A Computational Aquatic Ecosystem Dynamics Model of the Swan River, Western Australia

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Abstract Deterioration of water quality in the Swan River, Western Australia, has prompted the need to develop and assess strategies to ensure that the estuary is managed sustainably and that its ecological diversity is not threatened. To achieve these objectives, the development of a numerical model with prognostic capabilities was considered essential. Application of the model is closely integrated with the work of management authorities to provide a valuable tool to test different remediation strategies for the Swan River. The nature of these strategies requires that the model must contain a high level of process representation, species differentiation of several state variables and be applicable to a spectrum of spatial and temporal scales. These requirements sometimes conflict with the practical constraints of acceptable memory use and competitive real time run ratios from a model run perspective. The Centre for Water Research has developed a Computational Aquatic Ecosystem Dynamic Model (CAEDYM) using state-of-the-art computing techniques, which accommodates all the above requirements, and where management scenarios of ten years duration are a reality. An example of the advanced algorithm representation used in CAEDYM is presented to illustrate the ability of the model to capture the variability of the dynamic processes that occur at the sediment-water interface of the Swan River.

1. INTRODUCTION

Prediction of the dynamics of aquatic ecosystems has evolved in recent years into a multidisciplinary science incorporating elements of physics, chemistry and biology (Hamilton and Schladow, 1997). There has been a proliferation of numerical simulation methods in which hydrodynamic process models have been combined with empirical or process based biogeochemical models to develop coupled aquatic ecosystem models (Straskraba, 1994). One of the most important applications of these models is the assessment of potential eutrophication of estuaries or coastal seas, requiring a multi-disciplinary research effort involving hydrodynamicists, ecologists, chemists and modellers. This approach is now recognised as the best one to achieve system understanding, accurate prediction and to direct management strategies towards common consequences of eutrophication; algal blooms, deoxygenation and reduced ecosystem diversity. Examples of this approach are given by overseas cases such as San Francisco Bay (Hollibaugh 1996), the North Sea (Baretta et al., 1994) and Chesapeake Bay (Cerco, 1989). Relevant studies in Australia include Perth Coastal Waters (Lord et al., 1994), Port Philip Bay (Harris et al., 1996) and the recently commissioned study on Moreton Bay (Abal et al., 1996).

The Swan River, Western Australia, has suffered from a deterioration in water quality, specifically the occurrence of anoxia and an increase in the frequency and intensity of algal blooms in the upper estuary. The implementation of a program of study on the Swan River similar to previous integrated research efforts and driven by input requirements for development and application of an ecological model represents the best approach towards developing and assessing estuary management strategies, diagnosing potential water quality degradation issues and refining and developing monitoring strategies for sensitive ecosystem components. The development of a numerical biogeochemical model, CAEDYM, with prognostic capabilities was thus considered essential. This model serves as the hub of a multi-disciplinary research program on the Swan River which ties together 12 research projects examining different aspects of the ecology, physics and chemistry of the river. The results of these projects will improve the understanding of system dynamics and unify the previously disparate ecological research program.

Application of the model is closely integrated with the work of management authorities in order to provide a valuable tool to test different remediation strategies for the Swan River. In this paper we describe the capabilities and process representation of the model, and briefly outline the major development obstacles and the way that these were solved. We also give an example of the model application to demonstrate the necessity of high levels of process representation.

The application of CAEDYM in the simulation example illustrates the variability of rates of sediment oxygen demand (SOD) in the Swan River Estuary. From an estuary management perspective, SOD is highly important because of its contribution to water column anoxia and the associated potential for fish kills and redox-driven release of nutrients from the bottom sediments. Measured values of SOD flux based on benthic chamber enclosures are highly variable, from < 500 mg m^{-2} day^{-1} to > 4,000 mg m^{-2} day^{-1} (Douglas et al., 1997). Part of this variability has been attributed to changes in water temperature (Douglas et al., 1997), but the recent depositional history of organic material, particularly deposition associated with decay of phytoplankton blooms, may also contribute to the variability (Douglas, pers. com.). Clearly, only a process model of oxygen dynamics at the sediment-water interface which includes the resultant change in organic material in the sediments can encompass the variability of SOD observed in the Swan River Estuary.

In the present paper the processes included in the water and sediment oxygen dynamics include atmospheric exchange (Wanninkhof, 1992), oxygen production and consumption through phytoplankton photosynthesis and respiration respectively, water column nitrification, biochemical oxygen demand due to mineralisation of organic matter in the water column and in the sediments, and oxygen flux from the water column to the sediments (SOD). The last two processes are used together with a sediment porosity and diffusion coefficient (Ullman and Aller, 1982) in order to define the depth of the oxic layer in the sediments.

2. CAEDYM FEATURES

The representation of biogeochemical processes in ecological models has, historically, generally been treated very simplistically, to the extent that the pioneering work on modelling marine ecosystems (Riley et al, 1949; Steele, 1962) is still used as a template for many of the models that are currently used (Hamilton and Schladow, 1997). The approach adopted CAEDYM has been to have a self-contained ecological module which can be linked to the transport and hydrodynamic 'driver' modules. The level of sophistication and process representation included in CAEDYM is of a level hitherto unseen in any previous aquatic ecosystem modelling and will enable many different components of the system to be examined, as well as better representing the dynamic response of the ecology to major perturbations to the system (e.g. the response to various management strategies).

The application of CAEDYM as a tool to aid in management decisions and system understanding requires that the model must contain a high level of process representation, have enhanced process interactions and species differentiation of several state variables, and be applicable to a spectrum of spatial and temporal scales. The spectrum of scales relates to the need for managers to assess the effect of temporary events, such as anoxia at specific locations, through to understanding long-term changes that may occur over seasons or years over the selected domain.

The current modelling strategy adopted for use in the Swan River is to have a suite of hydrodynamic 'drivers' available to link with CAEDYM so as to examine processes or management strategies over time scales of hours (generally from a scientific knowledge point of view) through to years (generally for management purposes). The alternative to employing a suite of hydrodynamic models is to adapt the computation time according to the period to be simulated is to decouple the hydrodynamics from the biogeochemistry (e.g., COASEC; Lord et al., 1994; ERSEM; Baretta et al, 1994). Irrespective of the nature of either the hydrodynamic or ecological model, this decoupling means that the water quality state variables are simply transported by the velocity field, and there is no feedback from the biological processes to the physical processes, such as, for example, the effect of an algal bloom in decreasing water transparency. In addition to coupling with hydrodynamic models, CAEDYM can also be linked to surface and subsurface hydrological models for the catchment.

The ecological module used in CAEDYM consists of seven phytoplankton groups, five zooplankton groups, six fish groups, four macroalgae groups and three invertebrate groups, as well as state variables of seagrass and jellyfish (Table 1). The model also includes dissolved oxygen, biochemical oxygen demand, nutrients and suspended solids as state variables. A large number of these state variables must undergo advection throughout the domain via the application of a transport scheme (Figure 1). There is considerable flexibility in the time step used for the ecological component and longer time steps (e.g. 3-4 hours) may be desirable, in order to reduce the frequency of links to the transport module when long-term (i.e., seasonal or annual) simulations are run. There is also some flexibility as to which components of the system (i.e. state variables) the user chooses to simulate, hence CAEDYM has the ability to reduce to a simple 'P-Z-N' model if necessary.

	Species						
Group	Phytoplankton	Zooplankton	Fish	Macroalgae	Invertebrates	Seagrass	Jellyfish
1	Dinoflagellates	44 - 100 mm	Hardyheads	*Gracilliara*	Bivalves	*Halophila ovalis*	*Phyllorhiza punctata*
2	Fresh-water Cyanobacteria	100 - 300 mm	Perth Herring	*Cystosira*	Polychaetes		
3	Marine Cyanobacteria	> 300 mm (Gladioferens)	Yellow Tail Trumpeter	*Chaetomorpha*	Crustacean Grazers		
4	Cholorophytes	> 300 mm (Sulcanus)	Black Bream	*Ulva*			
5	Cryptophytes	>300 mm (Acartiura)	Sea Mullet				
6	Marine Diatoms						
7	Fresh-water Diatoms						

Table 1. Species Representation in CAEDYM

Vertical migration is simulated for motile and non-motile phytoplankton, and fish are migrated throughout the model domain according to a migration function based on fish mortality. A weighted grazing function is included for zooplankton grazing on phytoplankton and fish grazing on zooplankton, where the biomass grazed is related to both food availability and preference of the consumer to its food supply. Improved temperature, respiration and light limitation functions have been developed. The benthic processes include a self-shading component and beach wrack function for macroalgae, sediment bioturbation and nutrient cycling by polychaetes and effects of seagrass on sediment oxygen status. The model also incorporates oxygen dynamics and nutrient cycling in both the sediments and water column. A sediment pool of organic detritus and inorganic sediments, both of which may be resuspended into the water column, is included. Redox-mediated release of dissolved nutrients is simulated from the sediments to the water column.

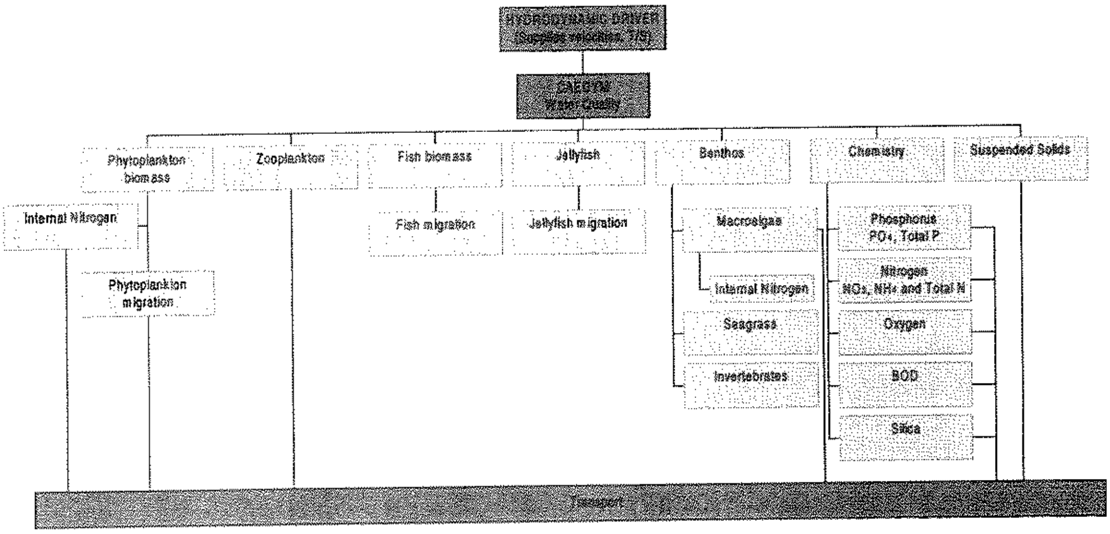

Figure 1. Process Representation in CAEDYM

3. CAEDYM STRUCTURE

The challenge in developing CAEDYM lies in including the full process and species representation outlined above whilst retaining low computer memory usage and fast execution speed such that real time run ratios are not compromised. The model domain representing the Swan River Estuary consists of the area from Fremantle to the Ellen Brook confluence including the Canning River above Kent Street Weir (Fig. 2). It can be seen that the majority of the domain is land. Representing the model domain on a Cartesian grid using a resolution of 100 m by 100 m in each horizontal direction by 1m vertically results in a grid size of 225 x 180 points, with only 15,000 of these being 'wet' points. Approximately 6.5Mb of memory is required for each state variable using this grid. Using a sparse grid where only 'wet' points are included in the grid, memory requirements can be reduced by 98%.

The transport of all the state variables (using a semi-Lagrangian advection scheme in CAEDYM) consumes a great deal of computer processing time, and is the principal limitation in achieving realistic run time ratios. Historically this problem has been circumvented by decoupling the hydrodynamic and ecological codes (as mentioned above), by use of relatively coarse spatial resolution and large time steps, or by using the model only for simulations of restricted length which have little application in ecological aquatic management. The present research on the Swan seeks to resolve these problems in order to reduce run time ratios that exist between the period to be simulated with the model and the length of computational time required for the simulation. The research will also examine the degree to which the spatial and temporal resolution used in the model can be reduced to facilitate faster run times without significantly influencing the simulation result. At this stage it is envisaged that simulation times of over 10 years will be realised.

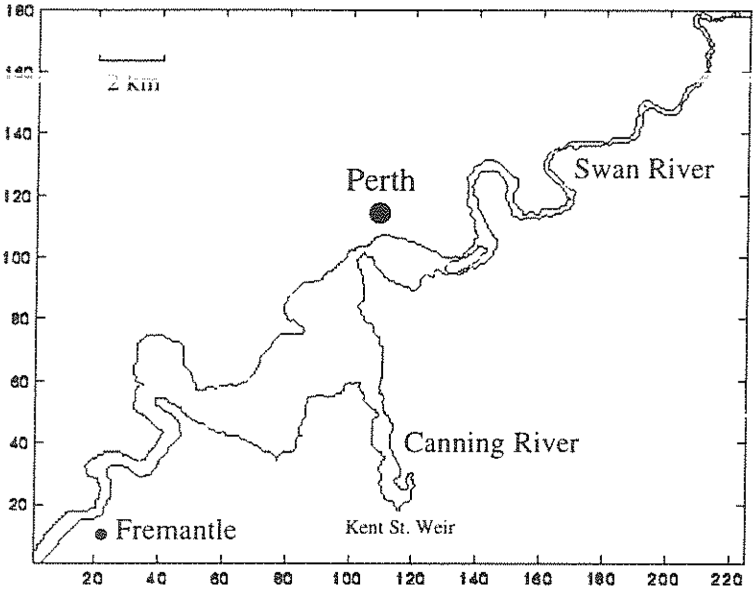

Figure 2. Swan River Model Domain

The main mechanisms currently in use for solving the problems associated extreme computational processing include:

- Advanced computing techniques: sparse co-ordinates, array processing and prolific exploitation of vector subscripts and maps have been used extensively in the present code. These techniques have resulted in a simulation time that for some algorithms is 0.5% of the time taken when these techniques are not invoked (e.g. with a standard Cartesian coordinate system).
- Greater computational power. The Centre for Water Research has increased the computing power of its fastest computer work stations by approximately 10-fold in the past two years. Coupled with decreased prices, this computing power can be readily utilised for a price and in a manner similar to the usage of desktop personal computers of 3-4 years ago.

The consequences of this approach mean that there can now be greater computational time devoted to the ecological component of the model and a greater number of state variables to advect in the transport module of the model.

4. SIMULATION EXAMPLE METHODS

Two simulations, each of length 26 days, were carried out under different conditions of water column phytoplankton biomass and temperature, as follows:

S1: Low temperature (18°C) and low water column phytoplankton biomass (< 10 mg chl*a* m^{-3}) over the entire simulation.

S2: High temperature (28°C) and high water column phytoplankton biomass. For this case the phytoplankton concentration was increased over the first 8 days by setting high water column nutrient concentrations ($[NO_3] + [NH_4] > 550$ mg L^{-1} and $[PO_4] > 150$ mg L^{-1}), which produced little nutrient limitation when combined with half saturation constants of 10 mg L^{-1} for phytoplankton uptake of phosphorus and 250 mg L^{-1} for nitrogen uptake. The biomass was then decreased artificially over the remainder of the simulation by setting $[NO_3] + [NH_4]$ to < 2 μg L^{-1} in order to impose severe nitrogen limitation of phytoplankton production.

To simulate conditions of the opaque benthic chamber enclosure of the sediments, the oxygen concentration was set to 7 mg L^{-1} in a single model cell at the bottom of the water column at day 12 of the simulation. This oxygen level equates closely to the concentration inside the chamber immediately following enclosure of the sediments. The timing of the chamber enclosure corresponds to the period in S2 of maximum SOD resulting from the decay of the phytoplankton bloom and deposition of organic material to the sediments. Vertical mixing of the water column was simulated by setting an arbitrary value of the vertical eddy diffusion coefficient of 1×10^{-5} m^2 s^{-1} between the cells in the model. To simulate benthic chamber enclosure at day 12, a single model cell at the bottom of the water column was selected in which the diffusion coefficient was set to zero, settling to this layer was prevented and light in it was set to zero.

5. RESULTS

In S1 the maximum water column concentration of chlorophyll *a* (chla_{max}) was maintained in the range 2-4 mg m^{-3} throughout the simulation. In S2 chla_{max} increased to ~ 60 mg m^{-3} by day 12 and then declined to ~ 1 mg m^{-3} by day 26. These two simulations thus produced very different values of areal chlorophyll *a*, expressed as mg chl *a* per m^2 of water column and resulted in substantially greater deposition of organic matter to the sediments prior to the benthic chamber deployment in the S2 case. Figure 4 illustrates the concentration of dissolved oxygen in the bottom water column layer which, after day 12, was representative of the concentration in the benthic chamber. The rapid rise in DO at day 12 shows when the benthic chamber was inserted over the sediments. The exponential decay of DO following day 12 proceeds at different rates in S1 and S2 due to the difference in accumulated organics in the sediments; some DO still persists at the end of the simulation in S1 but is removed entirely by day 17 in S2. The resultant flux of DO from the water column to the sediments never exceeds 1000 mg m^{-2} day^{-1} in S1, but is greater than 2000 mg m^{-2} day^{-1} for the S2 case (Fig. 5). The rapid decrease in the flux in the S2 case relates closely to the depletion of DO, and the flux therefore becomes zero at day 17. The depth of the sediment oxic layer was also quite different between S1 and S2. In S1 the depth declined from 22 cm immediately following dome enclosure of the sediments to 10 cm by day 25 but in S2 it declined rapidly from 10 cm at dome enclosure to 0 cm by day 17.

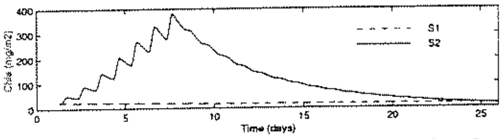

Figure 3. Areal phytoplankton concentration for the two cases

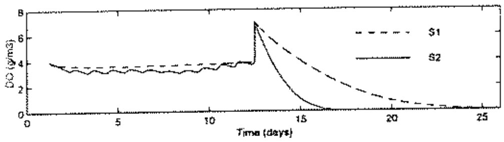

Figure 4. Dissolved oxygen concentration in the bottom layer for the two cases

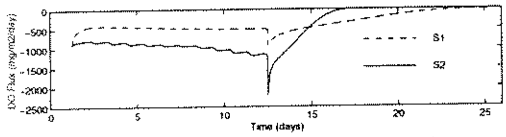

Figure 5. Sediment oxygen demand for the two cases

6. DISCUSSION

In order for a numerical model to fully capture processes related to water quality issues in the Swan River, advanced process representation and species differentiation, and their associated interactions must be included. The generation of numerical solutions based on a large number of algorithms which contain complex interactions is computationally demanding, and using conventional programming methods results in unacceptable memory use and real time run ratios for simulations of interest to managers. A numerical model, CAEDYM, has been developed which uses advanced programming techniques in conjunction major advances in computing power of desktop workstations, to deliver simulations with competitive run time ratios whilst retaining full process representation. This model is designed not only to aid the implementation of management strategies through long term simulations, but also to understand system dynamics of processes occurring on short time scales.

As one example of the ability of CAEDYM to resolve complex interactions, and to illustrate the importance of including these interactions in a numerical model, a simple benthic chamber experiment was simulated. Resulting sediment water column fluxes attained values in agreement with those presented in the literature and were dependent on mineralization rates within the sediment; indicating that sediment interactions constitute an important component of the overall oxygen budget. There are many instances of ecological models that rely purely on DO of water overlying the sediments to define the SOD and to thus determine the rate at which DO is removed from the water column (e.g Riley and Stefan, 1987; Hamilton and Schladow, 1997). The time history of changes in sediment composition is also extremely important and should be accounted for in aquatic systems where there are substantial changes in sediment organics due to factors such as phytoplankton bloom decay and deposition of organics. This approach is integral to the present modelling project being carried out on the Swan River Estuary, where the system is very dynamic, with frequent, short-lived and intense phytoplankton blooms (Thomspon and Hosja, 1996) and subsequent anoxia that may persist over time scales of hours to days (Douglas et al., 1997).

REFERENCES

Abal, E., B. Carmichael, D. Connell, B. Dennison, J. McEwan and S. Pearce, Brisbane River and Moreton Bay Wastewater Management Study, Brisbane Water, Brisbane City Council, 226pp, Brisbane, 1996.

Baretta, J.W., Ruardij, P., Vested, H.J. and Baretta-Bekker, J.G., Eutrophication modelling of the North Sea: two different approaches, *Ecological Modelling, 75/76*, 471-483, 1994.

Cerco, C.F., Chespeake Bay Three Dimensional Model Study. Coastal Zone '89, *Proc. 6th Symposium, Charleston, ASCE, 4*, 3601-3606, 1989.

Douglas, G. B., D. P. Hamilton, R. G. Gerritse, J. A. Adeney, and D. N. Coad, Sediment geochemistry, nutrient fluxes and water quality in the Swan Estuary, W.A., in *Managing Algal Blooms: Outcomes from the CSIRO's Multi-Diviisonal Blue-Green Algal Program*, edited by J. R. Davis, pp. 25-30, CSIRO Land and Water, Canberra, ACT, 1997.

Hamilton, D. P. and S. G. Schladow, Prediction of water quality in lakes and reservoirs: Part I: Model description. *Ecological Modelling, 96*, 91-110, 1997.

Harris, G., G. Batley, D. Fox, D. Hall, P. Jernakoff, R. Molloy, A. Murray, B. Newell, J. Parslow, G. Skyring and S. Walker, *Port Phillip Bay Environmental Study Final Report.* CSIRO, Canberra, Australia, 239pp, 1996.

Hollibaugh, J.T., (editor), *San Francisco Bay: The Ecosystem.* American Association for the Advancement of Science, San Francisco, California, USA, 542pp, 1996.

Lord, D.A., Imberger, J. and Pattiaratchi, C., Management of coastal waters in Western Australia: The use of integrated models, International conference on hydro-technical engineering for port and harbour construction: Yokosuka, Japan, 1994.

Riley, G.A., H. Stommel and D.F. Bumpus, Quantitative ecology of the plankton of the Western North Atlantic. *Bull. Bingham Oceanogr. Coll., 12(3)*, 1-69, 1949.

Riley, M. J and H. G. Stefan, MINLAKE: A dynamic lake water quality simulation model. *Ecoogical Modelling, 43*, 155-182, 1988.

Steele, J.H., Environmental control of phytosynthesis in the sea. *Limnol. Oceanogr., 7*, 137-150, 1962.

Straskraba, M., Ecotechnological models for reservoir water quality management. *Ecological Modelling 74*, 1-38, 1994.

Thompson, P. A. and W. Hosja, Temporal dynamics of nutrient limitation of phytoplankton from the Swan River estuary, Western Australia. *J. Mar. Freshwat. Res., 47*, 659-667, 1996

Ullman, W. J. and R. C. Aller, 1982. Diffusion coefficients in nearshore marine sediments. *Limnol. Oceanogr., 27*, 552-556.

Wanninkhof, R., 1992. Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res., 97(C5)*, 7373-7382.