Huon Estuary Fish Farm Load Scenarios

Final Report

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Introduction

As part of the recently completed Huon Estuary Study (HES Final Report - CSIRO Huon estuary Study Team, 2000), CSIRO developed a simple model of transport, nutrient cycling and algal blooms in the Huon Estuary. This model included loads from the catchment, the marine boundary and from salmon farm operations based on tons of feed in calendar year 1997.

The HES Final Report included a set of model scenarios which examined the effect of increases in salmon farm loads on predicted levels of nutrient and chlorophyll in the Estuary. These scenarios were not designed as realistic management scenarios, and salmon farm loads were simply scaled uniformly by factors of 2, 4 and 10, regardless of location in the estuary.

Huon Aquaculture occupies a number of salmon farm sites in the Huon Estuary, and has increased production substantially since 1997, particular at sites near the mouth of the Huon Estuary (Hideaway Bay and Flathead Bay). As part of its long term planning, Huon Aquaculture has commissioned CSIRO to use the Huon Estuary model to investigate a number of alternative load scenarios for its Huon Estuary sites. These scenarios are designed to assess how environmental impact depends on the location of fish farm loads (both along the estuary, and vertically within the water column). This report presents and discusses model results for these scenarios. We begin with a brief description of the model, and its application to the scenarios.

The Huon Estuary Model

The model implemented in the Huon Estuary Study and used here is based on the estuarine modelling package SEEM (Simple Estuarine Eutrophication Model) (Parslow et al, 1999). This modelling package was developed to provide a simple and robust model of nutrient cycling and phytoplankton biomass in estuaries, particularly estuaries subject to point source loads of available nutrients.

The model describes the cycling of nitrogen (or phosphorous, but not both) through four compartments: dissolved inorganic nutrient (DIN), phytoplankton biomass (PHY), labile particulate detritus (DET) and refractory organic material (REF). A full description of the model equations can be found in Parslow et al (1999), and and its application to the Huon Estuary is described in detail in Chapter 10 of the HES Final Report.

The Huon Estuary Study was primarily a field study with little resource allocated to modelling. The SEEM package was used there because it can be quickly and easily implemented and calibrated. The model proved able to capture the major seasonal and spatial patterns in the distribution of dissolved inorganic nitrogen and chlorophyll observed in the Huon Estuary. However, the model does have a number of inherent limitations, which are discussed in Chapter 10 of the HES Final Report, but are worth repeating here.

SEEM primarily represents cycling of nutrients in the water column. It represents sediment implicitly by allocating a fraction of each pool to sediment, and subjecting only the water column fraction to advection and mixing. It represents denitrification in bed sediments, but is unable for example to represent the seasonal or long-term accumulation or depletion of refractory organic material in sediments.

There are also limitations in the model's representation of physical circulation in the estuary. Physically, SEEM represents the estuary as a laterally-averaged system with 2 vertical layers and 15 boxes along the estuary (Fig. 1). The model represents circulation in the Huon Estuary as a classical 2-layer estuarine circulation, with outflow at the surface and inflow at depth. There is evidence from HES for lateral gradients across the estuary, with the fresh water plume tending to concentrate against the northern bank. There is also evidence from current meters that the mean surface flow may be directed upstream into the estuary on the southern side near the mouth, although the net surface flow averaged across the estuary is downstream.

The model (and the Huon Estuary Study it was based on) is restricted to the Huon Estuary itself. There is evidence from the Study that the estuarine circulation may extend beyond the mouth of the estuary into D'Entrecasteaux Channel, and that exchanges between the estuary and the channel may affect the fate and impact of nutrient loads in both regions.

The consequences of these limitations for the interpretation of scenario results is addressed in the discussion. The data generated by the Huon Estuary Study would support the implementation and calibration of more sophisticated models which address these limitations, and proposals to carry out this model development have been submitted.

The Scenarios.

The set of load scenarios specified by Huon Aquaculture are listed in Table 1. Loads are specified in tonnes of feed per year into model boxes, which are shown in Fig. 1. Also included in Table 1 for comparison are the estimated 1997 loads used in HES in calibrating the model, and the doubled 1997 loads (1997 x 2) simulated in the HES Final Report.

Scenarios 1-6 compare the relative effects and interactions of varying loads into box 13 (near the mouth of the estuary) and into box 11. In scenarios 1-3, the load into box 13 is 4300 tonnes p.a.; this is reduced in scenarios 4-6 by 1650 to 2650 tonnes p.a. Within scenarios 1 to 3 and 4 to 6, the loads into box 11 are reduced from 708 to 341 to 0 tonnes p.a.. Scenario 7 represents an allocation of load quotas across the estuary, with a total load approximately twice the 1997 load, as proposed by managers.

Loads into box 13 in Table 1 include loads at the Flathead Bay site, which strictly lies in box 14 (Fig. 1). However, in the model, box 14 is a boundary box, in which model variables are specified based on observations, rather than predicted, so it is not possible to allocate loads to box 14. Loads at Flathead Bay have therefore been allocated to box 13.

Table 1. Load scenarios specified by Huon Aquaculture and run here, plus 1997 and doubled 1997 loads. All loads are in tonnes p.a.

	Box13	Box12	Box11	Box10	Box8	Total
Scenario 1	4300	400	708	673	1351	7432
Scenario 2	4300	400	341	673	1351	7065
Scenario 3	4300	400	0	673	1351	6724
Scenario 4	2650	400	708	673	1351	5782
Scenario 5	2650	400	341	673	1351	5415
Scenario 6	2650	400	0	673	1351	5074
Scenario 7	2250	428	708	673	1248	5307
1997	1442			669	539	2650
1997 x 2	2884			1338	1078	5300
1997 x 4	5768			2676	2156	10600

These feed figures have been converted into net loads of nitrogen into the estuary using the same assumptions used in the HES Final Report. We assume the feed is 7.2% nitrogen by weight. Based on the wet weight of fish produced, and the nitrogen content of the fish, we estimated that 36% of the N in the feed is removed as live fish, and 64% is retained in the estuary. Of that 64%, we estimated 87% is released into the water column as dissolved inorganic nitrogen (DIN), and 13% as feed waste and faeces (DET). (Note that we have lumped urea in as DIN, because from the point of view of phytoplankton, it is likely to act functionally as DIN).

In the absence of more detailed information on temporal patterns of feed, the calculated annual loads of DIN are assumed to occur uniformly throughout the year, and are converted into model units (mg N s^{-1}) by scaling appropriately.

The model scenarios in the HES Report assumed that fish farm nutrient loads are injected into the bottom layer of the estuary. This can be expected to lead to maximum impact, as average flow in the bottom layer is upstream, while loads released into the surface may be rapidly transported downstream and out of the model domain. Huon Aquaculture has requested an assessment of the effect of different assumptions about the vertical allocation of loads. Specifically, for each of the scenarios above, they proposed three sub-cases: 100% of loads into the bottom layer, 50% of loads into the bottom layer, and 25% of loads into the bottom layer. These sub-cases are referred to e.g. for scenario 1, as respectively S1_100, S1_50 and S1_25. We have also repeated these three sub-cases for the 1997 and 1997 x 2 scenarios, to facilitate comparison with earlier results. Finally, we have included the 1997 x 4 scenario presented in the HES Report, with 100% of loads into the surface layer, as an upper benchmark for comparison.

Results for all the fish farm load scenarios have been normalised against model predictions with zero fish farm loads which were conducted in HES and included in the HES Final Report.

Results and Discussion.

As in the HES Final Report, the model has been run separately to steady-state for the river flow and loads and marine boundary conditions prevailing for eight of the spatial surveys carried out in the HES. Of these surveys, four corresponded to conditions characteristic of winter and early spring, with high marine boundary concentrations of nitrate, and phytoplankton biomass limited by flushing and light. These “winter” surveys were HES2 (Jul ’96), HES3 (Oct ’96), HES5 (Jun ’97) and HES10 (Aug ’98). The other four corresponded to late spring / summer conditions, with drawdown of DIN within the estuary, and evidence for N-limitation of phytoplankton biomass. These “summer” surveys were HES4 (Feb ’97), HES6 (Oct ’97), HES7 (Dec ’97) and HES8 (Feb ’98).

It would be preferable to simulate the entire 1996-98 field period continuously, but the model has not been calibrated in this mode. Because the estuary has a short flushing time, the steady-state simulations should capture reasonably well the direct effects of available nutrient loads (though not necessarily seasonal or longer-term sediment exchanges). Running the model for a range of summer and winter conditions gives an indication of the variability in impacts to be expected both seasonally, and with varying river flow.

With the 7 specified scenarios plus two HES scenarios, times the three vertical allocation sub-cases, times the eight surveys, the model has been run 216 times. We present the same indicators for each model run as we did in the HES Final Report: maximum chlorophyll a (Chl a) in the estuary, and DIN in the bottom layer in mid-estuary (box 8). The former is chosen as a measure of impact on phytoplankton bloom intensity. The latter is chosen as an indicator of the build-up of DIN excess to phytoplankton requirements in the estuary under “summer” conditions, and the accumulation of DIN (over and above the high marine nitrate present) under “winter” conditions.

Results are presented in both tabular and graphical form. Table 2 shows maximum Chl a for all scenarios and sub-cases, for all surveys. Table 3 shows the same results for DIN in mid-estuary bottom layer. Fig. 2 and 3 show predicted Chl a and DIN indicators for “winter” surveys, while Fig. 4 and 5 show indicators for “summer” surveys.

Because small changes in predicted indicators are hard to compare across scenarios and surveys, we have used the predicted indicator values with zero fish farm loads (calculated as part of HES and reported in Chapter 10 of the HES Final Report) as a reference point, and computed the percent change in each indicator for each scenario and survey from the reference value with zero fish farm load. These are presented in Table 4 (Chl a) and Table 5 (DIN). The predicted indicator values for zero fish farm loads are plotted in Fig. 2 to 5.

“Winter” Conditions

We consider first the results for “winter” conditions (surveys 2, 3, 5, 10). Predicted impacts on Chl a in winter are easily dealt with. Chl a is completely insensitive to fish farm loads under winter conditions (Fig. 2, Table 2, 4), as phytoplankton growth is already saturated by marine nutrients, and limited by light and flushing.

Bottom layer DIN does respond to fish farm loads in winter (Fig. 3, Tables 3, 5), but effects are relatively small at these load levels, again because marine DIN (nitrate) levels are relatively high. For 100% of loads into the bottom layer, the 1997 loads are predicted to increase DIN by only 4 to 11%, and doubled 1997 loads by 9 to 22%. Comparable results are predicted for scenario 7. Even for scenario 1, with the largest total fish farm loads, increases range from 11 to 27%.

There are two striking patterns in the results for winter DIN, which are also true for summer DIN and Chl a (see below).

- First, there is strong variation in sensitivity to loads among surveys, which largely reflects differences in the physical flushing regime. Of the "winter" surveys, HES3 (Oct '96) has by far the largest river flow (250 m^3 s^{-1}) and shows the least sensitivity to loads.
- Second, the predictions are very sensitive to the vertical allocation of fish farm loads. If fish farm loads are distributed 75% surface and 25% bottom, their impact on winter DIN is reduced by between 3 and 4 times, to levels of only 3 to 8% (Table 5), even under scenario 1. This is not too surprising, as input DIN loads in winter are participating only weakly in biological cycling within the estuary, and loads into the surface layer are rapidly flushed out of the estuary.

A key purpose of scenarios 1 to 6 is to compare the effects of loads at the mouth of the estuary (box 13) with those further upstream in box 11. The best way to gauge this is to compare scenarios 3 and 4, as the step from scenario 3 to 4 involves a decrease in feed in box 13 of 1650 t p.a., and an increase in feed in box 11 of 708 tonnes p.a.

For sub-case 1, with 100% of loads into the bottom layer, impacts under scenario 3 are slightly higher than under scenario 4: the 1650 tonnes p.a. in box 13 outweighs the 708 tonnes p.a. in box 11. However, under sub-cases 2 and 3, with 50 or 75% of load allocated to the surface layer, impacts under scenarios 3 and 4 are indistinguishable: ie the 1650 tonnes p.a. in box 13 is roughly equivalent to 708 tonnes p.a. in box 11.

These results can be understood in terms of the model's representation of physical circulation in the estuary. Loads injected into the bottom layer are transported upstream, so it makes little difference whether they are located in box 13 or box 11. Loads injected into the surface layer are transported downstream, and have less chance of being mixed downwards and recirculated within the estuary if they are injected in box 13 (adjacent to the boundary) than in box 11.

The differences among scenarios 1 to 7 in effects on winter DIN are very small in both absolute and relative terms, and almost negligible compared with differences among surveys. Even with 100% of loads allocated to the bottom layer, predicted DIN under scenario 1 is only 0.1 µM larger than under scenario 1.

These patterns in impacts on winter DIN are also evident in summer DIN and Chl a results discussed below, and in fact much more significant there. The differences among scenarios 1 to 7 in effects on winter DIN are very small in both absolute and relative terms, and almost negligible compared with differences among surveys. Even with 100% of loads allocated to the bottom layer, predicted DIN under scenario 1 is only 0.1 µM larger than under scenario 1. Given the high background marine DIN levels in winter, the impacts on winter DIN under all scenarios predicted by the model are of little significance for estuarine function, and it would be hard to attach significance (in terms of environmental impact) to differences among scenarios 1 to 7.

"Summer" Conditions

Results under "summer" conditions (surveys 4, 6, 7 and 8) are of more interest because this is the period when harmful algal blooms can occur, resulting in both environmental stress and impacts on fish farm operations. Results for Chl a in summer are shown in Fig. 4, Tables 2 and 4, and results for DIN in Fig. 5, Tables 3 and 5.

The patterns noted above are more pronounced under summer conditions. There is strong variation among surveys, again related to river flow. Sensitivity is low under high flow conditions (HES 7: 122 $m^3 s^{-1}$) and maximum under low flow conditions (HES 4, 6: 30 $m^3 s^{-1}$).

The effects of varying the vertical allocation of loads between surface and bottom layers is even more pronounced in summer, especially for DIN (Fig. 5). The impact of loads on Chl a (Table 2, 4) is reduced by about one third when 50% of loads are injected into the surface layer, and by half when 75% of loads are injected into the surface layer. The impact of loads on DIN (Table 3, 5) is reduced by half when 50% of loads are injected into the surface layer, and by two thirds when 75% are injected into the surface layer.

The relative impact of loads injected into box 13 and box 11 again can be judged by comparing scenarios 3 and 4. When all loads are injected into the bottom layer, impacts are greater in scenario 3: 1650 tonnes p.a. in box 13 outweighs 708 tonnes pa. in box 11. However, when 50% or 75% of loads are injected into the surface layer, impacts in scenario 3 are similar to impacts in scenario 4, implying that loads in box 11 have more impact mass for mass than loads in box 13. Both box 11 and box 13 are relatively close to the mouth of the estuary: loads injected further upstream would be expected to have more impact mass for mass than loads in either box 11 or 13, at least under sub-cases 2 or 3.

When loads are all injected into the bottom layer, the impacts on Chl a and DIN scale more or less with total load across all scenarios, so that impacts increase in reverse order from scenario 7 to scenario 1. However, the maximum increase in Chl a from scenario 7 to scenario 1 is only 0.2 mg Chl a m^{-3}, or 7% of the predicted value without fish farm loads. The maximum increase in bottom DIN from scenario 7 to scenario 1 is 0.1 µM, or 15% of the predicted value without fish farm loads. (Relative changes in DIN are larger because the base value is low.) These absolute differences among scenarios are all quite small compared with the variation among surveys, or spatial variation within the estuary. Because doubling fish farm loads results in only moderate impacts on Chl a and DIN, it is not surprising that variations in loads around this level have small effects. By comparison, the 1997x4 scenario with 100% of loads into the bottom layer increases summer Chl a by up to 86%, and summer DIN by up to 215%. Increases in scenario 1 still fall well short of these values.

Model Limitations

It is important that the model limitations described earlier be kept in mind when interpreting these scenario results.

The model simplifies the estuarine circulation by averaging across the estuary, so that flow is always directed out of the estuary in the surface layer and into the estuary in the bottom layer. This will tend to exaggerate the effect of different assumptions about the vertical allocation of loads. Particularly in the lower part of the estuary, there may be substantial horizontal recirculation within the surface and bottom layers. Current meter records indicate some tendency for surface flow into the estuary along the southern shore near the mouth. Model predictions about the effect of changes in vertical allocation of loads need to be treated cautiously until the three-dimensional circulation is better understood.

The model also assumes that nutrients advected out of the estuary in the surface layer have no further role in the estuarine nutrient cycle. Specifically, it assumes that the marine boundary conditions are fixed, independent of fish farm loads. If the estuarine circulation does extend into D'Entrecasteaux Channel, some fraction of the exported nitrogen may be transferred to the bottom layer by mixing or sinking, and transported back into the estuary. This could increase the impact of fish farm loads above levels predicted by the model.

The model treats sediments implicitly , and does not allow exchanges of nutrients with sediments on seasonal time scales or longer. There is some evidence from HES nutrient budgets that nitrogen is stored in sediments in spring and summer and exported in winter (HES Final Report, Chap 10). This seasonal exchange could serve to reduce impacts at some times, and increase impacts at other times of year.

The model is run to steady-state under the physical and boundary conditions corresponding to eight of the HES spatial surveys. Although these simulations do not capture the dynamical effects of rapid fluctuations in river flow, short estuarine flushing times mean that these steady-state simulations should capture behaviour during extended periods (i.e. a few weeks) of low or high river flow. The effect of river flow and flushing time on predicted sensitivity to loads is large and the predicted variability among survey simulations is likely to provide a reasonable guide to the range of impacts which can be expected. It is clear (and hardly unexpected) that impacts will be greatest during prolonged periods of low flow.

The indicator values presented here do not include two other contrasting scales of variation. There can be significant variation in chlorophyll and DIN on spatial scales which are small compared with model boxes. The HES data frequently showed vertical concentration of dinoflagellates and diatoms into thin horizontal layers (HES Final Report, Chap 5). Model values are averaged vertically over surface or bottom layers. This fine scale variation needs to be taken into account in comparing model predictions with observations.

The HES also found very large interannual variations in Chl a, which could not be directly related to physical forcing, but were associated with the development of intense dinoflagellate blooms in the 1997/98 summer. It appears that vertical migration by dinoflagellates allows accumulation of biomass to levels up to an order of magnitude greater those which water column nutrient supplies could otherwise support (HES Final Report, Chap. 10). The factors which promote dinoflagellate blooms are only partly understood, and so it is difficult to predict the impact of fish farm loads on the frequency of occurrence of dinoflagellate blooms. Experience elsewhere suggests their frequency increases as estuaries become more eutrophic. At minimum, their occurrence throws a large degree of uncertainty around model predictions for any specific year and load scenario.

Conclusions

The model limitations, and the high levels of natural variabilty, mean that the absolute values of Chl a and DIN indicators predicted for particular scenarios should be treated with some caution. The model scenarios should be regarded as providing an index of the sensitivity of these indicators to increases in load, and more attention should be paid to relative changes than absolute levels.

With this in mind, the strongest patterns to emerge here are the effects of river flow and flushing rate on impact, and the importance of assumptions about the vertical allocation of fish farm loads.

The former is hardly unexpected, and can be treated as part of natural variability. Impacts are likely to be greatest during extended periods of low flow.

The vertical allocation of loads has a dramatic effect on model predictions. If 50% of loads are allocated into the bottom layer, instead of 100% as in HES, the impact on summer DIN and Chl a is cut by almost a factor of 2. If the estuary was being managed with specific Chl a and DIN targets in mind, based on the HES 1997x2 predictions, the results here suggest that managers could in principle double the target feed quotas, if convinced that 50% of loads do go into the surface layer, and treble them if convinced that 75% of loads enter the surface layer.

The other principal aim of this study was to examine the effect of the location of loads along the estuary. These conclusions interact strongly with the vertical allocation of loads. If loads are allocated 100% into the bottom layer, then it makes little or no difference whether loads are allocated into box 13 or 11 as these loads are all advected into the estuary. If loads are allocated 50 or 75% into the surface layer, then horizontal location does matter: loads injected into surface waters near the mouth are rapidly flushed out of the estuary. (The limitations of the model, and the unresolved effects of variation in current direction across the mouth, and potential interaction with D’Entrecasteaux, need to be kept in mind.)

Again, it is clear that resolving the vertical distribution of loads is of primary concern. If loads are effectively delivered 100% into the bottom layer, then position along the estuary is relatively unimportant. If a substantial fraction of loads is delivered into the surface layer, then the predicted impact of loads is substantially reduced. Effects of location may then also be important, but the change in overall capacity would in any case have significant implications for quotas.

As stated in the HES report, the assumption that 100% of loads enter the bottom layer is "conservative" or precautionary, in the sense that it is the worst-case assumption for load impacts. It is obviously in the interests of both industry and managers if scenarios can be based on the actual vertical distribution of loads. Most of the DIN is released by fish excretion into the water column: it should be possible to establish its vertical distribution through studies of fish behaviour. Most of the particulate organic matter released will quickly find its way to the bottom anyway, so it is the fate of the dissolved fraction which requires study.

Note that the vertical allocation of loads in the model depends on the depth of the surface layer. The depth of the surface layer in the model is shown in Table 6 below. These depths were based on analysis of salinity profiles in HES. While the depth in the upper reaches of the estuary is relatively constant, the depth of the surface layer in the lower estuary is more variable over time.

Table 6. Surface layer depth vs model box number.

Box #	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Depth	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	5.5	5.5	5.5	8.6

Model Predictions, Uncertainty and Management.

It is not the role of this study to chose among scenarios or set management targets. Management indicators and target levels, and actions to achieve these, are set by regulators in consultation with industry and other stakeholders, including the community. This report presents predicted relationships between potential management actions (in the form of load allocations) and potential indicators (Chl a and DIN), based on the state of understanding and knowledge achieved through the HES. These predictions are intended to help managers and industry to choose among management actions and strategies.

The considerable level of uncertainty in these predictions, discussed above, is uncomfortable, but hardly unusual in managing natural environmental systems. This uncertainty creates two obvious kinds of risk for management of finfish farming in the Huon Estuary. There is a risk that feed limits will be set lower than needed to achieve agreed environmental objectives, resulting in foregone socio-economic return to industry and the region. There is a risk on the other hand that limits will be set too high, resulting in unacceptable environmental damage, and potentially also in economic losses to the industry. Managers need to balance these risks, taking into account socioeconomic and environmental values.

In the long-term, this uncertainty in predicting impacts of loads should be reduced, both through further scientific research, and equally or more importantly, through monitoring and assessing the environmental impacts of past management actions. Reductions in uncertainty should lead to modification and improvement of management strategies and actions.

In other areas of natural resource management, the need to deal with uncertainty has led to the development and adoption of adaptive or experimental management strategies, which explicitly recognise the need to monitor results of past and current actions, and incorporate formal procedures to use monitoring results to refine management targets and regulations. The application of these adaptive management strategies to the management of finfish farming in the Huon Estuary would appear to be in the interests of both industry and the environment.

References

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Parslow, J., Davidson, A., Hunter, J., 1999. Estuarine Eutrophication Models. National River Health Program, Urban Sub-Program. Report No 12, LWRRDC Occasional Paper 19/99.

Table 2. Predicted maximum Chl a (mg m^{-3}) in estuary for all surveys, scenarios and sub-cases.

Scenario	Bottom Percent	HES2	HES3	HES5	HES10	HES4	HES6	HES7	HES8
		"WINTER"				"SUMMER"			
1	100	1.0	1.8	0.7	0.8	4.5	3.8	3.6	3.3
2	100	1.0	1.8	0.7	0.8	4.5	3.8	3.6	3.3
3	100	1.0	1.8	0.7	0.8	4.4	3.8	3.6	3.3
4	100	1.0	1.8	0.7	0.8	4.4	3.7	3.5	3.3
5	100	1.0	1.8	0.7	0.8	4.3	3.7	3.5	3.2
6	100	1.0	1.8	0.7	0.8	4.3	3.7	3.5	3.2
7	100	1.0	1.8	0.7	0.8	4.3	3.7	3.5	3.2
1997	100	1.0	1.8	0.7	0.8	3.7	3.1	3.3	2.7
1997x2	100	1.0	1.8	0.7	0.8	4.3	3.7	3.5	3.2
1997x4	100	1.0	1.8	0.7	0.8	5.5	4.8	4.0	4.1
1	50	1.0	1.8	0.7	0.8	4.1	3.4	3.5	3.0
2	50	1.0	1.8	0.7	0.8	4.0	3.4	3.5	2.9
3	50	1.0	1.8	0.7	0.8	4.0	3.4	3.4	2.9
4	50	1.0	1.8	0.7	0.8	4.0	3.4	3.4	2.9
5	50	1.0	1.8	0.7	0.8	4.0	3.3	3.4	2.9
6	50	1.0	1.8	0.7	0.8	4.0	3.3	3.4	2.9
7	50	1.0	1.8	0.7	0.8	4.0	3.3	3.4	2.9
1997	50	1.0	1.8	0.7	0.8	3.6	2.9	3.3	2.6
1997x2	50	1.0	1.8	0.7	0.8	3.9	3.3	3.4	2.9
1	25	1.0	1.8	0.7	0.8	3.8	3.2	3.4	2.8
2	25	1.0	1.8	0.7	0.8	3.8	3.2	3.4	2.8
3	25	1.0	1.8	0.7	0.8	3.8	3.2	3.4	2.8
4	25	1.0	1.8	0.7	0.8	3.8	3.2	3.4	2.8
5	25	1.0	1.8	0.7	0.8	3.8	3.2	3.4	2.8
6	25	1.0	1.8	0.7	0.8	3.8	3.1	3.4	2.7
7	25	1.0	1.8	0.7	0.8	3.8	3.1	3.4	2.7
1997	25	1.0	1.8	0.7	0.8	3.5	2.9	3.3	2.5
1997x2	25	1.0	1.8	0.7	0.8	3.8	3.1	3.4	2.7

Table 3. Predicted DIN (µM) in mid-estuary (box 8), bottom layer, for all surveys, scenarios and sub-cases.

Scenario	Bottom Percent	HES2	HES3	HES5	HES10	HES4	HES6	HES7	HES8
		“WINTER”				“SUMMER”			
1	100	5.3	4.1	3.9	4.8	1.1	0.9	0.6	0.4
2	100	5.3	4.1	3.9	4.7	1.1	0.9	0.6	0.4
3	100	5.3	4.1	3.9	4.7	1.1	0.9	0.6	0.4
4	100	5.3	4.1	3.9	4.7	1.1	0.9	0.6	0.4
5	100	5.3	4.1	3.8	4.7	1.0	0.9	0.6	0.4
6	100	5.2	4.0	3.8	4.6	1.0	0.9	0.6	0.4
7	100	5.2	4.0	3.8	4.6	1.0	0.8	0.6	0.4
1997	100	4.9	3.9	3.4	4.3	0.8	0.6	0.5	0.3
1997x2	100	5.2	4.0	3.8	4.6	1.0	0.8	0.6	0.4
1997x4	100	5.8	4.4	4.5	5.3	1.6	1.3	0.8	0.6
1	50	5.0	3.9	3.5	4.3	0.8	0.7	0.5	0.3
2	50	5.0	3.9	3.5	4.3	0.8	0.7	0.5	0.3
3	50	5.0	3.9	3.5	4.3	0.8	0.6	0.5	0.3
4	50	5.0	3.9	3.5	4.3	0.8	0.6	0.5	0.3
5	50	5.0	3.9	3.5	4.3	0.8	0.6	0.5	0.3
6	50	5.0	3.9	3.5	4.3	0.8	0.6	0.5	0.3
7	50	5.0	3.9	3.5	4.3	0.8	0.6	0.5	0.3
1997	50	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3
1997x2	50	4.9	3.9	3.5	4.3	0.8	0.6	0.5	0.3
1	25	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3
2	25	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3
3	25	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3
4	25	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3
5	25	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3
6	25	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3
7	25	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3
1997	25	4.7	3.7	3.2	4.0	0.6	0.5	0.4	0.2
1997x2	25	4.8	3.8	3.3	4.1	0.7	0.5	0.4	0.3

Table 4. Percent change in predicted maximum Chl a (mg m^{-3}) in estuary from predicted value with zero fish farm loads for all surveys, scenarios and sub-cases.

Scenario	Bottom Percent	HES2	HES3	HES5	HES10	HES4	HES6	HES7	HES8
		“WINTER”				“SUMMER”			
1	100	0	0	1	1	41	47	12	45
2	100	0	0	1	1	40	46	11	43
3	100	0	0	1	1	39	45	11	42
4	100	0	0	1	1	37	44	10	41
5	100	0	0	1	1	36	42	9	40
6	100	0	0	1	1	35	41	9	39
7	100	0	0	1	1	35	41	9	38
1997	100	0	0	0	1	17	20	4	18
1997x2	100	0	0	1	1	35	41	9	37
1997x4	100	-1	0	1	2	72	86	24	77
1	50	0	0	1	1	27	32	8	28
2	50	0	0	1	1	27	31	8	27
3	50	0	0	1	1	26	30	7	27
4	50	0	0	1	1	26	30	7	26
5	50	0	0	1	1	25	29	6	26
6	50	0	0	1	1	24	28	6	25
7	50	0	0	1	1	24	27	6	24
1997	50	0	0	0	0	11	13	3	12
1997x2	50	0	0	1	1	23	27	6	23
1	25	-1	0	0	0	20	23	7	20
2	25	-1	0	0	0	20	23	7	20
3	25	0	0	0	0	19	22	6	20
4	25	0	0	0	0	19	22	6	19
5	25	0	0	0	0	19	22	5	19
6	25	0	0	0	0	19	21	5	19
7	25	0	0	0	0	18	20	5	18
1997	25	0	0	0	0	9	10	3	8
1997x2	25	0	0	0	0	18	21	5	18

Table 5. Percent change in predicted DIN (μM) in mid-estuary (box 8), bottom layer, from predicted value with zero fish farm loads, for all surveys, scenarios and sub-cases.

Scenario	Bottom Percent	HES2	HES3	HES5	HES10	HES4	HES6	HES7	HES8
		"WINTER"				"SUMMER"			
1	100	15	11	27	22	99	112	72	102
2	100	14	11	26	22	97	110	71	101
3	100	14	11	25	21	95	108	70	100
4	100	13	10	24	20	93	106	69	99
5	100	13	10	24	20	91	104	68	98
6	100	13	10	23	19	89	102	67	97
7	100	12	9	23	19	85	97	63	91
1997	100	6	4	11	9	37	42	27	39
1997x2	100	12	9	22	19	81	91	57	81
1997x4	100	24	18	44	37	193	215	125	176
1	50	8	6	14	12	49	55	35	51
2	50	7	6	13	11	48	54	35	51
3	50	7	5	13	11	47	53	34	50
4	50	7	5	13	11	46	53	34	50
5	50	7	5	12	10	46	52	33	49
6	50	7	5	12	10	45	51	33	49
7	50	6	5	12	10	43	48	31	46
1997	50	3	2	6	5	19	22	14	20
1997x2	50	6	5	12	10	41	46	28	41
1	25	4	3	8	6	27	30	18	27
2	25	4	3	7	6	26	29	18	27
3	25	4	3	7	6	26	29	18	27
4	25	4	3	7	6	26	28	18	26
5	25	4	3	7	6	25	28	17	26
6	25	3	3	7	5	25	28	17	26
7	25	3	2	6	5	24	26	16	24
1997	25	2	1	3	3	11	12	7	11
1997x2	25	4	3	7	6	26	29	18	26

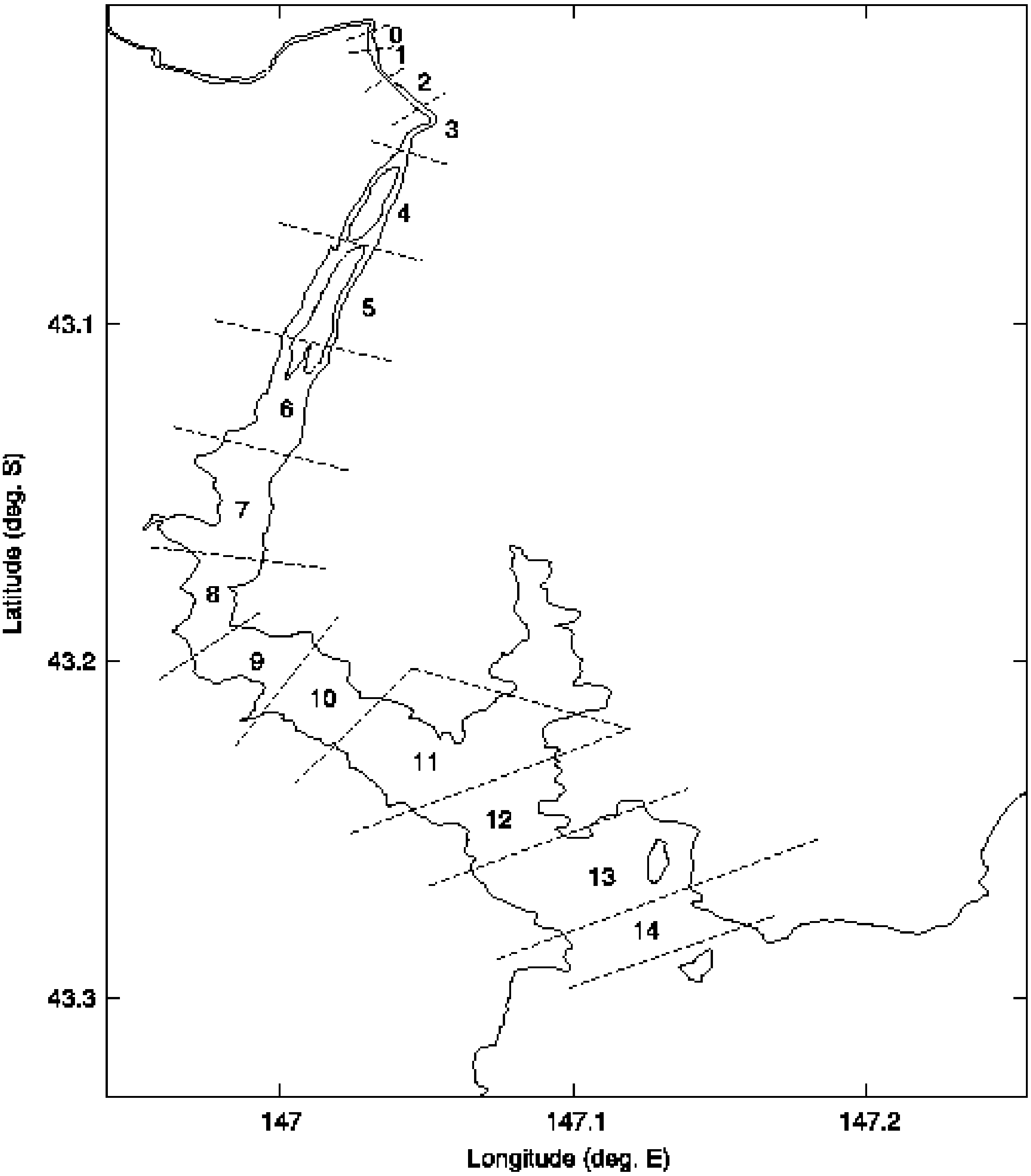

Fig. 1. Model box structure for the Huon Estuary.

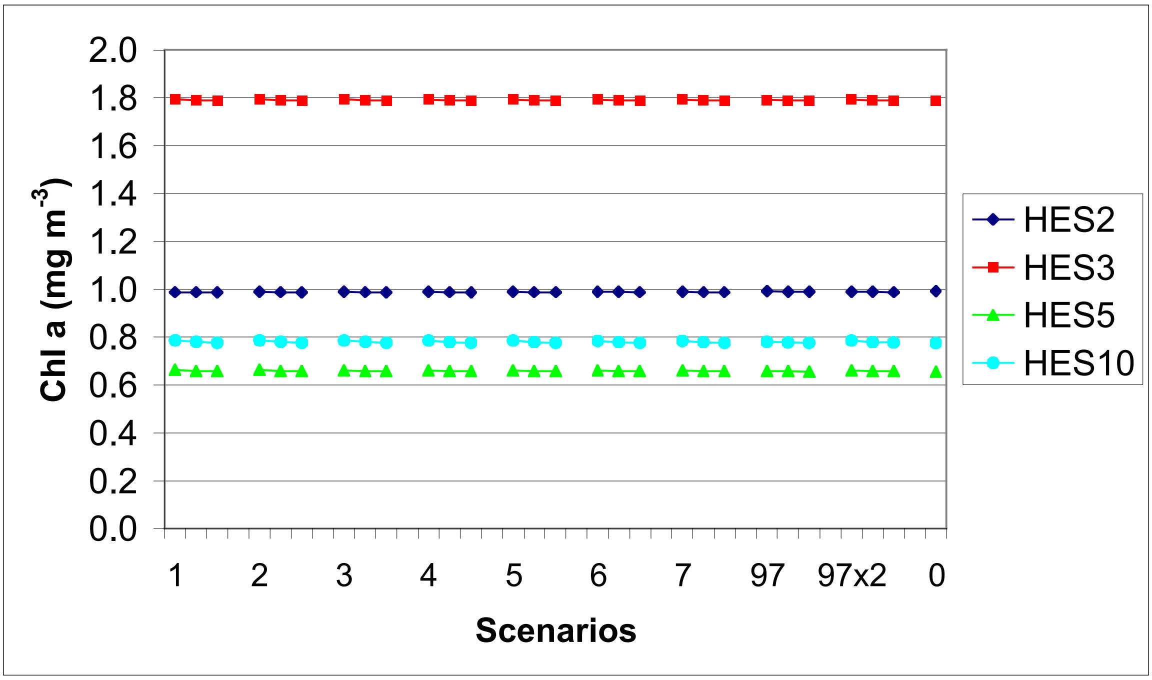

Fig. 2. Maximum predicted Chl a in estuary for "winter" survey HES2 (Jul '96), HES3 (Oct '96), HES5 (Jun '97) and HES10 (Aug '98), for scenarios 1 to 7, plus 1997 loads and 1997 loads x 2. Within each of these scenarios, the three sub-cases with 100%, 50% and 25% of loads into the bottom layer are presented from left to right respectively. Predictions with zero fish farm load (0) are also given for comparison.

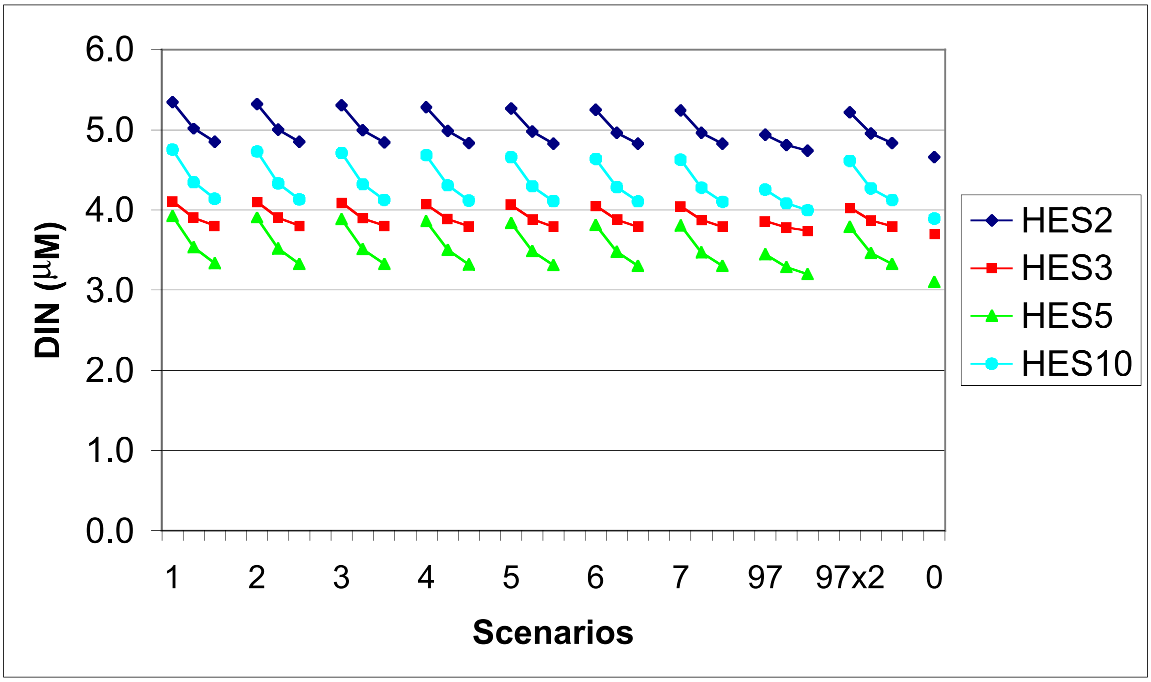

Fig. 3. Predicted DIN in mid-estuary (box 8), bottom layer, for “winter” surveys HES2 (Jul ’96), HES3 (Oct ’96), HES5 (Jun ’97) and HES10 (Aug ’98), for scenarios 1 to 7, plus 1997 loads and 1997 loads x 2. Within each of these scenarios, the three sub-cases with 100%, 50% and 25% of loads into the bottom layer are presented from left to right respectively. Predictions with zero fish farm load (0) are also given for comparison.

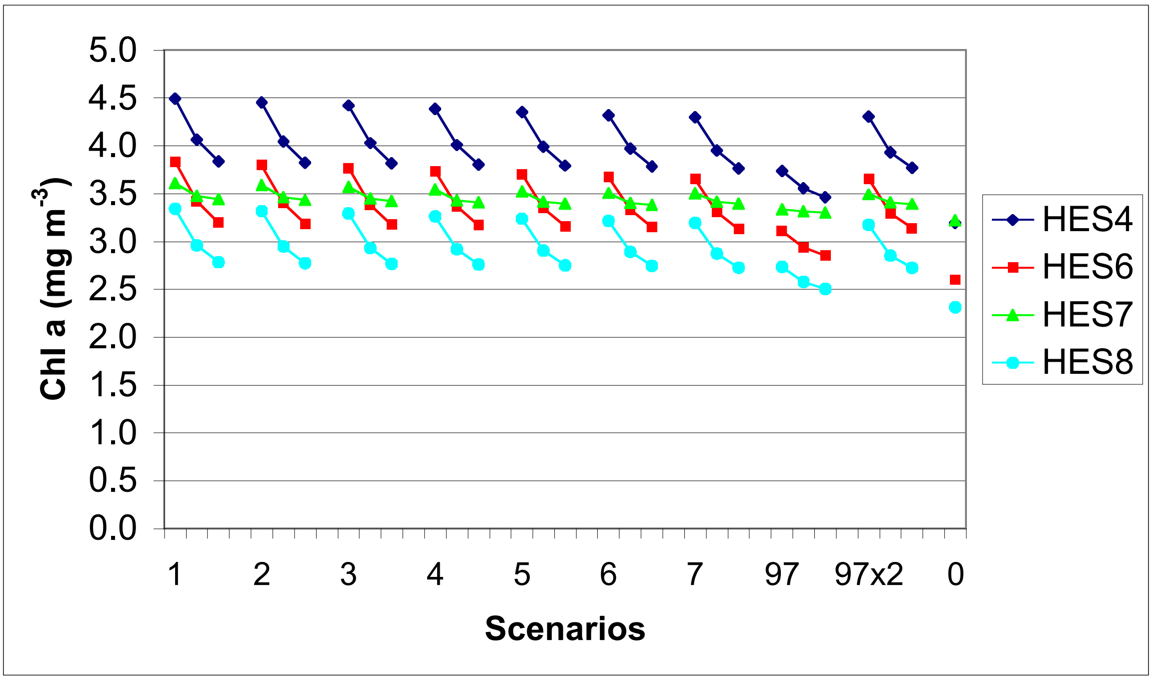

Fig. 4. Maximum predicted Chl a in estuary for "summer" surveys HES4 (Feb '97), HES6 (Oct '97), HES7 (Dec '97) and HES8 (Feb '98), for scenarios 1 to 7, plus 1997 loads and 1997 loads x 2. Within each of these scenarios, the three sub-cases with 100%, 50% and 25% of loads into the bottom layer are presented from left to right respectively. Predictions with zero fish farm load (0) are also given for comparison.

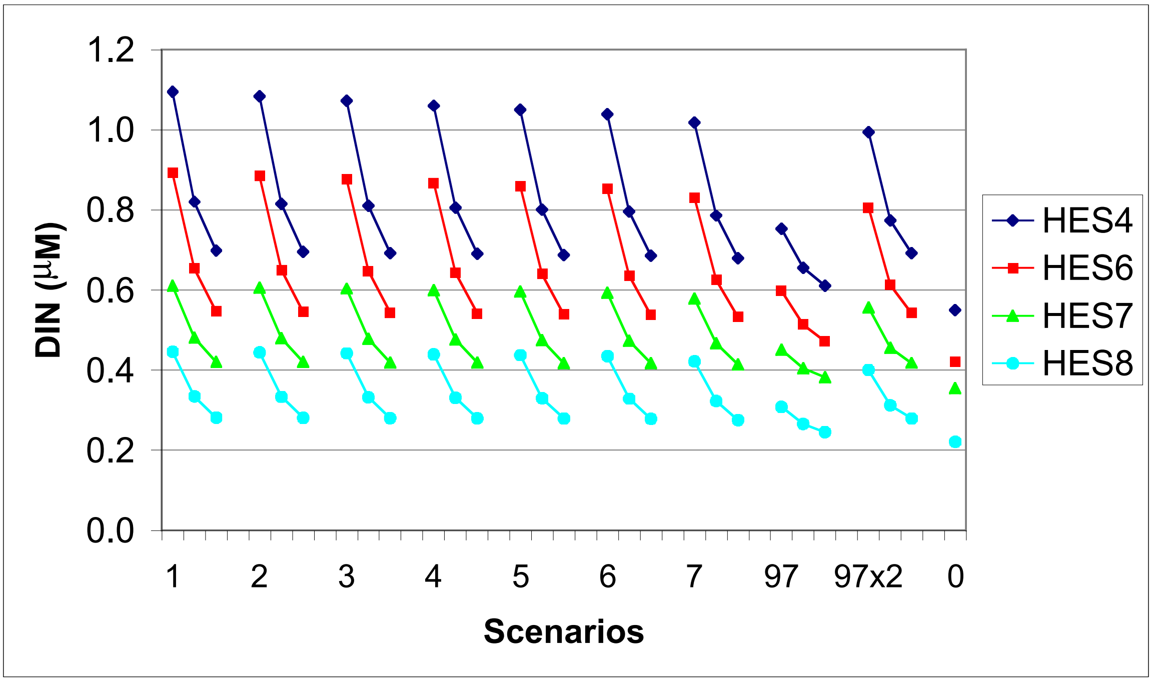

Fig. 5. Predicted DIN in mid-estuary (box 8), bottom layer, for “summer” surveys HES4 (Feb ’97), HES6 (Oct ’97), HES7 (Dec ’97) and HES8 (Feb ’98), for scenarios 1 to 7, plus 1997 loads and 1997 loads x 2. Within each of these scenarios, the three sub-cases with 100%, 50% and 25% of loads into the bottom layer are presented from left to right respectively. Predictions with zero fish farm load (0) are also given for comparison.