

# The Port Phillip Bay Ecosystem Model: Spatial and Temporal Pattern and Process.

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**Abstract** The Port Phillip Bay environmental study yielded a comprehensive set of observations of the key nutrient pools and fluxes with good spatial and temporal resolution. An ecosystem model of nutrient cycling in Port Phillip Bay has been developed and calibrated against this data set. The model spatial structure was chosen to resolve the principal gradients in the bay, associated with point sources and transport. Model-data comparisons were conducted at bay-wide, regional and local scales. A hierarchical approach to model calibration was adopted, with parameters adjusted first to match annual bay-wide pools and fluxes, and then refined to correct discrepancies at regional scales. Calibration at bay-wide scales was guided by results from simple 1-box steady-state models. The calibrated model matches annual pools and fluxes within observation error, and explains much of the observed spatial and temporal variation. Silicate limitation and nutrient trapping control the magnitude and duration of phytoplankton blooms in coastal waters.

## 1. INTRODUCTION

Port Phillip Bay, a large semi-enclosed bay in south-east Australia, was the subject of an intensive multi-disciplinary study from 1992 to 1996 (Harris et al. 1996). An integrated ecosystem model of nutrient fate and impacts in the bay was developed as part of the study, for scientific understanding and synthesis, and as a predictive tool for managers.

Murray and Parslow (1997, this volume) describe the functional components and key processes incorporated in the full simulation model, and the use of simple models to understand the bay-wide response to changes in nutrient loads. In this paper, we focus on the comparison of simulation model predictions and observations, and model calibration.

## 2. THE PORT PHILLIP BAY DATA SET.

The comprehensive field study yielded a particularly valuable data set for model development and calibration. In the water column, concentrations of nutrients, chlorophyll, particulate and dissolved organic matter, and light attenuation were measured on monthly

surveys (Longmore et al, 1996). Vertical profiles were measured at a set of fixed sites, and a subset of variables were measured underway along cruise tracks. The bay is relatively shallow (mean depth 14 m) and usually well-mixed vertically, so that the underway surface data provide a good estimate of the mean water-column properties.

Profiles of pore water and particulate nutrients in the sediments were obtained in winter and summer (Nicholson et al, 1996).

Microphytobenthos (MPB) chlorophyll was measured bay-wide on one occasion, and along a series of on-shore to offshore transects monthly (Beardall and Light, 1997). Macroalgal biomass was also measured quarterly on a series of transects through the principal macroalgal beds (Chidgey and Edmunds, 1997).

A key feature of the field program was the effort devoted to process studies measuring fluxes. Size-fractionated phytoplankton production was measured monthly at a series of sites using  $^{14}\text{C}$  P-I techniques, which also provided estimates of the light saturation parameter  $I_k$  (Beardall et al, 1996). Grazing dilution studies provided estimates of light and nutrient-saturated phytoplankton growth rates, and

microzooplankton grazing rates (Beattie et al, 1996). P-I curves for microphytobenthos were obtained by incubation of sediment cores (Beardall and Light, 1997). Benthic chambers were used to measure bio-irrigation rates, and net exchanges of nutrients, oxygen and carbon dioxide across the sediment-water interface (Nicholson et al, 1996). These measurements provided an empirical basis for the critical relationship between denitrification efficiency and sediment respiration rate (Murray and Parslow, 1997).

### 3. SPATIAL STRUCTURE IN THE OBSERVATIONS AND THE MODEL.

Physical models of Port Phillip Bay were developed by Walker (1997). The ecosystem model is based on a coarse-resolution transport model with a 1-day time step. Particle tracking in a high-resolution hydrodynamic model was used to estimate volume exchanges among cells in the transport model over each 24 h interval. This approach provided flexibility in spatial resolution, with short run times and accurate net exchanges. Because of the short run-time, we were able to undertake hundreds of model simulations, each simulating a period of 10 to 20 years.

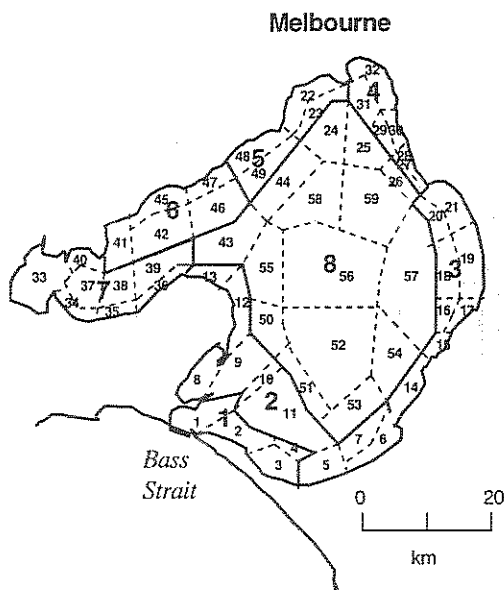


Fig. 1. Transport model boxes (dashed lines) and regions (solid lines, bold type).

The transport model divides the bay into polygonal "boxes". The model version discussed here had 1 water column and 1 sediment layer in each box, and 59 boxes (Fig. 1). Box boundaries in the direction parallel to shore approximately follow the 5, 10, 15 and 20 m contours. This provides a minimum level of depth resolution for modelling benthic plant dynamics. Box boundaries normal to the shore were chosen to resolve the gradients away from the major point sources.

The tidal flushing of Port Phillip Bay is restricted by the tidal flood delta, known as the Sands. Box boundaries in the Sands were chosen to resolve the major channels, and to reproduce the hydrodynamic model flushing time of ca 1 year.

For purposes of analysis and interpretation, the transport model boxes were aggregated into a set of 8 regions, also shown in Fig. 1. These regions are characterized by different patterns of environmental forcing and dominant ecological processes.

Regions 1 and 2 cover the Sands, a mixing zone between the interior of the bay and Bass Strait. Region 2 is extended westward along the coast to include the principal seagrass beds.

Regions 3 through 7 cover the coastal strip around the interior of the bay. In region 3 (East Coast), this strip is quite narrow and nutrient inputs from the Patterson-Mordialloc system are rapidly exchanged with the central bay. The Yarra River, which is the dominant source of freshwater, organic N, nitrate and silicate to the bay, flows into region 4 (Yarra) through Hobson's Bay. Significant phytoplankton blooms occur in this region following Yarra runoff events. Benthic chamber studies in Hobson's Bay yielded the highest sediment respiration rates and lowest denitrification efficiencies in the bay.

Region 5 (North West) lies between the dominant point sources (the Yarra River and the Werribee Treatment Plant (WTP) outfalls). Water quality in this region depends on circulation patterns, as water is advected either west from the Yarra, or north from Werribee.

Region 6 (Werribee) receives the outfall from WTP, which provides ca 50% of the total dissolved inorganic nitrogen (DIN) load to the Bay, primarily as ammonia. This load follows a

regular seasonal cycle, with a maximum in winter. High ammonia concentrations are observed in this region in winter, followed by a small chlorophyll bloom in spring.

Region 7 (Corio Bay) receives relatively little freshwater or nutrient input. Exchange with the rest of the bay is limited, and it becomes hypersaline in periods of low rainfall.

The principal macroalgal beds occur between the 4 and 10 m depth contours along the north and west of the bay. Seagrass beds are concentrated in the south, away from the major nutrient inputs, and shallower than 5 m.

Region 8 (Bay Centre) comprises the central basin, generally deeper than 15 m. It represents ca 40% of the bay area, and 70% of the volume. This region receives a small direct nutrient load (via atmospheric deposition), but otherwise is driven by nutrient cycled through the coastal regions. It is characterised by low and quite constant levels of DIN and chlorophyll. Sediment respiration rates are low, and denitrification efficiencies approach 100%. This large relatively uniform region operates close to steady-state, accounting for the fact that simple 1-box steady-state models provide quite good approximations to the bay as a whole (Murray and Parslow, 1997; see below).

The underway data allowed us to quantify the spatial variation in nutrients and chlorophyll at model scales. For ammonia and chlorophyll, levels of spatial variation within boxes were moderate (C.V. about 0.3), while levels of spatial variation among boxes within regions were generally lower (C.V. < 0.2). Spatial variability was higher near the major point sources.

Phosphate is present in great excess in Port Phillip Bay, and there is a strong gradient across the Sands to low oceanic concentrations in Bass Strait. The relative spatial variation within boxes and regions is quite low except in the Sands.

These patterns of spatial variation must be taken into account in comparing model predictions and observations. Model predictions in individual boxes represent arithmetic averages over the box volume. These can reasonably be compared with averages of underway observations within the box. Point observations in boxes can also be

compared with model predictions, but within-box spatial variation will increase observation error.

Not all boxes are sampled on each monthly cruise, and it is not clear how to include unsampled boxes in estimating regional or bay-wide averages. One solution is to compare the average of the underway observations with a model regional average with equivalent bias, calculated as an average over boxes weighted according to the number of underway observations in each box. We have used this approach extensively in model calibration.

#### 4. MODEL CALIBRATION.

The ecosystem model described by Murray and Parslow (1997) contains 16 state variables and 70 parameters. Most of these parameters have an eco-physiological interpretation, and prior ranges for parameter values were obtained from the literature. Direct estimates of some parameters were obtained from process studies. However, others, especially the mortality parameters, are semi-empirical and must be estimated by matching model predictions to observations.

There is increasing interest in the use of sophisticated robust statistical techniques to estimate parameters in complex ecological and biogeochemical models (Evans and Garcon, 1996). Unfortunately, the run-time for our model, although relatively short, precluded the use of these procedures. We hope to apply these techniques to a simpler version of the model in the future. In the meantime, we have used a more heuristic approach to model calibration.

Model calibration was conducted in a hierarchical manner. We first calibrated the model against estimates of mean, bay-wide, annual pools and fluxes, drawing heavily on the understanding derived from analysis of simple steady-state models. We then evaluated and fine-tuned the model performance at regional and seasonal scales. In general, it performed well: the exceptions are discussed below.

The simple model analysis described by Murray and Parslow (1997) suggested a step-wise approach to parameter adjustment. Because export of nitrogen to Bass Strait is quite small, the annual load is approximately balanced by denitrification losses. DIN release and net sediment respiration are then determined by the

denitrification parameters. For a given sediment DIN release and external DIN load, primary production is determined by the water column recycling efficiency. This is controlled directly by the parameters prescribing the DIN excretion by grazers, and indirectly by the sinking rate of large phytoplankton and detritus.

For a given level of primary production, phytoplankton biomass is determined by zooplankton grazing and mortality parameters, and by phytoplankton sinking rates. Primary production and phytoplankton biomass together determine the mean phytoplankton growth rate, (ca  $0.4 \text{ d}^{-1}$  in Port Phillip Bay). For a given phytoplankton growth rate, and level of light limitation, the ambient DIN concentration is determined by the half-saturation constant for N-limited growth,  $K_N$ . For given levels of primary production, concentrations of labile and refractory detritus and DON are determined by the respective production efficiencies and breakdown rates.

This picture is complicated by the inclusion in the model of several categories of primary producers which compete for light and nutrients. Changes to parameters affecting one primary producer tend to produce compensatory changes in others. These interactions were assessed by numerical experiments, including a full sensitivity analysis about the final parameter set.

The agreement between predicted and observed pools and fluxes is generally well within the uncertainty in the observations due to spatial and temporal extrapolation (Table 1). Nitrate and phosphate are interesting exceptions. The model underpredicts nitrate concentrations, which are determined primarily by phytoplankton uptake kinetics. It seems likely that the current model formulation underestimates ammonia inhibition of nitrate uptake. This has little effect on other aspects of the model behaviour.

The model apparently overestimates phosphate concentrations by about 25%. If there is no internal sink of phosphate, the model flushing time must be too long by the same fraction. However, calibration against salinity suggests the transport model flushing time is slightly too low (Walker, 1997). The predicted and observed cruise track weighted means disagree by less than 10%. The model predicts high phosphate concentrations in Corio Bay, which was

undersampled in the underway data. The remaining discrepancy could indicate a small net sink of phosphate in the sediment.

Table 1. Comparison of predicted and observed mean concentrations ( $\text{mg N m}^{-3}$ ) (except for macroalgae ( $\text{mg N m}^{-2}$ ) and phosphate ( $\text{mg P m}^{-3}$ )), and fluxes ( $\text{t N y}^{-1}$ ). CWT = Cruise-track weighted mean.

Mean annual bay-wide concentrations	Observed	Predicted
DON	32	34
Phytoplankton N	6.0	5.5
Macroalgae	250	270
Nitrate	3.5	.85
Ammonia	6.5	7.0
Phosphate	58	72
Phosphate (CWT)	64	70
Mean annual bay-wide fluxes		
Phytoplankton Prodn	30000	29400
MPB Prodn	12000	12700
Macroalgal Prodn	5000	5200
Water DIN recycling	18000	19200
Sediment DIN release	4 - 8000	6200
Filter feeder DIN excretion	3750	4300
Net sediment resp.	14000	13200
Denitrification	7000	6900

Given the number of model parameters, this good agreement between predictions and observations at the level of annual, bay-wide averages is hardly surprising. The comparison of model predictions and observations at seasonal and regional scales represents a much more exacting test of the model.

The model was able to reproduce the observed spatial and temporal variation in water column concentrations surprisingly well. For example, Fig. 2 compares predicted and observed annual mean chlorophyll concentrations in sampled boxes grouped by regions. The model not only captures the differences among regions, but also reproduces well the pattern of spatial variation among boxes within regions. The model also generally reproduces quite well the patterns of temporal variation within regions.

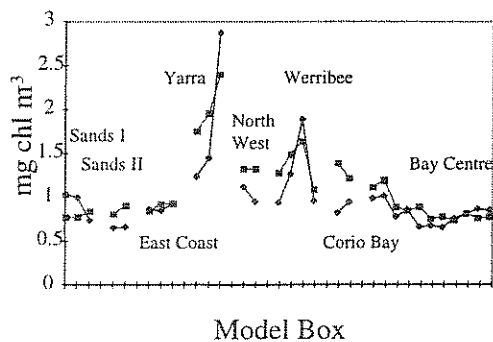


Fig. 2. Comparison of predicted (diamond) and observed (square) mean chlorophyll concentrations by box.

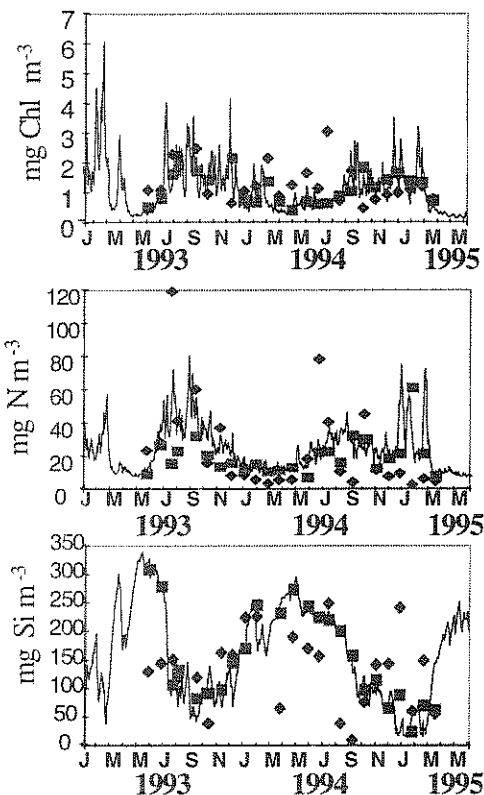


Fig. 3. Predicted and observed mean chl a, DIN and silicate in the Werribee region. Cruise track weighted mean predictions (squares), observations (diamonds), volume-weighted predictions (line).

Early model versions predicted diatom blooms in the Werribee region two to three times higher than observed. These versions did not include silicate. Field observations showed periodic depletion of silicate in the bay. Once silicate was included in the model, a much better match was

obtained between predicted and observed chlorophyll concentrations in the Werribee region (Fig. 3).

A large phytoplankton bloom was observed in the Yarra region associated with a runoff event in September 1993. The model predicts the average magnitude of this bloom correctly, but the predicted bloom tends to increase too quickly, and is too concentrated near the source (Fig. 2). This may be because the model does not allow adequately for stratification and turbidity associated with high river runoff.

In the model, rapid phytoplankton uptake of DIN near the major inputs, followed by sedimentation and sediment recycling, results in "trapping" of nitrogen in coastal regions. Recycling efficiencies are increased because organic loads and sediment respiration rates are locally high, and predicted denitrification efficiencies are low (consistent with observations). Thus, the magnitude and duration of coastal blooms depend on a balance between phytoplankton and macroalgal uptake and growth rates, phytoplankton and detritus sinking rates, and of course physical advection and mixing. Increases in benthic filter-feeder biomass also have disproportionate effects in shallow coastal boxes.

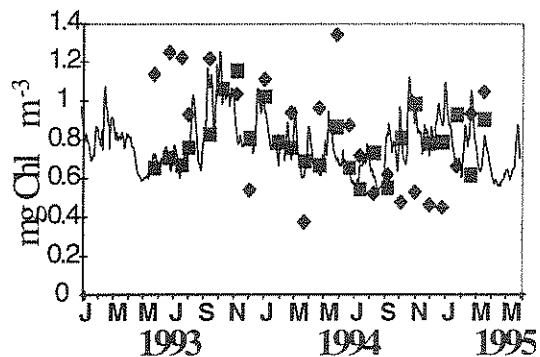


Fig. 4. Mean chlorophyll in the bay centre. (Symbols as in Fig. 4)

The second year of the field program (1994/95) was a low rainfall year in the Port Phillip Bay catchment and spring runoff from the Yarra River was virtually absent in 1994. The total estimated nitrogen load to the bay declined by about 20% from 1993/94 to 1994/95. In response, the observed chlorophyll and DIN concentrations in the bay centre showed a more

or less linear decline from May 1993 to January 1995.

The model predicts a seasonal cycle in chlorophyll, with a peak in spring and early summer associated with WTP and Yarra loads, and does not reproduce the observed interannual decline (Fig. 4). The model does reproduce the observed seasonal change in sediment respiration rates in the bay centre. This suggests that the interannual decline is associated with the factors controlling phytoplankton biomass and growth rates, rather than nutrient flux and primary production.

For a given nutrient flux, in the steady-state conditions prevailing in the bay centre, phytoplankton biomass is controlled directly by zooplankton or benthic filter-feeder dynamics. Interestingly, there was a rapid expansion of the introduced fan-worm, *Sabella*, throughout parts of Port Phillip Bay over the period of the study.

#### SUMMARY AND CONCLUSIONS.

In developing a model of the fate and impacts of nutrient loads in Port Phillip Bay, we have tried to strike a balance between realism and complexity. In analysing and calibrating this model, we have relied heavily on the use of simple model analogues, and adopted a hierarchical approach to model calibration. This combination has proved effective: the full model reproduces both the mean pools and fluxes, and most of the observed spatial and temporal variation in the bay, and we believe we have a good understanding of how and why it does so.

At the beginning of the study, management concerns focused on the whole bay response to changes in total nutrient load. Because of its low flushing rate, Port Phillip Bay is potentially vulnerable to eutrophication. By coupling water column and sediment dynamics, the model predicts an assimilative capacity for the bay, defined by the sediment denitrification capacity, of about 2 to 3 times current loads.

Managers have responded to the study findings by agreeing to incrementally reduce current nutrient loads. Future concerns are likely to focus on local and regional impacts around major point sources. Future model development will accordingly concentrate on improving model resolution and performance in these regions.

#### ACKNOWLEDGEMENTS

This work was funded by Melbourne Water and made possible by the researchers and managers of the Port Phillip Bay Environmental Study.

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