Port Phillip Bay
Integrated Model Scenarios
for
Nitrogen Load Reductions and
Aquaculture Loads

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NITROGEN LOAD REDUCTIONS AND MANAGEMENT.

Background.

The Victorian Government's agenda for the environmental management of Port Phillip Bay includes a goal to reduce the annual load of nitrogen discharged from the catchment to the Bay by 1000 tonnes N by 2006. Nitrogen currently enters Port Phillip Bay from a variety of major and minor sources (Parslow et al, 1999). In order to better understand the consequences of specific load reduction allocations, NRE has commissioned CSIRO to undertake scenario evaluations using the integrated model developed as part of the Port Phillip Bay Environmental Study (PPBES). These relate to load reductions from the Western Treatment Plant and the catchments of the Yarra-Maribyrnong and the Patterson- Mordialloc (see Part A of this report) and to new loadings from aquaculture proposals near Corio Bay and the south central Bay (see Part B of this report).

The formulation and behaviour of the PPBES Integrated Model have been fully described and documented previously (Murray and Parslow, 1997; Murray and Parslow, 1998). Briefly, the model predicts the biogeochemical and ecological impacts of nutrient loads to Port Phillip Bay. The model is based on an underlying 3-D hydrodynamic model (Walker, 1997), and a derived transport model which represents transport within the water column, and water column – sediment exchanges (Walker and Sherwood, 1997). The model represents the cycling of nitrogen, phosphorous, biogenic silica and carbon through the pelagic and benthic systems in Port Phillip Bay. It was developed and calibrated against data acquired during and prior to the PPBES, and forced by estimated loads from the principal sources during a baseline period from July 1991 to June 1995.

During the PPBES, a careful evaluation was undertaken of the model behaviour, its sensitivity to process formulation and parameter values, and its response to large scale changes in nutrient loads (Murray and Parslow, 1997). At the end of the study, a series of load scenarios were evaluated at the request of the PPBES User Committee (Murray and Parslow, 1998). The scenarios considered here are similar to those considered by Murray and Parslow (1998), but focus specifically on load reduction and allocation options, and their implications for 'environmental quality indicators' in relation to State Environment Protection Policy (SEPP).

PART A. Nitrogen LOAD REDUCTIONS.

Introduction.

NRE has requested CSIRO to examine the impact of nutrient load reductions resulting from changes to the loads from the Western Treatment Plant and the loads from the catchments of the Yarra-Maribyrnong and the Patterson- Mordialloc.

Load Scenarios.

Three load scenarios are considered in this report. These are:
Scenario 1: Baseline loads;
Scenario 2: 500 t N y^{-1} reduction in WTP load.
Scenario 3: 1000 t N y^{-1} reduction in Bay-wide load, distributed as 500 t N y^{-1} (WTP), 350 t N y^{-1} (Yarra estuary), 150 t N y^{-1} (Patterson-Mordialloc).
These scenarios are referred to in Tables and Figures as “baseline”, “WTP-500”, and “Bay-1000”, respectively.

As in previous model runs (Murray and Parslow, 1998), the baseline loads are the estimated 1991-95 loads. The estimates of loads for the 1991-95 period have recently been updated as part of an evaluation of the baseline (Parslow et al, 1999), and the updated baseline loads are used here. The changes are relatively minor, and the results of the scenarios presented here are directly comparable with those reported by Murray and Parslow (1998).

There is very large interannual variability in nitrogen loads into Port Phillip Bay (annual loads varied from 6500 to 9600 t N y^{-1} over the 1991-95 period). For Scenarios 2 and 3, load reductions are implemented as reductions in daily loads by a fixed percentage for each source. This percentage is chosen so as to achieve the nominated reduction in average annual load over the baseline period.

Nitrogen loads enter Port Phillip Bay in a variety of forms: NOx, NH_4, organic N. The relative proportions vary across sources. The load reduction targets are framed in terms of total N, and for each source, fixed percent reductions were applied to all forms. The average annual loads under the three scenarios are shown in Table 2.

In these scenarios, as in previous model reports, the model was run for a total of 12 years, with the 1991-95 loading and forcing repeated 3 times, so that predicted concentrations in the last 4 year iteration are independent of initial conditions. Model statistics have been computed from output over the last 4 years.

Spatial and Temporal Statistics.

The PPBES Integrated Model divides the Bay into 59 boxes, chosen so as to follow depth contours and provide more resolution in coastal areas than in the Bay Centre (Fig. 1). In previous analyses (Murray and Parslow, 1997, 1998), we have grouped these boxes into 8 regions, corresponding to areas with different dynamics and/or dominated by different sources. In this Study, we have instead grouped boxes according to the SEPP segments.

The SEPP segments are Hobsons, Corio,Werribee, Inshore and General (rest of Bay)[1]. It should be noted that the model only approximately resolves the SEPP segments. The Corio and Hobsons segments are represented by single model boxes. The offshore boundary of the Werribee segment is defined by the 10 m contour, and is therefore well-approximated by the model boxes. (In fact, the Werribee segment used

[1] The SEPP also identifies an ‘Aquatic Reserve’ Segment that can include specific categories of marine protected areas. No area of the Bay is currently included in this segment.

here is coincident with the Werribee region described in previous model reports.) However, the offshore boundary of the SEPP Inshore segment is defined as 600 m from the low water mark, while the model coastline boxes are typically several kilometers wide. Nonetheless, we have used values in these coastal boxes (excluding the Werribee, Corio and Hobsons segments) as an approximation to the SEPP Inshore segment.

It should be noted that the model is not well calibrated in Corio Bay, as the standard PPBES field surveys did not sample there. Sufficient data does exist, however, to show that the model greatly underestimates mean chlorophyll a, DIN, DON, sediment respiration and denitrification efficiency, and greatly overestimates Secchi disc depth in Corio Bay (Table 1). The likely explanation is that direct loads into Corio Bay from local creeks and drains are not included in the model due to a lack of time series data. While these loads are small on Bay-wide scales, they could have significant local impact in Corio Bay, which is poorly flushed. Given these deficiencies, the model results for Corio Bay are not reported.

Table 1. Comparison of median indicator concentrations measured in Corio Bay with those predicted by the PPBES model. Indicator concentrations drawn from Cowdell *et al*. (1985) and Berelson *et al.* (1995)

Indicator	Median found (1980-84)	Model prediction (1990-95)
Chlorophyll a (mg chl m^{-3})	2.5	0.26
DIN (mg N m^{-3})	10	5.8
Secchi disc depth (m)	3.5	8
PO_4 (mg P m^{-3})	78	114
SiO4 (mg Si m^{-3})	130	180
DON (mg N m^{-3})	200	56
Sediment resp. (mg N m^{-3})	60 (in 1995)	4
Denitrification efficiency (%)	75 (in 1995)	26

The model produces daily time series of concentrations and/or fluxes of key variables and processes in each model box. In this report, we present only summary statistics for these time series. Specifically, we have computed 10, 25, 50, 75 and 90 percentiles for key variables and fluxes for each fine box. We present the 50 and 90 percentile values for a subset of these variables as maps. Because of the large dynamic range of these variables, it is difficult to see the differences between scenarios by comparing maps. We have therefore presented maps of absolute values for the baseline scenario, and the values for the load reduction scenarios as percentages of the baseline values.

We have also computed 10, 25, 50, 75 and 90 percentiles for key variables and fluxes for the SEPP segments. Where SEPP segments contained more than one model box, we have weighted histogram frequencies associated with daily box values by box surface area. One can think of the resulting histogram as representing the probability distribution of values obtained by sampling randomly in time, and randomly over the area of the SEPP segment. These percentiles are presented as box and whisker diagrams and as Tables.

'Indicator' Variables.

We have presented spatial maps for five indicators:

- chlorophyll a (mg Chl m^{-3})
- dissolved inorganic nitrogen or DIN (mg N m^{-3})
- light attenuation Kd (PAR) (m^{-1})
- primary production (mg N m^{-3} d^{-1}), and
- sediment respiration (mg N m^{-2} d^{-1}).

Note that nitrogen forms the primary model currency and nitrogen is used as a surrogate for carbon and oxygen fluxes. Chlorophyll a is calculated assuming a fixed ratio of 7 mg N mg $Chla^{-1}$. Primary production and sediment respiration can be converted to carbon by multiplying by 5.7 mg C mg N^{-1}, or to oxygen by multiplying by 32 mg O mg N^{-1}.

The model calculates the diffuse attenuation coefficient Kd (m^{-1}) for downwelling irradiance (PAR) as:

$$Kd = K_B + k_{DON} \cdot DON + k_{DL} \cdot DET + k_{PHYN} \cdot PHYN,$$

where K_B is the background attenuation, DON is dissolved organic nitrogen, DET is total detrital N (labile plus refractory), and PHYN is phytoplankton N. Note that the model does not explicitly include the effects of suspended inorganic sediment, but includes an average background attenuation in K_B. This is likely to lead to underestimation of Kd in areas affected by the Yarra river plume, especially during periods of high runoff.

As well as these five indicators, we have calculated statistics for additional indicators, including: dissolved inorganic phosphate (DIP) (mg P m^{-3}), dissolved inorganic silicate (mg Si m^{-3}), dissolved organic nitrogen (DON) (mg N m^{-3}), benthic denitrification efficiency, and microphytobenthos production (mg N m^{-2} d^{-1}). Phosphate is present in excess in Port Phillip Bay, but silicate is co-limiting, especially in the Werribee region. Dissolved organic nitrogen is the primary form of N export from the Bay. Denitrification is the primary sink for nitrogen in Port Phillip Bay. It is non-linearly dependent on sediment respiration, and controls the large-scale response of the Bay to large changes in nitrogen load (Murray and Parslow, 1997).

The SEPP establishes specific objectives for chlorophyll-a (50 and 90 percentiles) and Kd (90 percentiles). For these indicators, we present Tables and plots comparing model output with the SEPP objective for each scenario.

SEPP objectives are also given for Secchi depth, but we have used light attenuation Kd, as it is directly calculated and used by the model, and the SEPP objective for Kd is framed statistically in terms of the 90 percentile. It is not so clear how to interpret the SEPP objective for Secchi depth, as no statistic is specified. There is an approximate inverse relationship between Kd and Secchi depth eg

Secchi depth = 1.7 / Kd (Raymont, 1980).

Results.

Spatial Distribution.

Chlorophyll a.

In the baseline run, predicted median chlorophyll a values are typically less than 1 mg Chl a m^{-3}, and approach 2 mg Chl a m^{-3} in Hobsons Bay and Werribee areas (Fig. 2A). The predicted 90 percentile values are around 4 mg Chl a m^{-3} in Werribee, and 7 mg Chla m^{-3} in Hobsons Bay (Fig. 2B). As might be expected, the principal effect of the 500 t N y^{-1} reduction in WTP load occurs off Werribee. The maximum relative reduction (to 75 to 85% of baseline median values) occurs offshore and north and south of the outfall (Fig. 2C). This geographic displacement is even more noticeable in the 90 percentile values, where the maximum reduction occurs well away from the outfall, and is located offshore and along the Bellarine Peninsula (Fig. 2D). The likely reason for this displacement is that peak phytoplankton biomass and production in spring adjacent to the outfall is silicate rather than nitrogen limited (Murray and Parslow, 1997).

The additional load reductions for the Yarra and Patterson-Mordialloc lead to broad but weaker reductions of order 10 to 15% in median chlorophyll, concentrated in Hobsons Bay and along the north-east coast (Fig. 2E). The effect on 90 percentile values is more pronounced, with reductions of order 15 to 25% over most of the northern half of the Bay (Fig. 2F). The relative reduction in Hobsons Bay may be smaller because of nitrogen saturation of phytoplankton production there.

Dissolved Inorganic Nitrogen

DIN concentrations in Port Phillip Bay show a wide dynamic range, and the baseline median and 90 percentiles are plotted on a $\log_{10}$ scale. Median values are quite low (less than 10 mg N m^{-3}) over most of the Bay, but approach 100 mg N m^{-3} off Werribee (Fig. 3A). The 90 percentile values approach 100 mg N m^{-3} in Hobsons Bay, and exceed 200 mg N m^{-3} off Werribee (Fig. 3B).

The 500 t N y^{-1} reduction in WTP load results in a strong local reduction in median DIN, by 20 to 25%, in the vicinity of the outfall (Fig. 3C), and a reduction by 20 to 25% in 90 percentile DIN along the north-west coast (Fig. 3D). The additional load reduction from the Yarra and Patterson-Mordialloc results in reductions in median DIN which are concentrated in Hobsons Bay and along the north-east coast (Fig. 3E). These reductions are more widespread for 90 percentile DIN, with 15% reductions extending down the east coast as far as the Patterson-Mordialloc input.

Primary Production

Water column primary production also has a large dynamic range, and is plotted using a $\log_{10}$ scale. Median values are around 3 mg N m^{-3} d^{-1} throughout most of the Bay, but approach 10 mg N m^{-3} d^{-1} off Werribee and in Hobsons Bay (Fig. 4A). The 90 percentile values reach a maximum of around 40 mg N m^{-3} d^{-1} in Hobsons Bay, and around 30 mg N m^{-3} d^{-1} off Werribee (Fig. 4B).

The effects of load reductions on water column primary production match the effects on chlorophyll a quite closely. Maximum effects of WTP load reductions occur offshore from Werribee (median, Fig. 4C), and across on the Bellarine Peninsula (90 percentile, Fig. 4D).Reductions in loads from the Yarra and Patterson Mordialloc systems occur near Hobsons Bay (median, Fig. 4E) and in a broad arc over the north-central part of the Bay (90 percentile, Fig. 4F).

Light attenuation Kd.

Maximum values of median Kd, about 0.3 m^{-1}, occur along the north-west shoreline and in Hobsons Bay (Fig. 5A). The 90 percentile values are much larger, around 0.7 m^{-1} in the north-west and Hobsons Bay (Fig. 5B). The reduction in WTP loads results in modest decreases (about 7%) in median Kd adjacent to WTP (Fig. 5C), and larger decreases (up to 10%) in 90 percentile Kd in neighbouring boxes (Fig. 5D).

Reductions in Yarra and Patterson-Mordialloc loads result in significant decreases (up to 10%) in median Kd in Hobsons Bay (Fig. 5E), and in 90 percentile Kd along the eastern coast (Fig. 5F).

As noted above, the model calculates light attenuation based on chlorophyll and dissolved and particulate organic matter. It does not include explicitly the effects of variation in inorganic suspended particulates, but instead uses a general background attenuation for the Bay. This means it is likely to underestimate Kd near sources of inorganic suspended solids, especially in Hobsons Bay and the Yarra plume. It follows that, while the absolute reductions in Kd due to decreases in nitrogen load predicted by the model may be reasonable, the percent reductions in Kd may be over-estimated.

Sediment Respiration

Sediment respiration rates (mg N m^{-2} d^{-1}) also have a wide dynamic range, and are plotted on a $\log_{10}$ scale. Sediment respiration is driven by deposition of labile organic matter, and elevated median values of around 200 mg N m^{-2} d^{-1} occur off Werribee and in Hobsons Bay, where water column production is high (Fig. 6A). Median rates are also elevated in the Bay centre, where the water column is deep, and particulate organic matter tends to accumulate. The 90 percentile rates follow a similar pattern (Fig. 6B). Note that both median and 90 percentile values are very low in the Sands.

The load reduction at WTP leads to maximum reductions of 30% in median sediment respiration rates in boxes offshore, and north and south of Werribee (Fig. 6C). Reductions of 30 to 40% in the 90 percentile rates are concentrated along the Bellarine Peninsula (Fig. 6 D). The maximum effect on chlorophyll a and water column primary production was also displaced away from the WTP outfall, and the displacement is exaggerated in the case of sediment respiration.

The additional load reductions for the Yarra and Patterson-Mordialloc result in widespread reductions of 25 to 40% in median respiration rates across the north-west and north-east parts of the Bay, extending down the east coast south of the Patterson-Mordialloc input (Fig. 6E). The reductions in 90 percentile rates are smaller in magnitude but more widespread, extending even into the eastern Sands.

Of the 5 indicators considered in this section, sediment respiration shows the largest relative response to load reductions. The non-linear feedbacks associated with denitrification are likely to be responsible.

SEPP Segment Percentiles

Chlorophyll a

Chlorophyll a 10, 25, 50, 75 and 90 percentiles for the SEPP segments under the three scenarios are shown in Fig. 7, Table 3A. The results are consistent with the mapped responses in individual boxes (Fig. 2). The Werribee SEPP segment shows only modest responses in all percentiles to the WTP reduction, with maximum % reduction in 50 and 75 percentile values. Recall that the maximum impact of WTP load reductions on 90 percentile chlorophyll is displaced offshore to the Bellarine Peninsula, outside the Werribee SEPP region (Fig. 2D).

The Yarra and Patterson-Mordialloc reductions produce a marked reduction in median and 75 percentile chlorophyll in Hobsons Bay, but only minor reduction in the 90 percentile value. Again, the maximum reduction in 90 percentile chlorophyll is displaced outside the Hobsons Bay region. The effects on the SEPP Inshore segment are quite modest, as this segment includes significant coastal areas which are not affected by the load reduction. The 90 percentile values show the largest response, again consistent with displacement of these effects away from the sources.

Chlorophyll levels are low in the General segment, and show a modest reduction, with largest impact again in the 90 percentile values (cf Fig. 2F).

Dissolved Inorganic Nitrogen

DIN percentiles are shown in Fig. 8 (note the log scale), and in Table 3B. Again, the largest effects are observed in Werribee and Hobsons Bay segments. There is a slight reduction in Inshore DIN percentiles, but effects on other segments are slight. This is consistent with the local impact of load reductions on DIN (Fig. 3).

Primary Production

The primary production percentiles show a similar response pattern to chlorophyll a (Fig. 9: note the log scale, Table 3C). The reduction in the Werribee segment in response to the WTP load reduction is more pronounced in the 50 and 75 percentiles than in the 90 percentile. The same is true of the response in Hobsons Bay to Yarra load reductions. Small reductions (10% or less) are predicted in the Inshore and General segments.

Light Attenuation Kd

Decreases in light attenuation in the Hobsons and Werribee segments, in response respectively to reductions in Yarra and WTP loads, are quite small, 10% or less (Fig.

10, Table 3D). The Inshore and General segments also respond to bay-wide load reductions, especially at the 75 and 90 percentile level.

Sediment Respiration and Denitrification Efficiency

The sediment respiration percentiles (Fig. 11, Table 3E) show a qualitatively similar response to chlorophyll a and primary production across segments. Denitrification efficiency (Fig. 12, Table 3F) shows an interesting mixed pattern of responses. In segments such as Hobsons Bay and Werribee, where respiration rates are high, decreases in respiration rate increase denitrification efficiencies at all percentile levels. In the Inshore segment, where respiration rates are low, decreases in sediment respiration rate decrease denitrification efficiencies. The General segment contains a mixture of high and low sediment respiration rates. Decreases in sediment respiration rate increase denitrification efficiency in the high respiration rate areas (50 to 90 percentiles), and decrease denitrification efficiency in the low respiration rate areas (25 percentiles).

Dissolved Inorganic Phosphate and Silicate

The phosphate distribution shows very little response to changes in nitrogen load, as one might expect (Fig. 13, Table 3G). However, silicate concentrations show a marked increase in response to decreases in nitrogen load in all segments (Fig. 14, Table 3H). This is not surprising, as silicate is used by large phytoplankton (diatoms), and becomes limiting to diatom growth at some times and in some regions. By reducing silicate limitation, N load reductions favour diatoms over other phytoplankton species.

Dissolved Organic Nitrogen

Dissolved organic nitrogen shows a marked reduction in response to both WTP and Yarra-Patterson-Mordialloc loads in all SEPP segments (Fig. 15, Table 3I). The DON response is global rather than local, in that all segments respond significantly to both the WTP reduction and the Yarra-Mordialloc reduction. This reflects the long break-down time of DON in the model, so that DON is effectively circulated throughout the Bay.

Microphytobenthos Production

Microphytobenthos production also shows a mixed response to load reductions (Fig. 16, Table 3J). Production decreases in the Inshore segment, presumably reflecting light saturation and N limitation of MPB production there. Production increases in the General segment, which includes the deeper Bay centre region, where MPB production is light limited, and load reductions decrease light attenuation. Production is mostly unaffected in the Werribee and Hobsons Bay regions, where MPB production is both light and nutrient saturated.

SEPP Objectives.

Of the model outputs, there are SEPP objectives for 50 and 90 percentile chlorophyll a, and 90 percentile light attenuation Kd. Table 4 shows the predicted values for each SEPP segment under the three model scenarios, compared with the SEPP objectives. Note that, for segments covering more than one model box, the model statistics are based on area-weighted histograms.

The chlorophyll 50 percentile objectives are met in all SEPP segments by predicted model medians. The 90 percentile objectives are met in four of the five segments- the predicted model values do not meet the SEPP objective in the Hobsons segment.

It was noted in model calibration (Murray and Parslow, 1997) that the model overpredicts mean chlorophyll in Hobsons Bay by about 20%. If the model overpredicts 90 percentile chlorophyll values by the same margin, then the SEPP objective would still be exceeded under all scenarios, but the Yarra load reductions would reduce chlorophyll 90 percentiles to values approaching the SEPP objective .

Under baseline loads, the 90 percentile Kd objectives are not met by predicted model statistics in Werribee and Hobsons segments. The reduction in WTP loads and Yarra loads does not reduce Kd sufficiently to meet objectives in either segment. As noted above, the predicted light attenuation is dominated by phytoplankton and related organic products, and is driven primarily by algal blooms stimulated by local nutrient inputs. It is probable that Kd is underestimated by the model in the Hobsons segment. The area-weighted segment wide statistics shown in Table 4 tend to hide the local spatial variation in statistics, which can be significant, especially in the Inshore segment. (Note that SEPP objectives apply to the instantaneous characteristics of the entire segment.) We have also compared local statistics for chlorophyll and attenuation coefficients, computed over time for individual model boxes, with the SEPP objectives for segments containing those boxes. In Fig. 17, the black boxes indicate local exceedance of SEPP segment objectives for the 90 percentile chlorophyll values, and 90 percentile light attenuation.

According to the model, the 90 percentile chlorophyll criteria are not met in coastal boxes along the north-west and north-east coasts, and in one box off the Bellarine Peninsula under baseline conditions. The exceedance off Bellarine disappears following the WTP load reduction. The Yarra and Patterson-Mordialloc load reductions eliminate exceedances in coastal boxes along the eastern shore. Note that the model calibration indicated good agreement or even under-estimation of mean chlorophyll in many of the non-compliant boxes.

Under baseline conditions, the model 90 percentile light attenuation Kd exceeds SEPP objectives in boxes through the Werribee region, and along the northern coast of the Bay. The reduction in WTP load has little effect, and 90 percentile Kd is reduced to levels below SEPP objectives in only one box, south of Hobson's Bay. The reduction in Yarra loads also has little effect, with one more box meeting SEPP objectives. The SEPP objectives for Kd are relatively uniform across segments, and somewhat inconsistent with objectives for Secchi depth, which show a 2-fold variation across segments. As a result, the SEPP objectives in the north and west are quite challenging.

There is sufficient uncertainty in model predictions (generally of order 10 to 20% or more), that individual predictions of exceedance should be treated cautiously. In the end, compliance or non-compliance with objectives must be based on monitoring, not modelling. However, the general conclusion from Fig. 17, that statistics can vary strongly within SEPP segments, and that local statistics and compliance may be more sensitive to load reductions than segment-wide statistics, is likely to prove robust.

Summary and Conclusions.

The load reductions considered here represent reductions of about 14% in WTP baseline loads, 19% in Yarra estuary loads, and 14% in Patterson-Mordialloc loads. A number of patterns are apparent in the model results, that should reduce the risks from nitrogen loads to the Bay. Reductions in DIN concentrations are concentrated adjacent to sources, while maximum responses in chlorophyll, primary production and sediment respiration are displaced away from the immediate source input. Local reductions in chlorophyll and primary production are typically of order 15 to 25%, and the combined 1000 t N y^{-1} reduction leads to significant reductions, of order 20%, across the northern half of the Bay. Larger percent reductions (up to 40%) are predicted for sediment respiration, and these are more confined to coastal boxes. Decreases in attenuation coefficient are smaller (5 to 15%) and concentrated in coastal boxes near sources. For chlorophyll, DIN, primary production and Kd, effects of load reductions are larger (in relative terms) for 90 percentiles than for medians.

Among the additional variables for which segment statistics are calculated, several different patterns of response to nitrogen load reductions are predicted. Denitrification efficiencies depend non-linearly on sediment respiration rates. Where respiration rates are very low, decreasing nitrogen loads tend to decrease respiration rates and denitrification efficiency. Where respiration rates are high, decreasing loads and respiration rates increase denitrification efficiency.

Microphytobenthos production also shows a mixed response to load reductions. In shallow areas where production is N-limited, MPB production decreases. In deeper areas, where MPB production is light-limited, it increases. In the Werribee segment, MPB production is light and nitrogen saturated, and shows no response.

As expected, phosphate shows little response to reductions in nitrogen loads, but silicate generally increases, as the Bay shifts more towards nitrogen limitation. This is likely to favour diatoms. Because of the long breakdown time of DON, percent reductions in DON are more uniform throughout the Bay.

For the baseline, comparison of segment statistics with SEPP objectives for chlorophyll (50 and 90 percentiles) and Kd (90 percentiles) shows only 3 cases of predicted exceedance : chlorophyll 90 percentile in Hobsons , and Kd 90 percentile in Werribee and Hobsons. The model predicts that load reductions should significantly reduce these exceedances.

Segment-wide statistics can, however, be misleading, especially for those variables such as chlorophyll and primary production, where maximum effects are displaced from the point at which nutrients are added. For example, the effects of reductions in the Yarra and WTP loads extend beyond the Hobsons and Werribee segments respectively , and in adjacent boxes within the Inshore or General segments. These latter segments include a wide range of water and sediment quality, and statistics for individual boxes within these segments can differ substantially from area-weighted segment-wide statistics. The model predictions (Fig.17) can therefore help in the design of monitoring programs intended to report compliance with objectives (for Environmental Quality Indicators) and to judge the extent to which the goals of the SEPP are met.

PART B. AQUACULTURE LOADS.

Introduction.

NRE has requested CSIRO to examine the impact of nutrient loads resulting from proposed aquaculture activities in western and southern Port Phillip Bay. In this report, we consider the impacts of activities at two proposed aquaculture sites. The first site involves a load of 100 tonnes N y^{-1} at a location just outside Corio Bay. The second site involves a load of 200 tonnes N y^{-1} from a fish farm (fish cage culture) in the south central Bay. At the second site , it has been suggested that this load might be compensated by developing a mussel farm adjacent to the fish farm, which would extract the equivalent of 200 tonnes N y^{-1}, offsetting the fish farm load.

The Scenarios.

The following aquaculture scenarios are considered in this report.
Scenario 1. 100 tonnes DIN y^{-1} added just outside Corio Bay (box 40, Fig. 18)Scenario 2. 200 tonnes DIN y^{-1} added to the southern bay.

- Scenario 2A. 200 tonnes DIN y^{-1} added to the southern bay (box 51, Fig. 18).
- Scenario 2B. 200 tonnes DIN y^{-1} added to the southern bay (box 52, Fig. 18) .

Scenario 3. 200 tonnes DIN y^{-1} added and 200 tonnes N y^{-1} harvested as mussel production in the southern bay.

- Scenario 3A. 200 tonnes DIN y^{-1} added and 200 tonnes N y^{-1} harvested as mussel production in the southern bay (box 51, Fig. 18)
- Scenario 3B. 200 tonnes DIN y^{-1} added and 200 tonnes N y^{-1} harvested as mussel production in the southern bay (box 52, Fig. 18)

The Pinnace Channel aquaculture site in the southern Bay in Scenarios 2 and 3 lies almost entirely within model box 51 (Fig. 18), and so one option is to locate N sources and sinks entirely in this box. This box lies between the Sands and bay centre, where the bottom depth increases steeply from 5 to 20 m. This is also a transitional zone between the rapidly flushed Sands, and the poorly flushed central bay. Given the limited spatial resolution of the box model, we thought it advisable to check on the effects of moving this source from box 51 to box 52, a large central bay box. We refer to scenarios with aquaculture in box 51 as 2A, 3A, and scenarios with aquaculture in box 52 as 2B, 3B.

We were requested by NRE to consider each aquaculture scenario against two background load scenarios: the baseline 1991-5 nutrient load (Parslow et al. 1999) and the target load (baseline - 1000 tonnes N y^{-1}), discussed in Part A. We refer to these as baseline and target loads. Thus we report here on a total of 10 model runs.

Nitrogen inputs from fish farms were treated as constant over time, and assumed to consist exclusively of ammonia. Implementation of mussel harvesting in the integrated model is more complicated, and is discussed in the next section.

Mussel Production.

We modelled the mussel production specified by NRE by introducing a specific new model variable (mussel biomass) and recording mussel net production. The mussel biomass was held constant at a predefined value in the area specified as for aquaculture and zero elsewhere; N and P involved in mussel production was removed from the system to maintain constant biomass.

The mussel net production was calculated on the basis of the mussel and plankton biomasses using a grazing and growth model similar to that implemented for the general filter-feeder variable in the Port Phillip Bay model (Murray and Parslow 1997). This model requires 6 parameters, clearance (C_ML), a maximum growth rate (mum_ML), growth efficiencies for mussels grazing on plankton (E_ML) or labile detritus (EDL_ML) and parameters specifying the non-assimilated fraction that was detrital as opposed to being released as ammonia (FDG_ML and FDGDL_ML). The equations and parameter values are described in Appendix 1.

The mussel biomass was adjusted so as to give a harvest of 200 tonnes N y^{-1}. (Table 5). As described in the appendix the productivity of these mussel beds proved to be low owing to the low level of food availability even with nutrient enrichment from fish-farms.

Table 5. Mussel biomasses and harvests under the model mussel harvest scenarios.

Background N load	Location Box no.	Biomass mg N m^{-2}	Biomass tonnes N	Harvest tonnes N y^{-1}	P:B
Baseline	51	18000	325	200.2	0.62
Baseline	52	1800	270	199.8	0.74
Target	51	19000	345	199.4	0.58
Target	52	1900	285	201.8	0.70

'Indicator' Variables.

We have presented spatial maps for six indicators:

- chlorophyll a (mg Chl m^{-3})
- dissolved inorganic nitrogen or DIN (mg N m^{-3})
- light attenuation Kd (PAR) (m^{-1})
- primary production (mg N m^{-3} d^{-1}), and
- sediment respiration (mg N m^{-2} d^{-1}).
- denitrification efficiency (%)

We present maps of predicted percentage changes of the 50 and 90 percentiles of these indicators under the ten model scenarios. Because the inputs are relatively small they have little impact at the bay-wide level or even the regional level; hence the 59-box level of resolution is required for model analysis.

Results.

We present results first for all aquaculture scenarios with baseline background nitrogen loads, and then compare results obtained using target background nitrogen loads. For the most part, similar results were obtained regardless of which background load was used.

Baseline loads.

Chlorophyll a.

Under control conditions, chlorophyll levels in the 3 boxes (boxes 40, 51 and 52) that are subject to inputs from aquaculture are all very low (<0.75 mg chl m^{-3}); these are below the average for Port Phillip Bay. Against this low background, the aquaculture loads do produce significant relative increases in chlorophyll (Figs. 19,20). However, rapid dispersal limits the local chlorophyll response.

The proposed input near Corio Bay (box 40) is located relatively close to the outfall of the Western Treatment Plant, which dwarfs its contribution. In the immediate vicinity of the Corio Bay aquaculture site, median chlorophyll increases by 7%, but the local 90%ile chlorophyll doesn't change, because high chlorophyll concentrations are dominated by episodic advection of nutrient input from the WTP. Small increases in median chlorophyll of 2 - 4% occur in other parts of Corio Bay, and being further from the WTP, these increases are also evident in 90%ile chlorophyll.

Imposition of aquaculture nitrogen loads in either box 51 or box 52 leads to 5-10% increases in chlorophyll throughout the southern central bay, and to smaller (2 -5%) changes in the northern central bay and the northern part of the Sands. The patterns are quite similar for either fish-farm location, although the peak increase is greater (10%) when loads are concentrated in box 51. (Box 52 is 8 times the area of box 51.) The increases in 90%ile chlorophyll are similar but a little smaller, reflecting the fact that aquaculture loads are assumed constant over time.

The addition of mussels largely eliminates these increases in chlorophyll. Very small increases (<2%) occur over much of the southern bay. When all aquaculture (including mussels) is established in box 52, there is a small (3%) drop in chlorophyll in that box. When aquaculture (including mussels) is established in the limited area of box 51, there are very large local decreases in chlorophyll: 47.1% on the median and 36.3% on the 90%ile. The environment is clearly locally stressed by such intensive mussel aquaculture, and this overgrazing is also reflected in reduced mussel productivity (Table 5). It appears that, when dispersed over a larger area, mussel culture can counteract the stimulating effects of nutrient release from fish farms on algal biomass.

Dissolved Inorganic Nitrogen

DIN concentration shows a very large range throughout the bay, and hence is plotted using a $\log_{10}$ scale. Because nitrogen loads are assumed to be input as DIN, there is an immediate local response to these inputs (Figs. 21,22). Because the inputs occur in boxes currently receiving low loads, percentile changes can be large.

Median DIN adjacent to the new Corio Bay input increases by 55% in response to the addition from this new source (Fig. 21B). This relative increase is from a very low baseline concentration of 5.9 mg N m^{-3} (0.42 μM). Increases in adjacent boxes are small. The local increase in the 90%ile is only 15% (Fig. 22B), because peak DIN concentrations are dominated by advection from the WTP. Because the load is concentrated in one box, the local increase is partly an artefact of the box volume.

DIN responds differently to inputs at the two scenario sites for fish farming in the southern part of the bay. When aquaculture is confined to box 51, there are significant local increases in both median and 90%ile DIN, and increases occur over the southern central bay and the northern part of the sands. The local enhancement of DIN concentration is increased when mussel farms are added, reaching 22% for median and 25% for 90%ile values in box 51.   When aquaculture is located in box 52, the increase in median and 90%ile DIN is reduced in magnitude, and largely restricted to that box. This increase is again enhanced by the presence of mussel farms.

Light attenuation Kd.

The model shows small increases in light attenuation (Fig. 23,24) with the largest response being up to 7% in the 90%ile value in Corio Bay (Fig. 24B). These changes occur throughout Corio Bay. However the model predicts very little change in response to the southern aquaculture scenarios (+1% for fish farms, -2 to -3% in response to fish farms + mussel harvesting). This lack of response occurs because attenuation in these more oligotrophic parts of the bay is dominated by attenuation due to the water itself and attenuation due to Dissolved Organic Matter. These do not change significantly in response to the changes in phytoplankton production and grazing.

Primary Production

Water column primary production exhibits a large range of values, and so is plotted using a $\log_{10}$ scale (Fig 25,26).

Like DIN, the change in median phytoplankton production in response to the new Corio Bay input is largely restricted to the immediate vicinity of that input. The 90%ile value in the immediate vicinity of the input shows no response at all to the new load, although other areas of Corio Bay do exhibit small increases in production. We hypothesize that increased macroalgal biomass, stimulated by a constant load of DIN, provides an increased capacity to take up N from other sources. Regional macroalgal biomass increases from 478 to 588 mg N m^{-2} under the Corio Bay aquaculture scenario; this is a 23% increase, and much larger than the phytoplankton regional biomass increase.

The response of primary production to aquaculture in the south of Port Phillip Bay closely resembles the response of chlorophyll. There is a general increase in primary production throughout the southern bay and northern sands in response to fish farm N inputs without mussel harvesting. This applies to both the median and 90%iles and regardless of whether loads are applied to box 51 or box 52. Increases are about 1.5 times the increase obtained for chlorophyll.

When mussel farming is added into box 51 the result is a large drop in production (17.5% in the median and 18.1% in the 90%ile) in box 51, with small increases in other south-central boxes. Mussel farming in box 52 leads to very small increases above the baseline production throughout the south-central bay. The largest of these increases, just over 2% in both median and 90%ile, occurs in box 52.

Sediment Respiration.

Sediment respiration rates (mg N m^{-2} d^{-1}) also have a wide dynamic range, and are plotted on a $\log_{10}$ scale. Sediment respiration is driven by deposition of labile organic matter, and elevated median values of around 200 mg N m^{-2} d^{-1} occur off Werribee and in Hobsons Bay, where water column production is high (Fig. 27). Median rates are also elevated in the Bay centre, where the water column is deep, and particulate organic matter tends to accumulate. The 90 percentile rates follow a similar pattern (Fig. 28). Note that both median and 90 percentile values are very low in the Sands.

In two of the input locations (boxes 40 and 51), organic deposition and sediment respiration are very low, and local nutrient loads can have large relative effects. Box 52, in the bay centre, acts as a settlement basin for detritus from throughout the bay and so has a higher background sediment respiration rate. These local (box-level) responses in the immediate vicinity of inputs can be highly sensitive to the box-size selected.

The model currently predicts offshore seagrass beds in boxes 10 and 11 in the Sands. In reality, the substrate in these boxes appears to be too unstable to support seagrass beds. These boxes show very large relative changes in sediment respiration rate in response to aquaculture loads (Table 6), but these responses are likely model artifacts due to the erroneous seagrass beds.

Large relative responses of sediment respiration in the immediate vicinity of the inputs (positive) and in the Great Sands (negative) dominate the changes in other boxes. We have truncated the scales in the maps (Fig. 27, 28), and present the extreme changes in Table 6.

Under the Corio Bay aquaculture scenario, there is a substantial (20 -25%) increase in both median and 90%ile sediment respiration throughout most of Corio Bay. Box 40 (the input site) shows a very large increase in sediment respiration. This respiration is fuelled by increase in macroalgal production as well as increased phytoplankton primary production (which is limited). There is a 20% fall in median sediment respiration on the southern shore of Corio Bay due to predicted damage to local seagrass beds. Over the whole Corio bay region, predicted seagrass cover falls from 21 to 12 mg N m^{-2}. The Corio Bay seagrass beds are a real feature (Bulthuis et al. 1992) and relatively robustly modelled, so the predicted impact on these beds is of concern.

Table 6. Responses of Sediment Respiration (percent baseline background) in locations receiving inputs (boxes 40, 51 and 52) and the seagrass beds in the sands (boxes 10 and 11) under baseline loads. Values outside the ranges used in Fig. 27, 28 are shown in **bold**.

	%ile	Box 10	Box 11	Box 40	Box51	Box52
Scenario 1	50	97	98	**215**	101	101
Scenario 1	90	94	92	**169**	101	100
Scenario 2A	50	81	85	100	123	108
Scenario 2A	90	**30**	**38**	100	115	104
Scenario 3A	50	78	90	100	**401**	96
Scenario 3A	90	**40**	**74**	100	**251**	97
Scenario 2B	50	89	88	100	117	109
Scenario 2B	90	**52**	**49**	100	112	105
Scenario 3B	50	106	105	100	90	106
Scenario 3B	90	112	115	100	89	107

In the absence of mussels, the response of sediment respiration is similar for fish farm loads into boxes 51 and 52: a 15-20% increase in respiration (both 50 and 90%ile) in box 51, and a 10% increase in median and 5% increase in 90%ile respiration in box 52, on a much higher baseline value. Note that sediment respiration shows a larger relative increase in box 51 than in box 52, even when aquaculture is based in box 52. The predicted decline in respiration on the Sands, due to the impact on (non-existent) seagrass beds, should be ignored.

With the inclusion of mussel harvesting, there is a local increase in sediment respiration at the site at which the mussels are grown, but a decline in sediment respiration in adjacent boxes. Mussel farms filter plankton and suspended detritus from water advected past, and concentrate organic matter in the local sediment. The local increase is mild for box 52, at only 6-7% in both median and 90%ile; the increase in the median value is reduced in the presence of mussels. Increases in local sediment respiration due to mussels in box 51 are very large: 250% of the 90%ile and 400% of median value. In box 51, mussel feeding and excretion are concentrated into a small area, and the baseline sediment respiration is also low. Again, large predicted responses in the Sands boxes 10 and 11 due to changes in predicted seagrass cover should be ignored.

Denitrification Efficiency.

In the model, denitrification efficiency is calculated as a bilinear function of detrital respiration (Murray and Parslow 1997). At low respiration rates, denitrification is inhibited by high sediment oxygen, while at high respiration rates, the absence of oxygen inhibits the preliminary nitrification of ammonia. It is thus at intermediate respiration rates that denitrification is most efficient.

Regions of the Bay with high sediment respiration rates and low denitrification efficiencies are not subject to load increases in any of the scenarios discussed here, so significant changes in median and 90%ile denitrification efficiency occur only in areas receiving low loads, i.e. the Sands and western Corio Bay. These areas respond to nutrient load increases with increased denitrification efficiency (Fig. 29, 30).

As we noted above, the response in model seagrass beds in the Sands is an artifact. The increases in sediment respiration rate and denitrification efficiency in Corio Bay and the northern Sands reflect changes in local sediment biogeochemistry, but are unlikely to be important bay-wide. As far as the bay-wide nitrogen cycle is concerned, areas currently exhibiting high denitrification efficiencies (most of the bay) are not significantly impacted by the scenarios. This applies even in Scenario 3B, where aquaculture and mussels deliver detritus directly to the central basin sediments, a critical site of bay-wide denitrification.

It should be noted that these conclusions about denitrification efficiency assume that the sediment organic load is spread evenly over the model box. In practice, organic loads from fish farm and mussel farm sites are likely to be concentrated directly under farms. This may well increase local sediment respiration rates to the point where denitrification efficiency falls close to zero. This is especially significant in the case of mussel farms, as mussels are potentially processing “background” bay nitrogen, and could significantly increase the efficiency with which this is recycled.

Target (Baseline - 1000 tonnes N y^{-1}) loads

Results for the scenarios under the target bay-wide loads are qualitatively very similar to those obtained under the baseline background loads. These target loads are the baseline N loads reduced by 1000 tonnes y^{-1} (Part A). Due to this reduction in background loads, the relative effects of aquaculture loads are often somewhat larger, but the patterns of response to aquaculture loads are very similar. The changes in background loads primarily affect the north-west and north-east coastal regions, which directly receive most of these loads (Part A). Corio Bay and southern Port Phillip Bay show only small responses to the proposed 1000 tonne N y^{-1} reduction. Hence, it is hardly surprising that the background reduction has little affect on conclusions about aquaculture loads.

Chlorophyll a.

The median values of chlorophyll a show very similar patterns of response to scenarios under baseline and target background loads. Under the target loads there is a small increase in the magnitude of both positive and negative relative changes (Fig. 31, 32). Positive responses increase because, with a lower baseline under the target loads, the effects of local inputs become more pronounced. Decreases in chlorophyll due to mussel grazing are exaggerated because increased mussel biomass and grazing pressure is required to maintain mussel production (Table 1) under the reduced bay-wide loads. The chlorophyll in box 51 in scenario 3A falls to 50% of the baseline. If the aquaculture with mussels is located in box 52 (scenario 3B), chlorophyll falls marginally from 97.4% to 96.9% of the respective baseline value.

There are some qualitative changes in the response of 90%ile chlorophyll in Corio Bay (scenario 1) under target background loads. This is not surprising as the 90%ile chlorophyll in eastern Corio Bay is dominated by intermittent inputs from the adjacent WTP, whose load is cut by 500 tonnes to obtain the target background loads. Addition of the 100 tonnes N loads into Box 40 causes the 90%ile chlorophyll in that box to actually decrease although increases do occur in neighbouring boxes. The decrease occurs because the continuous local input from aquaculture supports an enhanced macroalgal biomass, leading to a reduced response of phytoplankton chlorophyll to episodic nutrient inputs from the WTP. (The nutrient load from the WTP to the Bay does vary over a relatively smooth seasonal cycle, but input from the Werribee region to Corio Bay depends on variable currents and so is highly intermittent.)

Dissolved Inorganic Nitrogen.

Maps of the percentile change in DIN due to aquaculture loads under baseline and target bay-wide loads show no obvious differences (Fig. 33, 34). There are, in fact, marginal increases in the relative changes in DIN that are too small to be apparent in the maps. Away from the immediate vicinity of the major N sources, DIN concentrations under the baseline and target background loads are essentially the same.

Attenuation Kd.

As noted earlier, attenuation responds very weakly to any of the scenarios and this remains the case under target background loads (Fig. 35, 36). In the case of Corio Bay, the relative increase in attenuation in response to aquaculture loads is slightly stronger under target background loads. The small increase in attenuation under scenarios 2A and 2B is reduced still further as water and DON play larger relative roles in attenuation. With mussels, decreases in attenuation are reinforced, at least at the 90%ile, by the increased biomass and grazing pressure required.

Primary Production.

Primary production, like chlorophyll, shows slightly greater sensitivity to the aquaculture scenarios under target background loads (Fig. 37, 38). Again Corio Bay is an exception. Primary production does not actually decrease in box 40 with local N loading (as chlorophyll does), in fact it does not respond at all, locally, to the Corio Bay input. However, throughout the Corio Bay region the 90%ile primary production responds much more weakly to aquaculture loads under target background loads. Again, we attribute this to increases in macroalgal biomass.

Sediment Respiration.

Median sediment respiration in Corio Bay is more sensitive to aquaculture loads under the target background load, but 90%ile sediment respiration response is less sensitive (Fig. 39, 40). The median reflects an increased relative importance of the local nutrient source with lower WTP loads. The decline in the 90%ile response may again be due to interactions with macroalgae, which may act to reduce the variatiability in organic matter flux to sediments.

On the southern shore of Corio Bay (box 35), the response of sediment respiration rate to aquaculture loads reverses sign under the target background loads. In this box, the growth of seagrasses is sensitive to increases in DIN above baseline loads, but not when background loads are reduced to the target values.

Under scenarios 2A and 2B, the median sediment respiration shows a larger relative increase (against a lower baseline) throughout much of the southern bay. The 90%ile response differs little between current and target background loads.

Median and 90%ile sediment respiration rate responses to mussel farming are larger in the box containing the mussel production (Table 7), but are weakly affected elsewhere, with slight reductions in adjacent boxes.

Table 7. Responses of sediment respiration (percent target background) in locations receiving aquaculture inputs (boxes 40, 51 and 52) and the seagrass beds in the sands (boxes 10 and 11) under target background N loads. Values outside the ranges used in the maps (Fig. 39, 40) are shown in **bold**.

	%ile	Box 10	Box 11	Box 40	Box51	Box52
Scenario 1	50	94	96	**229**	101	101
Scenario 1	90	100	99	**170**	101	100
Scenario 2A	50	**52**	75	100	**126**	110
Scenario 2A	90	87	96	100	117	105
Scenario 3A	50	**71**	87	100	**486**	97
Scenario 3A	90	85	93	100	**293**	97
Scenario 2B	50	86	87	100	120	111
Scenario 2B	90	98	98	100	113	105
Scenario 3B	50	118	117	100	88	107
Scenario 3B	90	100	99	100	90	107

Again, predicted responses in the model seagrass beds in the Sands (boxes 10 and 11) should be ignored.

Denitrification

Only regions with low sediment respiration experience changes in denitrification efficiency in response to the scenarios under either background loading. Under target background loading, the areas so affected increase slightly in extent, and the magnitude of the response increases (Fig. 41, 42).

Summary and Conclusions.

The scenarios presented here involve only small changes (<3%) to the bay-wide N loads and are carried out against a background of changes to total loads some 5 to 10 times larger. They do not have major impacts upon the bay as a whole, but they can have significant local impacts. The extent to which these local impacts have been spatially resolved is affected by the size of the boxes in and adjacent to the affected areas.

The Corio Bay aquacultural input (scenario 1) has low to moderate impact on water-quality variables, with the exception of DIN, which increases by over 50% in the immediate vicinity of the inputs. Light attenuation exhibits only small responses to any scenario. Sediment respiration shows large percentile responses over a large area, but from a small background value. Perhaps ecologically more significantly, regional seagrass biomass nearly halves from 21 to 12 mg N m^{-2}, while macroalgal biomass increases from 478 to 588 mg N m^{-2}. In this case, the effects of increased nitrogen loads on benthic ecosystems are much more significant than their effects on the water column.

Fish farming in the southern bay at the intensities envisioned (scenarios 2A and 2B) has a small, but widespread, impact upon water-quality, reflecting the rapid mixing in that area. This low impact occurs in spite of the oligotrophic nature of the southern bay in which the fish farming is proposed. The low background chlorophyll and DIN means that small absolute changes appear as larger relative changes.

Relatively large changes in sediment respiration are predicted to occur under the fish-farming scenarios in the area of the northern boundary of the sands, again from a very low baseline. As with water quality, impact patterns are similar for both fish-farm locations (box 51 or 52). Predicted impacts on model seagrass beds in the central Sands is of hypothetical interests, as seagrass beds do not occur there. In the model, seagrass beds are adversely affected by elevated water column nutrient concentrations, due to epiphyte growth, and loss of seagrasses is predicted wherever significant increases in water column DIN occur.

It has been suggested that the impacts of nutrients released by intensive fish cage culture might be reversed by the culture and harvesting of mussels or other filter-feeders. The model shows that, provided the filter-feeders are distributed over a reasonably large area, chlorophyll in the presence of both fish-farms and mussels farms can be restored to near background conditions, although DIN and productivity are slightly elevated. If the area over which the mussels are farmed is too small, and their stocking density is too high, the resultant grazing pressure can result in major reductions in local phytoplankton density. In the high density scenario here (3A), mussels reduce chlorophyll levels by half and primary production by 20%. This also results in serious reductions in mussel production per unit biomass.

The predicted impacts of aquaculture on sediment biogeochemistry under scenarios 2 and 3 are locally substantial. Mussel farming increases the local impact, by concentrating the organic load to the sediment. Again, the local impact depends on stocking density. When intensive fish farming occurs in box 51, sediment respiration increases to 400% of the baseline value. However, when input is to box 52 the increase is much smaller (to 109%) because this input is spread over a larger area with a higher existing respiration rate. However, it should be stressed that the model distributes organic matter loads over the box area. Wherever farms are located, the local sediment fluxes under farms will be much larger than those predicted by the model under any scenario.

This is particularly relevant to impacts on denitrification efficiency. The distributed fluxes predicted by the model are not high enough to significantly reduce denitrification efficiency under any scenario. However, fluxes under fish farms and mussel farms are likely to be sufficiently high to severely reduce or shut down denitrification. The fish farms here are modelled simply as sources of DIN. In practice, fluxes of uneaten food and fish excretion result in very high organic matter loads under fish farms.

The model suggests that the food concentrations found in central Port Phillip Bay are so low as to lead to significantly reduced production to biomass ratios in mussels (see appendix). Depending on the configuration of farms, this may be exacerbated by local depletion. Productivity would presumably be increased if the mussels were located in northern or northeastern areas of the bay. If mussel beds were further separated from fish farms, they would still provide a bay-wide offset to the nitrogen load, but not necessarily a local offset.

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Appendix 1 - The Mussel Equations

The basic mussel grazing equation is taken from the filter-feeding production equation (Murray and Parslow 1997). Like other filter-feeders, mussels (ML) graze on all phytoplankton classes (PL, PS, PF), small zooplankton (ZS) and suspended microphytobenthos (MB); they also graze, at a lower efficiency, on labile detritus (DL). In this version of the model there is no growth of dinoflagellates PF and very little of the microphytobenthos biomass is suspended, so they do not significantly contribute to mussel growth.

$$MLCLEAR = ML \times C\_ML/(1 + (C\_ML \times (E\_ML \times (PS + PL + PF + MB + ZS) + E\_MLDL \times DL)/mum\_ML)$$

$$MLgrazePL = PL \times MLCLEAR$$

$$MLgrazePS = PS \times MLCLEAR$$

$$MLgrazePF = PF \times MLCLEAR$$

$$MLgrazeMB = MB \times MLCLEAR$$

$$MLgrazeZS = ZS \times MLCLEAR$$

$$MLgrazeDL = DL \times MLCLEAR$$

Mussels also transfer refractory detritus between the water-column and the sediment as a byproduct of grazing.

$$MLtransDR = DR \times MLCLEAR$$

Unlike other filter-feeders, mussel production results in a harvest that is removed from the system. In this way the harvest results in a sink resembling that due to denitrification, except that P too is removed.

$$MLharvest = E\_ML \times (MLgrazePL + MLgrazePS + MLgrazePF + MLgrazeMB + MLgrazeZS) + E\_MLDL \times MLgrazeDL$$

Material that is grazed by mussels, but which is either not ingested, or is ingested but is not assimilated as growth, results in the production of waste material. This waste is either in the form of ammonia or labile detritus. Again we split this material using a version of the equations used to divide up filter-feeder waste between these pathways. Phosphorous follows the same pathways as N, and P fluxes equal N fluxes multiplied by the P:N ratio. P release is handled implicitly in detrital P production but explicitly for phosphate release.

MLprodnDL = (1-E_ML) × FDG_ML × (MLgrazePL + MLgrazePS +MLgrazePF + MLgrazeMB +MLgrazeZS) + (1 - E_MLDL) × FDGM_LDL × MLgrazeDL

MLreleaseNH = (1-E_ML) × (1 - FDG_ML) × (MLgrazePL + MLgrazePS +MLgrazePF + MLgrazeMB +MLgrazeZS) + (1 - E_MLDL) × (1 - FDGDL_ML) × MLgrazeDL

MLreleaseP = MLreleaseNH × X_PN

Silica follows a somewhat different pathway to N and P. Silica is only present in diatoms (PL and MB) forming their indigestible tests. Silica is released immediately on ingestion in the form of detrital silica. In this we follow the formulation used for the existing filter-feeder model (Murray and Parslow 1997).

MLreleaseDSi = X_SiN × (MLgrazePL + MLgrazeMB)

Parameter values

The model requires six new parameters to implement the mussel production model. These are maximum growth, clearance rate, ingestion efficiencies on live matter and detritus and the fractional split of waste between detrital nitrogen and ammonia forms.

The annual production to biomass ratio of the mussel *Mytilus edulis* is 1.76:1 (Wilson et al. 1993); this is equivalent to 0.48% d^{-1}. We use a maximum growth rate (mum_ML) of 0.5% d^{-1} to replicate this situation in a well-fed mussel.

M. edulis filtration daily filtration rate is 113-185 l (g AFDW)$^{-1}$ (Wilson et al. 1993). AFDW is 0.07 WW and N is 0.75-1.5% WW (Longmore, personal communication). Therefore N content is about 14% of the AFDW. Filtration is thus 0.8 - 1.3 m^3 (g N)$^{-1}$ d^{-1}, this is about twice the rate used for other filter-feeders, suggesting mussels are adapted to grow at somewhat lower food concentrations.

Mytilus edulis assimilation is 38 or 50-64% efficient (from two references cited in Wilson et al. 1993). The former figure reflects an environment with a low organic matter content in the seston (19%), in the Sands much of the water-column matter is live plankton so higher efficiencies probably do apply. However, these figures do not include respiration and so will exceed growth efficiency E. We have used values of 0.5 and 0.25 for E_ML and EDL_ML. These are the same values as have been used for the generic filter-feeders.

We lack direct evidence on the fractional split between detritus and ammonia in mussel waste products. We therefore use the standard values for filter-feeders taken from the integrated model.

Table A1. Parameter values used for mussels.
mumML = 0.005 d^{-1}.
C_ML =0.001 m^3 (mg N)$^{-1}$ d^{-1}
E_ML = 0.5
E_MLDL = 0.25
FDG_ML = 0.25
FDGDL_ML = 0.75

Biomass

Mussel biomass must be pre-defined as it is held constant throughout a model run. The value in the aquaculture region is set so as to produce a harvest of 200 tonnes. The value in other boxes is set at zero.

We can make a preliminary estimate of the biomass required using steady-state analysis. Total ingestible plankton biomass in boxes 51 and 52 is about 6.75 mg N m^{-3} with a further 2.8 mg N m^{-3} of labile detritus. Based on the clearance equation and parameter values presented, this results in mussel production of 2 μg N (mg N)$^{-1}$ d^{-1} or a P:B ratio of 0.73 y^{-1}. Thus we need about 270 tonnes of mussel N to produce the 200 tonne annual harvest.

A mussel biomass of 270 tonnes N is about 2 - 3 times the estimated biomass based on mussel growth characteristics (Longmore personal communication), and the P:B ratio is also about 40% of the optimal value. The reason for this low productivity is the low biomass of plankton found in the centre of Port Phillip Bay. There is limited scope for increasing the productivity by altering the parameters; it is therefore unlikely the required biomass is substantially overestimated. The maximum growth efficiencies used are fairly close to assimilation efficiencies, and so are unlikely to be underestimated. We may have underestimated mum_ML. However, at low phytoplankton densities, production is limited by C_ML rather than mum_ML. C_ML could be up to 30% higher than the value used (equally, it could be lower).

The areas of box 51 and 52 are 18.1 and 145.3 km^2 so the required biomass densities are 15,000 and 1800 mg N m^2. We used these values as initial estimates of required mussel biomass. The estimate proved accurate for box 52 (199.8 tonnes N y^{-1}). However, in box 51 the harvest achieved was lower than that sought, because mussels reduced phytoplankton densities significantly. We found that a mussel density of 18,000 mg N m^{-2} was required to achieve an appropriate harvest (200.2 tonnes N y^{-1}). Likewise, for the scenarios carried out under the target background loads we had to further increase mussel biomass, to 19,000 and 1,900 mg N m^2 for boxes 51 and 52 respectively, to compensate for reduced productivity. These new biomasses give harvests of 199.3 and 201.8 tonnes N y^{-1}.

The biomass of mussels has to be increase to 325 tonnes N in scenario 2B because the mussels reduce phytoplankton densities by about 50%. Attempts to increase the harvest further would meet with severely diminishing returns.

References

Berelson, W.M., Heggie, D., Longmore, A., Kilgore, T., Nicholson, G. and Skyring, G. (1998). Benthic nutrient recycling in Port Phillip Bay, Australia. Estuarine, Coastal and Shelf Science 46, 917-934.

Bulthuis, D. A., Axelrad, D. M. and Mickelson, M. J. (1992) Growth of the seagrass *Heterozostera tasmanica* limited by nitrogen in Port Phillip Bay, Australia. Mar. Ecol. Prog. Ser. 89, 269-275

Cowdell, R.A., Gibbs, C.F., Longmore, A.R. and Theodoropolous, T. (1985). Tabulation of Port Phillip Bay water quality data between June 1980 and July 1984. Internal Report no. 98, Marine Science Laboratories, Ministry for Conservation, Queenscliff.

Murray, A. G. and Parslow J. S. (1997) Port Phillip Bay Integrated model: Final Report. Port Phillip Bay Environment Study Technical Report no. 44, Melbourne

Murray, A. G. and Parslow J. S. (1998) Port Phillip Bay Integrated model: Management Scenarios. Port Phillip Bay Environment Study Technical Report no. 44b, Melbourne

Murray, A. G. and Parslow J. S. (1999) Modelling of nutrient impacts in Port Phillip Bay - a semi-enclosed marine Australian ecosystem. Mar. Freshwater Res. 50, 597-611

Parslow, J., S. Sokolov, S. Murray (1999) Port Phillip Bay Baseline, Monitoring And Analysis For Nitrogen Load Reductions: Final Report Prepared for EPA. CSIRO, Hobart.

Raymont, J E G (1980) Plankton and Productivity in the Oceans 2nd Edition, Volume 1 Phytoplankton. Pergamon Press, Oxford

[1]State of Victoria (1997) State environment protection policy (Waters of Victoria) Schedule F6 (Waters of Port Phillip Bay) Victorian Government Gazette No S101 AGPS Publications Melbourne.

Walker, S. J. (1997) Hydrodynamic models of Port Phillip Bay. Port Phillip Bay Environment Study Technical Report no. 38, Melbourne

Walker, S. J. and Sherwood C. (1997) A transport model of Port Phillip Bay. Port Phillip Bay Environment Study Technical Report no. 39, Melbourne

Wilson, R. S., Cohen, B. F. and Poore, G. C. B. (1993) The role of suspension-feeding and deposit-feeding benthic macroinvertabrates in nutrient cycling in Port Phillip Bay. Technical Report no. 10, CSIRO Port Phillip Bay Study

Table 2. Average N loads (tonnes N y^{-1}) of rivers and drains entering Port Phillip Bay 1991-5 under the three bay-load scenarios.

	Yarra Estuary					Minor Creeks					Patterson-Mordialloc					WTP				BAY TOTAL
	NH4	NOx	Org N	Total		NH4	NOx	Org N	Total		NH4	NOx	Org N	Total		NH4	NOx	Org N	Total	
Baseline	161	555	1127	1843		13	21	57	91		188	324	544	1056		2407	357	900	3664	6654
WTP-500	161	555	1127	1843		13	21	57	91		188	324	544	1056		2079	309	777	3165	6155
Bay-1000	130	449	911	1490		13	21	57	91		161	277	465	903		2079	309	777	3165	5649

Table 3. Area-weighted segment statistics for model scenarios.

(A) Chlorophyll (mg Chla m^{-3})

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	3.42	0.62	1.01	2.04	4.26	7.48
Hobsons	WTP-500	3.44	0.61	1.00	2.03	4.27	7.52
Hobsons	Bay-1000	3.06	0.56	0.89	1.74	3.49	7.14
Werribee	Baseline	1.57	0.41	0.60	1.09	2.15	3.35
Werribee	WTP-500	1.42	0.39	0.54	0.93	1.89	3.12
Werribee	Bay-1000	1.43	0.39	0.54	0.92	1.90	3.15
Inshore	Baseline	0.97	0.35	0.52	0.73	1.06	1.70
Inshore	WTP-500	0.94	0.34	0.50	0.71	1.05	1.63
Inshore	Bay-1000	0.89	0.34	0.49	0.68	1.02	1.49
General	Baseline	0.87	0.55	0.62	0.73	0.93	1.28
General	WTP-500	0.82	0.54	0.60	0.70	0.88	1.19
General	Bay-1000	0.77	0.52	0.58	0.67	0.83	1.08

(B) DIN (mg N m^{-3})

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	45.24	14.70	18.66	28.15	52.31	96.90
Hobsons	WTP-500	44.53	14.50	18.43	27.48	51.43	95.54
Hobsons	Bay-1000	34.43	13.07	16.35	22.95	38.22	71.14
Werribee	Baseline	45.56	6.77	9.44	18.40	48.13	123.04
Werribee	WTP-500	36.68	6.37	8.41	15.46	38.67	97.64
Werribee	Bay-1000	36.49	6.33	8.37	15.33	38.33	97.03
Inshore	Baseline	10.98	5.39	6.18	7.38	9.68	15.55
Inshore	WTP-500	10.24	5.31	6.08	7.27	9.58	14.54
Inshore	Bay-1000	9.73	5.21	5.97	7.14	9.42	13.50
General	Baseline	6.87	5.11	5.53	6.12	6.90	8.22
General	WTP-500	6.59	5.00	5.42	5.98	6.74	7.88
General	Bay-1000	6.34	4.89	5.29	5.84	6.56	7.63

(C) Primary Production (mg N m^{-3} d-1)

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	17.64	2.84	5.38	12.23	24.25	37.57
Hobsons	WTP-500	17.66	2.80	5.36	12.12	24.34	37.86
Hobsons	Bay-1000	15.57	2.55	4.58	10.27	20.51	33.90
Werribee	Baseline	8.45	1.64	2.81	5.70	11.39	19.13
Werribee	WTP-500	7.52	1.51	2.46	4.67	9.91	17.09
Werribee	Bay-1000	7.56	1.50	2.44	4.64	9.92	17.27
Inshore	Baseline	4.09	1.33	1.93	2.82	4.36	8.07
Inshore	WTP-500	3.94	1.29	1.85	2.72	4.20	7.65
Inshore	Bay-1000	3.70	1.27	1.78	2.59	3.96	6.84
General	Baseline	3.14	1.56	1.88	2.57	3.60	5.10
General	WTP-500	2.93	1.49	1.81	2.44	3.36	4.65
General	Bay-1000	2.72	1.43	1.72	2.30	3.12	4.22

Table 3 (Cont.)

(D) Attenuation Coeffiient (m^{-1})

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	0.33	0.18	0.23	0.36	0.56	0.83
Hobsons	WTP-500	0.32	0.18	0.23	0.36	0.55	0.83
Hobsons	Bay-1000	0.30	0.17	0.21	0.33	0.49	0.74
Werribee	Baseline	0.28	0.18	0.21	0.28	0.44	0.65
Werribee	WTP-500	0.27	0.17	0.20	0.27	0.40	0.60
Werribee	Bay-1000	0.27	0.17	0.20	0.27	0.40	0.60
Inshore	Baseline	0.18	0.13	0.15	0.17	0.23	0.34
Inshore	WTP-500	0.18	0.13	0.15	0.17	0.22	0.33
Inshore	Bay-1000	0.18	0.13	0.15	0.16	0.21	0.32
General	Baseline	0.19	0.15	0.16	0.18	0.21	0.27
General	WTP-500	0.18	0.15	0.16	0.17	0.20	0.26
General	Bay-1000	0.18	0.15	0.16	0.17	0.20	0.25

(E) Sediment Respiration (mg N m^{-2} d^{-1})

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	80.10	12.75	27.15	50.18	90.77	164.37
Hobsons	WTP-500	79.73	12.35	26.78	49.87	89.82	164.14
Hobsons	Bay-1000	62.89	8.52	20.64	37.74	69.29	130.74
Werribee	Baseline	53.92	9.34	18.87	36.25	76.20	126.36
Werribee	WTP-500	46.95	7.49	15.45	29.52	65.67	114.34
Werribee	Bay-1000	46.76	7.34	15.26	29.25	65.48	114.35
Inshore	Baseline	5.95	0.53	0.80	1.83	7.15	14.50
Inshore	WTP-500	5.55	0.50	0.75	1.75	6.79	13.84
Inshore	Bay-1000	4.91	0.48	0.71	1.67	6.17	11.82
General	Baseline	19.90	2.00	7.49	17.46	28.28	40.67
General	WTP-500	18.39	2.09	6.39	16.06	26.04	37.88
General	Bay-1000	16.83	2.08	5.58	14.60	23.91	34.63

(F) Denitrification (%)

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	43.81	12.16	32.87	50.04	58.13	63.21
Hobsons	WTP-500	43.77	11.56	32.73	50.03	58.19	63.29
Hobsons	Bay-1000	46.11	12.90	35.44	53.24	60.04	63.75
Werribee	Baseline	48.67	23.31	38.98	54.30	61.62	64.54
Werribee	WTP-500	49.49	24.11	39.79	55.32	62.49	64.62
Werribee	Bay-1000	49.39	23.86	39.66	55.26	62.51	64.64
Inshore	Baseline	22.65	0.20	1.70	10.89	45.39	63.04
Inshore	WTP-500	22.03	0.15	1.38	10.33	43.59	63.00
Inshore	Bay-1000	20.62	0.11	1.11	9.46	40.25	61.79
General	Baseline	49.82	10.00	44.96	59.41	63.40	65.21
General	WTP-500	49.37	10.77	39.62	59.60	63.57	65.33
General	Bay-1000	48.83	10.93	35.24	59.79	63.76	65.42

Table 3 (Cont)

(G) DIP (mg P m^{-3})

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	78.83	69.84	73.30	77.45	83.19	90.86
Hobsons	WTP-500	78.58	69.60	72.96	77.19	83.00	90.76
Hobsons	Bay-1000	77.05	68.15	71.72	75.86	81.41	88.75
Werribee	Baseline	118.61	87.05	97.99	113.52	133.23	156.75
Werribee	WTP-500	118.92	87.03	98.05	113.89	134.01	156.95
Werribee	Bay-1000	117.74	85.91	96.88	112.76	132.86	155.74
Inshore	Baseline	66.75	27.27	48.47	68.85	78.65	105.10
Inshore	WTP-500	66.65	27.19	48.32	68.60	78.52	105.17
Inshore	Bay-1000	65.76	26.94	47.65	67.49	77.32	103.91
General	Baseline	70.13	55.55	63.49	69.15	74.79	84.88
General	WTP-500	69.95	55.26	63.12	68.83	74.65	84.90
General	Bay-1000	68.89	54.41	62.06	67.71	73.48	83.71

(H) SiO2 (mg Si m^{-3})

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	165.43	46.09	82.53	168.07	227.46	268.40
Hobsons	WTP-500	168.27	48.86	88.02	172.73	226.70	267.51
Hobsons	Bay-1000	181.20	58.84	111.61	192.77	230.81	270.16
Werribee	Baseline	148.67	34.02	65.29	138.41	223.81	278.49
Werribee	WTP-500	159.26	43.72	82.51	153.35	230.13	279.17
Werribee	Bay-1000	160.12	45.29	84.97	154.35	229.62	278.41
Inshore	Baseline	119.15	25.68	57.38	110.73	177.85	216.34
Inshore	WTP-500	122.93	27.57	63.46	116.70	181.12	217.44
Inshore	Bay-1000	126.88	29.70	70.08	122.20	183.66	218.73
General	Baseline	137.85	65.23	98.72	136.72	180.71	209.32
General	WTP-500	141.85	72.42	104.64	140.78	182.94	210.71
General	Bay-1000	145.41	81.82	110.42	144.13	183.40	210.73

(I) DON (mg N m^{-3})

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	37.54	31.20	33.32	36.91	41.26	44.37
Hobsons	WTP-500	35.94	29.95	31.80	35.31	39.53	42.47
Hobsons	Bay-1000	34.29	28.76	30.59	33.78	37.51	40.33
Werribee	Baseline	48.79	37.88	42.24	47.51	54.83	60.45
Werribee	WTP-500	45.51	35.77	39.66	44.41	50.84	55.75
Werribee	Bay-1000	44.43	34.87	38.70	43.33	49.70	54.60
Inshore	Baseline	29.84	7.45	19.98	31.75	37.74	47.87
Inshore	WTP-500	28.29	7.13	19.10	30.38	35.93	44.78
Inshore	Bay-1000	27.37	6.91	18.47	29.32	34.61	43.62
General	Baseline	32.57	23.99	28.80	32.11	36.03	41.22
General	WTP-500	31.01	22.95	27.54	30.65	34.37	39.11
General	Bay-1000	29.98	22.19	26.63	29.66	33.15	37.74

Table 3 (cont.)

(J) MPB Production (mg N m^{-2} d^{-1})

SEPP Seg		Mean	10%ile	25%ile	median	75%ile	90%ile
Hobsons	Baseline	23.98	7.70	14.30	25.19	33.33	39.26
Hobsons	WTP-500	23.92	7.65	14.11	25.44	33.11	39.36
Hobsons	Bay-1000	24.07	8.26	14.18	25.06	32.68	40.09
Werribee	Baseline	25.86	11.63	19.96	24.84	32.94	41.39
Werribee	WTP-500	25.42	11.85	19.33	24.54	32.28	40.54
Werribee	Bay-1000	25.41	11.86	19.29	24.51	32.28	40.54
Inshore	Baseline	11.72	0.12	1.69	9.32	19.23	27.75
Inshore	WTP-500	11.08	0.11	1.43	8.52	18.08	26.80
Inshore	Bay-1000	10.61	0.10	1.34	8.01	17.28	25.78
General	Baseline	17.93	1.58	5.73	17.71	27.00	37.27
General	WTP-500	18.51	1.41	6.50	18.83	27.77	37.66
General	Bay-1000	19.06	1.17	7.41	19.80	28.39	37.97

Table 4. Model predictions of area weighted 50 and 90 percentile chlorophyll concentrations (mg chl m^{-3}) and 90 percentile light attenuation Kd (m^{-1}) for SEPP segments under the three bay-load scenarios. Also shown are the regional SEPP criteria. Cases in which the model predicts exceedence of these objectives are in **bold**.

	Baseline	*WTP-500*	*Bay-1000*	*SEPP 50%*
Chl 50%				
Hobsons	2.04	2.03	1.74	<2.7
Werribee	1.09	0.93	0.92	<2.7
Inshore	0.73	0.71	0.68	<1.5
General	0.73	0.70	0.67	<1
Chl 90%				
Hobsons	**7.48**	**7.52**	**7.14**	<4
Werribee	3.35	3.12	3.15	<4
Inshore	1.70	1.63	1.49	<2.5
General	1.28	1.19	1.08	<2
Kd 90%				
Hobsons	**0.83**	**0.83**	**0.74**	0.5
Werribee	**0.69**	**0.63**	**0.63**	0.45
Inshore	0.37	0.35	0.34	0.45
General	0.31	0.30	0.29	0.35

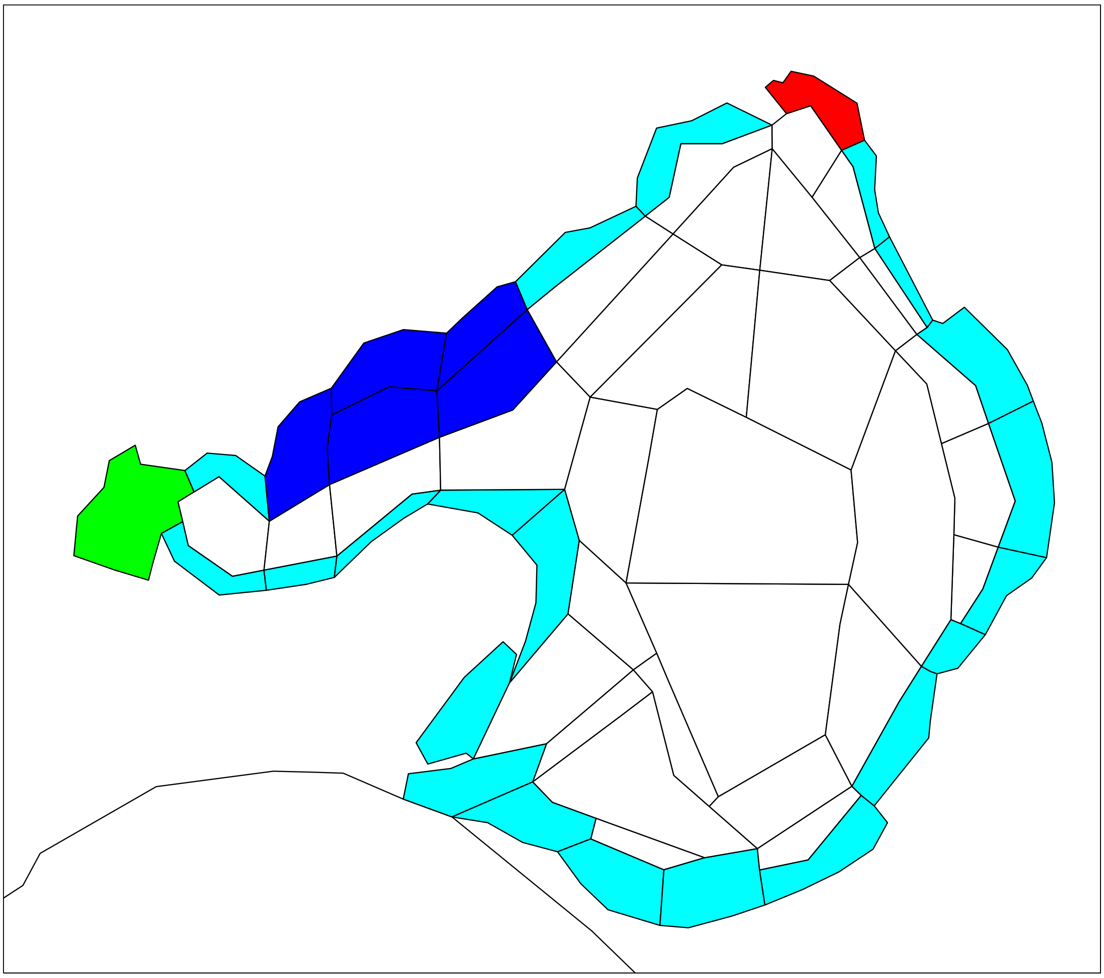

Figure 1. Spatial box structure of the PPBES integrated model, showing the model representation of SEPP segments: Corio Bay (green), Werribee (dark blue), Hobsons Bay (red), Inshore segment (cyan), and the General segment (white).

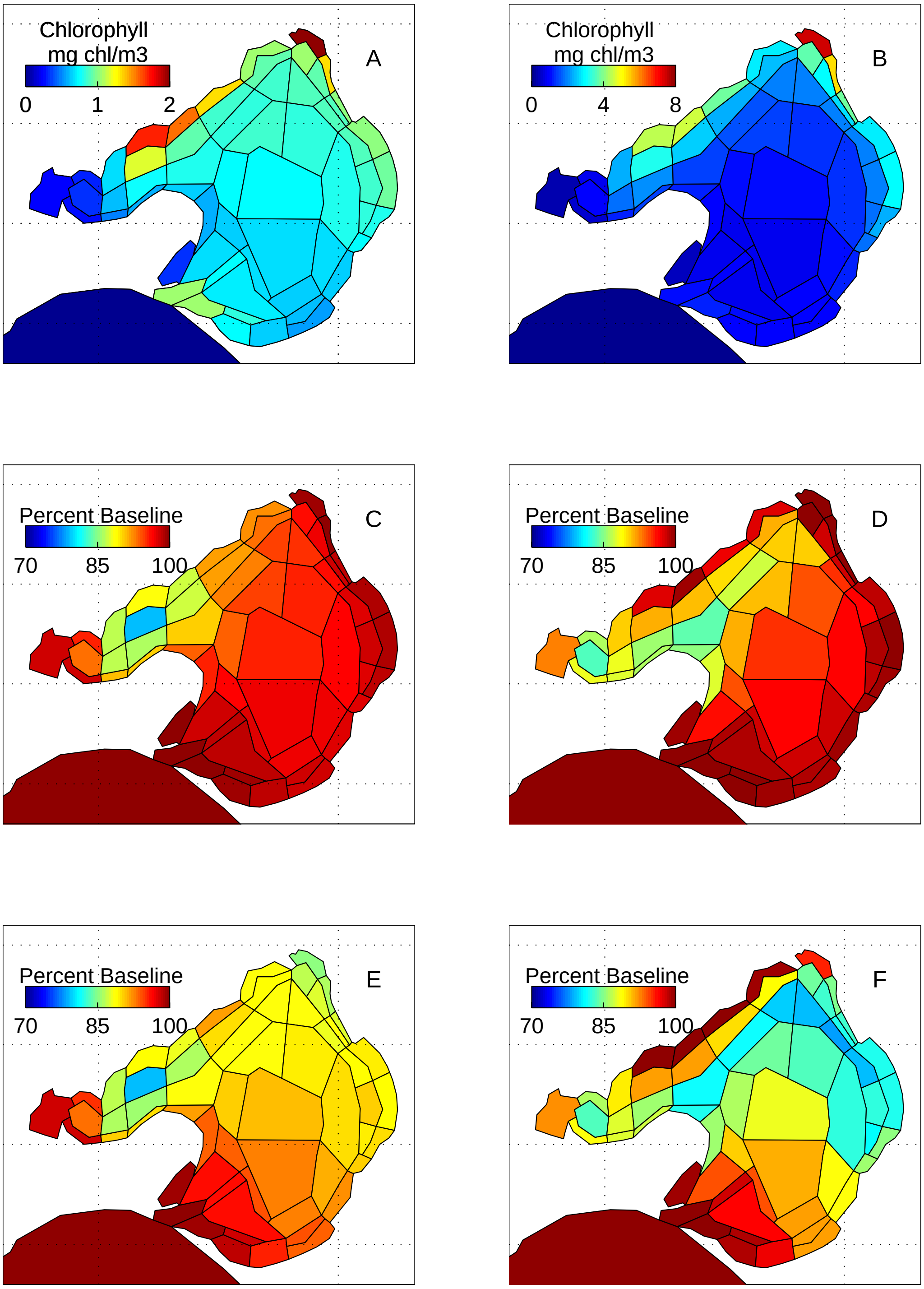

Figure 2. Effect of load reductions on chlorophyll distribution. A: baseline median chlorophyll; B: baseline 90 percentile chlorophyll; C: % of baseline median for WTP load – 500 t N y^{-1}; D: % of baseline 90 percentile for WTP load – 500 t N y^{-1}; E: % of baseline median for Bay-wide load –1000 t N y^{-1}; F: % baseline 90 percentile for Bay-wide load – 1000 t N y^{-1}.

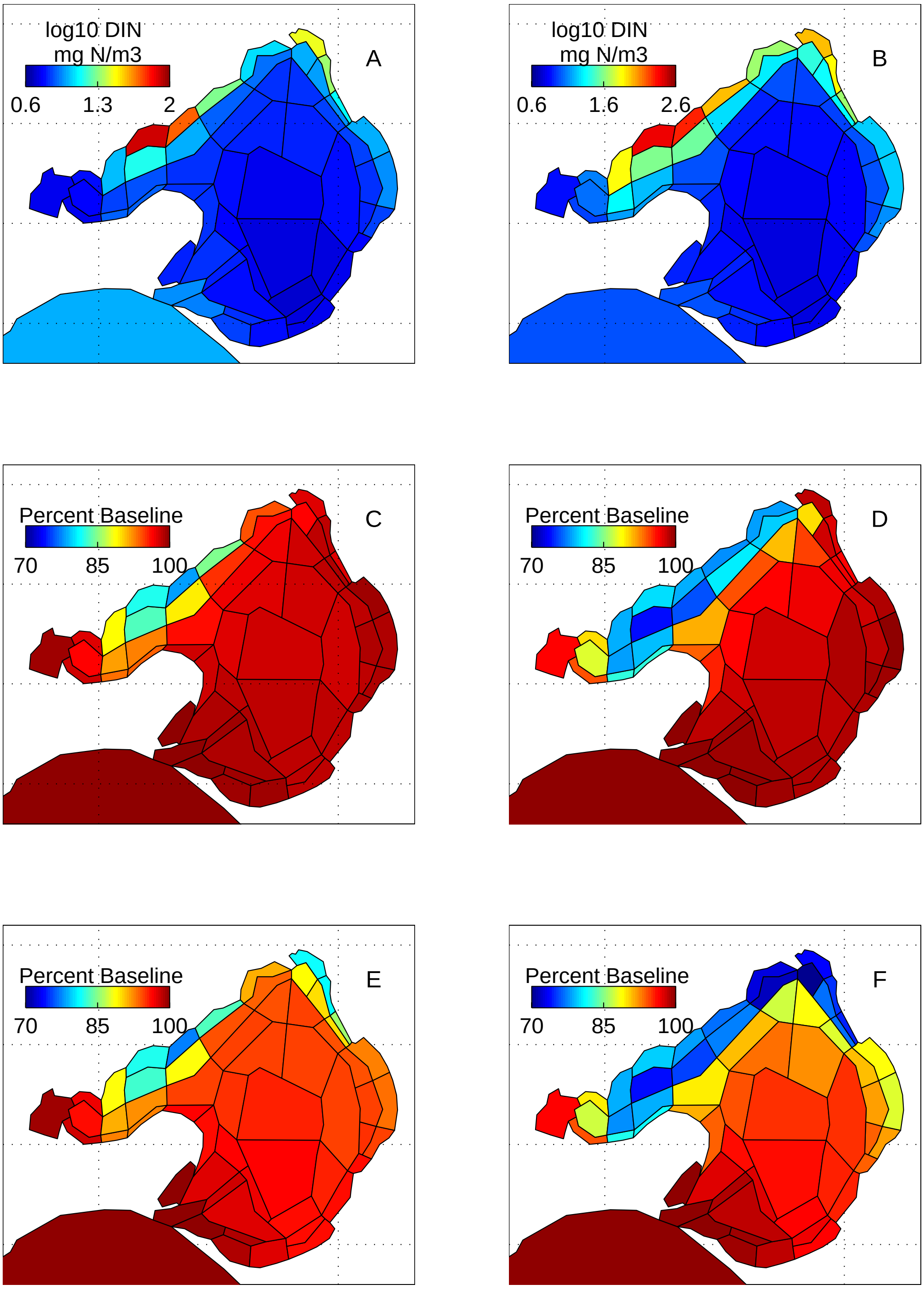

Figure 3. Effect of load reductions on DIN distribution. A: baseline median DIN; B: baseline 90 percentile DIN; C: % of baseline median for WTP load – 500 t N y^{-1}; D: % of baseline 90 percentile for WTP load – 500 t N y^{-1}; E: % of baseline median for Bay-wide load –1000 t N y^{-1}; F: % baseline 90 percentile for Bay-wide load – 1000 t N y^{-1}. Note $\log_{10}$ scale in A (4, 20, 100 mg N m^{-3}) and B (4, 40, 400 mg N m^{-3}).

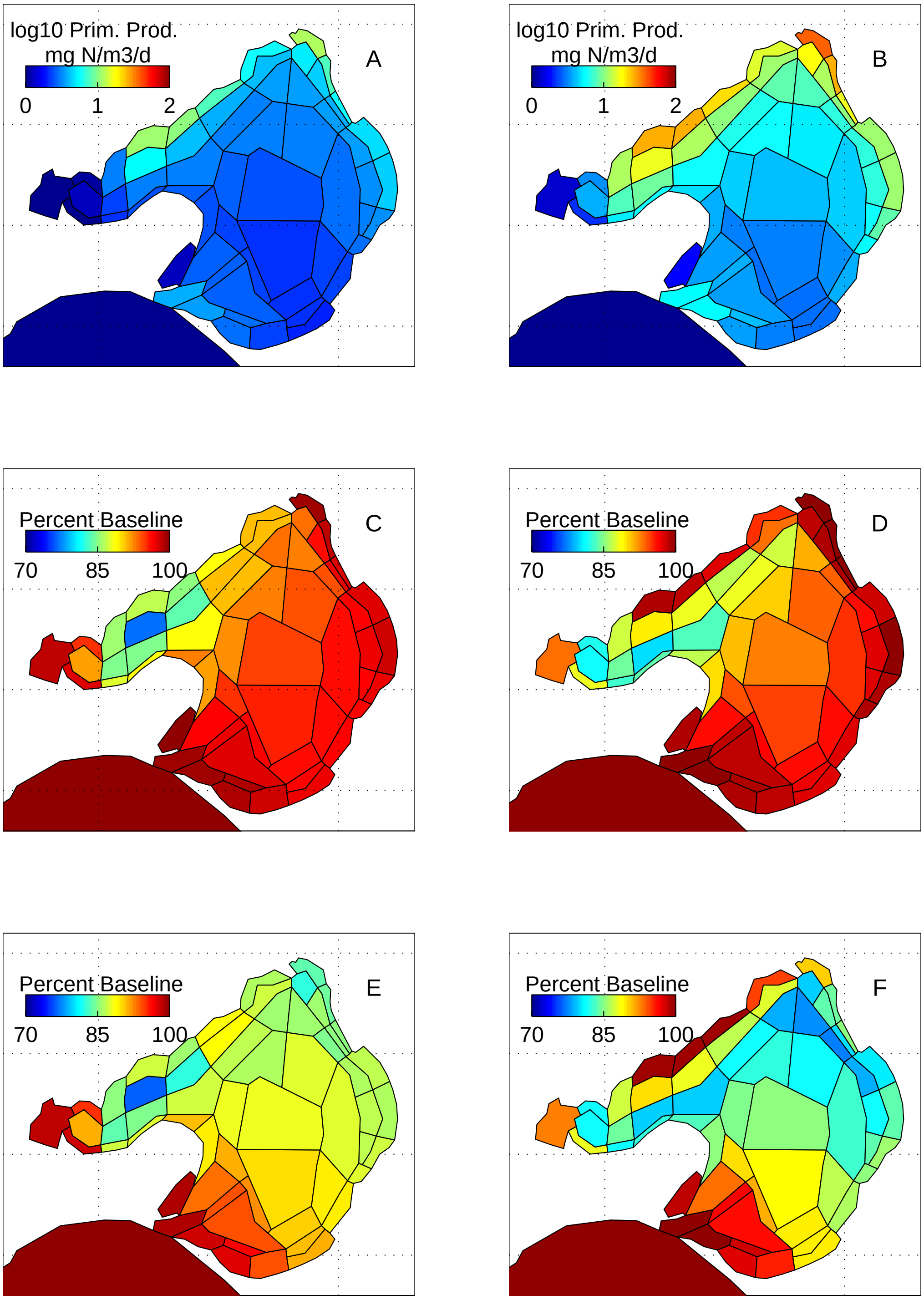

Figure 4. Effect of load reductions on primary production distribution. A: baseline median primary production; B: baseline 90 percentile primary production; C: % of baseline median for WTP load – 500 t N y^{-1}; D: % of baseline 90 percentile for WTP load – 500 t N y^{-1}; E: % of baseline median for Bay-wide load –1000 t N y^{-1}; F: % of baseline 90 percentile for Bay-wide load – 1000 t N y^{-1}. Note log_{10} scale in A and B (1, 10, 100 mg N m^{-3} d^{-1}).

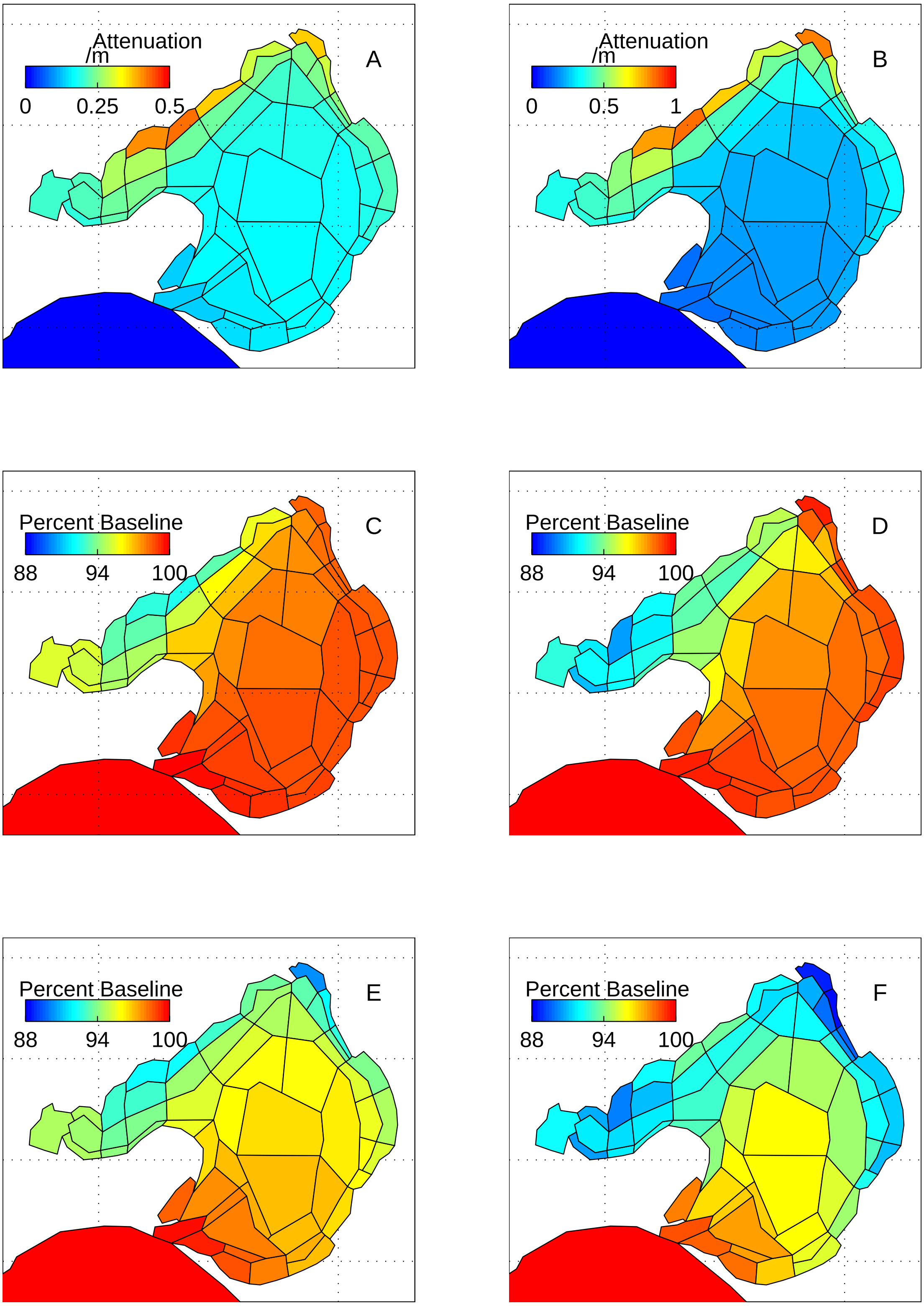

Figure 5. Effect of load reductions on light attenuation Kd. A: baseline median Kd; B: baseline 90 percentile Kd; C: % of baseline median for WTP load – 500 t N y^{-1}; D: % of baseline 90 percentile for WTP load – 500 t N y^{-1}; E: % of baseline median for Bay-wide load –1000 t N y^{-1}; F: % of baseline 90 percentile for Bay-wide load – 1000 t N y^{-1}.

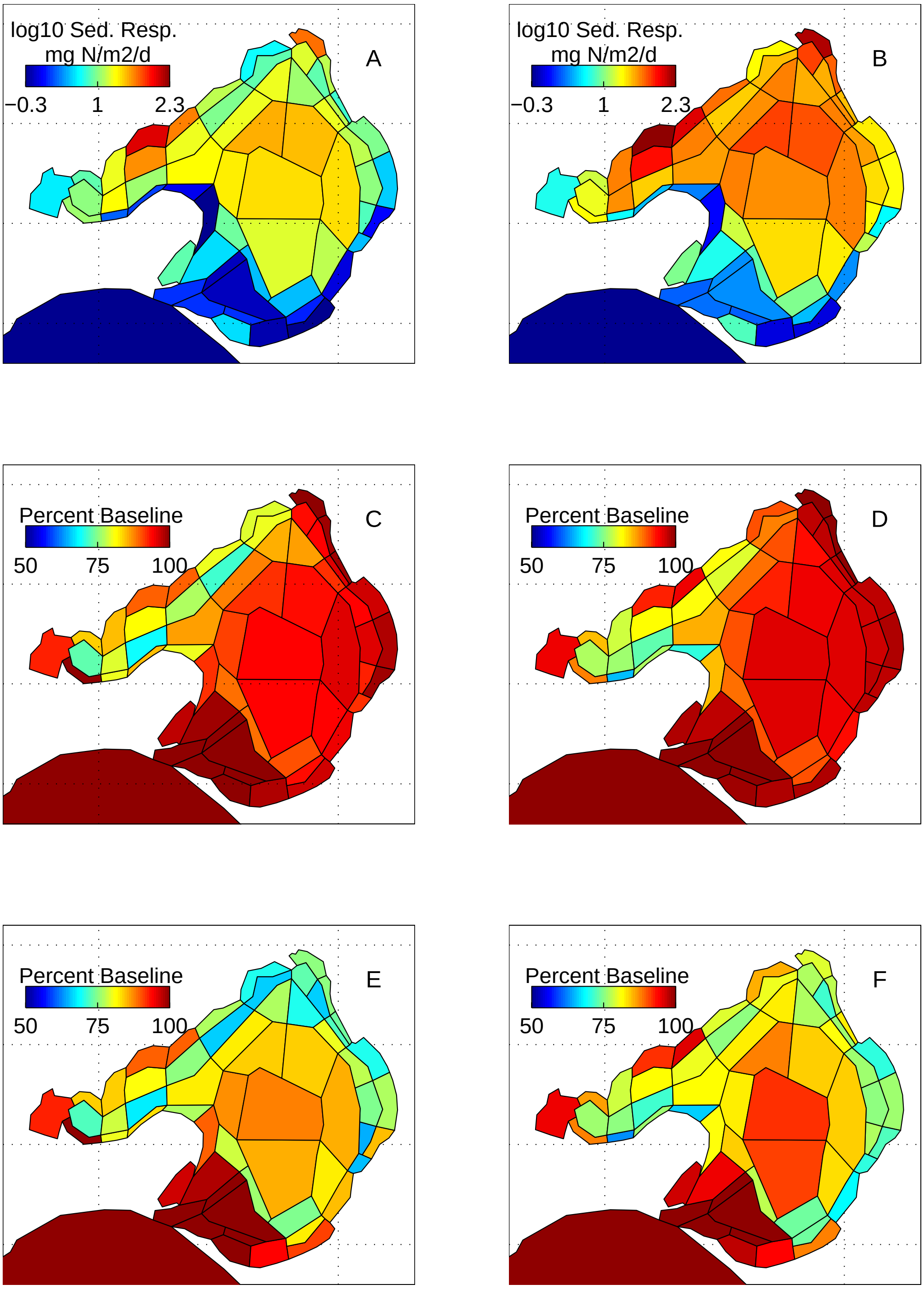

Figure 6. Effect of load reductions on sediment respiration distribution. A: baseline median sediment respiration; B: baseline 90 percentile sediment respiration; C: % of baseline median for WTP load – 500 t N y^{-1}; D: % of baseline 90 percentile for WTP load – 500 t N y^{-1}; E: % of baseline median for Bay-wide load –1000 t N y^{-1}; F: % of baseline 90 percentile for Bay-wide load – 1000 t N y^{-1}. Note use of log_{10} scale in A and B (0.5, 10, and 200 mg N m^{-2} d^{-1}).

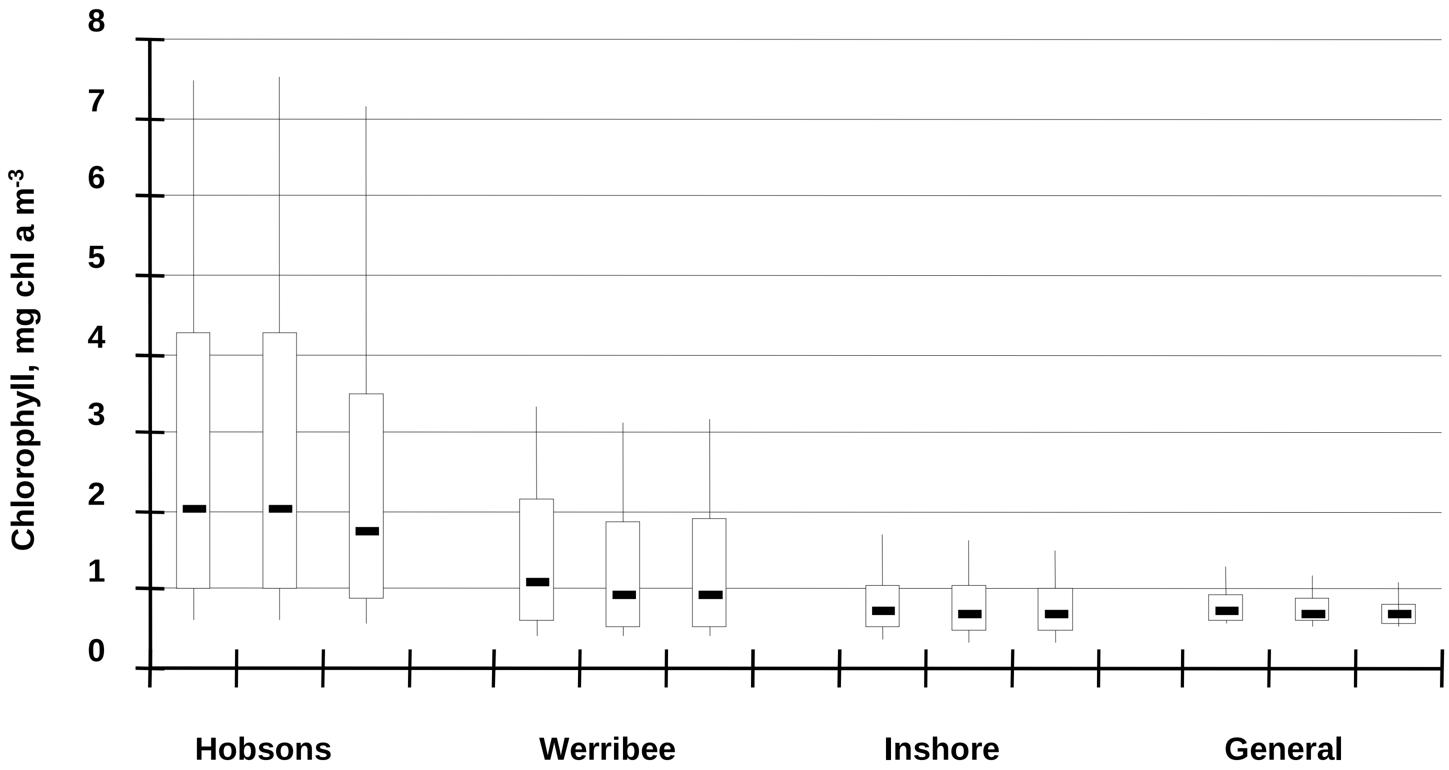

Figure 7. Box and whiskers plot of modelled chlorophyll a in the SEPP segments under the three scenarios (Baseline, WTP – 500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles.

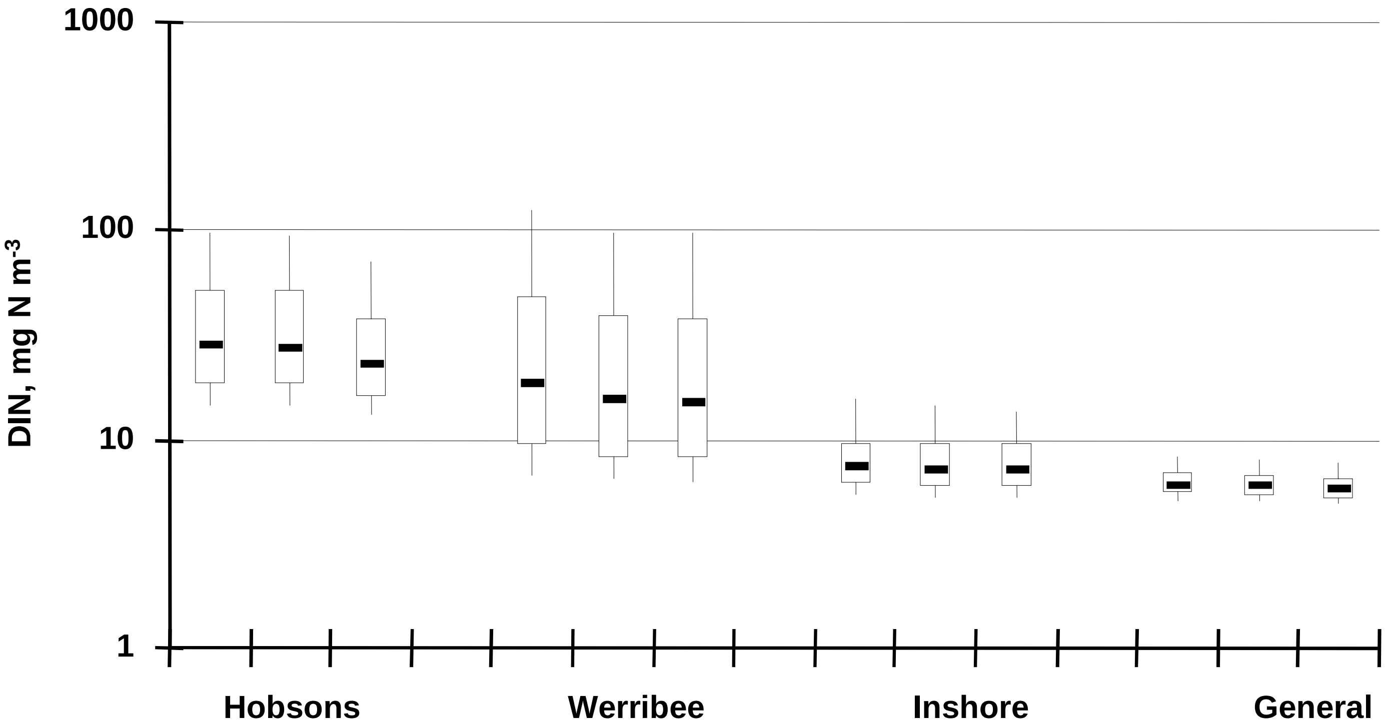

Figure 8. Box and whiskers plot of modelled dissolved inorganic nitrogen in the SEPP segments under the three scenarios (Baseline, WTP – 500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles. Note the use of a $\log_{10}$ scale.

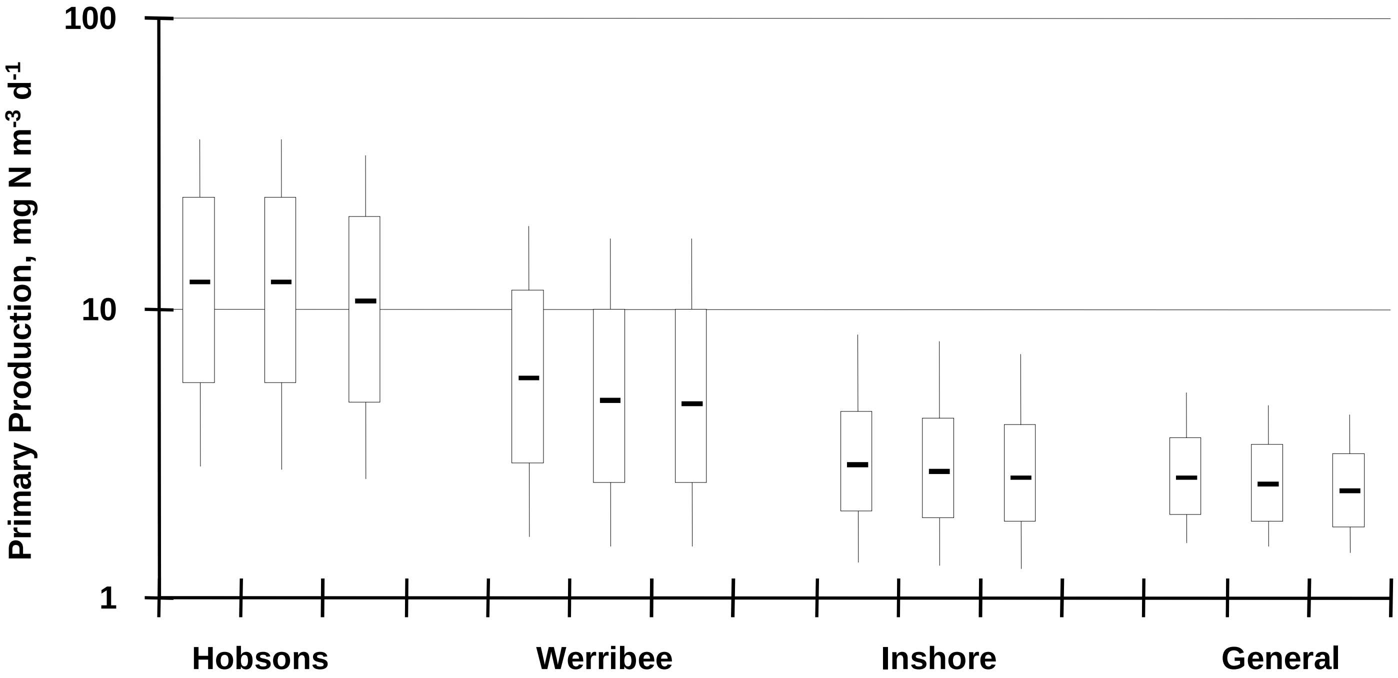

Figure 9. Box and whiskers plot of modelled primary production by phytoplankton in the SEPP segments under the three scenarios (Baseline, WTP – 500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles. Note the use of a $\log_{10}$ scale.

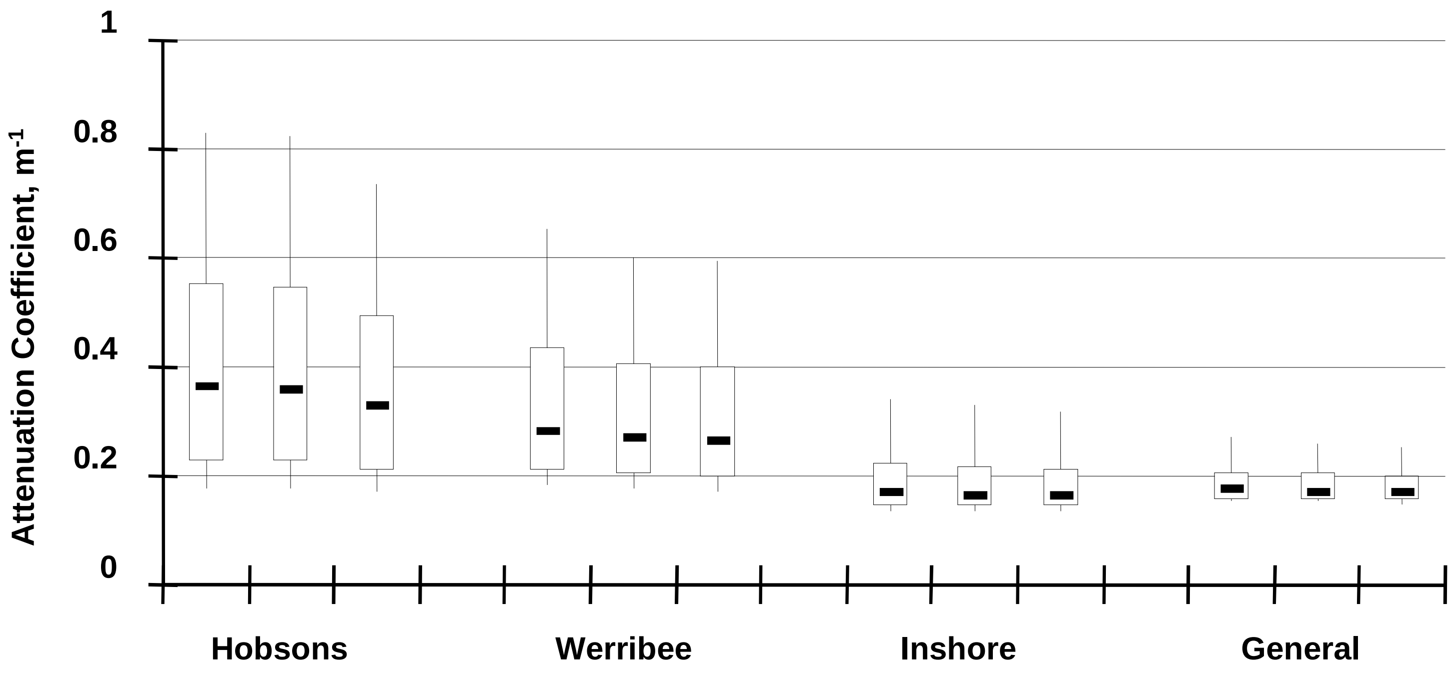

Figure 10. Box and whiskers plot of modelled light attenuation coefficients in the SEPP segments under the three scenarios (Baseline, WTP –500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles.

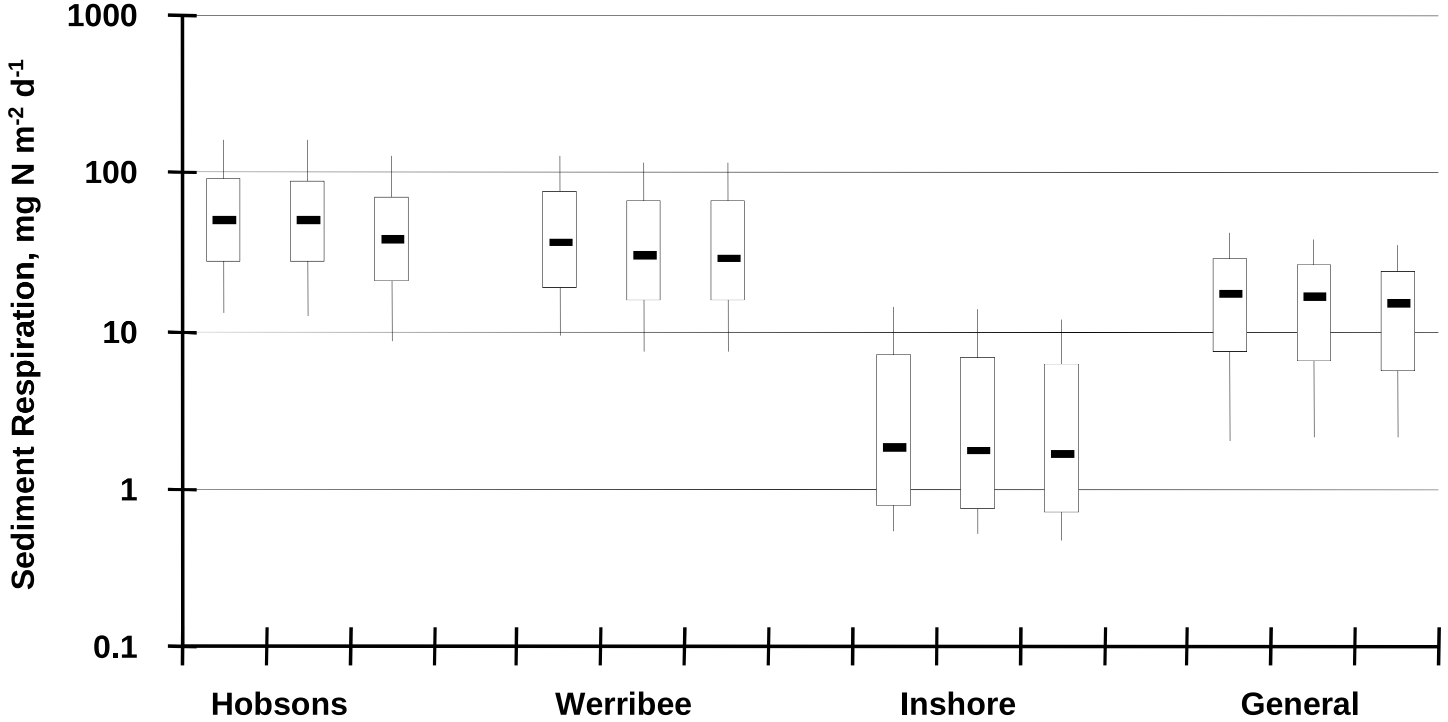

Figure 11. Box and whiskers plot of modelled sediment respiration in the SEPP segments under the three scenarios (Baseline, WTP – 500, Bay – 1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles. Note the use of a $\log_{10}$ scale.

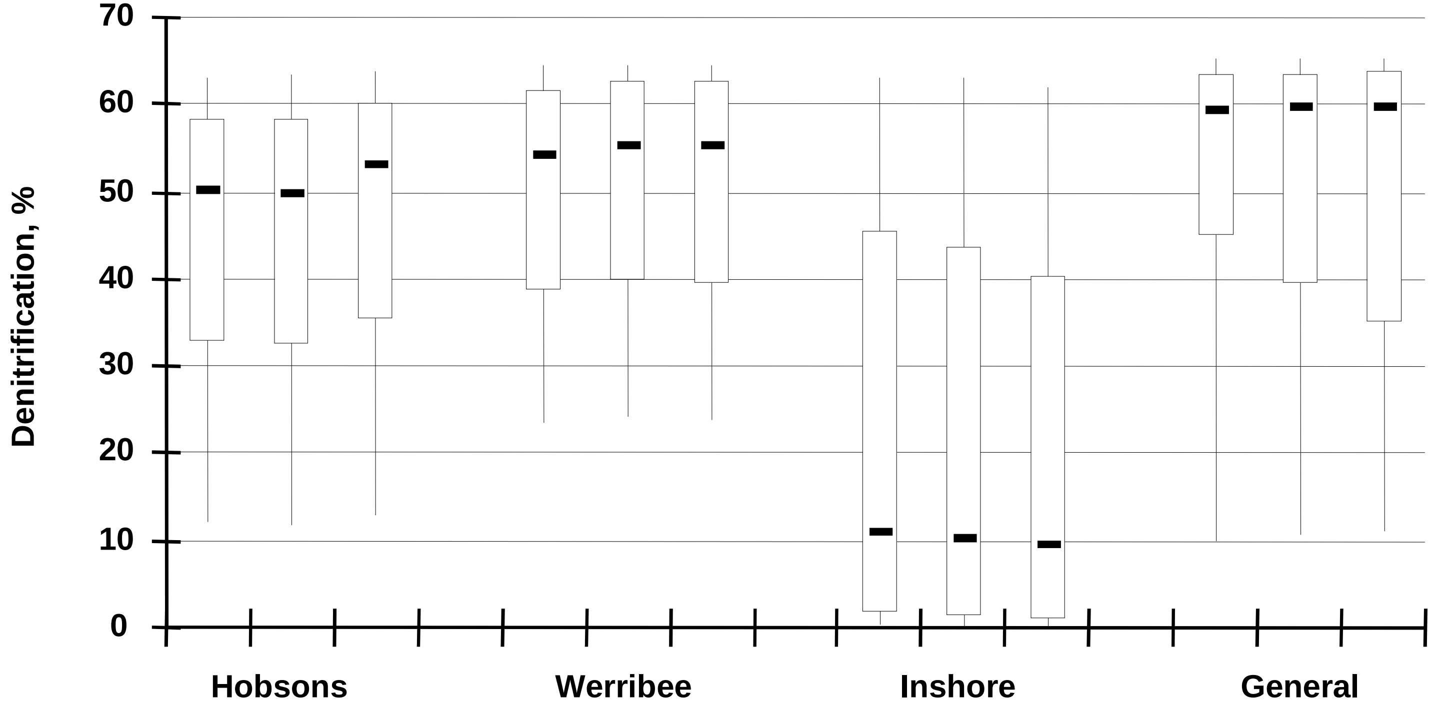

Figure 12. Box and whiskers plot of modelled percentage denitrification in the SEPP segments under the three scenarios (Baseline, WTP – 500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles

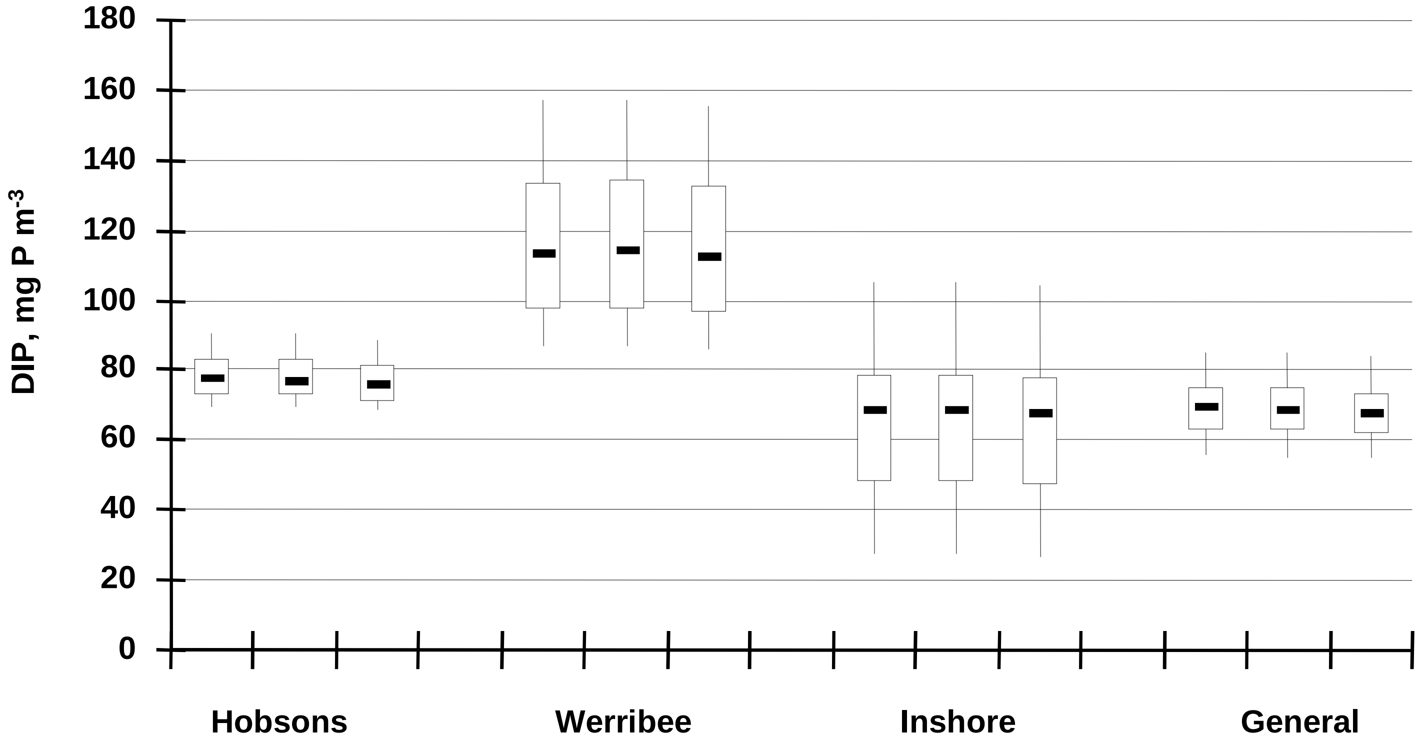

Figure 13. Box and whiskers plot of modelled dissolved inorganic phosphate in the SEPP segments under the three scenarios (Baseline, WTP – 500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles.

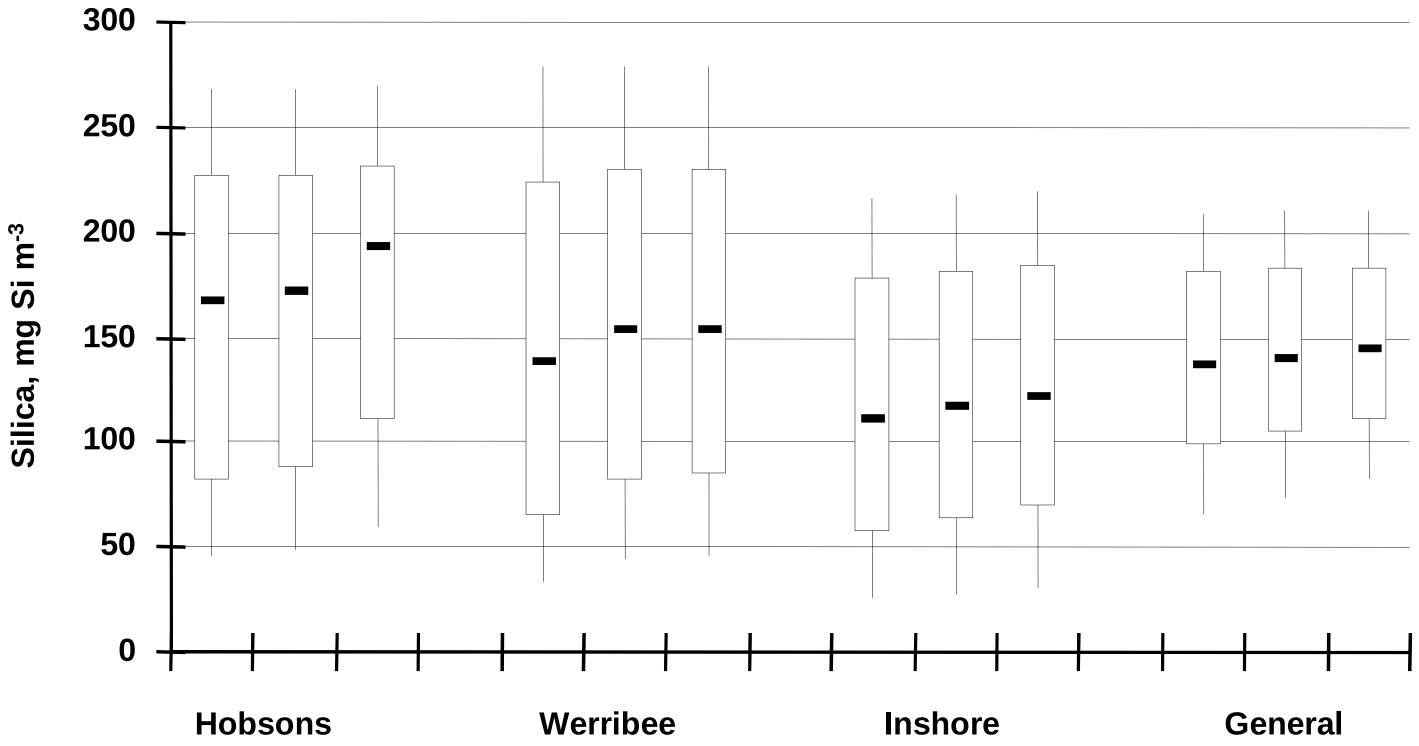

Figure 14. Box and whiskers plot of modelled dissolved inorganic silicate in the SEPP segments under the three scenarios (Baseline, WTP – 500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles.

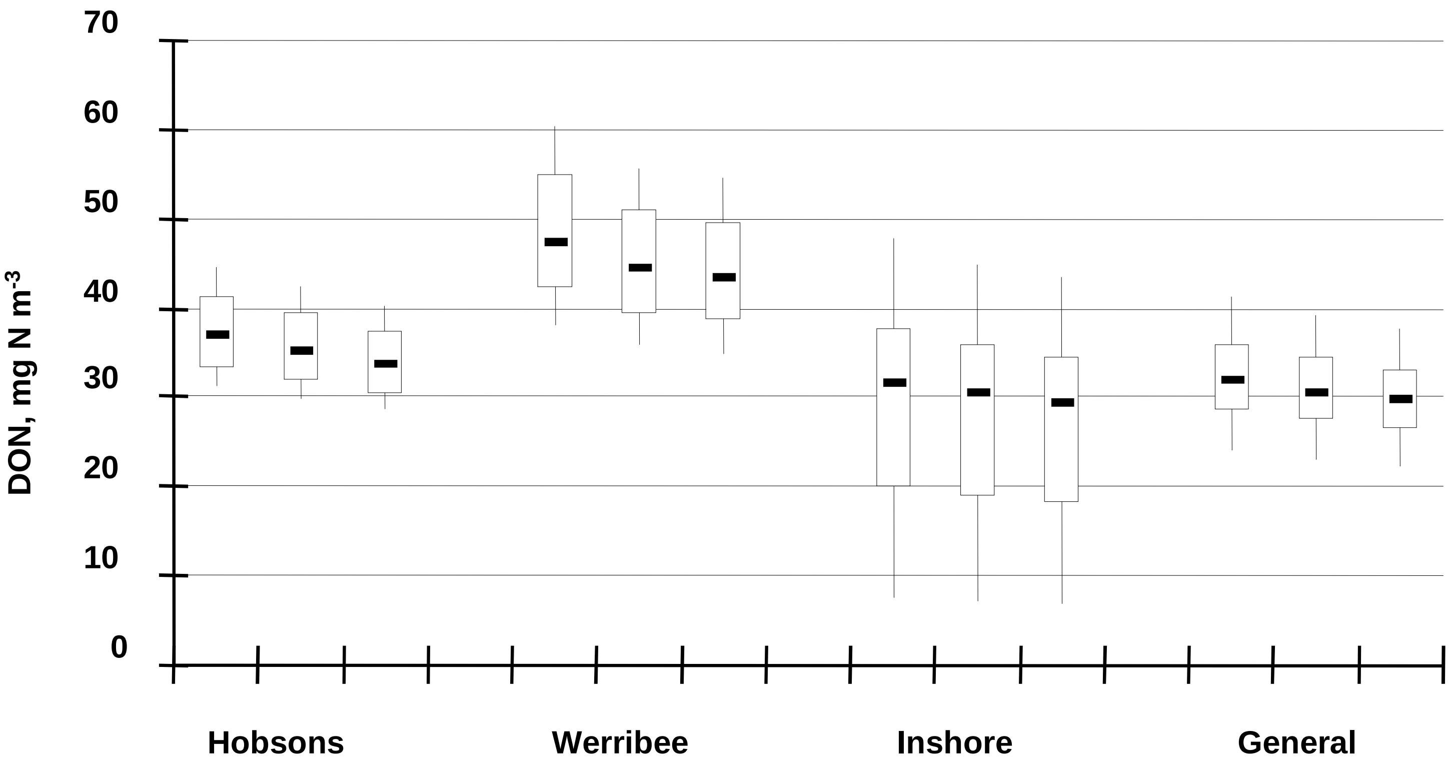

Figure 15. Box and whiskers plot of modelled dissolved organic nitrogen (DON), with oceanic background DON subtracted, in the SEPP segments under the three scenarios (Baseline, WTP – 500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles.

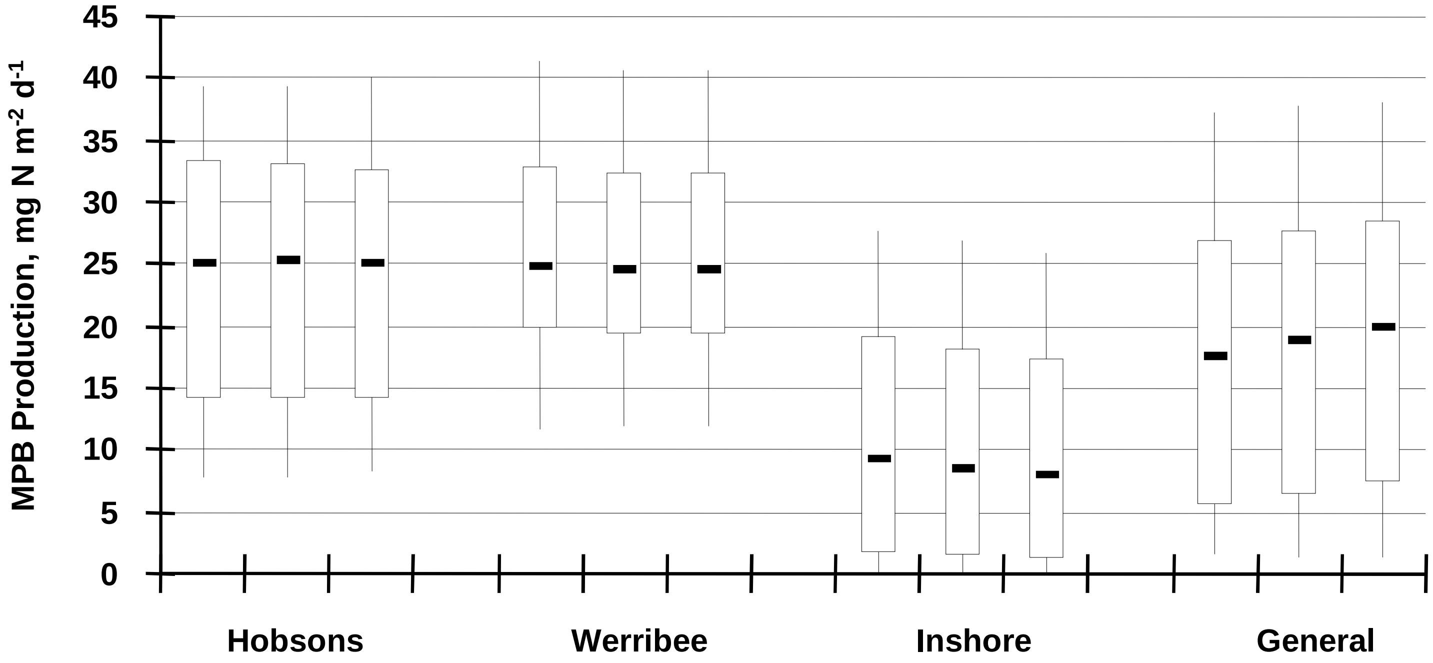

Figure 16. Box and whiskers plot of modelled microphytobenthos production in the SEPP segments under the three scenarios (Baseline, WTP –500, Bay –1000). The central black bar marks the median (50 percentile) value; the box covers the region of the 25 – 75 percentiles, while the whiskers cover the region of the 10 – 90 percentiles.

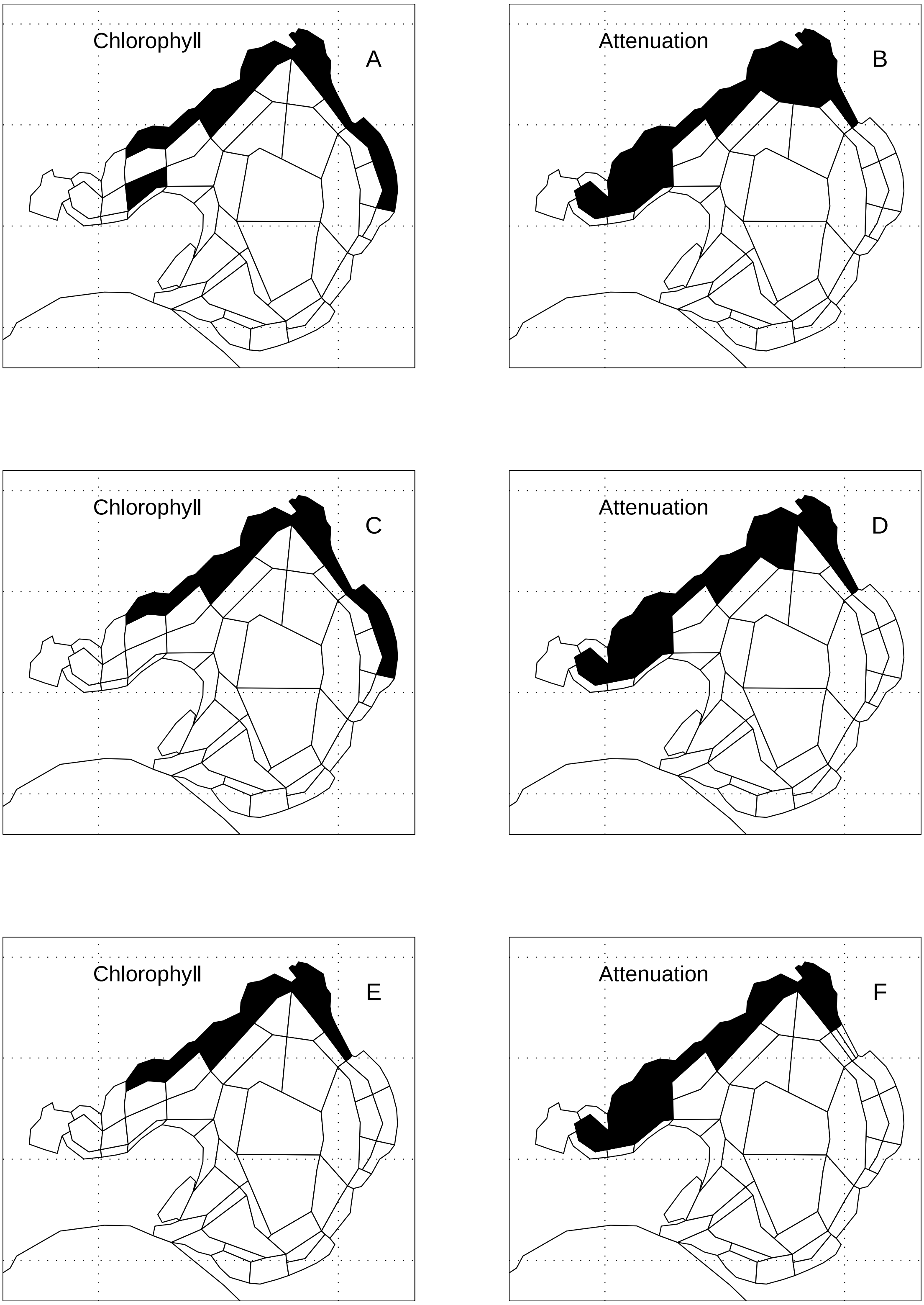

Figure 17. Distributions of predicted exceedences of local 90 percentile SEPP objectives for chlorophyll (A, C, E) and 10 percentile SEPP objectives for light attenuation coefficients (B, D, F) under the three loading scenarios: baseline (A, B), WTP loads – 500 t N y^{-1} (C, D) and Bay-wide loads –1000 t N y^{-1} (E, F).