Werribee River Estuary Environmental Flow Requirements

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General Disclaimer

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Executive Summary

The Werribee River has a catchment area of over 1424 km^2 (measured above the weir at Werribee) and flows into northern Port Phillip Bay. It is a highly flow stressed and regulated river system with diversions for irrigation at Pykes Creek, Merrimu and Melton Reservoirs and at the Lower Werribee Diversion Weir. The Victorian Government has committed to improving the river's ecological health.

This study is one of three projects designed to enhance the lower Werribee River: Its aims were to determine:

1. the current status and environmental values of the estuary
2. the key flow components required to restore ecological health to the estuary
3. risks to the ecological health of the estuary
4. opportunities for improving the ecological health of the estuary.

The Werribee estuary is 8.25 km long with an upstream limit defined by a ford constructed in the 1860's. The estuary is shallow, generally 2.5m or less in depth and is subjected to the tidal fluctuations of Port Phillip Bay – tidal variations in water level are typically about 0.5m. The tidal prism is approximately one-third of the estuary volume at low water.

Eleven longitudinal surveys of the estuary were conducted approximately monthly between 20th August 2004 and 16th May 2005. On each survey vertical profiles of temperature, salinity, dissolved oxygen, turbidity and pH were determined at 5 estuarine sites and one freshwater site. Samples were collected for nutrient analysis and algal speciation at two estuarine and one freshwater site. On two trips fish were surveyed. None of the species collected are considered threatened in Victoria, but several species with high recreational and commercial fishing value were collected, including Black bream, King George whiting and Snapper. All three of these species were collected as juveniles in the estuary, suggesting it acts as a nursery habitat for these species.

The current study shows that the Werribee estuary currently has a number of undesirable characteristics related to the effects of flow regulation that pose serious threats to the health of the ecosystem:

(i) The estuary was almost constantly in a low-flow condition during the study period. The winter-spring discharge maximum did not occur in 2004 leading to an extended period of strongly marine water in the estuary. Truly estuarine conditions (salinity < ~30) were confined to a small region in the upper estuary.

(ii) The estuary was highly eutrophic, with concentrations of nutrient species exceeding upper limits based on SEPP objectives and the ANZECC default trigger levels by up to an order of magnitude.

(iii) Algal communities were consistently high in response to the combination of low flows and elevated nutrient concentrations. Blooms of algae resulted in

excessive rates of photosynthesis leading to dissolved oxygen concentrations above saturation (equilibrium) values during survey times (approximately mid-morning to mid-afternoon).

There are a number of related risks to ecological functions as a result of these characteristics:

1. Disruption of the estuary's hydrodynamic cycle is likely to negatively affect the breeding activity and survival of estuarine species of fauna and flora adapted to the natural regime.

2. Increased incidence of hypoxic/anoxic conditions in the estuary as a result of both reduced circulation, increased organic loading of bottom waters and potential overnight oxygen depletion ("oxygen sag") may have negative effects on the aquatic fauna of the estuary. For example, anoxic conditions are uninhabitable for fish and will either result in fish deaths or reduce the amount of suitable habitat available.

3. There is a relatively high likelihood that blooms of toxic cyanobacteria (blue-green algae) will occur under the present eutrophic conditions. If this happens, it may result in closure of the estuary to human activity and mass mortality of estuarine organisms due to toxicity and/or oxygen depletion.

Given uncertainties over the ecological effects of changes in flow to estuaries recommendations for environmental flows are based on the principle that:

> *diversion of water from river systems should not disturb the major features of the estuarine hydrodynamic cycle.*

In the case of salt wedge estuaries such as the Werribee, this means that the following key characteristics should be maintained.

(i) Late winter to early spring flows sufficient to flush "aged" salt water from the estuary and allow migration of a well-oxygenated salt wedge upstream as the flows reduce.

(ii) Flows sufficient to maintain a salinity gradient both vertically and horizontally throughout the estuary. The gradients should ensure that water over the range of salinities from fresh to strongly marine is present in the estuary most of the time.

(iii) Avoidance of long periods of constant flow. The inherent variability of stream flow (including periods of cease-to-flow conditions if naturally occurring) should be maintained. This will require short periods when higher flows ("spates" or "freshes") enter the estuary. These serve also to improve its flushing characteristics.

The report makes the following recommendations:

Recommendation 1. A flow of at least 1000 ML/day measured at the Lower Werribee Diversion Weir should be maintained for at least 3 days in late winter/early spring (September or October) as a flushing flow to significantly reduce the salt wedge length. This flow should occur at least once annually unless natural flows have a lower frequency.

Recommendation 2. A minimum flow of sufficient volume should be provided to ensure that salinity gradients are maintained in the upper estuary. A layer (0.5 to 1m deep) of fresh to brackish water (salinity<10) should be present in the upper estuary under low flow conditions. Further analysis of the relationship between flow and salinity in the estuary is required to quantitatively determine the volume of flows required to achieve this objective.

Recommendation 3. Flows less than the minimum flow established in Recommendation 2 (including cease to flow conditions) should be allowed to occur at their natural frequency and timing. The frequency and timing of these flows, and any independence rules relating to this recommendation, will need to be formulated via further analysis of modelled flow data.

Recommendation 4. Periods of flow greater than 400 ML/d (2 day minimum) should occur at their natural frequency and timing to mimic natural freshes. The frequency and timing of these flows, and any independence rules relating to this recommendation, will need to be formulated via further analysis of modelled flow data.

Recommendation 5. Investigate the sources of nutrients entering the estuary and implement actions outlined in the Werribee River Catchment Nutrient Management Plan to reduce nutrient loadings

Recommendation 6. The provision of fish passage should be investigated at least at the bluestone ford and Lower Werribee Diversion Weir to allow migration of diadromous species between freshwater and the estuary/sea.

1. Introduction

The Werribee River has a catchment area of over 1424 km^2 (measured above the weir at Werribee; Victorian Data Warehouse web site) and flows into northern Port Phillip Bay (Figure 1). It is a highly flow stressed and regulated river system with diversions for irrigation at Pykes Creek, Merrimu and Melton Reservoirs and at the Lower Werribee Diversion Weir.

The Werribee River upstream of the township of Werribee is rated as being in “Poor” condition (Index of Stream Condition (ISC), DSE), whilst the Werribee River estuary has an ISC rating of “Very poor”. The hydrological sub-index for both ISC sites on the Werribee River are rated 2 out of a maximum of 10, reflecting high levels of flow stress in the system.

The Port Philip and Westernport Regional River Health Strategy (Melbourne Water 2005) rates the lower Werribee River as a region of “Very High” significance. The current condition is rated as “Poor” and a target condition of “Moderate” has been set. The water quality and aquatic life indices are ranked as “Good”, habitat stability as “Moderate”, vegetation and flow as “Poor”.

The Victorian Government has committed to improving the river’s ecological health by funding three projects designed to enhance the health of the Werribee River. These projects include:

- Habitat works and willow removal,
- Environmental flow needs of the river, and
- Environmental flow needs of the estuary

In turn these projects are part of larger project titled the *Vision for the Werribee Plains: the Next Step. Action Plan 2004* and includes a plan to enhance the environmental water reserve for the Werribee River by greater use of recycled water in the Werribee Irrigation District (Victorian Government, 2004).

The aims of the present estuary study are to determine:

1. the current status and environmental values of the estuary
2. the key flow components required to restore ecological health to the estuary
3. risks to the ecological health of the estuary
4. opportunities for improving the ecological health of the estuary.

2. Geomorphic Description of the estuary

The Werribee estuary is 8.25km long with an upstream limit defined by a ford located downstream of the Maltby bypass. The ford was constructed in the 1860's (Figure 2). and is situated close to the earliest crossing of the Werribee River (which was part of the first road to Geelong in the 1840's). Upstream of the ford fresh water forms a deeper long pool. Water drops about 0.5 m after flowing over the ford. About 100 m below the ford the estuary narrows to a shallow riffle area preventing boat access.

Land on the western side of the estuary is managed by Melbourne Water and is primarily used for dry land grazing of stock as part of the Werribee Farm, containing the sewerage treatment plant.

On the eastern bank of the estuary the dominant land uses are a golf course (upper estuary) and market gardens (lower estuary). A public boat launching ramp is located within a few hundred metres of the entrance of the estuary from Port Phillip Bay at the town of Werribee South (Figure 2).

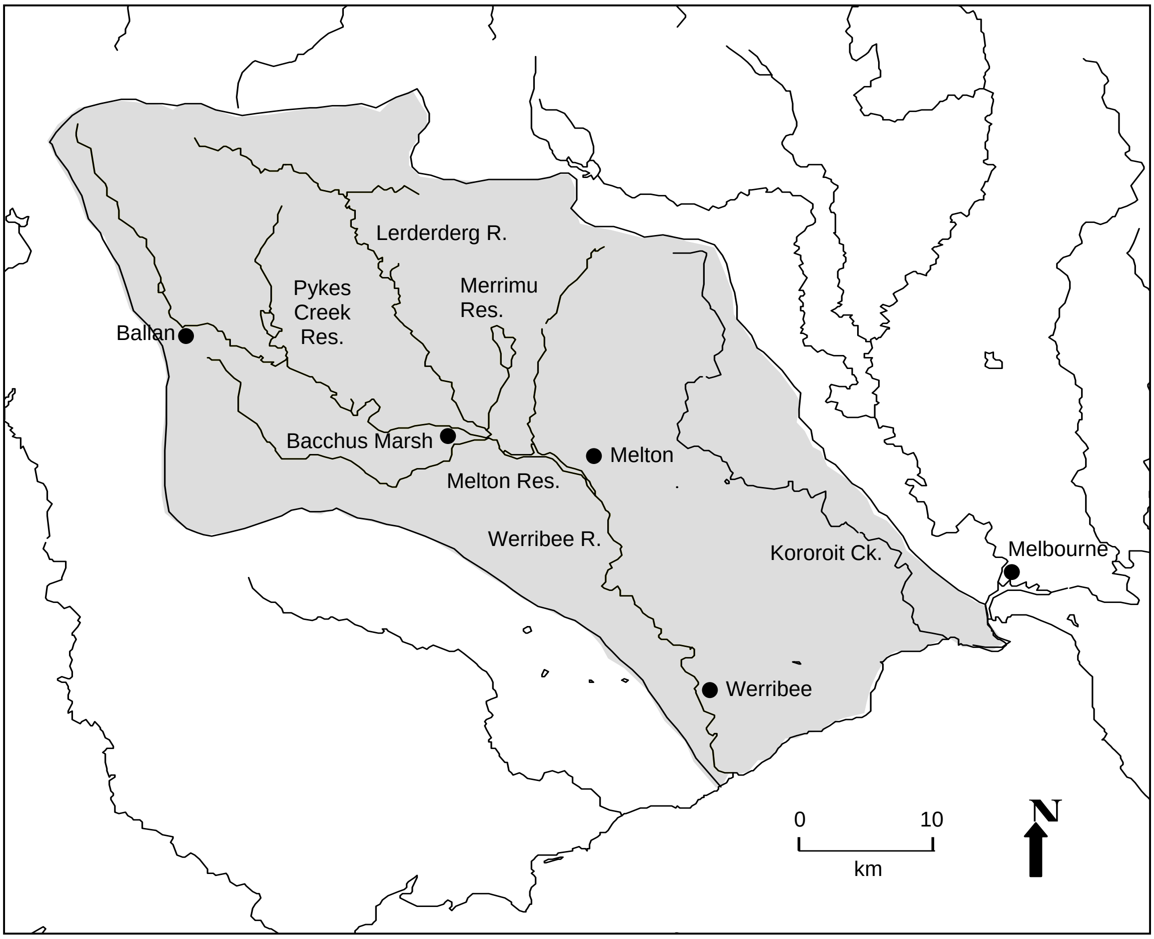


Figure 1: Catchment of the Werribee River (note that Kororoit Creek is not included in the catchment).

There are no tributaries flowing directly into the estuary but several stormwater drains enter from the eastern shore.

The estuary and lower Werribee River are contained within a generally steep-sided valley incised approximately 10m below the surrounding plains. In the upper estuary the valley sides come within 250m of each other at their narrowest point and form vertical cliffs of clay-rich sediment on one bank of the estuary at several places.

The estuary is subjected to the tidal fluctuations of Port Phillip Bay – the tidal range in water level is typically about 0.5m. A longitudinal echo-sounding survey of the estuary at close to low tide showed the lower 3.25 km of the estuary to have a mid-stream depth of ~2.5m and a relatively uniform bottom (Figure 3). Upstream of the lower 3.25km of the estuary the floor is much less uniform. Deeper basins (> 3m) are generally 30-150 m long and the maximum depth recorded was 3.9 m at a very sharp bend 5.8 km upstream (site WR04). Between 6.0 km and 6.7 km the estuary is very shallow (in places no deeper than 30-45 cm during low tide). Upstream of this shallow section the estuary is up to 1.8 – 2.1 m deep up to the navigable limit (7.7 km). At high tide approximately 0.5 m would be added to these depths.

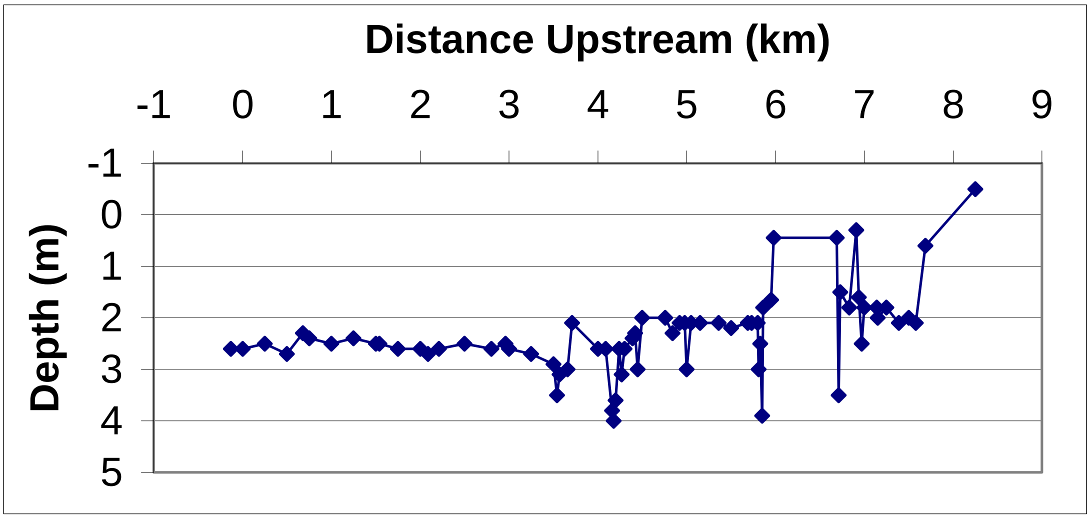


Figure 3: Mid-channel bathymetry of Werribee estuary measured by echo-sounding at close to low tide on 25 April 2005. The bluestone ford (8.25km upstream) is estimated to be 0.5 –1m above estuary water level.

At various locations along the estuary the composition of the bottom sediment was investigated visually or by sounding line, boat oar or Eckman Grab. In the uniform lower section (i.e. below ~ 3 km) the sediment is predominantly a black, gelatinous mud. From about 3 to 5 km the bottom is firm – either clay or sandy gravel. Above 5 km the bottom is comprised of a coarse gravel, with rounded cobbles and pebbles forming a virtually continuous pavement.

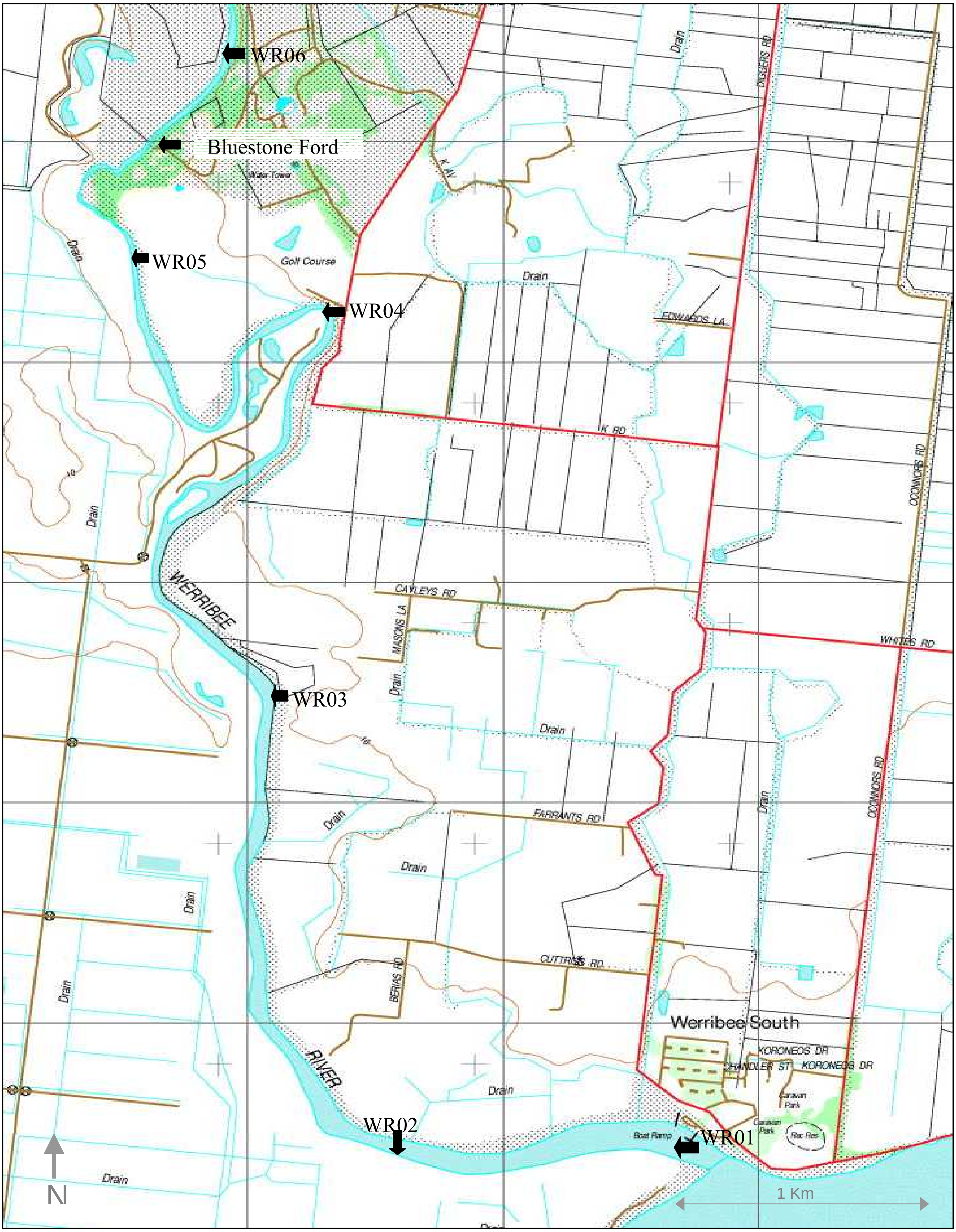


Figure 2: The Werribee River Estuary showing sample sites used during the study.

The estuary width decreases with increasing distance upstream (Table 1).

Table 1: Variations in estuary width (bank to bank) with distance upstream.

Site	Distance Upstream (km)	Width (m)
Estuary Entrance	0	120
WR01	0.28	152
WR02	1.50	93
WR03	3.58	65
WR04	5.78	31
WR05	7.42	18

3. Field and Laboratory Methods

3.1 Field Surveys

Eleven longitudinal surveys of the estuary were conducted approximately monthly between 20th August 2004 and 16th May 2005 (Table 2). During each survey vertical profiles of temperature, salinity, dissolved oxygen, turbidity and pH were determined at five estuarine sites and one freshwater site (located in the long pool immediately upstream of the bluestone ford). Locations of the sites are shown in Figure 2 and Table 3.
Measurements of these parameters were made with one of the following portable meters:
(i) TPS
(ii) Horiba
(iii) Yeo Kal 611

Throughout this report, salinity is given in dimensionless units according to the international Practical Salinity scale of 1978. Values correspond approximately to parts per thousand (or g salt/kg water).

During the surveys shown in Table 2, samples for other parameters were collected as indicated.

3.1.1 Nutrients

A “surface” (0.1m) and “near-substrate” (1.5 – 3.0 m) water sample (125mL) was collected using a submersible sampling bottle. After two rinsings the sample was collected in acid-washed HDPE bottles and stored on ice in the dark and transported to the laboratory within 24 hours of collection. Samples were frozen until analysis. Two estuarine sites (WR02, WR05) and one freshwater site (WR06) were sampled each month. Additional surface samples were taken in the vicinity of a drain that was discharging run-off after a high flow event on 27 January 2005.

3.1.2 Chlorophyll a and algal cell identification and enumeration

Algal samples for chlorophyll *a* measurement were collected each month from the surface and near-substrate at the same sites as for the nutrients. Algal cells were identified and enumerated on four trips and dominant species determined on a fifth trip. Samples for quantification were collected at the surface (0.1m) at two estuarine (WR02, WR05) and the freshwater site (WR06). The samples were stored on ice in the dark and transported to the laboratory within 24 hours of collection.

Table 2: Summary of sampling undertaken in the Werribee River estuary during the study.

Trip No.	**Date**	**T, S, DO, Cond**		**Turbidity**	**pH**	**WQ (2 depths /site)**	**Chl a (surface & depth)**	**Algae (surface)**	**Fish**
		Estuary	**FW**						
1	20-08-04	✓*	✓⊕	✓					
2	24-09-04	✓	✓	✓	✓	✓	✓	✓	
3	24-10-04 + bottom depths	✓	✓	✓	✓	✓	✓		
4	22-11-04 + bottom depths	✓	✓	✓	✓	✓	✓		
5	21-12-04	✓	✓	✓	✓	✓	✓≠	✓	✓
6	27-01-05 +channel flow	✓	✓	✓	✓	✓≠	✓		
7	28-02-05	✓	✓	✓	✓	✓	✓		
8	24-03-05	✓	✓	✓	✓	✓	✓	✓	
9	⊗ 25-04-05	✓	✓	✓	✓				
10	29-04-05	✓	✓	✓	✓	✓	✓	✓	✓
11	16-05-05	✓	✓	✓	✓	✓	✓	✓	

⊗ Included a bathymetric survey.
* 4 sites only, all other trips 5 sites.
⊕ 3 sites, all other trips 1 site.
≠ 4 sites sampled, all other trips 3 sites.

Table 3: Location of sample sites (see Figure 2 also).

Site	Distance Upstream (km)	Latitude (S)	Longitude (E)
WR01	0.28	37º 58.363’	144º 41.138’
WR02	1.50	37º 58.377’	144º 40.332’
WR03	3.58	37º 57.328’	144º 40.129’
WR04	5.78	37º 56.328’	144º 40.308’
WR05	7.42	37º 56.126’	144º 39.776’
WR06*	8.56	37º 55.759’	144º 40.053’

*Freshwater site.

3.1.3 Fish Surveys

Fish surveys were conducted on 14-16 December 2004 and 27-28 April 2005. Surveys were conducted in the lower estuary (WR02 region), in the mid-estuary (WR03 region), in the upper estuary (WR04 and WR05 regions), and in the lower reaches of the freshwater section of the river (WR06 region). As the aim was to provide a qualitative “snapshot” of the fish fauna present in the river at the time of sampling, a variety of methods was employed at each site and no attempt was made to standardise the sampling. Fyke nets and seine nets were used to sample fish at the estuarine sites and boat mounted electrofishing, fyke nets, bait traps and mesh nets were used to sample fish in the freshwater reach (see Appendix 4 for details of the fish sampling).

3.2 Laboratory Measurements

3.2.1 Nutrients

Frozen samples were thawed prior to analysis at Deakin University’s NATA Accredited Water Quality Laboratory. Nutrient concentrations determined were:

(i) Total Nitrogen (TN) and Total Phosphorus (TP).

Samples were digested in an autoclave using an alkaline persulphate reagent. This treatment converts all forms of N and P to the simple ionic forms nitrate ion (NO_3^-) and phosphate ion (PO_4^{3-}). The concentrations of these ions were subsequently determined using a Lachat “Quickchem” Multichannel Flow Injection Analyser.

(ii) Soluble Reactive Phosphorus (SRP) and NO_x^-

Filtered samples (0.45 μm) were analysed using the Lachat FIA without further treatment to determine the concentrations of simple inorganic forms of nitrogen (NO_x^- - the sum of nitrate ion (NO_3^-) and nitrite (NO_2^-) concentrations) and phosphorus (SRP^- the sum of all forms of phosphorus hydrolysable to phosphate ion in acid conditions). These simple ions are considered to be the most readily bioavailable forms of the nutrients.

3.2.2 Chlorophyll a

Chlorophyll a concentrations were measured by Ecowise Environmental using APHA Method 10 200H (APHA, 1998).

3.2.3 Algal Counts

The abundances of algae in samples (in cells/mL) were determined for the divisions:

- Bacillariophyta (diatoms)
- Chloromonadophyta (chloromonads)
- Chlorophyta (green algae)
- Crysophyta (golden algae)
- Cryptophyta (cryptophytes)
- Cyanophyta (blue-green algae)
- Dinophyta (dinoflagellates)
- Euglenophyta (euglenoids)

In addition dominant species and the total abundance of algae were determined.

All algal counts were performed by WSL Laboratories.

3.2.4 Fish identification, enumeration and measurement

All fish collected using methods other than seine nets were weighed and measured at the time of capture and then released. For the seine net samples (which typically contained many hundreds of fish per haul), a sub-sample of the catch was retained and preserved in formalin for identification and measurement in the laboratory. The sub-samples were intended to be approximately representative of the relative abundance of different species, although care was taken to retain individuals of rare species. As such, rare species are likely to be over-represented in terms of their relative abundance in the samples. Fish that were not retained were released at the site of capture.

3.3 Sources of Additional Information

3.3.1 Tides in Port Phillip Bay

Predicted tides for Williamstown were taken as the tides at the entrance to the Werribee River. Williamstown tides were obtained from the Bureau of Meteorology website:

www.bom.gov.au/cgi_bin/oceanography/tides

The tide times are given as Eastern Standard Time and the Werribee tides peak approximately 5 minutes before the listed Williamstown times.

3.3.2 River Discharge

Monthly discharge data for the Werribee River at Werribee Weir (Station 231204) was available from April 1982 to July 2004. This was listed on the Victorian Government's Data Warehouse:

www.vicwaterdata.net/vicwaterdata/standardreports

Mean monthly discharge for period 1983 – 2003 was also available from this source. Daily discharges for the entire period from 1911 to April 2005 were supplied by Theiss Services.

3.3.3 Rainfall

Long-term mean monthly rainfall as well as actual monthly and daily rainfall for Geelong (SEC and Norlane) and Melbourne (Melbourne Regional Office) were extracted from the Bureau of Meteorology website:

www.bom.gov.au/climate

3.3.4 Previous fish survey data

In addition to the surveys conducted as part of the current study, previously collected fish survey data was collated from the DSE aquatic fauna database.

4. Characteristics of the Estuary

4.1 Salinity

The lower estuary (i.e. site 3 and below; < 3.6 km upstream) had a strong marine (Port Phillip Bay; PPB) influence throughout the survey period. Salinities in this section generally exceeded 30 with only a weak vertical salinity gradient (Figure 4).

A shallow (< 1 m) freshwater lens (salinity < 10) was present in the upper estuary on all surveys except for the 28th April 2005. On this occasion, all water in the estuary had a salinity > 20. The maximum observed downstream extent of the freshwater lens was on 27th January and 24th March 2005 when water of salinity < 10 reached below site 4 (i.e. greater than 2.8 km downstream of the ford). The estuary was highly stratified in its upper reaches with salinity in the halocline increasing by 8 or more over a depth of 1 - 0.5 m on most surveys.

Water of intermediate salinity (i.e. 10-30) was generally confined to the middle section of the estuary (approximately 4-6 km) or to bottom waters above the shallow reef area (i.e. above 6.7 km).

The estuary is divided into two basins by a shallow, natural reef area between 6 and 6.7 km upstream. Seawater from PPB can move upstream without significant obstruction until it reaches this barrier. Its height is such that at low tide only a shallow layer of water covers it. On a flood tide more saline water from downstream travels upstream over this shallow section. Because of its greater density, it then cascades down to the bottom of the upstream basin. During the ebb tide the barrier traps this deeper, more saline water and surface water drains over it and across the reef downstream. Turbulence, particularly during the flood tide creates mixing of the surface and deeper waters, reducing the salinity of the latter and raising that of the former.

Table 4: Salinity of Site WR06, just upstream of the estuary. *During high flow conditions.

Date	Salinity
20th August 2004	1.0
24th September 2004	0.7
24th October 2004	1.3
22nd November 2004	0.05
21st December 2004	1.0
27th January 2005	0.06 – 2.59*
28th February 2005	0.96
24th March 2005	1.42
28th April 2005	1.22
16th May 2005	1.46

At the freshwater site Werribee River water was consistently of lower salinity (< 2**).**
There was little variation over depth at site 6 (approximately 300 m upstream of the

bluestone ford). A large rainfall event on 27th January 2005 appears to have led to variable salinities due to turbulent mixing at the time of survey (Table 4).

4.2 Dissolved Oxygen

Dissolved oxygen concentrations varied greatly both within each survey and over time. Values greater than 10mg/L, indicating significant supersaturation were found in surface waters on all trips except for January (Figure 5; Table 5).

Table 5: Oxygen status of Werribee estuary sites during each fieldtrip. Site visits having no symbol had DO concentrations between 5 and 10 mg/L.

	Site (surface)						Site (near substrate)					
Trip Date	1	2	3	4	5	6	1	2	3	4	5	6
1. 20 Aug	✓✓	✓✓	✓✓		-	-				x	-	-
2. 24 Sep	✓✓	✓✓	✓✓			✓✓	✓✓				x	x
3. 24 Oct	✓✓	✓✓	✓✓	✓✓		✓✓			✓✓	✓✓		x
4. 22 Nov			✓✓	✓✓	✓✓	✓✓				x		x
5. 21 Dec			✓✓	✓✓		✓✓		x				x
6. 27 Jan								x				
7. 28 Feb			✓✓	✓✓		✓✓				**xx**	✓✓	x
8. 24 Mar		✓✓	✓✓	✓✓	✓✓	✓✓				**xx**	**xx**	**xx**
9. 25 Apr		✓✓	✓✓		✓✓	-					**xx**	-
10. 28 Apr		✓✓	✓✓	x	x	✓✓				x	**xx**	✓✓
11. 16 May	✓✓	✓✓	✓✓			✓✓					**xx**	✓✓

- Not surveyed
- ✓✓ DO > 10 mg/L (supersaturation)
x DO < 5 mg/L (hypoxia)
xx DO < 1 mg/L (severe hypoxia/anoxia)

Mid estuary sites (WR02, 3, 4) and the freshwater site (WR06) most commonly had supersaturated surface waters. This is most probably due to high rates of photosynthetic activity, indicating algal bloom conditions. On two fieldtrips, supersaturation was observed throughout the water column at one or two upper estuary sites. Overall, 36 out of 63 survey site visits (57%) showed supersaturated surface conditions while 6 out of 63 survey visits (10%) showed supersaturated deep waters.

Low DO concentrations (DO < 5 mg/L) were encountered at 2 surface sites during the April fieldtrip but were more common (11 out of 63 site visits) in deep waters of the mid to upper estuary (sites WR02 – 5) and the freshwater site (WR06). Very low DO concentrations (<1 mg/L) were observed in the upper estuary (sites WR04, 5) during late summer and autumn (Feb – May; 7 out of 63 site visits) and in the freshwater reach in March.

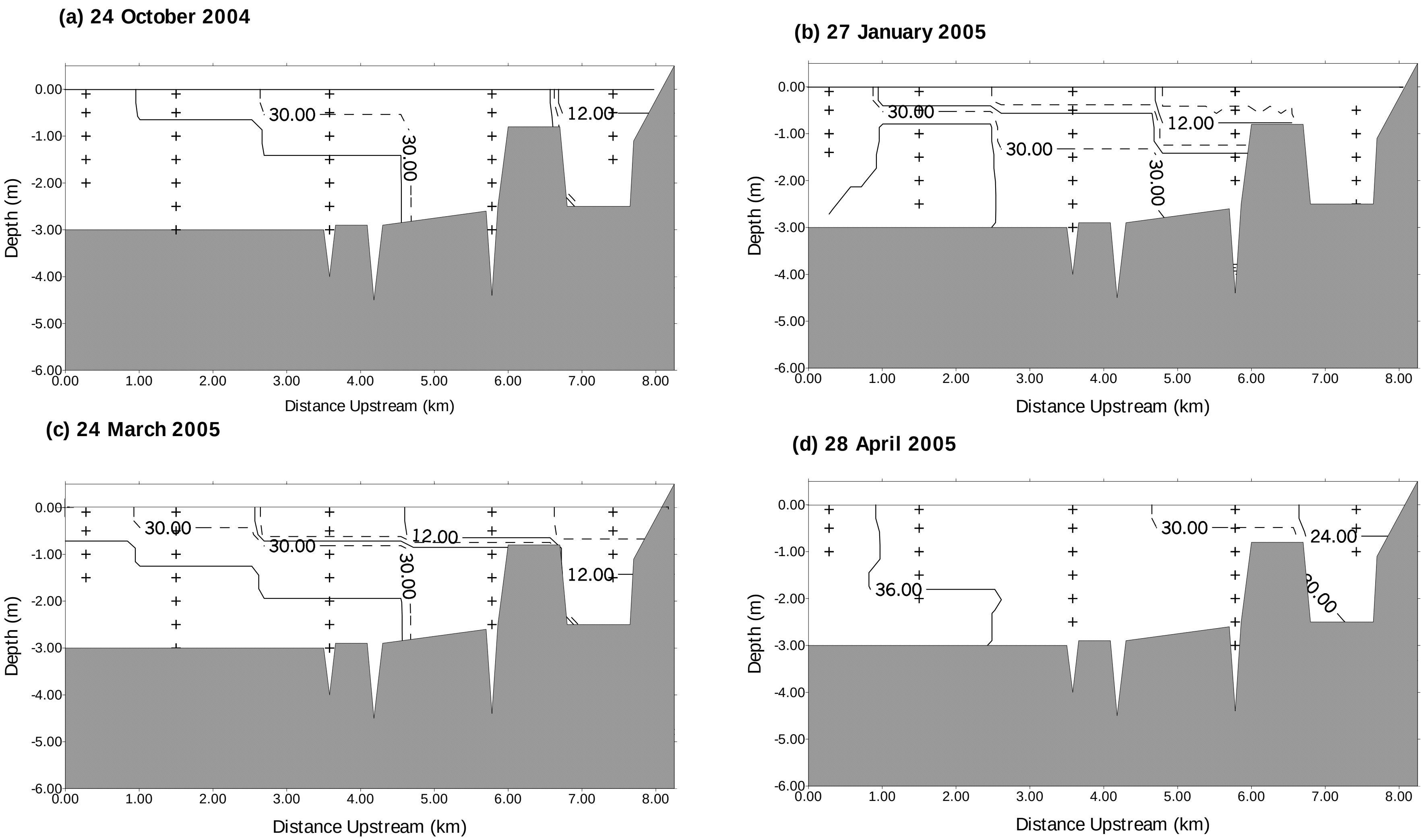


Figure 4: Longitudinal salinity profiles for selected surveys of the Werribee estuary (haloclines at intervals of 6 salinity units)

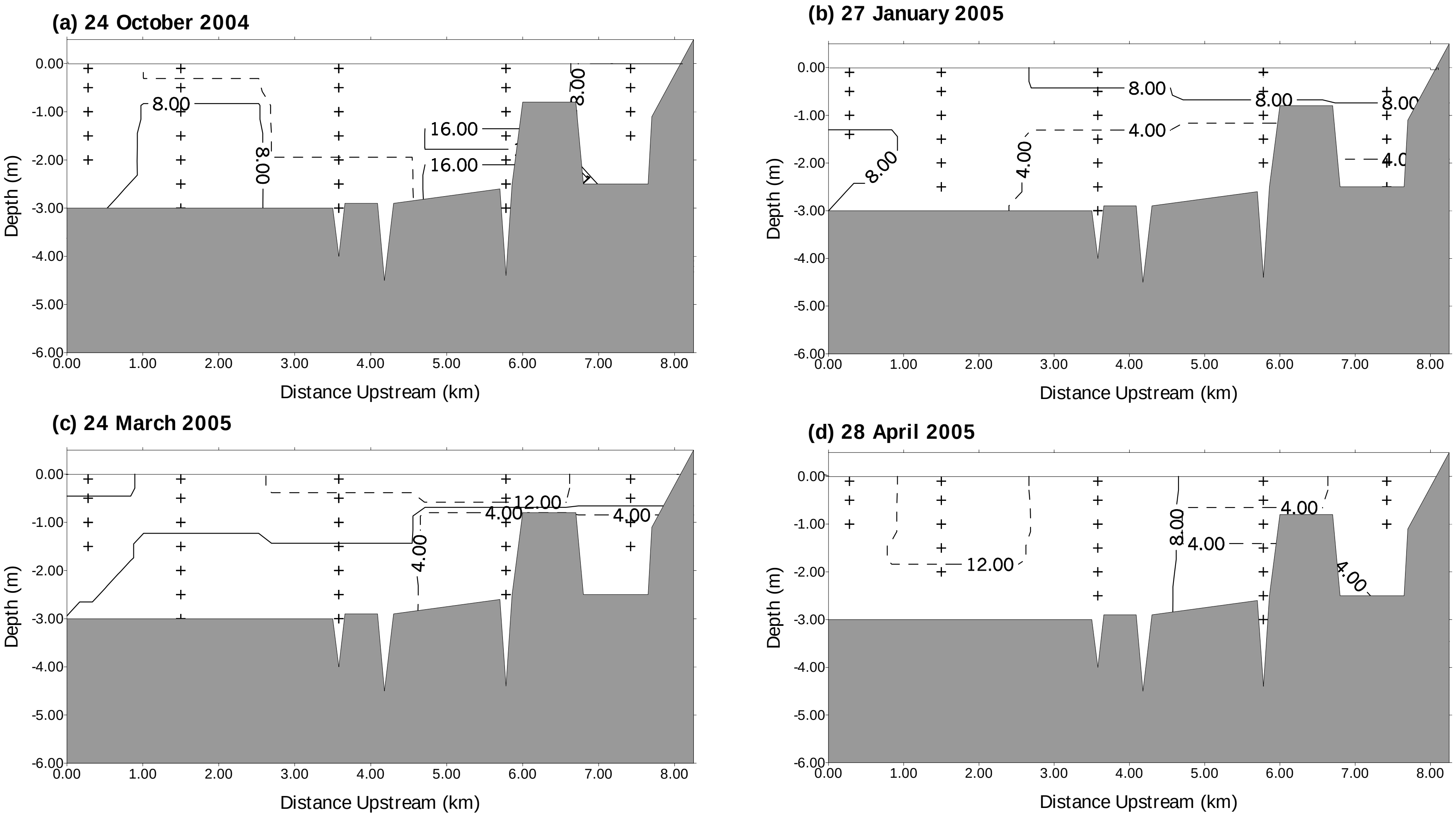


Figure 5: Longitudinal dissolved oxygen profiles for selected surveys of the Werribee estuary (oxyclines at intervals of 4mg/L)

4.3 Algal Community

Algal communities in surface waters were sampled on four occasions during the study, at 2 or 3 sites in the estuary and at the freshwater site (site 6). Cell counts (Table 6) confirmed the very high algal populations suggested by the DO data.

Table 6: Algal populations in surface (0.1m) waters of the Werribee estuary (sites 2, 3, 5) and freshwater reach (site 6).

Date	Site	Algal Count (cells/mL)	Dominant Group(s)
24/09/04	2	73,695	Chlorophyta/cryptophyta
	5	75,495	Chlorophyta
	6	206,420	Chlorophyta/cryptophyta
21/12/04	2	14,230	Bacilloriophyta/chlorophyta
	3	4,755	Bacilloriophyta/chlorophyta
	5	15,855	Chlorophyta/bacilloriophyta
	6	13,675	Chlorophyta/dinophyta
24/03/05	2	16,855 + 8,265*	Chlorophyta/cyanophyta*
	5	17,525	Chlorophyta
	6	24,305 + 2,135*	Chlorophyta/cyanophyta*
29/04/05	2	26,430 + 2605*	Cryptophyta/bacilloriophyta/cyanophyta*
	5	4,500 + 5,710*	Dinophyta/cyanophyta*
	6	9,955 + 425*	Dinophyta/chlorophyta/cyanophyta*
16/05/05	2	2,250	Dinophyta
	5	9,140	Chlorophyta
	6	16,535 + 4,270	Chlorophyta/cyanophyta

* Filaments of the cyanobacteria (*Planktolyngbya*).

Five algal groups dominated the assemblage over the survey period; chlorophyta (green algae), bacilloriophyta (diatoms), dinophyta (dinoflagellates), cryptophyta (cryptophytes) and cyanophyta (blue-green algae).

There is no general agreement on what biomass constitutes an algal "bloom". The term is taken to mean a population sufficient to impair water quality (Cottingham *et al*, 1995). These authors defined a cell count in excess of 2000 cells/mL as constituting a bloom and recommended that monitoring frequency should be increased if algae reach this level. The former NSW Department of Land and Water Conservation adopted 3 Alert Levels for algal blooms in inland waters:

Alert Level 1: 500 –2000 cells/mL
Alert Level 2: 2,000 – 15,000 cells/mL
Alert Level 3: >15,000 cells/mL.

Based on the Victorian criteria , the Werribee estuary and its adjacent freshwater reach have been in almost constant "bloom" over the survey period. If the NSW criteria for inland waters are applied (ie >15,000 cells/mL – see Fairweather and Napier 1998), then bloom conditions existed at one or more of the estuary sites sampled on 4 of the 5 trips.

Some algal groups were either not detected (Crysophyta, Chloromonadophyta) or were present in low numbers (< 100 cells/mL; Euglenophyta). The blue-green algae detected in high populations (*Planktolyngbya*) is not thought to produce toxic exudates (WSL, *pers. comm*.). However, small numbers of *Anabaena circinalis*, known to be potentially toxic, were detected in some samples.

Residence time of water in the estuary is a key determinant of the estuarine algal population. If water exchange is relatively rapid, there is insufficient time for population growth to create "blooms." Tidal exchange is most effective in the lower estuary and DO supersaturation is less commonly observed here as a consequence. The absence of supersaturation in January is probably a function of increased river flows during this trip that effectively flushed algal communities from the estuary. A combination of reduced river flow and long sunny days in late summer and autumn favours algal growth.

4.4 Nutrients

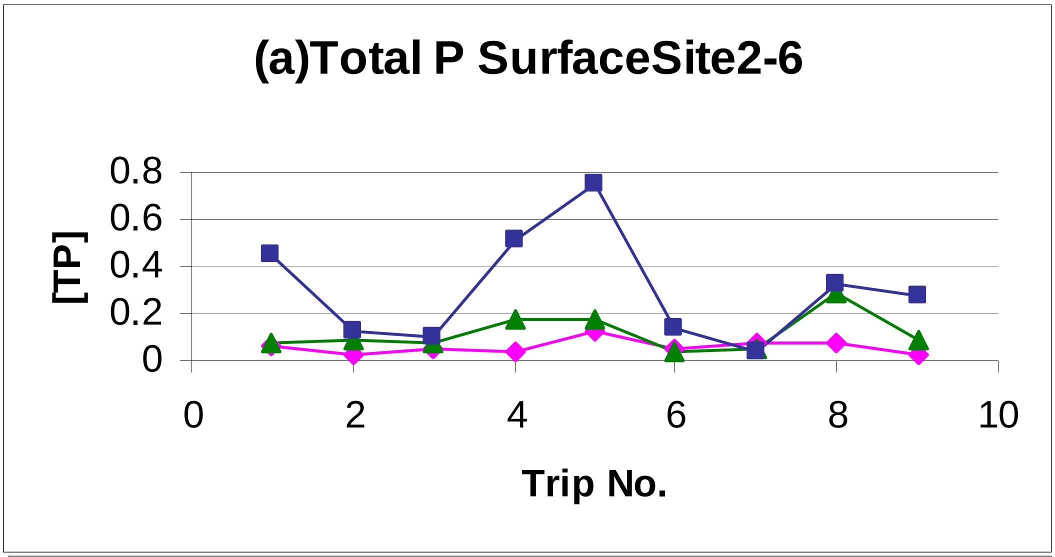
Nutrient samples were collected from surface (0.1m) and near-substrate waters (≥ 1.5m) at two estuarine sites (sites 2 and 5) and the freshwater sites (site 6).

Total phosphorus and soluble reactive phosphorus concentrations were generally highest at site 2 for both surface and deep waters samples over the survey period (Figure 6). Concentration of total nitrogen in surface and deep waters of all sites were generally similar and less than 1.5 mg/L (Figure 7).

Mean nutrient concentrations (Table 7) exceed the upper limit based on SEPP objectives (Werribee River Catchment Nutrient Management Plan) and the ANZECC (1999) default trigger levels for estuaries in south-east Australia (Table 8) by 3 to 15 times. Even the 10^{th} percentiles of pooled estuary sample concentrations exceed the ANZECC trigger values and are similar to the upper limit SEPP values (Table 8). The 10^{th} percentile concentrations for site 6, based on 18 samples, exceeded the default ANZECC trigger values for lowland rivers for nitrogen species (TN < 0.05mg/L; NO_x < 0.04 mg/L) but were below those for phosphorus species (TP <0.05mg/L; SRP <0.02mg/L). These comparisons show that the estuary and adjacent freshwaters are enriched in nutrients. This is probably a key factor contributing to the large algal populations observed.

Table 7: Mean nutrient concentration determined over 9 trips in both estuarine (sites 2, 5) and freshwater (site 6) locations.

Species	Mean Concentration at site (mg/L)					
	2		5		6	
	Surface	Bottom	Surface	Bottom	Surface	Bottom
TN	1.09	0.84	1.41	1.64	1.08	1.55
NOx	0.24	0.13	0.48	0.39	0.41	0.23
TP	0.30	0.31	0.12	0.23	0.06	0.12
SRP	0.22	0.17	0.06	0.18	0.02	0.04



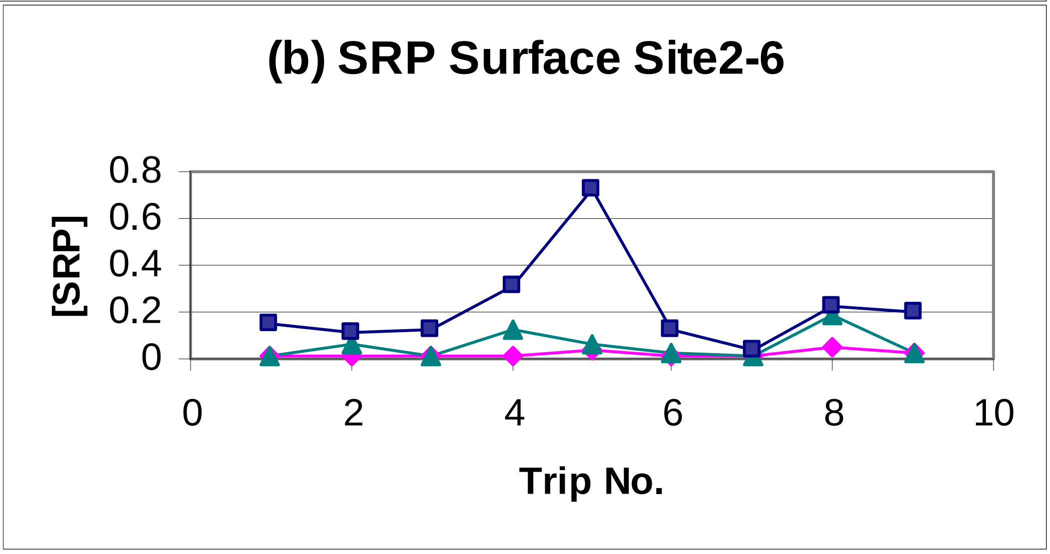


Figure 6: Temporal variation in phosphorus species (Trip No.1 was in September 2004, subsequent trips are monthly).

Key: site 2 – blue squares; site 5 – green triangles; site 6 – pink diamonds

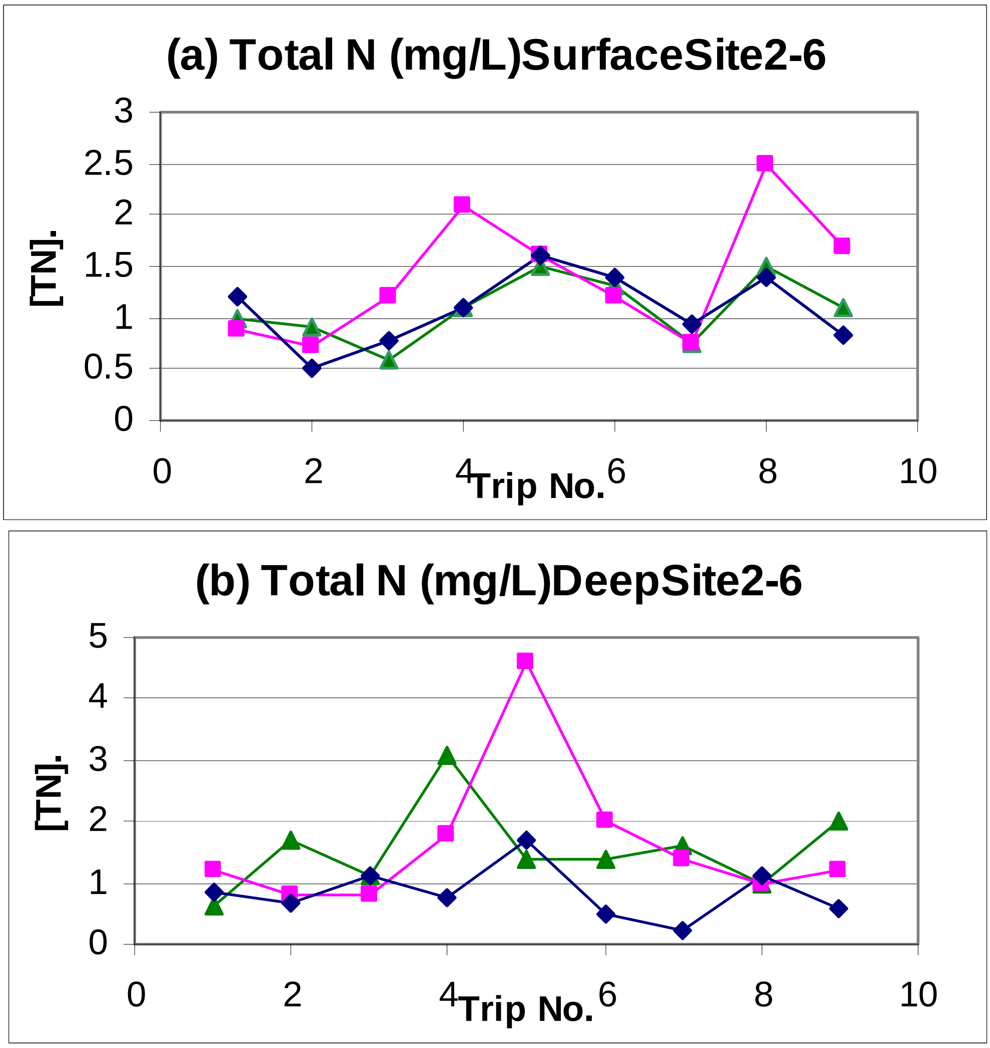


Figure 7: Temporal variation of total nitrogen at surface and deep sites (Trip No.1 was in September 2004, subsequent trips are monthly).

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Key: site 2 – blue diamonds; site 5 – pink squares; site 6 – green triangles

Table 8: Comparison of upper limit values based on SEPP objectives and ANZECC Trigger Levels to the 10th and 50th percentiles of Werribee estuary nutrient concentrations. (N = 37 samples).

Criterion	Nutrient Concentration (mg/L)			
	TN	**NOx**	**TP**	**SRP**
SEPP objectives	0.6	-	0.05	-
ANZECC Trigger Level	0.3	0.015	0.03	0.005
Werribee Estuary 10th Percentile*	0.59	0.04	0.05	0.02
Werribee Estuary 50th Percentile+	1.1	0.26	0.17	0.07

Highest nutrient concentrations were found on the December, January and February fieldtrips (Trips 4 –6; Figures 6,7). The reason for this is not clear for the December and February trips but the January maxima is related to a large rainfall event on the night before sampling. Geelong recorded 100 mm of rainfall on 27 January and highly turbid runoff draining from the market gardens on the eastern shore was observed running directly into the estuary. No flood peak associated with this rainfall was recorded at the Werribee Weir indicating the rainfall was not widespread in the catchment. Very high flow was recorded at the weir after 1 February when another rain event led to a major flood (maximum discharge on 3 February = 9,256 ML/day).

Table 9: Nutrient concentrations for additional surface samples taken on 27 January 2005 after heavy rainfall.

Sample	TN (mg/L)	NOx (mg/L)	TP (mg/L)	SRP (mg/L)
In Drain 5 m upstream of estuary	53	5.6	7.3	0.46
In Estuary 15 m from drain outlet	30	5.0	5.1	1.9
Estuary at site WR01	4.6	2.3	0.64	0.66
Estuary at entrance to PPB	3	1.6	0.42	0.39

After the rainfall event on January 27, one of the strongly flowing drains was sampled for nutrients and several nearby areas affected by the plume of highly turbid water discharging from the drain were also sampled (Table 9). Discharge from the drain at 1500 hrs was measured using a flow meter at 5.2 ML/day. This flow was estimated to be about half that observed at 0900 hours on the same day, and there was evidence that the drain had peaked at a higher discharge overnight. If a conservative mean flow of 5 ML/d over the period of observed discharge from the drain is assumed, then

256 kg/d of TN and 37 kg/d of TP are estimated to be entering the estuary from this single drain alone. At least four similar drains were observed to be discharging highly turbid water into the estuary further upstream, suggesting that upwards of 1000 kg/d of TN and 145 kg/d of TP was entering the estuary from these drains during and after the rainfall event. The impact of this nutrient enriched runoff was widespread, with elevated nutrient levels recorded at the estuary entrance and a plume of turbid water extending into Port Phillip Bay at least 1 km along the eastern shoreline at Werribee South.

4.5 Fish

A total of 25 species were collected during the two fish sampling trips (Tables 10 and 11). Of these, 18 species were marine or estuarine species and seven were freshwater species or diadromous species that spend significant periods of their life histories in freshwater. A search of the DSE Aquatic Fauna Database found that a total of 43 species had been recorded previously from the Werribee River catchment, including 22 marine or estuary species and 21 freshwater or diadromous species (Table 12). Seven records of species in the current study were new records for the catchment: Half bridled goby, King George Whiting, Lagoon goby, Smooth toadfish, Snapper, Soldierfish, Southern Fiddler Ray.

None of the species collected are considered threatened in Victoria, but several species with high recreational and commercial fishing value were collected, including Black bream, King George whiting and Snapper. All three of these species were collected as juveniles in the estuary, suggesting that the estuary acts as a nursery habitat for these species. Large numbers of very small Black bream (down to 16 mm fork length) were collected on both sampling trips, showing that spawning and juvenile recruitment had occurred in the estuary during the study period (Figure 8). Although the threatened Australian grayling has not been recorded from the Werribee catchment, it is present in nearby catchments, and is likely to occur or have previously occurred in the system, and needs access to the estuary for completion of its life cycle (Cadwallader and Backhouse, 1983).

Table 10: Numbers of fish measured using each method from the four sites sampled during fish surveys conducted from 14-16 December 2004.
Introduced species.

Common Name	**Species Name**	**Lower Site**		**Mid Site**		**Upper Site**		**Freshwater**
		Fyke	**Seine**	**Fyke**	**Seine**	**Fyke**	**Seine**	**E/F**
Australian Smelt	*Retropinna semoni*		3				6	
Australian Salmon	*Arripis trutta*		2					
Black Bream	*Acanthopagrus butcheri*		3	4		1	5	
Blue Spot Goby	*Pseudogobius sp.9*		13		5		32	
Bridled Goby	*Arenigobius bifrenatus*		17				1	
Common Carp#	*Cyprinus carpio*							4
Flatheaded Gudgeon	*Philypnodon grandiceps*							1
Glass Goby	*Gobiopterus semivestitus*				19			
Green Back Flounder	*Rhombosolea tuprinia*		8					
King George Whiting	*Sillaginodes punctata*		8					
Lagoon Goby	*Tasmanogobius lasti*				4			
Luderick	*Girella tricuspidata*			2				
Redfin perch#	*Perca fluviatilis*							3
Short Finned Eel	*Anquilla australis*	8		3		1		3
Smooth Toadfish	*Tetractenos glaber*	1	2	2				
Snapper	*Pagrus auratus*		1					
Soldierfish	*Gymnapistas marmoratus*		5					
Southern Fiddler Stingray	*Trygonorrhina guanerius*			1				
Tamar Goby	*Afurcagobius tamarensis*		17					
Yelloweye Mullet	*Aldrichetta forsteri*		25					
Yellowfin Goby#	*Acanthogobius flavimanus*			4				

Table 11: Numbers of fish collected using each method from the four sites sampled during fish surveys conducted from 27-28 April 2005. # Introduced species.

Common Name	Species Name	Lower Site		Mid Site		Upper Site	Freshwater		
		Fyke	Seine	Fyke	Seine	Fyke	Fyke	Bait Traps	Mesh net
Black Bream	*Acanthopagrus butcheri*	2	65	16	20	15			
Blue Spot Goby	*Pseudogobius sp.9*		12						
Bridled Goby	*Arenigobius bifrenatus*		51		32				
Common Galaxias	*Galaxias maculatus*							1	2
Flatheaded Gudgeon	*Philypnodon grandiceps*		3				1	37	
Glass Goby	*Gobiopterus semivestitus*		23						
Green Back Flounder	*Rhombosolea tuprinia*			1					
Half Bridled Goby	*Arenigobius frenatus*		2						
King George Whiting	*Sillaginodas punctata*		4						
Lagoon Goby	*Tasmanogobius lasti*		2						
Luderick	*Girella tricuspidata*								
Prickly Toadfish	*Contusus brevicaudatus*		1						
Redfin perch#	*Perca fluviatilis*						3		11
Short Finned Eel	*Anquilla australis*						23		
Smooth Toadfish	*Tetractenos glaber*	1	2	1	3	2			
Soldierfish	*Gymnapistas marmoratus*		21		2				
Tamar River Goby	*Afurcagobius tamarensis*		24						
Tupong	*Pseudaphritis urvillii*						1		
Yelloweye Mullet	*Aldrichetta forsteri*	1	2		30	1			
Yellowfin Goby#	*Acanthogobius flavimanus*		3						

Table12: Species recorded previously from the Werribee River catchment.

Introduced species. * Non-endemic native species. Source: DSE Aquatic Fauna Database.

Marine/Estuarine		**Freshwater/Diadromous**	
Common name	**Scientific name**	**Scientific name**	**Common name**
Australian anchovy	*Engraulis australis*	Australian smelt	*Retropinna semoni*
Australian salmon	*Arripis trutta*	Brown trout#	*Salmo trutta*
Black bream	*Acanthopagrus butcheri*	Chinook salmon#	*Oncorhynchus tshawytscha*
Blue sprat	*Spratelloides robustus*	Common carp#	*Cyprinus carpio*
Bluespot goby	*Pseudogobius olorum*	Common galaxias	*Galaxias maculatus*
Bridled goby	*Arenigobius bifrenatus*	Estuary perch	*Macquaria colonorum*
Eastern blue spot flathead	*Platycephalus fuscus*	Flatheaded gudgeon	*Philypnodon grandiceps*
Glass goby	*Gobiopterus semivestitus*	Freshwater herring	*Potamalosa richmondia*
Greenback flounder	*Rhombosolea tapirina*	Gambusia#	*Gambusia holbrooki*
Longfin goby	*Favonigobius lateralis*	Goldfish#	*Carassius auratus*
Luderick	*Girella tricuspidata*	Macquarie perch*	*Macquaria australasica*
Pikehead hardyhead	*Kestratherina esox*	Mountain galaxias	*Galaxias olidus*
Pilchard	*Sardinops neopilchardus*	Poached lamprey	*Geotria australis*
Prickly toadfish	*Contusus brevicaudas*	Redfin perch#	*Perca fluviatilis*
Sandy sprat	*Hyperlophus vittatus*	River blackfish	*Gadopsis marmoratus*
Sea mullet	*Mugil cephalus*	Roach#	*Rutilus rutilus*
Silver fish	*Leptatherina presbyteroides*	Short finned eel	*Anguilla australis*
Smallmouth hardyhead	*Atherinosoma microstoma*	Short headed lamprey	*Mordacia mordax*
Tamar River goby	*Afurcagobius tamarensis*	Southern pygmy perch	*Nannoperca australis*
White trevally	*Pseudocaranx dentex*	Tench#	*Tinca tinca*
Yelloweye mullet	*Aldrichetta forsteri*	Tupong	*Pseudaphritis urvillii*
Yellowfin goby#	*Acanthogobius flavimanus*		

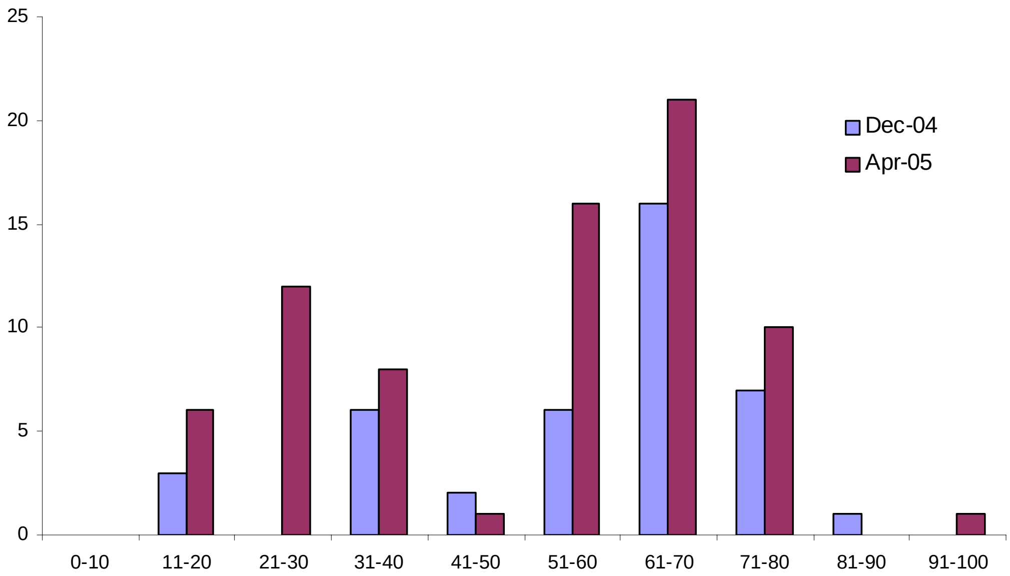

Figure 8: Length frequency plot showing the relative abundance of different sizes of black bream in the December 2004 and April 2005 surveys (only fish <100 mm TL are included in the graph).

4.6 pH, Turbidity and Chlorophyll-a Concentrations

The physico-chemical parameters of pH, turbidity and chlorophyll-a provided little useful information for the study objectives. Their values are included in the Appendices and briefly described in this section.

pH values for estuarine and freshwaters were predominantly in a range typical of natural waters (7 – 8.5). Higher values (> 8.5), probably linked to photosynthetic activity, were observed at site 6 on five trips. Three of these were during the calm sunny conditions of late summer and autumn (Appendix 1).

Water clarity was also high. Turbidity values rarely exceeded 20 NTU with the maximum value (37 NTU) being measured in January during a period of increased run-off (Appendix 1). The concentration of suspended solids increases in flood waters and this raises turbidity. The low turbidities at other times indicate the light climate was typically favourable for algal photosynthesis over the survey period. Low freshwater flows, particularly the absence of floods, would result in low suspended solid concentrations in inflowing freshwater. High algal populations would contribute to turbidity.

Chlorophyll-a concentrations were generally below the detection limit of the method used (0.01mg/L; Appendix 3). Concentrations were not well correlated with algal cell counts, partly because of the small size of some of the dominant algal species (WSL, *pers. comm.*). Because of this cell counts were regarded as a more reliable indicator of algal abundance than chlorophyll-a concentration.

5. Flow Related Issues in the Estuary

5.1 Disruption of the Estuarine Hydrodynamic Cycle

Mean monthly discharge of the Werribee River at the Lower Werribee Diversion Weir (Station 231204, Figure 9) is shown in Figure 10. The mean annual seasonality of flow is characteristic of western Victoria's Mediterranean climate. The late winter/early spring maximum (~400ML/day) coincides with the maximum difference between mean monthly rainfall and mean monthly evaporation. Discharge is highly variable from year to year (Table 13). Between 1982 and the present, low flows have been recorded in any month of the year (Table 13). The criteria in Table 13 correspond to flows of ~3, ~6 and ~20 ML/day compared to the mean flows shown in Figure 10 (minimum mean flow [May] = 24.1 ML/day).

The marked seasonal inequality in discharge results in an annual hydrodynamic cycle typical of western Victoria's estuaries. During winter and spring, high flows may flush all salt water from the estuary, which becomes an extension of the freshwater section of the river for periods up to several weeks (Figure 11). As flows recede through spring and summer, salt water reinvades the estuary in the form of a highly stratified salt wedge. As flow decreases the length of the wedge increases. Re-entry of well-oxygenated saline water into the estuary appears to be a trigger for breeding in many estuarine organisms, from zooplankton to fish (Newton 1996; Nicholson *et al*, 2004). During summer and autumn, salt water penetrates to its maximum extent and estuarine circulation is reduced. This can lead to extended periods of anoxia or hypoxia in deeper water of the estuary. The aerobic community is then confined to the surface water layer under these conditions – a layer found to be less than 1m thick in some estuaries (Sherwood and Rouse, 1997; Rouse, 1988). Spawning success in some species with floating eggs and/or larval life stages may be compromised by the presence of anoxic saline waters containing high concentrations of toxic substances such as hydrogen sulphide (H_2S) and ammonia (NH_3). The black bream (*Acanthopagrus butcherii*) for example has eggs which float in the halocline as they are neutrally buoyant in water of salinity 16-20 (Nicholson *et al* 2004; Sherwood and Backhouse 1982).

Two important features of the annual hydrodynamic cycle are relevant to the consideration of environmental flows:

(a) Winter flows sufficient to flush salt water in the wedge from the estuary. This bottom water, emplaced during the preceding summer/autumn, may be anoxic or hypoxic and reduces the volume of water having both adequate dissolved oxygen for respiration and optimal salinity for breeding of estuarine organisms.

(b) Summer/autumn low flows sufficient to maintain estuarine circulation. Turbulent entertainment of bottom salt water (either generated by wind, river flow or tidal forcing) into surface waters, and the subsequent transport of this from the estuary, allows replacement of bottom water. This reduces the incidence and longitudinal extent of hypoxic/anoxic conditions. In the Werribee estuary, tidal exchange is an efficient mechanism for water replacement in the lower estuary

(<~4km). Upstream of the cobble reef it has reduced effectiveness. In contrast, freshwater surface flows are most effective in this region of the estuary.

(a)

(b)

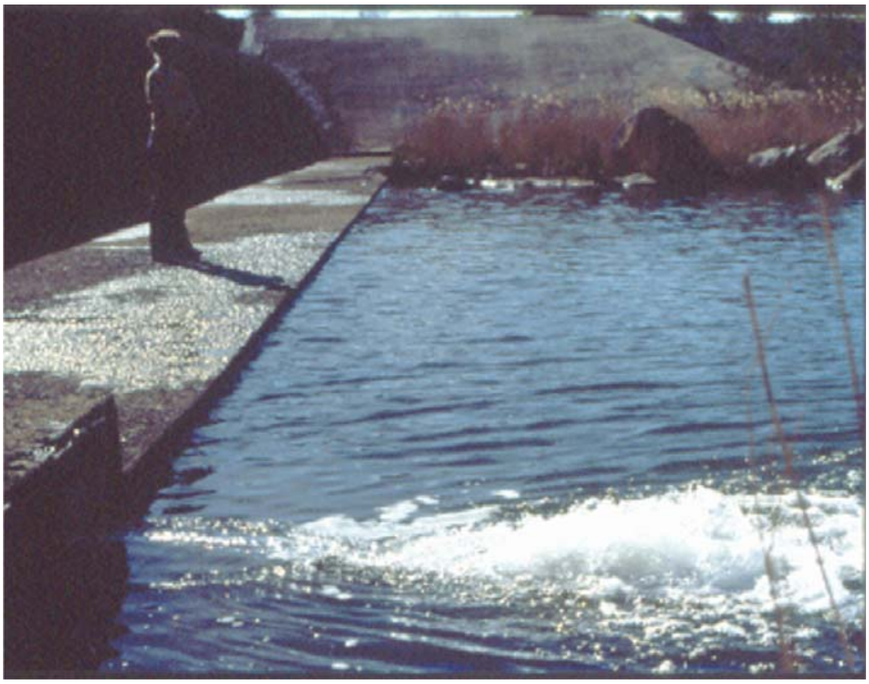

Figure 9: Lower Werribee Diversion Weir:

(a) looking downstream from the top of the weir, (b) flow downstream issuing from a small pipe in the base of the weir. This is the only flow at all times the weir is not overflowing (ie when discharge is recorded as zero).

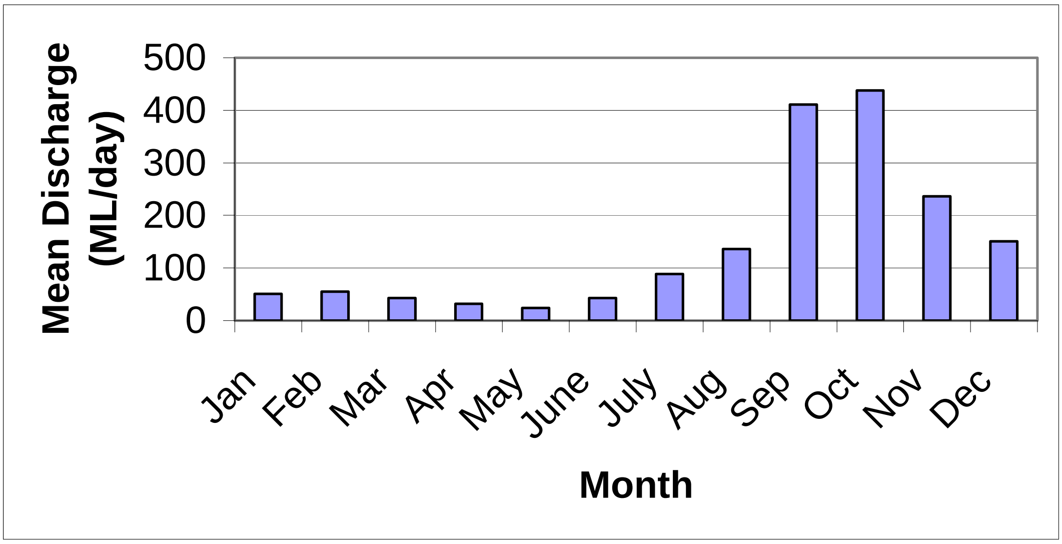

Figure 10: Mean daily discharge for each month for the Werribee River downstream of the Lower Werribee Diversion Weir (based on data from April 1983 to July 2004)

Table 13: Incidence of low flows at the Lower Werribee Diversion Weir between April 1982 and April 2005.(N = 23 years)

Criterion	**Monthly Incidence (April 1982 – April 2005)**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Q<100ML	3	1	4	5	9	7	7	1	1	1	1	1
Q<200ML	4	3	5	8	10	12	11	3	3	2	1	1
Q<600ML	9	13	11	16	18	18	15	12	10	6	6	6

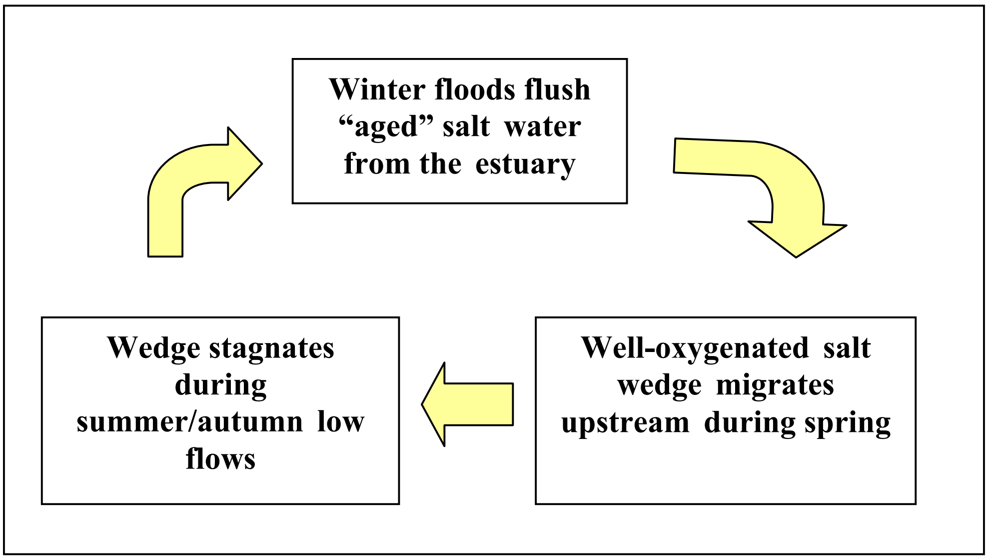

Figure 11: Annual hydrodynamic cycle of west Victorian estuaries (Sherwood, 1985).

5.2 Residence Time of Water in the Estuary

The width of the Werribee estuary reduces in an approximately linear relationship with distance upstream (Table 1; Figure 12).

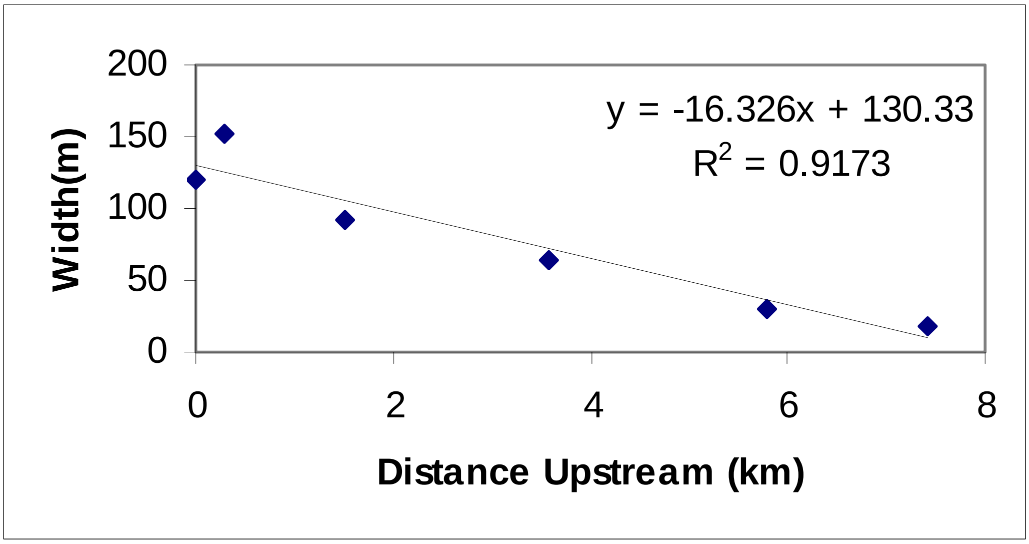

Figure 12: Variation of estuary width with distance upstream.

From this relationship and assuming an effective (navigable) estuary length of 7.5km the surface area is estimated to be:

Surface Area = $5.2 \times 10^5 m^2$

Further, assuming a mean depth at low water of 1.5m (Figure 3) the estuary volume is:

Volume = $7.8 \times 10^5 m^3$ (780 ML)

The tidal prism (volume of water exchanged during a tidal cycle) can also be estimated from the surface area and tidal range. Assuming a mean tide range of 0.5 m gives:

Mean Tidal Prism = $2.6 \times 10^5 m^3$ (260 ML)

The maximum (Spring tide) tidal range is approximately 1m and so the maximum tidal prism may be twice the mean.

These estimates of volume demonstrate the significant effect of tidal circulation on exchange of water in the estuary. This is particularly effective in the lower estuary (<4km). Mean residence time of water in the lower estuary is estimated to be two to three days even under low flow conditions because of the relatively large proportion of water exchanged during each tide.

In the upper estuary tidal exchange still operates but its effectiveness is reduced by the cobble reef, extending to just below low water level. The reef exerts important hydraulic control of exchange between the estuary's upper and lower basins. Surface water downstream of the reef cascades over it on a flood tide and its greater density results in it sinking beneath the fresher surface water of the upper basin. The turbulence generated by this process can lower the salinity of the intruding salt water. Figure 13 shows the correlation between surface salinity at site 4 and bottom salinity at site 5.

The volume of the upper basin is estimated to be 38 ML (assuming an average width of 25m, a length of 1 km and a mean depth of 1.5 m). This represents about 5% of the total estuary volume. The tidal prism in this section is approximately one third of this volume if a tidal range of 0.5m is assumed. Thus, flushing of deep water in the upper basin should result in complete water exchange every 3 days or so. Field measurements show this rate of exchange is not sufficient to prevent hypoxic conditions (DO < 5 mg/L) in upper basin water, particularly during late summer and autumn. During the 28th April survey, when the lowest salinity measured at site 5 was 20 , virtually the entire water column at sites 4 and 5 was hypoxic. This would place considerable stress on aerobic organisms in this section of the estuary.

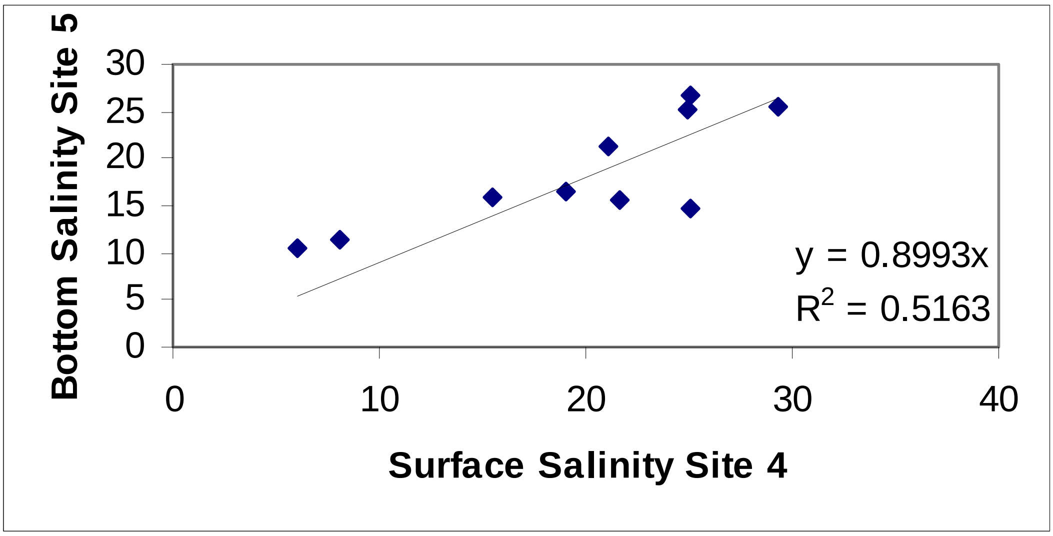

Figure 13: Relationship of surface salinity at Site 4 to deep water salinity at Site 5

Increased freshwater flows may increase flushing efficiency by generating stronger surface water flows during ebb (outflowing) tides. They may also provide better oxygenated surface water habitat for organisms in the upper estuary. During the present survey river flow preceding surveys was generally negligible (Table 14). The lowest surface salinities at site 5 were associated with either higher flow periods (22nd November, 24th March) or surface runoff during an intense rainfall event (27th January).

The effects of freshwater inflows were not detected at site 4 on 20th August or 22nd November, despite significant river discharge in the previous week. This suggests that mixing of fresh surface water with marine waters is effective in the upper estuary and that "pooling" of freshwater doesn't occur.

Table 14: Influence of river discharge on surface salinity at Sites 4 and 5 in the Werribee Estuary.

Trip	Total Discharge (ML)		Surface Salinity (0.1m)	
	1 day*	7 days*	Site 4	Site 5
1. 20th Aug 04	9.52	164	26.7	ND
2. 24th Sep 04	0	0	21.0	12.7
3. 24th Oct 04	0	1.96	24.3	6.3
4. 22nd Nov 04	0.3	47.1	19.9	2.2
5. 21st Dec 04	0	0	18.9	5.3
6. 27th Jan 05	0	0.3	5.9	1.2
7. 28th Feb 05	17.0	0	14.8	6.1
8. 24th Mar 05	0.3	89	8.0	2.3
9. 25th Apr 05	0	26.2	24.5	9.3
10. 28th Apr 05	0	0	27.5	20.0
11. 16th May 05	ND	ND+	24.3	6.0

* days before field trip.
\+ ND = No data.

5.3 Algal Community Dynamics.

The presence of a consistently high phytoplankton population in the estuary poses a risk to ecosystem health in two ways:-

(i) possible reduction in dissolved oxygen concentrations

(ii) blooms of potentially toxic blue-green algae.

High phytoplankton populations result in accelerated rates of oxygen production by photosynthesis during daylight hours. The rate of production exceeds the rates at which oxygen is either consumed by respiration or escapes back into the atmosphere. Water becomes “supersaturated” in dissolved oxygen (Table 4). Overnight however, in the absence of photosynthesis, dissolved oxygen concentrations decrease. In extreme situations, high overnight respiration rates by phytoplankton and other organism may reduce oxygen concentrations to levels too low to support aerobic organisms. Mass mortality of organisms unable to move out of the oxygen depleted region may occur (eg. “fish kills”). This situation may be exacerbated by bacterial remineralisation of organic matter resulting from the death of phytoplankton and other organisms. This bacterial oxygen demand increases as a result of phytoplankton blooms, placing an increased loading on dissolved oxygen concentrations.

Estuarine phytoplankton communities are characterised by a succession of dominant species (Rouse, 1988; Maher, 2001). The species assemblage changes in response to changes in physico-chemical parameters such as water temperature, salinity, turbidity or daylight hours and biological factors such as predation by zooplankton. If conditions favourable to toxin producing algae lead to a bloom in these species there could be significant impacts on both the estuarine ecosystem and its human amenity (Maher, 2001). A variety of potentially toxic algae have been detected in the estuary:

(i) Cyanobacteria
- *Oscillatoria* sp.
- *Planktothrix* sp.
- *Anabaena circinalis*

(ii) Dinophyta
- *Prorocentrum minimum*
- *Dinophisis acuminata*
- *Scrippsiella c.f. trochoidea*

While it is not possible to predict when particular algal species may bloom, physico-chemical conditions generally favourable to algal growth include:

- Long daylight hours
- Still water (i.e. no flow or low flows)
- High nutrient concentrations
- Low water turbidity.

Of these, the two factors potentially able to be manipulated in the Werribee estuary are the flow conditions and nutrient concentrations. Increasing flow reduces the residence time of algae in the estuary and enhanced turbulence reduces the time individual phytoplankton cells are in optimal light conditions (i.e. near the surface). Turbid waters may also act to lower light penetration. The effect of such a change is evident in the dissolved oxygen profile for the 27th January survey. Increased run-off during an intense storm (100mm of rainfall recorded at Geelong on this day) reduced the rate of photosynthetic activity so that no supersaturated DO concentrations were detected in the estuary.

Tidal processes appear to offer an effective mechanism to exchange water in the estuary. The results of the study show that the rate of tidal exchange, however, is insufficient to prevent algal blooms. Increased river discharges are required to provide an additional mechanism to accelerate flushing of algal cells from the estuary to avoid potentially toxic algal blooms.

6. Flow-related Environmental Risks

6.1 Flow Related Risks to Ecological Health of the Estuary

A detailed analysis of the effects of flow regulation on the hydrology of the lower Werribee River and its tributaries was conducted recently by Ecological Associates (2005). These effects include large reductions in median annual and daily discharge, reduced frequency of flood events, and increased frequency of low flow periods compared to modelled natural flows (Table 15).

The current study shows that the Werribee estuary currently has a number of undesirable characteristics related to these effects of flow regulation that pose serious threats to the health of the ecosystem:

(i) The estuary was almost constantly in a low-flow condition during the study period. The winter-spring discharge maximum did not occur in 2004 leading to an extended period of strongly marine water in the estuary. Truly estuarine conditions (salinity $< \sim 30$) were confined to a small region in the upper estuary (Figure 4).

(ii) The estuary was highly eutrophic, with concentrations of nutrient species exceeding upper limits based on SEPP objectives and the ANZECC default trigger levels by up to an order of magnitude.

(iii) Algal communities were consistently high in response to the combination of low flows and elevated nutrient concentrations. Blooms of algae resulted in excessive rates of photosynthesis leading to dissolved oxygen concentrations above saturation (equilibrium) values during survey times (approximately mid-morning to mid-afternoon).

There are a number of related risks to ecological functions as a result of these characteristics:

a) Disruption of the estuary's hydrodynamic cycle is likely to negatively affect the breeding activity and survival of estuarine species of fauna and flora adapted to the natural regime.

b) Increased incidence of hypoxic/anoxic conditions in the estuary as a result of both reduced circulation, increased organic loading of bottom waters and potential overnight oxygen depletion ("oxygen sag") may have negative effects on the aquatic fauna of the estuary. For example, anoxic conditions are uninhabitable for fish and will either result in fish deaths or reduce the amount of suitable habitat available.

c) There is a relatively high likelihood that blooms of toxic cyanobacteria (blue-green algae) will occur under the present eutrophic conditions. If this happens, it may result in closure of the estuary to human activity and mass mortality of estuarine organisms due to toxicity and/or oxygen depletion.

Table 15: Summary of the impacts of flow regulation on the hydrology of the Werribee River and its tributaries (reproduced from Ecological Associates 2005).

Hydrological Index	**Werribee River**				**Tributaries**		
	D/S Upper Werribee Diversion Weir	**Bacchus Marsh**	**D/S Toolern Ck**	**Werribee**	**Pykes Ck**	**Coimadai Ck**	**Djerriwarrh Ck**
Annual discharge	-17%	-27%	-25%	-42%	No data	-38%	-83%
Median daily discharge	-30%	-59%	+29%	-80%	No data	Zero in both cases	Zero in both cases
Flow duration curves	Reduced full-range	Reduced full-range	Increased low range	Reduced full-range	No data	Severely reduced low range	Severely reduced full-range
Seasonal distribution – median flows	Reduced all months, esp. Jun to Sep	Reduced Winter-Spring, increased Sum-Autumn	Seasonal flow reversal	Reduced Winter-Spring, increased Sum-Autumn	Seasonal flow reversal	NA	NA
Seasonal distribution – cease-to-flow duration	No impact	Less common Summer, More common late Autumn	No change – never occurred naturally	Minimal change – never occurred naturally	Not common currently	Less common Summer and Autumn	Increased all months especially Winter
Cease to flow spells	No impact	Reduced duration	No change – never occurred naturally	Minimal change – never occurred naturally	Currently low frequency and duration	Reduced frequency, Much increased duration	Much reduced frequency, Much increased duration
Flow events ≤1 ML/d spells	Reduced duration	Much reduced frequency, Much increased duration	Increased frequency, Much reduced duration	Increased frequency, Reduced duration	Currently high frequency and very low duration	Reduced frequency; Much increased duration	Much reduced frequency, Much increased duration
Flood magnitude - partial series	Up to 30% reduction (for 0.5 yr ARI) - floods <1 yr ARI affected	Up to 50% reduction (for 0.5 yr ARI) - floods <2 yr ARI affected	Up to 52% reduction (for 0.5 yr ARI) - floods <5 yr ARI affected	Up to 54% reduction (for 0.5 yr ARI) - full range affected	No data	Major reduction across range, but less so near 0.6 yr ARI	Up to 99% reduction (for 0.5 yr ARI) - full range affected
Event max. rates of rise	Increased	Increased	Increased	Increased	Not analysed	Decreased	Increased
Event max. rates of fall; recession duration	Increased max. rate of fall	Increased max. rate of fall	Increased max. rate of fall	Increased max. rate of fall	Not analysed	Increased max. rate of fall; recession duration shorter	No significant change in max. rate of fall or recession duration

Pierson *et al* (2002) reviewed ecological, geomorphic, hydrological and water quality impacts of freshwater flow on estuaries and identified 16 major flow-related processes which impact on estuarine environments (Table 16). The impacts have been categorised according to the relative flow magnitude for which their effects are most noticeable. Not all of these will be significant for all estuaries. The likelihood of each of the flow-related processes affecting the Werribee estuary is summarised below:

Table 16: Major ecological processes by which reduced estuary flows can impact on estuarine ecosystems (reproduced from Pierson *et al*., 2002).

Relative River Inflow	**Process**	
	No.	**Nature**
Low	1	Increased incidence of hostile water quality conditions at depth
	2	Extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive fauna
	3	Extended durations of elevated salinity in the upper-middle estuary adversely affecting sensitive flora
	4	Extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota
	5	Extended periods when flow-induced currents cannot suspend eggs or larvae
	6	Extended periods when flow-induced currents cannot transport eggs or larvae
	7	Aggravation of pollution problems
	8	Reduced longitudinal connectivity with upstream river systems
Middle-High	9	Diminished frequency of flushing of the estuary bed of fine sediments and organic matter – reducing the quality of physical habitat
	10	Diminished frequency of flushing of organic matter from deep sections of the estuary – reducing water quality
	11	Reduced channel maintenance processes
	12	Reduced inputs of nutrients and organic material
	13	Reduced lateral connectivity and reduced maintenance of ecological processes in water bodies adjacent to the estuary
All	14	Altered variability in salinity structure
	15	Dissipated salinity/chemical gradients used for animal navigation and transport
	16	Decreases in the availability of critical physical habitat features, particularly those components associated with higher velocities

(a) Low Flow Conditions.

Process 1. Increased incidence of hostile water conditions of depth.

Hypoxic conditions have been observed in deep water and in the upper reaches of the estuary.

Likelihood: HIGH

Process 2 and 3. Extended durations of elevated salinity in the upper – middle estuary adversely affecting sensitive flora and fauna.

Low salinity water had a very limited extent in the Werribee estuary during the survey period.

Likelihood: HIGH

Process 4. Extended durations of elevated salinity in the lower estuary allowing the invasion of marine biota.

Strongly marine conditions (salinity >30) extend well up the estuary to Site 4 and beyond.

Likelihood: HIGH

Process 5 and 6. Extended periods when flow-induced currents cannot suspend or transport eggs and larvae.

Tidal circulation appears effective and low river flow is unlikely to substantially increase water currents. Freshwater flow does however establish a marked halocline important for buoyancy control mechanism for eggs and larvae of some species.

Likelihood: MODERATE – HIGH

Process 7. Aggravation of pollution problems.

River flow may improve flushing of pollutants from the estuary, but river water quality is not high. For example it may not constitute a diluting flow for nutrients.

Likelihood: LOW

Process 8. Reduced longitudinal connectivity with upstream river systems.

Flow impeding structures at the bluestone ford and Lower Werribee Diversion Weir offer major impediments to migration of organisms such as fish between the estuary and the river. A reduction in river flow is a minor factor in comparison to these.

Likelihood: LOW

(b) Middle-High Flow Conditions.

Process 9. Diminished frequency of flushing of the estuary bed of fine sediments and organic matter – reducing the quality of physical habitat.

Large floods still occur in the Werribee River. The significance of any reduction in frequency or extent is not known.

Likelihood: UNKNOWN

Process 10. Diminished frequency of flushing of organic matter from deep sections of the estuary – reducing water quality.

Tidal flushing is effective in the estuary.

Likelihood: LOW

Process 11. Reduced channel maintenance processes.

Given the continued occurrence of high flows in the Werribee River the significance of this factor is unknown.

Likelihood: UNKNOWN

Process 12. Reduced inputs of nutrients and organic material.

The estuary is eutrophic – there is no evidence for a shortage of nutrients or organic material.

Likelihood: LOW

Process 13. Reduced lateral connectivity and reduced maintenance of ecological processes in water bodies adjacent to the estuary.
There are no water bodies connected to the estuary.

Likelihood: NOT RELEVANT

(c) All Flow Conditions.

Process 14. Altered variability in salinity structure.

As previously discussed, the impacts of altered flow regimes on the hydrodynamic cycle have important implications for the distribution of organisms and the breeding success of some species

Likelihood: HIGH

Process 15. Dissipated salinity/chemical gradients used for animal navigation and transport.

Freshwater or brackish outflows from the estuary are important in attracting the juvenile stages of diadromous species (eg. eels, galaxiids) into the river. Freshwater/ brackish outflows are also important for transporting eggs and larvae of some diadromous species into the marine environment, and act as adult migration triggers for diadromous species that migrate from freshwater to the estuary or sea to spawn. Reductions in freshwater outflow, therefore, are likely to reduce recruitment of diadromous fish in the catchment.

Likelihood: HIGH

Process 16. Decreases in the availability of critical physical habitat features, particularly those components associated with higher velocities.

The significance of this for the Werribee estuary lies primarily in the opportunities afforded to algal communities by lower surface water velocities, particularly in the upper estuary.

Likelihood: HIGH

7. Management Recommendations.

7.1 Key Characteristics of Environmental Flows.

Given uncertainties over the ecological effects of changes in flow to estuaries, these recommendations for environmental flows are based on the principle that:

> *diversion of water from river systems should not disturb the major features of the estuarine hydrodynamic cycle.*

In the case of estuaries in Western Victoria, this means that the following key characteristics should be maintained.

(i) Late winter to early spring flows sufficient to flush "aged" salt water from the estuary and allow migration of a well-oxygenated salt wedge upstream as the flows reduce.

(ii) Flows sufficient to maintain a salinity gradient both vertically and horizontally. The gradients should ensure that water over the range of salinities from fresh to strongly marine is present in the estuary most of the time.

(iii) Avoidance of long periods of constant flow. The inherent variability of stream flow (including periods of cease-to-flow conditions if naturally occurring) should be maintained. This will require short periods when higher flows ("spates" or "freshes") enter the estuary. These serve also to improve the flushing characteristics of the estuary.

7.2 Late winter to early spring flushing flows

Field surveys did not offer the opportunity to observe the estuary under a variety of high flow conditions. However, the magnitude of flows required to remove all salt water from the estuary can be estimated using a mathematical model proposed by Kuelegan (1966). Kuelegan studied the relationship between salt wedge length and discharge in laboratory tank systems. These model estuaries consisted of uniform channels, rectangular in cross-section, having constant width and depth. The relationship he found is:

$$\frac{L_o}{H_o} = A\left(\frac{2V_r}{V_\Delta}\right)^{-5/2} \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

Where:

L_o = length of the salt wedge

H_o = water depth at the front ('toe') of the wedge

V_Δ = $\sqrt{g' H}$ = known as the densimetric velocity

Vr = river velocity

A = a term dependent on channel dimensions

g' = reduced density = $\left(\frac{\Delta d}{d_m} . g\right)$

Δd = density difference between fresh and seawater

d_m = mean density of fresh and seawater

g = acceleration due to gravity (9.8 ms $^{-2}$)

For estuaries with widths much greater than depths:

$$A = 6 \left(\frac{V_\Delta H}{\nu}\right)^{1/4}$$

Where ν = kinematic viscosity of water.

Kuelegan (1966) demonstrated the usefulness of the model for predicting the wedge length of the Mississippi River estuary (USA). Imberger and Agnew (1974) found they could make reasonable estimates of the wedge length for the Blackwood River estuary (Western Australia), while Sherwood (1984) reached the same conclusion for the Gellibrand River estuary (Victoria).

Kuelegan's equation was applied to two sets of assumed dimensions for the Werribee estuary:

(i) Estuary mean depth = 1.5m
Estuary mean cross-sectional area = 40 m^2

These dimensions correspond approximately to the upper estuary.

(ii) Estuary mean depth = 1.5m
Estuary mean cross-sectional area = 100m^2

These dimensions correspond to the central region of the estuary.

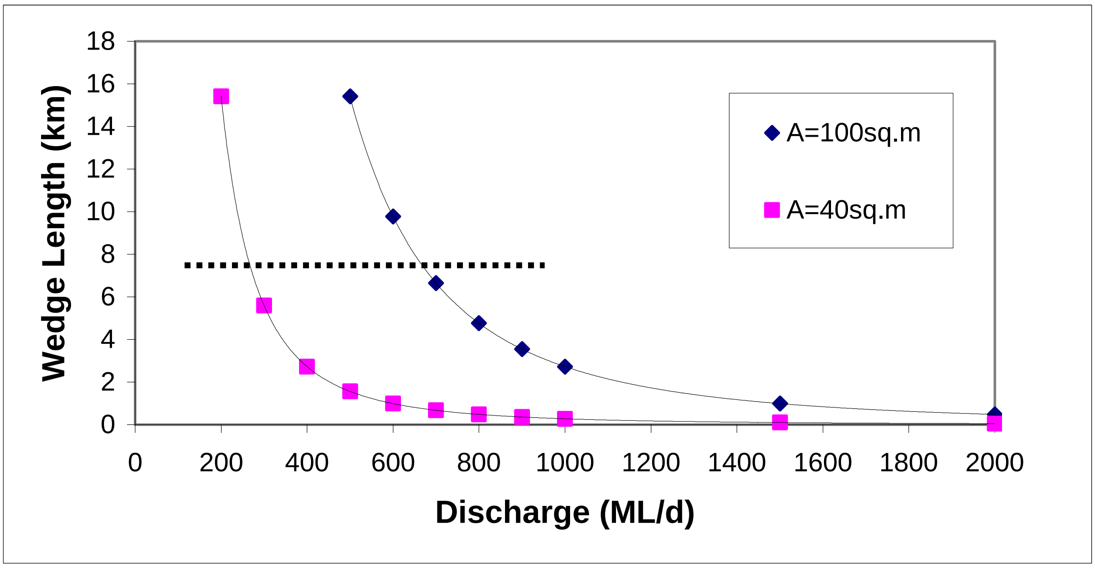

Figure 14: Prediction of the relationship between wedge length and discharge using Kuelegan's equation. The dotted line indicates the upstream limit of the Werribee estuary. The blue diamonds represent the central estuary and the pink squares represent the upper estuary.

The predicted salt wedge length is then calculated under various flows for a rectangular "box" estuary having each set of dimensions (Figure 14). The graphs suggest that in the upper estuary erosion of the salt wedge would occur at flows above 300 ML/day. A salt wedge in mid-estuary (say 5 km upstream) would retreat at flows greater than 800 ML/day. In both models the wedge length is significantly reduced for flows greater than 1000 ML/day. The frequency of such flows, based on two sets of discharge data for the Werribee River, are given in Table 17. The data collected before 1983 was discontinuous and has been treated separately from the more recent data. It is clear that the frequency of higher flows is lower in the more recent data set. This is most likely due to a combination of climatic changes and increased diversion of water for human uses over the time span of measurements. The relative contribution of each of these factors is not considered further here.

Table 17: Percentage of Werribee River flows, measured at the Lower Werribee Diversion Weir, less than the specified discharge. Two data sets were compared.

Q (ML/day)	Percentile of Flow	
	1911 – 1982*	1983 – 2004+
300	74.7	91.2
500	84.5	95.0
700	88.6	96.4
1000	88.7	97.8

* Discontinuous record – 7,307 data points
+ 7,738 data points.

Analysis of the more recent data set (Feb 1983 to July 2004) shows that flow exceeded 1000 ML/day on 176 days (2.2% of total days). High flow events typically lasted between 2 and 7 days and were most common over winter and spring (Table 18). After 1996 these high flows have become much less common.

Recommendation 1.

A flow of at least 1000 ML/day measured at the Lower Werribee Diversion Weir should be maintained for at least 3 days in late winter/early spring (September or October) as a flushing flow to significantly reduce the salt wedge length. This flow should occur at least once annually unless natural flows have a lower frequency.

The 3 day period of flood flow is recommended because it corresponds to the common duration of such flows in the historical records. Flushing of the estuary will not be instantaneous. Observations in other estuaries suggest it will take several days for salt water to be removed.

Table 18: Distribution of river flow events having Q > 1000 ML/day for at least one day between February 1983 and April 2005 (24 years). Note that data for January to June has been combined.

Year	Jan - June	July	Aug	Sept	Oct	Nov	Dec
82							
83				✓	✓	✓	✓
84				✓	✓		
85			✓	✓	✓	✓	✓
86				✓	✓		
87	✓	✓	✓				✓
88							
89	✓		✓	✓			
90	✓	✓	✓		✓		✓
91							
92				✓	✓	✓	✓
93				✓		✓	
94							
95					✓	✓	
96	✓	✓	✓	✓			
97							
98							
99							
2000					✓	✓	
01	✓						
02							
03							
04							
Total	5	3	5	8	8	6	6

Kuelegan's (1966) equation is based on a number of assumptions and these have been critically reviewed by Stephens and Imberger (1996). These authors found that a shallow sill midway along the Swan River estuary (Western Australia) and deep holes along the estuary led to a "hysteresis." Different relationships for wedge length versus discharge were found for an "advancing" and a "retreating" salt wedge. Given these effects, it is important that the Werribee estuary be studied under high flow conditions to test the assumptions underlying this flow recommendation.

7.3 Salinity gradient maintenance flows

Project resources did not extend to computer modelling the behaviour of the salt wedge under low flow conditions (programmes to do this are available). All of the field surveys were done under such conditions however.

The historical and more recent frequencies of low flow conditions in the Werribee River are compared in Table 19. In the more recent time period (1983 -2004), the frequency of low flows has increased significantly – for example, the 75th percentile flow is less than 50 ML/d in the recent period, whereas it was more than 300 ML/d historically. Long term monthly average flows for the recent time period show that the lowest mean flow in May is 24.1 ML/d at Lower Werribee Diversion Weir (Table 20).

Table 19: Frequency of various flow states for the Werribee River at the Lower Werribee Diversion Weir.

Percentile	**Discharge (ML/day)**	
	1911 – 1982*	**1983 – 2004⁺**
10	0	1.1
25	7	3.3
50	81	12.7
75	306	48.8
90	778	264

* Discontinuous record – 7,307 data points
⁺ 7,738 data points.

Over the survey period (from 1st July 2004 to 2nd May 2005), no flow over Werribee Weir was recorded on 217 out of 306 days (i.e. 71%). Besides a single very high flow event (Q_{max} = 9,255 ML on 3rd February 2005) there were 7 other flow events, each lasting at least two days and for which discharge exceeded 20 ML/day on a minimum of one day.

Table 20: Mean daily discharge for each month at Lower Werribee Diversion Weir (based on data from April 1983 to July 2004) and a mean daily discharge for this study period (1st July 2004 to 30th April 2005).

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Mean Q (ML/day)	50.4	55.0	42.5	31.9	24.1	43.0	88.8	136	411	438	236	151
Q ML/day for study Period	0.01+	676	5.6	3.6			3.0*	8.7	1.7	1.8	3.6	0.50

* 2004
\+ 2005

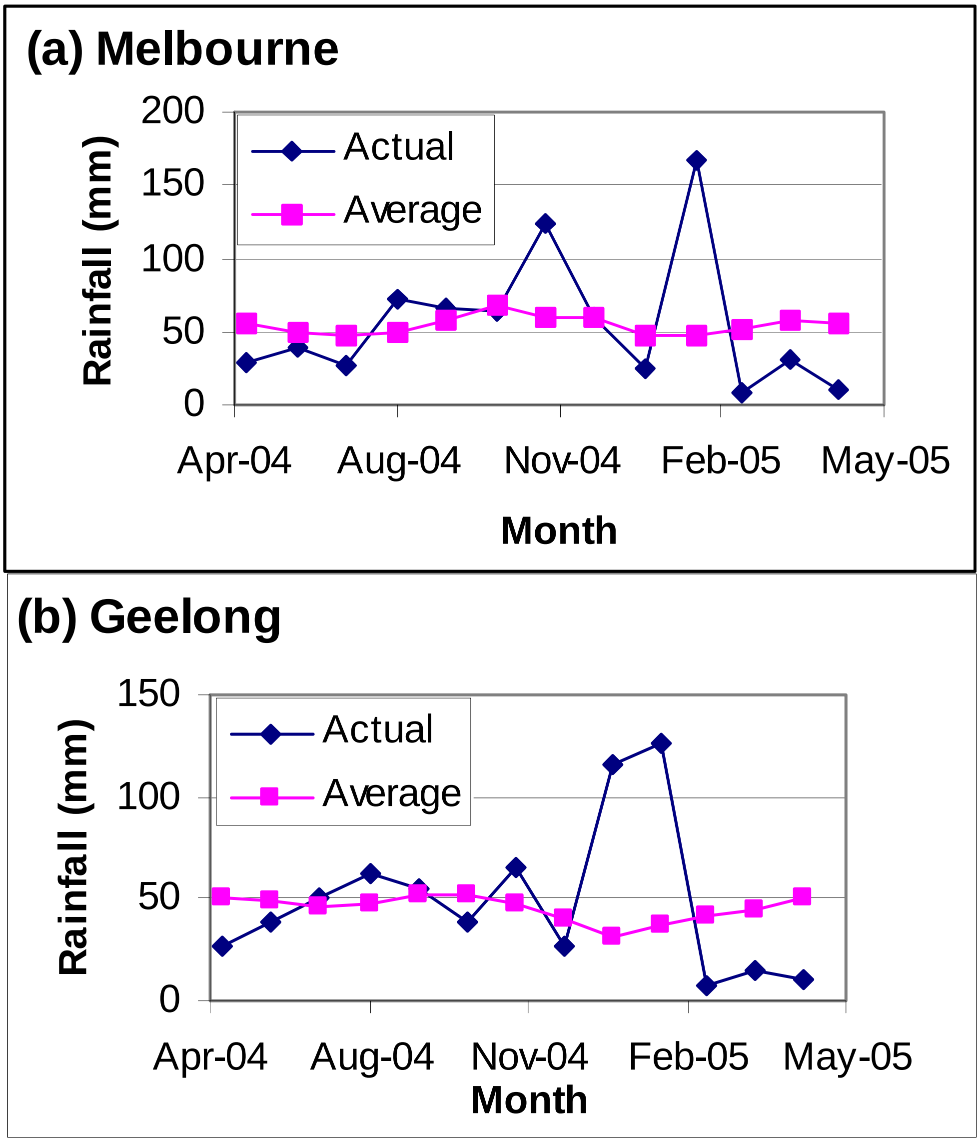

Figure 15: Actual and long- term average rainfall for Melbourne and Geelong over the survey period

These data show that the estuary had much less freshwater input than would normally occur. However, for most of the survey period, rainfall for Melbourne and Geelong was close to the long-term average (Figure 15). Despite this, the winter/spring flows were well below long-term means and are representative of what would be expected under extreme drought conditions. These findings suggest that upstream retention of rainfall run-off had a drastic effect on the volume of freshwater entering the estuary during the study period.

It is not possible to quantitatively determine the volume and duration of flows required to adequately maintain salinity gradients based on the scope of the current study. Further field measurements are required for an analysis of the relationship between flow and salinity under higher flow conditions.

Recommendation 2.

A minimum flow of sufficient volume should be provided to ensure that salinity gradients are maintained in the upper estuary. A layer (0.5 to 1m deep) of fresh to brackish water (salinity<10) should be present in the upper estuary under low flow conditions. Further analysis of the relationship between flow and salinity in the estuary is required to quantitatively determine the volume of flows required to achieve this objective.

7.4 Flow variability

Temporal variability in the input of freshwater flow is an inherent component of a functioning estuarine environment. Such variability, for example, results in variations in salinity that advantage euryhaline species adapted to highly variable salinity regimes. Loss of this variability has the potential to drastically alter community structure, with euryhaline estuary species replaced by stenohaline species adapted to either truly marine or freshwater environments. A minimum flow (Recommendation 2) will provide flows to ensure that a salinity gradient is maintained in the upper estuary. However, a minimum flow will not provide the variability required to maintain the estuarine ecological community. It is recommended, therefore, that the managed flow regime include periods of low flow (or cease to flow conditions) and freshes to mimic natural levels of flow variability. The frequency and timing of the recommended flows, and any independence rules related to meeting the recommendations, have not been specified here and will need to be formulated via further analysis of modelled flow data.

Recommendation 3.

Flows less than the minimum flow established in Recommendation 2 (including cease to flow conditions) should be allowed to occur at their natural frequency and timing. The frequency and timing of these flows, and any independence rules relating to this recommendation, will need to be formulated via further analysis of modelled flow data.

Recommendation 4.

Periods of flow greater than 400 ML/d (2 day minimum) should occur at their natural frequency and timing to mimic natural freshes. The frequency and timing of these flows, and any independence rules relating to this recommendation, will need to be formulated via further analysis of modelled flow data.

7.5 Non-flow Related Management Objectives.

7.5.1 Nutrient management

This study has shown that nutrient concentrations in the estuary are elevated and often well in excess of the objectives set under the SEPP objectives and ANZECC guidelines. Sampling of a drain flowing into the estuary during the January fieldtrip demonstrates that run-off from the surrounding market gardens is a major source of nutrients. This, combined with reduced freshwater flow and flushing efficiency, supports excessive algal growth that poses a considerable risk to the environmental health and recreational use of the estuary.

The need for a reduction in nutrient loadings in the Werribee estuary is well recognised in the Werribee River Catchment Nutrient Management Plan (NRE 1999) which established a series of management actions for implementation. Our results support the need for urgent action to manage nutrient inputs via implementation of the actions outlined in the Management Plan. Implementation of "Action Plan 5: Management of Irrigated Agriculture", which includes actions such as the installation of nutrient traps and improvements to drainage systems associated with market gardens, is considered a particularly high priority.

Recommendation 5.

Investigate the sources of nutrients entering the estuary and implement actions outlined in the Werribee River Catchment Nutrient Management Plan to reduce nutrient loadings

7.5.2 Fish passage

The Lower Werribee Diversion Weir and, to a lesser extent, the bluestone ford present barriers to fish migration in the Werribee River. Such barriers break the connectivity between the sea, estuary and river essential for the lifecycles of diadromous fish including galaxiids, tupong, eels and, potentially, the threatened Australian grayling.

Recommendation 6.

The provision of fish passage should be investigated at least at the bluestone ford and Lower Werribee Diversion Weir to allow migration of diadromous species between freshwater and the estuary/sea.

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Appendix 1: Parameters Measured in the Field

Appendix 1a Depth profile data 20/8/2004

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	11.8	32.5		13.26		5
	0.5	11.5	32.7		12.45		5
	1.0	10.8	34.8		12.86		3
	1.5	10.6	34.9		9.5		1
WR02	0.1	12.0	32.2		15.1		18
	0.5	11.9	32.3		14.9		18
	1.0	11.8	32.3		14.4		17
	1.5	11.4	33.0		14.4		16
WR03	0.1	12.4	29.4		11.8		9
	1.0	12.1	33.1		12.0		7
	2.0	12.0	33.9		9.7		3
	2.5	12.0	34.1		8.1-8.4		3
WR04	0.1	12.8	26.7		6.9		4
	1.0	12.2	31.95		2.6		2
	2.0	12.1	32.2		2.5		1.5
	3.0	12.0	32.4		2.2		1
WR05		Not sampled – water too shallow for boat access (<0.5m)					
WR07	0.1	8.2	1.0	1.31	12.62		10
	1.2		5.0		.		11
WR08	0.5	14.5	1.1	1.90			

WR07 - Princes Highway

WR08 - Werribee Bridge

Appendix 1b Depth profile data 24/09/2004.

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	14.5	32.7	50.3	11.35	8.18	4
	0.5	14.4	32.7	50.4	11.05	8.18	5
	1.0	14.3	32.9	50.6	10.16	8.20	5
	1.5	14.2	33.0	50.7	10.03	8.25	5
	2.0	14.1	33.6	51.4	10.25	8.29	5
WR02	0.1	15.0	32.6	20.1	16.05	8.35	21
	0.5	14.6	32.7	50.2	15.75	8.23	22
	1.0	14.2	33.1	50.9	10.29	8.19	8
	1.5	13.9	33.2	51.1	9.86	8.17	7
	2.0	13.8	33.7	51.8	6.62	8.18	6
WR03	0.1	15.9	26.2	41.5	9.72	7.96	4
	0.5	15.8	31.2	48.1	10.30	8.12	6
	1.0	15.1	32.7	50.1	10.49	8.15	8
	1.5	14.9	33.2	50.9	7.28	8.10	3
	2.0	14.9	33.2	51.0	7.25	8.10	2
	2.5	14.9	33.3	51.1	7.59	8.12	2
	3.0	15.0	33.3	51.1	7.54	8.12	2
WR04	0.1	16.5	21.0	33.4	7.42	7.58	4
	0.5	16.4	21.2	34.4	7.37	7.65	4
	1.0	16.2	30.0	46.2	7.65	7.98	1
	1.5	16.1	30.8	47.5	6.95	7.98	1
	2.0	16.0	31.2	48.1	5.92	7.97	1
	2.5	16.0	31.3	48.2	5.43	7.97	1
	3.0	16.0	31.4	48.3	5.62	7.98	1
WR05	0.1	17.0	12.7	24.5	5.40	7.20	6
	0.5	17.1	20.4	32.7	5.23	7.27	4
	1.0	17.3	21.1	33.5	3.85	7.27	4
	1.5	17.3	21.3	33.9	3.26	7.28	4
	2.0	17.4	21.2	33.8	3.11	7.29	7
WR06	0.1	15.8	0.7	1.67	12.62	8.03	10
	0.5	15.7	0.7	1.67	.	8.00	11
	1.0	15.5	0.7	1.67	10.50	7.98	11
	1.5	15.5	0.7	1.68	.	7.80	13
	2.0	14.9	0.7	1.70	.	7.66	13
	2.5	14.7	0.8	1.77	3.40	7.60	15
	3.0	14.3	0.9	1.97	2.26	7.47	18

Appendix 1c Depth profile data 24/10/2004.

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	17.8	40.9	52.5	10.11	8.37	1
	0.5	17.8	40.9	52.5	9.86	8.38	1
	1.0	17.8	41.0	52.5	9.95	8.38	1
	1.5	17.8	41.0	52.6	9.93	8.38	1
	2.0	17.8	41.0	52.6	9.88	8.38	1
WR02	0.1	18.0	33.6	44.3	12.05	8.53	1
	0.5	18.0	34.9	45.8	11.25	8.47	1
	1.0	18.2	39.4	51.2	7.50	8.26	6
	1.5	18.2	39.9	51.8	6.12	8.25	5
	2.0	18.1	40.3	52.1	6.00	8.23	5
	2.5	18.1	40.4	52.2	6.17	8.26	10
	3.0	18.0	40.5	52.2	6.30	8.27	12
WR03	0.1	19.2	28.3	39.0	14.66	8.56	6
	0.5	19.1	30.3	41.3	13.95	8.55	5
	1.0	19.0	35.3	47.2	12.35	8.45	3
	1.5	18.8	36.1	48.0	12.10	8.43	2
	2.0	18.7	36.3	48.1	11.96	8.44	1
	2.5	18.8	36.3	48.2	11.66	8.43	2
	3.0	18.7	36.3	48.2	11.52	8.43	2
WR04	0.1	20.2	24.3	34.7	14.78	8.08	3
	0.5	20.4	25.9	36.9	14.89	8.09	2
	1.0	20.7	27.1	38.7	15.90	8.10	1
	1.5	20.7	27.7	39.5	16.05	8.09	0
	2.0	20.7	28.4	40.3	15.70	8.54	1
	2.5	20.7	28.6	40.6	16.90	8.54	0
	3.0	20.7	28.8	40.8	16.60	8.54	1
WR05	0.1	19.7	6.3	9.9	7.90	7.52	5
	0.5	21.0	13.8	21.1	6.18	7.38	6
	1.0	20.9	14.7	22.3	6.6	7.40	6
	1.5	20.7	14.9	22.5	6.49	7.41	5
WR06	0.1	19.1	1.3	2.56	12.09	7.92	7
	0.5	19.1	1.3	2.56	12.20	7.89	8
	1.0	18.8	1.3	2.56	12.20	7.82	8
	1.5	18.4	1.3	2.56	12.05	7.79	9
	2.0	18.3	1.3	2.55	11.50	7.77	11
	2.5	18.0	1.3	2.55	9.88	7.71	11
	3.0	17.3	1.3	2.61	2.63	7.56	18

Appendix 1d Depth profile data 22/11/2004.

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	16.5	32.0	49.2	7.65	8.21	8
	0.5	16.6	32.0	49.1	7.66	8.21	9
	1.0	16.6	32.0	49.1	7.70	8.21	8
	1.5	16.7	32.0	49.1	7.68	8.21	8
	2.0	16.7	31.9	49.1	7.65	8.20	8
WR02	0.1	17.4	32.1	49.2	9.92	8.35	7
	0.5	17.4	32.1	49.2	9.85	8.35	10
	1.0	17.2	32.2	49.3	10.13	8.36	8
	1.5	17.1	32.3	49.5	9.67	8.33	7
	2.0	17.0	32.3	49.4	9.14	8.31	8
	2.5	17.0	32.3	49.5	8.66	8.28	9
	3.0	17.1	32.3	49.6	8.58	8.27	9
WR03	0.1	19.1	28.6	44.2	12.34	8.48	11
	0.5	19.1	28.6	44.3	12.15	8.48	10
	1.0	19.0	28.7	44.4	12.09	8.48	10
	1.5	18.9	28.8	44.6	11.43	8.44	8
	2.0	18.9	28.9	44.7	11.00	8.43	6
	2.5	18.7	29.5	45.6	9.10	8.25	3
	3.0	18.7	29.7	45.8	6.50	8.19	2
WR04	0.1	20	19.1	30.6	15.15	8.25	6
	0.5	19.9	19.1	30.6	14.87	8.25	6
	1.0	19.4	19.3	30.8	14.68	8.25	5
	1.5	19.1	21.9	34.4	13.80	8.33	4
	2.0	19.3	24.0	36.8	8.60	8.07	2
	2.5	19.8	26.3	41.2	3.80	7.77	2
	3.0	19.6	27.0	42.0	3.12	7.74	3
	3.5	19.9	27.0	42.0	2.65	7.71	3
WR05	0.1	18.8	2.2	4.3	12.51	7.66	8
	0.5	18.9	2.4	4.5	12.32	7.69	8
	1.0	20.7	16.3	26.5	11.58	7.47	7
	1.5	20.6	16.5	26.9	11.23	7.49	4
WR06	0.1	18.7	0.05	1.13	13.65	8.88	11
	0.5	18.6	0.05	1.13	13.20	8.85	11
	1.0	18.4	0.05	1.14	12.60	8.76	10
	1.5	18.3	0.05	1.15	12.45	8.65	10
	2.0	18.2	0.05	1.16	11.22	8.17	11
	2.5	18.0	0.05	1.23	7.49	7.72	8
	3.0	17.8	0.06	1.47	2.97	7.49	17

Appendix 1e Depth profile data 21/12/2004.

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	20.7	32.8	50.0	8.75	8.34	7
	0.5	20.4	33.0	50.3	7.95	8.29	12
	1.0	19.4	33.7	51.4	5.75	8.15	16
	1.5	19.3	34.1	52.0	6.10	8.20	6
	2.0	19.4	34.3	52.2	6.32	8.22	5
WR02	0.1	20.5	32.6	49.7	9.65	8.34	7
	0.5	20.1	32.7	50.0	9.30	8.34	9
	1.0	19.3	33.2	50.5	8.37	8.31	22
	1.5	19.1	33.4	50.8	5.69	8.19	15
	2.0	19.1	33.6	51.3	4.80	8.13	16
	2.5	19.2	33.8	51.5	3.95	8.13	14
	3.0	19.3	33.8	51.5	4.26	8.12	20
WR03	0.1	20.6	22.5	35.5	20.88	8.70	14
	0.5	21.5	28.6	44.2	11.65	8.48	5
	1.0	21.3	31.4	48.1	6.75	8.30	4
	1.5	21.2	31.6	48.3	6.65	8.30	5
	2.0	21.2	31.6	48.3	6.47	8.31	4
	2.5	21.1	31.6	48.4	6.45	8.31	3
	3.0	21.1	31.7	48.4	5.84	8.29	4
	3.5	21.1	31.6	48.4	5.25	8.29	3
WR04	0.1	20.3	18.9	30.3	12.65	8.32	13
	0.5	21.6	24.4	38.6	11.6	8.31	8
	1.0	22.2	27.8	43.0	9.37	8.28	2
	1.5	22.2	28.0	43.4	8.94	8.27	1
	2.0	22.2	28.1	43.4	8.73	8.26	1
	2.5	22.2	28.2	43.5	8.55	8.26	1
	3.0	22.2	28.2	43.6	8.29	8.25	1
	3.5	22.1	28.2	43.6	7.95	8.24	1
WR05	0.1	19.7	5.3	9.3	8.53	7.58	4
	0.5	22.7	14.6	23.9	10.32	7.61	8
	1.0	22.7	15.5	25.3	7.0	7.54	6
	1.5	22.6	15.6	25.4	7.52	7.54	5
	2.0	22.6	15.6	25.6	7.1	7.54	5
WR06	0.1	22.8	1.00	2.10	11.85	8.66	8
	0.5	22.1	1.00	2.10	11.27	8.63	13
	1.0	21.8	1.00	2.10	10.92	8.62	11
	1.5	21.6	1.00	2.10	10.65	8.57	9
	2.0	21.5	1.00	2.11	9.90	8.48	8
	2.5	21.2	1.00	2.13	8.35	8.26	8

	3.0	20.8	1.10	2.30	2.97	7.72	11

Appendix 1f Depth profile data 27/01/2005.

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	24.0	31.1	44.6	6.53	8.34	37
	0.5	24.0	31.7	44.8	6.47	8.35	36
	1.0	24.0	33.6	48.5	6.03	8.33	22
	1.4	24.0	35.0	49.4	9.93	8.29	12
WR02	0.1	24.2	18.4	27.7	6.39	8.37	23
	0.5	23.6	32.6	47.3	4.05	8.3	24
	1.0	23.2	37.2	52.0	5.77	8.26	8
	1.5	23.1	37.5	52.2	5.61	8.24	11
	2.0	23.1	37.7	52.4	4.98	8.19	11
	2.5	23.1	37.7	52.2	4.8	8.16	11
WR03	0.1	24.3	14.8	35.1	8.32	8.25	32
	0.5	24.1	24.5	35.4	7.65	8.24	35
	1.0	23.4	26.3	37.3	5.60	8.20	32
	1.5	23.5	32.8	46.2	2.52	8.19	32
	2.0	23.6	34.0	47.6	1.97	8.17	32
	2.5	23.6	34.3	48.3	1.83	8.17	30
	3.0	23.5	34.1	48.5	1.63	8.16	25
WR04	0.1	24.7	5.85	6.05	10.47	8.48	17
	0.5	24.5	6.20	10.1	9.95	8.48	17
	1.0	23.8	15.10	15.4	4.05	8.02	17
	1.5	23.5	25.00	28.5	1.82	7.94	13
	2.0	23.5	26.00	35.4	1.29	7.92	12
WR05	0.1	24.3	1.16	1.86	8.95	8.52	18
	0.5	24.3	1.82	2.93	8.61	8.49	19
	1.0	24.2	3.47	3.40	8.09	8.44	18
	1.5	23.4	17.50	26.5	0.11	7.34	12
WR06	0.1	27.1	1.27	1.35	14.75	8.99	26
	0.5	24.4	1.06	1.65	10.55	8.56	31
	1.0	22.6	0.98	1.65	5.95	7.92	31
	1.5	22.8	1.29	2.26	7.2	8.19	29
	2.0	22.5	1.59	2.53	2.17	7.89	17
	2.5	21.3	0.61	2.68	0.12	7.69	12
	3.0	20.9	1.53	2.55	0.19	7.59	12

Appendix 1g Depth profile data 28/02/2005.

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	22.8	27.1	38.0	9.32	8.41	8.1
	0.5	22.4	29.5	40.9	9.23	8.38	7.2
	1.0	21.5	33.1	45.5	9.35	8.25	7.3
WR02	0.1	22.9	28.0	42.4	9.17	8.31	8.6
	0.5	22.5	29.6	44.6	7.80	8.28	7.0
	1.0	22.2	31.0	46.9	7.30	8.24	8.2
	1.5	20.8	37.0	51.9	6.44	8.15	18.5
WR03	0.1	23.3	27.3	38.2	10.4	8.28	9.4
	0.5	23.1	28.0	38.4	10.31	8.30	9.6
	1.0	22.0	33.5	44.3	5.0	8.13	6.6
	1.5	21.2	34.5	48.0	4.22	8.07	6.1
	2.0	21.0	34.5	48.3	4.25	8.07	8.4
WR04	0.1	22.6	14.8	21.3	13.9	8.02	10.1
	0.5	22.6	16.15	24.9	9.44	8.09	13.4
	1.0	22.2	29.7	41.7	1.28	7.87	6.5
	1.5	22.1	30.4	43.4	0.63	7.86	6.0
	2.0	22.1	30.8	43.7	0.33	7.87	6.6
WR05	0.1	20.6	6.12	8.14	8.53	7.25	6.6
	0.5	22.0	15.16	22.07	13.01	7.51	5.9
	1.0	22.2	15.83	22.77	12.58	7.58	5.9
	1.5	22.7	15.83	23.37	12.30	7.39	7.3
WR06	0.1	23.9	0.96	1.76	10.34	8.29	9.2
	0.5	22.4	0.96	1.72	11.30	8.37	11.0
	1.0	21.1	0.95	1.63	11.90	8.41	12.0
	1.5	20.5	0.97	1.61	9.40	8.11	12.5
	2.0	19.9	0.94	1.60	9.72	8.04	12.3
	2.5	19.5	0.99	1.67	7.35	7.75	18.1
	3.0	19.3	1.10	1.73	1.65	7.38	27.0

Appendix 1h Depth profile data 24/03/2005.

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	17.8	32.7	45.7	6.57	8.74	4.2
	0.5	17.8	34.6	48.1	9.07	8.58	7.2
	1.0	17.7	37.5	51.8	8.55	8.30	11.7
	1.5	17.6	38.8	53.9	8.35	8.2	17.4
WR02	0.1	18.2	27.5	39.1	11.12	8.79	5.5
	0.5	18.2	32.6	46.6	10.09	8.70	5.6
	1.0	17.8	35.1	51.6	8.40	8.39	8.7
	1.5	17.9	37.8	52.7	6.71	8.21	10.0
	2.0	18.1	38.1	53.2	6.45	8.15	11.0
	2.5	18.2	38.4	53.5	6.32	8.10	11.6
	3.0	18.3	38.4	53.6	6.18	8.08	11.4
WR03	0.1	18.10	13.82	20.41	12.66	8.66	5.00
	0.5	18.20	15.40	20.63	10.65	8.70	5.50
	1.0	19.30	33.30	47.00	8.42	8.75	4.80
	1.5	19.00	34.60	48.00	7.98	8.65	6.50
	2.0	18.90	36.60	41.10	5.25	6.32	8.50
	2.5	18.90	36.90	51.60	5.86	8.25	9.00
	3.0	18.90	37.00	51.80	5.63	8.22	11.00
WR04	0.1	17.90	7.98	12.13	12.61	8.31	6.90
	0.5	17.90	8.28	13.04	12.07	8.35	6.80
	1.0	20.30	24.90	37.40	1.44	8.13	4.60
	1.5	20.10	27.40	39.20	1.62	8.25	5.30
	2.0	20.40	27.80	39.50	1.62	8.30	5.20
	2.5	20.40	28.10	39.90	1.95	8.37	5.80
WR05	0.1	18.1	2.30	2.18	10.58	8.03	3.3
	0.5	18.0	3.79	3.14	9.73	7.93	4.2
	1.0	19.8	10.70	15.71	3.51	7.30	8
	1.5	20.2	12.10	18.85	0.62	7.10	12
WR06	0.1	19	1.42	2.22	19.13	9.17	5.8
	0.5	19.3	1.42	2.23	17.87	9.18	6.0
	1.0	19.3	1.42	2.25	17.56	9.16	6.6
	1.5	19.2	1.43	2.27	17.40	9.00	10.4
	2.0	19.1	1.46	2.32	13.46	8.08	15.1
	2.5	18.8	1.50	2.35	2.48	7.72	12.9
	3.0	18.3	1.46	2.36	0.86	7.5	10.9

Appendix 1i Depth profile data 25/04/2005

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	19.28	38.87		8.6	8.49	5
	0.5	19.31	38.91		8.5	8.48	7
	1.0	19.5	39.05		8.5	8.49	20.2
	1.5	19.4	39.06		9.8	8.56	17.5
	2.0	19.26	39.03		10.0	8.58	14.6
WR02	0.1	19.25	37.3		11.9	8.7	5.4
	0.5	19.2	37.34		12.0	8.69	5.2
	1.0	18.95	38.15		9.5	8.62	3.8
	1.5	18.37	38.44		7.4	8.42	4.4
	2.0	18.35	38.44		6.5	8.42	5.9
	2.5	18.34	38.48		6.5	8.42	6.0
	3.0	18.37	38.53		6.5	8.42	NR
WR03	0.1	19.64	34.6		>20	8.92	15.2
	0.5	19.62	34.65		>20	8.91	15.2
	1.0	19.38	35.28		>20	8.71	8.3
	1.5	18.8	37.65		7.7	8.39	6.5
	2.0	18.8	37.95		6.9	8.38	5.5
	2.5	18.75	38.15		6.2	8.36	4
	3.0	18.72	38.25		5.9	8.36	4.8
	3.5	18.72	38.26		5.6	8.36	5.3
WR04	0.1	19.69	24.5		5.2	7.49	2.5
	0.5	19.79	25.6		5.2	7.52	2.5
	1.0	19.1	33.5		5.2	7.95	4.7
	1.5	19.03	34.37		5.3	8.06	5.8
	2.0	19.05	35		6.6	8.18	6.7
	2.5	19.03	35.36		6.5	8.18	5.5
	3.0	19.02	35.4		6.4	8.18	3.2
WR05	0.1	20.37	9.3		>20	9.09	260
	0.5	19.71	14.7		9.3	7.48	25.7
	1.0	19.97	24.49		0.9	7.08	13.5
	1.4	19.79	26.11		0.4	7.18	8.6
WR06				Not sampled			

Appendix 1j Depth profile data 28/04/2005

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	18.5	36.5	52.5	10.04	8.38	3.3
	0.5	18	37.5	52.4	9.89	8.37	6.5
	1.0	17.8	37.9	53.1	9.98	8.38	5.2
WR02	0.1	19.1	35.3	48.1	14.47	8.59	14.5
	0.5	19.1	35.4	48.8	15.10	8.64	13.8
	1.0	19.0	35.4	49.0	15.02	8.65	13.3
	1.5	18.6	35.7	48.5	13.13	8.59	13.0
	2.0	18.2	37.0	51.3	10.01	8.40	13.0
WR03	0.1	18.90	34.20	48.70	11.51	8.41	10.00
	0.5	18.80	34.50	48.80	11.74	8.41	9.50
	1.0	18.80	34.50	48.80	11.84	8.41	9.80
	1.5	18.70	34.50	49.00	11.22	8.40	11.00
	2.0	18.50	35.10	49.70	9.60	8.37	9.00
	2.5	18.30	35.70	50.20	8.83	8.36	10.50
WR04	0.1	19.60	27.50	41.50	5.90	7.67	7.60
	0.5	19.40	31.20	43.50	4.20	7.77	5.00
	1.0	19.10	34.00	47.40	3.40	7.77	5.00
	1.5	19.10	34.10	47.90	4.10	7.84	5.50
	2.0	19.00	34.80	48.60	4.60	7.94	5.00
	2.5	19.00	34.80	48.90	4.60	7.96	3.80
	3.0	18.90	34.90	49.10	4.20	7.96	3.70
WR05	0.1	19.6	20.00	26.1	1.42	7.33	8
	0.5	19.5	23.30	36.6	0.8	7.13	5.5
	1.0	19.5	25.60	36.90	0.42	7.12	4
WR06	0.1	16.2	1.22	2.01	14.8	8.53	8.8
	0.5	16	1.22	2.01	14.70	8.62	11.9
	1.0	16	1.22	2.01	15.40	8.64	11.8
	1.5	15.9	1.50	2.01	15.60	8.65	11.2
	2.0	15.9	1.22	2.02	15.60	8.66	11.0
	2.5	15.9	1.22	2.01	15.70	8.67	10.5
	3.0	15.8	1.22	2.02	15.6	8.62	11.0

Appendix 1k Depth profile data 16/05/2005.

Site	Depth (m)	Water Temp. (°C)	Salinity (ppt)	Conductivity (mS cm^{-1})	DO (mg L^{-1})	pH	Turbidity (NTU)
WR01	0.1	15.7	37.5	52.0	10.9	8.47	4.4
	0.5	15.7	37.5	52.2	11.05	8.49	4.5
	1.0	15.6	37.5	52.2	11.03	8.50	4.6
	1.5	15.6	37.5	52.2	11.05	8.5	4.5
WR02	0.1	15.8	36.5	51.4	12.74	8.53	6.0
	0.5	15.8	36.8	51.4	12.95	8.53	7.5
	1.0	15.8	36.9	51.4	12.85	8.53	8.0
	1.5	15.7	36.9	51.4	12.65	8.53	7.5
	2.0	15.6	36.9	51.5	12.20	8.52	6.5
	2.5	15.5	36.9	51.5	11.96	8.51	5.5
WR03	0.1	16.00	32.80	46.60	10.53	8.15	3.30
	0.5	16.20	33.00	46.60	10.30	8.18	3.50
	1.0	16.30	33.20	47.00	9.76	8.19	3.50
	1.5	16.50	35.40	49.50	9.64	8.26	4.00
	2.0	16.40	36.10	50.20	10.30	8.34	3.80
	2.5	16.20	36.20	50.60	9.90	8.36	4.20
	3.0	16.00	36.40	51.10	9.68	8.38	4.50
WR04	0.1	17.20	24.30	36.40	9.36	7.62	3.00
	0.5	17.20	25.70	37.60	9.10	7.61	2.50
	1.0	17.30	31.00	41.80	5.65	7.61	3.00
	1.5	17.50	33.60	47.70	5.25	7.76	1.50
	2.0	17.50	34.10	47.90	5.40	7.79	1.50
	2.5	17.60	35.20	48.10	5.65	7.82	1.50
	3.0	17.60	34.30	48.30	5.47	7.82	1.30
WR05	0.1	15.1	6.02	8.25	8.50	7.67	5
	0.5	17.1	15.10	21.50	5	7.13	15
	1.0	17.9	26.50	37.80	1.97	7.16	5
	1.5	17.9	27.00	38.20	0.29	7.11	3
WR06	0.1	14.8	1.46	2.42	17.75	8.82	8.5
	0.5	14.7	1.47	2.39	17.95	8.84	10.0
	1.0	14.4	1.68	2.39	17.60	8.81	8.9
	1.5	13.9	1.47	2.39	15.54	8.65	6.1
	2.0	13.9	1.47	2.40	14.92	8.61	6.0
	2.5	13.9	1.48	2.40	14.39	8.55	7.5
	3.0	13.9	1.49	2.40	13.42	8.47	11.5

Appendix 2: WR Algal count data for four sites from 2004/2005 sampling

Site	Date	Depth (m)	Algal Count WSL:ALG/1 (Cell ml^{-1})	Bacillariophyta (Cell ml^{-1})	Chloromonadophyta (Cell ml^{-1})	Chlorophyta (Cell ml^{-1})	Crysophyta (Cell ml^{-1})	Cryptophyta (Cell ml^{-1})	Cyanophyta (Cell ml^{-1})	Dinophyta (Cell ml^{-1})	Euglenophyta (Cell ml^{-1})
WR02	24/09/04	0.1	73,695	115	ND	57,680	ND	14,975	ND	925	<10
	21/12/04	0.1	14,230	9110	ND	small chlorophyta : 5100	ND	Cryptomonas : 10	ND	Protoperidinium: 10	ND
	24/03/05	0.1	16,855+8,265	1385	ND	14,280	ND	Cryptomonas : 1050	Planktolngbya : 8,265	140	ND
	29/04/05	0.1	26,430+2,605	7,050	ND	ND	ND	Cryptomonas : 18,870	Planktolngbya : 2,605	440	70
	16/05/05	0.1	2,290	135	ND	Monoraphidium : <10	ND	ND	ND	2,155	Euglena : <10
WR03	21/12/04	0.1	4,755	1835	ND	2390	ND	ND	520	ND	10
WR05	24/09/04	0.1	75,495	60	ND	74,885	ND	10	Aphanocapsa : 530	10	ND
	21/12/04	0.1	15,855	4900	ND	10925	ND	Cryptomonas : 10	ND	Protoperidinium: 20	ND
	24/03/05	0.1	17,525	1,330	ND	15,195	ND	Cryptomonas : 125	30+785	40	20
	29/04/05	0.1	4,500+5,710	635	ND	95	ND	Cryptomonas : 25	755+5,710	2,990	Traclomonas : <10
	16/05/05	0.1	9,140	1,385	ND	7,025	Mallomonas : 20	Cryptomonas : 45	390	Glenodinium: 275	ND

Site	Date	Depth (m)	Algal Count WSL:ALG/1 (Cell ml^{-1})	Bacillariophyta (Cell ml^{-1})	Chloromonadophyta (Cell ml^{-1})	Chlorophyta (Cell ml^{-1})	Crysophyta (Cell ml^{-1})	Cryptophyta (Cell ml^{-1})	Cyanophyta (Cell ml^{-1})	Dinophyta (Cell ml^{-1})	Euglenophyta (Cell ml^{-1})
WR06	24/09/04	0.1	206,420	70	ND	204,585	85	715	Aphanocapsa 965	ND	ND
	21/12/04	0.1	13,675	1,415	ND	9,720	ND	ND	90	2450	ND
	24/03/05	0.1	24,305+2,135	1,605	ND	21,030	ND	Cryptomonas: 1125	Planktolngbya 2,135	460	85
	29/04/05	0.1	9,955+425	290	ND	2,320	Mallomonas : 20	Cryptomonas : 145	2,460+425	4,655	Traclomonas : 65
	16/05/05	0.1	16,535+4,270	1,075	ND	8,970	Mallomonas : 20	Cryptomonas: 1,975	2,830+4,270	1,570	Traclomonas : 95

Appendix 3: Chlorophyll-a levels for four sites sampled during 2004/2005

Site	Date	Depth (m)	Chl a (mg L^{-1})
WR02	24/09/04	0.1	<0.01
	24/09/04	2.0	<0.01
	26/10/04	0.1	<0.01
	26/10/04	3.0	<0.01
	22/11/04	0.1	<0.01
	22/11/04	3.0	<0.01
	21/12/04	0.1	0.02
	21/12/04	3.0	0.03
	27/01/05	0.1	<0.01
	27/01/05	2.5	<0.01
	28/02/05	0.1	<0.01
	28/02/05	3.0	<0.01
	24/03/05	0.1	0.02
	24/03/05	2.0	0.02
	28/04/05	0.1	<0.01
	28/04/05	2.0	<0.01
	16/05/05	0.1	0.03
	16/05/05	2.5	<0.01
WR05	24/09/04	0.1	0.03
	24/09/04	1.5	<0.01
	26/10/04	0.1	<0.01
	26/10/04	1.5	<0.01
	22/11/04	0.1	<0.01
	22/11/04	1.5	<0.01
	21/12/04	0.1	0.02
	21/12/04	2.0	<0.01
	27/01/05	0.1	<0.01
	27/01/05	1.5	0.17
	28/02/05	0.1	0.04
	28/02/05	1.5	0.05
	24/03/05	0.1	0.02
	24/03/05	1	0.07
	28/04/05	0.1	0.03
	28/04/05	1	0.02
	16/05/05	0.1	0.03
	16/05/05	1.5	<0.01
WR03	21/12/04	0.1	0.08

Site	Date	Depth (m)	Chl a (mg L^{-1})
WR06	24/09/04	0.1	0.28
	24/09/04	2.0	0.02
	26/10/04	0.1	<0.01
	26/10/04	3.0	<0.01
	22/11/04	0.1	<0.08
	22/11/04	3.0	<0.01
	21/12/04	0.1	0.01
	21/12/04	3.0	0.04
	27/01/05	0.1	<0.01
	27/01/05	3.0	0.01
	28/02/05	0.1	0.02
	28/02/05	3.0	0.01
	24/03/05	0.1	0.05
	24/03/05	3.0	0.02
	28/04/05	0.1	<0.01
	28/04/05	3.0	0.06
	16/05/05	0.1	0.09
	16/05/05	3.0	0.02

Appendix 4: Fishing methods at each site on each sampling date

Lower estuary

14/12/04
5 single wing fyke nets (mesh size 12mm).
Time set: 1110
Time pulled: 1700
Total time set 400 minutes.

Five seine shots (7m length, mesh size 4mm)

27/04/05
5 single wing fyke nets (mesh size 12mm).
Time set: 0945
Time pulled: 1530
Total time set 345 minutes.

Two seine shots (65m length, mesh size 4mm).

Mid estuary

14/12/04
5 single wing fyke nets (mesh size 12mm).
Time set: 1140
Time pulled: 1800
Total time set 380 minutes.

Three seine shots (7m length, mesh size 4mm).

27/04/05
5 single wing fyke nets (mesh size 12mm).
Time set: 0945
Time pulled: 1530
Total time set 345 minutes.

One seine shot (65m length, mesh size 4mm)
One seine shot (7m length, mesh size 4mm)

Upper estuary

27/04/05 (WR04)
5 single wing fyke nets (mesh size 12mm).
Time set: 1100
Time pulled: 1445

Total time set 225 minutes.

14/12/04 (WR05)
5 single wing fyke nets used. Mesh size 12mm
Time set: 1215
Time pulled: 1721
Total time set 366 minutes.

Four seine shots (7m length, mesh size 4mm).

Freshwater

14/12/04
Boat-mounted electrofishing (Smith-Root® model 5 GPP)

Settings: Volts 50-500, Amps 9.0, Hz 60, PPS 60

102 minutes fishing time, 1821 seconds current application time.

Right Bank 1045-1140, 913 sec
Left Bank 1145- 1232, 908 sec
700m length of survey site.

27/4/05
Eight single wing fyke nets (mesh size 12mm).
Time set: 1635 27/4
Time pulled: 0840 28/4
Total time set 965 minutes.

One 3 1/2” mesh net set for 2 hrs
23 bait traps set for same period as fyke nets.