ASSESSING ALGAL GROWTH USING A 2-DIMENSIONAL HYDRODYNAMIC AND WATER QUALITY MODEL

W. Kamish[1]

[1]Civil Infrastructure Group, AECOM New Zealand Limited

ABSTRACT

One of the major sources of drinking water for Cape Town, South Africa had been suffering from blue-green algal growth. This raised concerns over the cost of treating water containing algal by-products and the potential health implications. It was believed that in addition to external nutrient loading, internal re-suspension of nutrients was also one of the key driving forces for the algal blooms. Qualitatively it was expected that algal blooms would be most evident following high wind speed events, relatively high air temperatures and low water levels.

To quantify this problem a study aimed at developing a strategy to address nuisance algal growth problems was commissioned. One of the tasks of this study was the evaluation of the in-dam nutrient dynamics. To accomplish this, a two-dimensional (2*D*) reservoir model was used. The model, CE-QUAL-W2, is based on the assumption that the water body shows maximum variation along its length and depth and can simulate the vertical and longitudinal distribution of velocity, constituent concentrations and temperature.

The objective of this study was to calibrate/corroborate the model for different years especially focusing on the ability of the model to reproduce the in-dam thermal characteristics and phosphate concentrations post high wind speed events.

Findings indicated that the reservoir experiences weak thermal stratification for short periods of time, but that it was easily broken down during wind events. In addition it was found that velocities generated at the bottom of the dam during high wind speed events were sufficiently large to induce re-suspension of sediments with the possible release of loosely adsorbed phosphates from the re-suspended sediments. External phosphate loading was also found to be major contributing factor in promoting algal growth in the dam.

KEYWORDS

Hydrodynamic, water quality, modelling, algal blooms, CE-QUAL-W2

PRESENTER PROFILE

Wageed Kamish (BSc Chem. Eng., MSc Civ. Eng., Pr. Eng.)
Wageed is a senior consultant at AECOM in New Zealand and has 19 years of experience in performing and managing water quality assessments, hydrodynamic and water quality modelling studies as well as hydrological modelling studies. More recently he has been involved in cleaner production projects as well as Computational Fluid Dynamics (CFD) modelling in support of detailed infrastructure designs.

1 INTRODUCTION

Voëlvlei Dam is an off-channel storage dam located adjacent to the Berg River about 5 kilometres south of Gouda in the Western Cape Province of South Africa. The catchment of the dam is relatively small (about 39 square kilometres) and the dam receives its water from two canals which divert water from the Klein Berg, Twenty-Four and Leeu Rivers (refer to Figure 1).

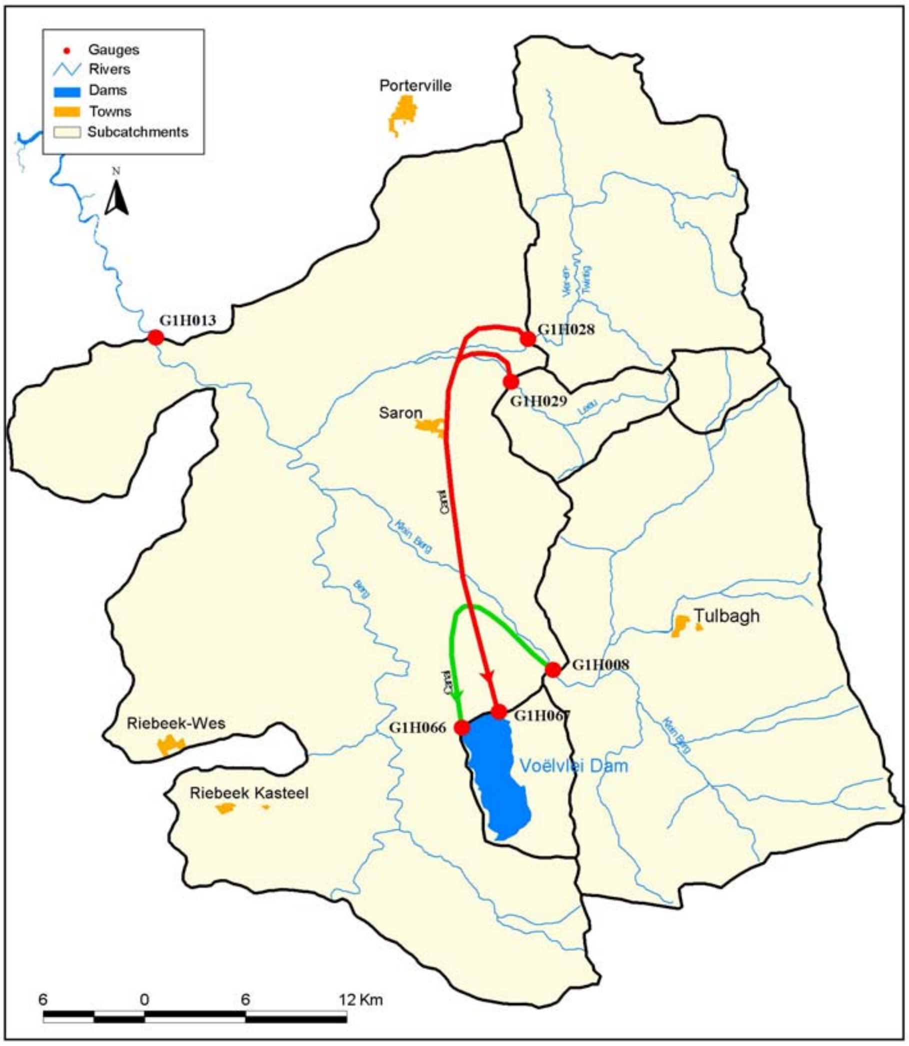

Figure 1: Schematic diagram of the location of Voëvlei Dam

The Dam supplies water to the Cape Town metropolitan area, to towns in the Swartland, and some irrigation water for downstream users. The water for the Swartland Scheme supplies Riebeek Kasteel, Riebeek West and Malmesbury, while the Voëlvlei Water Treatment Works (WTW) supplies the City of Cape Town (DWAF, 1992). The irrigation water is released into the Berg River along with water for the Withoogte Scheme which is then abstracted from Misverstand Weir further downstream (DWAF, 1994).

An earlier ecological assessment of the trophic status (degree of nutrient enrichment) by the Institute for Water Quality Studies found that Voëlvlei Dam can be classified as turbid and mesotrophic (0.5-2.5mg InOrg N/l and 0.005-0.025 mg InOrg P/l) (cited in Van Ginkel *et al*., 2000).

In a subsequent yield augmentation study, a proposal to increase the supply of water to Voëlvlei Dam by augmented pumping from the Berg River during the wet winter months (DWAF, 1999) was made. As part of study an ecologist investigated the potential impact of the Berg River transfer on the in-lake phosphorus concentrations and trophic state of Voëlvlei Dam and found that the dam already exhibited symptoms of eutrophication with sustained elevated concentrations of blue-green algae, associated taste and odour problems as well as hepatotoxin production. He further found that the in-lake phosphorus concentrations placed Voëlvlei at the meso-eutrophic boundary and that problems are already evident pertaining to aesthetics, recreational use, treatment of raw potable water and possible damage to ecosystem health. The implementation of catchment management to limit nutrient loads from the Twenty-Four Rivers and Klein Berg River catchments and possible phosphate stripping of inflow from the Berg River were thus recommended as prerequisites for implementation of the augmentation scheme.

Observations during an algal bloom experienced in the summer of 2000/2001 appeared to indicate that internal nutrient loading also played a role in supporting algal blooms. The algal bloom was preceded by a period of very high winds and it is well known that high winds can cause re-suspension of bottom sediments in shallow reservoirs. The phosphorus adsorbed to the bottom sediments can then become available for algal growth. An analysis of bottom sediments by the CMC has recently shown that the phosphorus content of the sediments was high (Van Driel, 2001).

The aforementioned studies and observations indicated that an approach to address the problem of nuisance algal should include a modelling study to determine the magnitude and role of internal and external sources of nutrients as well as the development of strategies to mitigate the impacts from these sources. It was important for the modelling study to capture the dam's behaviour during the impairment conditions[1].

This paper outlines the approach taken to quantify the effect of internal and external nutrient loading on algal growth in the dam, specifically focusing of the tools used in the process.

2 METHODS AND PROCEDURES

To quantify the physical and biochemical processes that occur in a waterbody it is essential that the transport as well as the kinetics of the constituents is understood. By capturing the processes that govern the transport and kinetics in a mechanistic way it is possible to develop a model that provides insight into the dynamics of the systems. With this in mind it was decided to use a hydrodynamic and water quality model to explain the behaviour of conservative as well as non-conservative substances and to test possible management options for controlling algal growth in the dam.

2.1 MODEL DESCRIPTION

CE-QUAL-W2 is a two-dimensional (2D), laterally averaged, coupled hydrodynamic and water quality model (Cole & Wells, 2008). The model is based on the assumption that the waterbody shows maximum variation in water quality along its length and depth and is therefore suited to relatively long and narrow waterbodies that exhibit water quality gradients in the longitudinal and vertical directions - it may be inappropriate for large waterbodies where Coriolis forces are present or where significant lateral gradients exist.

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[1] An understanding of when and under what conditions water quality impairment occurs

Vertical momentum transfer is not solved in the model and inaccurate results could be simulated where vertical acceleration is significant. The governing equations of state are solved using the finite difference method while turbulence in the model is represented by overall eddy coefficients. The model uses orthogonal cells to represent the numerical grid and as with any model, the increase in cell dimensions could lead to discretization errors.

The model uses laterally averaged equations of motions derived from the three dimensional equations of motion and continuity. The mathematical expression for the general model of fluid flow and heat transfer was developed from the basic principles of conservation of mass, momentum and energy. The governing equations are obtained by performing mass, momentum and energy balance of the fluid (in this case water) over a control volume.

The governing, laterally averaged equations of state for CE-QUAL-W2 are summarised as follows (Cole & Wells, 2008).

The laterally averaged continuity equation is:

$$\frac{\partial UB}{\partial x}+\frac{\partial WB}{\partial z}=qB \ (1)$$

Where,

B is the control volume width, (m)

U is the laterally averaged velocity in the x direction, (ms^{-1})

W is the laterally averaged velocity in the z direction, (ms^{-1})

q is the net lateral inflow per unit volume, (s^{-1})

The x-momentum equation is:

$$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z}= -\frac{B}{\rho}\frac{\partial P}{\partial x}+\frac{1}{\rho}\left(\frac{\partial B\tau_{xx}}{\partial x}+\frac{\partial B\tau_{xz}}{\partial z}\right)+gB\sin\alpha \quad (2)$$

Where,

τ_{xx} and τ_{xz} are the turbulent shear stresses acting in the x-direction on the x and z faces of the control volume, respectively

P is the pressure, (Pa)

ρ is the density, (kg/m^3)

α is the channel angle

The z-momentum equation equals:

$$\frac{1}{\rho}\frac{\partial P}{\partial z} = g\cos\alpha \quad (3)$$

There are thus 3 equations and 3 unknowns *U, W* and *P.* The equations of state relates the density to temperature and concentration of dissolved substances and was represented as:

$$\rho = f(T_w, \varphi_{TDS}, \varphi_{ISS}) \quad (4)$$

Thus, density is a function of water temperature (T_W), total dissolved solids (TDS) and inorganic suspended solids (ISS) concentrations.

The laterally free water surface equation was defined as:

$$B\eta\frac{\partial \eta}{\partial t} = \frac{\partial}{\partial x}\int_{\eta}^{h} UBdz - \int_{\eta}^{h} qBdz \quad (5)$$

Where η is the water surface and Bη is the width at the surface. To solve the above equations for U, W, η and ρ the appropriate initial and boundary conditions must be known.

In addition to solving the hydrodynamics, the model simulates the vertical and longitudinal distributions of temperature and selected biological/chemical constituents over time. These biological/chemical constituents include ammonium, nitrate/nitrite, labile organic matter, refractory organic matter, total inorganic carbon, alkalinity, total iron, dissolved oxygen, organic sediment and gas entrainment. Any number of generic, inorganic suspended solid, phytoplankton and Biological Oxygen Demand (BOD) groups can be also be simulated with the water quality routines.

The governing equation for mass transport used in the CE-QUAL-W2 model is defined as follows:

$$\frac{\partial \varphi B}{\partial t} + \frac{\partial \varphi BU}{\partial x} + \frac{\partial \varphi BW}{\partial z} - \frac{\partial\left(BD_x\frac{\partial \varphi}{\partial x}\right)}{\partial x} - \frac{\partial\left(BD_z\frac{\partial \varphi}{\partial z}\right)}{\partial z} = q_\varphi B + S_\varphi B \quad (6)$$

Where,

φ is the laterally averaged constituent concentration (mg/l)

D_x is the longitudinal temperature and constituent dispersion coefficient (m^2sec^{-1})

D_z is the vertical temperature and constituent dispersion coefficient (m^2sec^{-1})

The model has been applied to many rivers, lakes, reservoirs, and estuaries for nearly 30 years (Cole & Wells, 2008).

Inputs to the model include the following:

- *Bathymetric data* - Data representing the layout and volumetric dimensions of the waterbody

- *Initial Conditions* - Data representing the starting conditions within the reservoir in terms of temperature and reactant distribution

- *Meteorological Data* - Includes the site specific data for air temperature, wind speed, wind direction, dew point temperature and cloud cover

- *Upstream Boundary Conditions* - Includes the flow rates of the incoming streams as well as the time varying concentrations of reactants

- *Flow Rates of Releases* - Data describing the predicted (or measured) release pattern from the reservoir and is essential for volume balance calculations

- *Hydraulic parameters* – Includes horizontal and vertical diffusion coefficients for momentum as well as bottom friction (Chezy or Manning's n)

- *Kinetic parameters* – Includes kinetic coefficients affecting constituent kinetics

- *Calibration data* – Data required to corroborate the performance of the model

3 APPLICATION TO VOËLVLEI DAM

Data for construction of the numerical grid was obtained from the Department of Water Affairs (DWAF) – Geomatics Directorate, in the form of a sedimentation survey (Figure 2).

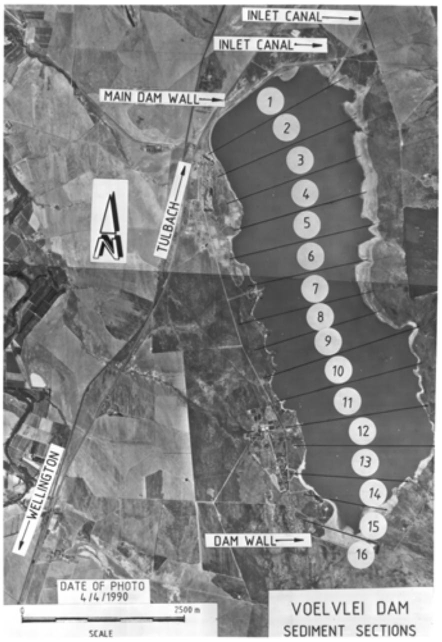

Figure 2: Locations of sediment survey data for Voëlvlei Dam

The bathymetric description of the dam is the most fundamental data required to construct a numerical grid which is a simplified mathematical description of the volume and shape of the dam. It is absolutely essential to construct an accurate description of the dam, as this will determine how well the water level is simulated. The water level in the dam is closely linked to water quality modelling and if hydraulic calibration is not achieved then water quality calibration will be difficult, if not impossible. In this particular case, the occurrence of algal blooms is of importance, making it vital to correctly simulate the water levels.

Bathymetry - The entire grid for Voëlvlei Dam was made up of 18 vertical layers and 17 horizontal segments with segments 1 and17 and layers 1 and 18 representing the boundary cells that have zero width (Figure 3).

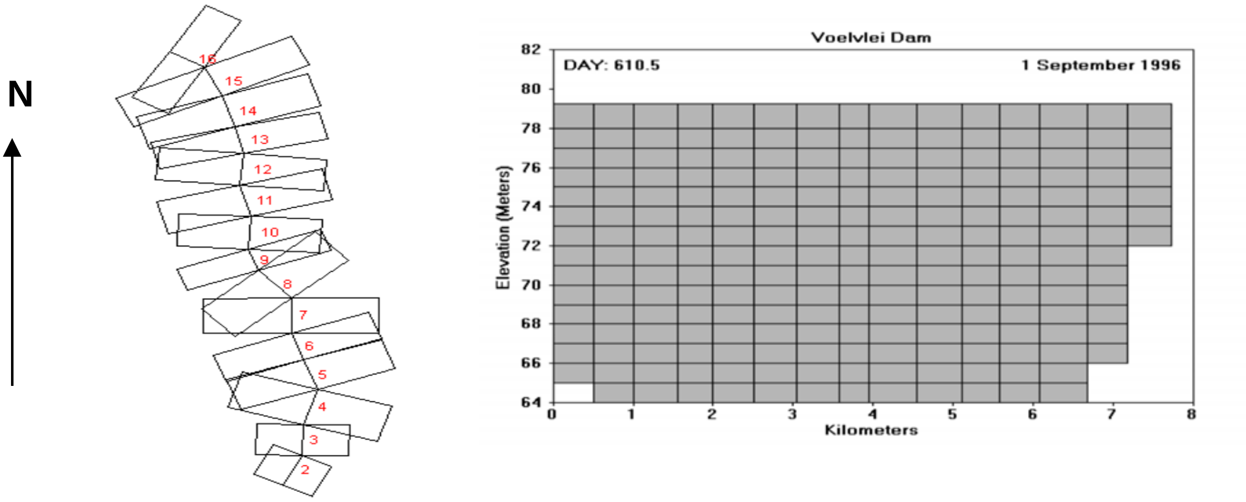

Figure 3: Horizontal segments and vertical layers for Voëlvlei Dam

Initial conditions - Initial conditions describe the state of the reservoir at the start of the simulating period and can be specified either as a single value, vertical profile or a longitudinal profile. For each simulation the initial conditions were estimated from the data captured in the DWAF Hydrological Information System database for that particular day. The position of the inflows to the reservoir was also considered as starting conditions and for this application the inflows were positioned at segment 16. Releases from the dam include abstractions at the Voëlvlei and Swartland water treatment works and releases for agriculture.

Meteorological Data – This information was obtained from a weather station situated at the Voëlvlei water treatment works and data was logged at an hourly interval.

Upstream Boundary Conditions - This data include the flow rates, temperatures and time varying concentrations of the incoming streams. Data for the inflow was readily available on a daily basis, but constituent data was only available on a two weekly basis and a substantial amount of infilling was required. The water quality data at gauging stations G1H008 and G1H029 were used to represent the inflow water quality while the daily flows at G1H066 and G1H067 were used (see Figure 1).

Release Flow Rates – Outflows from Voëlvlei Dam consist of abstractions of raw water to supply the Voëlvlei (G1H070M01) and Swartland (G1H068M01) water treatment works. Water is also released via an outlet canal (G1H065A01) to the Berg River for run-of-river irrigation (DWAF, 1999) and to supplement supplies to Withoogte water treatment works during summer.

3.1 MODELLING WATER QUALITY

The modelling of algae in an impoundment is not a trivial task, since all other water quality constituents are affected either directly or indirectly in the reactions that occur. CE-QUAL-W2 allows the user to specify which water quality constituents to model in the reservoir but this implicitly means that constituents can be omitted only after careful consideration of the effect that it may have on the other constituents. In most cases, however, the effect cannot be determined beforehand and the omission of any constituent could have a marked effect on the simulated output.

Water quality variables modelled include algae, phosphates, refractory dissolved organic matter (RDOM), labile particulate organic matter (LPOM), refractory particulate organic matter (RPOM), ammonium, nitrate/nitrite, dissolved oxygen, organic sediment, dissolved silica and particulate silica.

The lack of data for certain water quality variables (e.g. inorganic suspended solids, refractory dissolved organic matter, labile particulate organic matter and labile dissolved organic matter) in the inflows immediately limits the model in terms of calculating the external loading of these constituents.

3.2 CALIBRATION (1996 TO 1997)

Under steady state condition certain hydrodynamic and water quality parameters would remain constant, but because the system is dynamic these parameters change constantly. To determine whether the model is producing results that are realistic and whether the best value for certain parameters over a given period is used, it is necessary to perform a calibration.

3.2.1 HYDRAULIC CALIBRATION

The hydraulic calibration gives an indication whether the model is accounting for all the major inflows and outflows (water balance) and whether the bathymetry is an accurate description of the reservoir basin. The calibration for the period 2 September 1996 to 1 September 1997 is shown in Figure 4.

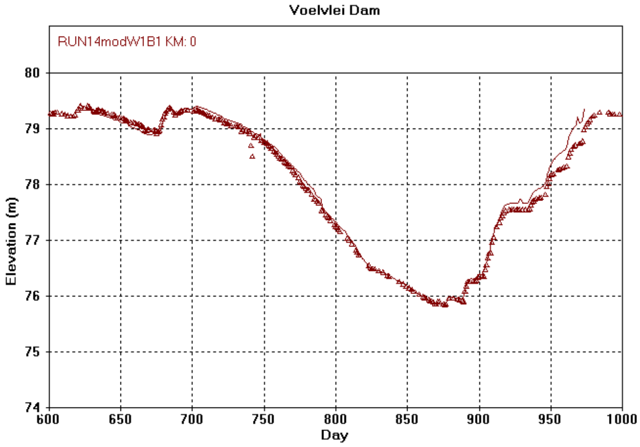

Figure 4: Water level calibration in Voëlvlei Dam (1996/7)

The simulation output agrees well with the measured data with only a slight overestimation in the latter part of the simulation period. This could possibly be explained by noting that an unmeasured abstraction is not simulated because of the absence of observed data. This abstraction could possibly be accumulating artificially in the dam. The agreement between the measured data and the simulated output was good enough to accept the bathymetry that had been constructed for the Dam.

3.2.2 WATER TEMPERATURE CALIBRATION (HYDRODYNAMIC CALIBRATION)

Calibration of the water temperature is in effect an attempt to calibrate the hydrodynamics and heat transfer within the reservoir. Water temperature data at the dam surface close to the dam wall (segment 16) was measured by the DWAF on an irregular basis and it was attempted to calibrate the temperature on this information. Without a profile of temperature throughout the dam it is difficult to say what the goodness-of-fit really is, because only one set of data existed for the calibration. It was however confirmed that stratification in the dam was very weak when it did occur (Van Driel, 2001) suggesting that at most times the dam is completely mixed and that the surface temperature is probably a reasonable reflection of the profile temperature. Figure 5 depicts the agreement between the simulated temperatures and the observed data. Figure 5 shows good agreement between the simulated and observed temperature - confirming that the hydrodynamic calibration of the dam was acceptable.

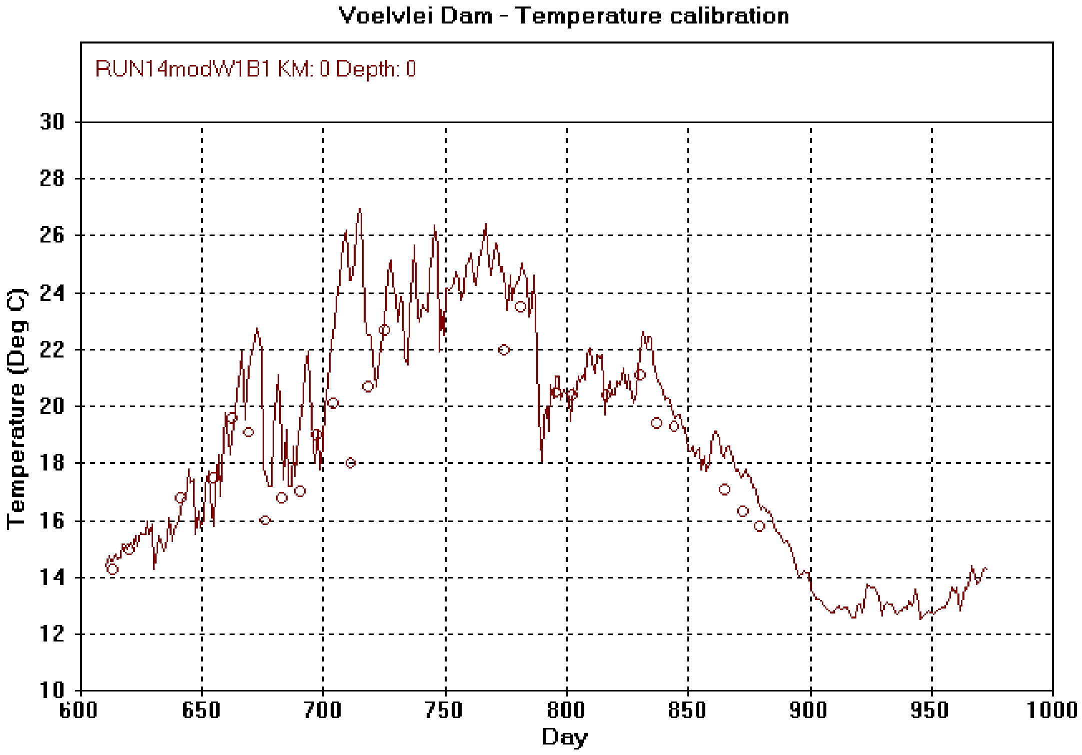

Figure 5: Surface temperature calibration at segment 16 in Voëlvlei Dam (1996/7)

3.2.3 WATER QUALITY CALIBRATION

According to Rounds and Wood (2001) the simulation of a conservative tracer provides a good diagnostic check of the model and is quite useful in determining whether a significant water quality source or sink has been omitted or erroneously represented by the model. It should also be noted that the initial concentration should also be as accurate as possible since this also has an influence on the calibration. Calibration of the chloride tracer is presented in Figure 6.

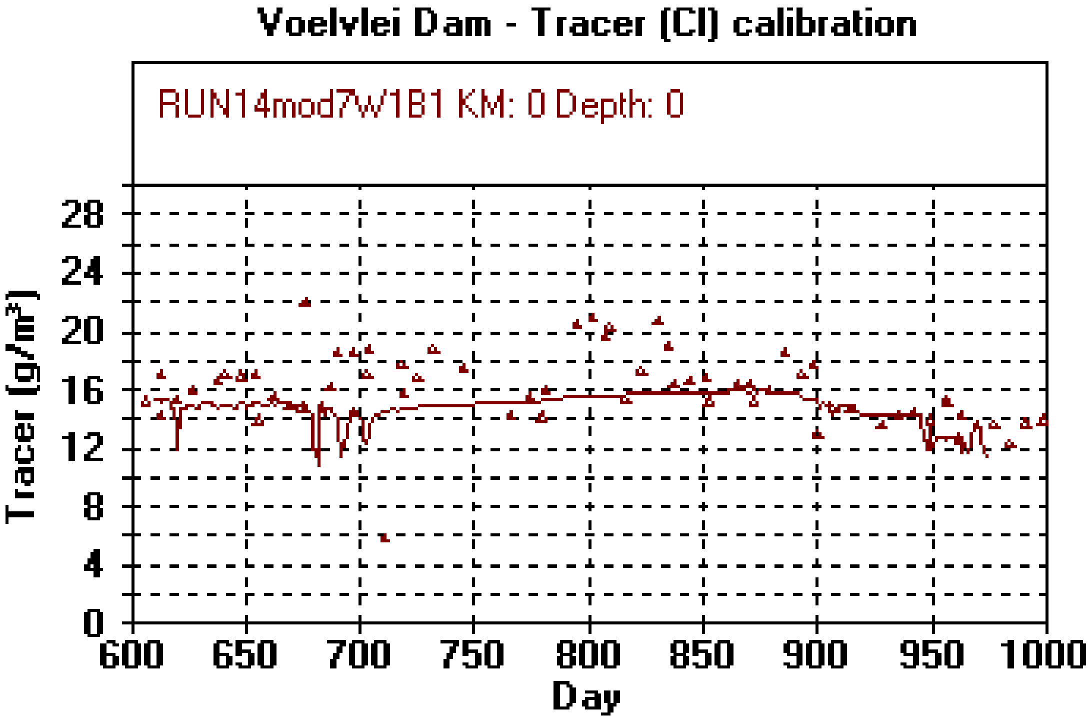

Figure 6: Surface chloride calibration at segment 16 in Voëlvlei Dam (1996/7)

From the comparison in Figure 6 it can be seen that no consistent overestimation or underestimation is apparent, indicating that no significant source or sink has been left out of the simulations. A reasonable simulation of these tracers would indicate that the advective and dispersive transported processes are well represented by the model. This is important since it provides the building blocks for simulating constituents that are influenced by transport processes as well as chemical and biochemical reactions, i.e. non-conservative constituents.

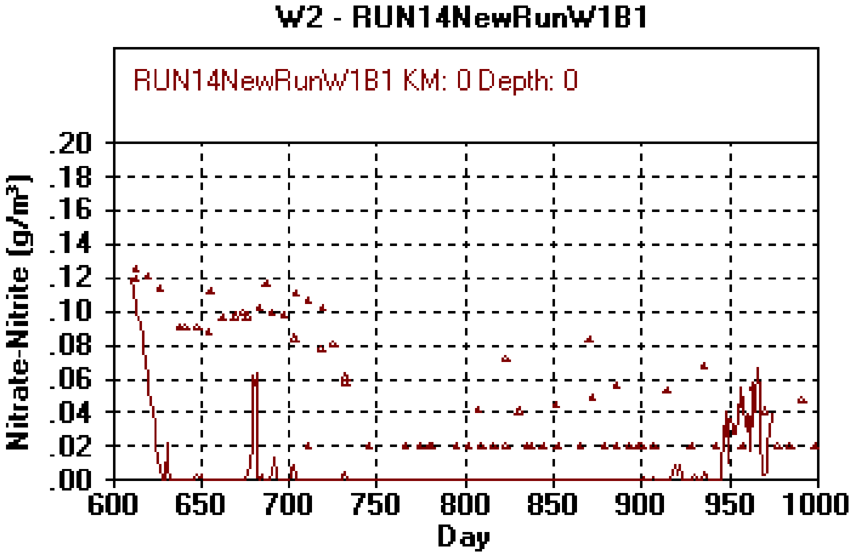

Figure 7: Surface nitrate calibration at Segment 16 of Voëlvlei Dam (1996/7)

In the model of the dam the sinks to the in-lake nitrogen concentration is represented by the outflows, photosynthetic process, denitrification and diffusion into the sediments while sources are represented as the inflows, algal respiration and nitrification. Figure 7 shows that the nitrate concentration at the dam wall is under-simulated indicating that the rate of nitrate "loss" is faster than what it should be. The parameters that could possibly contribute to this are the algal growth rate, nitrate decay rate and the nitrate settling velocity. At this point it was suspected that the algal growth rate is probably too high.

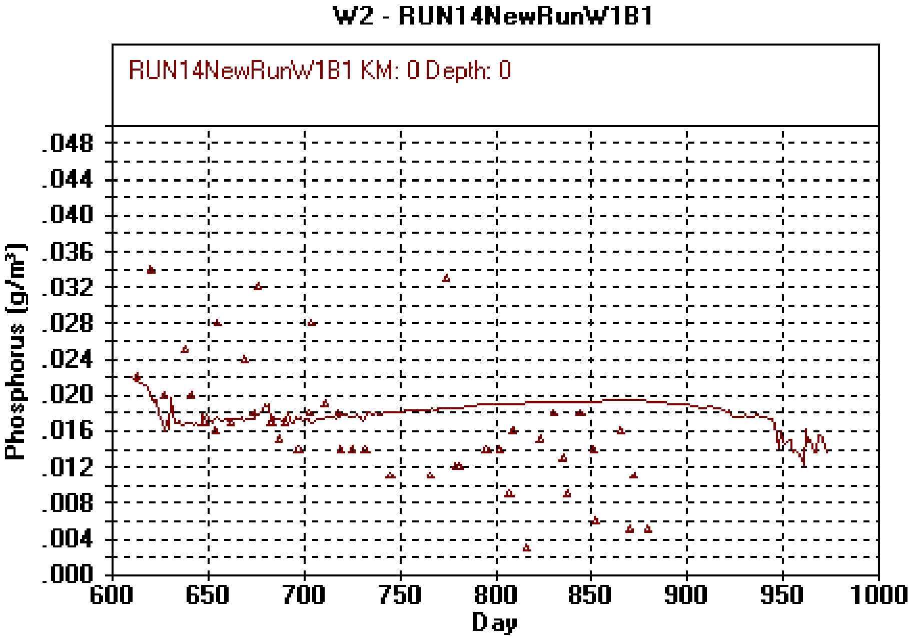

Figure 8: Surface phosphorus calibration at Segment 16 of Voëlvlei Dam (1996/7)

When modelling algae the phosphate concentration is probably the most affected water quality constituent because it is constantly being recycled from one form to another. Total phosphorus, although not a conservative, is less dynamic than phosphate and is often treated as a pseudo-conservative substance. In this model setup the sinks for phosphate include the outflows and photosynthesis while the sources include the inflows, respiration and the decay of organic material including dead algae (organic sediments).

The comparison of simulated and observed phosphate concentrations (Figure 8) indicates that all the phosphate in the system is not completely depleted. The decrease in phosphate concentration seems to follow the same pattern as that of the nitrogen but when the nitrate/nitrite is depleted the rapid decrease in phosphate concentration also stops.

Dissolved silica in the model is lost by the outflows and photosynthesis and is introduced by the inflows and the decay of organic material and particulate silica. The calibration for dissolved silica is shown in Figure 9.

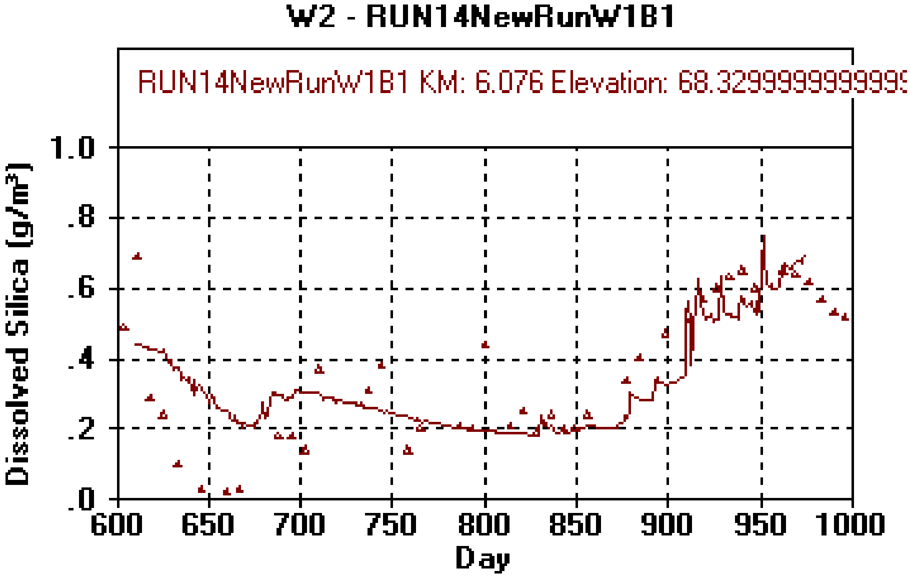

Figure 9: Dissolved silica calibration at the Withoogte WTW abstraction point (1996/7)

The fact that the dissolved silica is simulated reasonably well shows that the photosynthetic process and the decay of organic material is represented fairly accurately within the model.

The simulation of algal biomass is a challenging task. Bales et. al (2001) suggested four possible reasons for this:

1. Algae are not uniformly distributed throughout the reservoir and a single point may not be representative of the actual mean algal concentration in a reservoir segment.
2. When algae are modelled as a single assemblage having one growth rate function, a single mortality rate (as in our case) it does not allow for a distinction between different algal types and algal blooms.
3. Simulated algal concentrations are dependent on simulated constituents such as solids concentration, light penetration, nutrient concentrations and mixing. Errors in the simulation in any of these constituents will result in an error of the simulated algae concentration.
4. Chlorophyll-a is the variable measured to represent the algal concentration but the model simulates algal biomass. The relationship between algal biomass and chlorophyll-a is represented by a single (default) factor that perhaps was not verified with any data.

The algae calibration is shown in Figure 10.

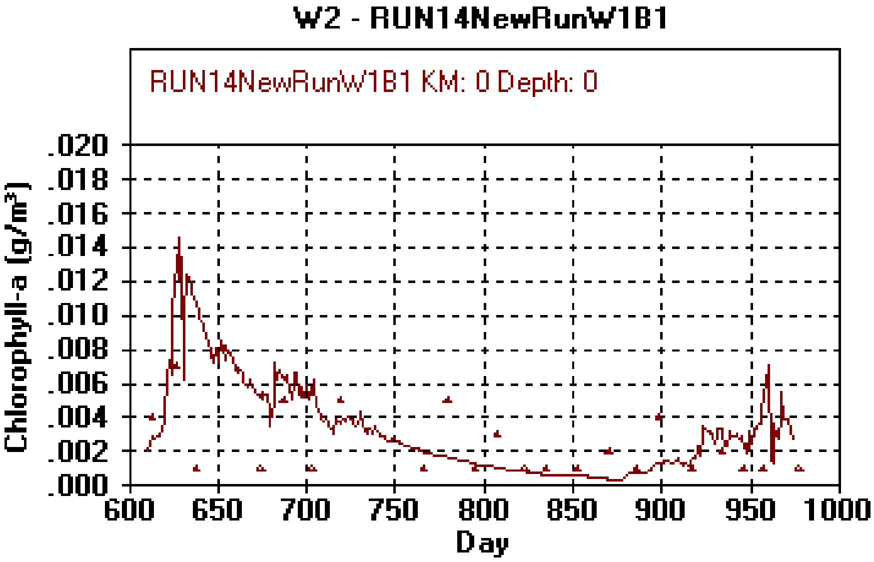

Figure 10: Chlorophyll-a calibration at the Voëlvlei Abstraction point (1996/7)

During the summer months there is little to no inflow to the dam and nutrients required for algal growth has to be obtained from within the dam. Simulations indicate that very low algae concentrations are present even during winter and these algae will definitely consume some of the nutrients available during the early summer. When the water temperature increases, however, a favourable environment is created and a possible elevation in algal concentration or even a bloom may occur. It is important to note that algal growth rate (and therefore algal biomass) is limited by the nutrients available. Increasing the growth rate will not increase the biomass beyond that producible given the available nutrient concentration. The maximum algal concentration is in the expected range given the in-lake nutrient concentrations. The fact that the simulated peak algal biomass concentration is occurring earlier than the observed peak indicates that the temperature rate multipliers may have to be adjusted.

4 RE-SUSPENSION POTENTIAL

In this study it was hypothesised that, *'Loosely adsorbed Phosphate is released into solution when the bottom sediments are re-suspended and this is most likely to occur under high wind-speed events.'*

Since this hypothesis inherently requires that sediment transport be modelled, and CE-QUAL-W2 does not simulate sediment transport, it was necessary to calculate the potential for re-suspension outside the model. This was accomplished by application of an approach developed by Kang *et al*. (1982) that relies on the calculation of wave height, period and length. Ijima and Tang (1966) developed the equations for wave height, period and lengths, which are dependent on mean depth, wind velocity and fetch.

Using this approach it was possible to calculate the bottom shear stress due to wind action at various segments in the dam as well as at various water depths.

4.1 CRITICAL SHEAR STRESS

The critical shear stress is defined as the point at which a particle could possibly go into re-suspension. This point is dependent on the size of the particles as well as the density of the particles at the bottom of the dam. Sediment sampling of Voëlvlei Dam was undertaken at three sites. Initially it was decided that the sediment sampling points should be in the same segments as the water treatment works, but this approach was eventually abandoned due to the small amount of sediments obtained at these sites.

For the combined sediment sample 90% of the sediments had a diameter less than 1mm and 84% of the sample was classified as sand. The density of the mixture was measured at 2678 kg/m^3. Using the information above and following the approach developed by Rooseboom (1992), the calculated critical shear stress for re-suspension of particles having a size of less than 1 mm and a density less than 2678 kg/m^3 was 0.79 kg/ms^2.

4.2 TOTAL SHEAR STRESS FROM CE-QUAL-W2

The calculation of the total shear stress in CE-QUAL-W2 is shown Figure 11 below and is based on contributions from interfacial velocity shear stress, wind wave generated shear and friction shear along the boundaries.

In the hypothesis it was assumed that the wind generated shear contributes the major component of the total shear stress during high wind-speed events and that this would be sufficient for sediment re-suspension. It should be noted that the wind generated shear stress decreases exponentially with depth and that a shallow depth would be associated with a bigger shear stress for the same wind speed and fetch. The total bottom shear stress as simulated in CE-QUAL-W2 over the period September 1996 to November 1996 is shown in Figure 11.

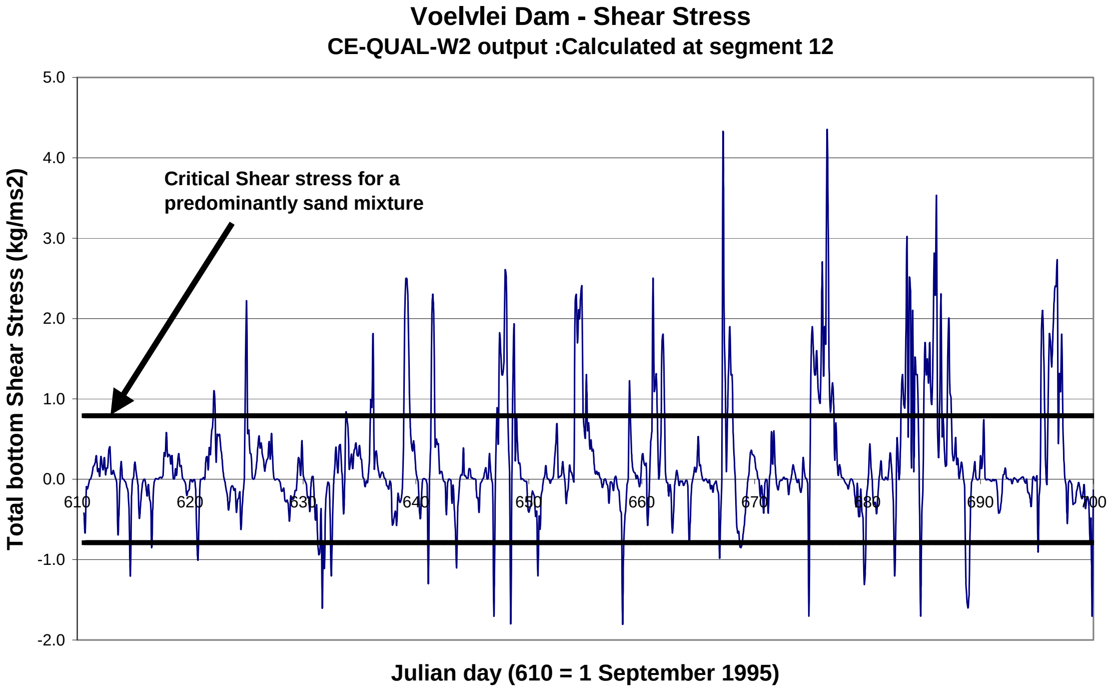

Figure 11: Total bottom shear calculated in CE-QUAL-W2

It can be seen from Figure 11 that the critical shear stress for re-suspension of the sediments in the dam was seldom exceeded, but did occasionally occur. These exceedances roughly correspond with the high wind speed events as shown in Figure 12.

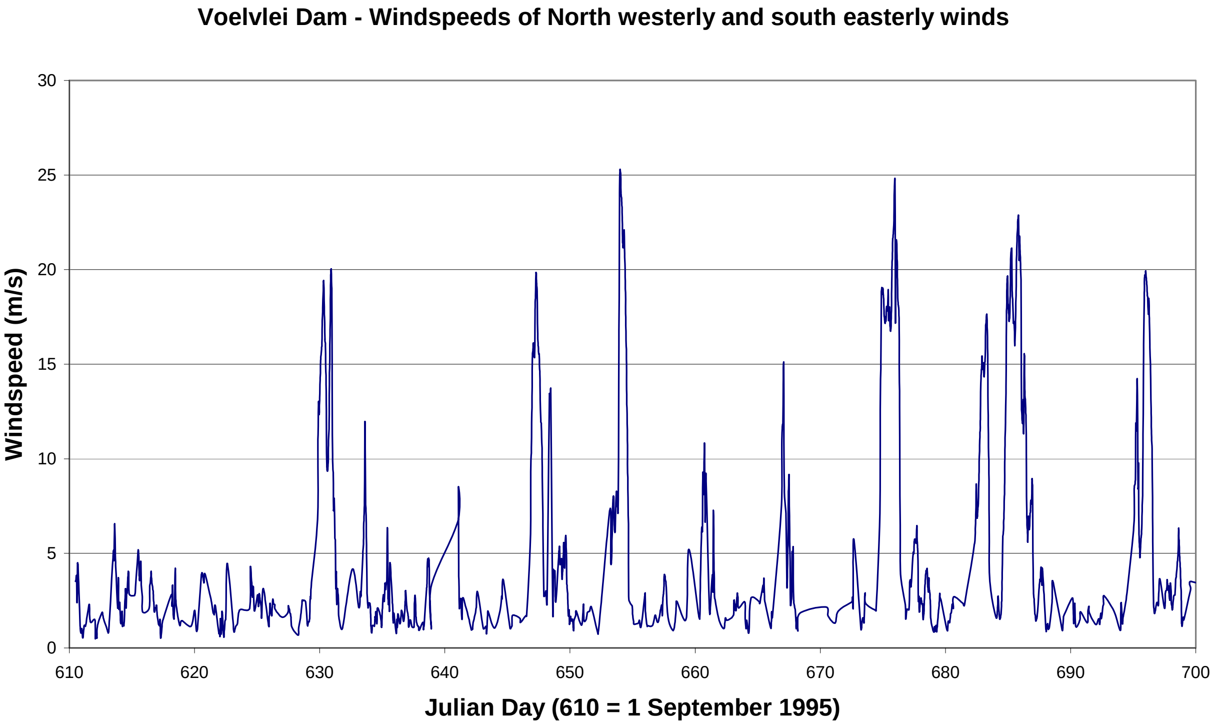

Figure 12: Wind speeds of winds along the longitudinal axis of Voëlvlei Dam

5 CONCLUSIONS

Based on the results the following conclusions can be made:

- If sufficient water quality and meteorological data are available a hydrodynamic and water quality model like CE-QUAL-W2 can be applied to better understand the processes that affect water quality in reservoirs. In this way it would be possible to isolate the driving forces (inflow water quality, meteorology or release structure etc.) which have the biggest effect on the resulting water quality.

- Determination of the type of algal species which are present in the reservoir is essential in accurately modelling the concentration of algae and other water quality parameters in the dam. Knowledge of the species present will allow the modeller to select values for algal growth parameters (Nitrogen and phosphate half saturation constants and temperature rate multipliers) which are appropriate - thus producing simulated outputs which are representative of reality.

- Although sediment transport could not be modelled with CE-QUAL-W2, external calculations based on the critical shear stress showed that re-suspension of certain sediment sizes were possible during specific wind events and that possible release of loosely adsorbed phosphates could occur under these conditions, providing an additional source of nutrients for the algae.

- Sediment sampling conducted in Voëlvlei Dam indicated that a substantial layer of sediment was not present at the bottom of the dam. Based on this it could be inferred that minimal additional phosphate would be added to the water column during re-suspension of sediment particles as a result of wind shear.

6 RECOMMENDATIONS

Based on the results and conclusions the following recommendations were made:

- A monitoring programme for the systematic monitoring of the pertinent data for assessing or modelling water quality in the reservoir should be instituted as soon as possible. Certain parameters are already monitored, but a comprehensive programme should include the following:

    a. Hourly meteorological data (air temperature, dew point temperature, wind speed, wind direction, and percentage sunshine).

    b. Inflow rates.

    c. Inflow and in-lake water quality

    d. Release rates.

- The diversion of the last winter peak inflow from the Kleinberg River provides the nutrients (especially phosphate) necessary to support algal growth in Voëlvlei Dam and could be diverted to reduce the risk of algal blooms during the summer months.

- The probability of the last peak inflow occurring within a specific window period should be determined based on a statistical analysis of the historical flow record of the Kleinberg River. This would provide some indication of when the last peak inflow is most likely to occur.

- A part of an integrated catchment management approach, a catchment study of the Kleinberg River catchment should be undertaken to determine the source of nutrients and to establish whether any source reduction methods could be implemented.

ACKNOWLEDGEMENTS

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REFERENCES

Bales, J.D, Sarver, K.M and Giorgino, M.J. 2001. *Mountain Island Lake, North Carolina: Analysis of ambient conditions and simulation of hydrodynamics, constituent transport, and water-quality characteristics, 1996-97*. U.S. Geological Survey. Water-Resources Investigations Report 01-4138.

Cole, T.M., and Wells, S.A. – CE-QUAL-W2: A *two-dimensional, laterally averaged, hydrodynamic and water quality model, Version 3.6*. Prepared for U.S. Army Corps of Engineers, 2008.

Department of Water Affairs and Forestry, South Africa, 1992. *Description of existing urban water supply infrastructure*. Prepared by R Blackhurst and PR Little of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. DWAF Report no. P G000/00/1490. NSI Report No. 1752/5131.

Department of Water Affairs and Forestry, South Africa, 1994. *Berg River Sub-system Analysis.* Prepared by RR Berg and M Thompson of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. DWAF Report no. P G000/00/4493. NSI Report No. 2030/5131.

Department of Water Affairs and Forestry, South Africa. 1999. *Hydrology. Volume I*. Prepared by GIBB Africa (Pty) Ltd in Consultation with Fongoqa Skade Toyi & Associates cc as part of the Voëlvlei Augmentation Scheme: Feasibility Study. DWAF Report Number PB G100-03-0799.

Ijima,T. and Tang, F.L.W. 1966. "Numerical calculations of Wind waves in shallow water." In *Proc. 10th Coastal Engr. Conf.*, Tokyo, pp.38-45.

Kang, S.W.,Sheng, Y.P. and Lick, W. 1982. *Wave action and bottom shear stresses in Lake Erie*. *J.Great Lakes Res*. 8(3):482-494.

Rounds, S.A. and Wood, T.A. 2001. Modeling Water Quality in the Tualitin River, Oregon, 1991-1997. U.S. Department of the Interior. U.S. Geological Survey. Water-Resources Investigation Report 01-4041.

Van Driel, D. 2001. Personal interview. 30 November, Athlone.

Van Ginkel, C.E., Hohls, B.C., Belchers, A., Vermaak, E. & Gerber, A. (2000). *Assessment of the Trophic Status Project*. Internal Report No. N/0000/00/DEQ/1799. Institute for Water Quality Studies. Department of Water Affairs & Forestry, Pretoria.