Port Phillip Bay

Integrated Model Scenarios for Large Yarra Floods

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Executive Summary

1. Runoff events that affect Port Phillip Bay have a spectrum of magnitudes and frequencies.
2. The Port Phillip Bay Environmental Study (PPBES) examined the part of this spectrum contained within a four year period from July 1991 to June 1995.
3. To aid management it is important to consider a high magnitude (and consequently low frequency) event not covered by the PPBES. A Yarra flood event with a frequency of 1:25 years was nominated.
4. Uncertainties arise in defining a 1:25 year runoff event and its impacts, due to the limited length of the runoff record, the need to extrapolate catchment models to predict loads from runoff, and the fact that impacts on the Bay do not depend simply on peak flows, but rather on the time course of flow and loads during a runoff event. This study adopted the approach of identifying three large flood scenarios that would be likely to encompass the impacts that could be expected from such an event.
5. From a bay-wide perspective the impacts of a large flood (a high magnitude low frequency event) depend primarily on the cumulative load. Several runoff events with large cumulative loads occurred during the PPBES baseline period, and the bay-wide impacts of scenarios considered here are similar to those observed during the PPBES.
6. From a local / regional perspective (Hobsons Bay and near shore areas on the north east of the Bay) the large flood scenarios considered here have significant short-term impacts on biogeochemical and water quality indicators over and above those observed during baseline conditions. The regional impacts of the flood scenarios were largely, but not exclusively, restricted to these regions of the Bay.
7. Different indicators show different spatial and temporal responses to the time course of loads during flood events. Local concentrations of dissolved inorganic nutrients and organic matter supplied in the runoff respond rapidly to flood loads, on time scales of hours to days, and peak concentrations are related to peak runoff and loads. Phytoplankton biomass responds more slowly, on time scales of days to weeks, and peak chlorophyll concentrations relate more to cumulative event loads.
8. While the model does not predict long-term (multi-year) or irreversible biogeochemical consequences of flood events against the background of 1991-5 baseline runoff and loads, the model does predict prolonged severe light attenuation and substantial oxygen depletion in Hobsons Bay during flood events, and these could have long-term ecological impacts on benthic communities.
9. These conclusions (#5 and #6) further amplify those recommendations of the PPBES dealing with the need to address catchment runoff as a source of nutrient and the establishment of Bay-based monitoring programs to deal with unforeseen impacts (eg climatic variability and exotic species).

Introduction

The Port Phillip Bay Environmental Study (PPBES), conducted from 1992 to 1996, assessed the state of Port Phillip Bay and its response to loadings of nutrients and toxicants from both point and diffuse sources (Harris et al, 1996). As part of that study, an integrated model of nutrient cycling and impacts in Port Phillip Bay was developed (Murray and Parslow, 1997). The model was used both to improve understanding of the fate and impacts of nutrient loads, and to predict the environmental consequences of management scenarios involving potential changes in nutrient loads (Murray and Parslow, 1998).

The integrated model was run using “real” forcing (observed or reconstructed) for the period July 1991 to June 1995. This period included both high runoff and low runoff years. The PPBES model analysis showed that nutrient loads from the Yarra catchment had significant effects on nutrient cycling and production both bay-wide, and locally in Hobsons Bay and northern coastal regions. However, it was not clear whether large floods (a high-magnitude/ low-frequency event), represented a substantial threat to the Bay, not captured by the PPBES analysis of the 1991-95 period.

This study was commissioned to assess this threat. Specifically, the study uses the PPBES model to examine the impact of a large flood event (nominally a 1 in 25 year event) in the Yarra catchment on Port Phillip Bay. This analysis involves a series of steps which are described in the following Sections. We begin by describing the historical record of runoff in the Yarra catchment, and the formulation of large flood runoff scenarios. We then describe the use of simple catchment models developed as part of PPBES to estimate nutrient loads associated with these flood scenarios. A brief description of the hydrodynamic and biogeochemical model runs is followed by a presentation of the environmental indicators used to describe the impacts. The scenario results are presented in both graphical and tabular form, with discussion and conclusions.

Large Flood Runoff Scenarios.

The longest historical (electronic) record of flow in the Yarra catchment is for the Yarra River at Chandler highway and extends back to 1976. The daily flow record from 1976 to 1995 is plotted in Fig. 1. A shorter record, dating back to 1980, is available for the Maribyrnong River at Keilor (Fig. 1). Much shorter records are available for some of the small subcatchments downstream of Chandler highway, but the Yarra and Maribyrnong tend in any case to dominate total flow.

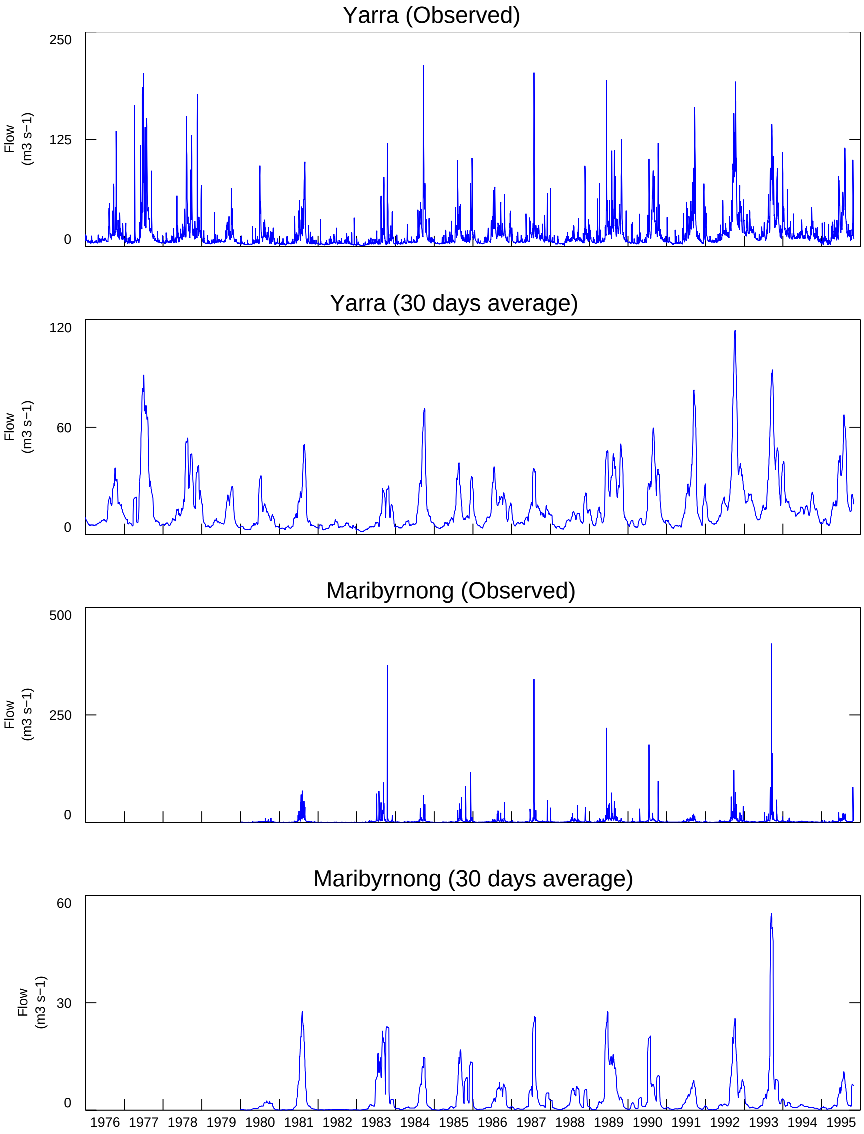

Figure 1. Plots of daily average flow (observed), and 30 day average flow, in the Yarra River at Chandler and in the Maribyrnong River at Keilor.

Peak daily flows in the Yarra River are around 230 cumecs, and values of this order occur in a number of years. Maximum daily flows in the Maribyrnong are larger, around 450 cumecs, and the maximum value in this record occurred during the PPBES Study period, in September 1993.

These historical records are of course not long enough to define a “1 in 25 year” event. We sought advice from catchment experts at Melbourne Water, and they recommended the flood event which occurred between 15 and 19 May, 1974, as an example of a ‘large flood’ event (Krapper, pers. comm.). While this event preceded the long-term records in Figure 1, Melbourne Water were able to provide us with daily Yarra flows measured at Banksia Street from 1 January to 23 May 1974, and with tables and plots of flows at higher temporal resolution for a few days surrounding the event for the Yarra and Maribyrnong Rivers and Merri Creek.

We used these records to reconstruct a flood event corresponding to the 1974 data. We used 1974 data from the Yarra River and Maribyrnong River, where available, and synthesized flows for other minor subcatchments (Merri, Moonee Ponds and Gardiners Creek) based on the Yarra River flows and regressions based on other events.

In order to produce a model scenario, we needed to incorporate this 1974 flood event into the 1991-95 time series used to drive the model. After comparison of the reconstructed flow record with the 1991-95 flows, we decided to replace the September 1993 flood event with the May 1974 flood event. Plots of the daily flows in the Yarra and Maribyrnong, and total flow at Westgate Bridge, for both the observed September 1993 event, and the reconstructed 1974 event, are presented in Fig. 2. We refer to this 1974-based flood event as flood scenario 1, or F1 for short. (Note that in this, and subsequent scenarios, only flows and loads from the Yarra catchment entering Port Phillip Bay at Westgate Bridge have been altered. Flows and loads from other diffuse and point sources are unchanged.)

The peak daily Yarra flow in the 1974 event is about 400 cumecs, much higher than any observed in the 1976 to 1995 record (Fig. 1). The peak Maribyrnong flow is about 500 cumecs, only slightly higher than that observed in the September 1993 event, which yielded the highest Maribyrnong flow observed in the Keilor record (Fig. 1). The superposition of these high flows in the Yarra and Maribyrnong in scenario F1 resulted in a peak daily average flow at Westgate Bridge of 1190 cumecs (Fig. 2), much higher than any in the 1991-95 period.

The 1974 flood was due to an intense rainfall event in the lower Yarra catchment. While this produced a large peak flow in the F1 scenario around 16 September, the flow in the preceding fortnight was quite low, much lower than the observed flow in early September 1993 (Fig. 2). Model results presented in this report suggest that impacts in Port Phillip Bay are more related to cumulative flows and loads over periods of several weeks, rather than to peak daily flows (see Results, Discussion and Conclusions below). To obtain a better index of flows in relation to impacts, we calculated running 30-d average flows for the Yarra and Keilor time series (Fig. 1).

The results were somewhat surprising. The peak 30-d average flow in the 20 y Yarra flow record occurred in September-October 1992, and the 30-d average flows associated with the flood events in 1991 and 1993 were also high. These three events, all in the PPBES baseline period, represent 3 of the 4 largest Yarra 30-d flow events in the 20 y record. Maribyrnong flow events tend to be of much shorter duration, so that the 30-d average is much less than the daily peak flow. Interestingly, the

September 1993 flow event in the Maribyrnong yielded approximately twice the 30-d average flow of any other event in the 16 year Maribyrnong flow recorded at Keilor.

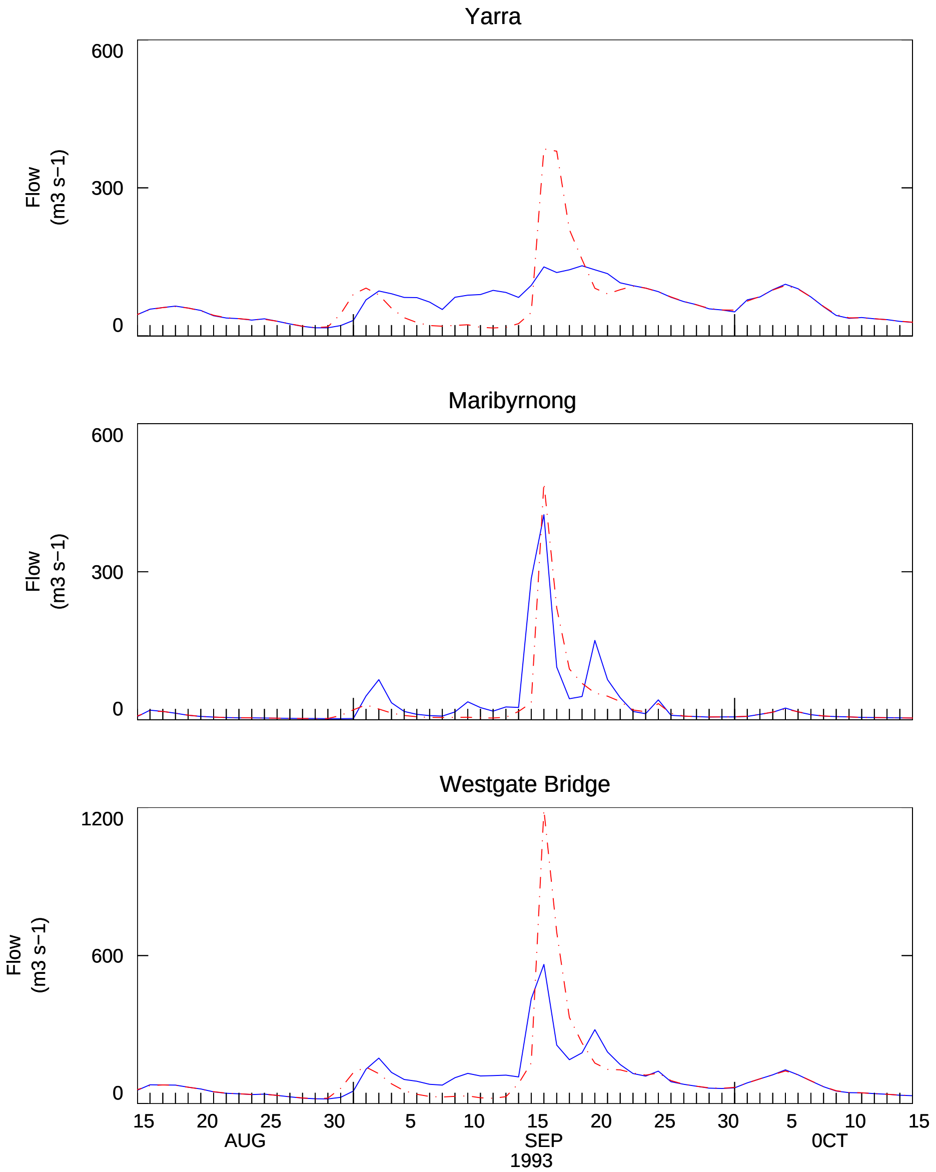

Figure 2. Observed (solid line) and flood scenario F1 (dashed line) flows for Yarra R., Maribyrnong R., and total flow at Westgate Bridge, in cumecs. Flood scenario (F1) is based on the May 1974 flood.

While the May 74 - based flood scenario F1 includes a high peak flow, its 30-d average flow is quite similar to that of the baseline September 1993 event (Table 1). It was not clear that, in terms of impacts on Port Phillip Bay, this scenario represented a ‘large magnitude/low frequency’ nutrient loading event outside the range of the events already simulated in the baseline. We therefore developed a second runoff scenario based on scaling up flows in September 1993.

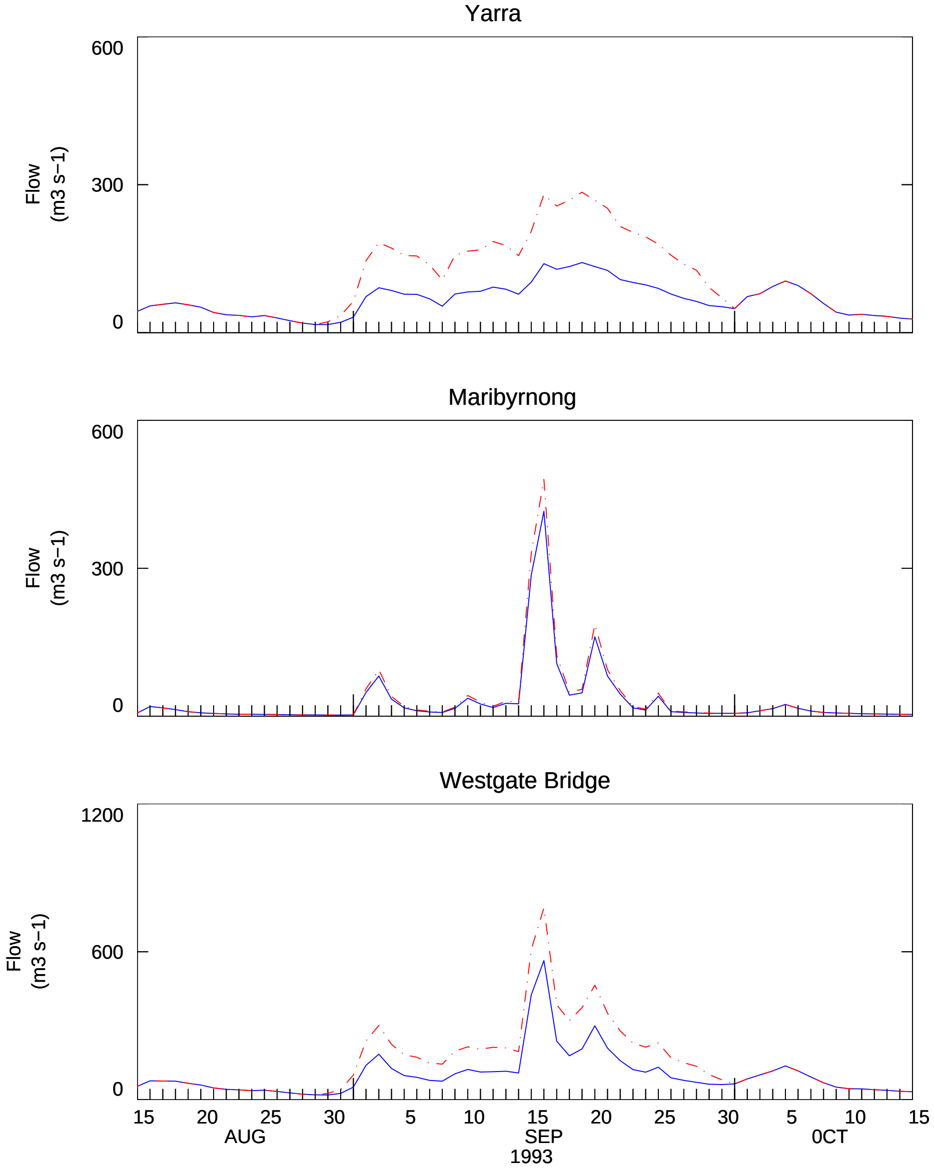

Figure 3. Comparison of observed daily flows (solid line), and scenario F2 daily flows (dashed line) in September 1993. Scenario F2 was created by scaling up the September 1993 flows.

The Maribyrnong flow observed in 1993 was large in terms of 30-d average flow compared with other years in 1980 to 1995 (Fig. 1), and the peak daily flow only slightly less than that observed in 1974. We scaled the Maribyrnong flow observed in

September 1993 by a factor of 1.16, so that the peak daily flow matched that observed in May 1974.

The Yarra flow observed in September 1993 was elevated over a period exceeding 30 days, but the peak daily flow was low compared with May 1974. We scaled the Yarra flow up by a factor of 2 throughout September, so it had a peak daily flow of almost 300 cumecs. By comparison, the 1974 event had a higher peak flow of around 400 cumecs (Fig. 2), but a lower 30-d average flow.

The resultant flood had a peak daily flow at Westgate Bridge of only about 800 cumecs, but a 30-d average flow of 254 cumecs, about 70% higher than the baseline September 1993 event and the flood scenario F1 (Table 1). We refer to this scenario as flood scenario 2 or F2 (Fig. 3). We can't justify this scenario as a 1 in 25 year event. Indeed, it is clear that the definition of a "1 in 25 year flood event" is somewhat subjective, depending on both the temporal window and the location of rainfall in the catchment. We can only say that scenario F2 represents a combination of unusually heavy and persistent rain in the upper Yarra catchment, combined with an intense downpour in the lower Yarra and Maribyrnong catchments.

Table 1. 30-d average daily flow (cumecs) observed in Sep-Oct 1992 and Sep 1993 flow events, and in flood scenarios F1 and F2.

	Sep-Oct 92	September 1993		
	Baseline	Baseline	Scenario F1	Scenario F2
Yarra	103	90	87	177
Maribyrnong	22	55	44	63
Westgate Br.	136	151	156	254

Large Flood Load Scenarios

Nutrient loads were computed from flows based on simple catchment models developed in PPBES (Sokolov, 1996) and updated subsequently (Parslow et al., 1999b). These catchment models represent a dynamic pool of nutrients in catchments, which is continually replenished at a prescribed rate, and washed out at a rate determined by both pool size and runoff. Loads for the flood scenarios were computed using the baseline catchment parameters estimated for the Yarra and Maribyrnong (Sokolov, 1996; Parslow et al, 1999b).

Note that PPBES loads into Port Phillip Bay at Westgate Bridge were computed by non-linear regressions relating the estimated net flux at Westgate to the sum of loads from the Yarra (at Chandler) and Maribyrnong (at Keilor) (Sokolov, 1996). This regression was based on 6 months of monitoring in the Yarra estuary in 1995. We have continued to use these regressions.

We stress that the catchment models have been calibrated against 8 years of forcing (1988-95), and application of these models and catchment parameters to the flood scenarios represents an extrapolation outside the calibration domain. This problem is even more severe for the regression linking Westgate Bridge to Yarra and Maribyrnong loads, based only on 6 months of data in 1995.

The estimated baseline and F1 loads at Westgate Bridge in September 1993 are shown in Fig. 4. In all cases, F1 loads are lower than baseline preceding the peak flow event, and higher than baseline during the peak event. However, nutrients do not all behave alike, and comparison of Fig. 4 and Fig. 2 shows that loads do not simply scale with total flow. There can be several reasons for this. For some nutrients, loads increase non-linearly with flows. For others, the pool of nutrients in the catchment may be small, and washed out by previous high flows.

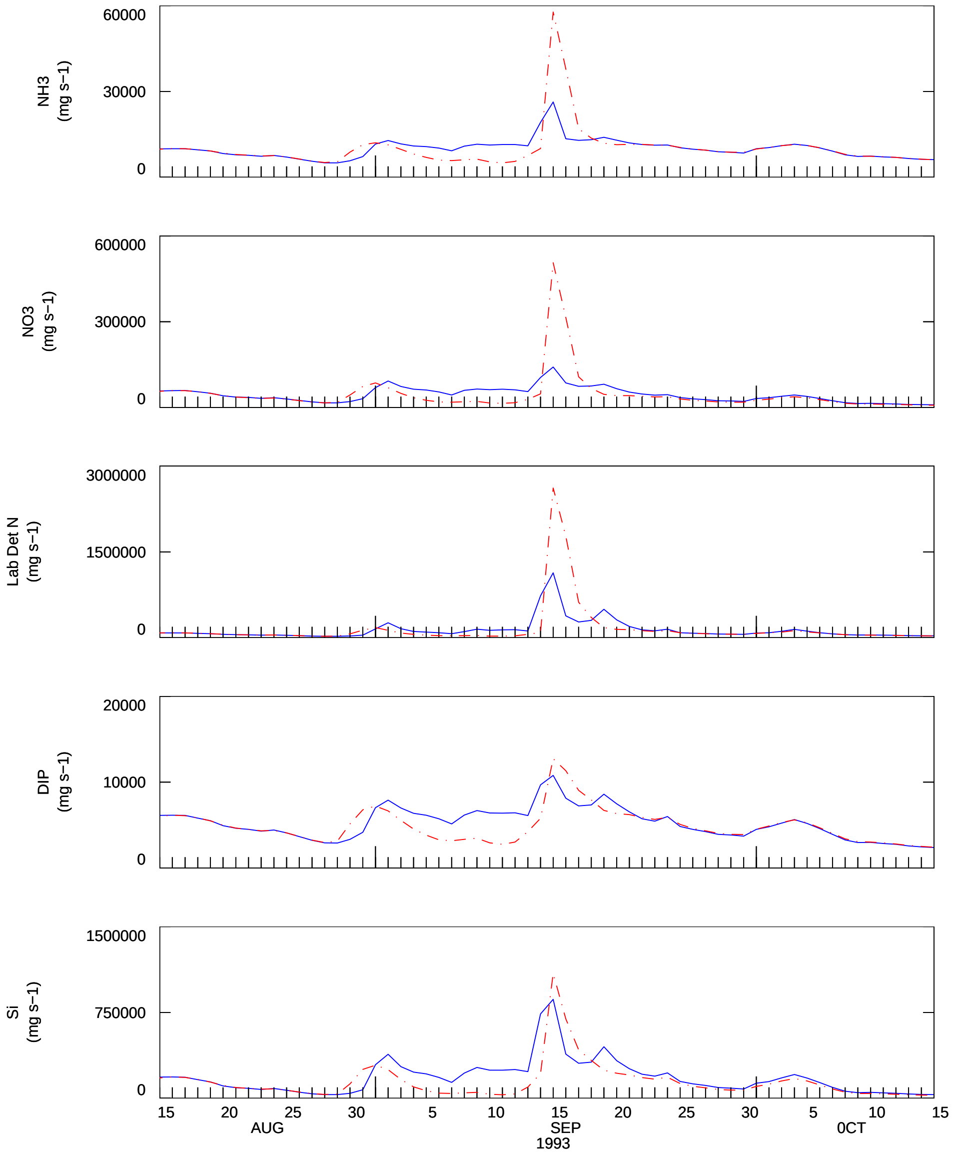

Figure 4. Predicted baseline loads (solid line) and scenario F1 loads (dashed line). All loads in mg s^{-1}.

There is clearer evidence of this in the time series of predicted loads for F2 (Fig. 5). In the case of nitrate (NO_3), dissolved inorganic phosphate (DIP) and biogenic silica (Si), washout results in a negligible increase in peak load, and a substantial decrease in loads compared with baseline in late September and early October.

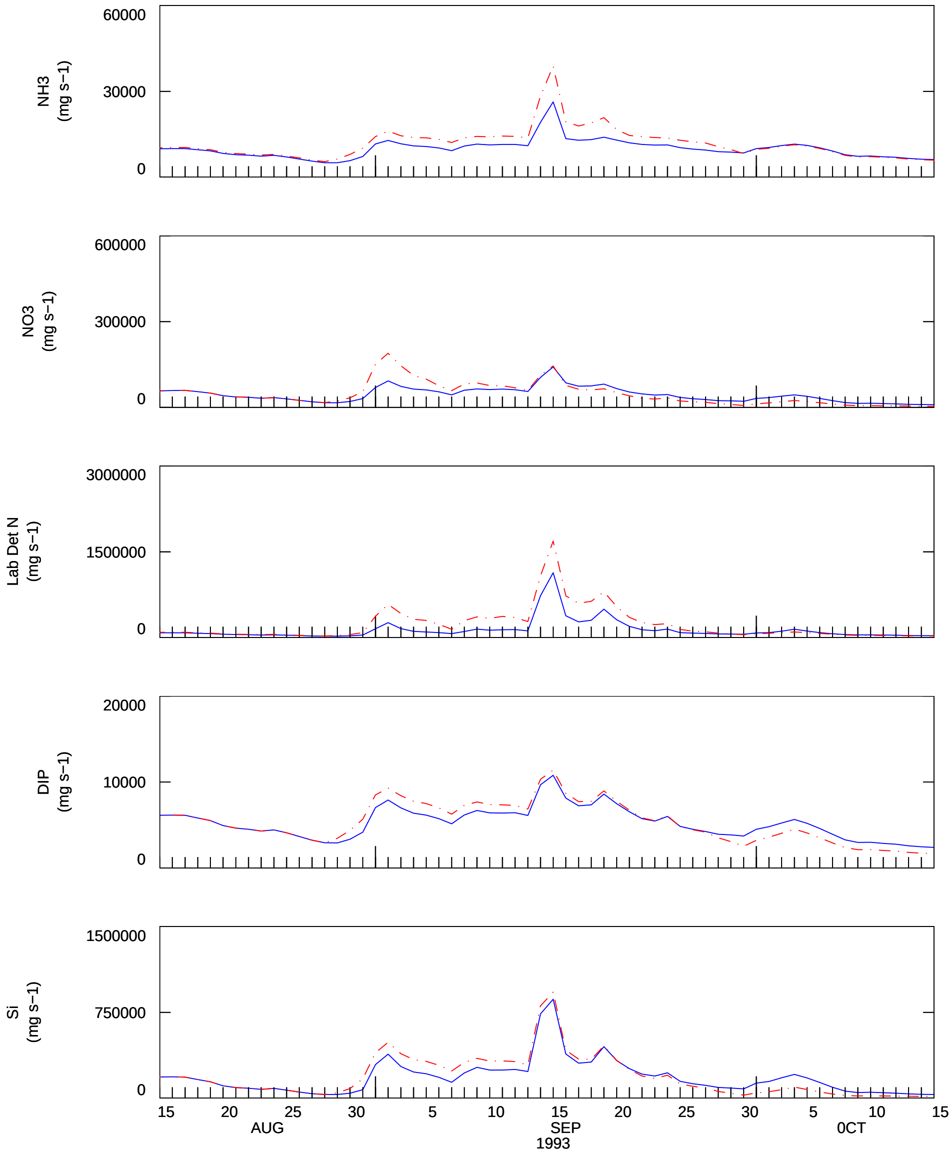

Figure 5. Predicted baseline loads (solid line) and scenario F2 loads (dashed line). All loads in mg s^{-1}.

The total (cumulative) event (30-d) loads are shown in Table 2. In scenario F1, the increased peak loads of NH_3, NO_3 and detrital N almost balance the decreased background loads, so that total event loads are similar to baseline. However, F1 event loads of DIP and especially biogenic silica are substantially lower than baseline. In scenario F2, all loads are increased over the September 1993 baseline, but loads of DIP and silicate are only slightly increased, and are still smaller than the event loads observed in the 1992 flood event.

Because of the uncertainty involved in extrapolating the catchment / load models outside the calibration range, we decided to create a third scenario F3. This scenario uses the same runoff as scenario F2, obtained by scaling up the September 1993 baseline Yarra and Maribyrnong flows. However, instead of using the catchment models, loads in F3 at Westgate Bridge are simply scaled up from baseline loads at Westgate Bridge by the same ratio as total flow. The F3 loads are plotted in Fig. 6. Total loads in scenario F3 (Table 2) are larger than in other scenarios, for all nutrients except detrital N, which is lower than in F2. Note that F3 event loads of dissolved inorganic nutrients represent 30 to 50% of average annual loads from the Yarra catchment, while F3 loads of detrital N and biogenic silicate represent about 80% of average annual loads.

Table 2. Total (30-d) loads in tonnes of ammonia (NH_3), nitrate (NO_3), detrital organic nitrogen (Lab_Det_N), dissolved inorganic phosphorous (DIP) and biogenic silica (Si), in baseline flood events in September-October 1992 (Base-92), and September 1993 (Base-93), and in flood scenarios F1, F2, F3. Average annual loads at Westgate Bridge for the baseline period 1991-95 (Annual) are also shown.

	Base-92	Base-93	Scen F1	Scen F2	Scen F3	Annual
NH_3	45	31	31	40	54	161
NO_3	214	156	159	179	272	555
Lab_Det_N	815	551	646	1044	931	1127
DIP	22	17	14	18	29	87
Silicate	959	700	497	800	1210	1615

Model Simulations.

Because changes in river runoff affect circulation and flushing of the Bay, we have rerun the hydrodynamic model for the 6 month period July 1993 to December 1993, including the modified flood scenarios. Exchanges calculated from the hydrodynamic model output (Walker and Sherwood, 1997) were then used to drive the transport and biogeochemical model.

The hydrodynamic model used at CSIRO Marine Research has been upgraded since the PPBES (Walker, 1997), and now uses an improved vertical mixing scheme. We therefore reran the hydrodynamic model under baseline flow, and compared output from the biogeochemical model under baseline forcing using the original PPBES exchanges with output using exchanges from the updated hydrodynamic model. Changes in biogeochemical variables and indicators were generally relatively small, mostly less than 10 percent. To ensure that the changes presented here are due to changes in flood forcing, rather than changes in the underlying hydrodynamic model, we compare results from flood scenarios with results produced using baseline forcing and the new hydrodynamic model exchanges.

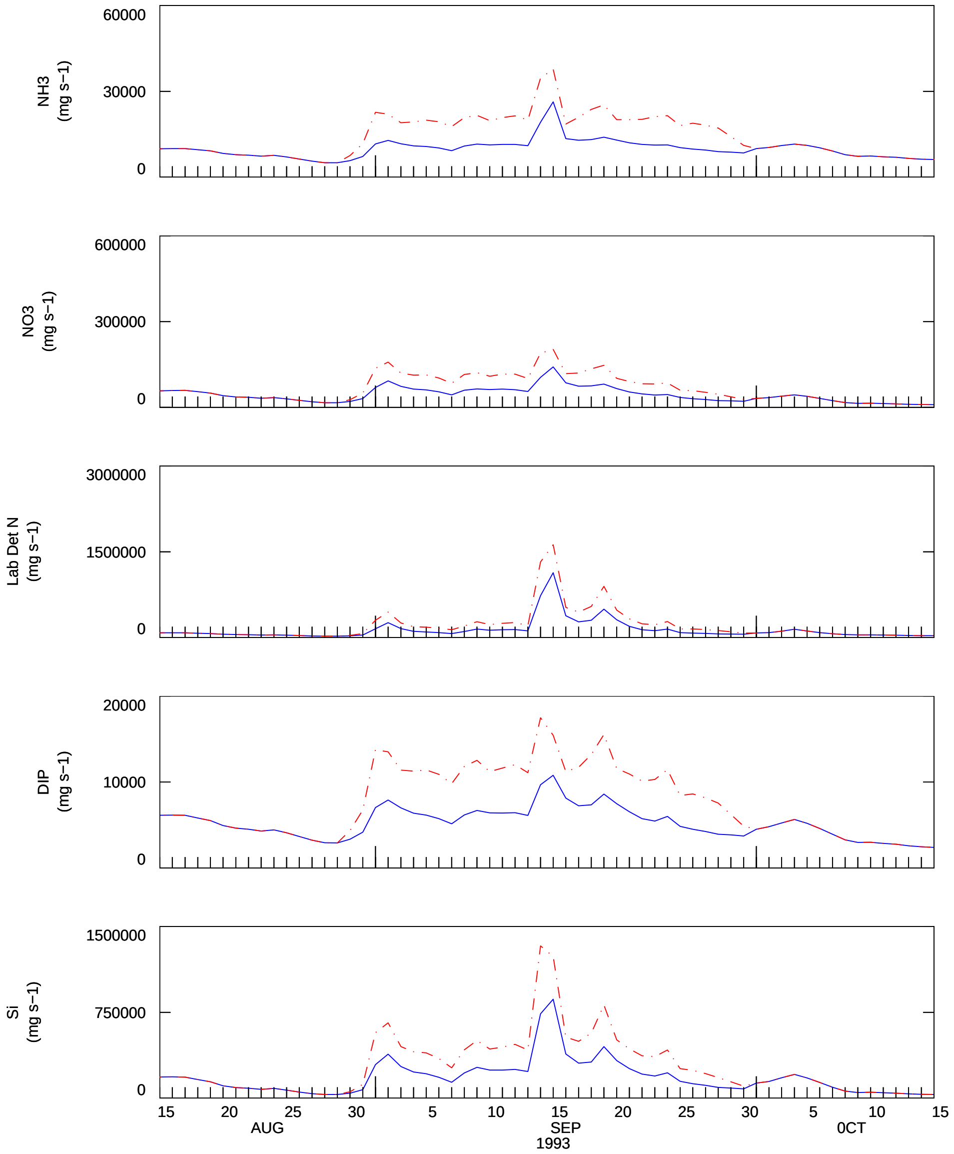

Figure 6. Predicted baseline loads (solid line) and scenario F3 loads (dashed line). All loads in mg s^{-1}.

Aside from the physical exchanges, in the biogeochemical (integrated) model simulations, we have modified only input flows and loads at Westgate Bridge. All other forcing of the integrated model (other loads, boundary conditions, etc) was identical to that used in the baseline runs.

Model Indicators of Large Flood Impact.

The model variables used as indicators are shown in Table 3. While some of these are standard indicators, others have been added because of the nature of Yarra flood inputs. In particular, labile detrital N is the dominant nitrogen fraction in Yarra loads (Table 2). The high input of organic matter can lead to high sediment and water column respiration and drawdown of oxygen, so dissolved oxygen has been included. The Yarra is particularly important as a Bay-wide source of silicate.

Table 3. Model indicators.

Description	**Abbreviation**	**Units**
Chlorophyll a (phytoplankton)	Chl	mg m^{-3}
Dissolved inorganic nitrogen (NH_3+NO_3)	DIN	mg N m^{-3}
Light attenuation Kd	Kd	m^{-1}
Primary Production (phytoplankton)	PP	mg N m^{-3} d^{-1}
Sediment Respiration	SedR	mg N m^{-2} d^{-1}
Microphytobenthos Production	MPBP	mg N m^{-2} d^{-1}
Dissolved silicate	Si	mg Si m^{-3}
Dissolved oxygen	DO	mg O m^{-3}
Labile Detrital N	LDN	mg N m-3 d-1
Denitrification Efficiency	Den	%

The spatial and temporal statistics have been chosen to reflect both the nature of the large flood impact, and aspects of the management regime for the Bay. To look at the detailed spatial distribution of impact, we present maps of model indicators for 5 key indicators (Chl, DIN, Kd, SedR, Si) under baseline conditions, and then plot the ratio of indicators under large flood scenarios to baseline indicators. As an overall summary of patterns at broader regional scales, we have used the State Environment Protection Policy (SEPP) segments , and present tables of all indicators by SEPP segment and scenario. (Fortunately, the SEPP defines Hobsons Bay, a site of maximum Yarra impact, as a separate segment .)

We have chosen the 30 day period of September 1993 as the temporal window for examining impacts. The largest impacts of flood events tend to occur during this period, although some impacts are detectable out to 60 days or longer. There is no evidence that flood scenarios resulted in persistent shifts in system behaviour in the model. For example, changes in mean and median indicator values over the 91-95 period changed by less than 2 percent in SEPP segments other than Hobsons Bay, and by less than 5% in Hobsons Bay, under scenario F3. We have computed both median and 90%ile values for this 30 day window. Statistics for SEPP segments were computed on an area-weighted basis, as described by Parslow et al (1999).

Results.

Spatial Distribution of Impacts.

Maps of the 5 key indicator statistics are shown in Fig. 7 to 8, while maps of the spatial distribution of flood scenario impact are shown in Fig. 9 to 13.

Chlorophyll.

Under baseline conditions, median chlorophyll levels are around 3 mg Chl m^{-3} in Hobsons Bay, and around 4 mg Chl m^{-3} off Western Treatment Plant (WTP). The 90%ile chlorophyll value is maximum in Hobsons Bay, around 20 mg Chl m^{-3}, reflecting a large transient bloom associated with the baseline September 93 flood event. Background levels throughout most of the Bay are low, around 1 mg m^{-3}.

Flood scenario F1 results in a moderate decline in median Chl in Hobsons Bay, and south along the east coast (the usual course of the Yarra plume). There is a more severe decline by a factor of 2 in 90%ile Chl in Hobsons Bay and in coastal boxes in the northwest, but moderate increases in scattered model boxes in the northern and eastern Bay.

Flood scenario F2 results in a moderate increase in median Chl throughout the northern Bay. While there is only a slight increase in 90%ile Chl in Hobsons Bay, there is a substantial increase of 60 % or so in Chl down along the east coast. Flood scenario F3 produces very similar Chl distributions to F2.

DIN

Under baseline loads, median DIN values are also maximum off WTP (Fig. 7), but elevated values around 100 mg N m^{-3} are also predicted in Hobsons Bay. The 90%ile values show a similar spatial distribution, but about 50% higher concentrations. Concentrations throughout most of the Bay are low, around 10 mg N m^{-3}.

Under flood scenario F1, median DIN concentrations are also reduced slightly in Hobsons Bay, while 90%ile values are increased slightly in Hobsons Bay and other boxes throughout the northern Bay. Under flood scenario F2, median DIN is increased by about 50% in Hobsons Bay, and the region under the Yarra plume along the NE coast. For 90%ile DIN, this increase is stronger and extended both further south along the east coast, and to the north-west coast. Again, similar results are obtained for scenario F3, although increases in 90%ile DIN are more pronounced for F2 than for F3.

Si

Under baseline loads, median silicate concentrations are maximum in Hobsons Bay, but elevated throughout the central and eastern Bay. They are low only in the western Bay, where the combination of high N and P loads and low Si loads from WTP tend to result in Si depletion by phytoplankton (Murray and Parslow, 1997). The 90%ile Si concentrations are higher, but restricted more to the eastern coast, reflecting the immediate influence of loads from the Yarra and east coast rivers.

The effects of all three flood scenarios on Si distributions are relatively slight. Si is reduced in the Yarra plume region under scenario F1, virtually unchanged in scenario

F2, and increased by about 30% in scenario F3. These results are quite consistent with the changes in Si loads (Table 2).

Kd.

Under baseline loads, light attenuation is maximum in Hobsons Bay, reflecting the influence of increased concentrations of phytoplankton and organic matter from the catchment. However, it is likely that this attenuation is still underestimated, as the PPBES light attenuation model does not properly account for the effects of suspended inorganic sediments, which are likely to be enhanced during flood events.

Under scenario F1, light attenuation is reduced in Hobsons Bay and within the Yarra plume. Under scenarios F2 and F3, light attenuation is increased by about 50% in Hobsons Bay, and within the Yarra plume. This distribution suggests contributions to Kd from both chlorophyll and organic matter in the plume.

SedR.

Under baseline forcing, sediment respiration is maximum in Hobsons Bay. This reflects primarily decay of organic matter settled out from the Yarra plume.

In flood scenario F1, median sediment respiration is decreased in Hobsons Bay, while the 90%ile value is slightly increased. Under scenario F2, there are large increases in sediment respiration in both Hobsons Bay, and along the east coast under the Yarra plume. Maximum increases are about a factor of 2, comparable to the relative increase in load of detrital N under F2 (Table 2). The effects are generally weaker, but show a similar spatial pattern in F3, consistent with the slightly lower detrital N loads in F3 compared with F2 (Table 2).

Regional Summary Statistics.

As summary indicators, we have computed area-weighted statistics for the SEPP segments over the 30 days of the flood event (Table 4). We have not compared these statistics to SEPP environmental quality objectives for chlorophyll, light attenuation or dissolved oxygen, as:

- the SEPP objectives apply to any waters within a segment; they are not intended to apply to averages across a segment;
- the SEPP objectives for these indicators relate to percentiles (50th and / or 90th) of the annual distribution of environmental levels rather than upper limits. Unusual events such as large floods would generally have little influence on such percentiles if their effects on environmental levels are of relatively short duration.

Partly to deal with the first point (i.e. environmental criteria are meant to apply locally within segments), and because the SEPP General and Inshore segments contain many model boxes which are distant from, and relatively unaffected by, flood events, we also present statistics for 5 key indicators for the individual model boxes in the Inshore and General segments adjacent to Hobsons Bay. As one might expect, these boxes usually show the largest impact of Yarra flood events within these segments. (Model boxes are shown in Fig. 3.5 in Murray and Parslow, 1997. The boxes in question are approximately 3 km by 5 km, and located south-east and south of Hobsons Bay.)

The Corio segment has been omitted from Table 4, primarily because the model is not well calibrated for Corio Bay (see Parslow et al, 1999a). In any case, Corio Bay is hydrodynamically distant from the Yarra inputs.

The Werribee segment tends to be dominated by loads from Werribee Treatment Plant, and one would not expect to see strong effects of large Yarra flood events on indicators in this segment. The results in Table 4 are generally consistent with this, except for DIN, which increases by about 10% under all scenarios, and Si, which decreases by about 10% under scenarios F2 and F3.

One would expect effects of Yarra floods to be attenuated by dilution in the large Central basin, and this is generally true, although there are some substantial increases, of order 20%, in the 90%ile values across the General segment for chlorophyll (Chl), DIN, primary production (PP), and labile detrital N (LDN). Comparison with Fig. 9 and 10 shows that increases in 90%ile values of Chl and DIN in the General segment reflect local increases of 20 to 40% in median values in model boxes in the northern part of the General segment, adjacent to Hobsons Bay. During Yarra floods, the median and 95%ile values of Chl, DIN, SedR and Kd in Box 31, adjacent to Hobsons Bay, are all substantially higher than area-weighted General segment statistics, and in the case of DIN and SedR, are more sensitive to flood scenarios.

Fig. 9 and 10 also show that large Yarra floods increase median and 90%ile indicators in the coastal region south-east from Hobsons Bay by 50% or more. However, the Inshore segment includes many coastal boxes which are distant from the Yarra inputs, and the effects of flood scenarios on Inshore segment statistics are correspondingly reduced, although 90%ile chlorophyll and primary production are increased by 20 to 25%. Again, in model box 30 in the Inshore segment adjacent to Hobsons Bay, indicators are substantially higher than segment-wide indicators during Yarra floods.

In boxes adjacent to Hobsons Bay, the 90%ile chlorophyll and attenuation statistics for the 1991-95 period under baseline conditions exceeded SEPP objectives for the Inshore and General segments (Parslow et al., 1999a). The results for boxes 30 and 31 (Table 4) show that this situation is likely to be exacerbated in years including large flood events.

Of the SEPP segments, it is Hobsons Bay which receives the brunt of Yarra flood events. Table 4 shows substantial increases, of order 50% or so, in most Hobsons Bay indicators (Chl, DIN, Si, Kd, SedR, PP, LDN) at both median and 90%ile levels, under scenarios F2 and/or F3. It was noted by Parslow et al (1999a) that the predicted 90%ile Chl and Kd statistics exceeded SEPP objectives in Hobsons Bay. Those statistics were based on the entire 4-year baseline period, and the values computed for the flood event are of course much higher.

It is worth noting the behaviour of some other indicators in Table 4. Under scenarios F2 and F3, median denitrification efficiency in Hobsons Bay drops to zero: i.e.

denitrification is shut down for more than 50% of the time. Of course, denitrification in Hobsons Bay was already severely impaired compared with the rest of the Bay under baseline conditions. Median denitrification efficiencies in the General segment, which are critical to the overall nitrogen balance in the Bay, are only slightly affected even during the flood event. Median microphytobenthos production in Hobsons Bay is also reduced to near-zero under scenarios F2 and F3, due to high light attenuation. Under these conditions, light attenuation will represent a major stress on any other benthic phototrophs.

The model predicts significant reductions in dissolved oxygen concentrations in Hobsons Bay under scenarios F2 and F3. In particular, under F2, oxygen drawdown is almost doubled, and the 10%ile oxygen level is reduced to about 80% saturation. This is a cause for concern, because the model is likely to underestimate oxygen drawdown substantially. The biogeochemical model represents only one water column layer (although the hydrodynamic model is a full 3-D model, and horizontal exchanges are computed based on particle movements in a stratified flow). The hydrodynamic model shows persistent stratification in Hobsons Bay over the entire flood event. This means that bottom water in Hobsons Bay is likely to be cut off from the surface layer, while the 1-layer biogeochemical model does allow oxygen exchange between the full water column and the atmosphere.

Based on Redfield oxygen:nitrogen ratios, predicted median sediment respiration rates in Hobsons Bay during the flood event represent an equivalent oxygen consumption rate of about 5600 mg O m^{-2} d^{-1}, or about 560 mg O m^{-3} d^{-1} in a 10 m water column. In practice, much of this bottom respiration may be supported by sulphate reduction. Predicted median oxygen consumption rates in the water column based on breakdown of detrital N are about 400 mg O m^{-3} d^{-1}. At these rates, combined sediment and water column respiration could deplete dissolved oxygen in an isolated bottom layer over periods of 10 to 20 days.

A more detailed 3-D model biogeochemical model would be required to predict oxygen drawdown in bottom waters accurately. However, these results are cause for concern, especially given that substantial oxygen sags have been observed in Hobsons Bay. Given that oxygen depletion could have long-lasting effects on bottom fauna, it should be regarded as one of the major risk factors for Hobsons Bay under large flood scenarios. The horizontal resolution of the current model is not sufficient to resolve fine scale distributions around the mouth of the Yarra estuary, but in spatial maps of model output, substantial oxygen depletion is confined to the Hobsons Bay box.

Discussion and Conclusions.

The analysis of historical runoff data and derived loads shows that from the perspective of potential impacts on the Bay, the definition of a “1 in 25 year” flood event is not a straightforward matter. We lack a sufficiently long runoff record to define such an event with statistical confidence. However, perhaps more importantly, the model results presented here show that the impact of a large flood event on Port Phillip Bay depends not just on the peak flow, but on the cumulative flows and loads over periods of a month or so (see further discussion below). On the basis of monthly average flows, the 1991-95 baseline period used to model Port Phillip Bay includes, by coincidence, three of the 4 most significant Yarra flood events in the 20 years from 1976 to 1995.

In this study, we have defined three large-flood scenarios. The first, F1, is based on a 1974 flood peak which resulted from an intense rainfall event in the lower Yarra and Maribyrnong catchments. This scenario delivers a much higher peak flow than any observed in the 1991-95 baseline period, but lower monthly average flows and loads than the baseline 1992 and 1993 Yarra floods. The second and third scenarios are based on scaling up the observed Yarra and Maribyrnong flows and loads in September 1993.

The application of baseline catchment models and parameters to these scenarios suggests that large prolonged flows may deplete pools of certain nutrients (nitrate, phosphate, silicate) in the catchment. If this is realistic, it may set an upper limit on flood loads and some impacts. On the other hand, it means that flood loads and impacts may depend on the pattern of rainfall and runoff in preceding years. A large runoff event following a drought may deliver much larger loads than one following years of high runoff. Application of catchment models to flood scenarios involves their extrapolation outside the historical data used to calibrate models, and this introduces additional uncertainty into predicted loads. Given the possibility that extrapolated catchment models underestimate flood loads, we included a third flood scenario in which loads are simply scaled with flow. Consequently it is believed that the actual impacts of a large flood are likely to fall within the range of impacts displayed by the 3 large flood scenarios.

Perhaps the most important conclusion to be drawn from these large flood scenarios, which were considered to be manifest of high magnitude/low frequency events, is that the impacts at Bay-wide / annual scales are qualitatively similar to those resulting from more frequent, smaller runoff events, and commensurate with overall changes in annual loads. In particular, there is no suggestion from model results that a large flood event could, by itself, tip the Bay over into a new mode of behaviour. For example, median denitrification efficiencies in the General segment during large floods are little changed from those predicted during baseline flood events (Table 4), and changes in long-term denitrification efficiencies following large flood events are negligible. (It should be stressed that this conclusion is only for flood scenarios inserted within the 1991-95 baseline loads.)

The model does predict that large flood events have significant local impacts, over and above the impacts predicted for baseline runoff events. These impacts are generally concentrated in Hobsons Bay and along the coast southeast of Hobsons Bay, reflecting the typical location of the Yarra flood plume. Maximum relative impacts are sometimes displaced from Hobsons Bay, but absolute concentrations of indicators such as nutrients and chlorophyll are very high in Hobsons Bay under the baseline flood event (Fig. 7, 8). Larger relative increases further away from the mouth represent much smaller absolute increases.

The predicted spatial and temporal distribution of impacts varies across both indicators and flood scenarios. Indicators such as DIN and labile detrital N are injected into the Bay in Yarra runoff and subsequently removed by uptake or settling. Concentrations of these indicators in Hobsons Bay and neighbouring boxes respond to flood loads on time scales of hours to days. The September 90%ile values for DIN in the vicinity of the Yarra plume are increased under scenario F1 compared with baseline (Fig. 10, Table 4) because the peak flow and load are higher, even though the integrated September DIN load under F1 is lower than baseline.

Indicators such as chlorophyll and sediment respiration respond to runoff on time scales of days to weeks. Chlorophyll 90%ile values in September in Hobsons Bay and nearby boxes decrease under scenario F1 compared with baseline, because the cumulative nitrogen load is lower. Chlorophyll median and 90%ile values increase substantially under scenarios F2 and F3 with larger cumulative nutrient loads, and these increases are distributed down the Yarra plume, and across the northern Bay.

Predicted local impacts of large floods are generally largest during the 30 day period used to generate the summary statistics presented here, but are not confined to this period. Depending on the indicator, impacts decline following flood events over time scales of weeks to one or two months.

Current SEPP objectives for indicators most relevant to nutrient cycling processes are not currently framed to take account of transient events such as large floods, and it is not clear what objectives, if any, are appropriate for water quality indicators under transient conditions. A defensible approach would be to frame criteria to avoid prolonged or irreversible biogeochemical and ecological impacts. The model simulations predict no long-lasting or irreversible biogeochemical impacts of the flood scenarios considered here, over those encountered during the baseline period. However, ecological impacts deserve further consideration, as they may involve local processes and components not explicitly represented in the model. We suggest two areas of concern.

Light attenuation tends to be high in Hobsons Bay, and increases substantially under flood conditions. (As noted above, the model is likely to underestimate light attenuation under these conditions.) The model indicates that bottom light levels will decrease so as to be severely limiting to benthic plants. If this persists for long enough, it may result in the loss of key benthic communities.

The model predicts substantial oxygen drawdown in Hobsons Bay under flood conditions. Again, the model is likely to underestimate oxygen drawdown under stratified conditions. Severe bottom oxygen depletion could result in loss of benthic communities, resulting in communities which are depauperate and/or subject to invasion by introduced pests.

Further targeted studies would be required to more precisely evaluate the risks associated with both light attenuation and oxygen depletion.

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Table 4. Indicator statistics (50 and 90%ile (or 10%ile), area weighted) for September 1993, by SEPP segment. The Inshore and General segments contain many model boxes which are distant from and relatively unaffected by Yarra floods. Because SEPP environmental objectives are intended to apply to all waters within a segment, we have provided statistics for 5 indicators (Chl, DIN, Si, Kd, SedR) for model boxes in the Inshore and General segments adjacent to Hobsons Bay, which are most affected by Yarra floods. These are model box 30, Inshore (adj), and model box 31, General (adj).

Chl 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	2.6	2.1	3.4	3.3
Werribee	2.6	2.6	2.6	2.6
Inshore	0.8	0.8	0.8	0.8
Inshore (adj)	2.3	2.0	2.8	2.7
General	0.7	0.7	0.8	0.8
General (adj)	1.6	1.5	2.1	2.1

Chl 90%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	19.4	12.2	21.5	28.4
Werribee	5.6	5.4	5.4	5.4
Inshore	2.3	2.2	2.9	2.8
Inshore (adj)	14.6	11.8	12.8	19.0
General	1.5	1.5	1.8	1.7
General (adj)	9.9	8.9	10.1	11.1

DIN 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	101	86	136	151
Werribee	39	44	44	42
Inshore	8	8	8	8
Inshore (adj)	66	59	94	89
General	6	7	7	6
General (adj)	25	20	32	26

DIN 90%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	163	199	260	257
Werribee	215	226	235	223
Inshore	21	23	22	22
Inshore (adj)	105	133	178	176
General	10	11	12	12
General (adj)	46	57	82	76

Si 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	327	267	287	416
Werribee	93	87	84	85
Inshore	113	110	102	106
Inshore (adj)	250	227	238	173
General	150	150	143	146
General (adj)	209	201	206	158

Si 90%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	526	462	542	717
Werribee	155	149	142	143
Inshore	216	210	203	211
Inshore (adj)	395	330	421	262
General	182	180	178	180
General (adj)	292	261	300	228

Kd 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	0.87	0.58	1.26	1.28
Werribee	0.30	0.30	0.30	0.30
Inshore	0.12	0.12	0.12	0.12
Inshore (adj)	0.28	0.27	0.43	0.36
General	0.12	0.12	0.12	0.12
General (adj)	0.27	0.25	0.32	0.30

Kd 90%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	1.81	1.92	2.56	2.47
Werribee	0.79	0.82	0.82	0.82
Inshore	0.36	0.37	0.39	0.38
Inshore (adj)	1.15	0.98	1.62	1.57
General	0.22	0.22	0.24	0.23
General (adj)	0.77	0.82	0.92	0.87

SedR 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	185	155	354	262
Werribee	52	52	53	53
Inshore	3	3	3	3
Inshore (adj)	39	34	68	53
General	15	15	16	16
General (adj)	35	29	49	39

SedR 90%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	413	506	595	545
Werribee	145	149	143	143
Inshore	22	24	24	24
Inshore (adj)	98	121	187	172
General	30	29	33	32
General (adj)	105	130	153	142

PP 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	13.9	10.7	18.1	17.5
Werribee	10.6	10.9	11.0	11.0
Inshore	2.4	2.4	2.4	2.4
General	2.0	2.0	2.1	2.1

PP 90%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	83.9	52.1	87.5	111.3
Werribee	24.8	24.6	25.4	25.4
Inshore	9.0	9.6	11.1	10.6
General	4.5	4.4	5.6	5.4

MPBP 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	6	11	1	3
Werribee	22	22	22	22
Inshore	8	8	8	8
General	17	16	15	16

MPBP 90%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	15	16	14	14
Werribee	25	25	25	25
Inshore	20	19	20	20
General	23	24	23	23

Den 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	6.8	17.0	0.0	0.0
Werribee	52.2	52.2	51.7	51.7
Inshore	16.5	16.6	16.7	16.6
General	62.2	62.3	61.5	61.6

Den 10%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	0.0	0.0	0.0	0.0
Werribee	20.7	19.0	21.3	21.2
Inshore	1.1	1.1	1.1	1.1
General	6.9	6.8	7.3	7.0

LDN 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	142	76	245	237
Werribee	16	16	16	16
Inshore	3	3	3	3
General	2	2	3	3

LDN 90%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	338	380	531	489
Werribee	69	67	69	69
Inshore	23	23	25	24
General	9	9	12	11

DO 50%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	7613	7681	7258	7409
Werribee	7908	7912	7914	7914
Inshore	7992	7992	7992	7993
General	7977	7977	7977	7977

DO 10%ile

	Baseline	Scenario F1	Scenario F2	Scenario F3
Hobsons Bay	7008	6580	6261	6513
Werribee	7612	7594	7617	7618
Inshore	7928	7928	7917	7922
General	7958	7960	7954	7956

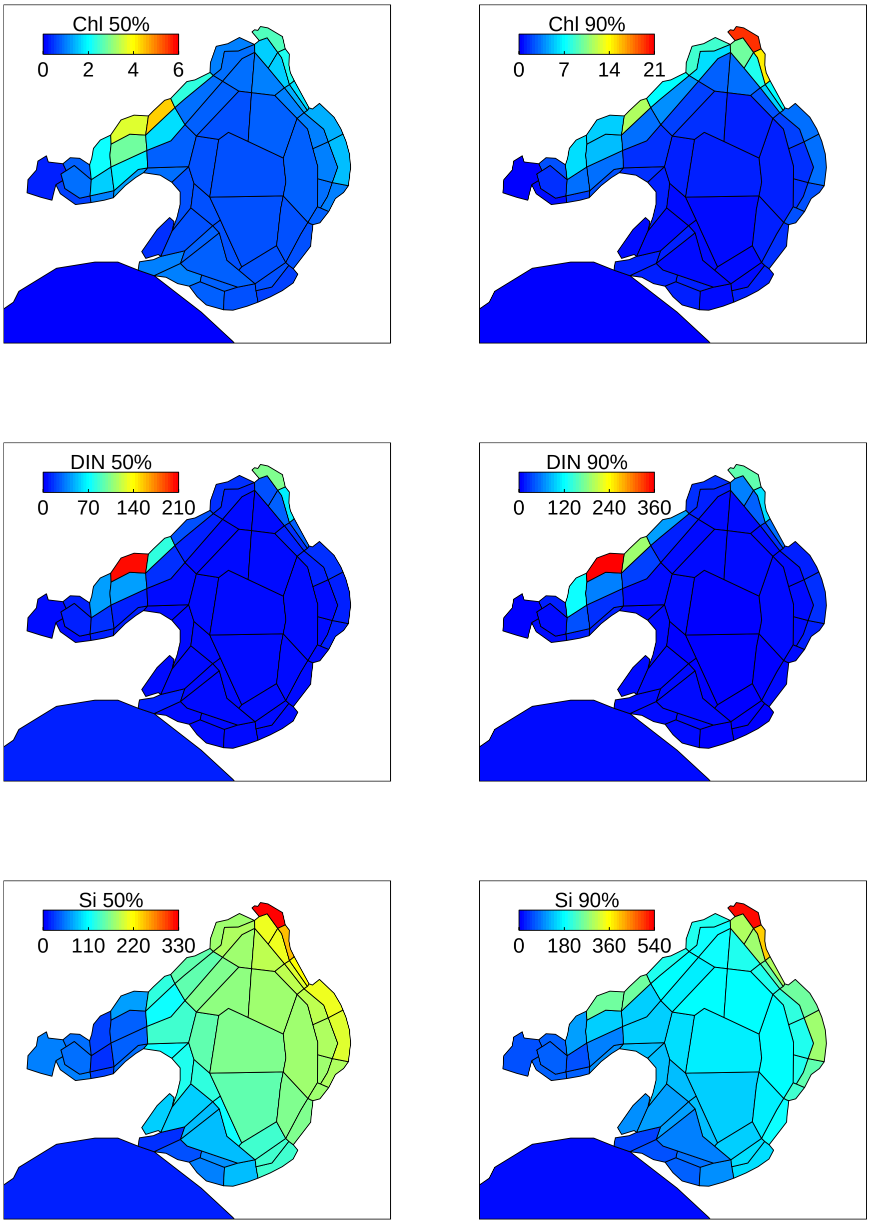

Figure 7. Distribution of 50 and 90%ile values for indicators Chl (mg m^{-3}), DIN (mg N m^{-3}) and Si (mg Si m^{-3}) for September 1993 under baseline forcing.

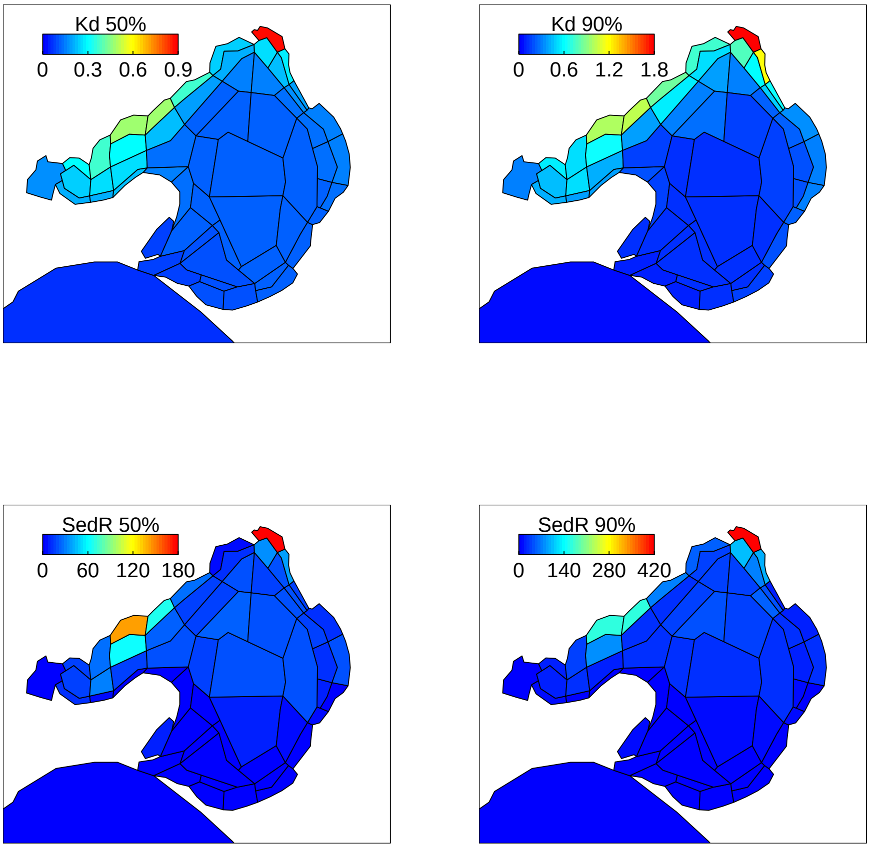

Figure 8. Distribution of 50 and 90%ile values for indicators Kd (m^{-1}) and SedR (mg N m^{-2} d^{-1}) for September 1993 under baseline forcing.

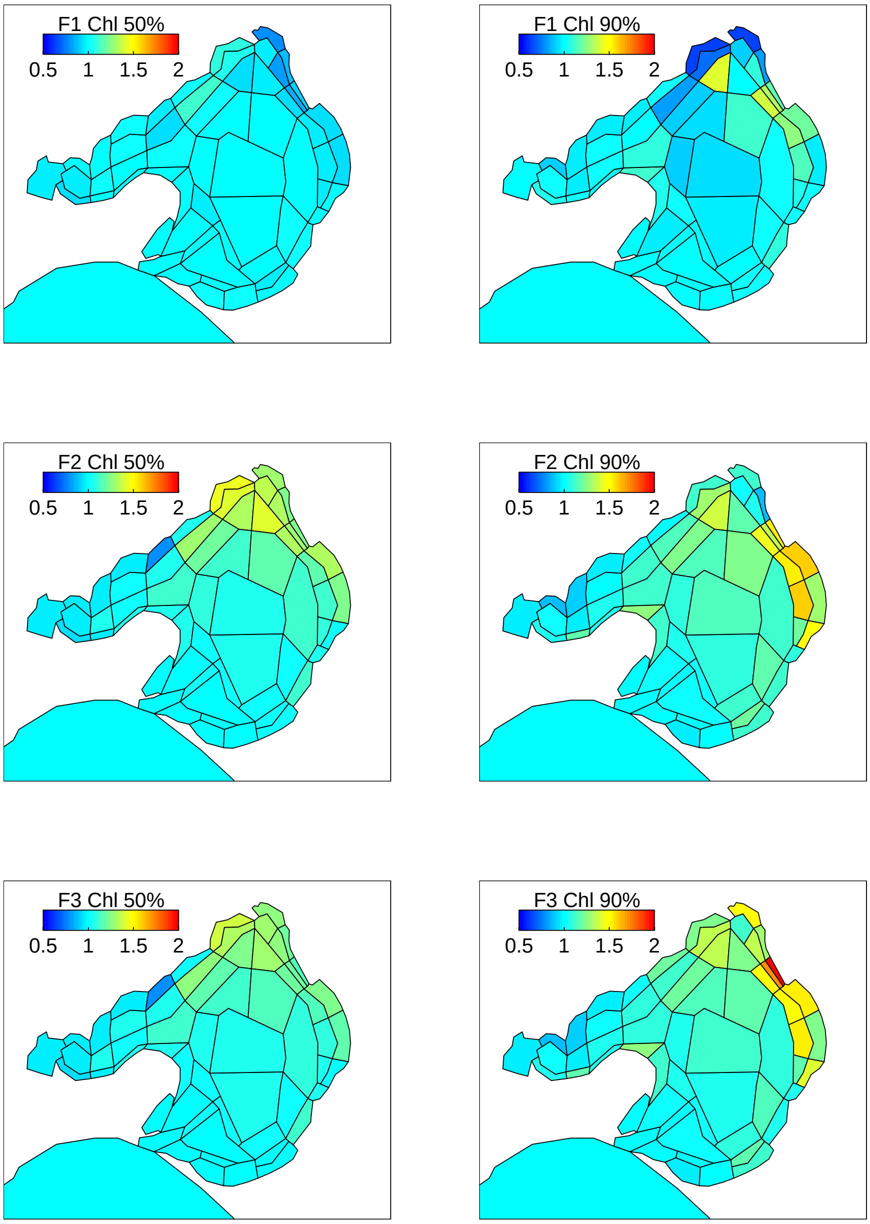

Figure 9. Ratio of flood scenario statistics to baseline statistics for Chl, 50 and 90%ile values. Baseline - September 1993, and flood scenarios - F1, F2, F3.

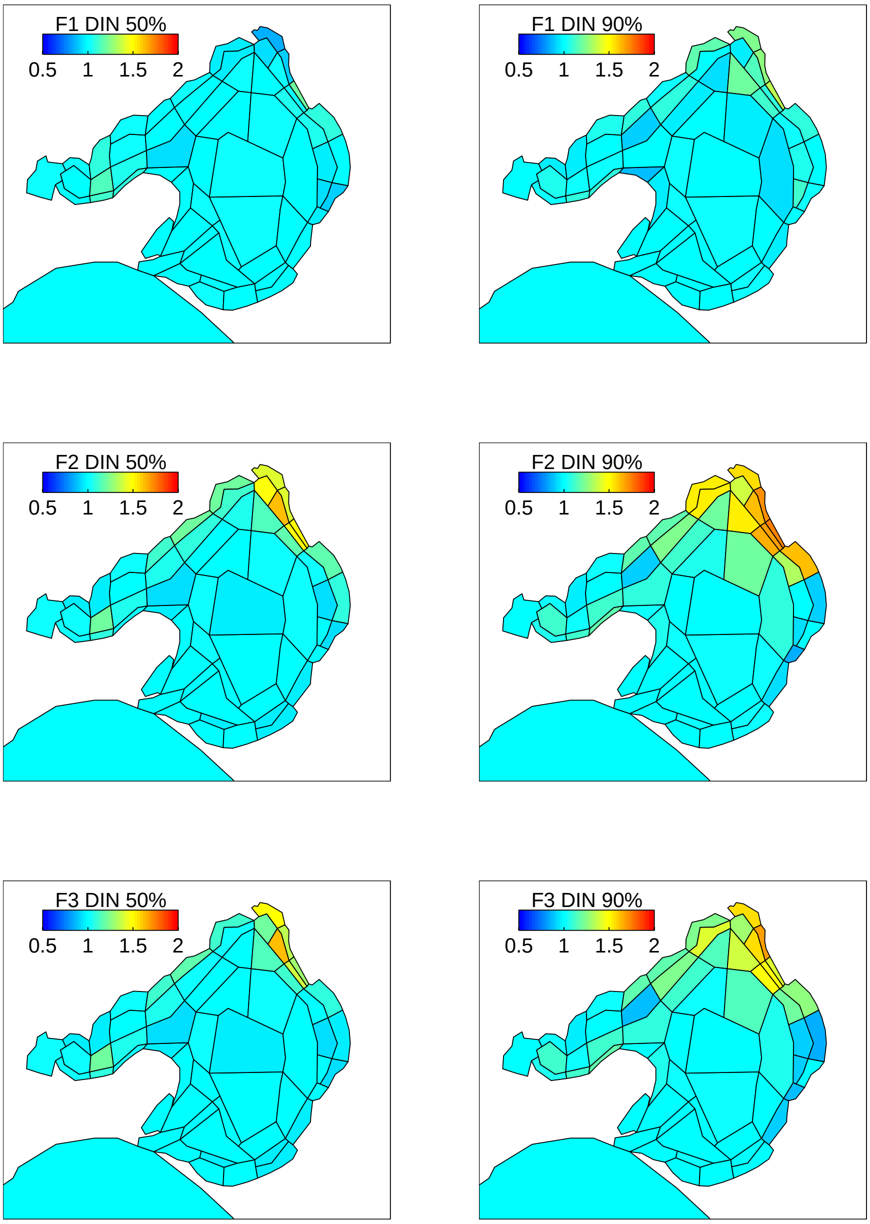

Figure 10. Ratio of flood scenario statistics to baseline statistics for DIN, 50 and 90%ile values. Baseline - September 1993 and flood scenarios F1, F2, F3.

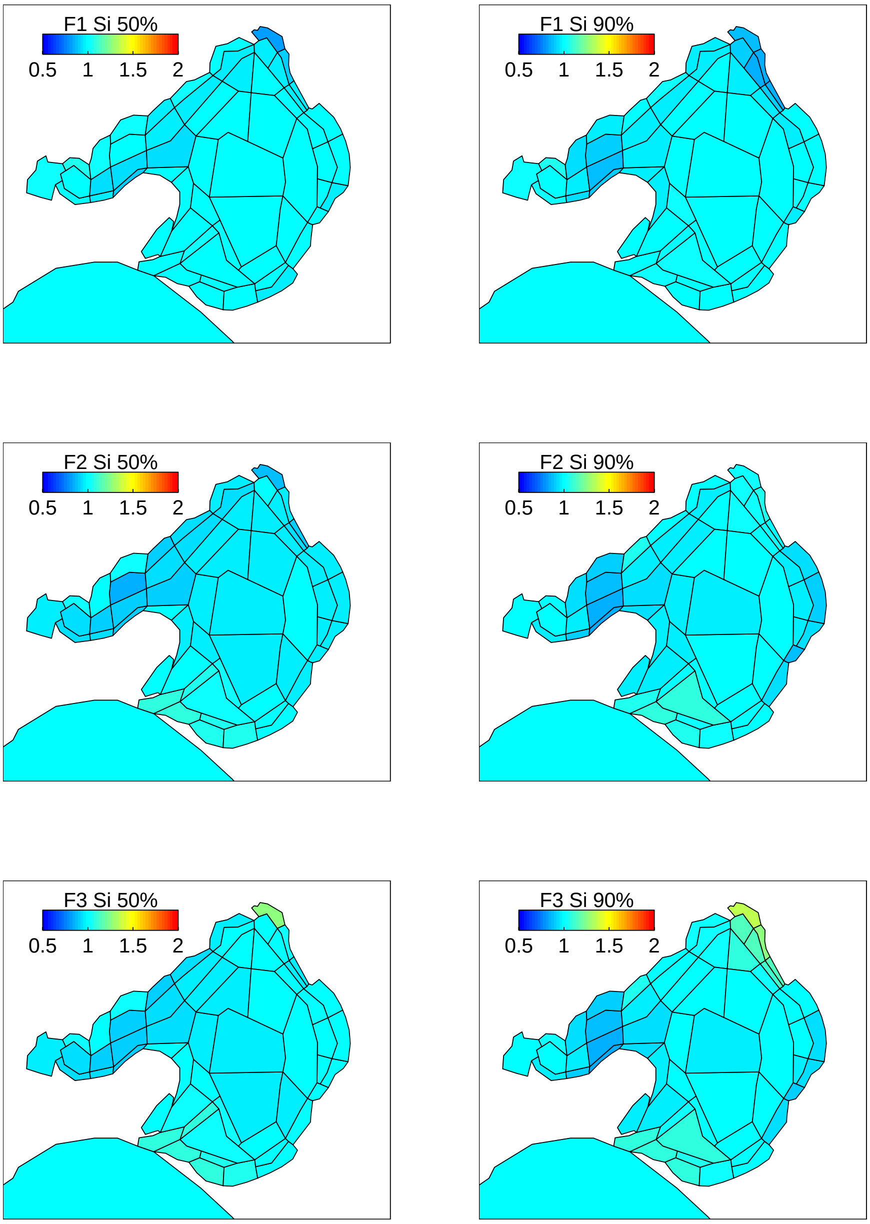

Figure 11. Ratio of flood scenario statistics to baseline statistics for Si, 50 and 90%ile values. Baseline - September 1993. and flood scenarios F1, F2, F3.

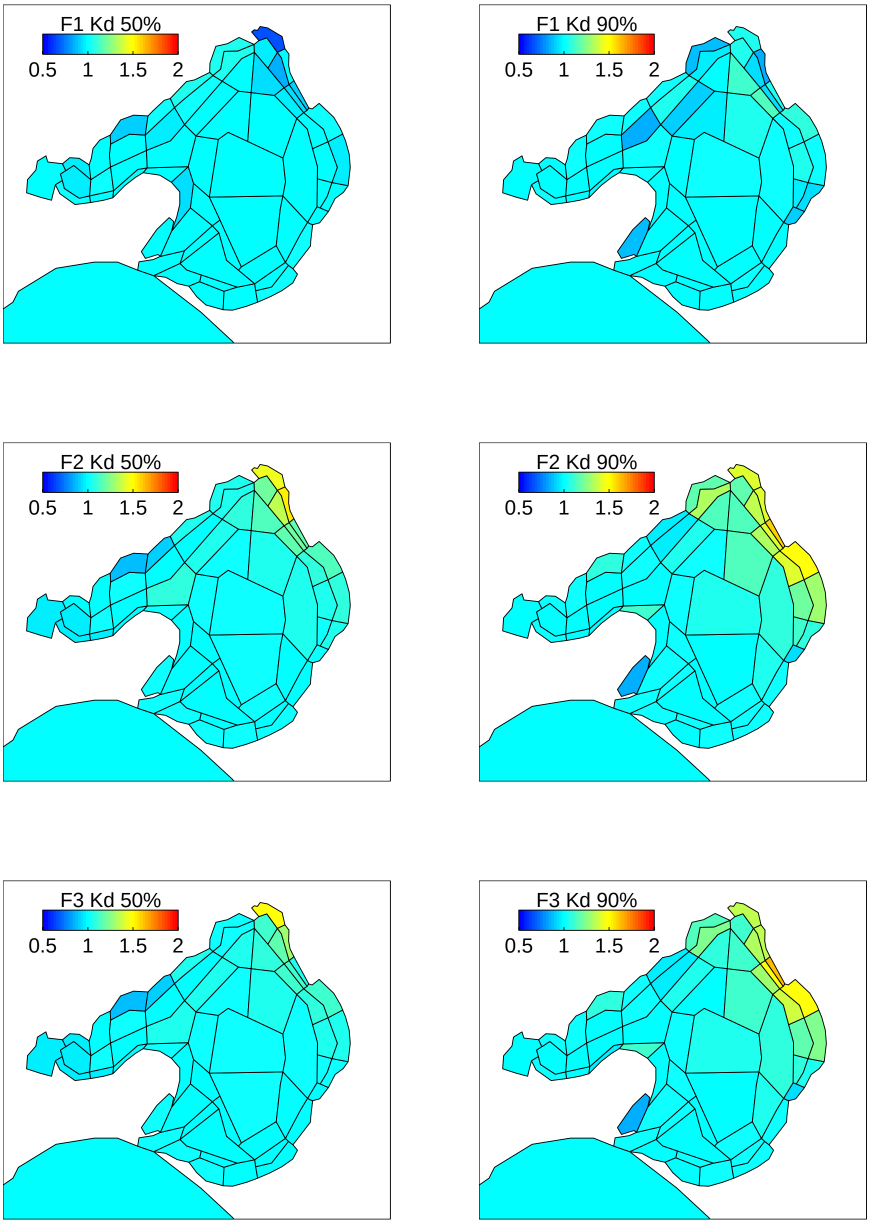

Figure 12. Ratio of flood scenario statistics to baseline statistics for Kd, 50 and 90%ile values. Baseline - September 1993 and flood scenarios F1, F2, F3.

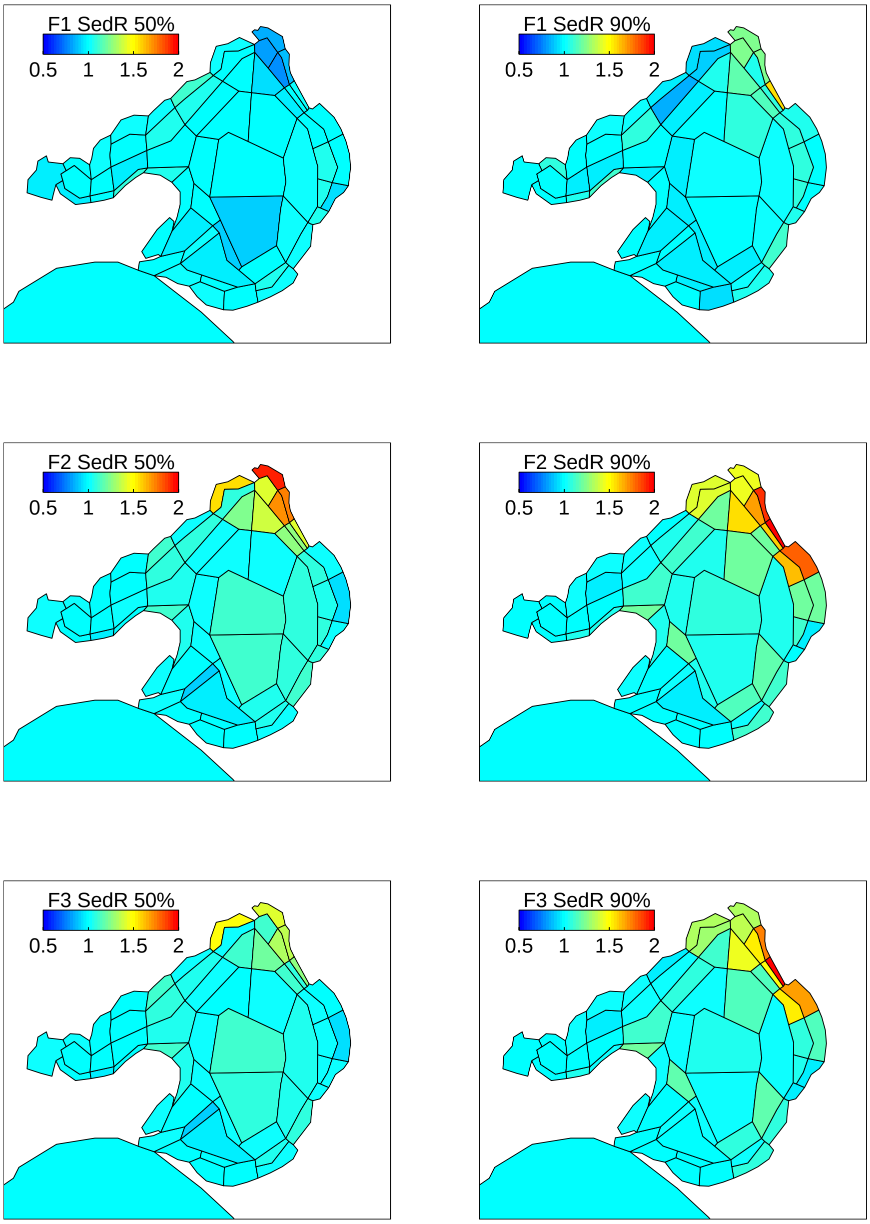

Figure 13. Ratio of flood scenario statistics to baseline statistics for SedR, 50 and 90%ile values. Baseline - September 1993 and flood scenarios F1, F2, F3.