water, while blooms of *Ceratium sp*. can produce organic compounds causing foul tastes and odours in the water. The removal of these compounds can cause huge increases in drinking water production costs due to the need for advanced treatment options. Algal blooms also pose several other practical problems in conventional water treatment processes, such as the formation of disinfection by-products such as trihalomethanes and chloro-acetic acids, and the clogging of filter beds.

Algal blooms can develop rapidly and managers of WTW have to rely heavily on results of water quality analyses for management decisions. Water quality analyses can, however, be delayed for up to fourteen days depending on factors such as: sampling, distance and accessibility to laboratory, laboratory sample turn-around times, specific method used in analysis, etc. (Swanepoel et al., 2008a). Therefore the use of predictive models to predict possible blooms of specific algae can be powerful tools for early warning and operational control of harmful algal blooms in drinking WTW. Methods used for the development of predictive models for algal blooms include the extraction of generic rules from ecological time-series data, by means of hybrid evolutionary algorithms (HEA) (Van Ginkel, et al. 2008)

In a previous study the HEA method was used to develop algorithms for algal bloom prediction. The rule set discovered by HEA was tested on long-term data in three South African reservoirs using different scenarios of real time, 7-days forward, 14-days forward, 21-days forward and 28-days forward forecasting of the abundance of the cyanobacterium, *Microcystis aeruginosa*. The tool has since been prepared in a ready-to-use Excel format and can be used by local water resource managers to predict blooms up to 28 days forward. The main objective of the present study was to evaluate the predictive value of this early warning tool.

Due to eutrophication, water quality in the Rietvlei Dam has severely deteriorated and algal blooms of especially *Microcystis aeruginosa* and *Ceratium hirundinella* have been observed. In times of extreme algal blooms, the amount of water produced by the plant (which has a capacity of 40 Mℓ/day) has been significantly reduced to 20 Mℓ or less per day. Rietvlei Dam, therefore, is an ideal setting where the predictive tool can be implemented and evaluated.

Several developments have taken place at Rietvlei Dam during the past few years, most recently that of the implementation of the SolarBee technology. Environmental changes have also been observed and the cyanobacterium *Microcystis aeruginosa* is no longer the most prominent bloom forming algae. The dinoflagellate, *Ceratium hirundinella,* has been responsible for huge mass occurrences as well. Therefore, a brief ecological overview was done in order to characterize the study area and to compare the current ecological status to previous data collected before the deployment of the SolarBees. This is an important step before evaluation of the model, since some of the input parameters used for predicting blooms might have changed significantly at Rietvlei Dam. The model was developed to predict blooms of *Microcystis aeruginosa* using pH, secchi depth, phosphorous and nitrogen concentrations and chlorophyll *a* concentrations. Data collected from the Rietvlei Dam was used to evaluate the influence of the SolarBees using unsupervised Self-Organizing Map (SOM) neural networks. This is in addition to the early warning tool that was evaluated for real-time, 14-days forward, and 28-days forward forecasting against data collected by the Department of Water Affairs at Rietvlei Dam. It was shown that the SolarBees had significant influences on the water quality and algal bloom formation in Rietvlei Dam. Data collected from the Bronkhorstspruit Dam, by Resource Quality Services Laboratories at Roodeplaat, was used to further investigate the performance of the prediction tool CEGAP in order to establish the confidence in its outputs and to discover strengths and limitations in the model.

1.2 PROJECT AIMS

The following were the aims of the project:

1. To compile a recent ecological overview of the water quality of the Rietvlei Dam and to describe the process configuration and advanced treatment options already employed to produce potable water.
2. To investigate the effect of habitat disturbance created by long distance circulation of the SolarBees on the development of cyanobacterial blooms and water quality.
3. To implement the prediction tool CEGAP and evaluate its performance as an early warning/prediction tool for water treatment works' managers.

CHAPTER 2: CHARACTERISATION OF THE STUDY AREA – THE RIETVLEI DAM

2.1 LOCATION AND CATCHMENT ACTIVITIES

The Rietvlei Dam lays South East of the City of Tshwane. The impoundment's morphology shows a shallow slope all the way around the perimeter with the exception of the area near the Dam wall and a portion of the south eastern shoreline. The impoundment has a length of 3.3 km and a maximum width of approximately 1.6 km with a full surface area of 204.13 Ha (Bornman et al., 2007). The Dam has a net capacity of 12,185 x 106 m^3 and a mean depth of 6.22 m (Steyn et al., 1975). The catchment area of the Rietvlei Dam is relatively small (492 km^2), stretching through Kempton Park to OR Tambo International Airport.

The area surrounding the Dam was declared a nature reserve in 1937 and opened to the public in 1994 (Bornman et al., 2007). Van Riebeeck Nature Reserve, now known as the Rietvlei Nature Reserve, covers a surface area of 3870 Ha within the limits of the City of Tshwane. The reserve is situated in the Bakenveld biome covered with rocky Highveld grasslands. The primary function of the Rietvlei Nature Reserve is to act as an active wetland for the filtration of incoming water. The natural peat wetland stretches 8 km in length and measures 400m in width. The wetland also includes a small (19.47 Ha surface area) Dam called Marais Dam. The wetlands stretch between Marais Dam and Rietvlei Dam for approximately 5 km. Wetlands form an integral part of a rivers systems' ability to recover from pollution. The soil is mainly alluvial and the most abundant flora in the wetland is the reed, *Phragmites australis* (Bornman et al., 2007).

Land use in the catchment area is primarily agricultural with cattle ranching and maize cultivation being most important. The impoundment is fed by one major inflowing river, the Hennops River (also known as the Swartspruit) and four small intermittently-flowing streams which drain the area directly to the north and the south of the impoundment. Hartebeespoort Waste Water Treatment Works (WWTW) is situated approximately 25 km upstream of the point where the river flows into the Rietvlei Dam. The effluent from this WWTW contributes between 20 and 70% of the water and most of the nutrients that flow into the Rietvlei Dam (Walmsley et al., 1978; Toerien and Walmsley 1979). The Rietvlei water treatment works (WTW) is situated on the eastern side of the Rietvlei Dam and is located at S25°52'40.32, E 28°15'52.56, which is approximately 25 km from the Pretoria CBD. The water sourced from the Rietvlei Dam is treated for potable purposes at Rietvlei WTW. Treated water from the Rietvlei WTW is pumped to various reservoirs where it mixes with water from Rand Water. The blending ratio is about 70% Rand Water and 30% from own sources. Therefore, the water quality of the water available in the Rietvlei Dam has a significant impact on the water treatment efficiency of the plant and drinking water quality of the people living in the City of Tshwane.

2.2 RIETVLEI DAM WATER QUALITY MONITORING

2.2.1 Water Quality Monitoring and Sampling

Monitoring of the dam and the water quality is performed by the Department of Water Affairs at Resource Quality Services as part of the National Eutrophication Monitoring Program (NEMP). Samples are taken at the Dam Wall on a bi-weekly basis. The monitoring done by the Tshwane Water Treatment Work personnel was done monthly.

Field samples

The sampling site near the dam wall is also the sampling site for the National Eutrophication Monitoring Programme (NEMP). On each sampling occasion conducted by Resource Quality Services (RQS), physical parameters such as electrical conductivity (EC) and pH were taken *in situ* at this site. The *in situ* measurements of temperature and oxygen were taken at 1-m depth intervals with an YSI meter.

Water samples

A one litre 0-5 m integrated sample was taken by the Department of Water Affairs (DWAF) at the dam wall. The respective NEMP water samples from each reservoir were then also subdivided into a macro inorganic sample, an algal identification sample and a chlorophyll (Chl *a*) sample. The macro inorganic samples (major inorganic chemicals) were analysed on automatic analysers at RQS of the Department of Water Affairs. The macro chemical variables measured were: suspended solids (SS), ammonium (NH_4), nitrate and nitrite (NO_3 + NO_2), ortho-phosphorus (PO_4-P), sulphate (SO_4), silica (Si), and total alkalinity (TALK). In addition, the Kjeldahl nitrogen (KN) and total phosphorus (TP) concentrations were determined using digestion methods (DWAF, 2006a and 2006b). To determine the dissolved inorganic nitrogen (DIN) concentrations, the sum of the ammonium, nitrate and nitrite was calculated. To determine the total nitrogen (TN) concentrations the sum of the Kjeldahl nitrogen, nitrate and nitrite concentrations was calculated.

Phytoplankton samples were preserved in Lugol’s solution and were identified under an inverted light microscope. The percentage dominance was calculated as a percentage of the total algal population. The microscopic method for algal identification is described in detail in the methods manual of the RQS (Department of Water Affairs and Forestry, 1997). Chlorophyll *a* content was measured by spectrophotometry by the RQS. The biovolume for algal species were then calculated as:

$$\mathrm{AB} = (\mathrm{AD}/100) * (\mathrm{Chl}a * 2.5)$$ (Van Ginkel et al., 2007)

Where:

AB is the algal biovolume measured as cm^3/m^3

AD is the algal dominance (measured as %)

Chl*a* is the measured chlorophyll *a* concentration (measured in µg/ℓ)

During this study two study periods were considered, namely (a) the two and a half years prior to the deployment of the SolarBees (2006-2008) and (b) the two and a half years post to the deployment of the SolarBees (2008-2010).

2.2.2 Multivariate Statistical Analysis

During investigation of variation of communities across a range of different environmental conditions, huge differences in species composition of the studied communities can be found (Van Ginkel, 2007). Ordination tools such as Canoco can be used to assess the data in order to determine this variation in the phytoplankton community. Gradual changes between sites and their communities are often related to differing and partially overlapping demands of the individual species for various environmental factors such as nutrient conditions and temperatures. The ordination diagram approximates the matrix of distance and angles between the species and environmental variables. It is a conclusion from correlations and dissimilarities between response variables or species and the environmental variables. It is a visual tool to determine the relationships between the species and the environmental variables, the correlations between the environmental variables and other significant relationships (Lepš and Šmilauer, 2003; Van Ginkel 2007).

To determine whether there were significant differences between the three different sampling sites in the dam, a Principle Component Analysis (PCA) was performed, of the data obtained from the City of Tshwane, using Canoco version 4.5. The resulting diagram (Figure 2.1) indicates that there is no significant difference between the sampling sites and as a result data of only one sampling site, namely at the dam wall, was used. The PCA analysis furthermore indicates that there is a similar seasonal trend which occurs between the samples during these monitoring periods (Figure 2.1).

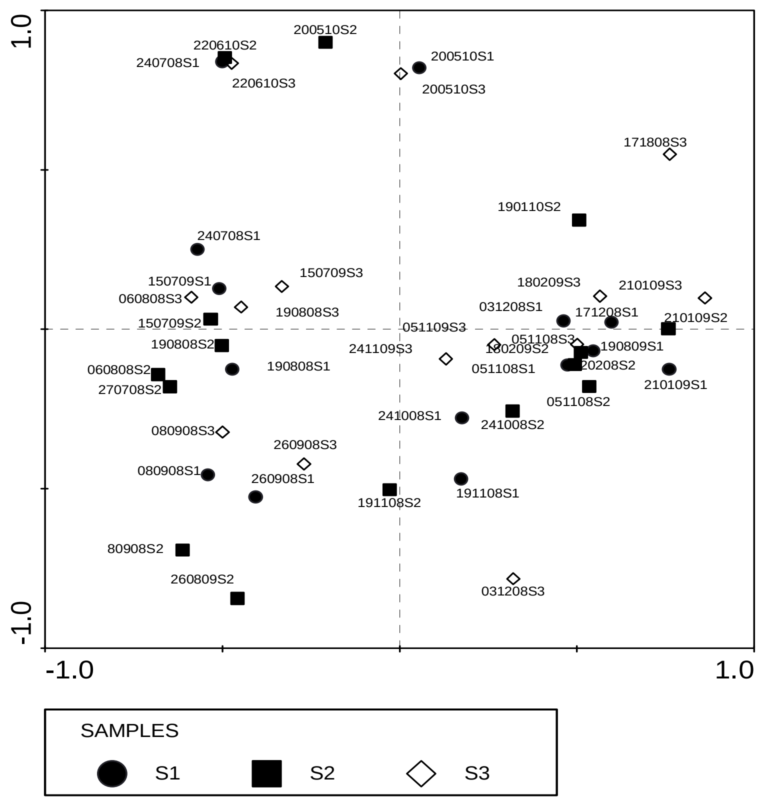

Figure 2-1: PCA ordination diagram showing the ordination of data from all 3 sampling sites in the Rietvlei Dam (Buoy 5 (S1), Dam Wall (S2) and Pole sampling sites (S3).

Using the data provided by the City of Tshwane's laboratory at Rietvlei Dam stretching from January 2006 to June 2008, the Canonical Correlation Analysis (CCA) in Figure 2.2 indicates that some environmental data may be represented by one point which is used to represent all of these data points. Temperature readings for the first five meters, dissolved oxygen for the first eight meters and some variables such as phaeophytin and chlorophyll *a* showed strong correlations between them and thus a single parameter can be used in the modelling analysis which serves as a surrogate for all these parameters, as they have a similar effect on the data. Environmental parameters that have the biggest effect on the data are: Secchi, EC, PO_4, TP, TN and CHLA. *Microcystis sp*. correlates closely with chlorophyll *a* indicating that it contributed to observed chlorophyll *a* values. It is also positively correlated with PO_4, TP and TN and negatively with Secchi. Most of the diatoms and green algae associate positively with nitrates and dissolved oxygen. The eigen values in Table 2-1 shows that the first two axes explain most of the variances observed in the species data with both *Microcystis sp*. and *Ceratium sp*. correlating closely with the first axis (explaining 18.1% of the variance). The variance in the species-environmental data is best explained by the first axis (31.2%) with most of environmental variables correlating with the first axis. Dissolved oxygen, dissolved magnesium and nitrates correlated with the second axis. The correlations were statistically significantly ($p<0.05$).

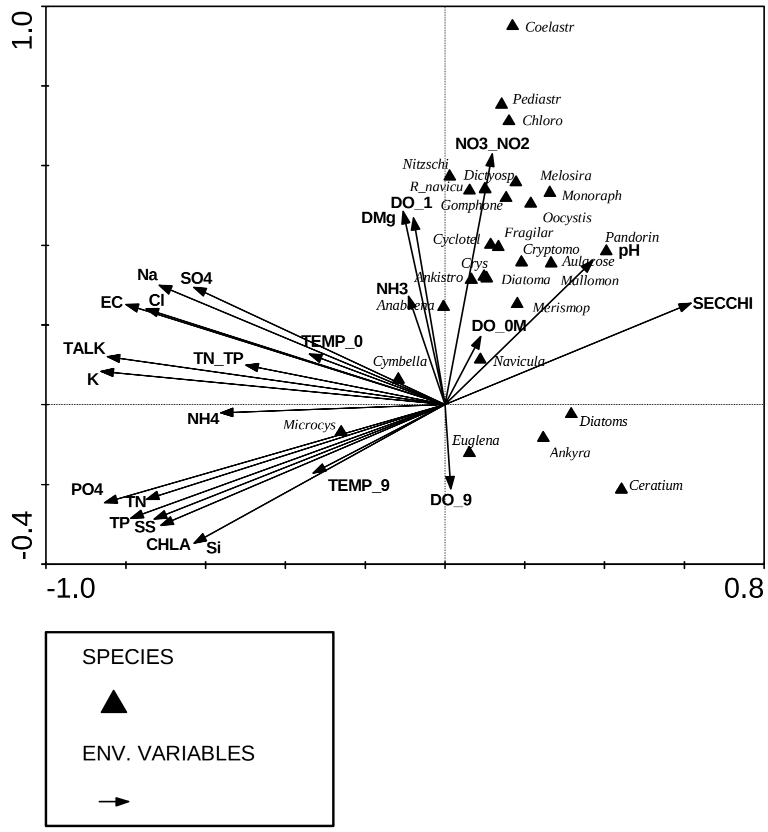

Figure 2-2: CCA ordination diagram indicating the predominant variables from the physical-chemical data and their correlations to one another and the algal species observed.

Table 2-1: Results from the CCA analysis of the Rietvlei Dam indicating the percentage of variance explained by the different axes.

Axes	***1***	***2***	***3***	***4***	***Total inertia***
Eigenvalues	0.829	0.600	0.304	0.280	4.573
Species-environment correlations	0.975	0.878	0.826	0.828	
Cumulative percentage variance:					
of species data	18.1	31.2	37.9	44.0	
of species-environment relation	31.2	53.7	65.2	75.7	
Sum of all eigen values					4.573
Sum of all canonical eigen values					2.659

<u>Summary of Monte Carlo Test</u>

Test of significance of first canonical axis: eigenvalue	0.829
F-ratio	7.527
P-value	0.0020
Test of significance of all canonical axes: Trace	2.659
F-ratio	1.967
P-value	0.0020

2.2.3 Rietvlei Dam Water Quality Characteristics and Key Challenges

Rietvlei Dam experienced its first algal blooms reaching massive proportions in the summer of 1972/73. In two surveys of South African impoundments, the Rietvlei Dam was ranked as the most eutrophic impoundment in the country in terms of phosphorus availability and growth potential or phytoplankton extent (Toerien et. al., 1975, Van Ginkel et al. 2001). Eutrophication is also defined as the enrichment of available food in aquatic systems with algal productivity representing the cornerstone of the food web. Harding et al., (2008) found that the Rietvlei Dam had increasing phosphorus concentrations and was rated the second highest impoundment on the basis of the measured median TP concentration of 0.250 ppm. The trophic state boundaries as used by the DWA Trophic Status Assessment (Van Ginkel et al., 2001) are summarized in Table 2.2.

Table 2-2: Trophic State Classification Boundaries per DWAF guidelines (Van Ginkel et al., 2001)

Variable	*Oligotrophic**	*Mesotrophic**	*Eutrophic**	*Hyper-eutrophic**
Total Phosphorus (mg/ℓ)	<0.015	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

*Values expressed as annual medians

2.2.4 Effect of Rietvlei Dam Source Water Quality on the WTW

Due to eutrophication related problems the City of Tshwane has upgraded the water purification plant several times over the past years (Table 2.3) in order to improve technology in an effort to produce cost effective and safe drinking water:

- The first 18 Mℓ/d plant was built in 1934
- The treatment capacity of the Plant was increased in 1988 to 40 Mℓ/d
- During the 1990s the plant saw the first full-scale application of the Dissolved Air Flotation and Filtration (DAFF) process in South Africa
- The new Granular Activated Carbon (GAC) filtration system was completed in 2000 and is the first operational application of open bed gravity filters for drinking water treatment in South Africa.
- Ozone became more cost effective, which led to a decision in 2006 to install ozone treatment as an additional barrier (Personal communication Coetzee, 2010).

Table 2-3: Process train at Rietvlei Water Treatment Works

Process	Plant 1990	Plant 1999	Plant 2011	Treatment objective
Pre-chlorination				
Pre-ozonation			■	Killing of algae, oxidation of Fe and Mn,
PAC adsorption				
Coagulation	■	■	■	Agglomeration of micro particles into flocs
Sedimentation				
DAFF	■	■	■	Removal of small suspended floatable particles
Ozonation			■	Inactivation of pathogens, oxidation of organics including taste and odour
Sand filtration	■	■	■	Removal of small suspended particles
GAC filtration		■	■	Adsorption of organic material
Chlorination	■	■	■	Primary Disinfection
Chloramination			■	Secondary Disinfection

The increased load of treated sewage water entering the dam as well as the increase in harmful algal blooms necessitated the installation of the advanced treatment processes. Not only did this result in huge capital expenditures but also an increase in operating costs (Table 2.4). The 1999 upgrade in installing GAC was for an amount of R40 million. The addition of ozone in 2010 was estimated to be about R23 million. This cost includes other civil additions such as laboratory and office areas. The 1999 upgrade with GAC was preceded by a pilot plant study which indicated that some 20-25% removal in organics, measured as DOC and chlorine demand could be expected. In practice, about 10-15% removal of these targeted compounds were achieved. However, incidents of taste and odour still occur.

Table 2-4: Maintenance and energy costs for technology used at Rietvlei Dam.

Process	Dosing Rate (mg/ℓ)	Chemical cost (R/kg)	Maintenance cost (R/kℓ)	Energy cost (R/kℓ)	Unit Cost (R/kℓ)
Chlorination	5 mg/ℓ	R 10			0.05
Ozonation	1.5 mg/ℓ pre-ozonation and 5 mg/ℓ main	R 30	0.02	0.04-0.07	0.35

However, due to the inconsistency of the raw water turbidity and quality, other treatment options were also investigated in order to improve the overall water quality in the impoundment. Different treatment chemicals were evaluated and some were found to be more effective than the ferric chloride option in use at the time. This included a Poly DADMAC blend (Sudfloc 3850 from SudChemie Pty Ltd) and this chemical enabled the plant to run more efficiently. The cost of the PolyDADMAC was, however, significantly higher than that of ferric chloride making the cost of chemical per litre about ten times the price of ferric chloride. Despite the increase in production costs, this would enable the plant to run without interruptions due to blockages of filters and would allow a better quality of water to be produced. This made the decision very difficult and prompted management to re-think purification strategies. SolarBees were subsequently installed.

2.3 USE OF SOLARBEEs AT RIETVLEI DAM

2.3.1 The SolarBee

The SolarBee long distance reservoir circulator is a solar powered water circulator designed to improve water quality in almost any sized surface water body (Figure 2.3). The SolarBee utilizes a patented near-laminar flow technology and does not require any other intervention. The SolarBee does not remove nitrate or phosphate but is based on the principle of habitat disturbance. This form of bio-manipulation selects against the harmful cyanobacteria whilst favouring edible green and beneficial algae which enhance complex aquatic food webs. This method of lake management treating the symptoms is in direct contrast with the traditional lake management approaches dealing primarily with the causes of eutrophication (Knud Hansen, 2007).

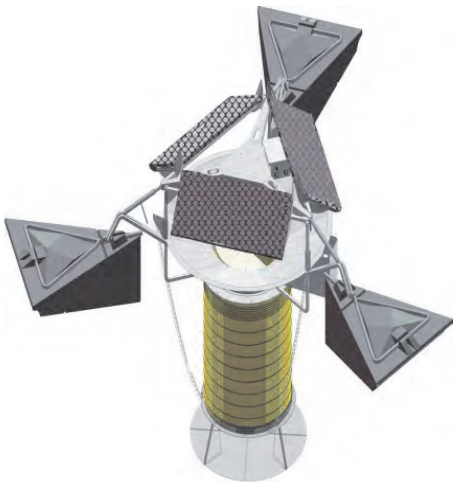

Figure 2-3: SolarBee indicating hose (yellow) and floats (black triangles), solar panels (rectangles). (taken from Knud Hansen, 2007)

This particular way of thinking relies on the fact that food enrichment goes into two different directions depending upon whether or not algal productivity is dominated by cyanobacterial algae. When the phytoplankton is dominated by cyanobacterial biomass, the food remains in the microbial level cycling between cyanobacterial biomass and decomposition. When algal productivity is dominated by non-cyanobacteria, both biomass and energy move up the food web into zooplankton, other invertebrates and fish. Therefore even in the case of a hyper-eutrophic impoundment the lake ecology is enhanced and the consequences of eutrophication minimized (Knud Hansen, 2007).

The method recommended by SolarBee for habitat disturbance of the cyanobacteria is that of epilimnion mixing, where the intake hose is set above the thermocline of the impoundment (Figure 2.4). This is the photic zone where algal growth is highest. One unit is capable of circulating 40 000 litres of water per minute and impacting on approximately 14 Ha of lake surface per machine. The following are the anticipated benefits of SolarBees:

- Taste and Odour reduction
- Reduction in frequency and occurrence of cyanobacterial blooms
- Better dissolved oxygen levels in impoundment
- Lower dissolved metals in water

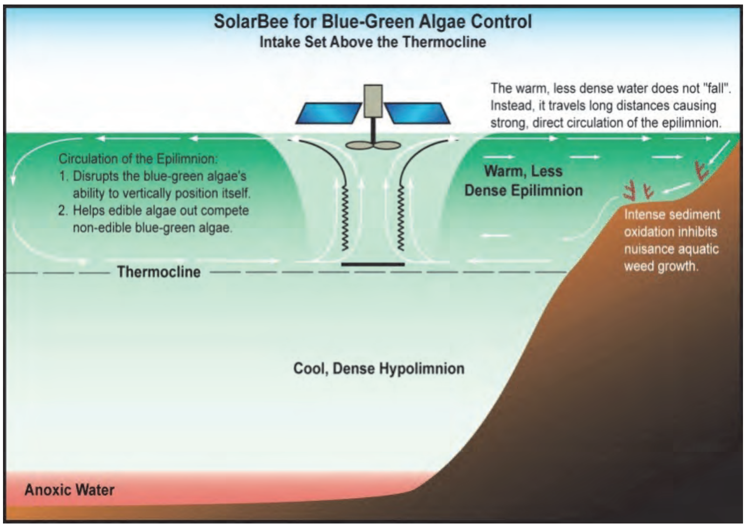

Figure 2-4: Recommended SolarBee setting for epilimnion mixing. (Taken from Knud Hansen, 2007).

2.3.2 Installation of SolarBees at Rietvlei Dam

Installation of the first six SolarBee units took place in July 2008. These units were placed in the south eastern area of the dam which is the main feed to the Dam and the area in which the cyanobacteria are most likely to grow due to the high nutrient levels and slower moving water in this area (Figure 2.5). An 80% likelihood of success was estimated for this particular scenario. During that time significant concentrations of *Ceratium* species were already present in the Rietvlei Dam. Three of the six units installed, were purchased by the *Harties-Metsi-a-Me* project for use in the Rietvlei Dam. In 2009, a further 10 units were purchased and installed in May, allowing this to be a full scale SolarBee installation with a 95% probability of success.

Figure 2-5: Placement of SolarBee machines in Rietvlei Dam. Yellow circles = first installation July 2008, White circles = second installation May 2009 and Red circles indicate sampling points.

2.3.3 Effect of Solarbees on Rietvlei Dam Water Quality

During the current study the measured variables of the two sampling groups (Table 2.5) pre and post installation of SolarBees, were used to describe the water quality. The complete dataset, which corresponds to 44 variables and 62 samplings (62 and 61 samples pre and post SolarBees installation, respectively) were used. The pH ranged between 8.2 and 9.5. EC and all the salts measured that would contribute to EC (Ca, Mg, K, Na, SO4 and Si) showed a significant decrease post the installation of the SolarBees.

Table 2-5: Descriptive statistical values of the datasets pre and post the SolarBees. (n=62 pre and n=61 post).

Variable	Pre SolarBees				Post SolarBees			
	Mean	Minimum	Maximum	Std.Dev.	Mean	Minimum	Maximum	Std.Dev.
Ca	31.1111	26.1200	34.898	2.4688	29.7779	25.0010	45.0000	2.8219
Cl	52.1881	34.8770	75.617	9.5719	46.5534	29.1030	63.7110	9.3411
Ph	8.2547	7.0620	9.485	0.5527	8.2623	7.3270	9.2050	0.3901
EC	53.5715	42.6000	66.161	5.9196	48.4358	37.3000	56.6000	5.2978
SECCHI	2.3123	0.1000	8.100	1.3016	1.6316	0.2000	3.8000	0.7878
SS	11.1841	2.5000	183.000	22.4267	13.3238	2.5000	62.5000	10.8674
MgHARD	43.1492	38.2250	49.048	2.6269	48.9013	23.8780	90.2360	10.4970
THARD	128.9151	113.3565	144.351	7.8443	132.3667	103.5510	198.4450	16.9219
TALK	118.0358	97.5375	137.867	9.2934	121.9521	97.7500	201.0000	17.4364
DMg	12.4385	11.0190	14.139	0.7573	14.0399	5.4550	26.0120	3.1519
K	10.6570	8.2285	13.265	1.5451	8.2250	5.7200	10.7000	1.3276
Na	52.5007	35.4070	70.982	9.8920	41.2089	18.0000	55.3470	9.1971
Si	3.3224	0.4000	6.130	1.4899	3.8200	0.5530	6.0700	1.3723
SO_4	57.4419	41.2560	76.843	9.9712	48.2825	31.7980	94.3990	11.3426
TN	2.8715	0.8590	21.408	2.6019	2.1722	0.4260	5.3250	0.9514
NH_3	0.0401	0.0025	0.215	0.0437	0.2654	0.0100	1.3000	0.2032
NH4	0.3947	0.0355	1.518	0.3530	0.1403	0.0000	1.7500	0.2419
NO_3_NO_2	0.9460	0.0400	2.536	0.7372	0.6487	0.0050	1.7950	0.4955
DIN	1.3407	0.0920	3.837	1.0221	0.7890	0.0300	3.0500	0.6287
TP	0.5292	0.2420	2.454	0.2965	0.3339	0.0700	1.4000	0.2583
PO_4	0.3694	0.0200	0.954	0.1672	0.1125	0.0060	0.5300	0.0826
TN_TP	5.7506	1.5929	14.641	3.2194	8.1596	0.0000	37.8714	7.4102
DIN_DIP	5.4137	0.2382	80.600	10.3085	13.3147	0.4050	158.7500	24.0392
DO_0M	8.0934	4.2000	16.360	1.8664	8.5298	2.2800	22.7500	3.5310
DO_1	7.7144	3.2500	15.400	2.4545	7.6569	1.9900	15.1500	3.0213
DO_2	7.5325	3.1600	16.750	2.5666	7.1015	2.0200	14.6100	2.9955

Variable	Pre SolarBees				Post SolarBees			
	Mean	Minimum	Maximum	Std.Dev.	Mean	Minimum	Maximum	Std.Dev.
DO_3	7.2008	2.7900	16.700	2.4430	6.5725	0.7400	13.1400	3.0468
DO_4	6.5332	2.6600	15.300	2.2006	5.9647	0.2300	12.3500	2.9981
DO_5	6.0621	2.5400	14.760	2.3519	5.4216	0.1500	12.2200	3.0423
DO_6	5.2454	1.2900	13.760	2.4450	4.9162	0.1200	12.2300	3.1372
DO_7	4.4261	0.6300	12.610	2.6261	4.3775	0.0500	11.5200	3.0580
DO_8	3.8430	0.2700	12.590	2.6603	3.7084	0.0500	11.1200	2.9317
DO_9	3.2440	0.0500	10.600	2.6349	3.1875	0.0500	10.2600	2.9518
TEMP_0	18.9887	10.0100	26.130	4.8073	17.0107	7.3500	24.3500	4.6578
TEMP_1	18.6821	9.9800	26.130	4.8100	16.7584	7.2900	24.2200	4.5124
TEMP_2	18.5302	9.8700	25.840	4.7753	16.5982	7.2600	24.1700	4.4887
TEMP_3	18.3697	9.8700	25.210	4.7405	16.3715	7.2500	24.0800	4.4188
TEMP_4	18.1085	9.8600	24.820	4.6669	16.1342	7.2500	23.8600	4.3840
TEMP_5	17.9327	9.8500	24.450	4.5803	15.8480	7.2100	23.7300	4.3292
TEMP_6	17.6006	9.8200	24.440	4.4040	15.4394	7.1700	23.7000	4.2028
TEMP_7	17.2425	9.8100	23.160	4.3021	15.0892	7.1400	22.2200	4.0107
TEMP_8	16.9272	9.8000	23.060	4.1595	14.8134	5.4400	21.0500	3.7635
TEMP_9	16.5683	9.8100	22.500	3.9844	14.8134	5.4400	21.0500	3.7635
CHLA	64.2420	2.0810	1558.200	196.1148	107.1912	4.8300	681.1000	122.6764

2.3.3.1 Effect on Nutrient Concentrations

There were significant differences in the nutrient concentrations (Table 2.5), such as NH_3, NH_4 and PO_4. Both PO_4 and NH_4 levels which decreased from an average of 0.37 mg/ℓ to 0.11 mg/ℓ and 0.39 mg/ℓ to 0.14 mg/ℓ, respectively. This occurred, despite the significant increase in NH_3 from an average of 0.04 to 0.27 mg/ℓ. A significant decrease in temperature was evident for measurements at all depths. This decrease is shown for the surface temperature was ± 2°C at all the depths. There was no significant difference in the DO concentration pre and post the deployment of the SolarBees.

2.3.3.2 Secchi Depth

In Rietvlei Dam maximum Secchi depth of 2.85m in the 2006- 2008 period decreased to a maximum of 2.56m in 2008-2010. Maximum Secchi depths were obtained during winter and autumn/spring time when the water temperature at the surface was between 10-19°C in the study period 2006 – 2008. During most of the summer periods in the 2008-2010 study period and half of the winter season, the Secchi depths for Rietvlei Dam were low. The first six SolarBee units were installed in early July 2008 during one of the worst *Ceratium* blooms experienced which explains the very low Secchi depth measured. It is interesting to note that the 2008-2010 study period was is characterised by a more even distribution of Secchi depth than the 2006-2008 study period where extreme highs and lows were found.

2.3.3.3 Cyanobacterial Dominance

Cyanobacteria are one of the few organisms that have adapted to stagnant conditions and some have evolved internal gas vesicles that allow them to regulate their buoyancy in the water column. During the day in calm waters, cyanobacteria come near the surface in order for them to have a competitive advantage over the non-cyanobacteria for light atmospheric carbon dioxide and atmospheric nitrogen (N_2 for those cyanobacteria capable of fixing N_2 directly). At night they can settle down into deeper more nutrient rich waters (Knud Hansen, 2007). Many of these cyanobacteria are also capable of producing potent cyanotoxins with hepatotoxic and neurotoxic effects. These toxins cause lethal and sub-lethal effects in humans and other organisms and bloom biomasses adversely impact on aquatic biota. The incidence and duration of freshwater algal blooms is increasing worldwide (Hudnell et al., 2010). This is due to increasing fresh water usage demand and excessive nutrient input as well as global climate change. The chlorophyll *a* content is a measure of algal density and is the product of algal pigmentation. In Rietvlei Dam chlorophyll *a* levels increased from maximum levels of 92µg/ℓ in 2006-2008 to 189 µg/ℓ in the 2008-2010 study period. The seasonal pattern of chlorophyll *a* production was also different. It changed from a spring/autumn and summer phenomenon in 2006-2008 to being mainly a winter phenomenon in 2008-2010.

The significant *Ceratium sp*. bloom during the winter of 2008 is probably the reason for the exceptionally high chlorophyll maximum levels. At Rietvlei Dam, the *Ceratium* concentrations increased dramatically from a maximum biovolume of 108 cm^3/m^3 (2006-2008) to a maximum of 673 cm^3/m^3 (2008-2010). Some of the highest levels of *Ceratium* were recorded during installation of the first six SolarBees (July 2008) and it has remained prevalent during the winter and autumn/spring periods. This alga is motile and can also move up and down in the water column using its flagella. It is troublesome in the production of drinking water because it is a large alga and blinds the filters resulting in more backwashes being required. This can be mitigated somewhat if pre-chlorination is applied.

Microcystis aeruginosa have long been implicated in the poor water quality in the Rietvlei Dam. The occurrence of *Microcystis* species in the Rietvlei Dam during the 2006-2008 study period reached a maximum biovolume of 145 cm^3/m^3 with the highest concentration of cyanobacteria occurring in the summer months. During the 2008-2010 period the biovolume of *Microcystis* dramatically decreased to a maximum biovolume of 19.8 cm^3/m^3 during the summer months (November 2010). This significant change in the biovolume of this particular nuisance species as well as the change in algal species dominance suggests that the SolarBee application in the Rietvlei Dam may have caused this particular change.

2.3.4 Effects of SolarBees on Water Treatment Costs at Rietvlei WTW

A desktop feasibility study was done in order to determine the cost savings possible with the SolarBee installation (Table 2.6). The projected cost saving on chemicals alone was estimated at R591 297.30 per year and this does not include the cost savings which are due to backwash water savings and production data. Since the SolarBees estimated lifespan is 25 years the estimated cost benefit over 25 years would be R14.78 million rand. The effect of the SolarBees has been noted to be cumulative, that is, the effect of the SolarBees increases with each passing year (Personal Communication Knud Hansen, 2010). Therefore this cost saving may be even more than what was anticipated as the benefits for the ecological system of the impoundment is an added benefit.

Table 2-6: Feasibility study to determine the cost benefits to anticipated savings using the SolarBee (SB) (March 2008)

	Sudfloc (Low algal activity)	Sudfloc (High algal activity)
Approximate days per year(days)	200	165
Volume water treated (ML)	43	43
Dosing Rate (mg/l)	10	20
% Reduction in dosing rate due to SB	0	30
Dosing rate with SB (mg/l)	10	11
Mass of Coagulant per day without SB (kg)	430	860
Mass of coagulant per day with SB (kg)	430	473
Cost of Coagulant per day (R/kg)	R9.26	R9.26
Cost per day without SB	R3 981.80	R7 963.60
Cost per day with SB	R3 981.80	R4 379.98
Annual dosage cost without SB	R796 360.00	R1 313 994.00
Annual dosage cost with SB	R796 360.00	R722 696.70
Projected Annual Cost Saving	**R591 297.30**	

2.4 CONCLUSION

Rietvlei Dam can be classified as a eutrophied impoundment with high levels of PO_4, NH_4 and chlorophyll *a*. The impoundment experienced large blooms of harmful cyanobacteria, in particular that of *Microcystis sp*. but an increase in the occurrence of *Ceratium sp.* has replaced *Microcystis sp* as the dominant species in the dam, after the deployment of the SolarBees. There was a significant difference observed in the water temperature from surface temperature up to a depth of 9 m pre and post the deployment of the SolarBees. This difference of ±2°C could also contribute to the decrease in *Microcystis sp*. growth. Most notably there was a significant decrease in the levels of PO_4 from pre to post the installation of the SolarBees. The results strongly suggest that the habitat disturbance created by the long distance circulation of the SolarBees is responsible for the ecological changes observed in the dam. These changes could have an effect on the prediction performance of the early warning agent because the parameters that changed significantly form part of the algorithms used in the rule set.

CHAPTER 3: DETERMINATION OF THE EFFECT OF THE SOLARBEES USING SELF-ORGANISED MAPPING (SOM)

3.1 INTRODUCTION

The Rietvlei Dam has long been plagued with cyanobacterial blooms of particularly *Microcystis* species due to its hyper-eutrophic status (Van Ginkel *et al.* 2001; Harding 2008). The dam experienced its first harmful algal blooms during the summer of 1972/73. Due to the inconsistency of the raw water turbidity and quality, other treatment options were investigated in order to improve the overall water quality in the impoundment. In 2008, six solar powered long distance reservoir circulation units were installed in the reservoir to disturb the cyanobacterial habitat. A further 10 units were installed in 2009. The long distance circulation (LDC) unit or SolarBee, as a treatment option, requires a paradigm shift as to what is required to change the ecological state of an impoundment. The SolarBee does not remove nitrate or phosphate and does not limit algal growth through a direct step of decreasing nutrient availability. Rather the principle of the LDC implementation is that of habitat disturbance. This form of bio-manipulation selects against harmful cyanobacteria. Since the installation of the SolarBees, improved clarity of water and decreased chlorophyll *a* levels have been noted. Most importantly during the summer of 2010 not one incidence of cyanobacterial blooms have been sustained while during the winter of 2010 other dams in the area have recorded high *Microcystis* concentrations while Rietvlei Dam did not have any *Microcystis spp.* present. This study presents limnological data on the pre and post deployment of SolarBees for harmful algae control conditions using Self-Organised Mapping (SOM).

3.2 MATERIALS AND METHODS

3.2.1 Water Quality Monitoring and Sampling

Monitoring of the dam and the water quality was performed by the Department of Water Affairs at Resource Quality Services as described in section 2.2.1.

3.2.2 Statistical analyses:

STATISTICA version 10 software was used to determine differences between the pre and post deployment of the SolarBees datasets. The Kolmogorov-Smirnov and Lilliefors tests for normality were used to determine if the datasets were distributed parametrically. If the data did not meet the assumptions of normality in the distribution of all variables, the non-parametric Kruskal-Wallis ANOVA (for comparing multiple independent samples) was used to determine differences between the pre and post deployment of the SolarBees datasets.

3.2.3 Self-Organised Mapping Method

Self-Organised Mapping (SOM) was developed as an unsupervised neural network method which has properties of both vector quantisation and vector projection algorithms as developed by Kohonen (1982; 1988), but it may make use of supervised pre-classification to assist in the training (Kohonen 1995). The primary application for SOM toolboxes is clustering and data segmentation.

SOM_QuickPick was the method that was used (Vesanto 2000), and has an input layer which contains the known variables and a hidden layer which is used to cluster and ordinate the data with the mapping of the clustered layer as the output (Recknagel *et al.* 2006). The learning process in the hidden layer is as follows:

- The weight for each output unit is initialised;
- The process within SOM cycles until the weight changes are negligible for each input pattern (the present input pattern finds the winning output unit, finds all units in the neighbourhood of the winner and updates the weight vectors for all those units);
- The size of the neighbourhoods is reduced if required (Kohonen and Honkela, 2007).

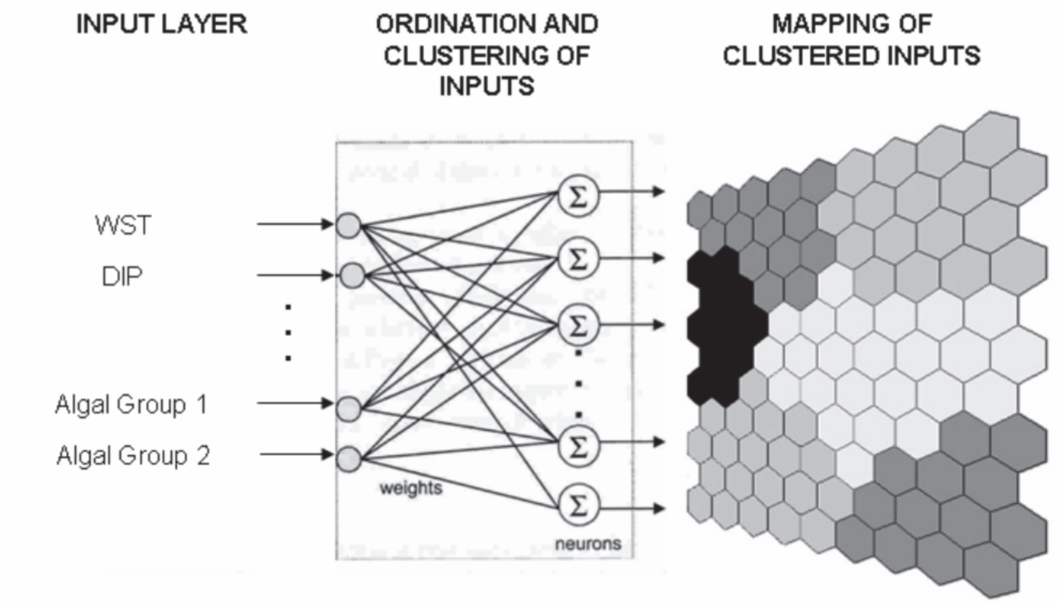

Figure 3-1: The structure of the non-supervised SOM for ordination and clustering of inputs (redrawn from Recknagel *et al.* 2006)

The input data set were pre-classified according to the different data sets that were used and groupings to classify or categorise the data set.

The input variables, including TP and PO_4, TN and DIN, and surface temperature and dissolved oxygen were prepared in the format as required by the SOM_QuickPick toolbox (Vesanto *et al.* 2000). The normalisation method used within the Matlab toolbox was the ‘range’ normalisation method as it provides the best values for the final quantization error (FQE) and the final topographic error (FTE). This method of normalisation scales the variable values between [0,1] with a simple linear transformation:

$x^1 = (x - \min(x))/(\max(x) - \min(x))$.

The transformation parameters are the minimum value and range (max (x) – min (x)) of the variable. Note that if the transformation is applied to new data with values outside the original minima and maxima, the transformation values will also be outside the [0,1] range.

The SOM_QuickPick then add the labels according to the manual categorisation. An additional map showing the frequency of certain results within each result were obtained from normalised input data with the Euclidean distance between the input being calculated and then visualised as a distance matrix – the U matrix a) and a partition map b) (K-means).

The SOM uses colour plane visualisation and is shown as a honeycomb for the U matrix map, the manual categorisation as linked to the self-organised clusters, and the colour coded range of normalised values for each of the components or variables. The U matrix is a unified distance matrix for the creation of the self-organising map (Ultsch and Siemon 1990, Kohonen 1995, Iivarinen *et al.* 1994, Kraaijveld *et al.* 1995). The colour coded range of normalised values for each of the components or input variables allows one to see correlations between different components that was organised into nearby, or the same clusters. A label map is created by the SOM_QuickPic and indicates the frequency for all the components within the self-organised clusters according to their location. These labels are then used to compose the partitioned map which is used to interpret the maps of the variables by comparing the location map to the SOM maps produced by the model for each variable.

The vectors are positioned on a regular low-dimensional grid in an ordered fashion making the SOM a powerful visualisation tool. Therefore, it was decided to use this particular tool to visualise the effect, if any, of the application of SolarBee in the Rietvlei Dam. The data for Rietvlei Dam from 2006 – June 2008 and the data from July 2008 – 2010 were used to ordinate, cluster and map the temperature, oxygen, electrical conductivity(EC), nutrients, chlorophyll *a* and algal groups with respect to the before and after situation in the Rietvlei Dam. The SOM results are obtained from normalised input data with the Euclidean distance between the inputs being calculated and then visualised as a distance matrix – the U matrix a) and a partition map b) (K-means).

3.3 RESULTS

3.3.1 Phytoplankton composition and cell densities

The Rietvlei Dam frequently experienced harmful blooms of mainly *Microcystis* species prior to the installation of the SolarBees. Since the deployment of the SolarBees in 2008 until the December 2010 the species composition (Figure 3.2) has changed significantly. The extent and the presence of the Cyanophyceae has decreased significantly from the pre to post periods of the installation of the SolarBees, which consisted primarily of *Microcystis*. There is a significant difference ($p=0.019$) in the biovolume of *Microcystis* sp. pre and post the SolarBees.

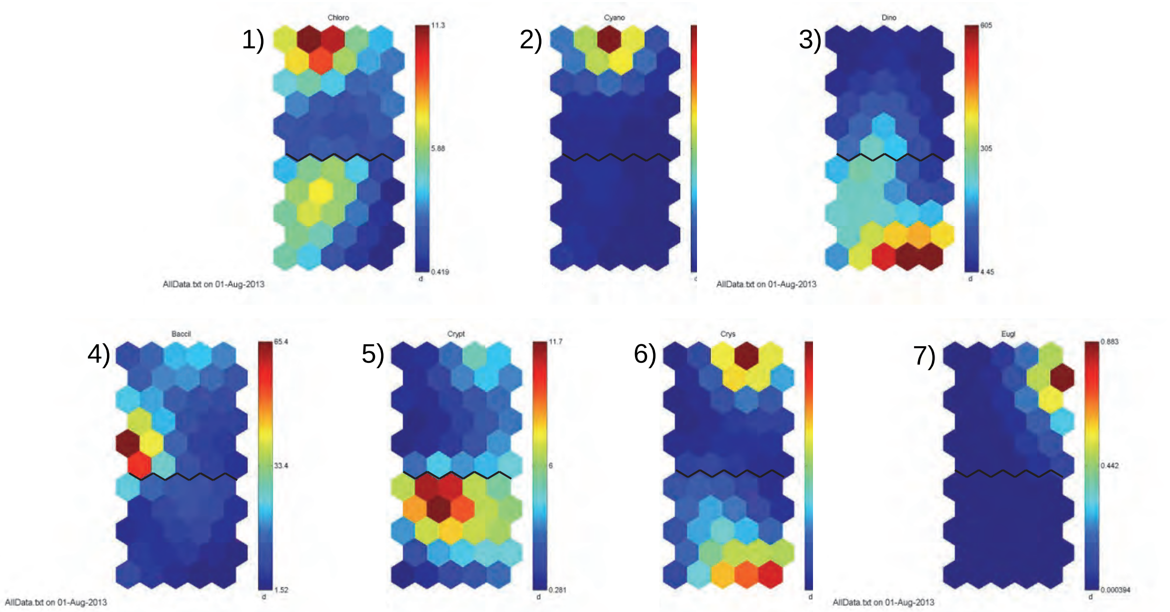

Figure 3-2: Self organised maps representing the extent (bars) and the changes in total biovolume of the different phytoplankton groups' for the pre (upper section) and post (bottom section) periods of the installation of the SolarBees. The groups are 1) Chlorophyceae, 2) Chyanophyceae, 3) Dinophyceae, 4) Baccilariophyceae, 5) Cryptophyceae, 6) Crysophyceae and 7) Euglenophyceae. (n=62 pre and post SolarBees).

Two other groups of phytoplankton indicate a major change (Figure 3.2), namely the presence of the Dinophyceae (*Ceratium hirundinella*), that were dominant in extremely high biovolume during the period post the installations. Secondly, the Cryptophyceae (*Cryptomonas* sp.) showed an increase, although still with low biovolume, thus not being a dominant species.

As was seen in section 2.2.3 there were significant differences in the nutrient concentrations, such as NH_3, NH_4 and PO_4. Both PO_4 and NH_4 levels which decreased from an average of 0.37 mg/ℓ to 0.11 mg/ℓ and 0.39 mg/ℓ to 0.14 mg/ℓ, respectively. This occurred, despite the significant increase in NH_3 from an average of 0.04 to 0.27 mg/ℓ. These changes are also evident in Figures 3.3 and 3.4. A significant decrease in temperature was evident for measurements at all depths. This decrease is shown for the surface temperature in Figure 3.5 and was ± 2°C at all the depths.

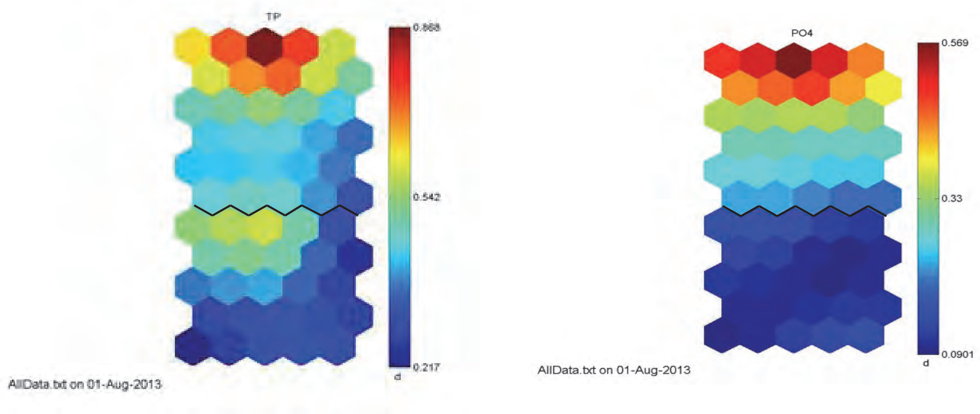

Figure 3-3: Self-organised maps showing the changes in extent pre (upper section) and post (lower section) SolarBees for total phosphorus (TP) and dissolved inorganic phosphorus (as PO4-P) in the Rietvlei Dam

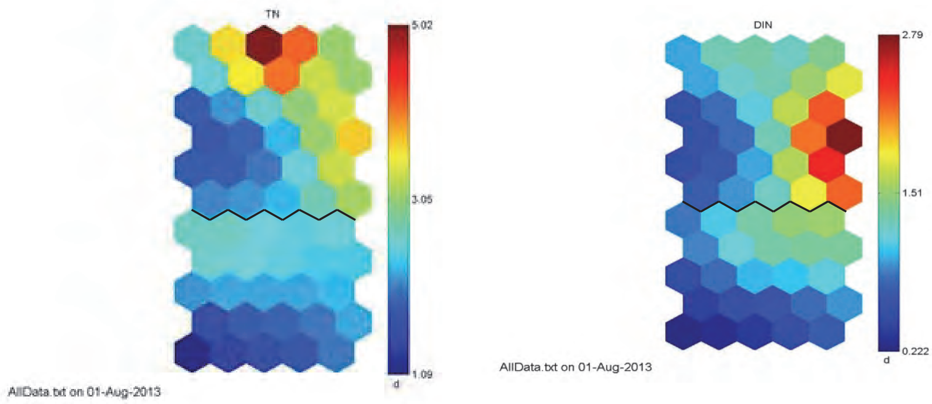

Figure 3-4: Self-organised maps showing the changes in extent pre (upper section) and post (lower section) SolarBees for total nitrogen (TN) and dissolved inorganic nitrogen (DIN) in the Rietvlei Dam

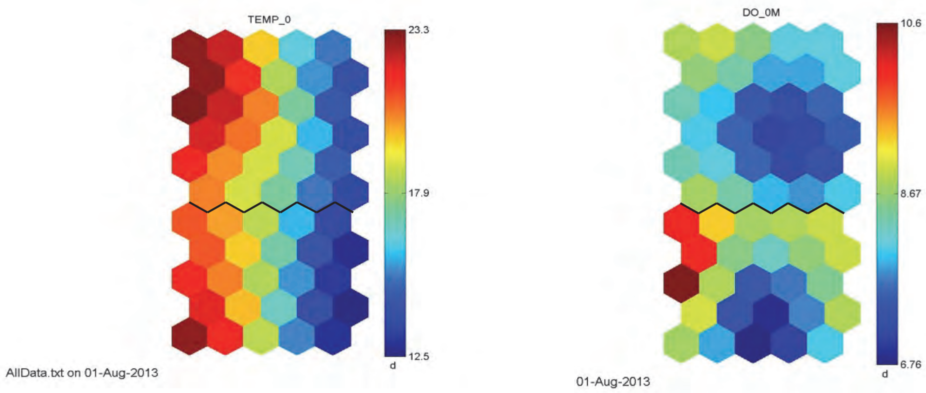

Figure 3-5: Self organised maps showing the differences in pre (upper section) and post (lower section) SolarBees conditions for surface temperature (Temp_0) and dissolved oxygen (DO_0) in the Rietvlei Dam

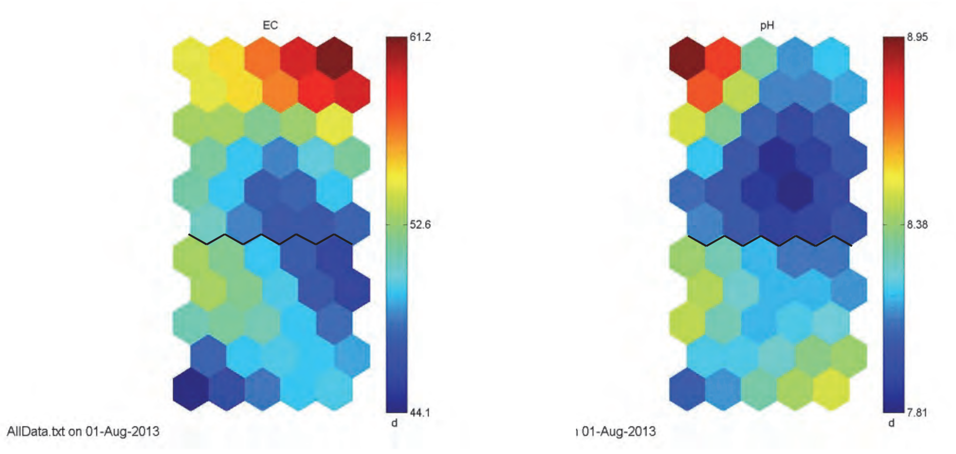

Figure 3-6: Self organised maps showing the differences in the pre (upper section) and post (lower section) SolarBees conditions for electrical conductivity (EC) and pH in the Rietvlei Dam

The pH ranged between pH 8.2-9.5. EC showed a significant decrease ($p<0.05$) post the installation of the SolarBees (Figure 3.6).

Both PO_4 and NH_4 were also measured since January 2007 at the inflow to Rietvlei Dam. No significant differences were observed in these variables, pre and post the deployment of the SolarBees in the inflow into the reservoir (Figure 3.7). Furthermore, rainfall measured closed to the reservoir showed no significant difference in down pour during these two time periods.

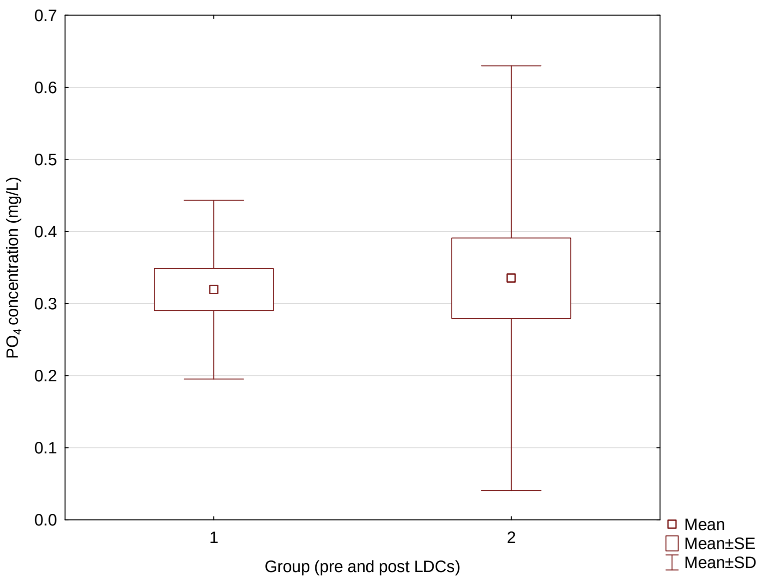

Figure 3-7: PO4 levels measured at the inflow to Rietvlei Dam during the time period (1) pre and (2) post the deployment of the SolarBees.

However there was a significant difference between the PO_4 levels at the inflow into Rietvlei Dam and the PO_4 levels observed at the dam wall in the time period after the installation of the SolarBees (Figure 3.8).

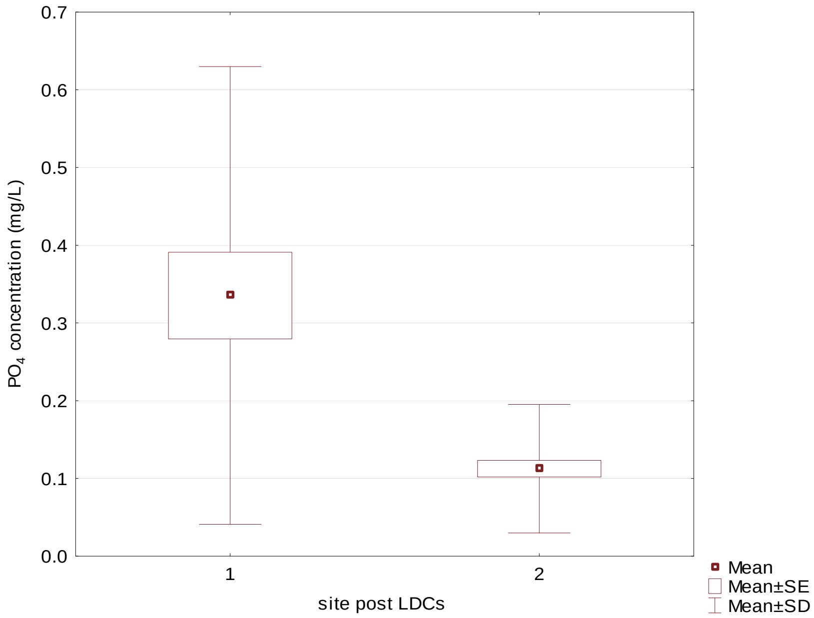

Figure 3-8: PO4 levels measured at the inflow to Rietvlei Dam (1) and at the dam wall of Rietvlei Dam (2) in the time period after the deployment of the SolarBees.

3.4 DISCUSSION

The goal of ecological friendly approaches to the treatment of harmful algal blooms is to attempt to restore conditions so that it would enable the growth of more beneficial genera and to out-compete cyanobacteria (Hudnell et al., 2010). Water circulation is such a treatment and would counteract the result of decreased flow rates experienced in a reservoir and shift the competitive advantage from Cyanophyceae to Chlorophyceae and Baccilariophyceae (Huisman et al., 2004, Hudnell et al., 2010). This was evident in the case of the Rietvlei dam where the impact of LDC's was investigated.

SolarBee units were designed to enable near-laminar flow intake from radial directions and velocities that decrease with distance from the unit (Hudnell, et al., 2010). The units output flow combine with influent flow as well as wind- and thermal-driven surface currents to redistribute the water across the treatment zone, thus, creating long distance circulation of the epilimnion (Hudnell et al., 2010).

The SolarBees deployed in the Rietvlei Dam strongly suppressed the bloom formation of *Microcystis sp*, but did not eliminate Cyanophyceae from the water body. Unlike what has been previously shown in studies (Huisman et al., 2004, Hudnell, et al., 2010), there was not a significant increase in the densities of Chlorophyceae and Baccillariophyceae, although the number of Chlorophyceae genera increased. This is an indication of improving water quality. There was a significant increase in the densities of Dinophyceae, Chrysophyceae and Chryptophyceae. The bio-volume of *Ceratium sp* increased dramatically since the initial deployment of the SolarBees.

Several changes were also noted in the chemical and physical parameters of the reservoir's water. There was a significant difference in the temperature of the water from surface temperature up to a depth of 9 m pre and post the deployment of the SolarBees. This difference of ±2°C could also contribute to the decrease in *Microcystis sp*. growth. The average temperature in the first 4 meters changed from 18°C to 16°C. This is below the optimum temperature range for *Microcystis aeruginosa* growth (Venter et al., 2009). The EC also decreased after the deployment of the SolarBees together with SO_4 and Secchi depth. The decreases in these parameters were, however, also evident in the inflow into Rietvlei Dam. Total alkalinity showed a significant increase in both the inflow water into Rietvlei Dam and the at the dam wall of Rietvlei dam.

Most notably there was a significant decrease in the levels of PO_4 from pre to post the installation of the SolarBees despite the fact that there was not a significant difference in PO_4 at the inflow to the dam during these time periods respectively. There was also a significant decrease in the TN and DIN values post installation of the SolarBees in the dam.

The success of the SolarBees in creating changes in the water column can be explained by the flow diagram in Figure 3.8. Although the epilimnion is mixed, there is usually not any active flow in a specific direction. Wind action is seldom continuous and the SolarBees force the water in the epilimnion to be in continuous circulation. This has an impact on specifically four variables that favour cyanobacterial growth:

a) Energy loss occurs due to continuous circulation with the resultant effect of decreased surface water temperatures and increased dissolved oxygen.
b) There is now continuous forced aerated water flow into the shallower riparian zone, which impact on the development of an anoxic water/sediment interface. This cause an increase in pH and the Redox potential, which both contribute to decreased recirculation of nutrients from the sediments as oxygenated conditions, prevent the release of nutrients from the sediments and also the anoxic bacteriological breakdown under anoxic conditions.
c) The continuous flow prevents water stagnation during hot, wind still days. This is a condition that is not ideal for cyanobacterial growth.
d) The continuous laminar flow may also impact on the buoyancy regulation of the cyanobacteria, thus preventing the cells from moving to the ideal position in the water column.

In addition, the massive increase in *Ceratium sp*. bio-volumes that caused extremely high Chlorophyll *a* concentrations after the implementation of the SolarBees, could have contributed towards the depletion of the nutrients.

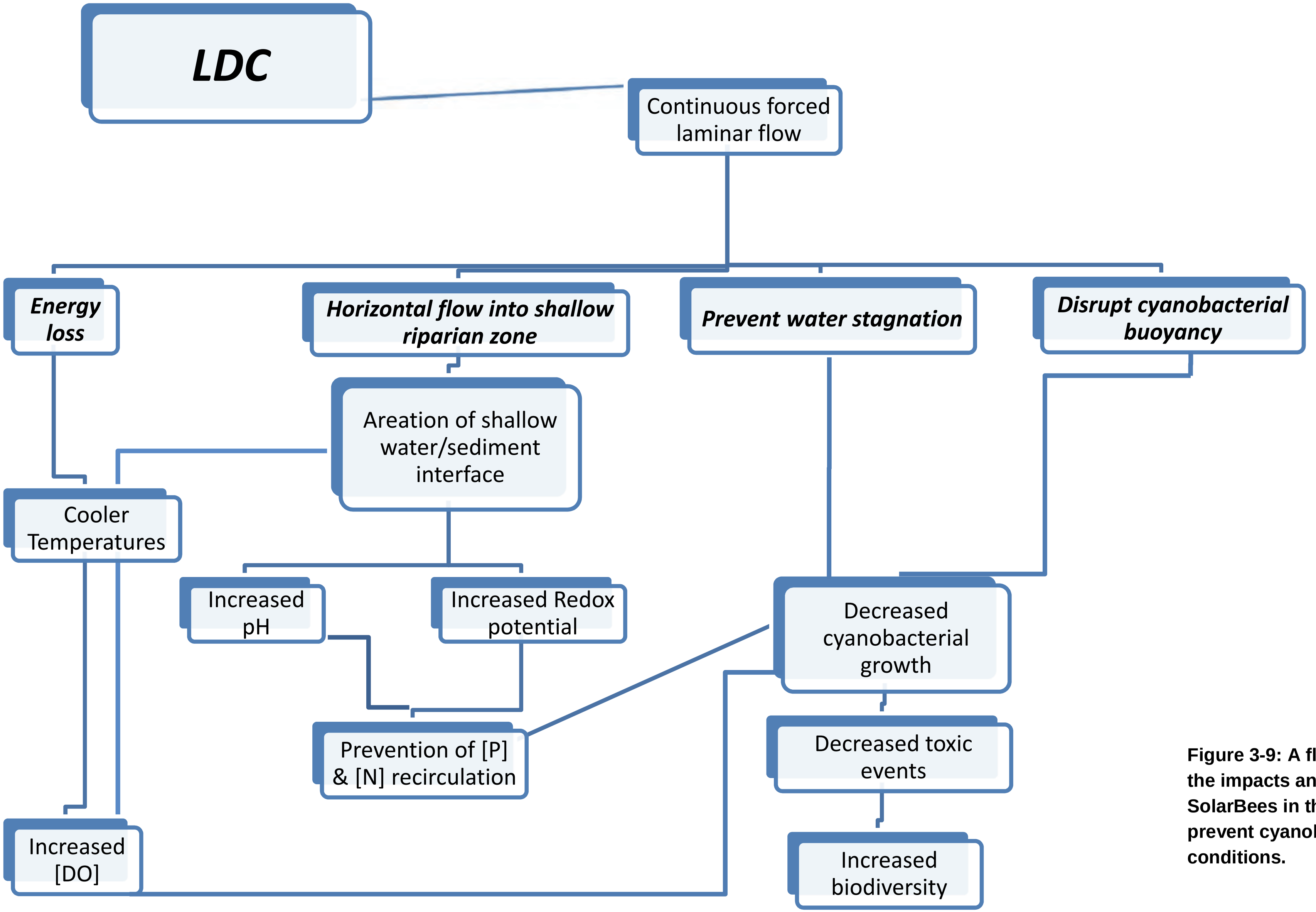

Figure 3-9: A flow diagram indicating the impacts and successes of the SolarBees in the Rietvlei Dam to prevent cyanobacterial bloom conditions.

3.5 CONCLUSION

The study showed that, through habitat disturbance, all these factors produce adverse conditions for the development of cyanobacteria and contributed towards the success of the SolarBees in the Rietvlei Dam. The success of the decreased cyanobacterial growth also contributes to decreases in the occurrence of toxic cyanobacterial events and can contribute to increased biodiversity. The impact of the SolarBees should be monitored continuously. This will enable Rietvlei WTW's management to determine the continued successes, or the development of any other potential problems, like the *Ceratium hirundinella* bloom, to make informed management decisions.

CHAPTER 4: EVALUATION OF THE PERFORMANCE OF THE PREDICTION TOOL FOR MICROCYSTIS/CERATIUM BLOOMS IN THE RIETVLEI DAM

4.1 INTRODUCTION

The real time rule-based agent for *Microcystis* has been developed and validated by means of limnological time-series data and hybrid evolutionary algorithms (HEA), by van Ginkel (2008). The HEA was designed to assemble and optimize both the structure and parameters of real-time predictive rules using genetic programming and genetic algorithms. In order to develop the rule-based agent for *Microcystis*, merged limnological time-series data of the hypertrophic reservoirs Hartbeespoort, Rietvlei and Roodeplaat Dams have been used for training. Rigorous leave-*k*-out cross-validation for a total of 36 years (12 years from each reservoir during the period 1991 to 2004) of data was used to do the rule-based development training, excluding the years 1993 and 2004 (from each reservoir) to use later for testing the developed rule agent. This rule set was then also tested on Bon Accord and Klipvoor Reservoir data that had not been used in the training data set. These reservoirs are of the same trophic status and most are known to experience severe cyanobacterial blooms. The agent proved to be generic for the five warm, temperate and hypertrophic dams of which four were monomictic and one dimictic. It can be implemented for forecasting outbreaks of *Microcystis* blooms, which affect the drinking water supply and water treatment costs of many South African reservoirs. Although this model has already been validated conceptually (Van Ginkel et al*.* 2007 & Van Ginkel, 2008), for it to be acceptable as a tool it should be validated operationally and the data to be used should also be statistically validated.

The present study provided the opportunity to also test the robustness of the early warning/prediction tool being applied in case of advanced water treatment procedures. The main aim of this study is to use data collected prior to as well as after the deployment of the SolarBees to implement the model and assess its applicability and robustness as an early warning/prediction tool.

4.2 MATERIALS AND METHODS

4.2.1 Data collection:

Data used were from the bi-weekly sampling done by Resource Quality Services at the Dam-wall (see section 2.2.1). Chlorophyll *a* (CHLA) was determined together with and *Microcystis* dominance (MicD) as a percentage of the phytoplankton population in the laboratories of Resource Quality Services. The *Microcystis* biovolume (MicB) was calculated as:

$$\text{MicB} = (\text{MicD}/100) * (\text{Chl}a * 2.5) \qquad \text{(Van Ginkel et al., 2007)}$$

Where:

MicB is the *Microcystis* biovolume measured as cm^3/m^3

MicD is the *Microcystis* dominance (measured as %)

Chl*a* is the measured chlorophyll *a* concentration (measured in µg/ℓ)

The daily input data of the model requires the following variables: TP, DIP, Secchi depth, pH, TN, DIN, surface water temperature (Tsurf), CHLA and *Microcystis* dominance and *Microcystis* biovolume respectively. The forecast results are given as *Microcystis* biovolume real-time (RTF), 7, 14, 21 and 28 days forward. Since bi-weekly sampling was done the RTF, 14 and 28 days forward forecasts were used for validation. Two datasets were collected, namely a dataset containing bi-weekly data from: January 2006 – June 2008 (before SolarBees), and a dataset containing bi-weekly data from: August 2008 –December 2011 (after SolarBees).

4.2.2 Statistical analyses:

The data were selected according to dates which were accompanied by the most complete set of data required for the implementation of the prediction tool. The selected physical-chemical and biological variables were then entered into the model in Excel 2007 format (as the model is provided in Excel 2007 format (Figure 4.1)). The rule based agent then forecasted the algal biovolume (cm^3/m^3). The observed data (Real time: RT) for algal biovolume together with the forecasted data (RTF; 14 and 28 days forward) for algal biovolume were then compared to evaluate the model's performance.

Reservoir Name:												Real Time Forecasted MicB	7-days forward Forecasted MicB	14-days forward Forecasted MicB	21-days forward Forecasted MicB	28-days forward Forecasted MicB
Measured Input Data	Date	TP	DIP	Sec	pH	TN	DIN	Tsurf	Chl a	MicD	MicB	MicB	MicB	MicB	MicB	MicB
Unit		ug/L	ug/L	m		mg/L	mg/L	°C	ug/L	%	cm^3/m^3	cm^3/m^3	cm^3/m^3	cm^3/m^3	cm^3/m^3	cm^3/m^3
	2008/07/07	0.239	0.121	2.5	8.69	2.115	0.934	18.70	40.93	0.1	0.0921	1.3	7.7	6.6	7.6	4.3
	2008/07/21	0.322	0.146	1.3	8.62	2.819	0.9	17.80	175.45	0.1	0.3948	16.7	32.2	27.1	19.9	4.7
	2008/08/04	0.269	0.093	1.1	8.36	2.543	0.937	15.70	129.15	0	0	13.6	22.1	21.7	13.7	2.9
	2008/08/18	0.3493	0.102	1	8.87	1.602	0.897	17.80	119.485	0	0	15.4	21.9	20.7	15.2	5.2

Figure 4-1: The Excel (2007) spreadsheet containing the rules of the predicting tool that is used for data input in order to predict biovolumes of *Microcystis sp.*

The observed and forecasted data were then subjected to statistical analysis, using STATISTICA version 10, during which the following tests were performed:

5. Descriptive statistics for the direct value comparison
6. Kolmogorov – Smirnov and Lilliefors test for normality, which indicated that the data mostly did not meet the assumption for normality.
7. Pearson Product-Moment Correlation Coefficient was used to obtain the R value.
8. The Goodness of fit was used to obtain the RMSE

4.3 MODEL EVALUATION

A model can be qualitatively or quantitatively evaluated (Bennet *et al*, 2013). For this report we will use different quantitative methods for comparing the predicted values of *Microcystis/Ceratium* biovolume to the observed *Microcystis/Ceratium* biovolume. Visual inspection of the observed and predicted time series data will be used to qualitatively asses the model.

4.3.1 Dataset before the SolarBees: January 2006 – June 2008

4.3.1.1 Direct comparison

The direct comparison of values shows the similarity in characteristics between the output and the observed values (Table 4.1).

Table 4-1: The descriptive statistics for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis* and *Ceratium* biovolume for Rietvlei Dam.

Variable	*Valid N*	*Mean*	*Median*	*Min*	*Max*	*Std.Dev*
Mic RT	63	78.31498	0.053010	0.00000	3495.432	440.3522
Mic RTF	63	15.08093	4.480303	0.16858	518.748	65.2706
Mic 14	63	11.83383	4.701317	0.43969	315.385	39.4979
Mic 28	63	8.05314	6.486053	-4.90730	191.835	24.0921

	Valid N	Mean	Median	Min	Max	Std.Dev
Cer RT	64	37.68226	0.032081	0.00000	663.0905	123.2277
Cer RTF	64	7.66949	4.214708	-1.01561	63.4689	12.1081
Cer 14	63	10.06029	4.701317	0.43969	203.6520	25.7714
Cer 28	62	5.22865	6.563351	-4.90730	14.4832	5.2186

The analyses show that the predicted biovolumes for both *Microcystis* and *Ceratium* are not in the same range as the observed biovolumes. The average predicted values for both *Microcystis* and *Ceratium* biovolumes in the Rietvlei Dam are under estimated by the model.

4.3.1.2 Residual method

The most common method to evaluate a model's performance is to calculate the difference between the observed and the predicted data points. The RMSE and MSE are usually preferred since they are functions of the residuals (*Residuals* are differences between the observed values and the corresponding predicted values and thus represent the variance that is not explained by the model.) The RMSE expresses the error metrically in the same units as the original data.

Table 4-2: The RMSE for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis* and *Ceratium* biovolume in Rietvlei Dam.

	RTF	***14 Days***	***28 Days***
Microcystis **RMSE**	4.894	19.712	59.385
Ceratium **RMSE**	10.923	13.642	31.182

The real time prediction showed the smallest error in the prediction of *Microcystis* biovolumes (Table 4.2). However it should be kept in mind that the 14 days forward prediction could predict *Microcystis* biovolumes almost 80% correctly. The real time prediction and 14 days forward showed the smallest error in the prediction of *Ceratium* biovolumes

To test the ability of a model to preserve the pattern of the data, performance metrics must include how data points and their errors relate to each other. The best known measure is the correlation coefficient (Bennet *et al*, 2013). It is used to indicate how variation in the observed variable is explained by the predicted variable but does not indicate casual dependence. The Pearson Product-Moment Correlation Coefficient is commonly used for model evaluation (Bennet *et al*, 2013).

Table 4-3: The Correlation Coefficient for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis* and *Ceratium* in Rietvlei Dam.

	RTF	***14 Days***	***28 Days***
Microcystis **R**	0.9897	0.0415	0.0305
	p=0.00	p=0.749	p=0.814
Ceratium **R**	0.1638	0.0605	0.0060
	p=0.203	p=0.640	p=0.963

In the case of the occurrence of *Microcystis* in the Rietvlei Dam the model could only preserve the pattern of the data significantly for the RTF prediction (Table 4.3). There was no significant correlation between the observed and predicted values for *Ceratium* (Table 4.3) in Rietvlei Dam.

4.3.1.3 Visual inspection

A time-series is used to exhibit the observed vs. the predicted values for the different forecasts.

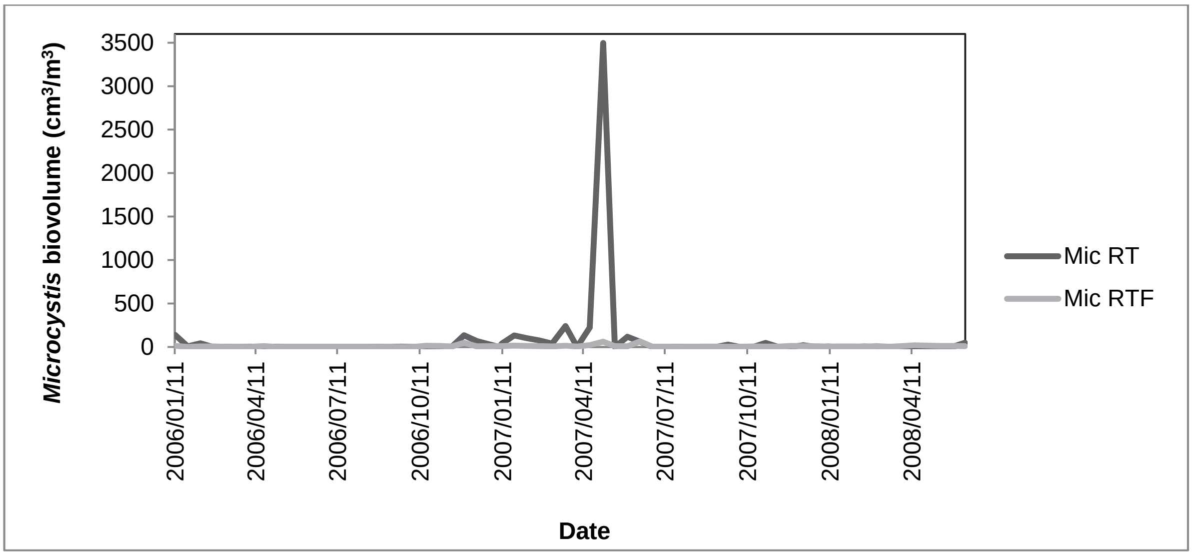

Figure 4-2: Predicting the abundance of *Microcystis sp.* in the Rietvlei Dam for the period 2006 to 2008. Observed (dark grey) vs. predicted (light grey) time-series values for real time (RT), 14days forward and 28 days forward.

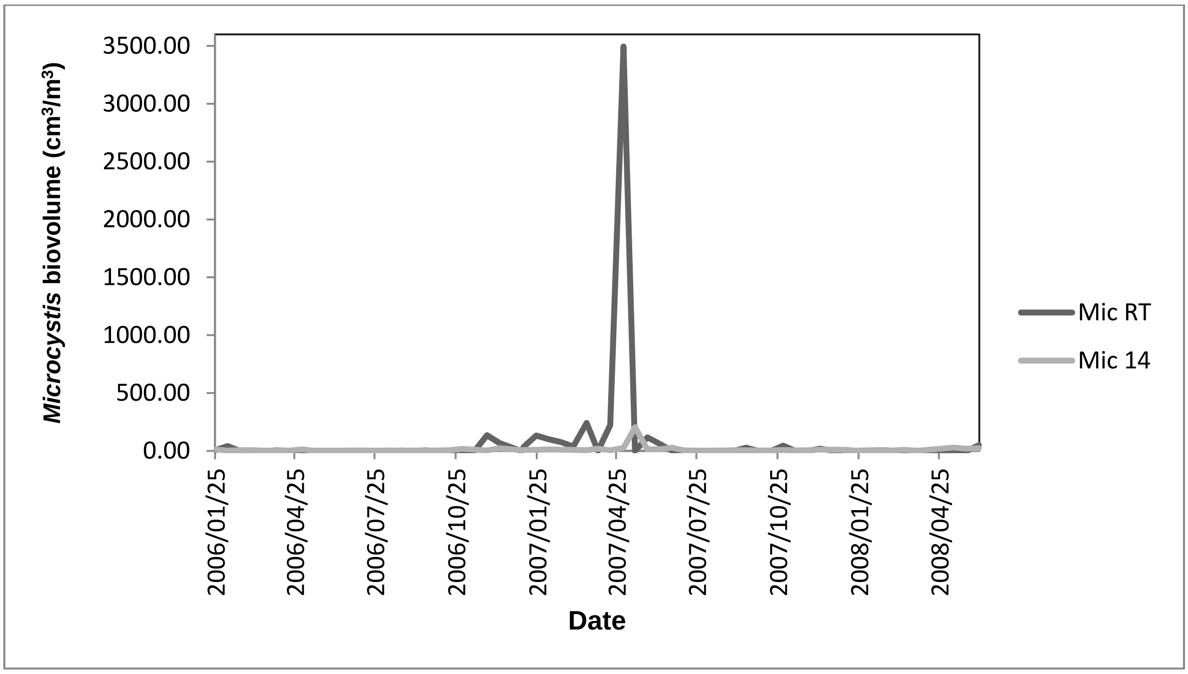

Figure 4-3: Predicting the abundance of *Microcystis sp.* in the Rietvlei Dam for the period 2006 to 2008. Observed (dark grey) vs. predicted (light gray) time-series values for 14days forward.

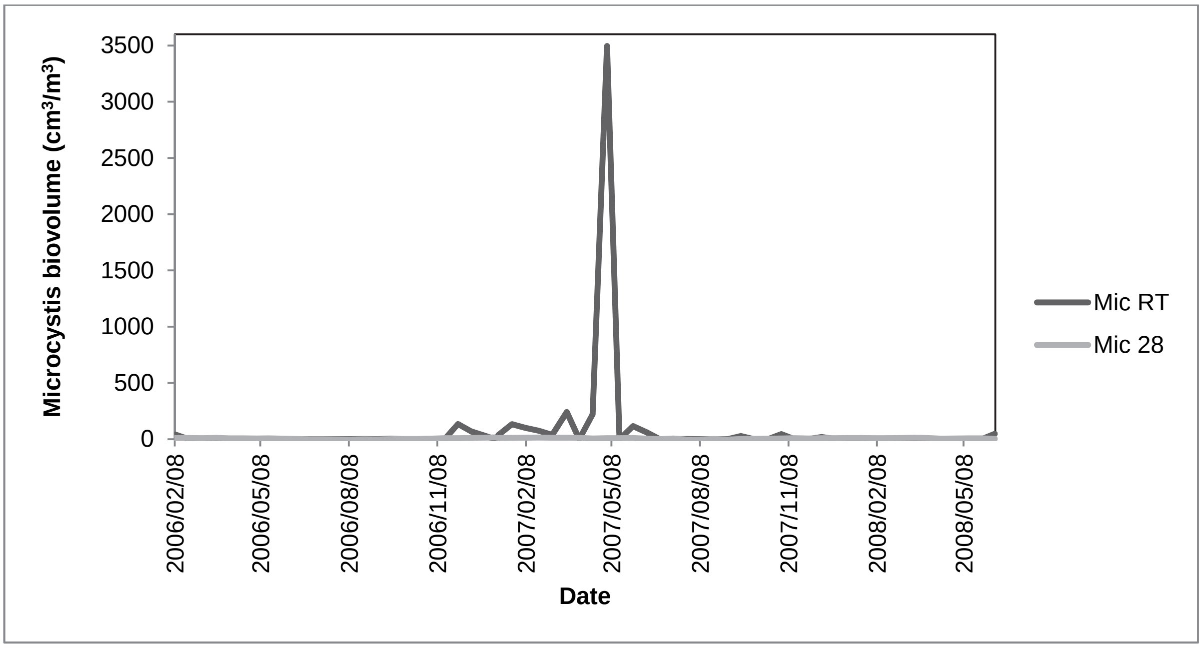

Figure 4-4: Predicting the abundance of *Microcystis sp*. in the Rietvlei Dam for the period 2006 to 2008. Observed (dark grey) vs. predicted (light grey) time-series values for 28 days forward.

It is clear from Figures 4.2 -4.4 that although, the ranges of the observed and predicted values are significantly different, and there is a concordance in the temporal prediction of an upcoming *Microcystis* bloom for the real time and 14 days forward prediction. This is further supported by the significant correlation ($p<0.05$, $n=62$) of the observed and real time predicted data. Although there is a relatively small error in the prediction of 14 days forward there is no significant correlation (Table 4.2) between the observed and the predicted values of the blooms. It is much lower than the observed values.

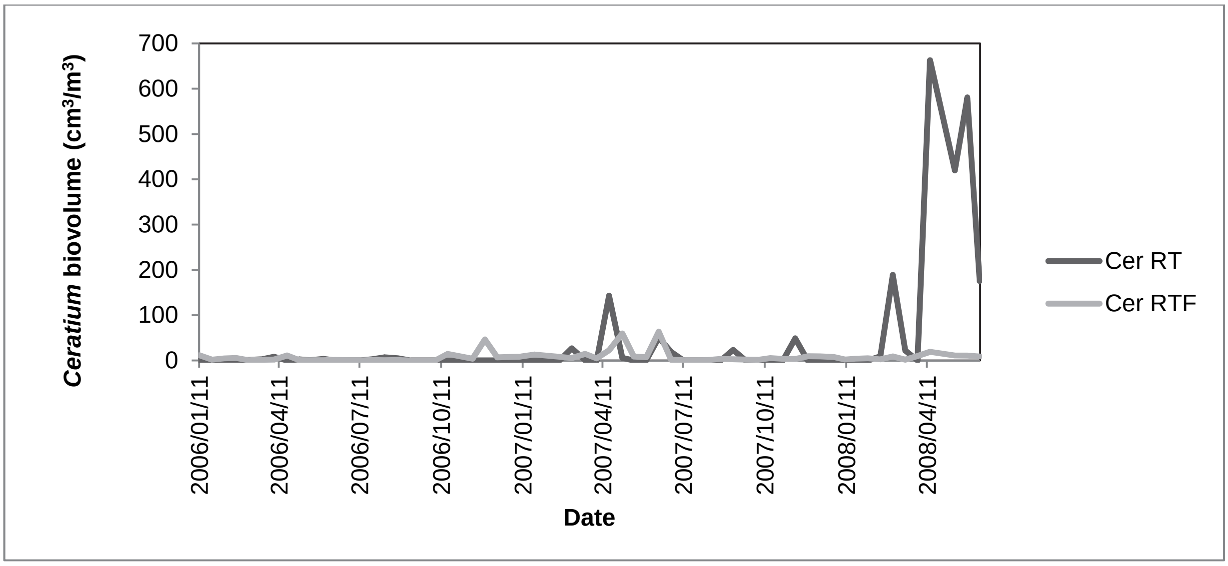

Figure 4-5: Predicting the abundance of *Ceratium sp*. in the Rietvlei Dam for the period 2006 to 2008. Observed (dark grey) vs. predicted (light grey) time-series values for real time (RT).

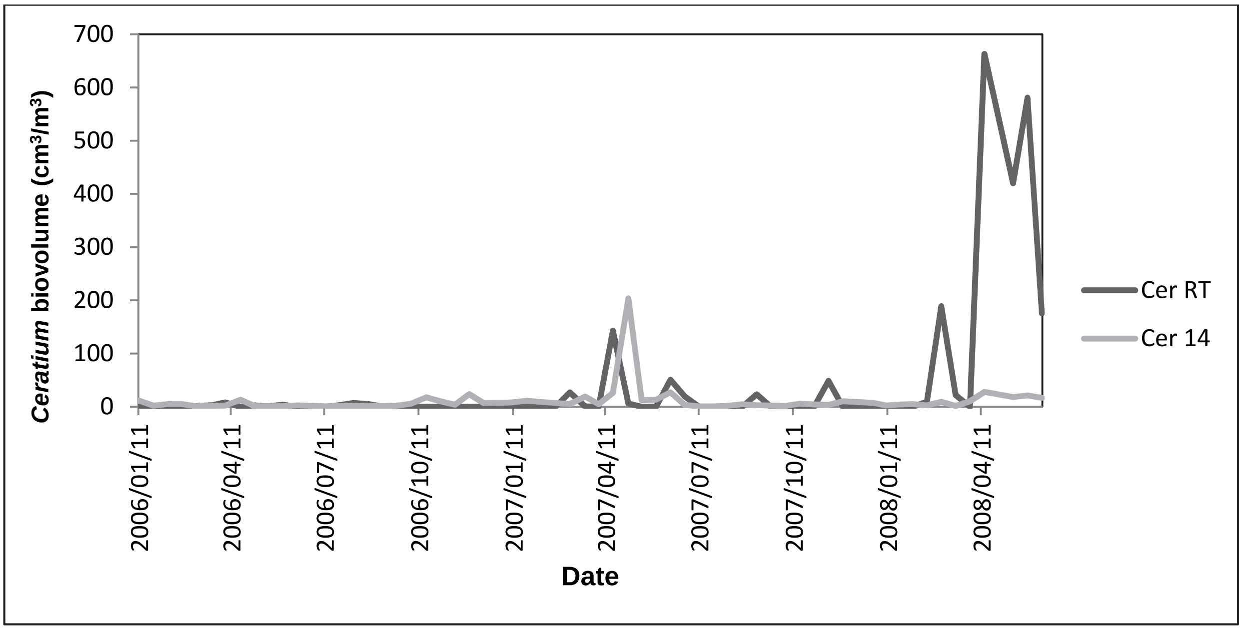

Figure 4-6: Predicting the abundance of *Ceratium sp*. in the Rietvlei Dam for the period 2006 to 2008. Observed (dark grey) vs. predicted (light grey) time-series values for 14 days forward.

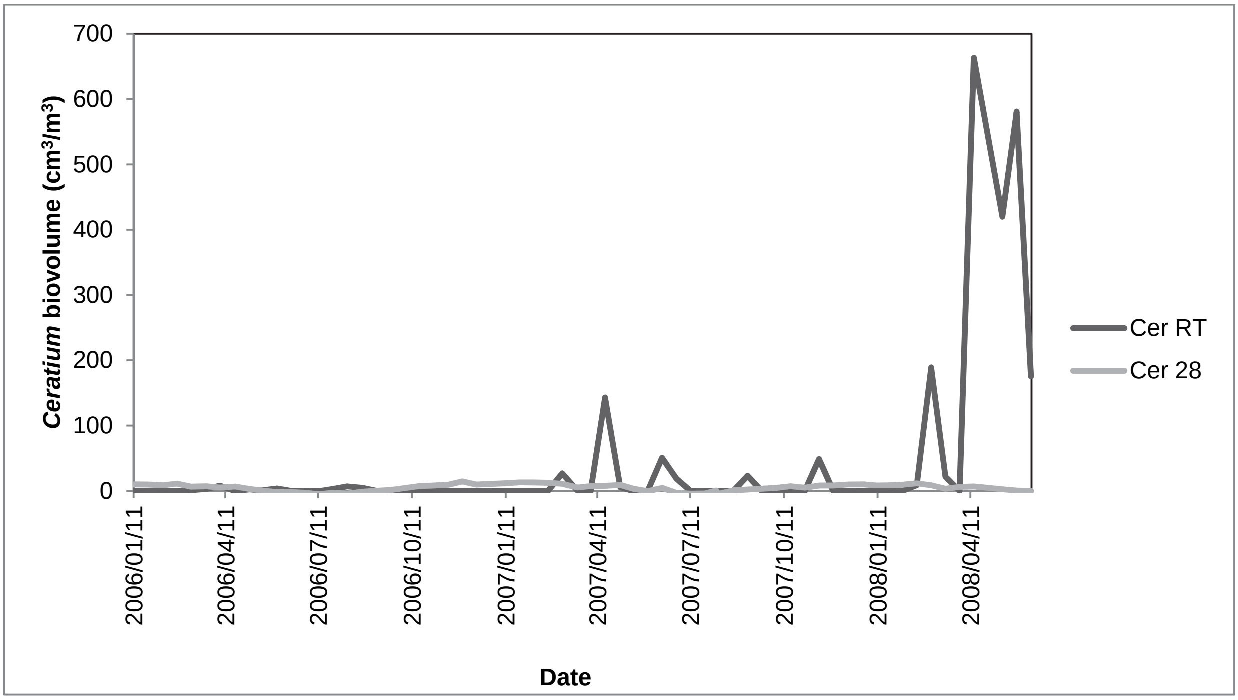

Figure 4-7: Predicting the abundance of *Ceratium sp*. in the Rietvlei Dam for the period 2006 to 2008. Observed (dark grey) vs. predicted (light grey) time-series values for 28 days forward.

The ranges of the observed and predicted values for *Ceratium* (Figures 4.5 - 4.7) are significantly different; there is however a concordance in the temporal prediction of an upcoming *Ceratium sp* blooms for the real time as well as the 14 days forward prediction. No significant correlation was however evident between the observed and real time predicted data or observed and 14 days forward predicted biovolumes. This could possibly be attributed to the fact that *Ceratium sp.* only formed large blooms towards the end of the sampling period.

4.3.2 Dataset after the SolarBees: August 2008 – December 2011

4.3.2.1 Direct comparison

When the biovolumes for the observed and predicted data are compared (Table 4.4) it is clear that the average values are in the same range especially in the case of the 28 days forward prediction for *Microcystis*. The predictions for *Ceratium* biovolumes were not at all in the same range as the observed values. The average values for *Ceratium* biovolumes predicted were in all cases far lower than the observed *Ceratium* biovolumes.

Table 4-4: The descriptive statistics for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis sp.* and *Ceratium sp.* biovolume for Rietvlei Dam.

Variable	***Valid N***	***Mean***	***Median***	***Min***	***Max***	***Std.Dev***
Mic RT	99	5.73158	0.00000	0.0000	153.2475	23.55254
Mic RTF	99	13.30807	8.80488	-13.1162	104.5890	15.06376
Mic 14	98	20.58651	14.70757	0.9722	103.0000	22.60399
Mic 28	97	8.64784	6.68123	-4.6647	103.0000	17.31030
Variable	**Valid N**	**Mean**	**Median**	**Min**	**Max**	**Std.Dev**
Cer RT	93	331.8578	153.4875	0.0000	2043.300	406.6677
Cer RTF	93	14.7124	9.0001	-13.1162	104.589	17.8148
Cer 14	93	22.3824	15.0225	0.9722	103.000	24.3104
Cer 28	93	8.6308	6.6812	-4.6647	103.000	17.6746

4.3.2.2 Residual method

As can be expected the relative error for the *Microcystis* predictions were significantly smaller than in the case of the *Ceratium* predictions (Table 4.5).

Table 4-5: The RMSE for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis sp.* and *Ceratium sp.* biovolume for Rietvlei Dam.

	RTF	*14 Days*	*28 Days*
Microcystis **RMSE**	1.456	1.033	2.566
Ceratium **RMSE**	40.944	32.05	300.932

Significant correlations were evident between the observed and predicted biovolumes (real time forecasted, 14 days and 28 days forward) for *Microcystis* (Table 4.6). Despite the fact that the predictions for the *Ceratium* biovolumes exhibited a relatively large error and was well under estimated there was a significant correlation between the observed biovolumes and the real time forecasted biovolumes as well as the 14 days forward prediction (Table 4.6).

Table 4-6: The Correlation Coefficient for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis sp.* and *Ceratium sp.* biovolume for Rietvlei Dam.

	RTF	*14 Days*	*28 Days*
Microcystis **R**	0.1998	0.4552	0.3399
	p=0.050	p=0.000	p=0.001
Ceratium **R**	0.3460	0.2871	-0.0535
	p=0.001	p=0.005	p=0.611

4.3.2.3 Visual inspection

The model underestimated the *Microcystis* biovolumes but did predict main bloom events accurately (Figures 4.8 -4.19) in both the real time forecasted and 14 days forward predictions. The 28 days forward prediction failed to predict bloom events correctly (Figure 4.10).

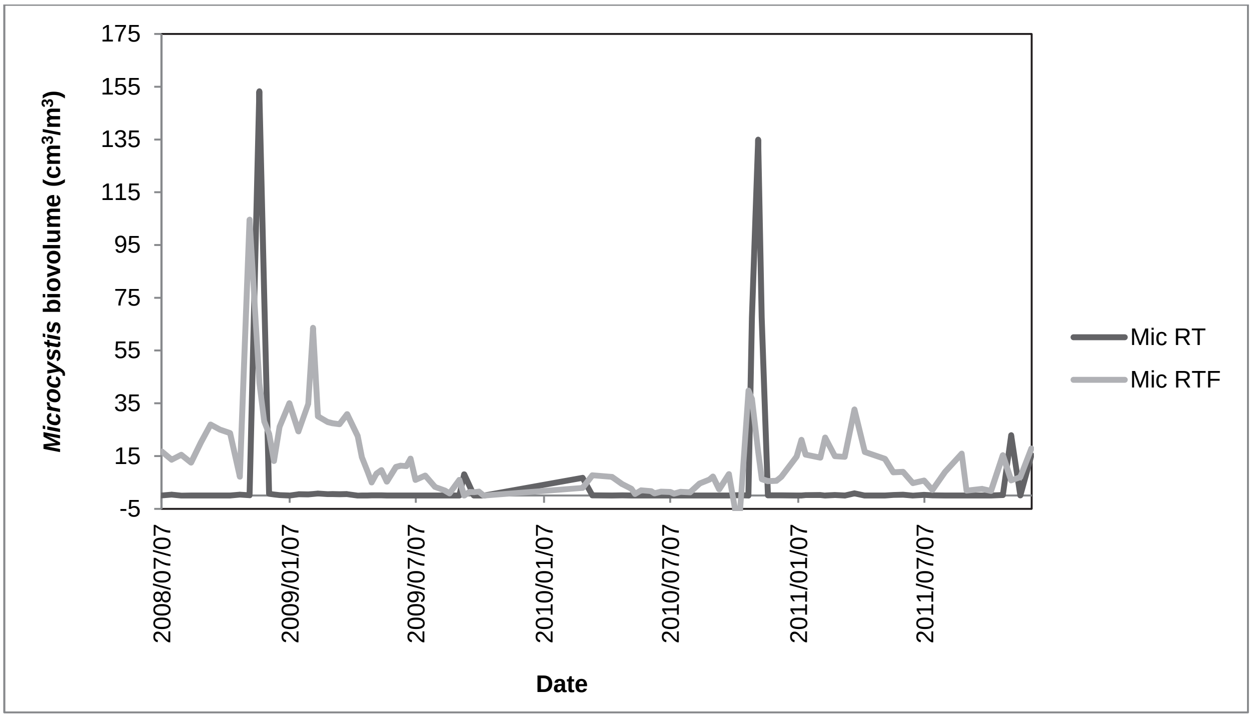

Figure 4-8: Predicting the abundance of *Microcystis sp*. in the Rietvlei Dam for the period 2008 to 2011. Observed (dark grey) vs. predicted (light grey) time-series values for real time (RT).

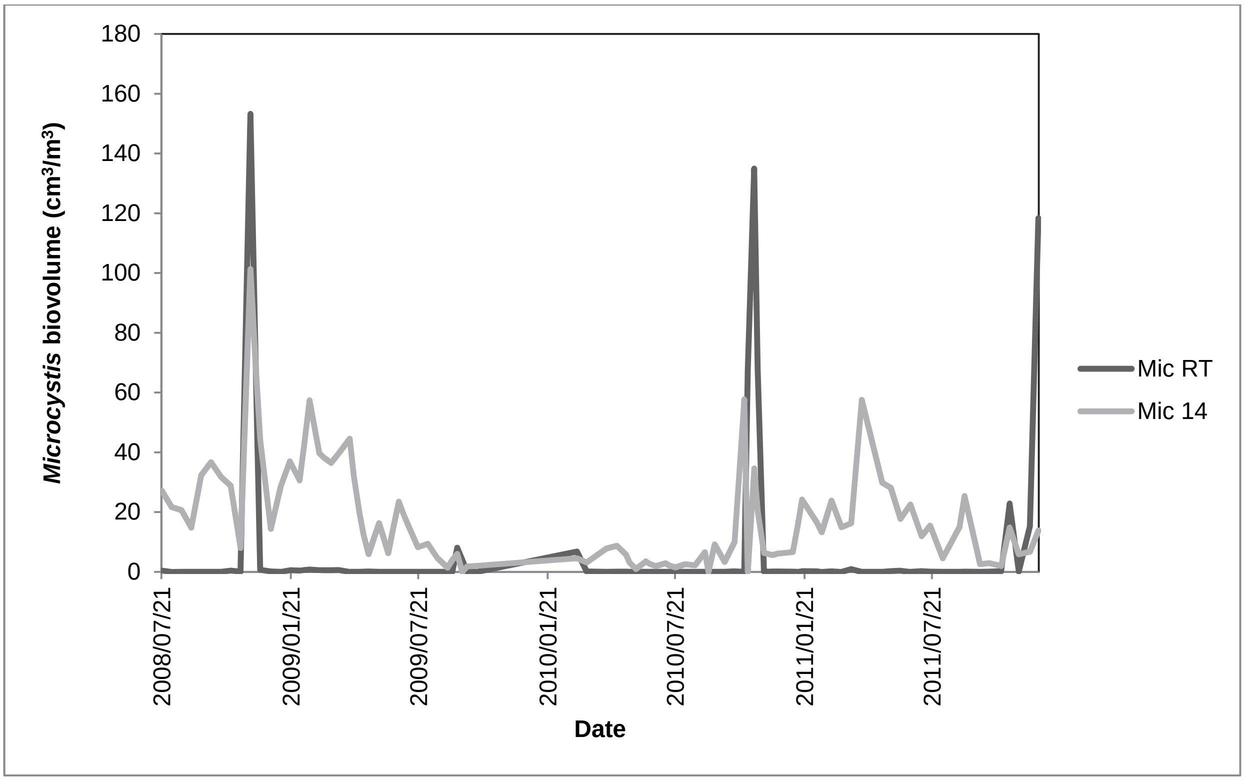

Figure 4-9: Predicting the abundance of *Microcystis sp*. in the Rietvlei Dam for the period 2008 to 2011. Observed (dark grey) vs. predicted (light grey) time-series values for 14days forward.

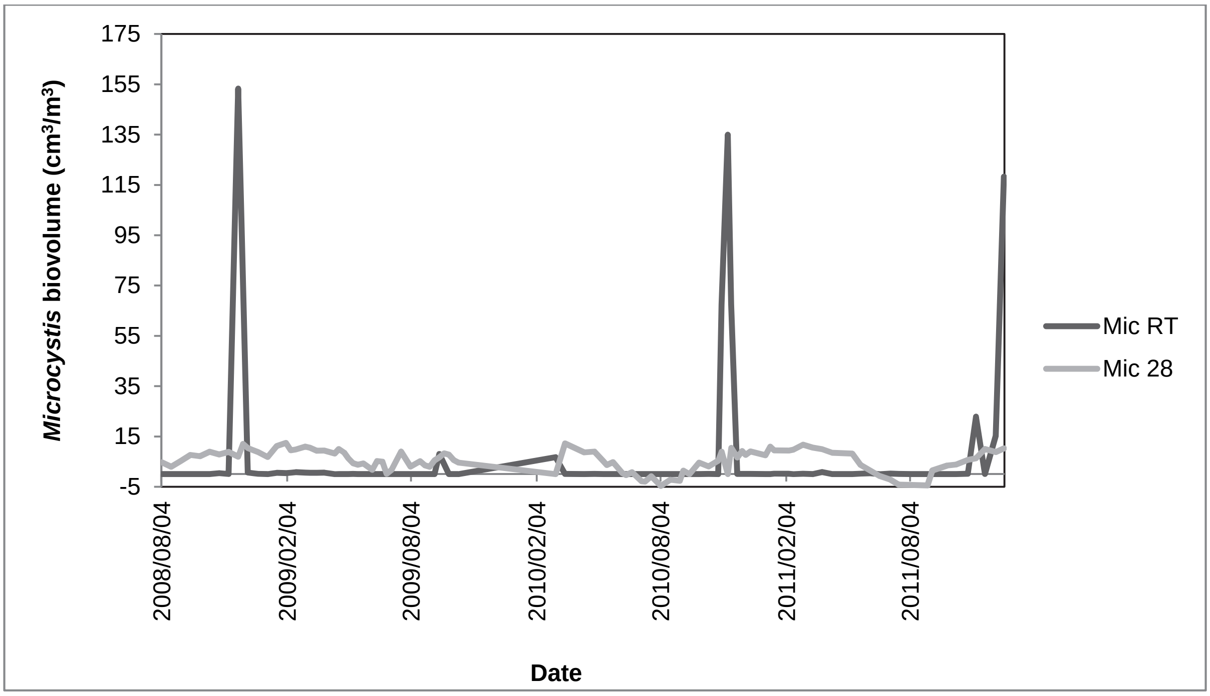

Figure 4-10: Predicting the abundance of *Microcystis sp*. in the Rietvlei Dam for the period 2008 to 2011. Observed (dark grey) vs. predicted (light grey) time-series values for 28 days forward.

Rietvlei Dam experienced prolonged and intense blooms of *Ceratium* from September 2009 to February 2009 and reached maximum biovolumes of 1328 cm^3/m^3. The model under estimated the magnitude of these bloom events but managed to predict major bloom events for both the real time forecasted and the 14 day forward prediction.

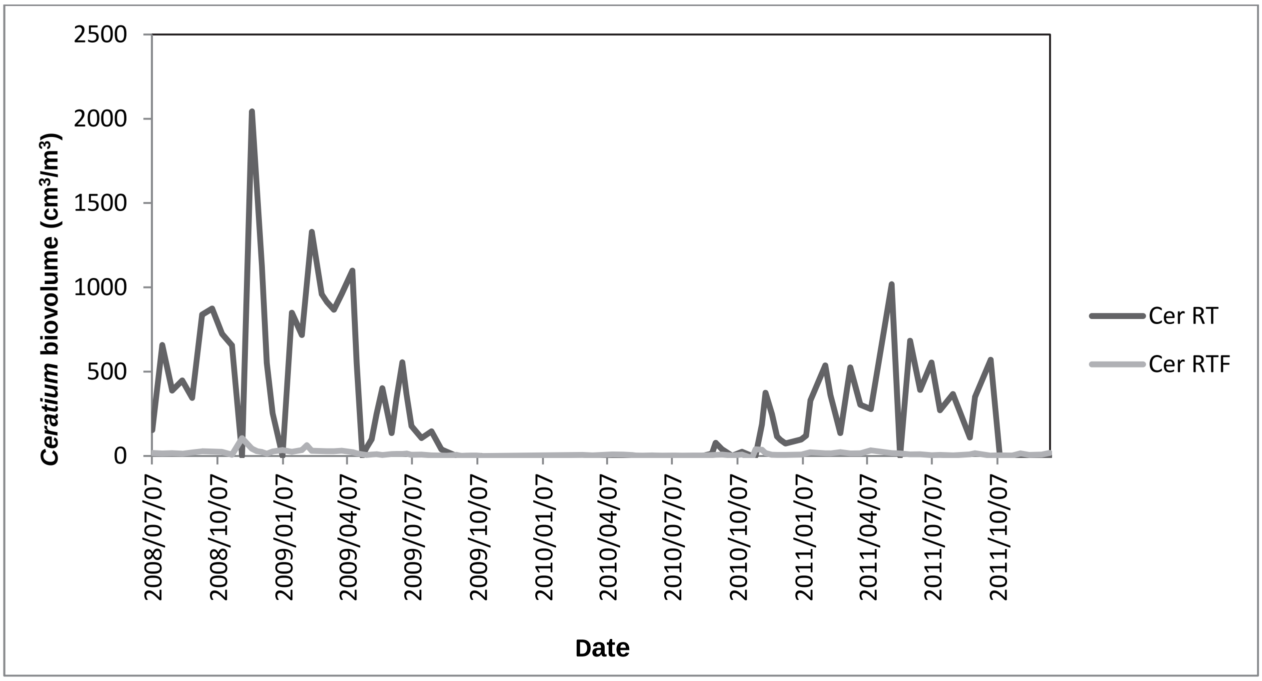

Figure 4-11: Predicting the abundance of *Ceratium sp*. in the Rietvlei Dam for the period 2008 to 2011. Observed (dark grey) vs. predicted (light grey) time-series values for real time (RT).

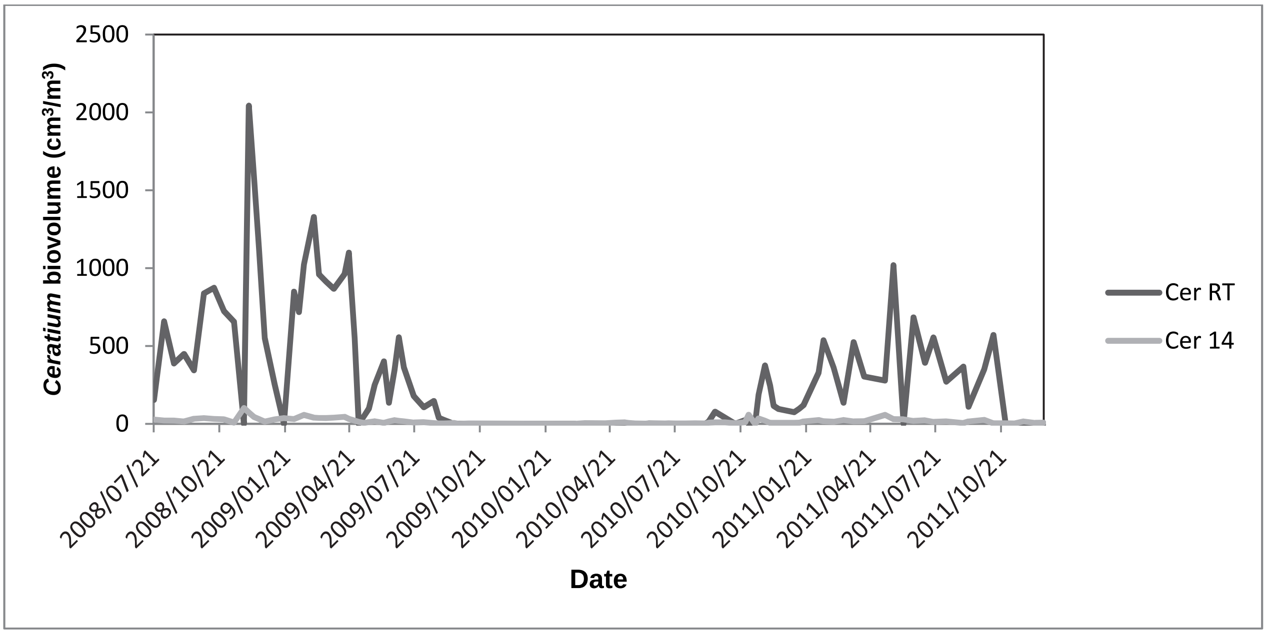

Figure 4-12: Predicting the abundance of *Ceratium sp*. in the Rietvlei Dam for the period 2008 to 2011. Observed (dark grey) vs. predicted (light grey) time-series values for 14days forward.

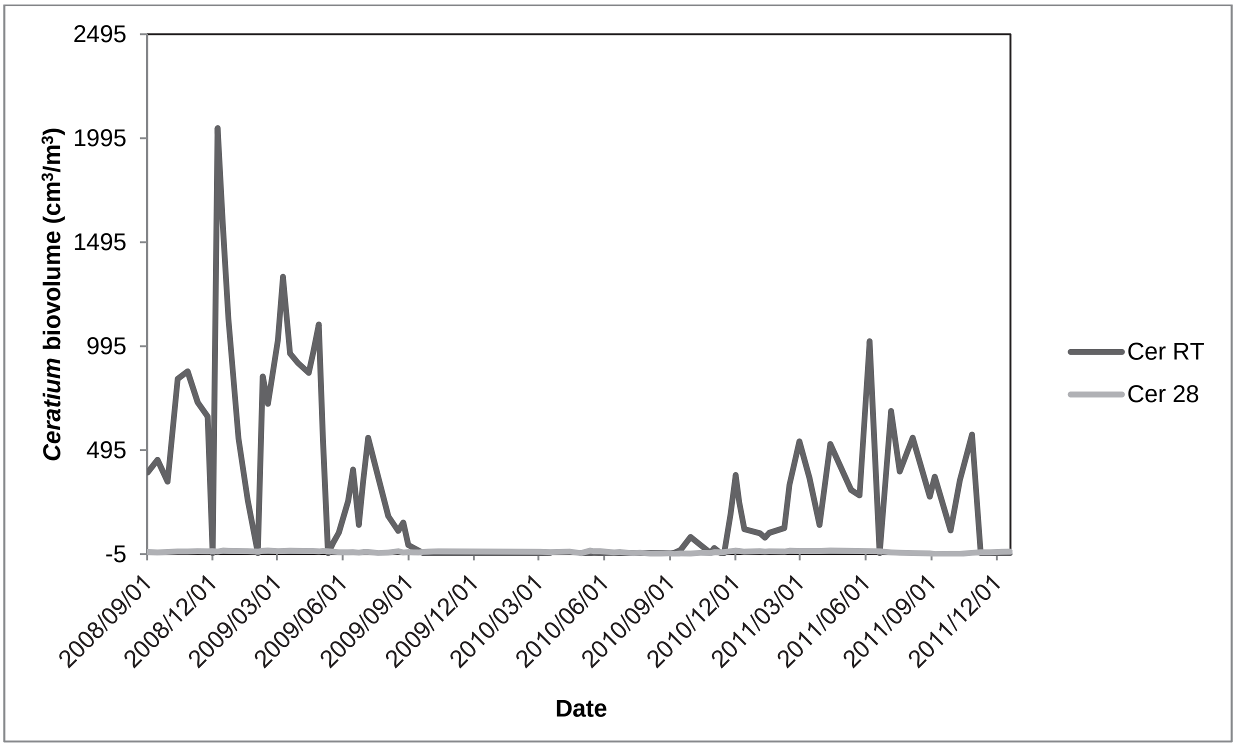

Figure 4-13: Predicting the abundance of *Ceratium sp*. in the Rietvlei Dam for the period 2008 to 2011. Observed (dark grey) vs. predicted (light grey) time-series values for 28 days forward.

4.4 DISCUSSION

A total of 5 years of bi-weekly data was used to test the applicability of the prediction tool CEGAP to predict *Microcystis sp* and *Ceratium sp.* blooms in the Rietvlei Dam. This is unseen data for this particular rule agent. Due to continuous developments at the Rietvlei WTW the dataset was divided into a dataset prior to the installation of the SolarBees (2006-2008) and a dataset post the installation of the SolarBees (2008 - 2011). Previously it was reported that the SolarBees, a method of habitat disturbance, had a significant effect on the occurrence of *Microcystis* as well as some nutrients present in the Rietvlei Dam. It is thus for this reason that the dataset was subdivided so that the possible influence of the SolarBees on the prediction tool could also be detected.

For the period 2006 – 2008 an extreme *Microcystis* bloom occurred during May 2007. The extent of this peak was mostly under-predicted by the prediction tool. However, there were no other significant differences between the average observed values and the average predicted values. A significant correlation exists between the observed and predicted *Microcystis* biovolume for the real time forecasted, prediction. The R value of the real time forecasted prediction indicates a particularly good fit of the predicted data. This was not true for any of the other predictions.

The model failed to produce good predictions for the *Ceratium* blooms that occurred especially towards the end of the sampling period. Visual inspection showed that the model could predict *Ceratium* blooms for both the real time forecasted and 14 days forward predictions but not always in time.

For the period after the installation of the SolarBees, the dataset exhibited quite a difference in the performance of the prediction tool. For the period 2008-2011 there is a significant correlation between the observed and the predicted biovolumes for both *Microcystis* and *Ceratium*. The RMSE was very small for all the *Microcystis* predictions and ranged between 1 and 2.5. The prediction tool produced mostly under-predicted values. The R value of the 14 days forward indicates a particular good fit of the predicted data.

4.5 CONCLUSION

The prediction tool could be successfully applied to the data obtained for *Microcystis sp.* after the full installation of the SolarBees. The model predicted *Microcystis* blooms timely especially after the deployment of the SolarBees. The prediction tool appears to be robust enough to not be influenced by the impact of the SolarBees in the Rietvlei Dam for the prediction of *Microcystis aeruginosa* and *Ceratium hirundinella.*

CHAPTER 5: EVALUATION OF THE PERFORMANCE OF THE PREDICTION TOOL FOR *MICROCYSTIS/CERATIUM* BLOOMS IN THE BRONKHORSTSPRUIT DAM

5.1 INTRODUCTION

The deployment of the SolarBees in Rietvlei Dam had significant influences on the water quality and algal bloom formation in the dam. These changes were noted in several of the parameters that the prediction tool, which was being tested, was based on. It was therefore of interest to also evaluate the performance of the early warning/prediction tool in an impoundment of similar nature but without the disturbance of habitat and resultant effects created by the SolarBees. The early warning/prediction tool was subsequently evaluated using real-time data collected by the Department of Water Affairs at Bronkhorstspruit Dam, which does not have any SolarBees but fell into a similar geographical area and temperature range as the Rietvlei Dam.
For a model to be used in research, management and decision-making, we have to establish confidence in the outputs in such a model. Bronkhorstspruit Dam was data used to investigate the performance of the prediction tool in order to establish the confidence in its outputs and to discover strengths and limitations in the model. For this chapter we will use different quantitative methods for comparing the predicted values of *Microcystis* biovolume to the observed *Microcystis* biovolume as well as comparing the predicted values of *Ceratium* biovolume to the observed *Ceratium* biovolume in Bronkhorstspruit Dam (BHSP). Visual inspection of the observed and predicted time series data will be used to qualitatively asses the model.

5.2 MATERIALS AND METHODS:

5.2.1 Data collection

Bi-weekly sampling was done by Resource Quality Services Laboratories at Roodeplaat (see section 2.2.1). Only one dataset was collected for Bronkhorstspruit Dam containing bi-weekly data from July 2005 to February 2012. The daily input data of the model requires the following variables: TP, DIP, Secchi depth, pH, TN, DIN, surface temperature (Tsurf), Chl*a* and *Microcystis/Ceratium* dominance and *Microcystis/Ceratium* biovolume respectively. The forecast results are given as *Microcystis/Ceratium* biovolume real-time (RTF), 7, 14, 21 and 28 days forward. Since bi-weekly sampling was done the RTF, 14 and 28 days forward forecasts were validated.

5.2.2 Statistical analysis

The data were selected according to dates which were accompanied by the most complete set of data required for the implementation of the CEGAP prediction tool. The selected physical-chemical and biological variables were then entered into the model in Excel 2007 format (as the model is provided in Excel 2007 format). The rule based agent then forecasted the algal biovolume (cm^3/m^3). The observed data (Real time: RT) for algal biovolume together with the forecasted data (RTF, 14 and 28 days forward) for algal biovolume were then compared to evaluate the model's performance. The observed and forecasted data were then subjected to statistical analysis, using STATISTICA version 10, as was done in section 4.2

5.3 RESULTS

5.3.1 Direct comparison

In contrast to what was observed in Rietvlei Dam the prediction tool overestimated the average biovolumes of *Microcystis sp.* in the Bronkhorstspruit Dam (Table 5.1). The model predicted the average *Ceratium* biovolumes in the same range as that what was observed for all the predictions. It is import to note that the prediction of average biovolumes for *Microcystis* and *Ceratium* is exactly the same.

Table 5-1: The descriptive statistics for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis sp*. and *Ceratium sp.* in the Bronkhorstspruit Dam.

Variable	***Valid N***	***Mean***	***Median***	***Min***	***Max***	***Std.Dev***
Mic RT	169	0.71045	0.00000	0.00000	29.32650	3.54179
Mic RTF	163	8.09162	7.29401	-5.48391	28.91720	5.43631
Mic 14	167	10.0244	9.44854	0.56489	44.96020	6.26748
Mic 28	163	5.62763	6.79436	-4.44729	13.50467	4.73459
Variable	**Valid N**	**Mean**	**Median**	**Min**	**Max**	**Std.Dev**
Cer RT	169	16.8704	15.2800	0.00000	108.5940	17.1382
Cer RTF	163	8.09162	7.29402	-5.48391	28.9172	5.43631
Cer 14	167	10.0244	9.44855	0.56489	44.9602	6.26748
Cer 28	163	5.62763	6.79436	-4.44729	13.5047	4.73460

5.3.2 Residual method

The RMSE (Table 5.2) and MSE are usually preferred since they are functions of the residuals. The RMSE expresses the error metrically in the same units as the original data. The prediction 14 days forward, exhibits the smallest error for both the *Microcystis* biovolume and the *Ceratium* biovolume prediction.

Table 5-2: The RMSE for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis sp.* and *Ceratium sp.* biovolume for Bronkhorstspruit Dam.

	RTF	***14 Days***	***28 Days***
Microcystis **RMSE**	9.878	1.88	7.7326
Ceratium **RMSE**	18.285	18.176	20.686

The correlation coefficient is used to indicate how variation in the observed variable is explained by the predicted variable but does not indicate casual dependence (Bennet *et al*, 2013). The Pearson Product-Moment Correlation Coefficient is commonly used for model evaluation (Bennet *et al*, 2013). From Table 5.3 it is clear that the model could predict the timing of *Ceratium* bloom events accurately for up to 14 days forward. This was not the case for *Microcystis*.

Table 5-3: The Correlation Coefficient for observed (RT) values and Real time forecasted (RTF), 14 and 28 days forward values of *Microcystis sp.* and *Ceratium sp.* biovolume for Bronkhorstspruit Dam.

	RTF	***14 Days***	***28 Days***
Microcystis **R**	-0.0345	-0.0567	0.0518
	p=0.670	p=0.484	p=0.522
Ceratium **R**	0.4036	0.2286	0.1527
	p=0.000	p=0.004	p=0.058

5.3.3 Visual inspection

Using a visual inspection it is clear that the model was not able to forecast the *Microcystis* bloom events (Figures 5.4 - 5.9). This is supported by the low correlation coefficient R values (Table 5.3). The 28 day forecast did manage to predict seasonal patterns with blooms occurring during summer as would be expected in any eutrophic impoundment.

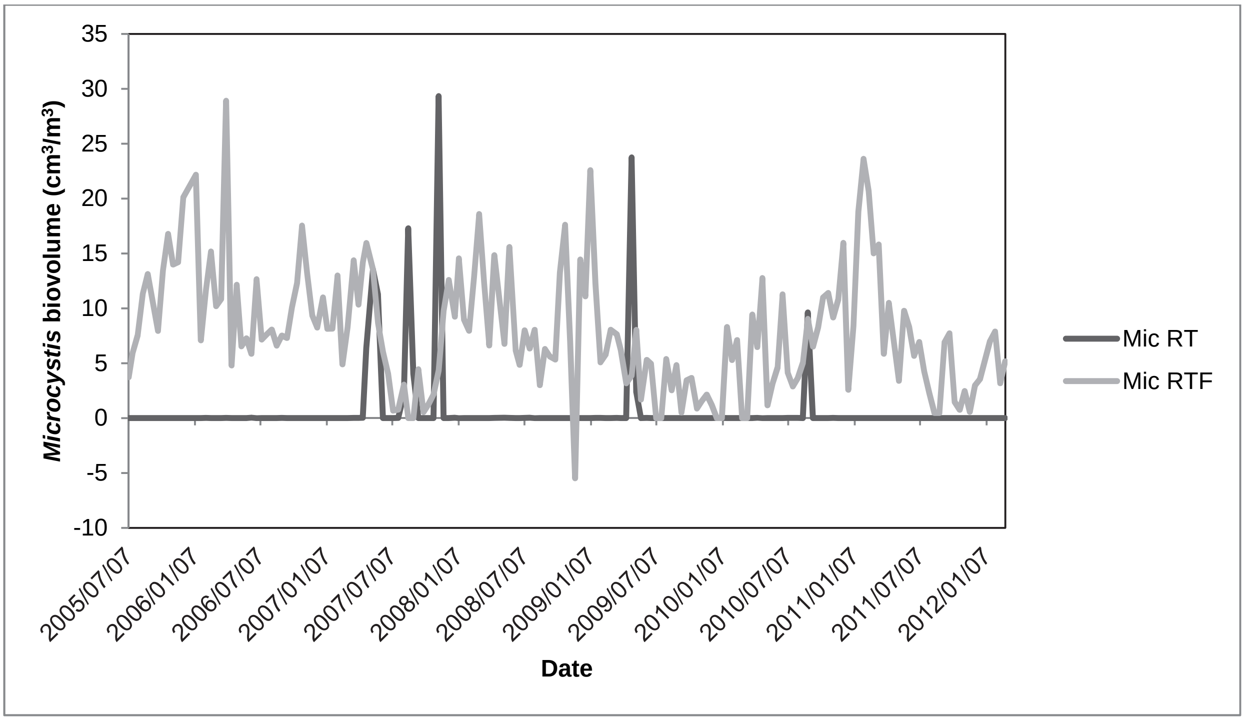

Figure 5-1: Predicting the abundance of *Microcystis sp.* in the Bronkhorstspruit Dam for the period 2005 to 2012. Observed (dark grey) vs. predicted (light grey) time-series values for real time (RT).

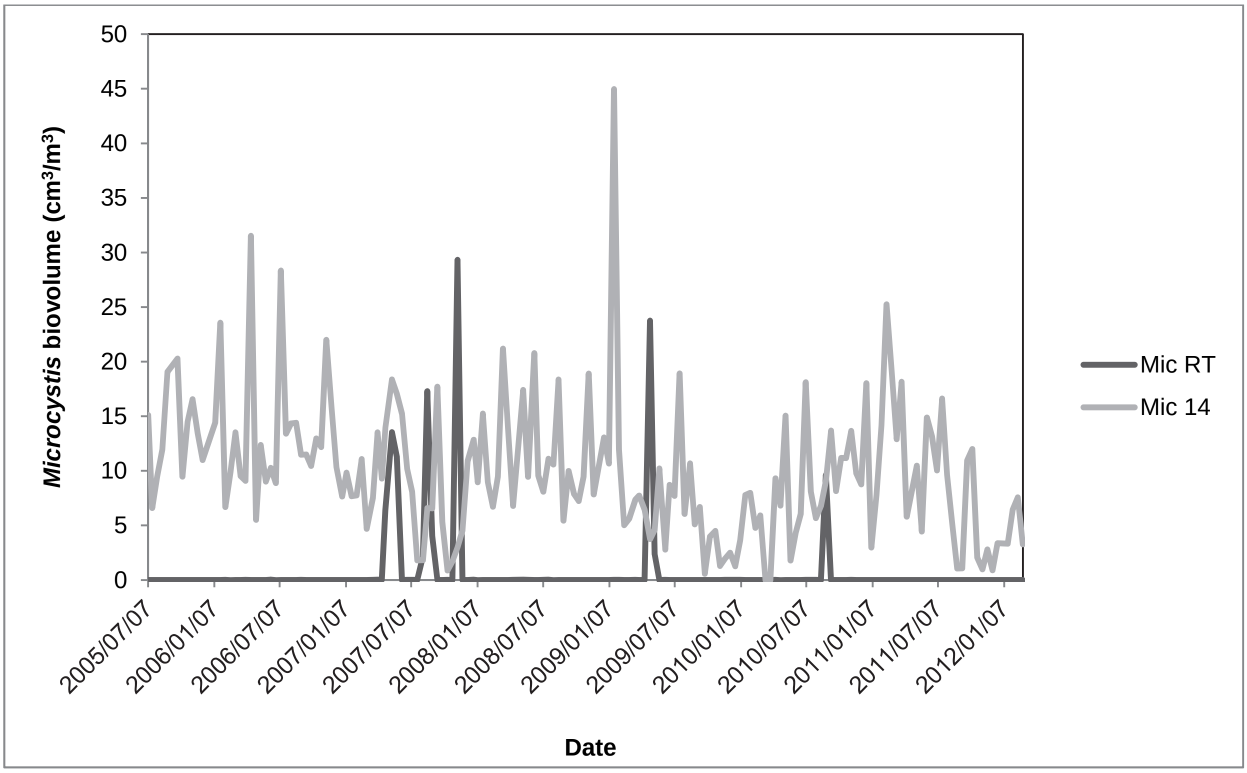

Figure 5-2: Predicting the abundance of *Microcystis sp.* in the Bronkhorstspruit Dam for the period 2005 to 2012. Observed (dark grey) vs. predicted (light grey) time-series values for 14days forward.

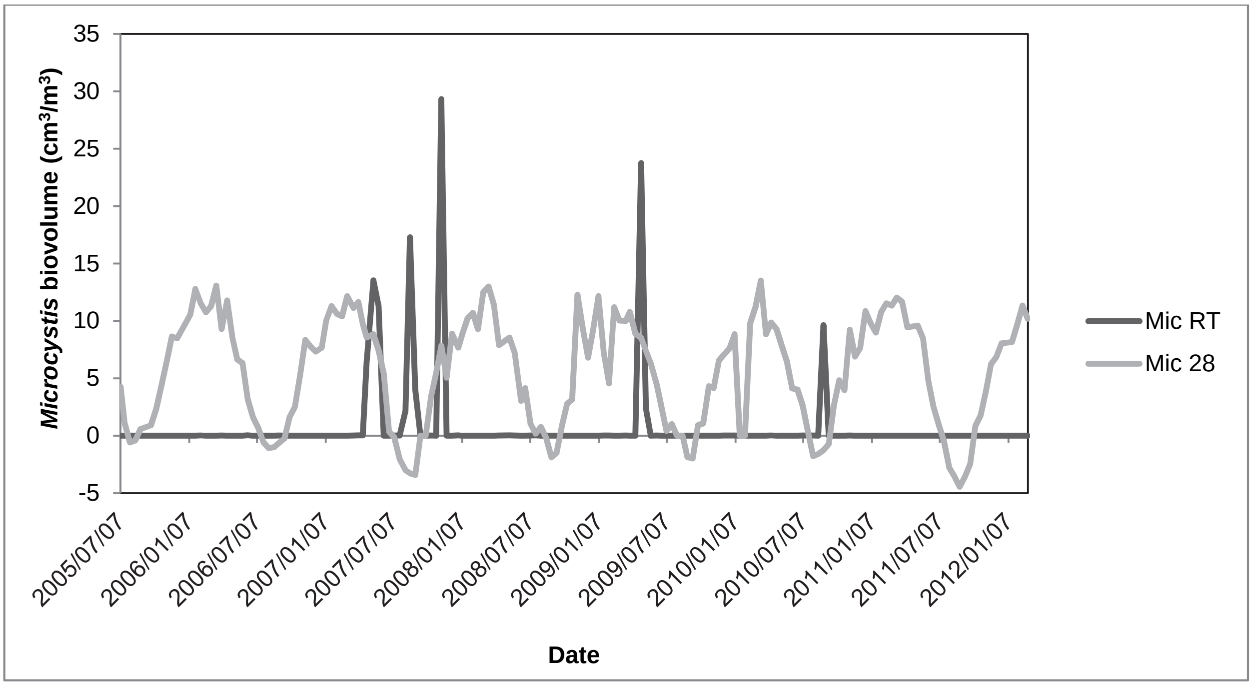

Figure 5-3: Predicting the abundance of *Microcystis sp.* in the Bronkhorstspruit Dam for the period 2005 to 2012. Observed (dark grey) vs. predicted (light grey) time-series values for 28 days forward.

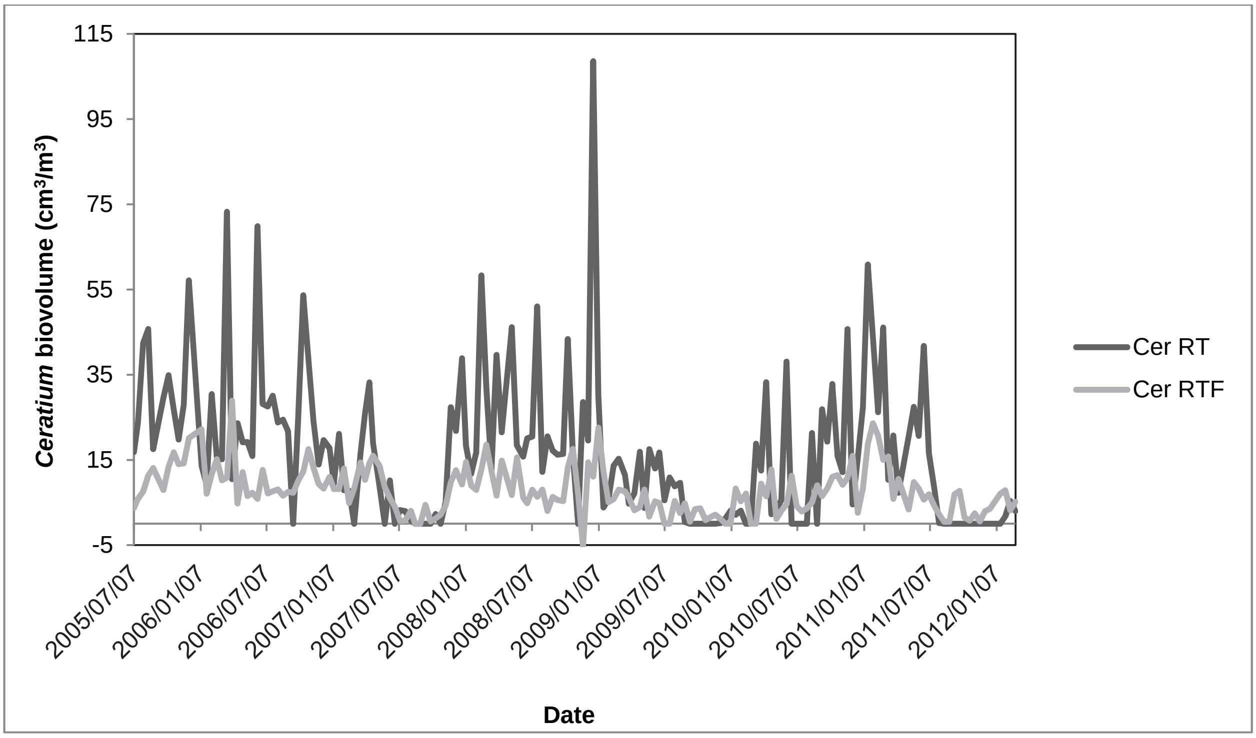

Figure 5-4: Predicting the abundance of *Ceratium sp.* in the Bronkhorstspruit Dam for the period 2005 to 2012. Observed (dark grey) vs. predicted (light grey) time-series values for real time (RT).

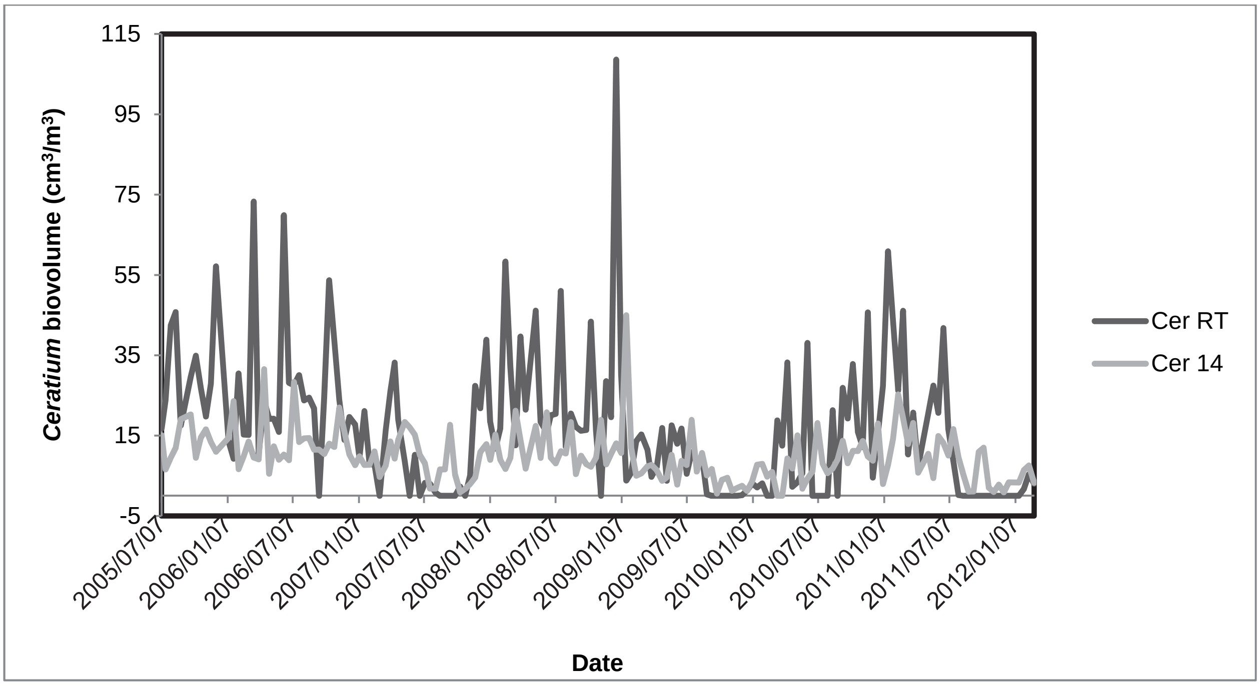

Figure 5-5: Predicting the abundance of *Ceratium sp.* in the Bronkhorstspruit Dam for the period 2005 to 2012. Observed (dark grey) vs. predicted (light grey) time-series values for 14days forward.

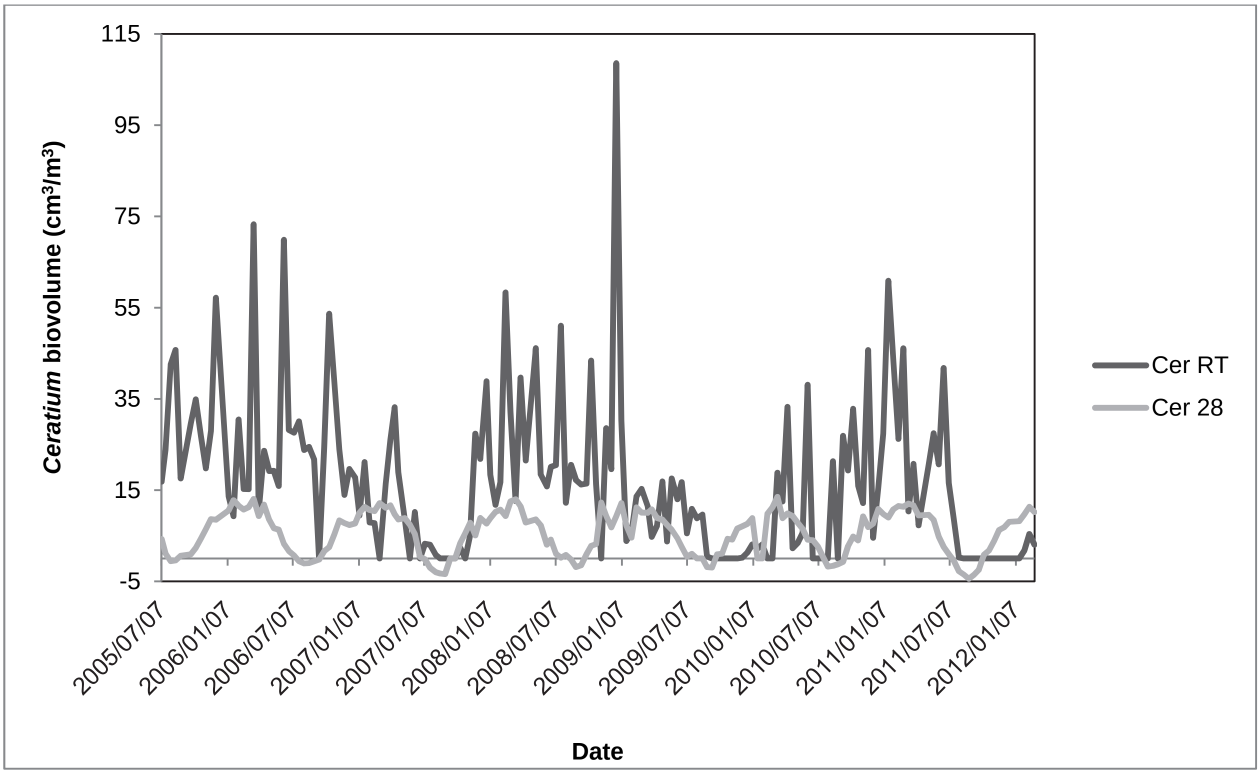

Figure 5-6: Predicting the abundance of *Ceratium sp.* in the Bronkhorstspruit Dam for the period 2005 to 2012. Observed (dark grey) vs. predicted (light grey) time-series values for real time (RT), 14days forward and 28 days forward.

The time series reveal that the occurrence of significant correlations for the predicted values to the observed values of *Ceratium* biovolumes are mainly due to accurate predictions displayed in Figures 5.7 – 5.8

between the RT, RTF and 14 days forward of *Ceratium* biovolume. However in contrast to the predictions in the Rietvlei Dam the model under predicted the extent of *Ceratium* blooms.

5.4 DISCUSSION

A rule based agent (CEGAP) prediction tool was specifically created for the real time (RTF), 7 days, 14 days, 21 days and 28 days *Microcystis* biovolume forecasting, and a second was specifically created for the RTF *Ceratium* biovolume forecasting. However, for the purpose of this study, the rule based agents for the real time forecast, 14 days and 28 days forward predictions of *Microcystis* biovolume were used for Bronkhorstspruit Dam data to predict both *Microcystis* and *Ceratium* biovolumes. Bronkhorstspruit Dam is classified as a mesotrophic impoundment and the difference in trophic state of the testing dataset and the training dataset could cause the difference in observed versus predicted bloom events. Another factor that needs to be taken into account is the dominant algal species in the Dam. *Ceratium* blooms regularly occur in the system.

The predictions for *Ceratium* were very successful as can be seen by the higher correlation coefficient R values (Table 5.3). There was a significant ($p<0.05$) correlation between the observed biovolumes and the RTF and 14 days forward predicted biovolumes. Both these models were able to predict the individual bloom events with accuracy, however; they did not manage to predict the magnitude of the events. The 28 days forward forecast were able to predict seasonal patterns of abundance but also made errors with regards to the magnitude of blooms. When the data is closer inspected it is noted that the mean biovolumes predicted for *Microcystis* and *Ceratium* were exactly the same. The model most probably predicts the bloom event and do not discriminate between the species since it does contain chlorophyll *a* as a variable in the calculation. This would then explain why the model could predict *Ceratium* blooms so well in the Bronkhorstspruit Dam but not *Microcystis* (that rarely forms blooms in the Dam).

5.5 CONCLUSION:

Despite the power of quantitative comparisons the adoption and implementation of the model in question depends strongly on the qualitative and often subjective considerations (Bennet *et al*, 2013). Often models are valued not for the accuracy in magnitude but for its predictive power of patterns and events. Thus although a model can be selected for the lowest error it might be more sensible to choose a model that best preserved data patterns. This depends on the ultimate goal and use of the model. Although the model, which was developed for the prediction of *Microcystis* biovolume, did perform acceptably in predicting *Microcystis*, it predicts bloom events of *Ceratium* very well in the Bronkhorstspruit Dam. This might be a result of the particular choice of input or observed data since Bronkhorstspruit Dam is firstly amesotrophic impoundment and secondly rarely experience *Microcystis* blooms such as the Hartbeespoort Dam, but are dominated by *Ceratium* blooms. It would therefore be fair to conclude that the model predicted *Ceratium* blooms very well for up to 14 days forward.

CHAPTER 6: GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The habitat disturbance created by the long distance circulation of the SolarBees resulted in several ecological changes in the Rietvlei Dam. Many of the parameters used by the early warning agent are part of the algorithms used in the rule set. The disturbance of the epilimnion in Rietvlei Dam did have an effect on the performance of the prediction tool. However, despite these changes the prediction tool could be successfully applied to the data obtained for the prediction of *Microcystis sp.* in the Rietvlei Dam. The model predicted *Microcystis sp.* blooms effectively and timely especially for the 14 days forward prediction. The RMSE for *Microcystis sp.* prediction 14 days forward in Rietvlei Dam was 1.033. The prediction tool appears to be robust enough to not be influenced sudden changes in the environment. The early warning tool also predicted bloom events of *Ceratium sp.* very well in the Bronkhorstspruit Dam, but not that of *Microcystis sp.* The RMSE prediction for the 14 days forward was 18.176. Since the biovolumes predicted for *Microcystis* and *Ceratium sp.* in Bronkhorstspruit Dam were exactly the same it is concluded that model most probably predicts the bloom event and do not discriminate between the species since it does contain chlorophyll *a* as a variable in the calculation.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

For future research, the following recommendations can be made:

1. The prediction tool predict the events of expected algal blooms of *Microcystis aeruginosa* and *Ceratium hirundinella* accurately, but do not predict the extent of the blooms accurately, thus further model development in predicting *Microcystis aeruginosa* and *Ceratium hirundinella* can be developed by using the biovolume of both species in the development of algorithms for the development of predictive capacity for the other.
2. The model can be implemented for real-time forecasting for reservoir managers at other plants where the in-take water contain as dominant species one or both of *Microcystis aeruginosa* and *Ceratium hirundinella*.
3. The methodology can assisted national water management in setting different scenarios
4. Develop capacity in South Africa to use the Hybrid Evolutionary Algorithm (HEA) RULE set development in all research spheres, as the method is applicable to any type of numerical data
5. As a Super Computer are available at the University of the Western Cape and is necessary to conduct these model development studies, the Department of Water Affairs may investigate the availability to Departmental modelling development, also for other research work on water quality.
6. Investigate the cause and effects for the changing composition of the phytoplankton introduced by long distance circulation.

REFERENCES

1. Bennett ND, Croke BFW, Guariso G, Guillaume HA, Hamilton SH, Jakeman AJ, Marsili-Libelli S, Newham LTH, Norton PT, Perrin C, Pierce SA, Robson B, Seppelt R, Voinov AA, Fath BD, Andreassian V, (2013). Characterising performance of environmental models. Environmental Modelling & Software 40: 1-20
2. Bornman MS, Van Vuuren JHJ, Bouwman H, De Jager C, Genthe B, Barnhoorn IEJ, (2007). Technical Report. Application of chemical and biological assays and sentinel species for measuring EDC activity and the potential health risk in the Rietvlei Nature Reserve (RNR). Water Research Commission Project K5/1505.
3. Cape Water Solutions. http://www.capewatersolutions.co.za/2010/02/06/typical-household-water-consumption/ Accessed 21/11/2013.
4. Cao H, Recknagel F, Cetin L and Zhang B, (2008). Process-based simulation Library SALMO-00 for lake ecosystems. Part 2: Multi-objective parameter optimization by evolutionary algorithms. Ecological Informatics 3, 181- 190.
5. Carmichael WW, (2001). Assessment of blue green algal toxins in raw and finished drinking water. In: AWWA Research Foundation Report, American Water Works Association Denver, CO, USA. ISBN 1-58321-076-8, 1-49
6. Department of Water Affairs and Forestry (DWAF), 2006a. Resource Quality Services, Macro Laboratory. Method 0007003, Automated determination of dissolved nitrogen (Kjeldahl). Revision 4, 8 pages, Approval date 2006-07-12, Pretoria, South Africa.
7. Department of Water Affairs and Forestry (DWAF), 2006b. Resource Quality services, Macro Laboratory. Method 0015003, Automated determination of total phosphorus as phosphomolybate. Revision 5, 10 pages, Approval date 2006-07-12, Pretoria, South Africa.
8. Downing TG and Van Ginkel CE, (2003). Cyanobacterial Monitoring 1990-2000: Evaluation of SA data. WRC Report No. 1299/1/03. ISBN 1-77005-012-6. 45pp.
9. Harding WR (2008). The Determination of Annual Phosphorus Loading Limits for South African Dams WRC Report No 1687/1/08
10. Harding WR and Paxton BR (2001). Cyanobacteria in South Africa: A review. WRC Report No TT153/01. ISBN 1 86845 7745.
11. Hudnell HK, Jones, C, Labisi B, Lucerno V, Hill DR and Eilers J, (2010). Freshwater harmful algal bloom (FHAB) suppression with solar powered circulation Harmful Algae 9: 208-217.
12. Iivarinen, J., Kohonen, T., Kangas, J., and Kaski, S. (1994) Visualizing the clusters on the self-organizing map. In Carlsson, C., Järvi, T., and Reponen, T., editors, *Proceedings of the Conference on Artificial Intelligence Research in Finland*, 122-126. Finnish Artificial Intelligence Society, Helsinki, Finland.
13. Knud Hansen, CF, (2007). Paradigm shift for Cyanobacteria control through long distance reservoir circulation (LDC) Empirical experience with SolarBee circulation since 2000 SolarBee Internal Memorandum.

14. Kohonen T (1995) *Self-organising maps*. Springer-Verlag. Heidelberg.
15. Kohonen, T, and Honkela, T. (2007). Kohonen network. *Scholarpedia* 2.1: 1568.
16. Kraaijveld, M.A., Mao, J and Jain, A.K. (1995) A nonlinear projection method based on Kohonen's topology preserving maps. *IEEE Transactions on neural networks,* 6 (3). 548-559.
17. LepŠ J and Šmilauer P, (2003). Multivariant Analysis of ecological data using CANOCO First Edition Cambridge University Press ISBN 0 521 89108 6.
18. Nonneman D and Zimba PV, (2002). A PCR-based test to assess the potential for microcystin occurrence in channel catfish production ponds. Journal of Phycology. 38: 230-233.
19. Rand Water. http://www.waterwise.co.za/site/water/environment/situation.html Accessed 25/11/2013
20. Recknagel F, Van Ginkel, CE, Cao H, Cetina L and Zhanga B, (2008). Generic limnological models on the touchstone: Testing the lake simulation library SALMO-OO and the rule-based *Microcystis* agent for warm-monomictic hypertrophic lakes in South Africa, *Ecological Modelling* 215: 144–158.
21. Steyn DJ, Scott WE and Toerien DF, (1975). The eutrophication levels of some South African impoundments. 1. Rietvlei Dam. Water SA 1(2): 45-51
22. Swanepoel, A, Du Preez, H, Schoeman, C, Janse van Vuuren, S and Sundram, A, Condensed Laboratory Methods for the Monitoring of phytoplankton, including Cyanobacteria, in South African Freshwaters. Water Research Commission, South Africa. WRC Report No.:TT 323-08, 108 pp., (2008a).
23. Symone CS, Araujo PS, Carlos HS, (2008). A case on qualitative model evaluation using data about river water quality. Ecolocical Informatics 3, 13-25.
24. Toerien DF; Hyman KL and Bruwer MJ, (1975). A preliminary trophic state classification of some South African impoundments. Water SA 1: 15-23.
25. Toerien DF and Walmsley RD, (1979). The chemical composition of the upper Hennops River and its implications on the water quality of the Rietvlei Dam. Water SA 5(2): 77-88
26. USEPA (United States Environmental Protection Agency) (1999) Protocol for developing nutrient TMDL's USEPA 841-B-99-007 Washington
27. Ultsch, A. and Siemon, H.P. (1990) Kohonen's self organizing feature maps for exploratory data analysis. In *Proceedings of ICNN'90, International Neural Network Conference*, 305-308, Kluwer, Dordrecht
28. Van Ginkel C, Cao H, Recknagel F & Du Plessis S, (2007). Forecasting of dinoflagellate blooms in warm-monomictic hypertrophic reservoirs in South Africa by means of rule-based agents. Water SA, 33 (4): 1-8.
29. Van Ginkel CE (2003). National distribution of cyanobacteria and toxic events. Presentation at the Nutrient Management Workshop at the WISA Conference in Cape Town, South Africa.
30. Van Ginkel CE (2008) Investigating the applicability of ecological informatics modelling techniques for predicting harmful algal blooms in hypertrophic reservoirs of South Africa. Thesis submitted for the degree of Doctor of Philosophy, North-West University, Potchefstroom.
31. Van Ginkel CE and Conradie B, (2001) Potentially toxic algal incident in the Orange River, Northern Cape,

32. Van Ginkel CE, Hohls BC, Belcher A, Vermaak E and Gerber A, (2001). Assessment of the Trophic Status Project Main Report Report number N/0000/00/DEQ/1799 of the Institute for Water Quality Studies Department of Water Affairs, Pretoria
33. Van Ginkel CE, (2008). Investigating the applicability of ecological informatics modeling techniques for predicting harmful algal blooms in hypertrophic reservoirs of South Africa PhD Thesis North West University.
34. Van Ginkel CE, Du Plessis S and Bezuidenhout JJ, (2010). Investigating the Applicability of Ecological Informatics Modelling Techniques for Predicting Harmful Algal Blooms in Hypertrophic Reservoirs of South Africa. WRC Report Number: TT 451/10, Pretoria.
35. Vesanto, J., Himberg, J., Alhoniemi, E. and Parhankangas, J. 2000. *Book Som toolbox for Matlab 5.* Helsinki University. Helsinki. Espoo. 59pp.
36. Walmsley RD; Toerien DF and Steyn DJ, (1978). Eutrophication of four Transvaal Dams. Water SA 4(2): 61-75