

ASSESSING THE IN-LAKE FACTORS THAT CONTROL ALGAL GROWTH IN VOËLVLEI DAM USING A 2-DIMENSIONAL HYDRODYNAMIC AND WATER QUALITY MODEL

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ABSTRACT

Voëlvlei Dam is one of the major sources of drinking water to the City of Cape Town. In recent times, however, the effect of algal growth in the Dam has been a considerable cause for concern. This is particularly apparent when considering the cost of treating raw water that had experienced a severe algal bloom. It is believed that internal cycling of nutrients is one of the key driving forces and that elevated phosphate concentrations may occur. This would be most evident following high windspeed events, relatively high air temperatures and low water levels.

In an attempt to quantify this problem a study aimed at developing a strategy to address nuisance algal growth problems was jointly commissioned by the Department of Water Affairs and the Cape Metropolitan Council. One of the tasks of this study was the evaluation of the in-lake nutrient dynamics and 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 in water quality along its length and depth and can simulate the vertical and longitudinal distribution of thermal energy (water temperature). The model's water quality routines allow for the simulation of up to 21 water quality constituents in addition to water temperature.

The objective of this exercise was to calibrate the model for at least 3 different years especially focusing on the ability of the model to reproduce the in-lake thermal characteristics and phosphate concentrations during high windspeed events. This was accomplished by configuring the model to include an uncommon occasion when elevated algal counts resulted in taste and odour problems in the treated water and then identifying the physical conditions (e.g. high windspeeds, low water levels, high temperatures etc.) that prevailed prior to and during this episode.

Preliminary findings indicate that the reservoir is weakly stratified for short periods of time and stratification is easily broken down during wind events. In addition it appears that water velocities generated at the bottom of the dam during high windspeed events are sufficiently large to induce re-suspension of sediments with the possible release of loosely adsorbed phosphates from the re-suspended sediments.

1.0 INTRODUCTION

On the 14th of May 2001 a meeting was held at Ninham Shand, with the representatives from the Department of Water Affairs & Forestry's Western Cape Regional Office, the Cape Metropolitan Council and the West Coast District Council. The objective of the meeting was to discuss the water quantity and quality problems experienced at Voëlvlei Dam and to propose a way forward to deal with these. One of the recommendations was that Ninham Shand investigate strategies to mitigate the negative effects of poor water quality in Voëlvlei Dam.

Voëlvlei Dam is an off-channel storage dam located off the Berg River about 5 km south of Gouda. The catchment of the dam is relatively small (about 39 km²) and the dam receives its water in two canals which divert water from the Klein Berg, Twenty-Four and Leeu Rivers (refer to Fig 1).

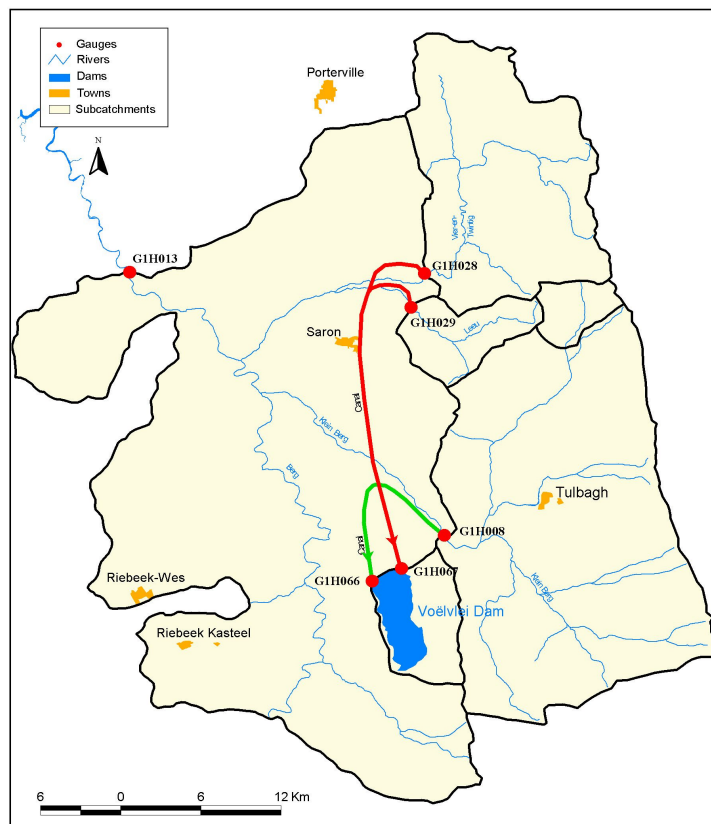


Figure 1 - Schematic diagram of the location of Voëlvlei Dam

Historically water quality in Voëlvlei Dam was regarded as good. An assessment of the trophic status (i.e. degree of nutrient enrichment) by the Institute for Water Quality Studies found that Voëlvlei Dam can be classified as turbid and mesotrophic (i.e. moderately enriched with nutrients) (Van Ginkel *et al.*, 2000).

A recent study by Gibb Africa investigated a proposal to increase the supply of water to Voëlvlei Dam by pumping water from the Berg River during the wet winter months (DWAF, 1999). As part of study, Bill Harding of Southern Waters investigated the impact of Berg River transfer water on

the in-lake phosphorus concentrations and trophic state of Voëlvlei Dam (Gibb Africa, 1999). He found that Voëlvlei already exhibited symptoms of eutrophication with sustained elevated concentrations of blue-green algae, associated taste and odour problems and hepatotoxin production. He also found that the in-lake phosphorus concentrations placed Voëlvlei at the meso-eutrophic boundary and that problems are already evident pertaining to aesthetic, recreational use, treatment of raw potable water and possible damage to ecosystem health. He found that the elevated in-lake nutrient concentrations were probably the result of high nutrient loadings into the dam. He recommended the implementation of catchment management to limit nutrient loads from the Twenty-Four Rivers and Klein Berg River catchments. He also recommended phosphate stripping of inflow from the Berg River should it be decided to proceed with the Voëlvlei Augmentation Scheme.

Anecdotal observations during the algal blooms experienced in the summer of 2000/2001 appear to indicate that internal nutrient loading also plays a role in algal blooms. It seems that the algal bloom was preceded by a period during which very high winds were experienced. It is well known that high winds can cause resuspension of bottom sediments in shallow reservoirs. The phosphorus bound 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, personal communication).

These studies and observations indicated that an investigation to address the problem of nuisance algal should include a study to determine the magnitude and role of internal and external sources of nutrients and the development of strategies to mitigate the impacts from these sources. A study was formulated to achieve these objectives.

The City of Cape Town CMC Administration is currently also investigating the feasibility of upgrading the water treatment works to deal with the deterioration in water quality and associated algal blooms. This investigation will provide valuable information on water treatment costs and will be used to evaluate the benefits of improving the trophic status of Voëlvlei Dam.

1.1 Objectives of the project

Overall objective of the study: Enable the Department of Water Affairs & Forestry and Cape Metropolitan Council to start implementing a strategy to manage the negative impacts of nuisance algal blooms in Voëlvlei Dam.

Intermediate objectives: To achieve the overall objective, a number of intermediate objectives have to be met:

- The extent of the algal bloom problems needs to be known,
- A list of prioritized options to manage the amount of nutrients exported to Voëlvlei Dam, must be available,
- A list of prioritized in-lake management options to reduce the in-lake nutrients and associated algal blooms, must be available,
- Other long term water supply options for the Western Cape that may affect the algal management strategy adopted for Voëlvlei Dam, must be known, and
- the previous four intermediate objectives must have been integrated into a medium term management strategy to mitigate the negative impacts of algal blooms on Voëlvlei Dam.

2.0 NUTRIENT CHARACTERISTICS OF SHALLOW AND DEEP RESERVOIRS

The nutrient characteristics of deep and shallow reservoirs (or lakes) are quite different (Figure 2) (Cooke et al., 2002).

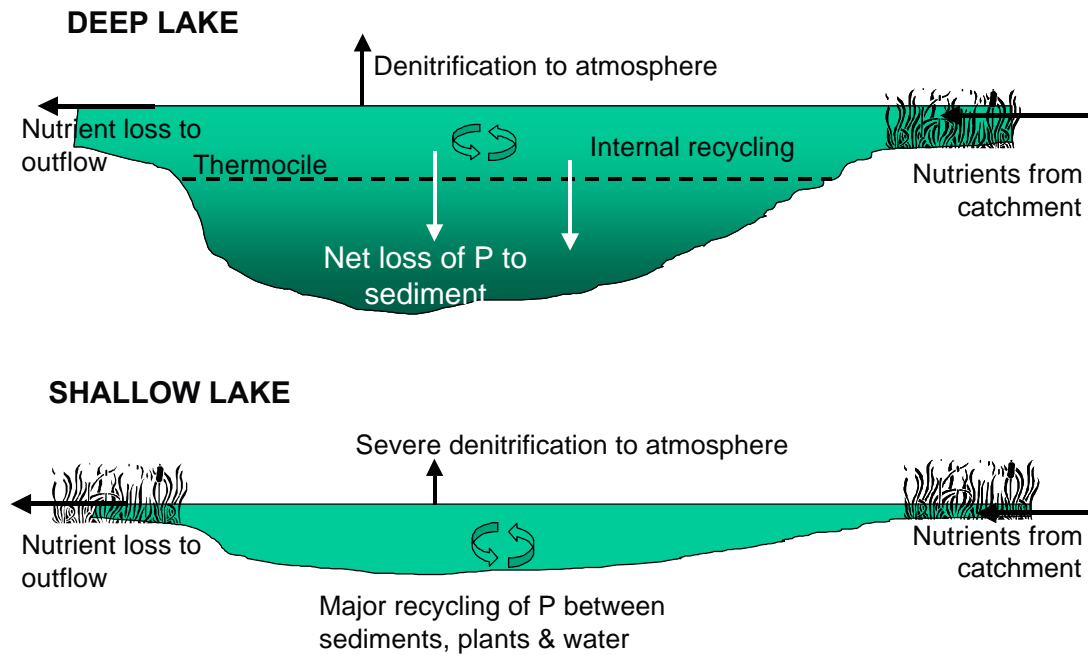


Figure 2 Differences between deep and shallow lakes

In **deep lakes** (or reservoirs), the bulk of the nutrient rich sediments remain in the deepest portion of the lake. Nutrient cycling is limited to the upper water layers and macrophytes and bottom growing plants are limited to the small shallow areas of the dam or lake. The clear water of the dam is maintained by predatory fish (piscivores) keeping the numbers of the fish that feed on zooplankton low. Zooplankton feed on algae and keep the algal concentrations down.

In **shallow lakes** (or reservoirs) water is mixed throughout the water column and nutrients are easily mobilised from the sediments. This is referred to as internal loading. If sufficient macrophytes and submerged water plants are present, sediment resuspension by wind action or by bottom-feeding fish (benthivores) is limited. Water plants support abundant number of piscivores which in turn control the bottom and algal feeding fish. Zooplankton thrive by keeping the suspended algae low. Water is generally clear and plant and animal diversity is high.

However, if enough nutrients or suspended sediment enters a shallow lake, suspended algae or turbidity may increase to a point where the lack of light in the deeper water could kill submerged water plants. Under these conditions, piscivores would be limited leaving planktivores and benthivores to thrive resulting in a mechanism that reinforces high turbidity by high algal growth and by stirring of the sediment. Internal loadings become high and coarse fish (carp and other bottom feeders) and waterfowl lured by the open landscape surrounding a shallow lake, add to the problem. In the absence of rooted water plants, shoreline erosion and erosion of the reservoir bottom by wind or boat action, helps to maintain the turbid state and high internal loadings.

Based on these observations, a theory was developed that shallow lakes and reservoirs can exist in two alternative stable states (Figure 3) (Hosper, 1998, Moss, 1998, 2003).

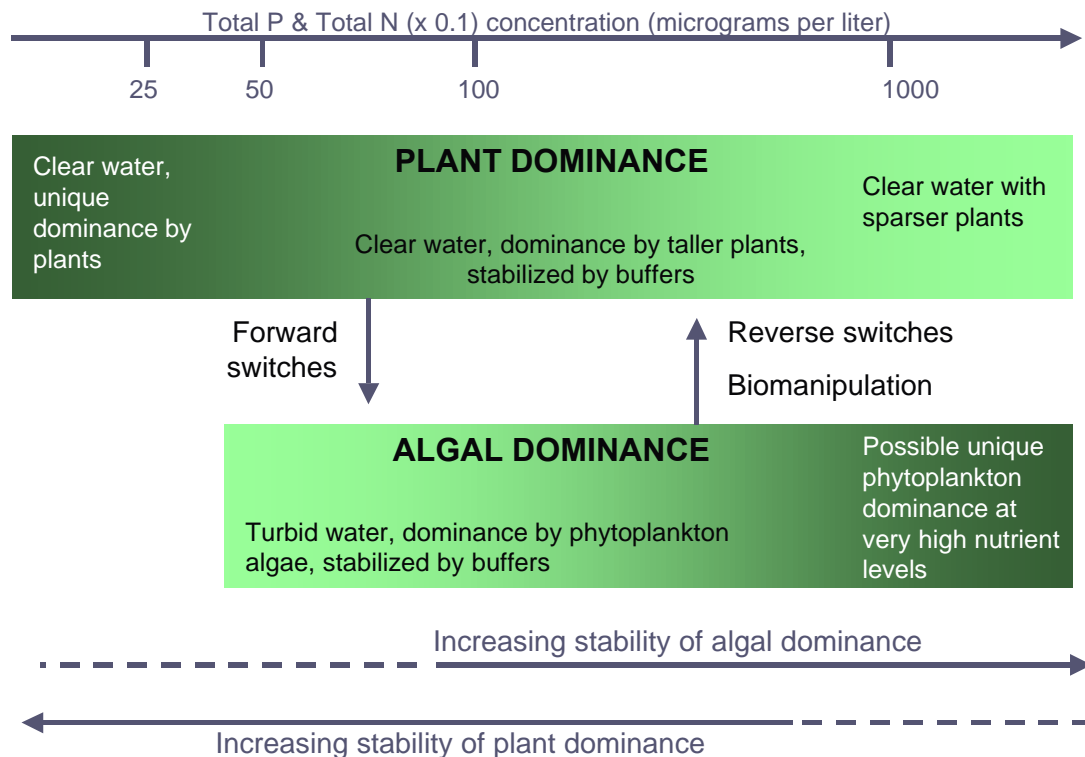


Figure 3 The alternative states model that summarises the current understanding of shallow lakes.

The hypothesis of the alternative states model is that shallow lakes can exist, over a wide range of phosphorus concentrations, in either of two states, a plant-dominated clear-water system or an algal-dominated turbid-state. A change from a plant-dominated system to an algal-dominated system requires a switch such as the removal of water plants or the introduction of highly turbid inflow. The switch works better if it coincides with an increased in nutrient enrichment. The switch back to a clear water plant-dominated system is usually accomplished through biomanipulation and works better if it coincides with a reduction in nutrient concentrations.

There are also buffer mechanisms that maintain the stable state (Hosper, 1998). For example, a stable turbid state is often maintained by wind-induced resuspension of sediment in plant-free lakes or reservoirs and by resuspension of sediments induced by bottom feeding fish (benthivores) unhindered by plants. A forward switch to a clear-water stable state can be maintaining a deeper depth to reduce wind exposure of sediments or complete drawdown and drying of sediments or a reduction of bottom feeding fish. Hosper (1998) lists in greater detail the stable states, the buffer mechanisms and switches between the two states.

Water fowl can play a major role in the ecology of shallow water bodies. Some birds are plant eaters and can prevent the establishment of rooted water plants. Water fowl can also contribute significantly to the nutrient loads through their faeces (Tobiessen & Wheat, 2000). For example, it was found that migrating geese could increase the nutrient loading to wetlands by as much as 40% for total nitrogen and by 75% for total phosphorus (Kitchell et al., 1999) and Cooke et al. (2001) reported that Canadian geese could defecate up to 90 times per day in winter, adding substantial nutrient loads to lakes

3.0 SIMULATING THE PHYSICAL AND CHEMICAL PROCESSES IN VOELVLEI DAM

To quantify the physical and biochemical processes that occur in a dam it is essential that the transport as well as the kinetics of the constituents are 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 these dynamic systems. With this in mind it was decided to use hydrodynamic and water quality model to explain the behaviour of conservative as well as non-conservative substances and to test possible management options.

3.1 Introduction to CE-QUAL-W2

CE-QUAL-W2 is a two-dimensional (2-D), laterally averaged, hydrodynamic and water quality simulation model (Cole & Wells, 2001). The model is based on the assumption that the water body shows maximum variation in water quality along its length and depth. Therefore, the model is suited to relatively long and narrow water bodies that show water quality gradients in the longitudinal and vertical directions. The two-dimensional model simulates the vertical and longitudinal distributions of thermal energy (water temperature) and selected biological and chemical constituents in a water body with time.

Inputs to the model include the following:

- *Bathymetric data* - Data representing the layout and volumetric dimensions of the water body.
- *Initial Conditions* - Data representing the starting conditions within the reservoir in terms of temperature and reactant distribution.
- *Meteorological Data* - This data includes the site specific values for air temperature, wind speed, wind direction, dew point temperature and cloud cover.
- *Upstream Boundary Conditions* - This data includes the flow rates of the incoming streams as well as the time varying concentrations of the reactants being modelled.
- *Flow Rates of Releases* - This includes the data describing the predicted (or measured) release pattern from the reservoir and is essential for volume balance calculations.

3.2 Configuring the model for Voëlvlei Dam

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

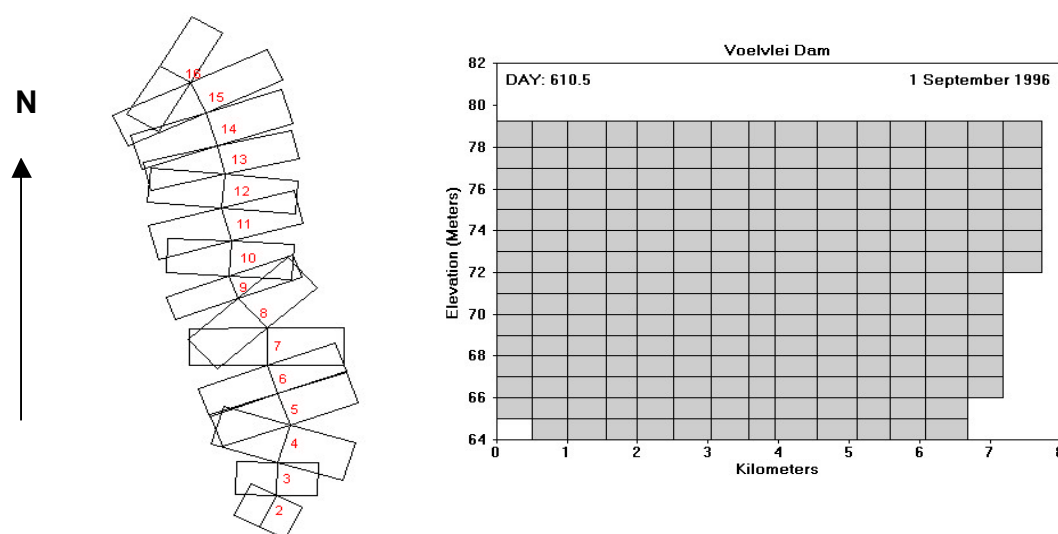


Figure 4 - Representation of horizontal segments and vertical layers for Voëlvlei Dam

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 or a vertical profile or a longitudinal profile. For each simulation the initial conditions were estimated from the data captured in the DWAF Hydrological Information System (HIS) database for that particular day.

The position of the inflows to the reservoir is also considered as starting conditions and for this application the inflows were positioned at segment 16. Other 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. This information was once again sourced from the HIS database.

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.

3.3 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 any 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 before hand and the omission of any constituent could have a marked effect on the simulated output.

Water quality variables modeled 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.

3.4 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.

Hydraulic Calibration

The hydraulic calibration gives an indication whether the model 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 5.

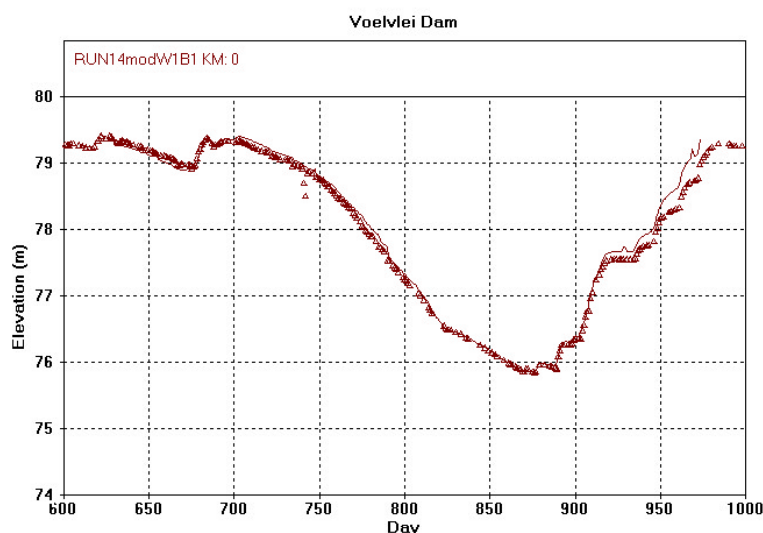


Figure 5 - Comparison of measured and simulated water levels in Voelvlei Dam

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. This exercise was considered to be the hydraulic calibration for the model.

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 has, however, been confirmed that stratification in the dam was very weak when it did occur (pers. comm., Dr D Van Driel) 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 6 depicts the agreement between the simulated temperatures and the observed data. An obvious shortcoming of this calibration is the fact that it is not known whether the temperature simulated at the levels below the water surface level has a good agreement with the observed data. Analysis of the figure depicting the agreement between the simulated temperature and the measured temperature shows a good agreement - confirming that the hydrodynamic calibration of the dam is acceptable.

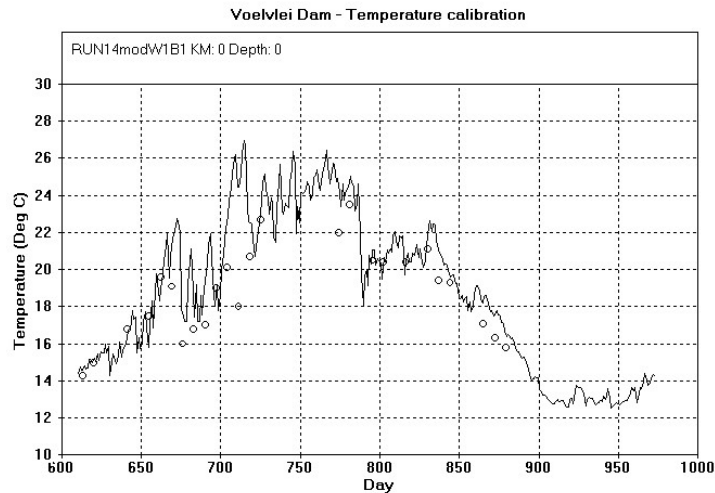


Figure 6 - Surface temperature at segment 16 in Voelvlei Dam

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 chloride concentration should also be as accurate as possible since this also has a big influence on the calibration.

The comparison of the measured and simulated chlorides concentrations is shown in Figure 7

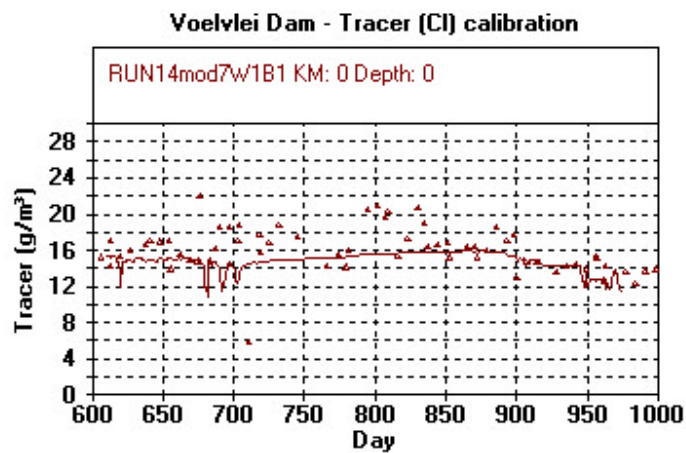


Figure 7 - Surface chloride concentrations at segment 16 in Voelvlei Dam

From the comparison it can be seen that no consistent overestimation or underestimation is apparent (Figure 7), 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.

In the configured model of the Dam the sinks to the in-lake nitrogen concentration is represented by the outflows, photosynthetic process, de-nitrification and diffusion into the sediments while sources are represented as the inflows, algal respiration and nitrification. Figure 8 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 possible parameters that could possibly contribute to this are the algal growth rate, nitrate decay rate and the nitrate settling velocity. At this point it is suspected that the algal growth rate is probably too high.

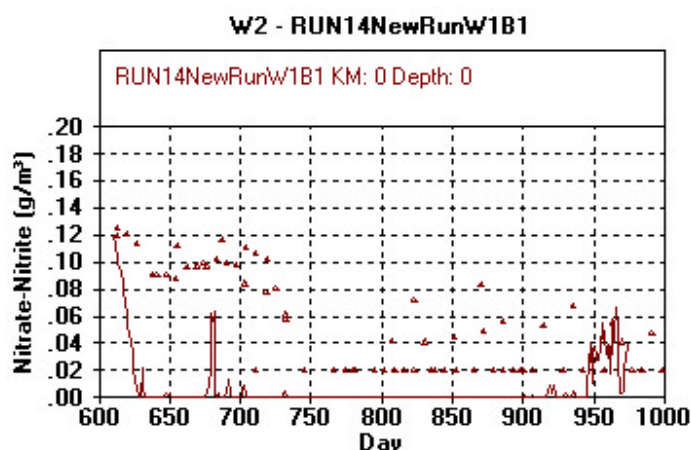


Figure 8 - Surface nitrate concentration at Segment 16 of Voëlvlei Dam

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).

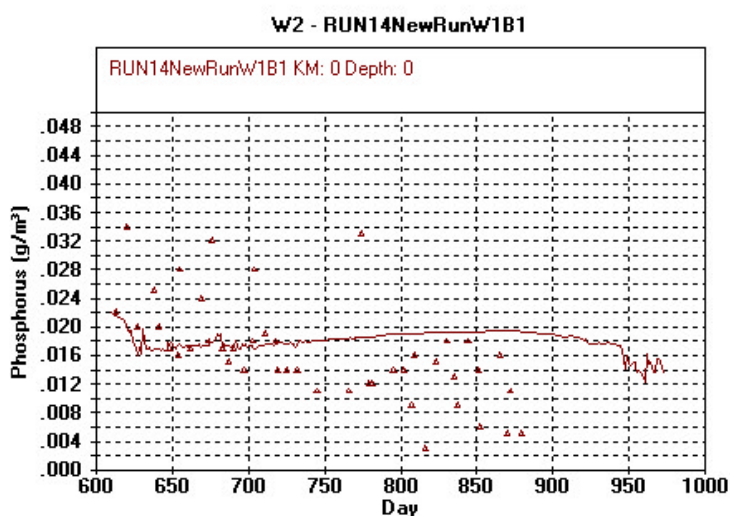


Figure 9 - Surface phosphate concentration at segment 16 in Voëlvlei Dam

The comparison of simulated and observed phosphate concentrations (Figure 9) seems to indicate that all the phosphate in the system is not used up completely and that algal growth is probably limited by the nitrate/nitrite concentration. 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 concentrations also stop.

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.

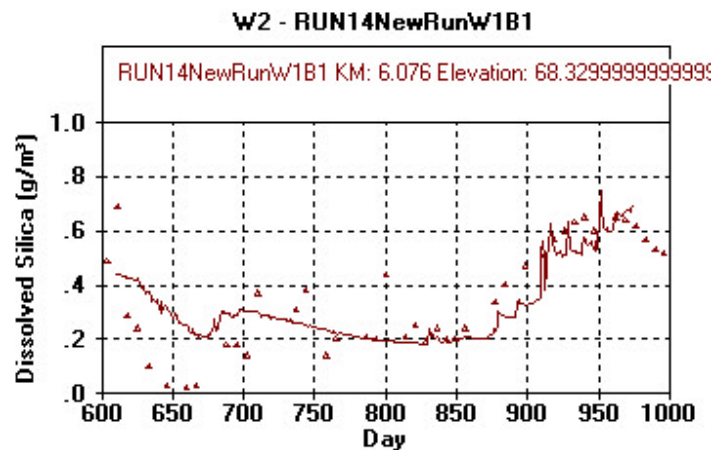


Figure 10 - Dissolved silica concentrations at the Voëlvlei Abstraction point

The fact that the dissolved silica is modeled reasonably well shows that the photosynthetic process and the decay of organic material is probably 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 is 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.

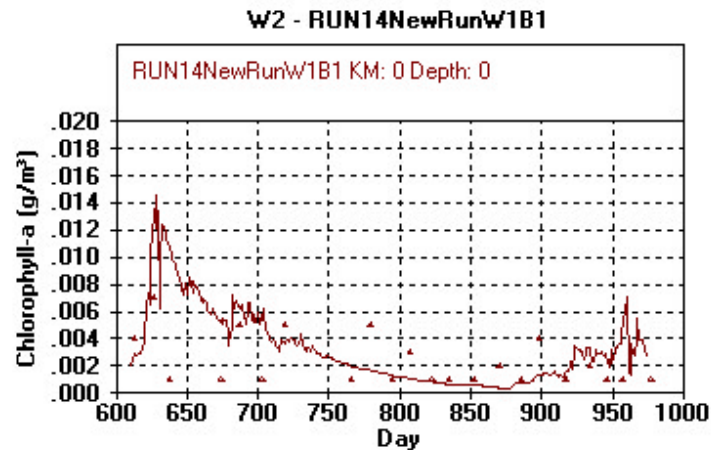


Figure 11 - Algae concentration at segment 16 in Voëlvlei Dam

Figure 11 shows the variation in algal concentration over the calibration period. It can be appreciated that if more data and information were available on the algal species present that calibration on algal-related-parameters would be limited to a minimum.

During the summer months there is little to no inflow to the dam and nutrients required for algal growth has to be obtained from in the dam. Simulations of the dam 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 could be 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 nutrient level. The maximum algal concentration seems to be in the expected range given the in-lake nutrient concentrations. The fact that the maximum algal biomass is occurring earlier than when it should indicates that the temperature rate multipliers may have to be adjusted.

4.0 CONCLUSIONS

With adequate in-lake data it should be possible to configure a model that captures the major physical and water quality processes that occur within a waterbody. A calibrated model (representing mechanistic processes) is a very useful tool in understanding what is happening within a dam. The model also allows managers to run management scenarios in a manner that will identify the most suitable strategy.

Although the uncommon, high concentrations of algae that occurred in Voëlvlei Dam in late 2000 has not been simulated yet, it will be possible to test several management scenarios when this is done. These would include:

1. Scenario modelling
 - Modelling the effect/s of reducing the nutrient concentration in the inflows from the Klein Berg River.
 - Modelling the effect/s of maintaining the water level within the dam above a certain threshold level.

- Modelling the water quality impacts of pumping water from Berg River during winter months.
2. Short term predictions based on real-time data, modelling and calibration. This should be particularly useful during the summer months when nuisance algal blooms could be expected.

5.0 ACKNOWLEDGEMENTS

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