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A multi-dimensional receiving water quality model for Botany Bay (Sydney, Australia)

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Abstract: Multi-dimensional numerical models are a valuable tool for computing a vast quantity of elements across a range of scales. The ecological condition of a waterway is an example of a complex system of inter-connected variables in which a change in any condition may cause a response in many system processes. Numerical models are increasingly applied in environmental decision making processes for estuaries, such as understanding and mitigating eutrophication .

Botany Bay is a highly modified estuary of Sydney, Australia. The catchment is approximately 1,165 km^2, and it accommodates Sydney's international and domestic airport, a shipping terminal, chemical and mining products industries, residential land, beaches, national parks and a RAMSAR wetland. As the landing place of Captain James Cook, the bay is historically significant and is now utilised for day-tripping, fishing and sailing. This estuary, and its complexity, is a spectacular example of meshing a highly valued environment within anthropogenic development.

The Botany Bay Costal Catchments Initiative (BBCCI) was a project of the Australian Government and the Sydney Metropolitan Catchment Management Authority which aims to develop a water quality improvement plan for the bay and catchment. To achieve this, the BBCCI looked to numerical modelling to better understand the effects of land-derived nutrients and sediments as well as algal growth in the estuary. The project objectives were to model receiving water quality under diffuse pollutant loads arriving from the catchment (suspended solids, nitrogen and phosphorus). This paper describes the configuration of the multi-dimensional model for the assessment of receiving water quality.

The chosen multi-dimensional process model was the dynamically coupled three-dimensional hydrodynamic and biogeochemical model ELCOM-CAEDYM. It was a highly detailed model with an ocean boundary and twenty-one river, sewer and urban creeks inflows and three algal groups. Hydrodynamic, nutrient and algal data from long-term and current field monitoring programmes was used to define appropriate boundary forcing conditions, phytoplankton autological parameters, and to validate the model.

The high parameterisation requirement of complex process models revealed process questions that need to be understood for Botany Bay, as well as some technical considerations that were addressed. This paper presents these considerations in the model set-up and validation. Assumptions and limitations of the methodology are addressed and we present information about the constraints in modelling for awareness in future applications as well as for further development of the model.

Keywords: *Estuary modelling, phytoplankton, Botany Bay, ELCOM-CAEDYM*

1. INTRODUCTION

The estuary consists of a bay and two river channels (Figure 1): the Cooks (~11km) and the Georges (~40 km). The Cooks is highly modified and is surrounded by dense urban settlement. The surrounds of the Georges are mixed urban development and undisturbed bushland. The morphology of the Georges is largely intact until Chipping Norton Lakes, a relict of from sand mining, and the artificial estuary end at a weir.

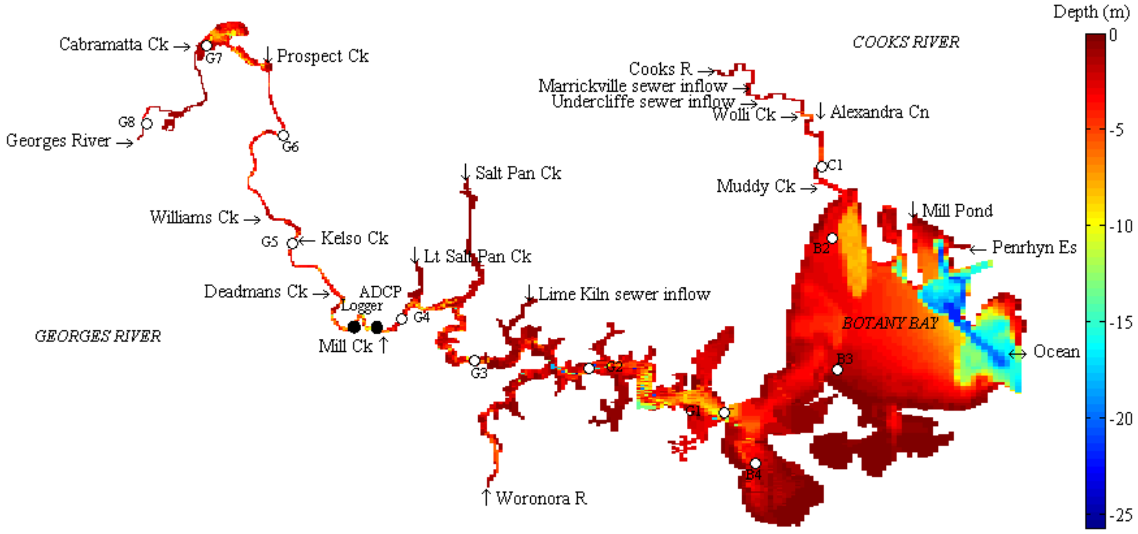


Figure 1. Botany Bay bathymetry, boundary inflows and 2007-2008 routine monitoring stations.

2. METHODS

2.1 Field data

Long-term water quality data (1986-2006) (chlorophyll-a, phytoplankton species counts, nutrient concentrations and water chemistry) for the Georges and Cooks estuaries were analysed for model parameterisation and validation (2007 Sydney Water, *pers. comm.*). Routine monitoring of 13 locations (Figure 1) was conducted in 2007-2008 to assess the current ecological condition and seasonal dynamics (data not reported here). Conductivity, temperature and water level data was recorded by a data logger at the mid-estuary (Figure 1) from April 4 2007 to September 11 2007. Currents at the mid-estuary (Figure 1) were measured by ADCP, using both a boat-moored and a benthic-deployed instrumentation during spring and neap tidal cycles (18 September 2008 and 10 October 2008).

2.2 Model description and configuration

The three-dimensional hydrodynamic model ELCOM (Estuary, Lake and Coastal Ocean Model) was dynamically coupled to CAEDYM (Computational Aquatic Ecosystem DYnamics Model). ELCOM solves unsteady Reynolds-averaged, hydrostatic, Boussinesq, Navier-Stokes and scalar transport equations (Hodges et al. 2000, Hodges and Dallimore 2006, Laval et al. 2003). CAEDYM completes ecological equations for primary production, secondary production, nutrient cycling, oxygen dynamics, as described in Hipsey et al. (2006) and validated in Robson and Hamilton (2003), Chan et al. (2002), Hipsey et al. (2006), Griffin et al. (2001) and applied at Lake Burragorang, New South Wales (Romero et al. 2004), the Swan River, Western Australia (Chan et al. 2002), Barbamarco Lagoon, Italy (Spillman et al. 2008), and Lake Kinneret, Israel (Bruce L. C. et al. 2006).

Domain and boundary conditions

A bathymetry was constructed by assembling and standardising hydrographic data from the NSW Department of Natural Resources, Sydney Water and University of New South Wales (Dr Matt Taylor, PhD Thesis, *pers. comm.*). The datum was discretised to a variable grid with uniform 50 m y-cell lengths and incrementally increasing x-cell lengths from 50 m to 200 m. Ten downward vertical layers (1m, 1m, 1m, 1m, 2m, 2m, 3m, 4m, 6m and 9m) were defined. The catchment was subdivided into 18 subcatchments, and daily flow and loads of total nitrogen, total phosphorus, total organic carbon, total suspended solids, and biological oxygen demand were simulated for the 18 inflow boundaries (BMT WBM 2007). The total nutrient concentrations were then partitioned into dissolved and particulate fractions using in-house data (DECC Great Lakes CCI, 2007 Jocelyn Dela-Cruz, *pers. comm.*) and the best available literature of stormwater quality (Fletcher et al., 2004). Phytoplankton concentrations were not allocated to inflows.

Sewage overflows are a potentially significant source of freshwater and nutrients. Modelled sewer overflows for 225 sewers (2007 Sydney Water, *pers. comm.*) were lumped according to their location within the inflow subcatchments. Sewer inflow boundaries were included where no drainage inflow point was defined (Marrickville, Undercliffe and Lime Kiln Bay, Figure 1). Nutrient loads were estimated (2007 Sydney Water *pers. comm.*) and partitioned into dissolved fractions using the best available data (Fletcher et al., 2004). Model bathymetry and inflow locations are shown in Figure 1.

Initial conditions and forcing

Simulations were initiated with an initial horizontal salinity gradient. Inflow boundaries were allocated zero salinity. The ocean boundary salinity was set to a constant 35.6. Inflow and open boundary temperatures varied monthly according to the long-term estuary data and ocean data (DOM 2009). The model was forced with daily rainfall recorded at Sydney Airport and sea level recorded from the Manly Hydraulics Laboratory Port Hacking Tidal Gauge. The model was allowed a 60-day warm-up period.

Phytoplankton

An extensive list of modelling applications was consulted to configure the model algal growth parameters (Ford et al. 2005, Chan and Hamilton 2001, Chan et al. 2002, Robson and Hamilton 2004, Spillman et al. 2007, Ajani et al. 2000, Murrell and Lores 2004, Kostoglidis et al. 2005, Lin et al. 2008, Romero et al. 2004, Spillman et al. 2008, Robson et al. 2006, Robson et al. 2008, Bruce et al. 2006). This, a detailed analysis of field data (not reported here) and calibration runs, led to the incorporation of three phytoplankton groups (Table 1):

Table 1. Salinity, temperature and respiration configuration of modelled phytoplankton groups.

Group no.	Key genera	Community representation	S_{min}	S_{max}	T_{std}	T_{opt}	T_{max}	Respiration rate
1	Chlorophyte	euryhaline year-round background	2	36	15	30	40	0.11
2	Dinoflagellates	Upper estuary mid-summer bloom	0.1	15	18	20	40	0.07
3	Marine diatoms	euryhaline spring-summer-autumn bloom	12	38	14	17	28	0.07

3. RESULTS

3.1. Model performance

Water level and velocity

The data logger indicated a 2 hour water level lag from the height of the open ocean (not shown). This is consistent with the reported tidal prediction (NSW Maritime 2007). The model reproduced this lag (Figure 2) however the amplitude of free surface height variation was underestimated, possibly due to bathymetric drag. The measured spring tide velocity range was 0-0.4 m s^{-1} (Figure 3) and 0-0.2 ms^{-1} in a neap tide (not shown). The model has reasonably reproduced this range (0-0.5 m s^{-1}, Figure 4), however the measured and modelled data were not from the same year so the data could not be compared directly.

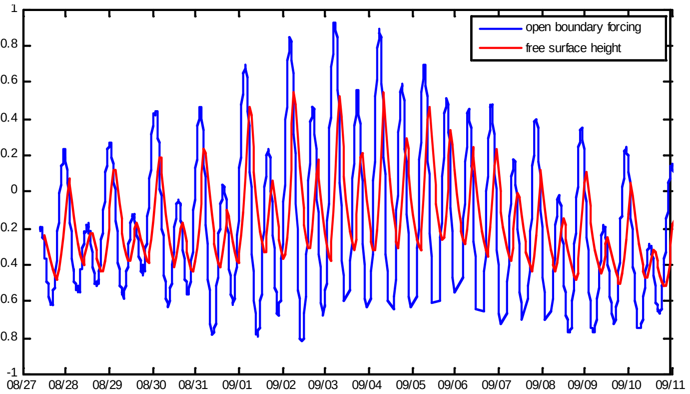


Figure 2. Modelled water levels in the mid-estuary (red) compared with boundary forcing during a spring tide (blue).

Salinity and temperature

The performance of the hydrodynamic output was assessed according to its fit within historical data, noting if the data was collected in a drier or wetter year than the long term average. The model under-predicted salinity at G8 and G7 (Figures 5) possibly due to an underestimation of catchment freshwater flows or insufficient salt-water propagation up the estuary. Salinity in the lower Georges estuary (B4) is overestimated by the model. The under-prediction of salt in the upper estuary and under-prediction of fresh in the lower estuary suggests that the dendritic bathymetry and discretisation at the course grid scale is causing insufficient salt-water penetration up the estuary or momentum loss of freshwater down the estuary.

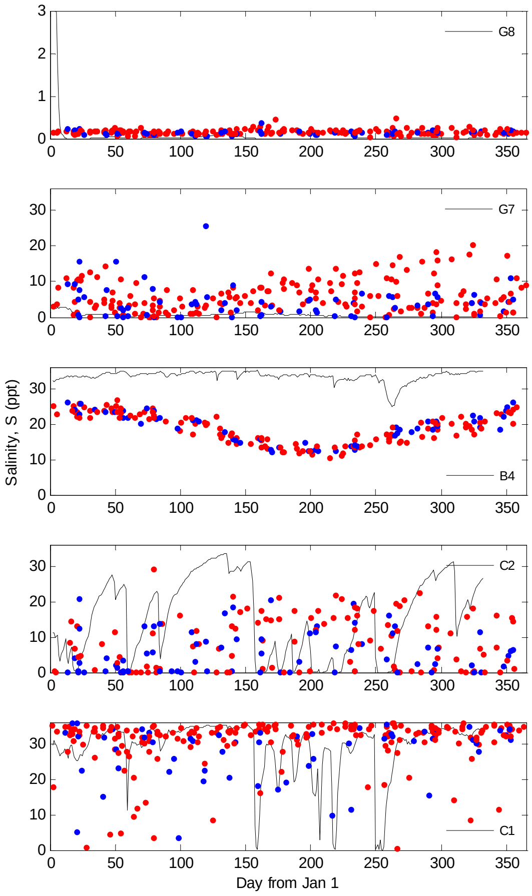


Figure 5. Modelled (-) and measured salinity (● = wet year, ● = dry year)

In previous versions of the model salinity in the upper Cooks had been overestimated. It was hypothesised that a key source of freshwater was overlooked. Upper Cooks inflow was increased by 10% and the result produced representation of historical salinity range (Figure 5). Salinity in the lower Cooks estuary was captured (Figure 5). The seasonal temperature variation was reproduced for all parts of the estuary (Figure 6). Slight over-estimation of modelled temperature in the lower Georges may be due to the absence of a cooler freshwater flow.

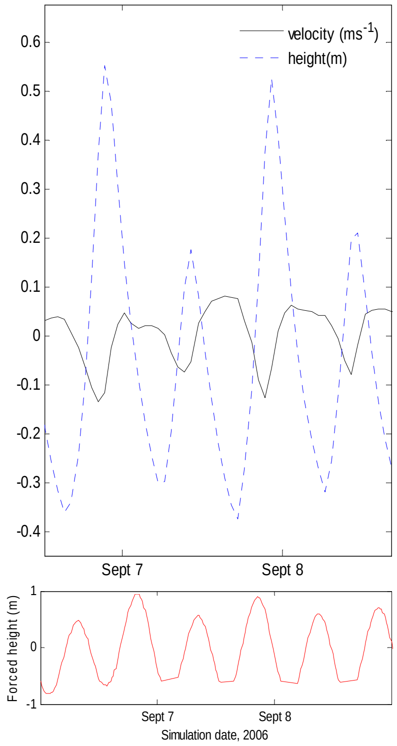


Figure 4. Modelled velocity range during a spring tide.

Nutrients and phytoplankton

The model agrees well with the historical range and intra-annual peaks of oxidised nitrogen (NO_3) (Figure 7), ammonium (NH_4) (Figure 8) and filterable reactive phosphorus (FRP, modelled as phosphate, PO_4, Figure 9) in all parts of the estuary. Lower Georges' phytoplankton (B4, Figure 10) were over-predicted and without bound (25 - 100 μg L^{-1}). Analysis of the functional operation (not shown) suggested that Group 1 may need temperature adjustment. Also, inflows currently assume an equal phytoplankton concentration to that of the neighbouring cell of the domain, and this caused a positive loop of algal growth.

Figure 6. Modelled (-) and measured temperature (● = wet year, ● = dry year)

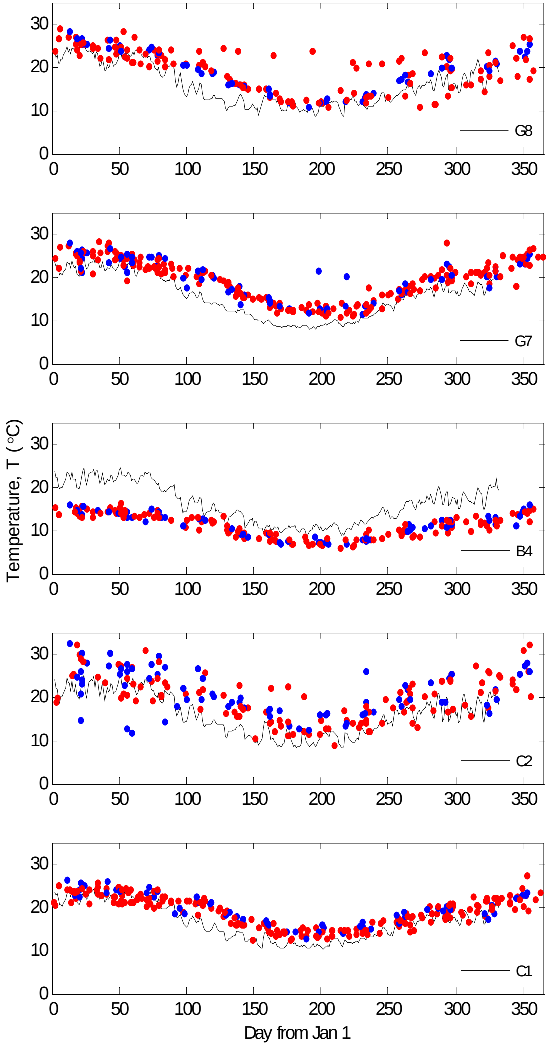


Figure 7. Modelled (-) and measured oxidised nitrogen (NO$_x$)

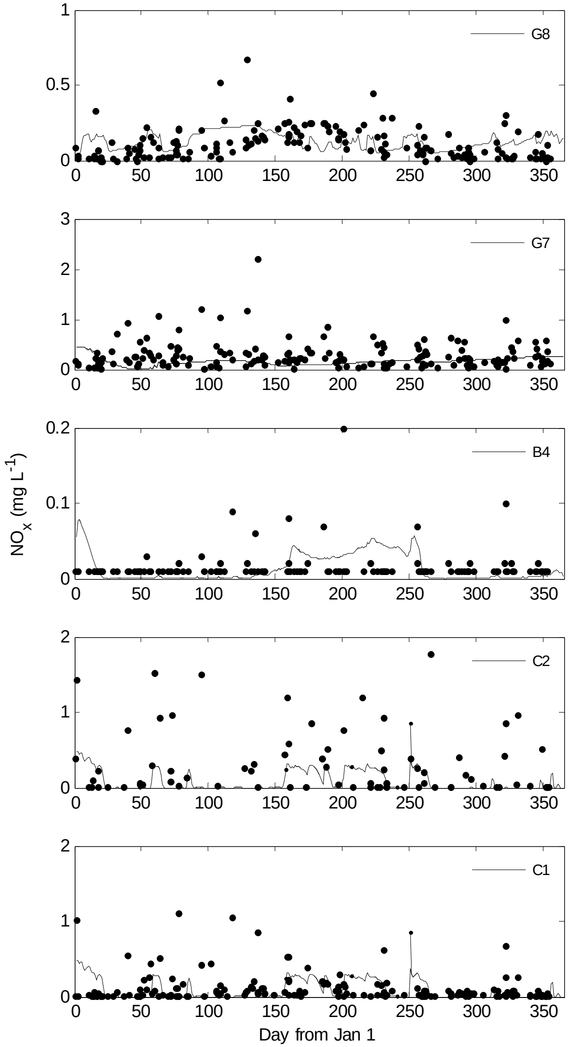
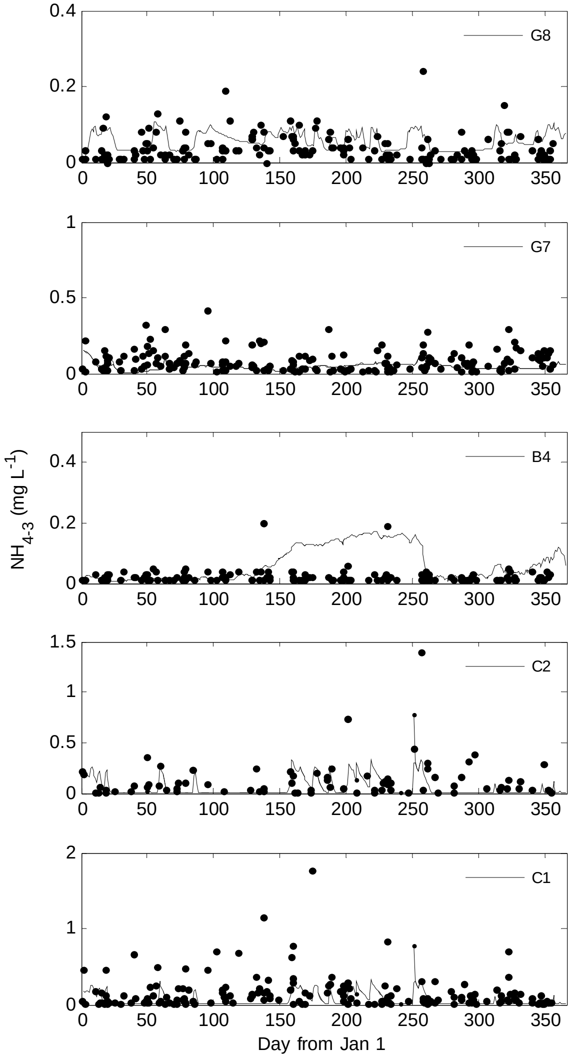


Figure 8. Modelled (-) and measured ammonium (NH$_4$)



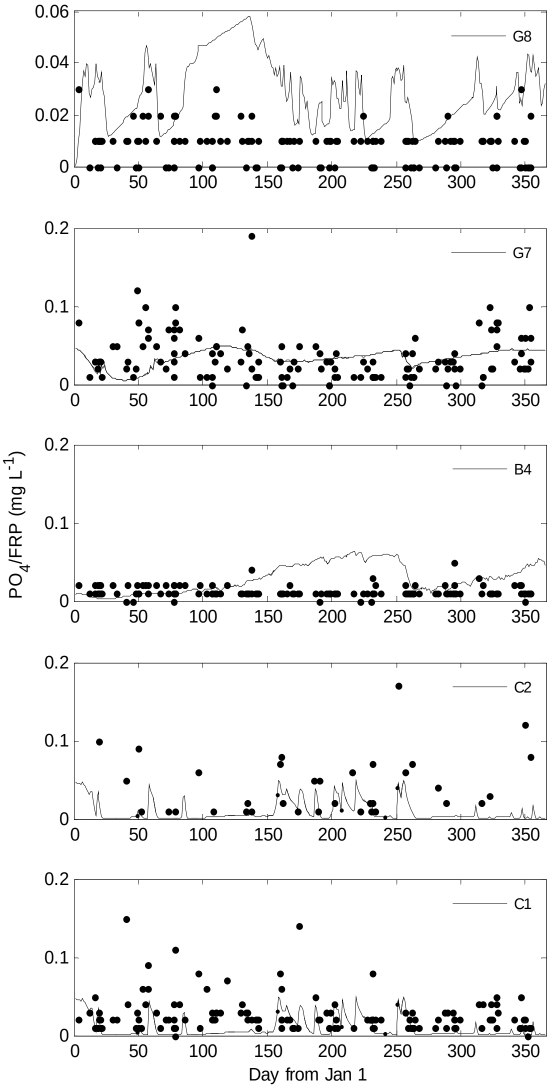


Figure 9. Modelled (-) and measured phosphorus (PO$_4$/FRP)

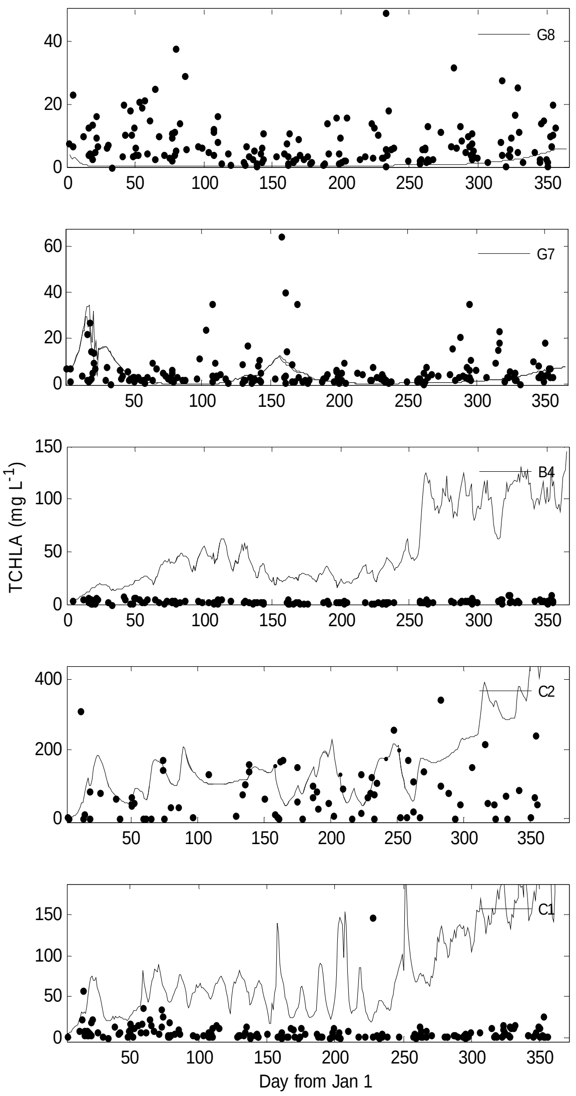


Figure 10. Modelled (-) and measured total chlorophyll-a (TCHLA)

4. CONCLUSIONS AND RECOMMENDATIONS

The model will receive the following improvements: bathymetry straightening techniques to rectify the salt balance (Wadzuk and Hodges 2001), calibration of phytoplankton at inflows to investigate the role of external phytoplankton sources, and analysis of suspended solids, benthic conditions and sediment fluxes. Additional recommendations include to test the model against higher resolution monitoring data using 2007 catchment modelling conditions, and to trial model performance during algal bloom events.

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REFERENCES

Ajani, P.A., R.S. Lee, T.R. Pritchard and M. Krogh (2000), Phytoplankton Dynamics at a Long-Term Coastal Station off Sydney, Australia. *Journal of Coastal Research.* New Zealand.

Bmt Wbm (2007), Modelling the catchments of Botany Bay, Technical Report, Brisbane, Australia. 43 pp.

Bruce L. C., Hamilton D., Imberger J., Gal G., Gophend M., Zoharyc T. and Hambrighte D. K. (2006), A numerical simulation of the role of zooplankton in C, N and P cycling in Lake Kinneret, Israel *Ecological Modelling,* 193(3-4), 412-436.

Chan, T.U. and D.P. Hamilton (2001), Effect of freshwater flow on the succession and biomass of phytoplankton in a seasonal estuary. *Marine and Freshwater Research,* 52(869-884.

Chan, T.U., D.P. Hamilton, B.J. Robson, B.R. Hodges and C. Dallimore (2002), Impacts of Hydrological Changes on Phytoplankton Succession in the Swan River, Western Australia. *Estuaries and Coasts,* 25(6B), 1406-1415.

Dom (2009), Coastal Sea Surface Temperatures. Australian Department of Defence Directorate of Oceanography & Meteorology, Sydney, Commonwealth of Australia,.

Ford, P., P. Tillman, B. Robson and I.T. Webster (2005), Organic carbon deliveries and their flow related dynamics in the Fitzroy estuary. *Marine Pollution Bulletin,* 51(1-4), 119-127.

Griffin, S.L., M. Herzfeld and D.P. Hamilton (2001), Modelling the impact of zooplankton grazing on phytoplankton biomass during a dinoflagellate bloom in the Swan River Estuary, Western Australia. *Ecological Engineering,* 16(3), 373-394.

Hipsey, M.R., J.R. Romero, J.P. Antenucci and H. D. (2006), Comutational Aquatic Ecosystem Dynamics Model: CAEDYM v2.3 Science Manual, Technical Report, Centre for Water Research, Perth. 90 pp.

Hodges, B.R. and C. Dallimore (2006), Estuary Lake and Coastal Ocean Model: ELCOM V2.2 Science Manual, Centre for Water Research, Perth. 54 pp.

Hodges, B.R., J. Imberger, A. Saggio and K.B. Winters (2000), Modeling Basin-Scale Internal Waves in a Stratified Lake. *Limnology and Oceanography,* 45(7), 1603-1620.

Kostoglidis, A., C.B. Pattiaratchi and D.P. Hamilton (2005), CDOM and its contribution to the underwater light climate of a shallow, microtidal estuary in south-western Australia. *Estuarine, Coastal and Shelf Science,* 63(4), 469-477.

Laval, B., J.R. Imberger, B.R. Hodges and R. Stocker (2003), Modeling Circulation in Lakes: Spatial and Temporal Variations. *Limnology and Oceanography,* 48(3), 983-994.

Lin, J., L. Xie, L.J. Pietrafesa, H. Xu, W. Woods, M.A. Mallin and M.J. Durako (2008), Water quality responses to simulated flow and nutrient reductions in the Cape Fear River Estuary and adjacent coastal region, North Carolina. *Ecological Modelling,* 212(3-4), 200-217.

Murrell, M.C. and E. Lores (2004), Phytoplankton and zooplankton seasonal dynamics in a subtropical estuary: importance of cyanobacteria. *Journal of Plankton Research,* 26(3), 371-382.

Nsw Maritime (2007), Tidal Predictions for Sydney Harbour JULY 2008 – JUNE 2009. South Australia, National Tidal Centre, Bureau of Meteorology.

Robson, B.J., P.A. Bukaveckas and D.P. Hamilton (2008), Modelling and mass balance assessments of nutrient retention in a seasonally-flowing estuary (Swan River Estuary, Western Australia). *Estuarine, Coastal and Shelf Science,* 76(2), 282-292.

Robson, B.J. and D.P. Hamilton (2003), Summer flow event induces a cyanobacterial bloom in a seasonal Western Australian estuary. *Marine and Freshwater Research,* 54(2), 139-151.

Robson, B.J. and D.P. Hamilton (2004), Three-dimensional modelling of a Microcystis bloom event in the Swan River estuary, Western Australia. *Ecological Modelling,* 174(1-2), 203-222.

Robson, B.J., I.T. WebsterandU. Rosebrook (2006), Biogeochemical modelling and nitrogen budgets for the Fitzroy Estuary and Keppel bay, Technical report, CSIRO, Indooroopilly. 53 pp.

Romero, J.R., J.P. Antenucci and J. Imberger (2004), One- and three-dimensional biogeochemical simulations of two differing reservoirs. *Ecological Modelling,* 174(1-2), 143-160.

Spillman, C.M., D.P. Hamilton, M.R. Hipsey and J. Imberger (2008), A spatially resolved model of seasonal variations in phytoplankton and clam (Tapes philippinarum) biomass in Barbamarco Lagoon, Italy. *Estuarine, Coastal and Shelf Science,* 79(2), 187-203.

Spillman, C.M., J. Imberger, D.P. Hamilton, M.R. Hipsey and J.R. Romero (2007), Modelling the effects of Po River discharge, internal nutrient cycling and hydrodynamics on biogeochemistry of the Northern Adriatic Sea. *Journal of Marine Systems,* 68(1-2), 167-200.

Wadzuk, B. and B.R. Hodges (2001), Model Bathymetry for Sinuous, Dendritic Reservoirs. *6th International Workshop on Physical Processes in Natural Waters.* Girona, Catalonia, Spain.