Modelling Treated Waste Disposal in Port Phillip Bay and Bass Strait: Biogeochemical and Physical Removal

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Abstract Large cities, such as Melbourne, generate substantial quantities of sewage, which, after treatment, must be disposed of. Melbourne's sewage is disposed of via two routes, that treated at the Western Treatment Plant is disposed of in enclosed Port Phillip Bay, while the Boags Rock outfall empties into the exposed Bass Strait. In Port Phillip Bay biogeochemical processes control the fate of waste, while in the Bass Strait physical mixing rapidly disperses the waste. These different processes require very different ecosystem models. Port Phillip Bay requires detailed modelling of water-column and in-sediment processes, in particular detailed models of recycling processes, and also modelling of benthos – water-column interactions. Interaction of these components gives the model a non-linear response to change in load. The Bass Strait ecosystem model is simple with no modelling of the sediment and limited modelling of water-column recycling. This model's behaviour is largely controlled by the physical environment.

1. INTRODUCTION

Safe disposal of sewage represents a fundamental problems for increasingly dense urban populations. Environmental impacts must be minimised, while cost is controlled. Modelling is a very useful tool for assessing and predicting these environmental impacts. The appropriate model and the level of its complexity depends upon the environment in question. In this paper we shall examine models of two very different environments into which treated waste is disposed.

The city of Melbourne is one of Australia's two largest cities, and as such generates considerable quantities of sewage. This waste is disposed of via two routes, part is sent via the Western Treatment Plant to Port Phillip Bay, while the remainder is disposed of into Bass Strait at Boags Rock (Fig. 1). Port Phillip Bay is a large (1950 km^2) semi-enclosed bay, while Bass Strait is relatively open to the Southern Ocean. Nutrients input to Port Phillip Bay can potentially accumulate, and biogeochemical processes have been found by Harris et al. [1996] to be responsible for maintenance of water-quality. Nutrients input to Bass Strait are rapidly mixed into oligotrophic oceanic waters.

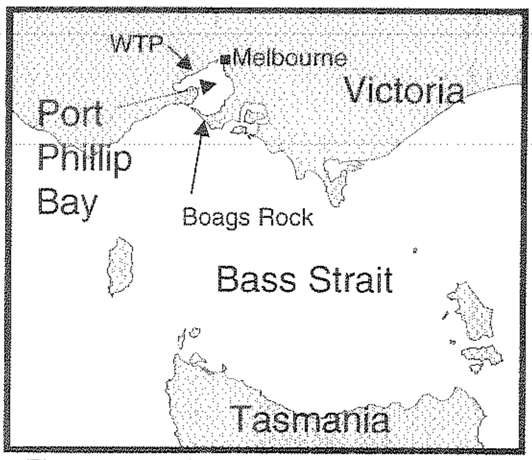

Figure 1. Location of the outfalls from which Melbourne's treated waste is disposed

Studies of environmental impacts have been funded by Melbourne water for both the Port Phillip Bay (Harris et al. [1996]) and Boags Rock (Andrewartha et al. [1998]) outfalls. Both these studies involved development of ecosystem models, which will be discussed and compared in the following sections.

2. PORT PHILLIP BAY

Port Phillip Bay is connected to the ocean via a narrow entrance and deep narrow channels through a shallow tidal delta area (regions 1 and 2 in Fig. 4). As a result, exchange of water, and dissolved or suspended material, with the ocean is very slow (1 year) and this ecosystem is effectively isolated.

Nutrient inputs to the bay are provided by the atmosphere and from the Yarra and Patterson Rivers and Mordialloc Creek, but a large proportion of the inputs of both nitrogen and phosphate come from the Western Treatment Plant (WTP) located at Werribee on the north-western coast of the bay. These WTP inputs are well regulated and so they vary mostly on a seasonal basis, with relatively little of the inter-annual and short-term variation observed in discharges from rivers. The inputs from the WTP are released at the coast directly into the bay.

Very high nutrient concentrations would build up in response to inputs from the WTP (and other sources) if export to the ocean were their fate, this is indeed the case for phosphate (mean = 58.4 mg m^{-3}). However, nitrogen concentrations are low, and the bay's water-quality is generally good. The reason for this low nitrogen concentration is that the bay's sediments exhibit efficient denitrification (Harris et al. [1996]).

In spite of this denitrification, recycling plays a dominant role in supporting primary production (Murray and Parslow [1999], Fig. 2). Using observations to constrain fluxes we are able to derive a consistent estimated annual N budget for the bay. N release from the sediments (SRc = 6200) is comparable to external inputs from the Western Treatment Plant, rivers and the atmosphere (7600 tonnes N y^{-1}, only 4900 as DIN). Even more recycling of N occurs in the water-column (WRc) and from benthic filter-feeders (FRc) supporting a primary production of about 29400 tonnes N y^{-1} by phytoplankton (PPP) and 5200 tonnes N y^{-1} by macroalgae (MAP). In the sediments, there is a further 12700 tonnes N y^{-1} microphytobenthos primary production (MPBPP). In order to understand the bay's ecosystem, therefore, recycling processes must be understood in detail.

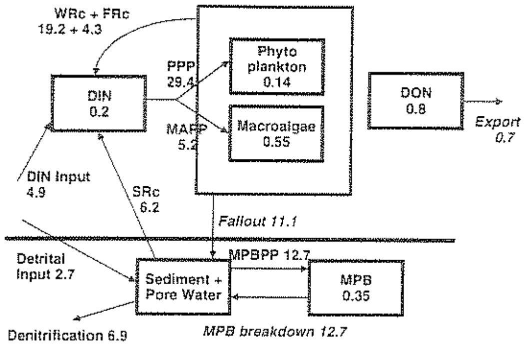

Figure 2. The nitrogen budget of Port Phillip Bay, kT N or kT N y^{-1}

As a part of an integrated study (Harris et al. [1996]), we have implemented a model of the ecosystem in Port Phillip Bay (Murray and Parslow [1997], [1999]). This model was discussed at MODSIM 97.

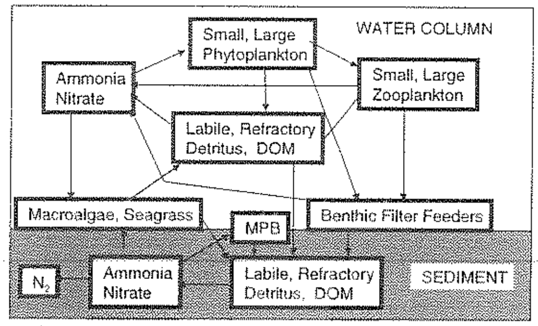

Figure 3. The nitrogen cycle in the Port Phillip Bay ecosystem model.

As the budget shows (Fig. 2) this model had to incorporate detailed models of in-sediment processes and of water-column recycling (via several types of grazers and detritus) in order to generate the estimated primary production of 29400 tonnes N y^{-1}. Competition by macroalgae for the nutrients released is substantial, and so this had to be incorporated too. This competition is disproportionately affected by WTP inputs since much of the macroalgal biomass is concentrated in the vicinity of the WTP's outfall (Murray and Parslow [1997]). Because of spatial and temporal differences in dynamics and response to N loads, the phytoplankton was split into small and large categories. Seagrass, as a valued habitat and indicator of eutrophication, was also included in the model although it had little direct effect on water-quality. There are 13 nitrogen variables in the resultant model (Fig. 3), excluding implicit N_2.

The model also included Silica cycling, because supply of Si proved locally limiting on large phytoplankton off the WTP. Phosphate was included as a nearly passive tracer of water motion.

Separate sets of model equations that describe different processes, but operating on largely the same variables, are implemented for the sediment and water-column; zooplankton variables are not implemented in the sediment. Certain special variables (macroalgae, seagrass and benthic filter feeders) exist only at the boundary between the sediment and water-column and interact with both.

The ecosystem model is given a spatial resolution by being implemented in a 59 box structure (Fig. 4) controlled by a transport model (Walker [1999]). This model defined the bay's geographical structure and handled the movement of substances, both horizontally and vertically, and inputs of nutrients and water from the atmosphere, WTP and major rivers. The transport model also handled exchanges with Bass Strait, which are critical for the conservative Si and P budgets, and account for significant DON export (Fig. 2).

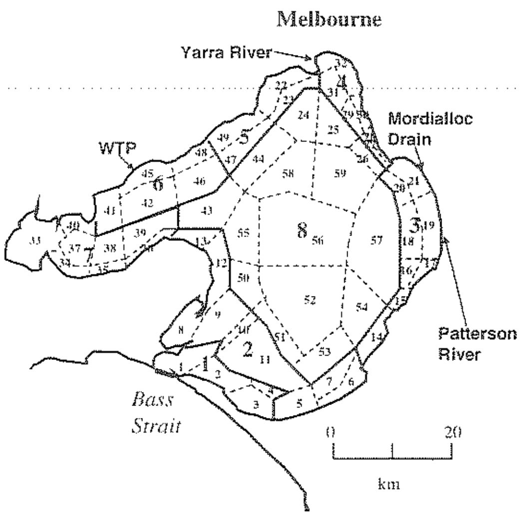

Figure 4. Spatial Structure of the Port Phillip Bay model, showing nutrient sources.

The transport model was itself derived from a hydrodynamic model, which generated currents to kilometre scale resolution (Walker [1999]).

Spatial resolution enabled depth restricted components, such as macroalgae and seagrasses to be incorporated into the ecosystem model and allowed local features to be modelled. Different local ecosystems were used to group these 59 boxes into 8 internally similar regions (Fig. 4) for the analysis of model results. The regional characteristic communities are controlled by depth and proximity to nutrient input sites (Murray and Parslow [1999]). Away from the immediate vicinity of nutrient inputs, ecosystem processes are largely in balance most of the time. The local values of variables, while showing some variation, lack large bloom events most of the time. Significantly, this is true in the central region with 50% of the area and 70% of the bay's volume (Fig. 5).

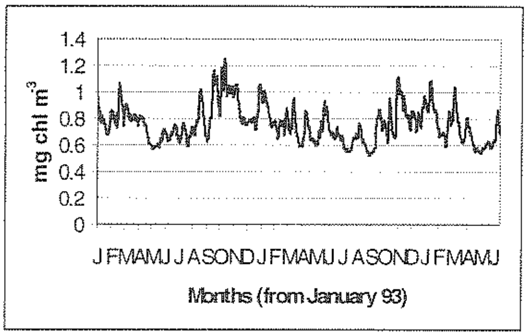

Figure 5. Modelled chlorophyll in central Port Phillip Bay.

The bay's response to nutrient loads is controlled by denitrification. The modelling of denitrification is based on denitrification rate increasing as oxygen supply falls, while nitrification rate decreases. The model uses sediment respiration rate, and hence oxygen uptake, as a substitute for the inverse of oxygen availability. Since ammonia released from detrital breakdown must first be nitrified before it is denitrified, this model results in highest proportional denitrification at low to moderate sediment respiration rates.

If nutrient loads are increased then respiration in the sediment increases and hence (unless loads are initially very low) denitrification efficiency decreases. As a result there is a non-linear response of primary production to increases in nutrient loads and this in turn fuels more sediment respiration. The increase in rate of return from input accelerates as loading increases, until there is a sudden transition from a biodiverse mesotrophic environment to a low diversity eutrophic one. This onset of eutrophication in response to increased loads is discussed in detail by Harris et al. [1996] and Murray and Parslow [1997, 1999].

3. BASS STRAIT

Bass Strait is the shallow sea that separates Tasmania from the Australia mainland. The strait is well mixed internally and has open exchanges with the Southern Ocean in the west and Tasman Sea in the east. Very low background concentrations of nutrients and chlorophyll exist in Bass Strait and the adjoining oligotrophic oceans.

The Boags Rock outfall discharges via a pipeline into the offshore Bass Strait. Strong advective currents mitigate local effects of the discharge and transport nutrients away from the outfall.

However, the discharge is comparable to WTP's and the potential for environmental impacts exists. For this reason Melbourne Water commissioned a study of the outfall, for which we developed an ecosystem model.

The effect of discharges is local enrichment of the water with nutrients that directly support production of phytoplankton; this production competes with dispersal. The geographical location of different environments changing as the discharge plume moves with the currents. There is little role for recycling in this process. Due to the offshore discharge, and continuous variation in the plume's position, there is little competition from fixed macroalgae.

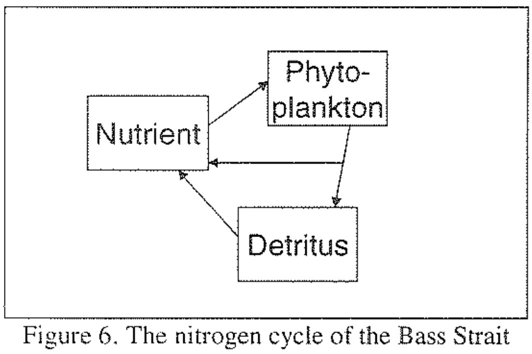

Figure 6. The nitrogen cycle of the Bass Strait ecosystem model

To analyse this simple ecosystem we derive a simple model (Murray and Parslow [1998]). This model consist of only one nutrient pool, one phytoplankton pool and one detrital pool (Fig. 6), based on labile detritus used in the Port Phillip Bay model. Process rates are temperature sensitive and light and DIN concentration control photosynthesis.

Modelled water-quality depends upon the relative rates of the growth of phytoplankton and the dissipation of the input plume. The growth rate of the phytoplankton is controlled by processes described in the ecosystem model – but the dissipation of the plume depends upon the physical mixing processes described by the hydrodynamic model (Andrewartha et al. [1998]). This model uses a polar grid centred on the outfall to maximise the local resolution.

Because the boundaries of the affected area are weakly defined, concentrations just fade away gradually from the outfall. Because the current alter continuously the position of the outflow plume varies. Implementation and analysis of the ecosystem in terms of spatial boxes and regions is not appropriate. The model is implemented directly on the hydrodynamic model's grid. This gives a much slower execution than was achieved in the Port Phillip Bay model, but, given that the model is much simpler, fewer runs are required for its analysis.

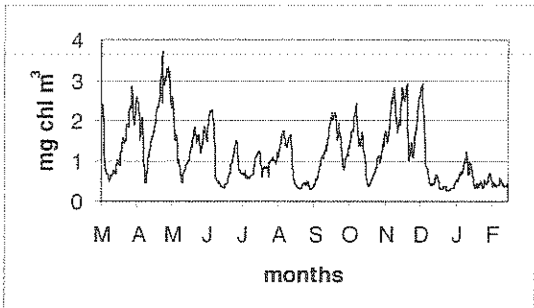

Figure 7. Modelled chlorophyll within 3 km of Boags Rock outfall 1997-8

Analysis of a standard run shows that chlorophyll within 3 km of the outfall experienced blooms of from about 0.5 mg chl m^{-3} to 1.5 to 4 mg chl m^{-3} on about 10 occasions over the course of a year (Fig. 7). The timing, although not the size, of these blooms is insensitive to ecosystem model parameterisation. Their timing is driven by variations in the rate of physical dispersion.

If currents are unidirectional (as is largely the case in the last two months shown in Fig. 7) production is controlled by the relatively low rate at which very low oceanic chlorophyll concentrations can respond to sudden enrichment as these pass the plume. If the currents are more complex, then elevated chlorophyll is mixed back into the plume. This leads to higher initial concentration and hence more vigorous response to the enrichment. At the same time, slower effective dispersal leads to increased use of nutrients for production, relative to their dispersal.

Larger scale analysis of the model is not easily done simply by increasing the area over which it is carried out. As area over which averaging occurs is increased the resultant values derive from conditions in increasingly disparate areas, which makes detection of specific features impossible. An alternative approach, which allowed direct comparison of the model with observations under different conditions, was to plot both predictions and observations against salinity (Fig. 8). This Lagrangian approach abolished spatial problems and removed the effect of small spatial errors in the model. Such errors can result in large apparent differences between prediction and observation in the presence of strong gradients. DIN varies inversely with salinity, but chlorophyll shows a more interesting pattern. Low and high salinity water have low chlorophyll, while intermediate salinity water has the highest chlorophyll (Fig. 8). This peak occurs between the recently released low salinity, high nutrient, water in which the phytoplankton have not yet had time to grow, and the background high salinity oligotrophic water.

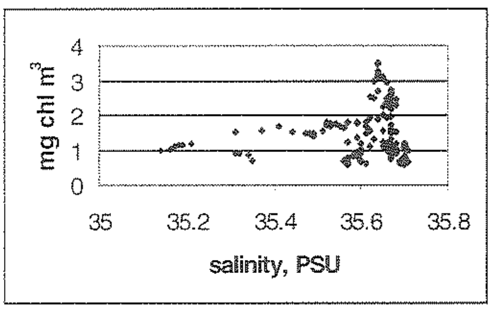

Figure 8. Observed chlorophyll versus salinity near Boags Rock, March 1997

Early versions of the model tended to over-predict the initial response to nutrient addition. A number of alternative explanations are considered by Murray and Parslow [1998]. Incomplete small scale mixing may make nutrients less available to phytoplankton than they appear to be from average concentrations, or secondary nutrients may be exhausted, or grazers may concentrate at the outflow. We lack the evidence to discriminate between these hypotheses, but we were able to reproduce the local low chlorophyll by introducing an inhibition term related to inverse salinity. This is as a proxy measure, since it is very unlikely fresh-water *per se* has much effect on the phytoplankton given the relatively small volumes discharged.

The appropriate ecosystem model for the Boags Rock outfall is thus a simple model with little biological feedback. Water quality is largely controlled by the interaction of phytoplankton growth and nutrient input with physical dispersion processes.

4. DISCUSSION

Two similar discharges of treated sewage from the same city are made into marine waters separated by only a few tens of kilometres, in both cases natural processes clean up the input nutrients reasonably effectively. But these processes are very different and entirely different models are used to describe them (Table 1).

TABLE 1
Summary of Port Phillip Bay and Bass Strait Ecosystem Models

Model	Port Phillip Bay	Bass Strait
Variables	13 (N alone)	3
Export	10%	100%
Denitrification	90%	0%
Recycling	5 × (7 ×)	<1 ×
Chlorophyll	Stable	Varying
Analysis	Spatial	Lagrangian
Load response	Non-Linear	Linear

In Port Phillip Bay it is biogeochemical processes that maintain water quality. These depend upon long-term interactions between water-column processes, in-sediment processes, and nutrient inputs. Recycling dominates over inputs in control of primary production so that phytoplankton plus macroalgal production is some 5 times input: inclusion of MPB production increases primary production to 7 times N input. Persistent spatial patterns are strongly apparent in the ecosystem, and these provide a basis for analysis of the effects of nutrient discharges. The ecosystem responds non-linearly to loading, and excessive loads can result in damage to the self-cleansing mechanism, which may be difficult to reverse.

In Bass Strait it is the physical dispersion of inputs that maintains water-quality; this dispersion varies continuously and hence the chlorophyll concentration varies. The ecosystem's response is controlled by short-term processes, which allow phytoplankton to use only some of the nutrients before the plume disperses. Recycling processes play only a limited role in the growth of phytoplankton in the plume. As we are interested in the response of the phytoplankton to the mobile discharge plume spatial analysis is of limited use. A Lagrangian analysis of nutrients and chlorophyll with respect to the salinity field is more informative.

The differences apparent between these two environments are partly a result of different scales of interest. Nutrient inputs from WTP do impact on the entire of Port Phillip Bay, but the Boags Rock input has negligible effect on much of Bass Strait; hence our main foci of interest are the whole bay for Port Phillip Bay and the outfall plume for Bass Strait. Locally, in the vicinity of the WTP, Port Phillip Bay does behave like the Boags Rock outfall area. Input nutrients mix with relatively oligotrophic bay-centre water and this interaction produces local blooms (Murray and Parslow [1997]). Similarly the Bass Strait ecosystem is, at larger distances from Boags Rock, like that of central Port Phillip Bay weakly perturbed by inputs and with production based on recycled nutrients (Murray and Parslow [1998]).

To summarise, it is the role of recycling and denitrification, which makes Port Phillip Bay so different from Bass Strait. Due to the significance of these processes a complex ecosystem model is required, and this model exhibits non-linear response to load changes. Bass Strait production around Boags Rock is largely driven by directly input nutrients and physical mixing processes, so a simple ecosystem model with limited feedback is all that is required (or justifiable).

ACKNOWLEDGMENTS
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Andrewartha, J. R., A. G. Murray, J. S. Parslow and S. J. Walker. Boags Rock Environmental Impact Assessment Program task 6.4: field data, hydrodynamic modelling and water quality modelling, final report. CSIRO Marine Research OMR-119/107, Hobart, 1998

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 Press, Canberra, 1996

Murray, A. G., and J. S. Parslow. Port Phillip Bay integrated model: final report. Port Phillip Bay Environmental Study Technical Report 44, Canberra, 1997

Murray, A. G., and J. S. Parslow. Boags Rocks Environmental Impact Assessment Program task 6.4: Water Quality Modelling. CSIRO Marine Research OMR-122/107, Hobart, 1998

Murray, A. G. and J. S. Parslow. Modelling nutrient impacts in Port Phillip Bay – a semi-enclosed marine Australian ecosystem. *J. Mar. Freshwater Res*, 50, 597-612, 1999

Walker, S. J. Coupled hydrodynamic and transport models of Port Phillip Bay, a semi-enclosed bay in south-eastern Australia. *J. Mar. Freshwater Res.* 50, 469-481, 1999