Application of 1D and 3D Hydrodynamic Models Coupled to an Ecological Model to Two Water Supply Reservoirs

J.R. Romero, **C.P. Dallimore, J.P. Antenucci, D.P. Hamilton, J. Imberger, D.A. Horn and A. Deen**[a]

Centre for Water Research, University of Western Australia, Crawley WA 6009, Australia
(romero@cwr.uwa.edu.au)

[a]*Sydney Catchment Authority, Penrith, NSW 2750*

Abstract: A one-dimensional (1D-DYRESM) and three-dimensional (3D-ELCOM) hydrodynamic model were coupled to a common ecological model (CAEDYM) and applied to 2 different, but inter-connected reservoirs. A 1D water quality (WQ) simulation (DYRESM-CAEDYM) of large ($V=2$ km^3, $A=82$ km^2, $L=50$ km) and deep ($z_{max}=90$ m) Lake Burragorang during a drought (1992-1995) compared well with field data. DYRESM-CAEDYM simulations of much smaller ($A=5$ km^2), shallower ($z_{avg}=9$ m) and low residence time (*ca.* 1 month) Prospect Reservoir over 8 years (1983-1991) were validated against a comprehensive WQ record, with no modifications to the Lake Burragorang application other than to daily forcing and bathymetry files. Lake Burragorang is subject to occasional flood events involving rapid temporal evolution of spatial variations that cannot be simulated by a 1D model. A winter flood in Jun. 1997, with comprehensive spatial monitoring, took *ca.* 1 week to travel to from tributary to dam wall (~ 50 km) as a nutrient-laden underflow. Grids (100-200m×100-200m×1-2m) needed for 3D model run times to follow the evolution of the flood event were too large to resolve the narrow and complex geometry of this reservoir, but by 'straightening' the domain, larger grid sizes with suitable run times yielded good validation results. A 3D simulation of Prospect Reservoir during the onset of seasonal stratification indicated poor WQ from the 2 inflows is 'contained' to below the metalimnion, where its accessibility to algae is restricted by the stratification. A simulation with a bubble plume destratification system indicated that these inflows would be inserted into the mixed layer and available to phytoplankton. This study demonstrates that physical events (e.g. floods, destratification) often dictate the dominant responses of the biogeochemistry that produce an observed pattern of WQ. This suggests accurate validation and prediction of physical processes is the basis of accurate forecasting of natural or anthropogenic influences on reservoir WQ.

Keywords: Reservoirs, Water Quality, Hydrodynamics, Modelling, Spatial and Temporal Variability, Management Tool

1. INTRODUCTION

In this study a one-dimensional (1D) and a three-dimensional (3D) hydrodynamic model are coupled to a water quality (WQ) model, and applied to two reservoirs near Sydney, Australia. Specifically, the effects of natural floods on a large reservoir and bubble destratification on a moderately-sized, low-residence time reservoir were evaluated with the 3D model. The ID model was used to evaluate the seasonal evolution of WQ in both reservoirs. The main scientific aim was to demonstrate that a single ecological model could be coupled to 1D and 3D hydrodynamic models to understand reservoir WQ dynamics, thus serving as tool to make more effective management decisions.

Application of 1D (DYRESM) and 3D (ELCOM) hydrodynamic models with the ecological model (CAEDYM) to two different systems also offers a rigorous multi-system validation of ELCOM, DYRESM and CAEDYM if calibrated on one system and applied to the second. The 3D hydrodynamic model has been applied to investigate Kelvin waves in Lake Kinneret [Hodges et al., 2000], saline gravity currents in a coastal freshwater lake [Dallimore et al., submitted] and an underflow in a large canyon-shaped water supply reservoir [Romero and Imberger, submitted]. CAEDYM has been applied to a large water supply reservoir [Romero and Imberger, submitted] and a shallow, eutrophic Greek lake [Romero and Imberger, 1999*a*].

2. STUDY SITES AND MODEL INPUTS

One reservoir, Lake Burragorang, is large (V=2 km^3) (Figure 1) and dominated by occasional floods from a moderately steep catchment. The 1D WQ model (DYRESM-CAEDYM) was applied over a 3 year drought from Jun. 1992-Jun. 1995 (Figure 2). Inflow WQ was output from the river model HSPF [AWT 2000, 2001] for 4 of the 7 primary rivers [Romero et al., 2002]. Regression equations of measured discharge versus WQ were used to provide data for the other 3 inflows [Romero et al. 2002]. The 3D WQ model (ELCOM-CAEDYM) was then applied to a flood event during Jun.-Jul. 1997.

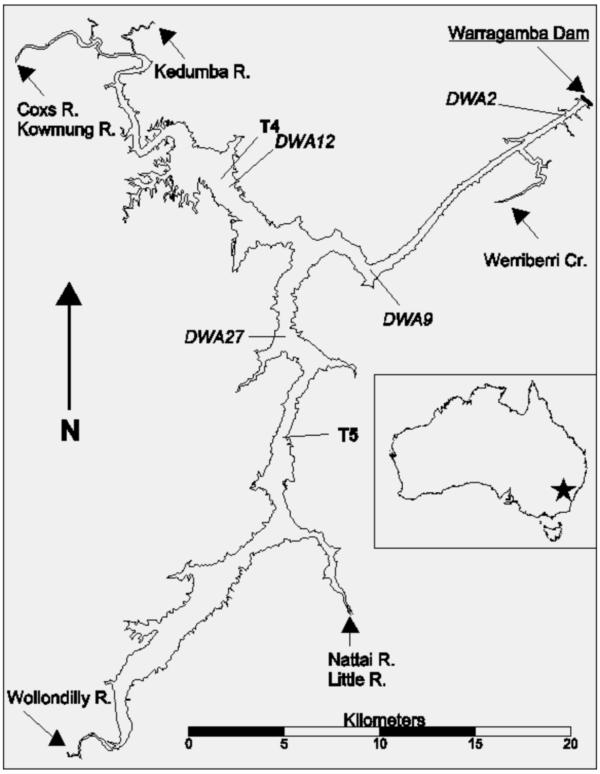

Figure 1. Primary inflows, thermistor chain locations (T1-T5) and WQ monitoring sites (DWA2-DWA27) in Lake Burragorang.

Inflows may be diverted into or away from reservoirs to alter flushing rates or reduce nutrient or contaminant inputs. The relative importance of internal loading increases as the residence time increases as has been demonstrated with numerical modeling studies of moderate size (A=5.25 km^2) and depth (z_{max}=24 m, z_{avg}=9 m) Prospect Reservoir over 1.5 years from 1989-1990 (Figure 3) [Hamilton, 1999; Schladow and Hamilton, 1997; Schladow and Hamilton, 1995; Hamilton et al., 1995]. Here, we extend the simulation duration for Prospect Reservoir to over 8 years (1983-1991). ELCOM-CAEDYM was also applied to Prospect Reservoir during 2 weeks in Oct. 1990, corresponding to the onset of seasonal stratification. Evaluation of the effect of a bubble destratification system was also simulated with the ELCOM-CAEDYM model.

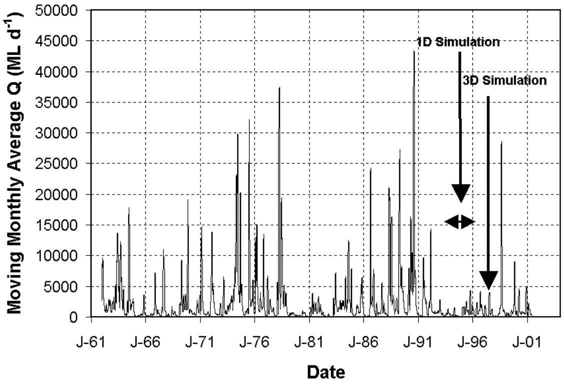

Figure 2. Monthly total inflow of the 7 gauged streams into Lake Burragorang from 1962-2001.

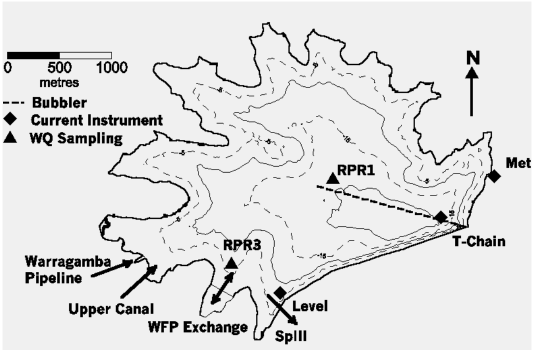

Figure 3. Primary inflows, outflows, thermistor chain location, WQ monitoring sites (RPR1, RPR3) and the bubbler (dashed) line in Prospect Reservoir. Isobath intervals are at 5 m.

3. 1D WQ SIMULATION OF LAKE BURRAGORANG

DYRESM-CAEDYM was applied to a drought period from 1992-1995 (Figure 2). The simulated temperatures (T) at the surface and bottom were reproduced well (Figure 4A). Interannual variations of both surface and bottom summer T over the 3 years were captured by the model. The simulated dissolved oxygen (DO) compared well with field data in the epilimnion and hypolimnion (Figure 4B). The extent of winter reoxygenation and summer hypolimnetic deoxygenation reflects accurate modelling of the interannual DO patterns. Total phosphorus (TP) was modelled well in the surface and bottom waters under stratified and fully mixed conditions (Figure 4C). Increases in hypolimnetic TP were due to internal loading, which was evident during the drought. Interannual

NO_3 variations were simulated accurately with the 1D model, however the seasonal dynamics were not captured well (Figure 4D). Winter (Jul.) NO_3 peaks in the surface waters were consistently under-predicted as were hypolimnetic levels. Chl*a* at the surface (3 m) was reasonably well simulated (Figure 4E).

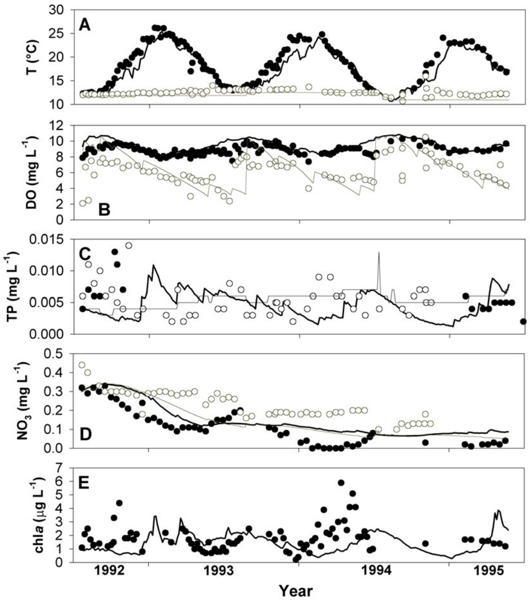

Figure 4. 1D WQ simulation of Lake Burragorang of A) T, B) DO, C) FRP, D) NH_4 and E) chl*a*. Symbols are field data (filled-3m, open-75m) and lines (black-3m, gray-75m) are simulation results.

4. 1D WQ SIMULATION OF PROSPECT RESERVOIR

DYRESM-CAEDYM was then applied to Prospect Reservoir with no modifications to the ecological configuration or the WQ parameters used in Lake Burragorang (Figure 5). Overall thermal stratification patterns reproduced well by the model (Figure 5A). Higher T in both the surface and bottom waters during the last 2 years resulted from a change in the inflow T arising from Lake Burragorang. From 1981-1989 withdrawals were extracted from the upper hypolimnion of Lake Burragorang thus providing a stable inflow T of 12-14 ºC throughout the year (Figure 4A). A large flood in 1990 (Figure 3) caused poor WQ in the hypolimnion of Lake Burragorang, thus withdrawals were from the mixed layer in 1990-1991 in order to improve WQ in Prospect. T in the pipeline inflows then followed the seasonal surface water variations of Lake Burragorang (Figure 4A), which resulted in changes to thermal stratification patterns in Prospect Reservoir. The low residence time (ca. 30 days) of Prospect Reservoir and its large proportion of inflow from Lake Burragorang (ca. 80%) make thermal budget very sensitive to changes in inflow T. Higher T can also be expected to enhance rates of biogeochemical processes.

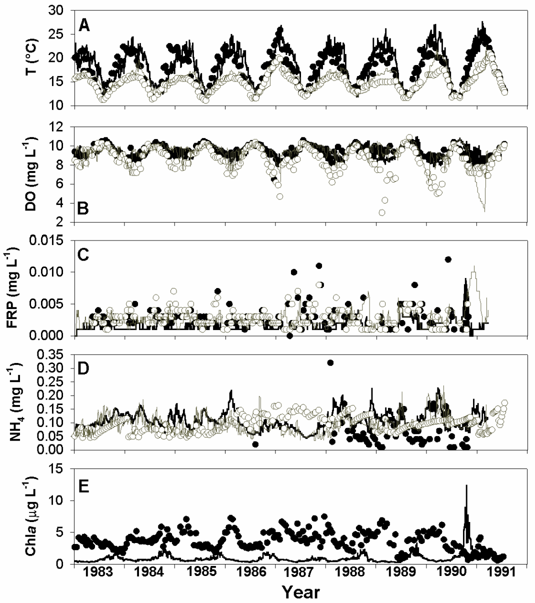

Figure 5. As figure 4 for Prospect Reservoir of A) T, B) DO, C) FRP, D) NH_4 and E) chl*a*. Depths are 3 m and 12 m (mid-depth).

The other WQ state variables were simulated satisfactorily except for chl*a*. Several phytoplankton model configurations will likely improve the modelled biomass. All algal groups were configured with constant internal nutrient stores. Our current research is examining luxury nutrient uptake and storage to model phytoplankton dynamics. DO levels were modelled well as compared with field data (Figure 5B). The levels of both PO_4 (Figure 5C) and TP (not shown) in the surface layer were underestimated by a factor of ~2, which likely contributed in part to the low phytoplankton biomass estimates (see below). NH_4 (Figure 5D), NO_3 (not shown) and TN (not shown) were overestimated by ca. 50%, however reactive silica was simulated extremely well (not shown). Phytoplankton biomass was substantially lower (ca. 0.5-2 µg chl*a* l^{-1}) than field observations (2-6 µg chl*a* l^{-1}) (Figure 5E). Our current research is examining luxury nutrient uptake and storage to model phytoplankton dynamics. Further, field investigations will refine internal loading estimates and provide validation data.

5. 3D WQ SIMULATION OF A FLOOD IN LAKE BURRAGORANG

Because of the complex bathymetry of Lake Burragorang, model idealizations (Figures 6B & 6C) of the actual reservoir morphometry (Figure 6A, Figure 1) have been used to reduce simulation run times. The idealization involves 'straightening' the basin morphology so that the Cartesian grid is aligned with the stream-wise and cross-stream axes. Application of this 'straightened' morphometry with a curvilinear approach allows modelling with modified Cartesian Navier-Stokes equations that retain first-order dynamical effects of horizontal curvature [Hodges and Imberger, 2001]. This approach was applied to Lake Burragorang morphometry with the thalweg from the Wollondilly River to the dam with two grid sizes, 800×200×2.2 m (Fig. 8B) and 500×100×2.2 m (Fig. 8C). Parameters to model the effects of basin curvature [Hodges and Imberger, 2001] were calculated during the 'straightening' process and applied in the simulations. Longitudinal WQ variations were emphasized here, so assumptions for accurate lateral prediction were relaxed by damping internal waves in the cross-stream direction.

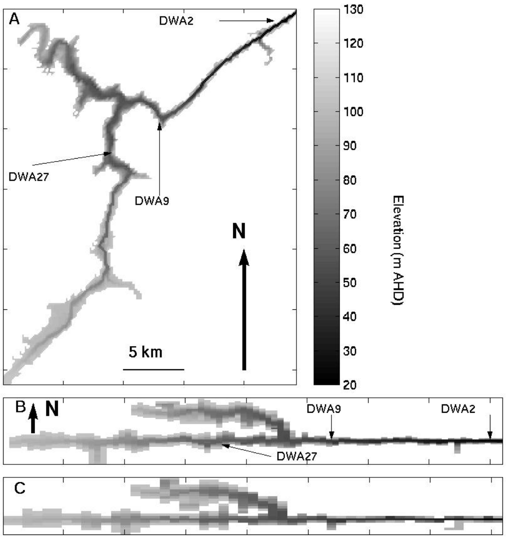

Figure 6. The bathymetry of Lake Burragorang used in 3D hydrodynamic modelling. (A) bathymetry with a 200m×200m horizontal grid, (B) a 500 m longitudinal (stream-wise) × 100 m (cross-stream) 'straightened' horizontal mesh and (C) as for (B) but with a 800m×200m horizontal mesh (from Romero and Imberger, submitted).

ELCOM simulations of the 1997 flood event were run with the straightened (800m×200m and 500m×100m) grids (Figure 6). Each horizontal resolution case was run with two vertical resolutions (1m and 2.2m). The model simulation output was compared to measured bottom T at 4 stations (DWA2, DWA9, DWA12, DWA27 in Figure 1). Using the dam wall arrival as an index of the accuracy of the simulated underflow travel time across the reservoir, all 4 cases were close to the estimates for field monitoring, which has a temporal resolution of 2 days (Figure 7). The simulated underflow T, however, was consistently too low. This discrepancy may have been caused either by the simple 1D (in the vertical) initial conditions used here or alternatively by insufficient entrainment of ambient reservoir water into the underflow in the model. The ELCOM-CAEDYM simulation of the 1997 flood event used the 800x200x1m grid.

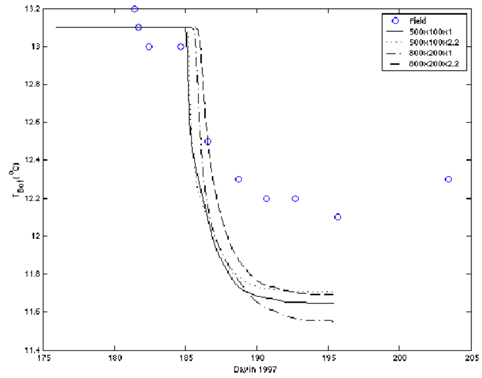

Figure 7. Measured and simulated bottom temperatures near the dam wall at DWA2 during the 1997 flood at grid resolutions of 800×200×1m, 800×200×2.2m, 500×100×1m and 500×100×2.2m.

The majority of the flow during the 1997 flood (>90%) entered Lake Burragorang via the Wollondilly River. Inflow WQ for ELCOM-CAEDYM forcing was from hourly HSPF output and was characterized by large peaks in particulates and nutrients (not shown). The underflow clearly dominated the WQ during and several weeks after the event, particularly in the region of the dam wall (not shown). High suspended solids and nutrients from the underflow remained as a 'pool' essentially 'trapped' in the profundal regions of the reservoir near the dam. The evolution of a DO minimum from the upward displacement by the underflow of the anoxic hypolimnion is an interesting dynamic captured by the model (Figure 8). Further, such winter underflow events, if cool and turbid, may cause persistent stratification through the winter months, as suggested by Ferris and Tyler [1992].

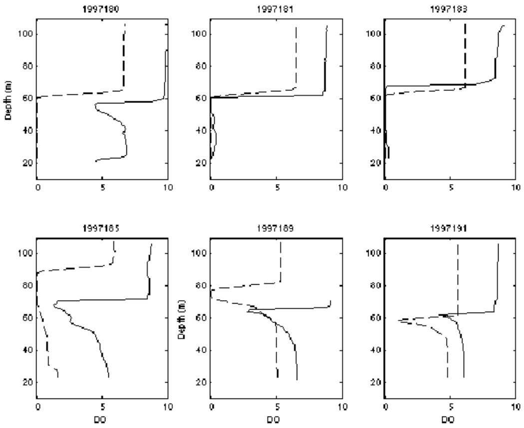

Figure 8. Measured (—) and simulated (--) dissolved oxygen profiles at station DWA2.

6. 3D WQ SIMULATIONS OF THE EFFECT OF A BUBBLER IN PROSPECT RESERVOIR

About 80% of the inflow into Prospect Reservoir (ca. 30 day residence time) is from Warragamba Pipeline with the remainder from the Upper Canal. NH_4 concentrations are quite high in the warmer Upper Canal inflow and FRP is substantially higher in the cooler Warragamba inflow during Oct. 1990 (not shown). Two simulations were run, with and without a bubble destratification system, for 2 weeks beginning 17 Oct. 1990. After the first week (not shown), mixing induced by the aerator led to reservoir. Simulations with no bubbler produced relatively poor WQ as pipeline inflows occurred as intrusions into the metalimnion. This intrusion is most clearly seen as NH_4 and FRP levels at mid-depth. When the bubble plume is simulated the inflow is indistinguishable as an intrusion and is mixed over the depth of the lake.

After a further week of a simulation 31 Oct. the water column was stratified in both simulations (Figure 9). However, the surface T was considerably warmer and the stratification stronger without the bubbler. In addition to weaker stratification, the operation of the bubbler led to dramatically different levels of insertion for both the Warragamba and Upper Canal inflows. When the aerator is off the Warragamba Pipeline inflow is cooler than the surface layer and the phosphorus rich water enters the hypolimnion. Conversely, with the bubbler, the inflow T was injected into the surface layer and the nutrient rich water was available to phytoplankton in the epilimnion. Although there is currently insufficient field data to validate these simulations, the results highlight how different operational strategies can potentially have strong influences on the WQ and dynamics of Prospect Reservoir.

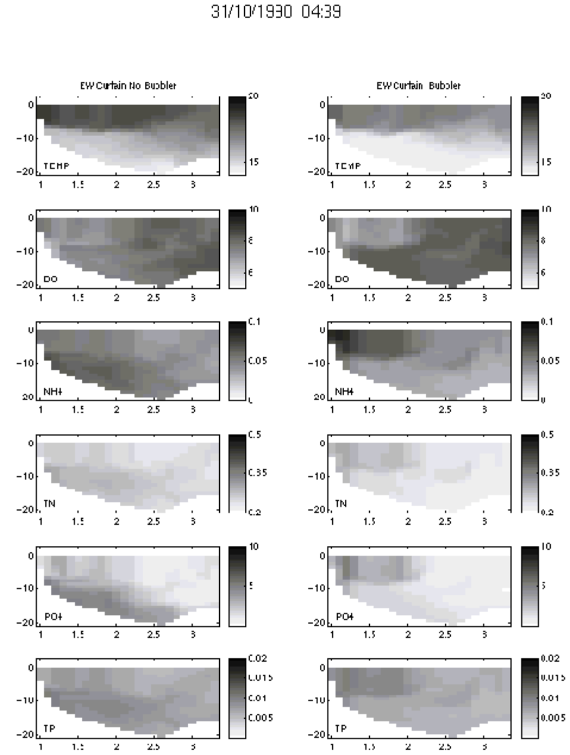

Figure 9. Simulated T, SS, DO, NH_4, TN, FRP and TP along the east-west transect in Prospect Reservoir.

7. CONCLUSIONS

Application of WQ models as management tools remains to be demonstrated effectively in reservoir settings. One approach is to develop 1D and 3D hydrodynamic models that utilize a common ecological model. In this manner, both conceptually and physically, the fate (ecological model) and transport (hydrodynamic model) components required to accurately simulate the spatial and temporal distribution of WQ can be developed and validated by suitable specialists.

This modelling approach also provides a scientific setting to test ecological hypotheses. The aim of our applied research is to develop a calibration-free suite of models to simulate fate and transport of particles, nutrients and contaminants in lakes and reservoirs. An initial step towards this goal is demonstrated by this study in which a single ecological model (CAEDYM) with no changes to model parameters was coupled to 2 hydrodynamic drivers (DYRESM and ELCOM). The application was to two substantially different systems (Prospect Reservoir and Lake Burragorang) at two temporal scales (years and weeks). This study demonstrates that differences in physical forcing and the resultant hydrodynamics are the dominant influences on these two systems over both seasonal and event (flood) time scales. This suggests accurate validation and prediction of physical processes are the basis of accurate forecasting of natural and anthropogenic effects on lacustrine dynamics. Our current modelling research is focused on seasonal simulations of spatial longitudinal gradients of DO [Romero and Imberger, 1999*a*] and nutrients [Romero et al., 2002] that occur seasonally in Lake Burragorang.

8. ACKNOWLEDGEMENTS

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