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Port Phillip Bay Integrated Model: Nitrogen Load Scenarios

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FOREWORD

(Port Phillip Bay Environmental Study Management Committee)

The quality of water in Port Phillip Bay is a key factor in Melbourne's social and economic life, and the ecological integrity of the Bay's ecosystem.

In the latter half of the nineteenth and the first half of the twentieth century scant regard was given to the impact of the expanding urban settlements and catchment activities on Port Phillip Bay water quality. While this was not unusual for those times there was growing disquiet, and an emerging preference for decisions that would mitigate rather than reinforce these adverse impacts.

Scientific studies of the Bay commenced in 1888 and building on studies over the following decades the first comprehensive environmental study of the Bay and its catchment was completed in 1968-71. This was a landmark study and it provided a sound basis for Government decisions to reduce gross pollution from point source discharges that were a major threat to the Bay at that time. These decisions were significant in the history of the Bay and many involved actions that had long lead times, including the Government's 1969 decision that treated effluent from the proposed South Eastern Purification Plant at Carrum be discharged into Bass Strait rather than into the Bay. In 1975 Government approved the State environment protection policy for Port Phillip Bay that provided a framework to tackle gross pollution sources.

Ensuing programs included: reducing the backlog of properties to be sewered, the improvement of treatment plant performance and better control of industrial waste. The diversion of sewage flows away from Carrum in 1975 resulted in substantial reduction in nitrogen and contaminant loads to the Bay. Since then the Western Treatment Plant has been progressively upgraded with the construction of major new lagoon systems. The nitrogen load from the plant has been reduced by some 40% compared to the early 1970s.

By the late 1980s gross point source pollution had been effectively controlled. The challenge was to now tackle the less visible sources of pollution, including: diffuse sources such as urban stormwater with its high load of nutrients (mainly nitrogen) and other contaminants, and the cumulative impact of our everyday activities. This was consistent with the 'continuous improvement' concept to the mitigation of existing and potential impacts of human activities on the environment that by this time had achieved widespread support.

In 1991 Government initiated the current study, in order to inform its agenda for environmental management of the Bay catchment in the coming decades. Decisions were required that consolidated and continued to improve the water quality in the Bay. Modelling of the consequences of various nutrient loading options – along with social, economic, and technical information from other sources – helped guide these decisions and set priorities.

The Government acted on findings of the study and, in consultation with the community, revised the State environment protection policy for the Bay. A target that aimed for a 1000 tonne reduction in the annual nitrogen load to the Bay by 2006 was established.

This report describes management scenarios (options) covering a range of nutrient inputs from the main sources, which are the Yarra River and Western Treatment Plant (WTP). For the Yarra, low and high load scenarios are examined in conjunction with current and reduced levels of input from WTP. The impact of minor creeks and drains is also included in this analysis.

Port Phillip Bay Environmental Study Management Committee:

Melbourne Water

Department of Natural Resources and Environment

Parks Victoria

Victorian Channels Authority

Environment Protection Authority

EXECUTIVE SUMMARY

The response of Port Phillip Bay to changes in the management of its major nutrient sources is investigated using the integrated model developed as part of the Port Phillip Bay Environmental Study. Scenarios are run to investigate the effect of changes in nitrogen load via minor creeks (Mordialloc Creek, Patterson River, Werribee River and Kororoit Creek all with doubled N loads), the Yarra River (40%, 130% and 170% of current N load), and the Western Treatment Plant (85% and 115% of current N load). These scenarios were specified by the Port Phillip Bay Environmental Study User Committee.

The scenarios involve relatively small changes in bay-wide N load (17% or less), and most bay-wide biogeochemical fluxes and pools change almost in proportion to these changes. Changes in the Yarra N load are slightly more effective in changing bay-wide pools and fluxes, because of positive feedback involving local changes in denitrification efficiency in Hobsons Bay. However, bay-wide pools and fluxes offer only weak guidance for management decisions about changes in loads of this magnitude. Local and regional effects are relatively large, and much more significant for management decisions.

The specified changes in N loads from the major sources (WTP, Yarra and Patterson-Mordialloc system) have strong impacts in their respective adjacent coastal regions (respectively Werribee and Corio Bay regions, the Yarra region, including Hobsons Bay, and the East Coast Region). Impacts in the Bay Centre are roughly proportional to the change in bay-wide load, and interactions among sources are otherwise weak, except that the Yarra has a significant impact on East Coast water quality. Thus, in choosing among sources as a target for N load reduction, managers must assess the comparative benefits achievable in the associated coastal regions.

Regional responses involve different processes and environmental indicators. The western part of the Bay is an important site for seagrass and macroalgae. Decreases in WTP loads lead to reductions in DIN and increases in light penetration, resulting in expansion of seagrass at the expense of macroalgae. Reductions in DIN and in the extent of Si limitation in the western Bay might also be expected to reduce the frequency of dinoflagellate blooms.

Decreases in loads from the Patterson-Mordialloc system decrease chlorophyll and DIN levels in the eastern Bay, including some of Melbourne’s eastern shore beaches. The Yarra flows into Hobsons Bay, which the PPBES showed to be stressed, in terms both of water quality and sediment biogeochemistry. Increases in N loads from the Yarra have significant local and regional impacts on water and sediment quality, which are magnified by a reduction in local denitrification efficiency. As a result, bloom duration following large runoff events is greatly extended, and there is a risk of prolonged oxygen depletion in bottom waters. Increases in N loads from the Yarra also increase bloom intensity along the eastern shore beaches, and, in the absence of changes to Si load, an increase in Si limitation in the western Bay.

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1. INTRODUCTION

Port Phillip Bay is a large (1950 km^2) semi-enclosed bay in south east Australia. The Bay's catchment includes the cities of Melbourne and Geelong and the Bay represents a valuable resource to one of the most densely populated parts of Australia. Uses include fisheries, recreation, conservation, transport and disposal of treated effluent. The recently completed Port Phillip Bay Environmental Study (PPBES), conducted from 1992-96, assessed the impact on the Bay of toxicant and nutrient discharges from point and diffuse sources (Harris et al. 1996).

As part of the PPBES, CSIRO Division of Marine Research developed a detailed simulation model of the cycling, fate and impacts of nutrient loads on Port Phillip Bay water quality and ecology. The physical transport model (Walker and Sherwood, 1997) divides the water column and underlying sediment into 59 polygonal boxes, and represents exchanges of dissolved and particulate material within the water column, and between water column and sediment. The ecological / biogeochemical model (Murray and Parslow, 1997) describes the cycling of nitrogen, phosphorus, silica and carbon through a size-fractionated plankton ecosystem, and through benthic systems, including microphytobenthos, macroalgae, seagrasses and benthic filter feeders. The model includes four detrital fractions: labile and refractory detritus, dissolved organic matter and detrital silica, and represents biogeochemical processes in the sediment, including denitrification, which play a key role as a sink for nitrogen. For a detailed description of these models, including formulation, forcing, calibration and analysis, the reader should consult Walker and Sherwood (1997) and Murray and Parslow (1997).

The integrated model has been developed for use both as a scientific tool, to synthesize PPBES field results and understand the way the Bay functions, and as a management tool, to predict likely responses to changes in the management of the Bay, particularly in relation to nutrient loads. Murray and Parslow (1997) presented model results for a range of large-scale changes to bay-wide nutrient loads, which were designed to improve scientific understanding of the factors maintaining the Bay's current ecological status. A key finding was that the model responds almost linearly to small changes in nutrient loads, but that the response becomes highly non-linear for large changes. At two to three times current loads, a breakdown in denitrification, combined with the slow flushing rate, results in a rapid transition to a highly eutrophic state.

A more careful examination of spatial and temporal response to changes in loads from the principal sources was undertaken. This report presents an analysis of the model response to a set of load scenarios agreed by the PPBES User committee.

2. THE SCENARIOS

The scenarios addressed in this report and agreed by the PPBES User Committee involve changes in nitrogen loads from separate sources, imposed on a baseline scenario. Changes in loads from three sources were considered: the Yarra River, the minor creeks (Patterson River, Mordialloc Creek, Werribee River and Kororoit Creek), and the Western Treatment Plant (WTP).

The baseline load scenario used here was based on the estimated time series loads to Port Phillip Bay for the period 1991-95. Physical forcing was available for this period, and the model has been calibrated and validated against observations for this period, particularly for the 1993-95 PPBES field program. There was considerable interannual variation in nutrient loads from diffuse sources over the 1991-95 period, with higher loads in wet years (1991-94) and low loads in 1994-95, a year of particularly low rainfall and runoff (Table 1a).

The WTP load in 1991-93 has been modified in the baseline load scenario. The annual WTP loads in 1991-93 exceeded 4000 tonnes N, whereas the loads in 1993-95 were less than 3500 t N y^{-1}, the future EPA licence limit to apply from December 2001. In the baseline scenario, we have applied the observed 1993-94 WTP load in each of 1991-92 and 1992-93, thereby ensuring that baseline WTP loads satisfy the future EPA licence limit in each year. The baseline loads from the three sources (Yarra River, minor creeks and WTP) are shown in Table 1a, both as t N y^{-1}, and as fractions of the annual bay-wide load.

In the scenarios, the baseline time series of daily N loads were scaled up or down by a fixed percentage. Thus, the scenarios considered here assume that the modifications to catchment or WTP management result in increases or decreases in total load, without changing the relative pattern of short-term, seasonal or interannual variation. Six scenarios were considered in addition to the baseline, and the percentage changes in loads involved in these scenarios are summarised in Table 1b.

Table 1a. Baseline Loads from the Yarra River, Western Treatment Plant and Minor Creeks. Loads are shown as t N y^{-1}, and as a fraction of bay-wide loads, allowing for 1000 t N y^{-1} from the atmosphere.

	t N y^{-1}			Fraction of bay-wide load		
Year	**Yarra**	**WTP**	**Minor**	**Yarra**	**WTP**	**Minor**
91/2	1782	3455	1228	0.24	0.46	0.16
92/3	2242	3455	1312	0.28	0.43	0.16
93/4	1933	3455	1226	0.25	0.45	0.16
94/5	1037	3401	1172	0.16	0.51	0.18
mean	1748.5	3441.5	1234.5	0.24	0.46	0.17

Table 1b. The scenario loads as a percentage of baseline loads.

Scenario	Minor Creeks	Yarra	WTP	Bay-wide
1	200%	100%	100%	117%
2	100%	40%	100%	86%
3	100%	130%	100%	107%
4	100%	170%	100%	117%
5	100%	100%	85%	93%
6	100%	100%	115%	107%

Scenario 1 involves a doubling of the N load from the minor creeks and drains. These sources are dominated by the Patterson-Mordialloc system. The annual average load increases from 1235 to 2470 t N y^{-1}.

Scenarios 2, 3 and 4 involve changes in the Yarra N load to 40%, 130% and 170% of baseline respectively. The corresponding annual average loads are 700, 2270 and 2970 t N y^{-1}. Scenario 4 was not requested by the PPBES User Committee, but represents an increase in bay-wide N load comparable to that involved in scenario 1, and provides interesting insight into local impacts in Hobsons Bay.

Scenarios 5 and 6 involve reductions and increases in the baseline WTP load of 15%, corresponding to annual loads of about 3000 and 4000 t N y^{-1} respectively. The increases in bay-wide N load in Scenario 3 and Scenario 6 are both ca 500 t N y^{-1}.

In order to ensure that model results are independent of initial conditions, we run the model over a 12-year simulation period, repeating the 1991-95 forcing 3 times, and analyse predictions for the last 4 years only. Thus, the scenario results represent the equilibrated response of the bay to long-term changes in catchment management and loads, not the transient response immediately following a reduction in load.

The specified scenarios refer only to nitrogen, and we have not modified silicate or phosphate loads. Interactions between nitrogen and silica limitation can have strong local effects on phytoplankton bloom concentrations (Murray and Parslow, 1997), and the decision not to modify silicate loads does influence the scenario results. This is discussed further below.

3. RESULTS

3.1. Bay-wide response

We discuss first the responses of the key bay-wide average annual fluxes and pools involved in the nitrogen cycle. These are expressed as fractional change relative to baseline, and compared with the percent change in total bay-wide load (Table 2). The bay-wide primary production (PP) flux responds almost linearly to changes in loading, regardless of source (Table 2), although it is slightly more sensitive to inputs from the Yarra. Very similar comments apply to the fluxes of recycled N that support primary production: recycling in the water-column (WRc), efflux from the sediment (SRc), and release from epibenthic filter-feeders (FRc). WRc is slightly less sensitive and FRc slightly more sensitive than PP. SRc and sediment respiration (Sresp) are most sensitive to changes in the Yarra load.

Denitrification changes almost in proportion to loads from minor creeks, the Yarra and WTP. Denitrification is the dominant N sink, and DON export is the next most important sink. DON production shows a weaker response to loads, so that the relative importance of denitrification as a sink increases slightly for small increases in loads.

Table 2. Normalised bay-wide effects of scenarios on model N fluxes (PP = Phytoplankton primary production, WRc = water-column recycling, SRc = release from the sediment, FRc = release from filter-feeders, Sresp = sediment respiration and MPBP = primary production by microphytobenthos).

		PP	WRc	SRc	FRc
	Baseline t N/y	33477.95	21903.69	6377.645	4218.042
Scenario	Relative Bay-wide Load				
1 (2 × minor)	117%	1.160	1.147	1.171	1.170
2 (0.4 × Yarra)	86%	0.885	0.894	0.857	0.879
3 (1.3 × Yarra)	107%	1.077	1.071	1.105	1.076
4 (1.7 × Yarra)	117%	1.188	1.176	1.258	1.180
5 (0.85 × WTP)	93%	0.936	0.941	0.892	0.918
6 (1.15 × WTP)	107%	1.066	1.061	1.111	1.084
		Sresp	MPBP	Denitrif-ication	Net DON Production
	Baseline t N/y	13388.08	10979.03	7010.437	892.7309
Scenario	Relative Bay-wide Load				
1 (2 × minor)	117%	1.167	0.951	1.163	1.083
2 (0.4× Yarra)	86%	0.867	1.036	0.876	0.933
3 (1.3 × Yarra)	107%	1.089	0.971	1.075	1.043
4 (1.7 × Yarra)	117%	1.213	0.933	1.171	1.104
5 (0.85 × WTP)	93%	0.908	1.019	0.923	0.963
6 (1.15 × WTP)	107%	1.091	0.985	1.073	1.042

Microphytobenthos production (MPBP) responds weakly and negatively to increased loads because these result in higher water-column chlorophyll and reduced bottom light levels. Because MPB production contributes to DON production in the sediment, this may account for the lower sensitivity of DON production.

Changes in Yarra loads, tonne for tonne, have more effect on bay-wide fluxes than do changes in inputs to the other sources. This is primarily due to local suppression of denitrification in Hobsons Bay. It was noted above that, for large increases in total loads, the Bay responds non-linearly because higher sediment respiration and oxygen consumption decrease denitrification efficiency over extensive regions of the Bay. Both observations (Nicholson et al. 1996) and model results (Murray and Parslow 1997) show that, under current loads, sediment respiration is highest, and denitrification efficiency lowest, in Hobsons Bay. As loads from the Yarra are increased, the area of suppression of denitrification increases, resulting in a local amplification of the increased nitrogen addition through efficient recycling. The spatial distribution of changes in denitrification rates are examined in more detail in a later section.

The same mechanism should weakly amplify increases in loads from the WTP, but this may be partly counteracted by competition for nutrients by macroalgae, also discussed later.

While the fluxes generally respond slightly more than linearly to changes in load, the bay-wide pools generally respond less than linearly (Table 3). This is not too surprising: one would expect the turnover rate of pools as well as the size of pools to contribute to increased fluxes. For the zooplankton mortality formulation used in this model, a simple analysis suggests that chlorophyll should increase like the square root of primary production. In fact, chlorophyll increases almost linearly with changes in loads; this can be partly attributed to a switch from small to large phytoplankton at increased loads. Phytoplankton biomass, like primary production, is more sensitive to Yarra loads than to loads from other sources.

DON, the largest water-column N pool, responds much like DON production to changes in loads under all the scenarios. This is not surprising as DON production is balanced primarily by export to Bass Strait, which is proportional to the pool size.

DIN is only slightly affected by the increase in minor creek loads and by decreases in the Yarra load. It responds more strongly to changes in WTP loads and to increases in the Yarra load. The reason for this response is that there is already local accumulation of DIN near WTP and in Hobsons Bay, in excess of phytoplankton uptake capability, and this increases in response to increased loads. DIN input from the east coast is quickly dispersed into the bay centre, where it is rapidly taken up by phytoplankton and so does not accumulate. Nitrate is more sensitive to changed loads from the Yarra and minor creeks than from WTP, but this simply reflects the nitrate to ammonia ratios in the discharges. Phosphate levels are fairly insensitive to the load changes. The phosphate load is not adjusted in the scenarios but organic matter inputs are assumed to have Redfield Ratio, so changes in detrital N inputs do affect the modelled P load.

Table 3. Normalised effects of scenarios on model bay-wide phytoplankton and nutrient pools (PL = large phytoplanton, PS = small phytoplankton, DON = dissolved organic nitrogen, DIN = dissolved inorganic nitrogen).

		Chlorophyll	PL	PS	DON
	Baseline mg N (or chl) m^{-3}	0.901	4.586	1.719	34.988
Scenario	Relative Bay-wide Load				
1 (2 × minor)	117%	1.147	1.188	1.038	1.069
2 (0.4 × Yarra)	86%	0.896	0.867	0.972	0.946
3 (1.3 × Yarra)	107%	1.070	1.090	1.019	1.033
4 (1.7 × Yarra)	117%	1.170	1.215	1.052	1.079
5 (0.85 × WTP)	93%	0.954	0.944	0.981	0.946
6 (1.15× WTP)	107%	1.048	1.058	1.020	1.050
		DIN	NO_3	NH_4	PO_4
	Baseline mg N (or chl) m^{-3}	8.315	0.902	7.412	80.611
Scenario	Relative Bay-wide Load				
1 (2 × minor)	117%	1.067	1.082	1.065	1.027
2 (0.4 × Yarra)	86%	0.942	0.909	0.946	0.977
3 (1.3 × Yarra)	107%	1.051	1.103	1.044	1.013
4 (1.7 × Yarra)	117%	1.151	1.336	1.129	1.032
5 (0.85 × WTP)	93%	0.943	0.963	0.941	0.997
6 (1.15 × WTP)	107%	1.070	1.053	1.072	1.003

3.2. Spatial Structure of the Model

Port Phillip Bay contains a variety of different environments ranging from the well-flushed waters in the southern sands to nutrient rich waters off Werribee and near the Yarra discharge. A model structure of 59 fine boxes has been used to capture this spatial variation (Fig. 1). These 59 boxes are grouped into 8 regions for most analysis purposes, although sometimes it is useful to refer back to the level of individual fine boxes. The baseline model behaviour in relation to this spatial structure is discussed in Murray and Parslow (1997).

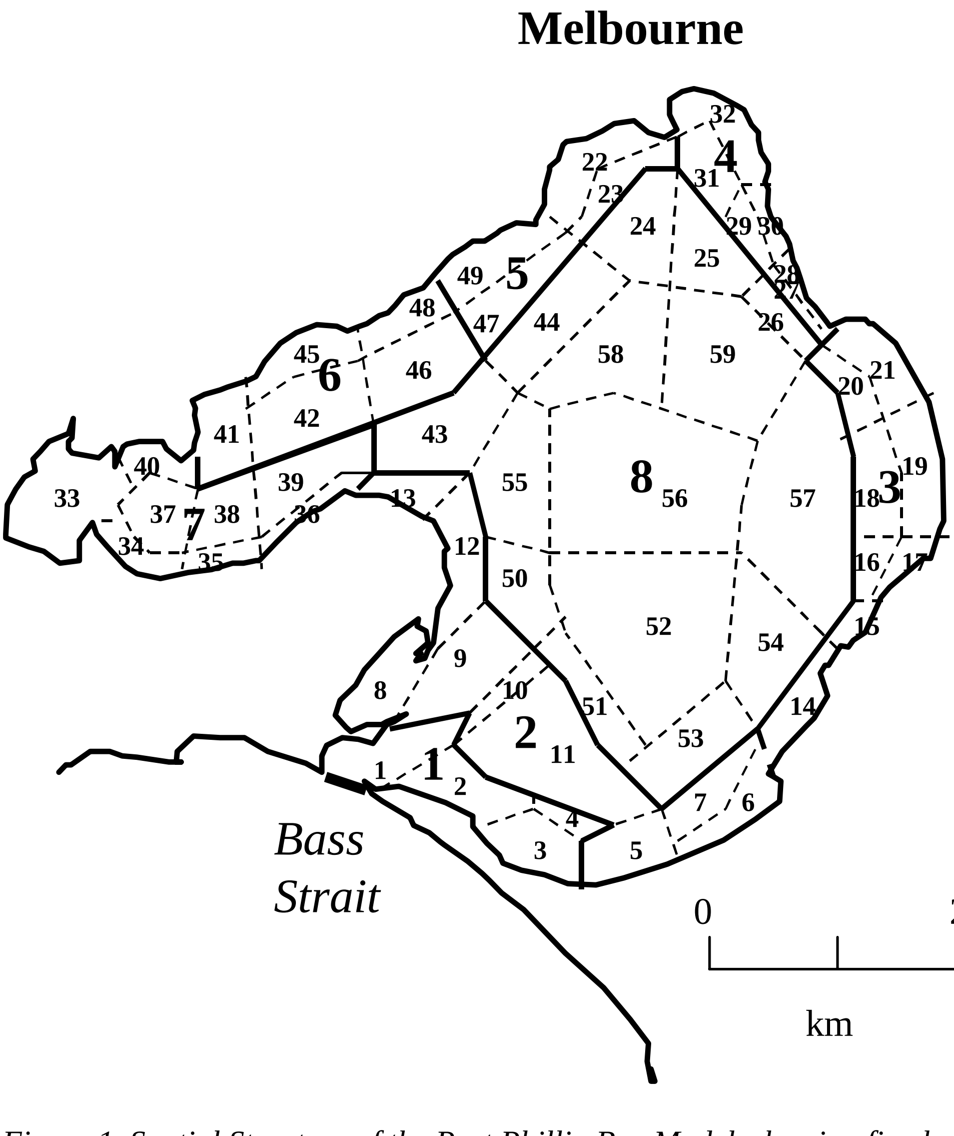

Figure 1. Spatial Structure of the Port Phillip Bay Model, showing fine boxes and regions. The regions are: 1 – Sands I; 2 – Sands II; 3 – East Coast; 4 – Yarra; 5 – NW; 6 – Werribee; 7 – Corio Bay; and 8 – Bay Centre.

3.3. Spatial Response of Chlorophyll

We examine first the change in chlorophyll distribution, as a primary indicator of water quality, under the different load scenarios. Changes in regional annual mean chlorophyll values are shown in Fig. 2. Doubling the loads from minor creeks has most effect on the east coast (where the Patterson River and Mordialloc Creek discharge). Changes to loads from the Yarra River and WTP have most effect in their respective adjacent regions. The sands are largely unaffected by any of the input changes. The north-west is mildly affected by changes to the Yarra and WTP loads, but not by changes to minor creeks. (Although Kororoit Creek and Werribee River discharge into this region, the associated loads are negligible almost all of the time.) Corio Bay is moderately sensitive to changes in WTP outflow. The Bay centre shows more response to changes in loads from the minor creeks and the Yarra River, as these represent larger total load changes than the WTP scenarios.

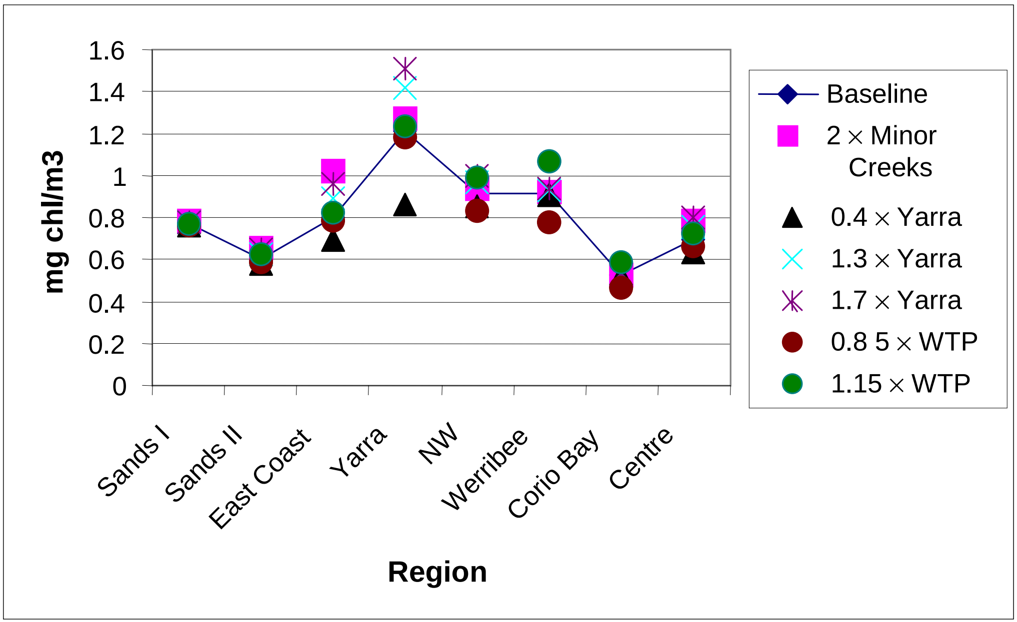

Figure 2 Regional mean chlorophyll values under the model scenarios.

The baseline annual mean chlorophyll concentration is unevenly distributed over the Bay, being concentrated in northern and western areas, in particular in Hobsons Bay and off the WTP discharge point (Fig. 3). The changes in annual mean chlorophyll concentration, expressed as a percentage of the baseline mean chlorophyll, are shown for each scenario in Fig. 4. Changes to the WTP discharge have most effect in the northern and western Bay (NW, Werribee and Corio Bay regions, the northern fringe of the central region and the north-western sands II). Increases in loads from the minor creeks increase chlorophyll strongly in the eastern shore and adjacent bay-centre boxes, although smaller increases occur throughout the Bay centre and the sands II regions. Changes in the Yarra load have most effect on the Yarra region, and adjacent boxes in the Bay centre and east coast region. At very high or very low Yarra loads, effects are observed throughout the Bay Centre, extending into the sands.

There is considerable overlap between the regions influenced by minor creeks and the Yarra, but much less overlap between these and the domain of influence of the WTP. The absolute increases in chlorophyll for the 1.7 X Yarra discharge and doubled minor creek discharge are similar, but because background chlorophyll levels are higher in the region of the Yarra inflow, the percentage change is somewhat less. The same applies at a local level; chlorophyll levels in Hobsons Bay and immediately off the WTP show smaller percentage changes than do neighbouring boxes with lower background concentrations.

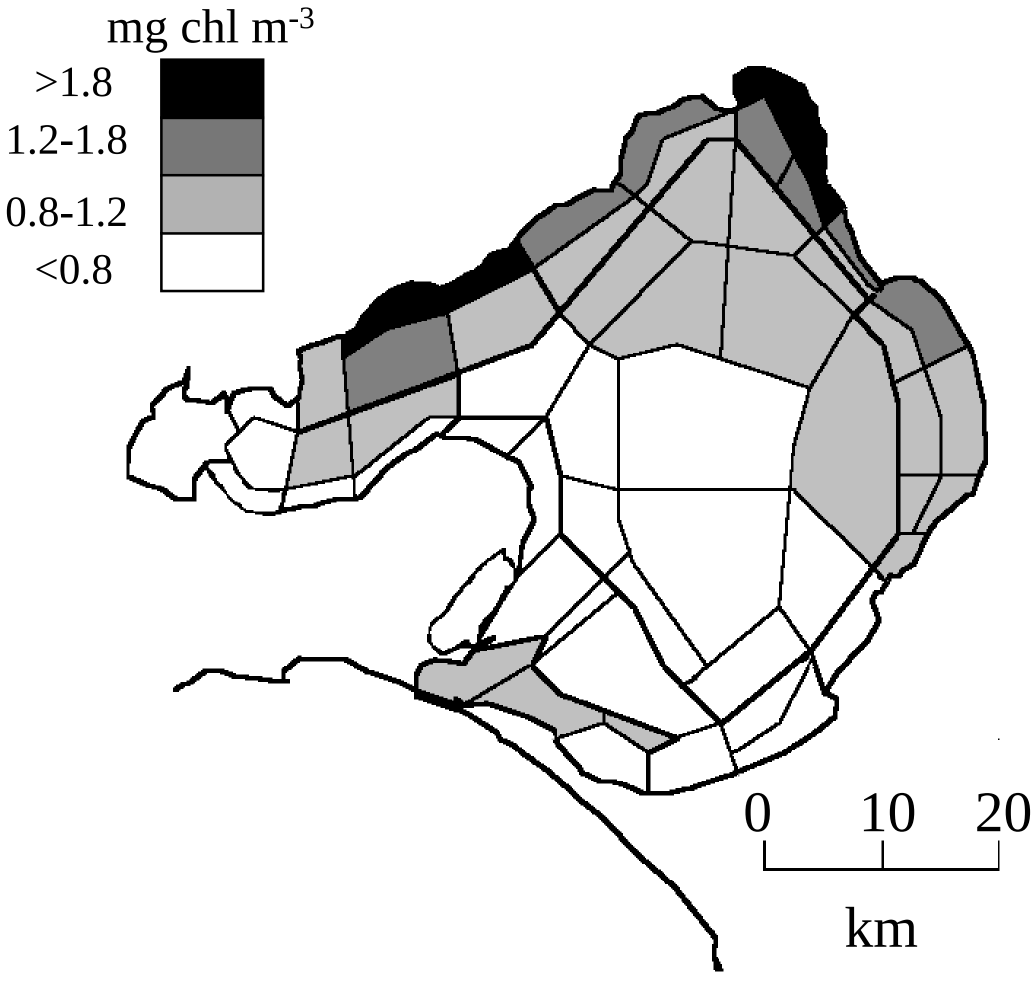

Figure 3. Distribution of annual mean chlorophyll concentrations under the baseline run.

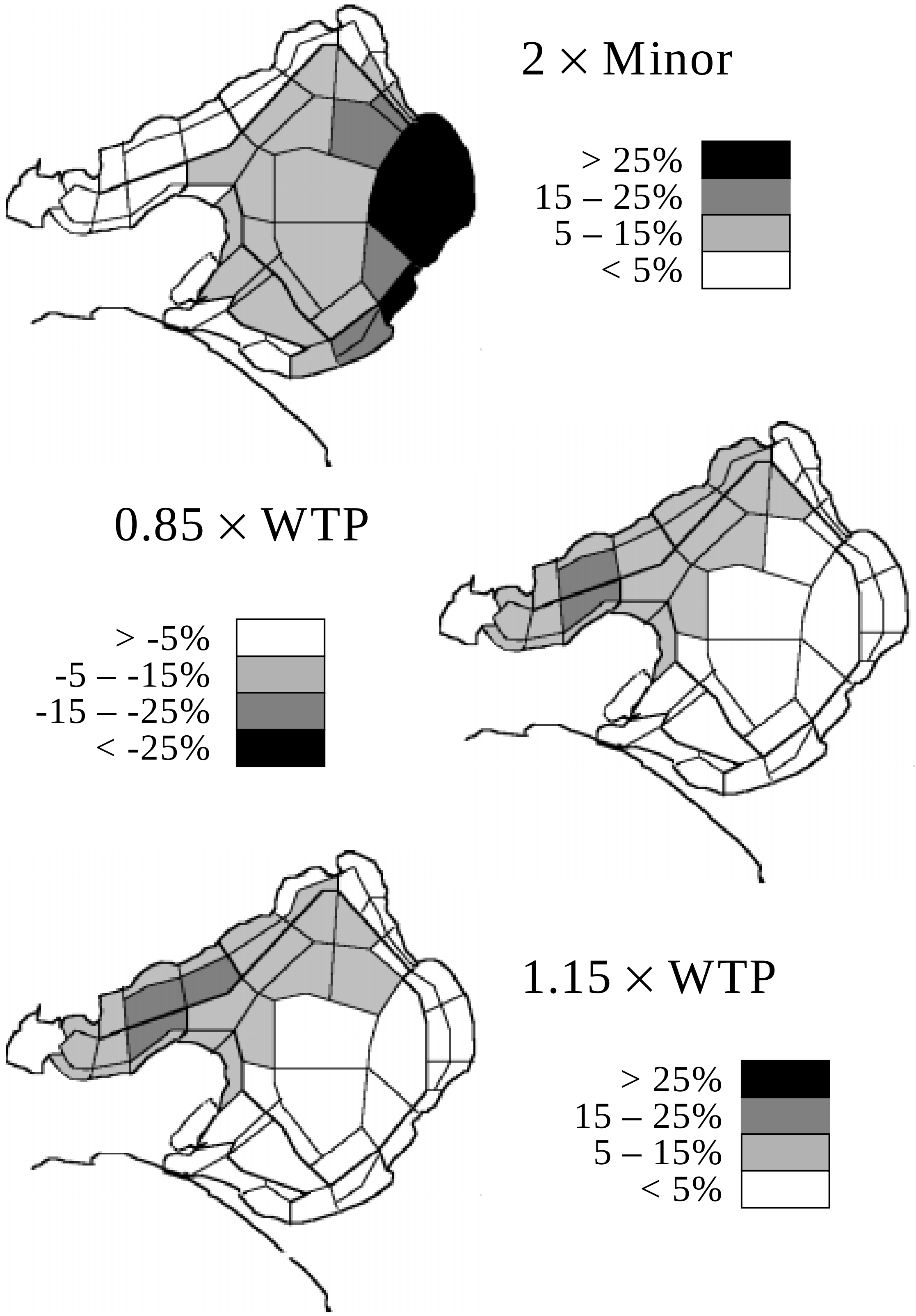

Figure 4a. Distribution of percent change in annual mean chlorophyll for Minor creeks and WTP scenarios relative to baseline run. Note that changes are negative for reduced loads, positive if loads are increased.

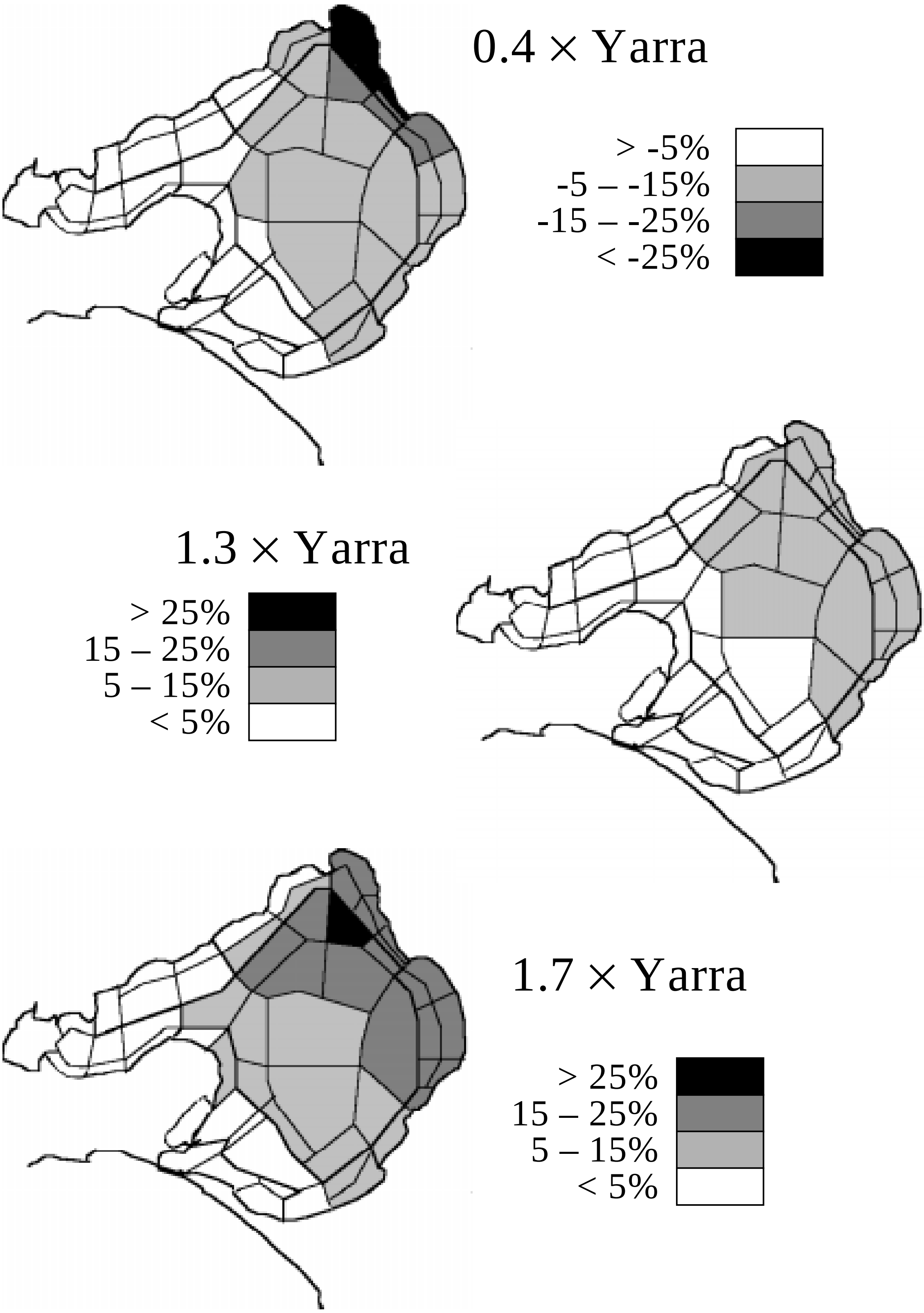

Figure 4b. Distribution of percent change in annual mean chlorophyll for the Yarra scenarios relative to the baseline run. Note that changes are negative for reduced loads, positive if loads are increased

Because the scenarios involve changes in N load only, they involve implicit changes in N:Si input ratios. Under high Yarra N loads, more of the Si load from the Yarra is utilised in the north-eastern Bay, and chlorophyll in the (Si limited) Werribee region falls slightly, although not enough to be apparent in Fig. 4.

The increased loads from the Werribee River and Kororoit Creek in the minor creeks scenario have no visible effect on local annual mean chlorophyll levels in Fig. 4, mostly because the input from these rivers is very small, except for one short but intense flood event in September 1993. The peak chlorophyll value resulting from this flood only increases from 15.3 to 16.5 mg Chl *a* m^{-3} when the nitrogen load is doubled. The baseline Si:N ratio in these discharges is close to 3, that is close to the modelled Si:N of diatoms. When N inputs are doubled, the Si load is apparently not sufficient to meet the demands of diatom growth.

3.4. Variation of Chlorophyll Within Regions

For management purposes, we are interested in changes in the variability of chlorophyll within regions, as well as changes in the annual mean. We have summarised changes in the frequency distribution of chlorophyll values within regions by plotting the 10, 25, 50, 75 and 90 percentiles as box and whisker diagrams (fig. 5).

In the southern sands (Fig. 5a) the upper percentile values are largely controlled by the chlorophyll concentration imposed at the Bass Strait boundary and so are generally independent of loads. The lower percentile values are slightly sensitive to the N load, and consequently variation declines as load rises. The source of the nutrients has little effect on the behaviour of chlorophyll in this region.

In the northern sands (Fig. 5b) the median chlorophyll level responds to changes in load, but the range of chlorophyll variation is constant.

Chlorophyll along the east coast (Region 3) shows little sensitivity to changes in WTP discharges (Fig. 5c), but is very sensitive to changes in loads from the minor creeks, as the Patterson River and Mordialloc Creek discharge in this region. The interquartile range is less sensitive to changes in Yarra loads than to comparable changes in the load from the minor creeks, but the 90^{th} percentile value is only marginally less sensitive, indicating that Yarra flood events extend to this region. (Managers may place more weight on the 90^{th} percentile (bloom) levels.

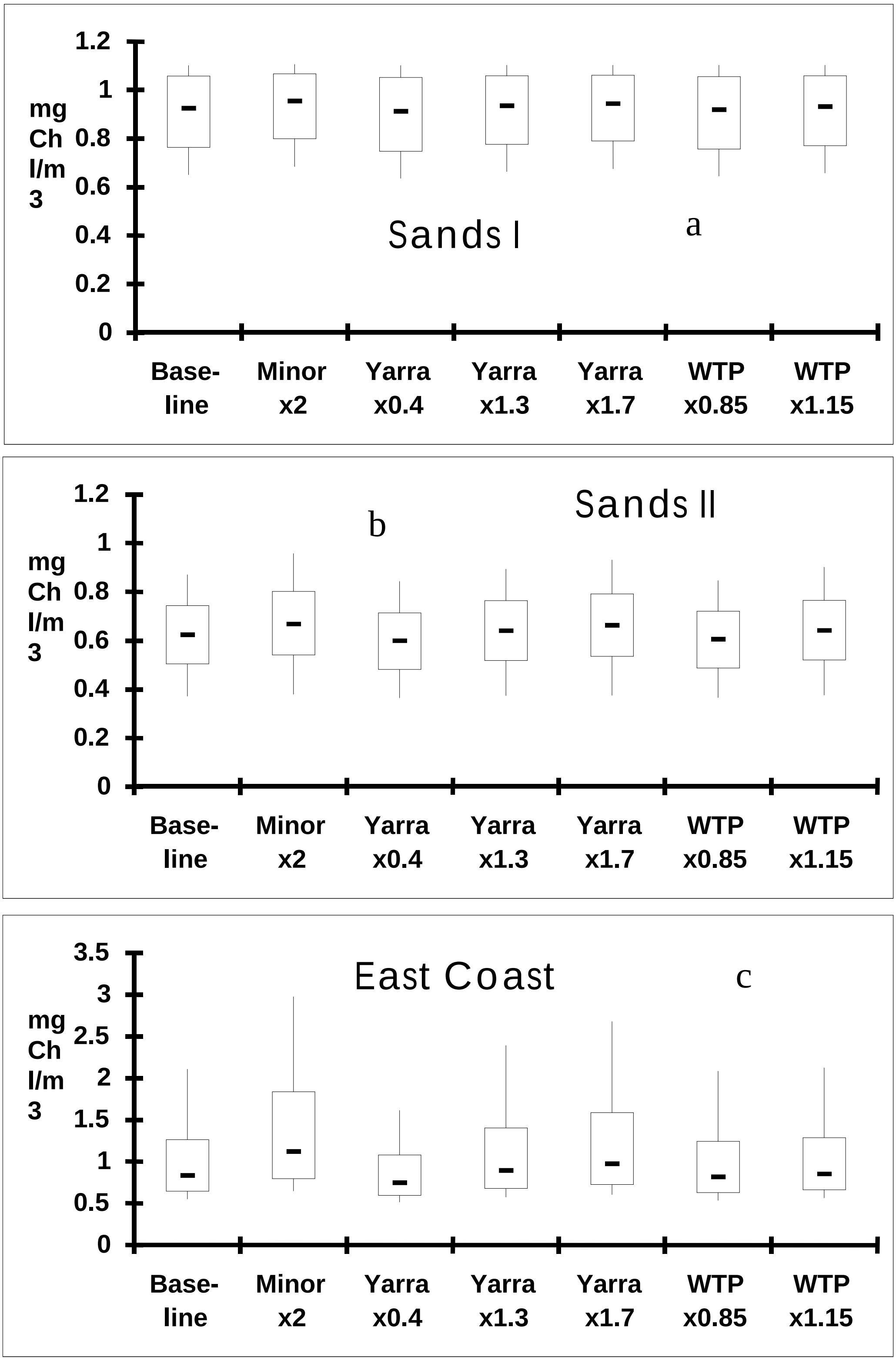

Figure 5a-c. Regional variation in chlorophyll a under the loading scenarios. The box defines the interquartile range, while the whiskers define the 10-90 percentile range, and the bar defines the median.

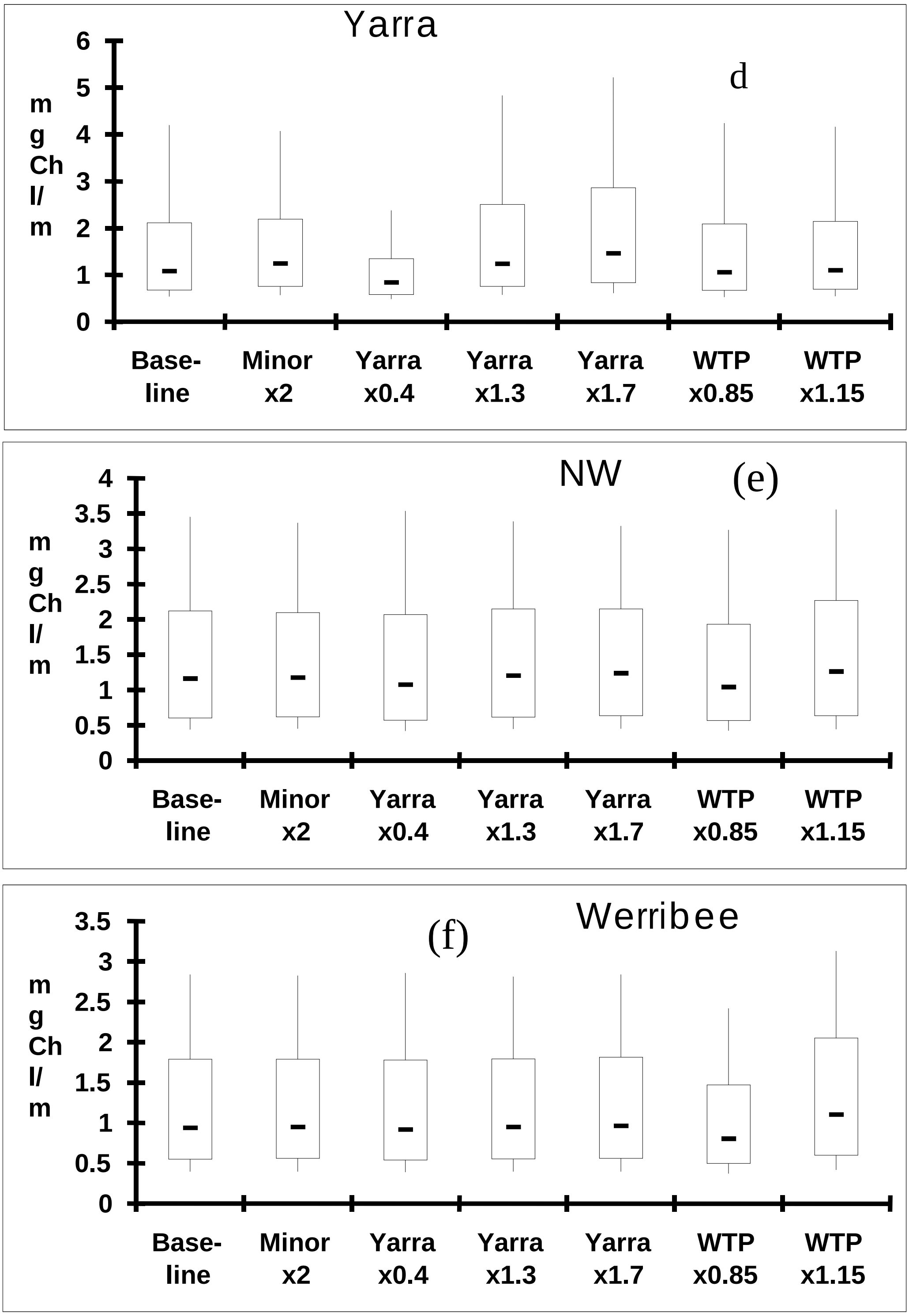

Figure 5d-f. Regional variation in chlorophyll a under the loading scenarios. The box defines the interquartile range, while the whiskers define the 10-90 percentile range, and the bar defines the median

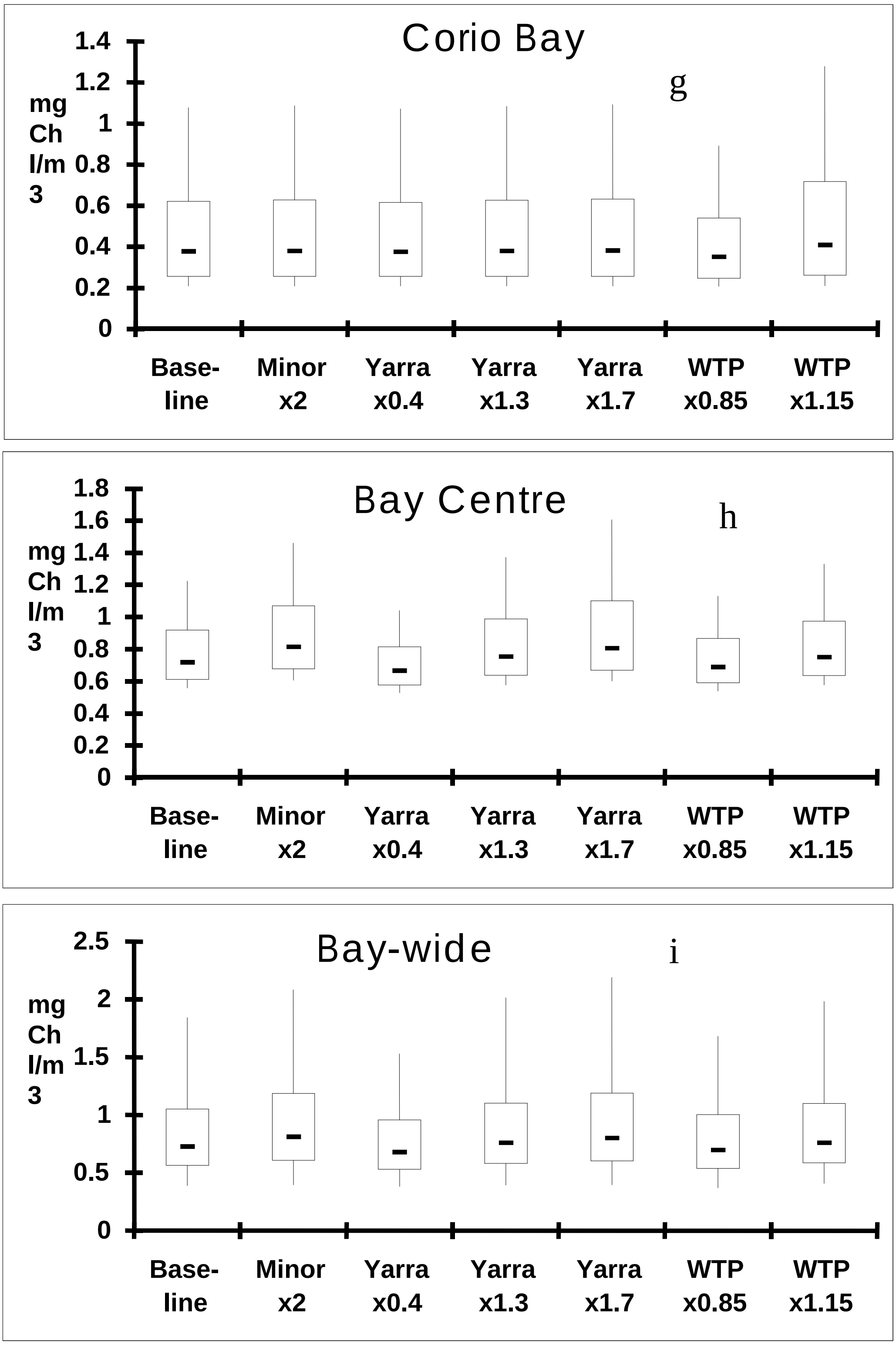

Figure 5g-i. Regional variation in chlorophyll a under the loading scenarios. The box defines the interquartile range, while the whiskers define the 10-90 percentile range, and the bar defines the median

Chlorophyll in the Yarra region is insensitive to loads from sources other than the Yarra River (Fig. 5d). It is very sensitive to input changes from the Yarra, but responds less to the change from 1.3 to 1.7 times current loads than would be expected from the response to the 1 to 1.3 time load change. This suggests local utilisation of nutrients is less effective at high loads, possibly due to increased Si limitation.

Chlorophyll in the NW region shows little sensitivity to minor creek discharge (in spite of receiving loads from Kororoit Creek and the Werribee River) and is only moderately sensitive to changes in Yarra inputs and WTP inputs (Fig. 5e). Surprisingly, chlorophyll in this region shows less sensitivity to changes in loads than chlorophyll in the Bay centre; this may be a result of Si limitation and/or competition with macrophytes.

Chlorophyll in the Werribee Region (6) is insensitive to changes in loads from sources other than the WTP, the dominant local source (Fig. 5f).

Chlorophyll in Corio Bay (region 7) is also sensitive only to changes in the WTP load (Fig. 5g). The relative increase in upper percentile (bloom) chlorophyll levels in response to increases in the WTP load is larger in the Corio Bay region than in the Werribee Region.

The Bay Centre (8) is sensitive to changes from all input sources, although it is a little less sensitive to changes in WTP inputs than to comparable changes in inputs from other sources (Fig. 5h). The doubled minor creeks load and the 1.7X Yarra load, which are comparable, have the same effect on chlorophyll in the Bay Centre.

Bay-wide, the chlorophyll frequency distribution appears to depend only on the total bay-wide load, independent of the N source (Fig. 5i). The 1.7X Yarra load and the doubled minor creeks load give almost identical results, as do the 1.3X Yarra and 1.15X WTP load.

Over most of the Bay most of the time predicted chlorophyll levels are low. In all regions except the Yarra, chlorophyll is less than 1 mg m^{-3} more than half the time; in the Bay Centre, it is less than 1 mg m^{-3} 80% of the time. Only in the Yarra region does chlorophyll exceed 4 mg m^{-3} more than 10% of the time. Even off Werribee and in the NW region, blooms much larger than 6 mg Chl *a* m^{-3} are very rare, but in the Yarra region they occur in more than 5% of samples. Locally, predicted chlorophyll values in this region can be much higher. In the fine box representing upper Hobsons Bay, chlorophyll levels exceed 10 mg Chl *a* m^{-3} 5% of the time. However, the model calibration suggested that bloom intensities immediately adjacent to the Yarra's mouth are exaggerated by the model, while predicted concentrations averaged over the Yarra region as a whole correspond well to observations (see Murray and Parslow 1997).

3.5. Chlorophyll Time Series: Yarra and Werribee

The box and whiskers diagrams discussed above give a general guide to the frequency distribution of predicted chlorophyll values. The variability is due both to spatial variation within regions, and temporal variation on interannual, seasonal and shorter time scales. Temporal variation in the vicinity of nutrient sources is clearly associated with variation in loads. This is best illustrated by time series plots.

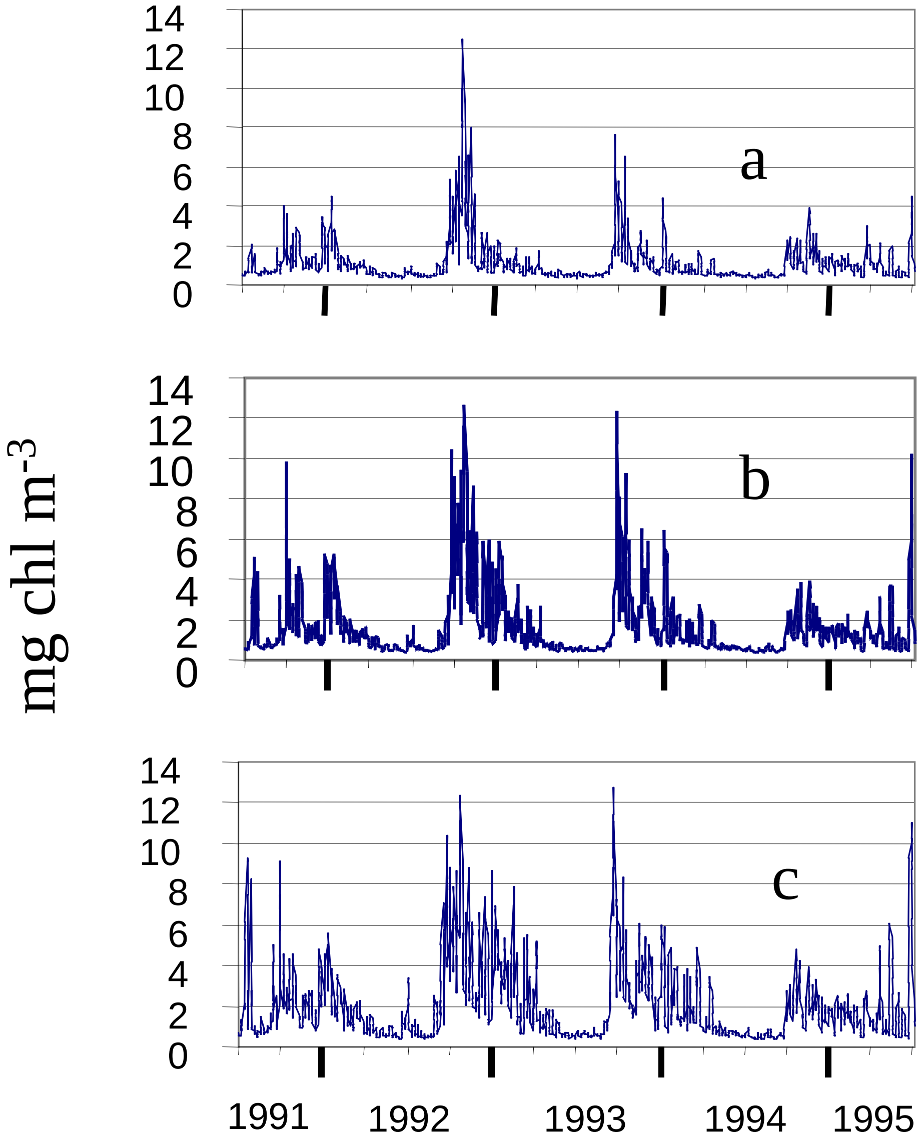

Figure 6. Model generated time series for chlorophyll a 1991-5, Outer Hobsons Bay (Fine box 31). a) 0.4 X Yarra N load; b) 1 X Yarra N load; c) 1.7 X Yarra N load.

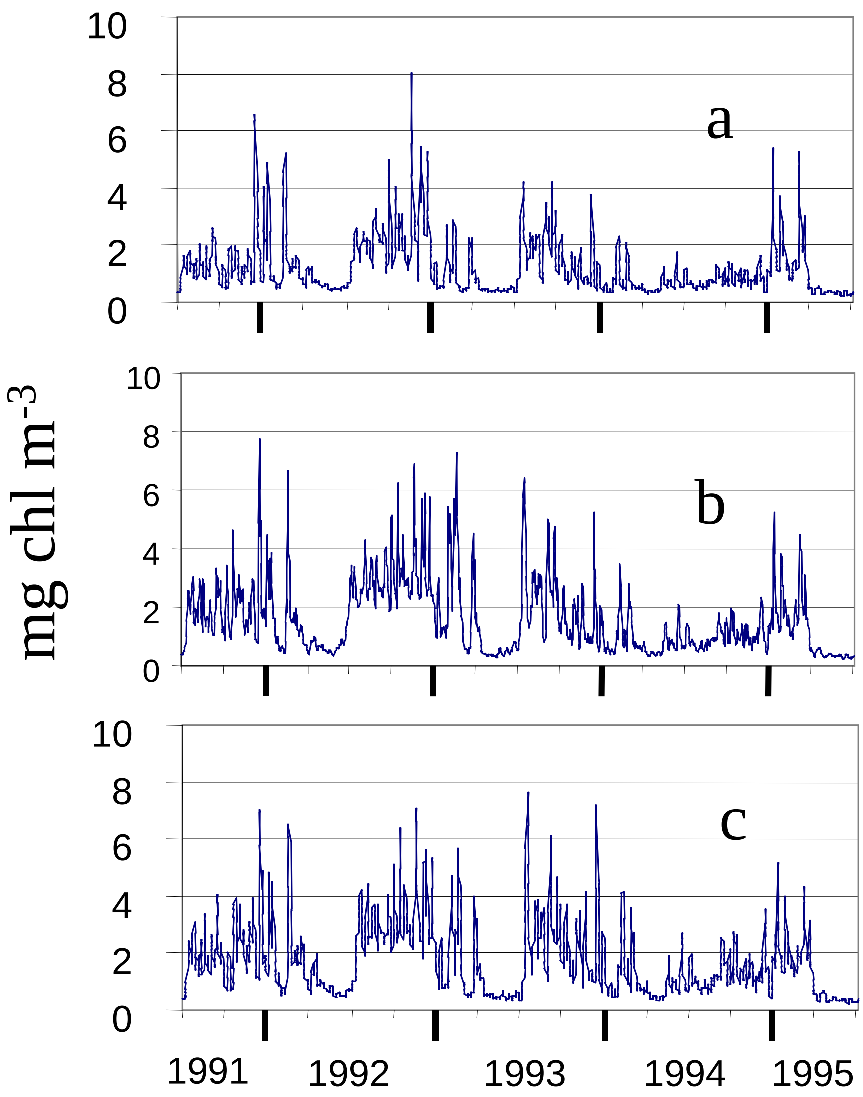

Figure 7. Model generated time series for chlorophyll a 1991-95, off WTP (Fine box 42). a) 0.85 X WTP N load; b) 1.0 X WTP N load; c) 1.15 X WTP N load.

We present chlorophyll time series from two sites, one in Hobsons Bay and one off WTP. The Hobsons Bay site is box 31 in outer Hobsons Bay the location of MAFRI sampling station 9. At this site, we compare time series for 0.4, 1.0 and 1.7 times Yarra N loads (Fig. 6). The Werribee time series is from box 42, offshore and south of the WTP input. Its location with respect to the WTP is comparable to that of box 31 with respect to the Yarra. Time series for loads of 0.85, 1, and 1.15 times WTP N loads are compared at this site (Fig. 7). Note that the relative change in N loads from WTP is small compared to that from the Yarra, both in terms of bay-wide input and most particularly in terms of the local input. Time series describe the last 4 years of the 12 year model run, July 1991 to June 1995.

The Hobsons Bay site shows a distinctive pattern of changes between the low (0.4 times), baseline (1.0 times) and high (1.7 times) N load scenarios (Fig. 6). Changes in N load over this large range (4.25 X) do not lead to comparably large changes in chlorophyll levels in the initial phase of blooms induced by Yarra floods, but rather to changes in the rate of decline of chlorophyll blooms following the flood. Under low loads this is rapid and blooms last for only a few weeks in spring. Under the high load scenario blooms persist through summer and autumn as well. This change is a significant change in ecosystem behaviour, and may be attributable to changes in local denitrification efficiency (see below).

At the Werribee site, where inputs are regulated and continuous, there are no input events comparable to the Yarra floods. Both background and bloom chlorophyll values increase by about a third and the length of the periods in which chlorophyll is very low, in late summer and autumn, are not changed (Fig. 7a and 7b). Isolated larger blooms, comparable to those under the higher load, occur under the low load scenario, and indeed the largest single chlorophyll spike occurs under the low load scenario. In general, however, there is not a qualitative difference between the behaviour of chlorophyll under the two scenarios, merely a quantitative one that is in line with the local change in N loads.

3.6. Variation of DIN Within Regions

DIN concentrations also respond to changes in local sources, and as one might expect, DIN tends to be more concentrated in the vicinity of sources than chlorophyll. As before, we have plotted the 10, 25, 50, 75 and 90 percentile values, but present results for only three regions: Yarra, Werribee, and the bay centre (Fig 8).

DIN concentration in the Yarra region responds little to changes in loads from the minor creeks or from the WTP. It is, however, even more sensitive than local chlorophyll to changes in the Yarra loads and, unlike chlorophyll, shows no tendency to saturate as the N load is increased from 1.3X to 1.7X.

DIN in the Werribee region is only sensitive to changes in loads from the WTP. Both the 75 and the 90 percentiles show an increase of about 60% between the 0.85 and 1.15 times WTP load scenarios. A similar relative increase in these upper percentiles in Corio Bay has a strong effect on the modelled distribution of seagrasses in the region.

DIN in the Bay Centre responds to loads in a way that is very similar to chlorophyll. Similar changes in bay-wide load lead to similar changes in Bay Centre DIN, regardless of source. Scenarios with similar bay-wide loads, the 1.3X Yarra load and 1.15X WTP load, and the 1.7X Yarra load and 2X minor creeks, produce similar responses in Bay Centre DIN.

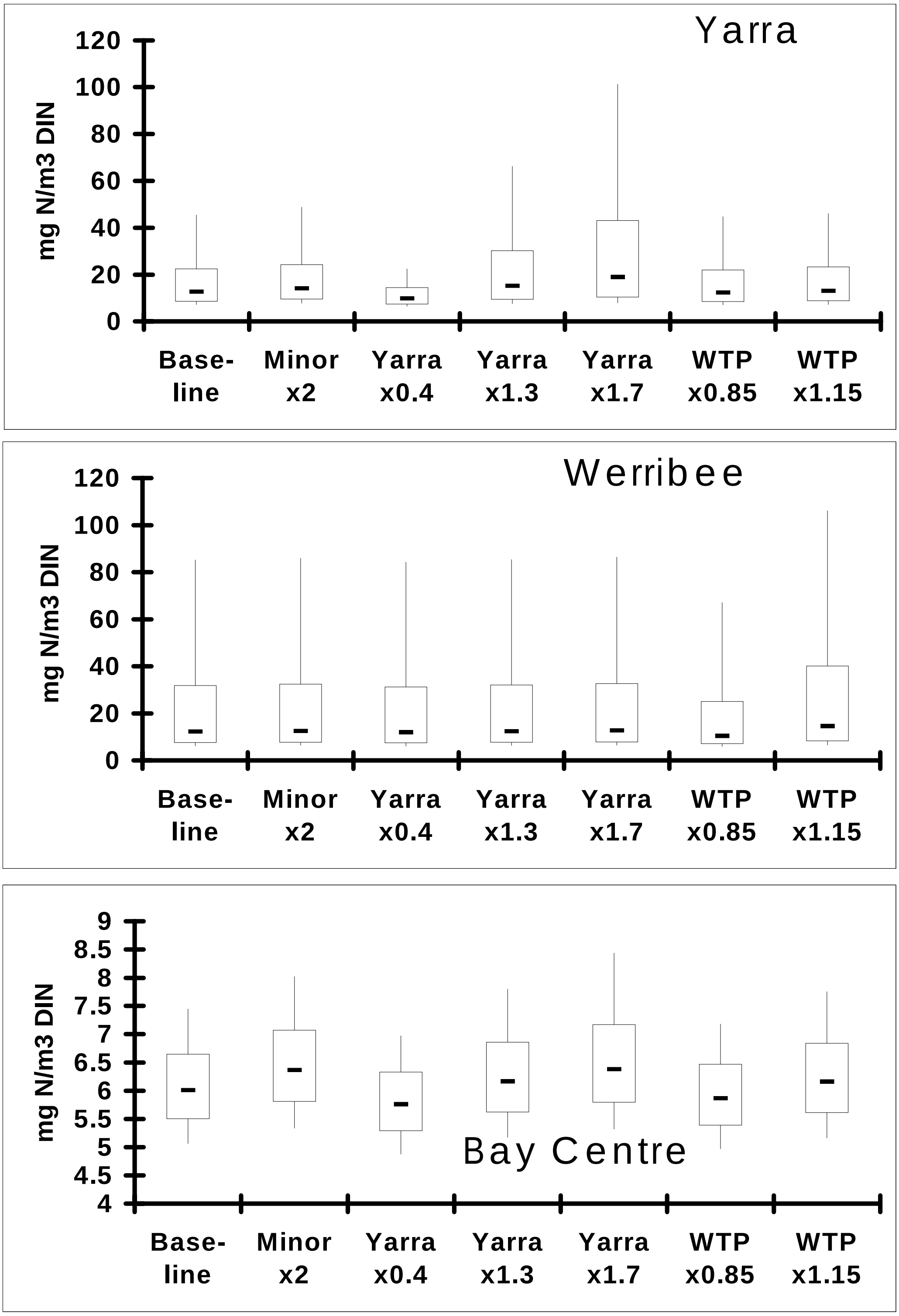

Figure 8. Regional variation in DIN under load scenarios. The box defines the range of 25-75% of DIN values (i.e. middle 50% of values), while the whiskers define the 10-90% range. The regions covered are the Yarra, Werribee and Bay centre.

3.7. Variation in light availability within regions

Chlorophyll, and other water column components (DON, detritus and the water itself), increase light attenuation in the model. Light attenuation or water clarity is a key component of water quality and plays a dominant role in controlling the distribution and productivity of phytobenthos.

As an index of water clarity and impact on benthic plants, we have calculated light levels at 10 m as a percentage of surface light. The frequency distributions of these indices are shown as box and whisker plots by scenario for the Yarra, Werribee and East Coast regions (Fig. 9). Because light levels fall off exponentially with depth, relative differences in bottom light among scenarios would be more pronounced at 20 m, and less pronounced at 5 m.

Under baseline conditions, median water clarity in the Yarra and Werribee regions is comparable. Periods of high light penetration occur more frequently in the Yarra region, but the lowest light penetration also occurs in the Yarra during flood events. Median baseline light penetration is much higher in the East Coast region (and in the Bay Centre). Predicted water clarity in the Yarra region responds strongly to changes in Yarra N loads. Under high Yarra N loads, less than 2% of surface light reaches 10 m more than 25% of the time. Light penetration off Werribee also responds to changes in WTP load, with significant shifts in the 10 and 25 percentile levels. Light penetration in the East Coast region responds strongly to changes in load from both the Patterson-Mordialloc and the Yarra, with significant reductions in the 10 and 25 percentile light levels at increased loads.

Water quality and depth are major factors in the control of the distribution of benthic plants, which is discussed in the next section.

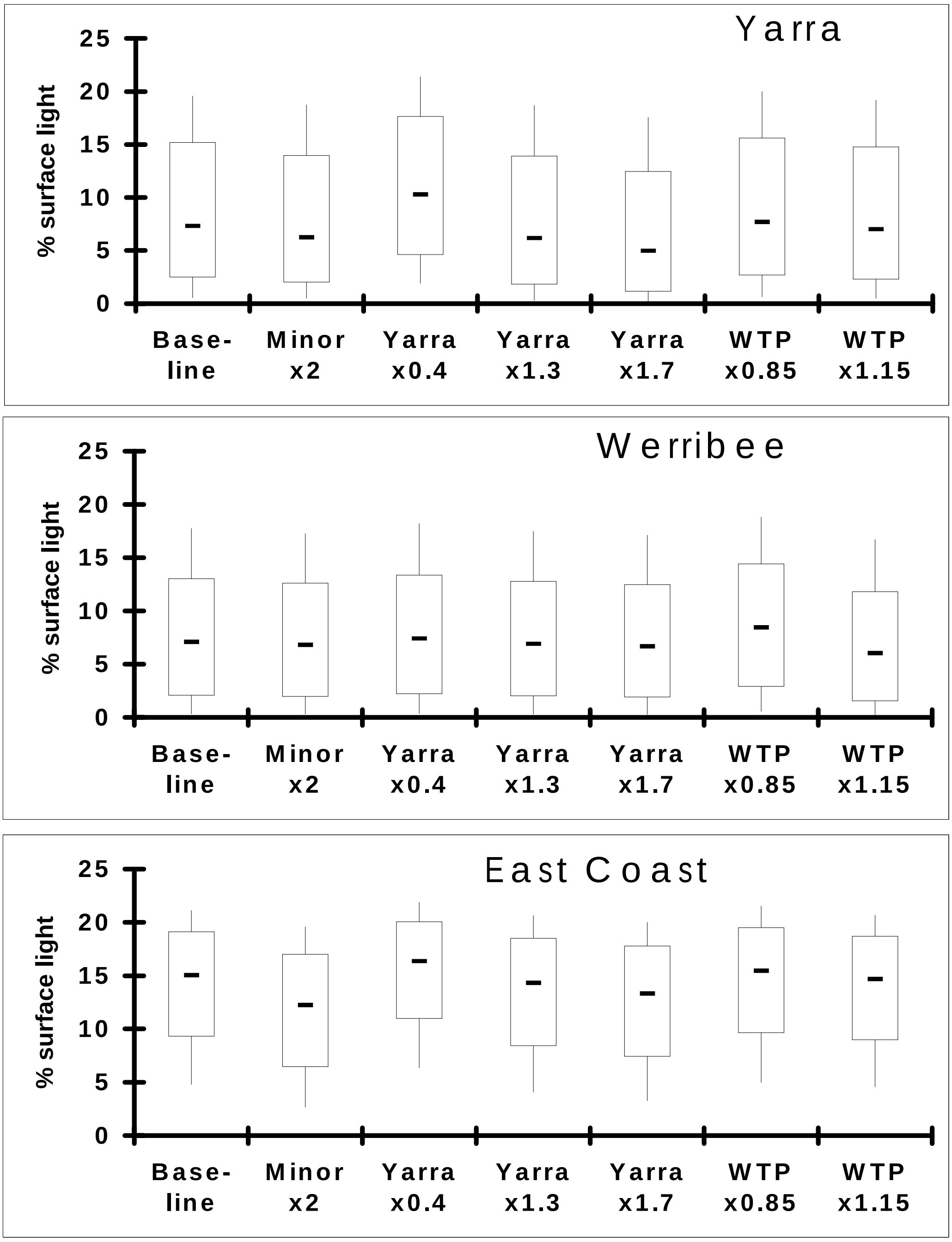

Figure 9. Variation in light intensity at 10 m as a percentage of surface light under loading scenarios by region. The box defines the range of 25-75% of chlorophyll values (i.e. middle 50% of values), while the whiskers define the 10-90% range. The central black dot shows the median value. The regions covered are: the Yarra, Werribee and East Coast.

3.8. Benthic Flora

Benthic plants play several major roles in the Port Phillip Bay ecosystem. Their total production is comparable to that of phytoplankton (Murray and Parslow 1997), with which they compete for nutrients. Seagrass beds are a valuable habitat and an important nursery for fish larvae. Macroalgal beds produce considerable amounts of detritus. Decay of macroalgal detritus accumulated on beaches can cause unpleasant odours. Decay of macroalgal detritus at the sediment surface can cause significant drawdown of bottom oxygen, particularly if large amounts of detritus are produced suddenly eg after storm events. Microphytobenthos contribute about half the organic matter in the sediments. The role of this production in controlling denitrification in the sediments is still unclear.

Because benthic flora are concentrated in specific regions, their bay-wide biomass and production are sensitive to local nutrient sources. Macroalgal production is most sensitive to changes in WTP loads, and least sensitive to changes in loads from the minor creeks (Table 4). This pattern of response reflects the fact that most macroalgal biomass is located in the north west of the Bay, nearest to the WTP and furthest from the Patterson and Mordialloc. Macroalgal production increases with increasing N load, indicating that the positive effects of nutrient addition outweigh the negative effects of decreased bottom light.

Table 4. Bay-wide annual macroalgal production as t N y^{-1}, and as a fraction of baseline production, under the scenarios.

Site	Baseline	Minor	Yarra			WTP	
Load X	1	2	0.4	1.3	1.7	0.85	1.15
Prodn (t N y^{-1})	4855.5	5247.5	4481.2	5084.6	5476.9	4298.8	5414.3
Prodn X	1	1.080	0.922	1.067	1.127	0.885	1.115

Seagrass distribution changes almost inversely to that of macroalgae. Increased N loads from the WTP cause declines in seagrasses; the seagrasses in Corio Bay are particularly sensitive. Reduced (0.85X) WTP load encourages seagrass growth and increased biomass on the northern shore of Corio Bay, while at baseline loads the model only predicts seagrass growth on the southern shore of Corio Bay. Seagrasses in the western part of the northern sands (sands II), but not in relatively isolated Swan Bay, are also affected by WTP loads. Changes to loads from the Yarra and the minor creeks affect model seagrass beds in the north eastern part of the sands. However, the seagrass beds predicted in this region using the standard model are exaggerated. In reality, sediment instability in this region of the sands appears to prevent seagrass growth. For the prescribed scenarios, the real effects of changes to non-WTP loads on seagrasses are likely to be negligible. (It should be noted that seagrass distribution in Port Phillip Bay is limited to water of less than about 5 m depth and that the nearshore model boxes are currently bounded offshore by the 5 m depth contour. Finer spatial resolution is needed to address the response of seagrass beds in more detail.)

As we have already seen, bay-wide microphytobenthos production decreases as loads are increased, although it is less sensitive than phytoplankton production. Microphytobenthos production in most coastal boxes increases slightly as N loads increase, except in the Yarra region. In the sands and in Corio Bay the MPB also react positively and rather more sensitively to increased loads. These regions are characterised by very low nutrient availability and seagrasses that also compete with MPB. Increases in MPB production in the Sands are proportional to changes in bay-wide load, i.e. up to 15% for changes in loads to minor creeks or 1.7 times Yarra N. Changes in Corio Bay are smaller and only occur in response to changes in WTP loads.

In coastal waters, MPB have ample light, and the increases in chlorophyll and detritus resulting from increased N loads do not reduce bottom light levels sufficiently to reduce MPB production, except in Hobsons Bay. Instead MPB benefit from increased nutrient availability, particularly in the oligotrophic south of the Bay. In the Bay centre, however, MPB biomass and production falls as N loads increase because of increased light attenuation over greater depth. As this region occupies about half the Bay area, and MPB biomass in Corio Bay and the sands is low, the effect of the decrease in bottom light in the Bay centre dominates the bay-wide response.

3.9. Denitrification and Oxygen

The particular importance of denitrification in maintaining the health of Port Phillip Bay has been clearly identified (Harris et al. 1996). For large increases in bay-wide loads, a major decline in denitrification efficiency, leading to severe eutrophication, is a serious risk (Murray and Parslow 1997). We have already attributed differences in the sensitivity of bay-wide fluxes to changes in load from different sources to local changes in denitrification efficiency in the vicinity of these sources. We now consider directly the spatial patterns of changes in denitrification associated with the scenarios.

Doubling loads from the minor creeks has small effects on denitrification efficiency at the regional level, presumably because the added N disperses quickly and does not lead to significant increases in local organic flux to the sediment. There is a small decrease in average efficiency off Werribee (42.6 to 37.1%), and a slight increase in Corio Bay (52.6 to 56.2%), as the WTP load increases from 0.85 to 1.15 times the current load.

Changes in Yarra inputs have a stronger local effect: denitrification efficiency in the Yarra region falls from 48.4 to 34.6% as the Yarra load increases from 0.4 to 1.7 times current load. In upper Hobsons Bay the effect is even more dramatic. For 0.4X Yarra load, denitrification is suppressed completely for only a few days at the height of the annual spring flood events (2.05% of the period of the run, see Table 5). Under the default run (and in those runs for which Yarra inputs are not changed) denitrification ceases on 6.3% of days, while under 1.3X Yarra load, denitrification ceases for 9.5% of the time. In the high load scenario (1.7X load) this suppression occurs for over a month during and following the main flood and again for shorter periods in November and December (15.9% of the period of the run). In 1994 there is no spring flood and even under 1.7X load denitrification is never completely suppressed.

A slight drop of 3% in denitrification efficiency relative to the baseline run is apparent in the bay centre under 1.7X Yarra loads and doubled minor creek loads.

Table 5. Percentage of time for which denitrification ceases in upper Hobsons Bay (model box 32) under the Yarra loading scenarios.

	0.4 × Yarra	1 × Yarra	1.3 × Yarra	1.7 × Yarra
Percent of run.	2.05%	6.3%	9.5%	15.9%

Oxygen levels in Hobsons Bay also fall during and following Yarra flood events. Under the baseline run the minimum concentration of oxygen in fine box 32 (upper Hobsons Bay) is about 80% of saturation. Under 0.4X Yarra N load, this oxygen minimum increases to 90% saturation. When Yarra N loads are increased to 1.3X and 1.7X, the minimum oxygen concentration falls to 72% and 63% of saturation respectively. Given that the inflow event also results in stratification, average column oxygen does not reflect bottom water conditions. There is a significant risk of local bottom water anoxia under these high Yarra load scenarios. Off Werribee, oxygen levels rarely fall below 90% under any scenario due to the lack of transient peak load. On one occasion, associated with mass mortality of macroalgae in a storm, oxygen in the Werribee region falls briefly to 82-86% of saturation (depending on scenario).

Denitrification does not appear to be seriously disrupted by any of the scenarios described, except locally in the Yarra region and in particular in upper Hobsons Bay. These local effects partly explain why increases to inputs from the Yarra cause a disproportionate increase in bay-wide primary production. Hobsons Bay is also the most probable site of bottom water anoxia, which would further inhibit denitrification, and possibly result in long-term changes in benthic communities. Note, however, that the model overpredicts bloom intensities immediately adjacent to the Yarra mouth (Murray and Parslow 1997), and so the deterioration in this local environment may not be quite as bad as the model predicts. A more highly resolved model of Hobsons Bay would be required to examine these local events.

4. DISCUSSION AND CONCLUSIONS

The model scenarios were selected to inform managers about the sensitivity of water quality and ecological health to changes in N load and the dependence of these effects on the nutrient source. In this report, we have used chlorophyll *a*, DIN, light penetration and dissolved oxygen as the key water quality indicators, and have considered impacts on benthic plants as one example of ecological impact. In considering bay-wide response, we have considered a broader set of pools and fluxes associated with nitrogen cycling in the Bay.

These scenarios involve relatively small changes in the bay-wide nitrogen load, with a maximum change of 17%. It is perhaps not surprising that, for changes of this order, most bay-wide pools and fluxes respond almost linearly to changes in bay-wide N load. (There are exceptions such as microphytobenthos, which respond only weakly to changes in load, because these involve counterbalancing changes in nutrient and light availability.) At the bay-wide level, the small differences in sensitivity among fluxes and among sources are not of direct significance to management, except as they reflect differences in local impacts. Previous analyses have predicted that the bay-wide ecosystem can respond strongly and non-linearly to a doubling or trebling of bay-wide loads. However, for smaller changes of the magnitude considered here, we must look to the local and regional impacts to provide guidance for management decisions.

The scenarios do involve substantial changes in loads from each of the three major sources, the Patterson-Mordialloc system, the Yarra River and WTP, and these changes do have significant implications for local and regional water quality and system function. Not surprisingly, these effects are greatest in the adjacent regions, and to some extent, we can treat the regional impacts of the major sources as being decoupled. Thus, choice among sources for management action is likely to depend on a comparative evaluation of the associated regional impacts and benefits. We can summarise these regional responses as follows.

Under baseline loading, the minor creeks, rivers, and drains contribute ca 1200 t N p.a., and doubling this load represents the (equal) largest change in bay-wide load considered here, and a major perturbation for the east coast region where most of these inputs are delivered through the Patterson Mordialloc system. The Bay shoals relatively quickly along the eastern shore, and inputs from these minor sources are dispersed relatively quickly into the Bay centre. It is not surprising then that doubling the N input from this source increases chlorophyll over a broad area, including most of the Bay centre. Over the East Coast region, it results in an increase in chlorophyll of about 50% at the median, 75 and 90 percentile levels. This does produce significant decreases in bottom light, although this region is not a major contributor to benthic plant production, again because of the rapid shoaling. (Of course, locally important benthic communities may still be adversely affected. At greater depths, bottom light levels drop much more quickly for a given change in light attenuation.)

The East Coast region is also strongly affected by major runoff events from the Yarra, which account for some of the more intense blooms. Under baseline loads from minor creeks, rivers and drains, reducing the Yarra load to 0.4X reduces the 90 percentile chlorophyll values in the East Coast region by about 25%.

Kororoit Creek and Werribee River are also included in the minor creeks, along with the Patterson-Mordialloc. Over the study period, these have negligible input, except for one flood event in 1993. The effects of doubling their input are undetectable in statistical indices in the adjacent NW region.

Changes to the WTP load have most impact on the adjacent Werribee and Corio Bay regions, with smaller impacts on the North-West region. Physical exchange between this region and the Bay Centre is variable (Corio Bay is poorly flushed). A key feature of the Werribee Region is that phytoplankton (diatom) blooms appear to be strongly limited at times by Si, and DIN accumulates in the water column. It is not surprising then that increasing the N load increases Si limitation, and leads to a larger percent increase in DIN than in chlorophyll. Although this is not well captured in the present model, one might expect increases in DIN accumulation and Si limitation to increase the frequency and intensity of dinoflagellate blooms.

The western part of the Bay shoals more gradually, and is an important site for benthic plant production. Changes in N loads from Werribee have significant implications for benthic plant production and composition. In the model, seagrass have a high light requirement and are adversely affected by high water column DIN (due to epiphyte growth). Conversely, macroalgae have a low light requirement and are favoured by high water-column DIN. Thus, it is not surprising that increasing the N load from WTP results in a replacement of seagrass by macroalgae. Because of the Si limitation, it also results to some extent in a switch from phytoplankton to macroalgae production.

Changes in the Yarra load strongly affect the Yarra region, but spill over into the East Coast and Bay Centre regions. The most striking aspect of changes in the Yarra load is the impact on local water quality and sediment biogeochemistry. Hobsons Bay is already a site of high chlorophyll, high sediment respiration, reduced oxygen and low denitrification efficiency. All these are strongly affected by changes in load. Thus, the response of Hobsons Bay to increases in Yarra N load provides an example in miniature of the predicted bay-wide response to doubling or trebling of bay-wide load. It leads to a large decrease in regional denitrification efficiency, and increase in N recycling from the sediment. This does not increase peak bloom intensity, but instead greatly increases bloom duration following runoff events. There is also an associated decrease in water column oxygen, which seems likely to involve episodic bottom water anoxia.

Aside from these local effects, the decrease in denitrification efficiency means that increases in N loads from the Yarra produce a disproportionate increase in bay-wide productivity. As noted above, the Yarra has quite a strong impact on bloom levels in the East Coast region, especially in the northern section.

The Yarra is also the major source of Si. Increases in Yarra N loads without concurrent increases in Si load result in more Si limitation in the Werribee region, which may increase the likelihood of dinoflagellate blooms. Conversely, decreases in Yarra N loads should reduce Si limitation in the Werribee region.

Nutrient loads from the Yarra are strongly pulsed, and currently the more severe impacts on water quality are associated with large runoff events. Catchment management practices, which led to a decrease in peak load and an increase in background load, should reduce the frequency and severity of peak load impacts. Given the nonlinear feedback in this region, this could also lead to an improvement in average water quality. Further model scenarios to address management options involving changes in the temporal pattern of Yarra loads may be worth consideration.

In using a simulation model of this kind for management scenarios, it is important to consider the uncertainties involved in model predictions. We have not attempted to quantitatively assess uncertainty in model predictions in a formal Bayesian sense: this is not currently feasible for a model of this complexity. We therefore confine ourselves to qualitative remarks.

At the bay-wide level, the baseline model has been calibrated against observed pools and fluxes, and good agreement has been achieved. Given that the scenario changes in bay-wide load are relatively small, and the bay-wide response is nearly linear, we can attach a higher degree of confidence to the scenario predictions at the bay-wide level.

Predictions at the regional level involve larger relative changes in regional loads, and more evidence of non-linear feedback. Of the three principal sources and associated regions, the WTP scenarios involve small relative changes in loads (15%), and again approximately linear responses in most water column pools and fluxes, with reduced uncertainty. As we noted above, the current model does not represent dinoflagellate blooms appropriately, and we can only point to predictions of high DIN under Si limitation as being likely to promote dinoflagellate blooms. The model processes involved in predictions of the effect of changes in light attenuation and increased DIN on seagrass and macroalgae are also poorly calibrated, and rely heavily on results of process studies from other systems. We can be fairly confident about the direction of predicted change in phytobenthos distribution, but not about the magnitude.

Although the load from the Patterson-Mordialloc system is doubled, the response in water column variables appears to be approximately linear, probably because dispersion and dilution of this load into the Bay Centre is a dominant process. Further consideration of the impact of predicted changes in water quality on local benthic communities in this region is warranted, as this is not well represented in the model.

Large changes in the Yarra N load do produce non-linear positive feedbacks at the regional scale, so that impacts on regional water quality are magnified. This non-linearity depends primarily on the relationship between sediment respiration and denitrification efficiency. The empirical basis for this relationship, and uncertainties attached to it, are discussed extensively by Murray and Parslow (1997). In these scenarios, the feedback occurs through a spatial and temporal expansion of the high respiration rate and low denitrification efficiency already observed in Hobsons Bay. In this sense, one might argue that these predictions involve less uncertainty than the extrapolation of the respiration - denitrification efficiency relationship to the entire Bay.

Because of the strong local and regional nature of impacts from the Yarra load, the vertical and horizontal resolution of physical transport is more critical. As discussed in Murray and Parslow (1997), and above, it is arguable that the transport model resolution in Hobsons Bay is marginal. This may account for the model tendency to overestimate bloom intensities in the inner part of Hobsons Bay, and underestimate intensities further away. The standard model is still a one-layer model and is likely to underestimate bottom oxygen depletion under strongly stratified conditions.

The standard model does not capture the dynamic impact of sediment loads in Yarra flood events on light attenuation and this would also lead to overly rapid bloom development. These will be particularly important if managers wish to consider scenarios involving changes in sediment loads from the Yarra.

Choices about where to reduce N loads will of course depend on assessments of the feasibility and costs of different management actions, as well as the resulting environmental improvements. In broad terms, the model scenarios presented here suggest a choice between reductions in the diffuse Yarra load, which will address an area of significant local environmental impact and risk in the north-east of the Bay, and reductions in the WTP load, which may have a broader more diffuse impact on benthic habitat in the western Bay.

In making this choice, managers may well wish to consider additional indices or summary statistics of water quality and ecological impact. In a written report of this kind, it is only feasible to present a subset of the model output. Model output files for these scenarios have been stored by, and can be revisited if necessary.

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