Role of Hydrodynamic and Water Quality Reservoir Modelling in Water Resource Decision Support in South Africa

A. J. Bath

Water Corporation, PO Box 100, Leederville WA 6902 (andrew.bath@watercorporation.com.au)

Abstract: Bulk supply reservoirs hold more than 50 percent of the mean annual runoff of South Africa and play an important component of the bulk water supply infrastructure. Over many parts of the country, there has been deterioration in the water quality of reservoirs. These changes in water quality have been caused by increased contaminant loads delivered from diffuse and point sources as well as by processes within the reservoir (e.g. stratification and eutrophication). This paper shows how mathematical models and decision support systems have contributed to the management of reservoirs. This paper describes the development of a DSS using the hydrodynamic model CE-QUAL-W2 and post processor POST. Three South African case studies are described that address reservoir operation (Vaal River), reservoir diagnostics (Roodefontein Dam), and water quality forecasting (Fika Patso Dam). Over the past ten years, the model has been used successfully in a wide range of applications and has provided a valuable management tool.

Keywords: CE-QUAL-W2; Decision support; Hydrodynamic modelling; Reservoirs; Water quality

1. INTRODUCTION

In South Africa, the climate varies from semi-desert in the west to sub-humid in the east. The average rainfall is just over half the global average and the distribution of rainfall is uneven across the country. More than 60 percent of runoff is generated from only 20 percent of the land area. Most metropolitan and industrial growth centres are situated far from large rivers necessitating construction of large water resource schemes to store and transfer water. In South Africa, bulk supply reservoirs store 27000 million m^3 of water representing more than 50 percent of the mean annual runoff. Reservoirs thus play a key role in the supply of water to a population of almost 44 million people over an area of 1.1 million km^2 (see Figure 1). Deterioration has occurred in the quality of surface water resources in many areas of South Africa. This is caused by river regulation, and increased pollutant discharge. Within reservoirs, water quality can deteriorate further as a result of processes described below.

Stratification occurs in a reservoir as a result of surface heat exchange across the air-water interface, and also by differences in chemical density (caused by salts and suspended solids) within a reservoir. Stratification causes isolation of the hypolimnion from the atmospheric oxygen exchange in the epilimnion, and subsequent deoxygenation. Onset of anaerobic conditions often results in the release of iron and phosphorus from bottom sediments and increases water treatment costs [Bath et al., 1997].

Eutrophication manifests itself in excessive growth of aquatic plants, both attached and planktonic, to levels that interfere with desirable water uses [Thomann and Mueller, 1987]. Growth of aquatic plants generally results from an excess concentration of plant nutrients such as phosphorus and nitrogen. Eutrophication has occurred in many South African reservoirs as a result of increased discharge of nutrients from wastewater, and return flow from agricultural and urban areas. Increased production of aquatic plants causes: large diurnal variation in dissolved oxygen, increased sediment oxygen demand that reduces the oxygen content in the hypolimnion, and increased phytoplankton that clog filters at water treatment plants. Some algae produce extracelluar products that impart taste and odours in treated potable water, while some algae produce toxic blooms [Bath et al., 1997].

Salinisation has become a widespread problem. Natural salinisation arises in catchments where the geology and soils contain large quantities of mineral salts that undergo dissolution and transport during periods of leaching and runoff. Man-made salinisation is a result of point and diffuse sources from industrial, mining and domestic sources. Diffuse sources include agricultural return flow, urban runoff, mining activities, and atmospheric deposition. Salinisation has increased the salt (total dissolved solids) content that degrades the water for domestic, industrial and agricultural use.

Micropollutant contamination in South Africa by toxic heavy metals or organic compounds is generally not detected. However, metals associated with clay and sediment particles (iron, aluminium, manganese) and humic acids are found in many reservoirs. In reservoirs that have an anoxic hypolimnion, sediment release of iron and manganese may influence water treatment [Bath et al., 1997].

Microbiological contamination by faecal matter is the medium for the spread of diseases such as dysentery, cholera and typhoid. Studies show that informal settlements with poor sanitation have increased contamination of river systems [DWAF, 1993]. Consequences include increased water treatment costs and health risks for recreational users.

Erosion and sedimentation Average sediment yields for South African catchments range from 10 to 1000 tonne/km^2/year giving rise to high turbidity and sedimentation problems. Erosion has affected the agricultural sector through soil loss, but also affected reservoirs through loss of storage, sedimentation during floods, high turbidity increasing treatment costs, and aesthetic problems for recreational users.

Reservoir Operation influences water quality where (1) water is transferred between catchments resulting in dramatic changes in quality of the recipient reservoir, (2) compensation releases are made from upstream water bodies resulting in disruptive changes in water quality downstream, and (3) release of hypolimnetic (bottom) water may directly influence downstream users [Bath et al., 1997].

Reservoir water quality is managed by (1) control of contaminant sources in the upstream catchment through point and diffuse source control, and (2) control of water quality in a reservoir. Examples of reservoir management practices include: abstraction of water from a particular layer (selective abstraction), scour releases, control of water level, destratification, deactivation of reservoir sediments, and bio-manipulation [Hanson et al., 1987]. Use of any one of these methods requires an understanding of the hydrodynamic and water quality response. This information is usually obtained using mathematical models.

2. RESERVOIR MODELS

In 1925, the Streeter Phelps Equation (commonly known as the oxygen sag equation) was developed to describe the oxygen regime in the Ohio River, in the USA. It became apparent that the equation, although simple in form, was unable to provide information on more complex aquatic systems. The Delaware Estuary model [Thomann, 1963] was developed for the Federal Water Pollution Control Administration and included a modified version of the Streeter Phelps equation for simulation of multiple compartments. The model was developed to evaluate multiple point source loads and spatially variable properties of the estuary. This has been acknowledged as one of the first decision support tools in the field of water quality management [Orlob, 1992].

Early empirical lake eutrophication models used a simple (zero-dimensional) nutrient budget to predict changes in trophic status of a reservoir [Vollenweider, 1969]. More detailed description of the processes taking place within water bodies was carried out by Chen and Orlob [1971]. This work resulted in the development of the one-dimensional model LAKECO [Chen et al., 1975]. More intricate models of biological processes were developed, examples of which include CLEAN, and CLEANER [Park et al., 1972]. Studies of the eutrophication of the Great Lakes resulted in extension of one-dimensional descriptions into two-dimensional and multi-dimensional models. This required simulation of advection, wind mixing, and thermal stratification. Wind induced mixing of Lake Ontario was studied and yielded two- and three-dimensional models [Simons, 1973].

In the early 1970's, modelling of lakes and reservoirs received a new injection of interest by the need to evaluate the impact of water storage and stratification of impoundments on downstream riverine ecosystems. Particular attention focused on heat exchange processes at the air-water interface. These studies resulted in development of one-dimensional hydrodynamic reservoir models that included simulation of dissolved oxygen [Markofsky and Harleman, 1973]. The US Corps of Engineers produced a one-dimensional reservoir water quality model, CE-QUAL-R1. Stefan and Ford [1973] extended upon earlier heat exchange formulations and developed a total energy integration approach for medium sized dimictic lakes. Their model provided successful simulation of the annual thermal cycle in such water bodies. DYRESM was developed by Imberger et al., [1978] for lakes influenced by saline inflows, and also uses a total energy budget approach to produce a one-dimensional Lagrangian description of the thermal and salinity patterns in impoundments. DYRESM is being continuously enhanced and includes: bubble-plume destratification options, graphical user interface, and simulation of water quality and ecological variables using CAEDYM. Hodges et al., [2000] have developed a three-dimensional hydrodynamic model, ELCOM, that may be linked to CAEDYM to provide a 3-D water quality and ecological simulation capability.

3. DECISION SUPPORT SYSTEMS (DSS)

In the early 1960's, when mathematical modelling of water quality was in its embryonic form, models were generally used, and developed for research purposes and provided little information for decision makers. In recent years, advances in computer hardware coupled with increasingly complex problems in water quality management have stimulated greater use of mathematical models as tools to assist decision makers. Even though these models are designed to enhance the decision support process, the quantity of information they require for implementation on a particular problem, and the copious output they are capable of producing seemed at times to restrict their acceptance by those in a decision making role. To enhance the use of models in decision-making, it has been accepted that software should be user-friendly. This requires integrated data processing, modelling and visualization software. Such an assemblage of software makes up a decision support system (DSS).

Loucks et al. [1982] state that decision support for water quality management must include more than a simulation capability, it must make decision support tools acceptable to decision makers. In the past, modellers generated, interpreted and plotted the results so that they can be used by a manager, planner, or decision maker. With the advent of computationally fast personal computers, a decision maker may prefer to set up the model to resolve a specific problem. This requires not only a suitable platform to run the model but also model run times that are short enough to ensure fast turn around. Unfortunately, most hydrodynamic models are sufficiently demanding in terms of hardware that the model run times do not allow immediate production of results. In such a case, the decision support system can be designed so that the model is run in batch process outside the DSS shell and imports the results in file form. Within the DSS, the results can be interpreted through a graphical user interface that allows selection, inspection and comparison of results. If the model has a comparatively short run time, it could be used within the DSS interactively.

Early development of DSS in South Africa involved the use of nutrient budget models for reservoirs [Grobler, 1986]. Recently, hydrodynamic models are being used in a range of water resource applications [Görgens et al., 1993; Bath et al., 1997]. Orlob [1992] states a DSS may include three elements: an information manager, a set of analytical tools, and a user interface. The information manager is used to receive, identify and store data. These data may be used in setting up the model, or later for interpreting the results. Analytical tools, such as mathematical models, are the core of the decision support system. The user interface allows the user to select specific files, edit data, determine model parameters, display graphical or tabular data, and produce animations.

Loucks et al. [1985] developed a water quality management plan for the Ave River Basin in northern Portugal that used user-friendly, menu-driven programs for interactive decision making. Arnold and Orlob [1989] developed a DSS for water quality management of the Santa Ana River in Southern California. The DSS allowed a comparative assessment of alternative management schemes.

4. DSS DEVELOPMENT

CE-QUAL-W2 (W2) is a two-dimensional water quality and hydrodynamic code supported by the US Army Corps of Engineers [Cole and Buchak, 1993]. W2 uses a two-dimensional vertical and longitudinal fixed grid. It is assumed the water body is homogeneous across the lateral width of the grid. For most reservoirs this is a valid assumption. W2 is suited to relatively long and narrow water bodies that show water quality gradients in the longitudinal and vertical directions. The model is widely used in stratified surface water systems such as lakes, reservoirs, and estuaries. W2 computes water levels, horizontal and vertical velocities, temperature, and 21 water quality variables such as dissolved oxygen, nutrients, organic matter, algae, pH, carbonate chemistry, bacteria, and dissolved and suspended solids. The latest version of W2 (version 3) includes sloping riverine sections, capability of simulating entire river basins with rivers and inter-connected lakes, reservoirs, and estuaries.

Internationally, W2 has been in use for the last two decades as a tool for water quality managers to assess the impacts of management strategies on reservoir, lake, and estuarine systems. In South Africa, when W2 was first used, it was found the model was demanding in terms of hardware and run times were comparatively long. At this time, it was accepted a decision support system was required where W2 could be run in batch process outside the DSS shell, and the results imported for processing.

A DSS shell was built around W2 containing three elements: a pre-processor and data base developed to store and manipulate input data; the numerical simulation model W2; and a graphical user interface to visualize output. The graphical user interface (called POST) was developed to meet specific information and presentation needs for projects in South Africa. POST was developed to take W2 output and measured data to produce a range of time series, scatter, profile, isopleth, and 2-D plots using both simulated and measured data [Görgens et al., 1993]. Furthermore, the interface was developed to produce animated output to enhance visualization. POST has proved extremely valuable in the calibration of W2, assessment of model output and presentation of results.

5. CASE STUDIES

From 1991 to 1999, W2 was set up using 15 reservoir data sets. These applications included forecasting of water quality (existing and future reservoirs), development of system operating rules, and scenario analysis for water quality management [Görgens et al., 1993; Bath et al., 1997]. From these applications, three case studies are briefly described to illustrate the use of the W2-DSS in reservoir management (see Figure 1 for location of the reservoirs in South Africa).

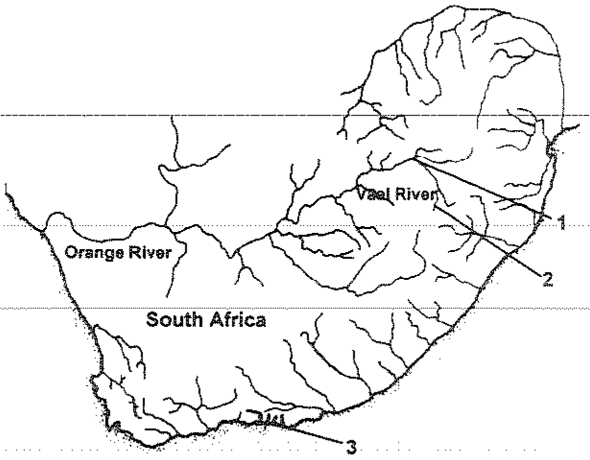

Figure 1. Map of South Africa showing the main river systems and position of the Vaal River (1), Fika Patso Dam (2) and Roodefontein Dam (3).

5.1 Vaal River

The Vaal River forms part of the Vaal River Water Supply System that supplies water to the industrial powerhouse of the country (see Figure 1). The area supplied from the river system generates more than 50 percent of the gross geographic product of South Africa, and 80 percent of the electricity. The system is used to supply water to 7 million people. Water is abstracted from the river, treated and used for domestic, industrial and mining purposes. The Vaal River, below Vaal Dam, also receives wastewater discharges that increase the total dissolved solids (TDS) concentration during the winter (low flow period). During the winter, low TDS water is occasionally released from Vaal Dam into the Vaal River to reduce the TDS below a trigger value of 600 mg/L.

W2 was used to assess the hydrosalinity patterns in the Vaal River to determine the influence of (1) low TDS water released from Vaal Dam to dilute the river, and (2) abstraction from the Vaal River for water treatment [Bath and Quibell, 1998].

The Vaal River below Vaal Dam was modelled over a reach of 50 km. W2 was configured using a grid containing 100 vertical segments (500 metre long) and 13 horizontal layers (1 metre deep). Daily monitoring data for all inflows and 5 points along the river length were carried out during a period of release from Vaal Dam were used to calibrate W2. The W2-DSS user interface was used to produce animations showing detailed mixing conditions in the Vaal River. In the upper river, density stratification occurred with low salinity water from Vaal Dam flowing over the more saline (and dense) river water. In the lower river reaches, large parcels of Vaal Dam water formed a plug-flow pattern as they passed along the river. Analysis showed that abstraction from the bottom layers of the river (where the river was stratified) would beneficially remove high TDS water and none of the lower TDS dilution water released from Vaal Dam.

For the first time, a predictive model was available that simulated complex mixing brought about by inflows, outflows, stratified flow, abstraction and wind mixing. Furthermore, W2 has provided information also used in waste load allocation studies of the Vaal River [Bath and Quibell, 1998].

5.2 Roodefontein Dam

Roodefontein Dam is located on the Southern Cape Coast, has a full supply capacity of 1.4 million m^3, and supplies water to agricultural and domestic users (see Figure 1). Since construction of Roodefontein in 1988, the water treatment plant has been unable to remove iron and dissolved organic carbon from water supplied to users [Ninham Shand, 1998].

W2 was configured and calibrated using one year of daily input data to simulate water temperature, mixing conditions, total dissolved iron, dissolved oxygen and sediment release. Initial results showed high release of iron from sediments in the bottom of the reservoir and low export of iron from the upper catchment. Calibration of W2 confirmed that bottom sediments exert a high demand for oxygen and also release a considerable mass of iron. The iron content of the hypolimnion may exceed 20 mg/L. W2-DSS graphics routines were used to examine stratification and vertical mixing within the reservoir. It was evident that the reservoir remained stratified for 9 to 10 months each year. During this period, the bottom layers were completely anoxic, and the concentration of iron ranged from 5 to 16 mg/L. In contrast, the surface waters were aerobic and contained little iron (less than 1 mg/L).

W2 was reconfigured to simulate the influence of a floating offtake that withdraws water from 2 metres below the surface. Results showed the floating offtake would selectively withdraw surface water with low iron content. Based on these findings, the local authority designed and implemented a floating offtake. Within days of implementation of the floating offtake, the iron content of the water at the treatment works decreased to less than 1 mg/L. This resulted in increased filter run times, less backwash water, and improved treatment control. Thus, a simple application of W2 provided considerable benefits and savings in water treatment [Ninham Shand, 1998].

5.3 Fika Patso Dam

Fika Patso Dam is located on the northern border between South Africa and Lesotho (see Figure 1). The reservoir has a storage capacity of 28 million m^3. Since construction, in 1986, the reservoir contains good quality water that was supplied to users without treatment. At an adjacent reservoir, water quality deteriorated causing considerable water treatment problems. Concern was expressed that water quality would also deteriorate in Fika Patso. To design the new water treatment plant information was needed to predict changes in water quality [Bath and Timm, 1994; Bath, 1995].

W2 was configured and calibrated to provide detailed information on the salinity, nutrients, algal and sediment interactions. A fixed grid configuration was used of 28 vertical segments (300 m long) and 30 layers (2 m deep). Four years of input data were used to configure and calibrate the model. W2 showed the low nutrient and algal response was attributed to extremely low input from the upstream catchment, minimal sediment release and limited stratification. When run over a period of 17 years, W2 showed that the reservoir would show little change in water quality and remain in a pristine state. However, it was also shown that development of the upstream catchment would cause deterioration in water quality. Based on this information, a conventional treatment plant was designed and commissioned to filter, stabilise and disinfect the water. After eight years, the reservoir still yields high quality water. W2 provided a valuable decision support tool and produced information that supported the design of the water treatment plant [Bath and Timm, 1994].

6. CONCLUSIONS

Water quality is an important consideration in the management and planning of river systems in South Africa. Deterioration has occurred in the quality of water resources in many areas of South Africa and influenced nearly all water users.

Development of an appropriate management plan for a reservoir requires information. This information is obtained from monitoring and also from the use of numerical models. Numerical models have been used for almost 40 years to predict the water quality of reservoirs. Early modelling effort focused on academic information needs. More recently, integration of hydrodynamic models into DSS has improved their use as applied tools.

In South Africa, W2-DSS has been used successfully to assess: changes in external load, stratification, hydrodynamic mixing, and internal loading derived from sediment release. This information has been used in wasteload allocation studies, design of water and wastewater treatment plants, ecological impact assessments, and refinement of system operating rules. Overall, decision support tools have contributed to the management of water resources in South Africa.

7. ACKNOWLEDGEMENTS

The author acknowledges support provided in the development of the decision support system using W2, namely Tom Cole (US Army Corps of Engineers), Ed Buchak (John Edinger and Associates), Professor André Görgens (Ninham Shand Consulting Engineers, Cape Town) and Nico van Beest (who programmed POST).

8. REFERENCES

Arnold, U., and G.T. Orlob, Decision support system for estuarine water quality management, *Journal Water Resources Planning and Management ASCE*. 115 (6), 775-792, 1989.

Bath, A.J., Water quality assessment: Fika Patso & Swartwater Dams, Department of Public Works, Qwa-Qwa Government, by Ninham Shand Pty Ltd, South Africa, 1995.

Bath, A.J., K. de Smidt, A.H.M. Görgens, and E.J. Larsen, The applicability of hydrodynamic reservoir models for water quality management of stratified water bodies in South Africa: application of DYRESM and CE-QUAL-W2, Water Research Commission, 304/2/97 by Ninham Shand, South Africa, 1997.

Bath, A.J. and T.D. Timm, Hydrodynamic simulations of water quality in reservoirs of Southern Africa, ICOLD proceedings, 18th congress, Durban, 625-633, 1994.

Bath, A.J. and G. Quibell, Use of a hydrodynamic model to optimize system operating rules for the Vaal River Barrage, South Africa, Proceedings of the IAWQ conference, Vancouver, BC, Canada, 1998.

Chen, C.W. and G.T. Orlob, Ecological simulation for aquatic environments, Office of water resources research, Department of the Interior, August, 1971.

Chen, C.W., M. Lorenzen and D.J.A. Smith, Comprehensive water quality-ecologic model for Lake Ontario, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Admin. Washington, D.C., 1975.

Cole, T.M. and E.M. Buchak, CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, User Manual, Environmental Laboratory, US Army Corps of Engineers, Waterways Experimental Station, Vicksburg, MS, Instruction report ITL-93, September 1993.

DWAF, South African water quality guidelines, Volumes 1 to 4, Department of Water Affairs and Forestry, Pretoria, 1993.

Görgens, A.H.M., A.J. Bath, A.Venter, K. de Smidt and G.v.R. Marais, The applicability of hydrodynamic reservoir models for water quality management of stratified water bodies in South Africa, Water Research Commission, 304/1/93 by Ninham Shand Pty Ltd and University of Cape Town, South Africa, 1993.

Grobler, D.C., Assessment of the impact of eutrophication control measures on South African Reservoirs, *Ecological Modeling,* 31, 237-247, 1986.

Hanson, M.J., M.J.Riley, and H.G. Stefan, An introduction to mathematical modeling of lake processes for management decisions, Report compiled for the Legislative Commission on Minnesota Resources State of Minnesota by the University of Minnesota St. Anthony Falls Hydraulic laboratory, 1987.

Hodges, B., J. Imberger, A. Saggio, and K. Winters, Modelling basin scale internal waves in a stratified lake, *Limnology and oceanography* (in press), Centre for Water Research, manuscript ED1452BH, 2000.

Imberger, J., J. Patterson, B. Herbert, and L. Loh, Dynamics of reservoirs of medium size, *Journal of the Hydraulics Division ASCE,* 104 (4), 725-743, 1978.

Loucks, D.P., P.N. French, and M.R.Taylor, Water resources and environmental planning using interactive graphics, *Water Supply Management* 6 (2) 303-320, 1982.

Loucks, D.P., M.R. Taylor, and P.N. French, Interactive data management for resource planning and analysis, *Water Resources Research.* 21 (2) 131-142, 1985.

Markofsky, J. and D.R.F. Harleman, Prediction of water quality in stratified reservoirs, *Journal of the Hydraulics Division. ASCE,* 99 (5), 729-745, 1973.

Ninham Shand, Plettenberg Bay Coastal Catchments Study, Phase 2 water quality assessment: water resource development schemes, Department of Water Affairs and Forestry and Plettenberg Bay Municipality, South Africa, 1998.

Orlob, G.T., Water quality modelling for decision making, *Journal of Water Resource Planning & Management ASCE,* 118(3) 295-307, 1992.

Park, R.A., D. Scavia, and N. Clersi, CLEANER, the Lake George model. Contribution 184, US International Biological Program, Rensselaer Polytechnic, Troy, N.Y., 1974.

Simons, T.J. Development of three-dimensional numerical models of the Great Lakes. Science Series 12, Canada Centre for Inland Waters, Burlington Ontario, Canada, 1973.

Stefan, H. and D.E. Ford, Temperature dynamics in dimitic lakes, *Journal of the Hydraulic Division ASCE,* 101 (1) 97-114, 1973.

Thomann, R.V., Mathematical model for dissolved oxygen, *Journal Sanitary Engineering. Division ASCE,* 89 (5) 1-30, 1963.

Thomann, R.V. & J.A.Mueller, Principles of surface surface water quality modeling and control, Harper and Row, New York, 1987.

Vollenweider, R.A., Moglichkeiten und grenzen elementarer modelle der stoffbilanz von seen, *Archive Hydrobiologie,* 66 (1), 1-36, 1969.