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Mixing, Flushing and CTD Surveys of the Waters of Port Phillip Bay

C. Pattiaratchi, R. Phillips, C. Oldham and A. Perkins
Department of Environmental Engineering
Centre for Water Research
The University of Western Australia
Nedlands 6907, Western Australia

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CSIRO Environmental Projects Office
Building 9, Forestry Site, Banks Street
Yarralumla, ACT, Australia

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EXECUTIVE SUMMARY

As Task P2 of the Port Phillip Bay Environmental study (PPBES), the Centre for Water Research, University of Western Australia (CWR, UWA) was contracted by the CSIRO to collect and analyse field data to examine the mixing processes in Port Phillip Bay (PPB). In particular, the exchange between Port Phillip Bay and Bass Strait and the transport characteristics of the Yarra River and Werribee effluent plumes were subjected to detailed investigation using field data.

The main requirements of the study were to provide information on mixing processes and to quantify turbulent exchange rates in PPB. These requirements were achieved through the execution of CTD and microstructure surveys.

Intensive CTD surveys have been undertaken over the whole Bay and also in three important mixing areas: the Great Sands region and in the receiving waters for the Yarra River and the Western Treatment Plant discharges. Microstructure surveys were undertaken only in the vicinity of the Yarra and Werribee discharges.

The Bay Wide CTD Survey

Measurements of salinity, temperature and turbidity were taken over the whole Bay in four separate surveys carried out during two periods in the months of May and September/October 1994, respectively. Results from the field surveys are presented and described.

The distribution of salinity and temperature over the two periods show distinct seasonal variation. Between the May and September/October surveys, temperature decreased by about 5°C in the centre of PPB and by 2°C at the peripheries; salinities were 0.2 to 0.4 pss higher throughout PPB. Turbidity levels are related to the freshwater input to the bay. In the first May survey there was a region of high turbidity near the eastern shoreline. This was absent for the first survey in September but was evident during the second.

Salinity is the principal conservative parameter within the study and plays the major role in defining density and, therefore, mixing characteristics. The horizontal distribution of this parameter is determined by the inputs to the bay, hence, the salinity reduces towards the coastline. Evaporation is also likely to play a significant role in the distribution. Largest gradients are associated with the Yarra Estuary at one end of PPB and the Sands region at the other. The water column is vertically well mixed except in the vicinity of the Yarra Estuary where there is strong vertical stratification.

During periods of high discharge the influence of the Yarra Estuary can be traced for over 20 km along the eastern shoreline and approximately 10 km into the bay. The influx from the Western Treatment Plant is also noticeable but to a lesser extent.

The results from these surveys provide an excellent data set against which to verify the performance of a numerical model simulating the transport of conservative tracers in PPB, which includes the main freshwater discharges.

The Sands Flushing Experiment

Measurements of temperature, salinity and current flows were carried out over the Great Sands region between the 7th and 12th of May, 1994. Results from this survey are presented and described in terms of the mixing between the Bass Strait and Port Phillip Bay waters. These data are used to calculate the tidal exchange ratio (R) and to estimate the flushing time for PPB.

Using the data sets for the 7 and 10 May, the tidal exchange ratios have been calculated at the entrances to the three main channels as follows:

Channel	R (7 May-94)	R (10-May-94)
West channel	0.08	0.085
Symonds Channel	0.02	0.072
South Channel	0.007	0.008

From these it is apparent that tidal exchange is greater for higher tidal ranges and that the largest exchange occurs in the West and Symonds Channel. This latter observation is in agreement with results from the HF radar survey of surface currents and is attributed to the short length of these channels relative to the South Channel and their large current flow.

The combined tidal exchange ratio for the three channels is 0.032 for May 7 and 0.05 for May 10. Estimation of flushing time yields a period of 353 days. However, due to the diurnal inequality of the tides the flushing time may be higher than this value.

The Yarra Plume Experiment

The objectives of the Yarra Plume experiment were to gain an insight into the transport and mixing characteristics of the water discharging from the Yarra Estuary.

CTD profiling was undertaken in this region between the 17th and 22nd September, 1994 and the 5th and 6th October, 1994. Results from the survey are presented and related to the prevailing tide, wind and river flow conditions.

Microstructure profiling was undertaken between the 18th and 21st September to measure the turbulent characteristics of the water column under different stratification and meteorological forcings. The measurements are used to identify the likely mixing mechanisms and to calculate the dissipation of TKE from which the vertical eddy diffusivity is obtained.

It was found that, the waters from the Yarra estuary discharge into Hobsons Bay as a buoyant surface jet. The dimensions of this vary considerably depending upon river discharge and wind regime. The extent is largest during high river discharges and with offshore winds. Plume depth increases as a result of onshore winds and/or high river discharge. Entrainment at the base of the surface jet forms a well mixed plume which becomes dispersed into the bay. The microstructure data show the three primary mixing processes operating within the study area to be wind stirring, interfacial and bottom boundary shear. The well-mixed plume can be distinguished from the ambient PPB water and can, therefore, be used as a tracer to define the long term fate of the Yarra derived water.

The Werribee Plume Experiment

The objectives of the Werribee Plume experiment were to gain an insight into the transport and mixing characteristics of the waters discharging from the Western Treatment Plant (WTP). CTD profiling and microstructure surveys were undertaken in this region between the 23rd and 26th September, 1994. Results from the survey are presented and related to the prevailing tide, wind and river flow conditions.

The effluent from the WTP main drains discharge into PPB as buoyant surface jets. The tide currents in the area are low and advective transport and mixing characteristics are dominated by surface wind stress. Observations were undertaken mostly during westerly winds of >5 m/s. During such periods the plumes were well mixed and flowed eastwards around Wedge Point towards the mouth of the Werribee River. Whilst flowing past the Point, the plume is forced offshore by the Wedge Spit. Mixing occurs through the combined processes of wind stirring and interfacial shear.

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1. INTRODUCTION

As Task P2 of the Port Phillip Bay Environmental study (PPBES), the Centre for Water Research, University of Western Australia (CWR, UWA) was contracted by the CSIRO to collect and analyse field data to examine the mixing processes in Port Phillip Bay (PPB), Melbourne.

The main requirements of the study were to provide information on mixing processes and to quantify turbulent exchange rates in PPB. These requirements were achieved through the execution of CTD and microstructure surveys.

CTD surveys have been undertaken over the whole bay and also in three important mixing areas: the Great Sands region, the discharge of the Yarra Estuary into PPB and the discharge of the effluent from the Western Treatment Plant. Microstructure surveys were undertaken only in the Yarra and Werribee discharges.

These surveys are reported here as:

- The Bay-wide CTD survey;
- The Sands flushing experiment;
- The Yarra plume experiment; and
- The Werribee plume experiment.

Data reports listing the full data sets for the bay-wide CTD measurements and the Sands experiments are listed in Svenson and Pattiaratchi (1994 a, b) and Svenson and Pattiaratchi (1994c), respectively.

1.1. Port Phillip Bay

Port Phillip Bay is a large, almost totally enclosed, shallow marine basin (Figure 1.1). It has a surface area of approximately 1,950 km^2 and a mean depth of 12.8 m. The connection with the open ocean (Bass Strait) is limited to a 3 km wide entrance channel in the south-west. The main basin is barred from the entrance by the Great Sands region, a triangular area of shallow sand flats occupying an area of over 150 km^2. Three principal channels cross the Sands: the West, Symonds and South channels. Of these the South and West Channel are dredged to allow shipping to pass. At the north-eastern end of the Sands, the bathymetry drops from 6 m to around 22 m in the main body of the Bay.

The tides are semi-diurnal with a high diurnal inequality, driven predominantly by the ocean tide in the Bass Strait and exhibit a significant reduction in amplitude and change of phase over the Sands region. Tidal elevation amplitudes range from 0.4 m at the Heads to 0.2 m at the north of the bay (Hunter, 1992). Ebb and flood currents at the entrance are about three hours out of phase with tidal height so that maximum ebb currents occur at the time of low water at the Entrance and maximum flood currents occur at the time of high water (MMBW/FWD, 1973). Tidal current amplitudes range from 0.8 m/s in the Sands region through 0.05 m/s in the centre of the bay, to 0.02 m/s in the northern part of PPB. With the reduction in tidal influence in the bay, water circulation and mixing within the water column is dominated by wind (Pattiaratchi *et al.*, 1989).

Three important mixing areas have been identified. These are associated with the discharge of the Yarra Estuary into Hobsons Bay; the discharge of effluent from the Western Treatment Plant (WTP) and the confluence of the Port Phillip Bay water and the Bass Strait water over the Great Sands Region. This latter area plays an important role in restricting the flushing of PPB.

1.2. The Yarra Estuary

The Yarra Estuary is located to the north-east of PPB. The average discharge of the Yarra Estuary is given as 28.3 m^3/s and it is classified as a salt wedge estuary (Hunter, 1992). Under high flow conditions, the salt wedge extends from the mouth, upstream to King Street, and under low flow conditions, it extends to Bridge Road. The present study concerns the transport and mixing characteristics of the buoyant plume once discharged to the Bay. The study area is shown in Figure 1.2 (a).

1.3. The Western Treatment Plant (WTP)

The WTP is located within the Werribee area on the western shores of PPB (Figure 1.2 (b)). It collects sewage from the western, central and northern suburbs of Melbourne and discharges the treated effluent through five outlets (15 East, 145West, Little River, Lake Borrie and Murtcaim). The outflow is estimated to be 4.8 m^3/s (Hunter, 1992).

The transport and mixing characteristics of the effluent plumes have been studied previously by Pattiaratchi *et al.* (1989). This study aims to augment this and to provide additional data in this location.

1.4. The Great Sands Region

As mentioned previously the Great Sands region bars the main bay from the entrance channel (Figure 1.2 (c)). Its presence is responsible for inhibiting the exchange of water between PPB and the Bass Strait (Hunter, 1992).

For the study salinity was used as a natural tracer to investigate the mixing through the Great Sands region and to calculate the tidal exchange ratios at the entrances of the three main channels to the bay. The ratios are then used to estimate a flushing time for the bay.

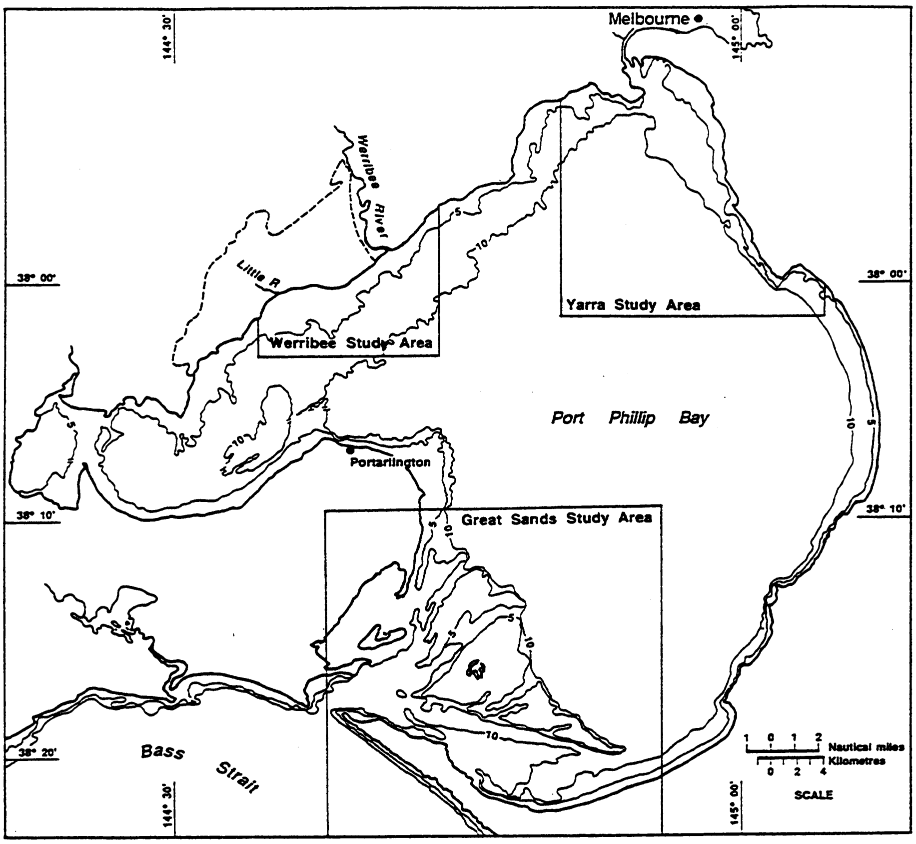

Figure 1.1: Location map showing study areas

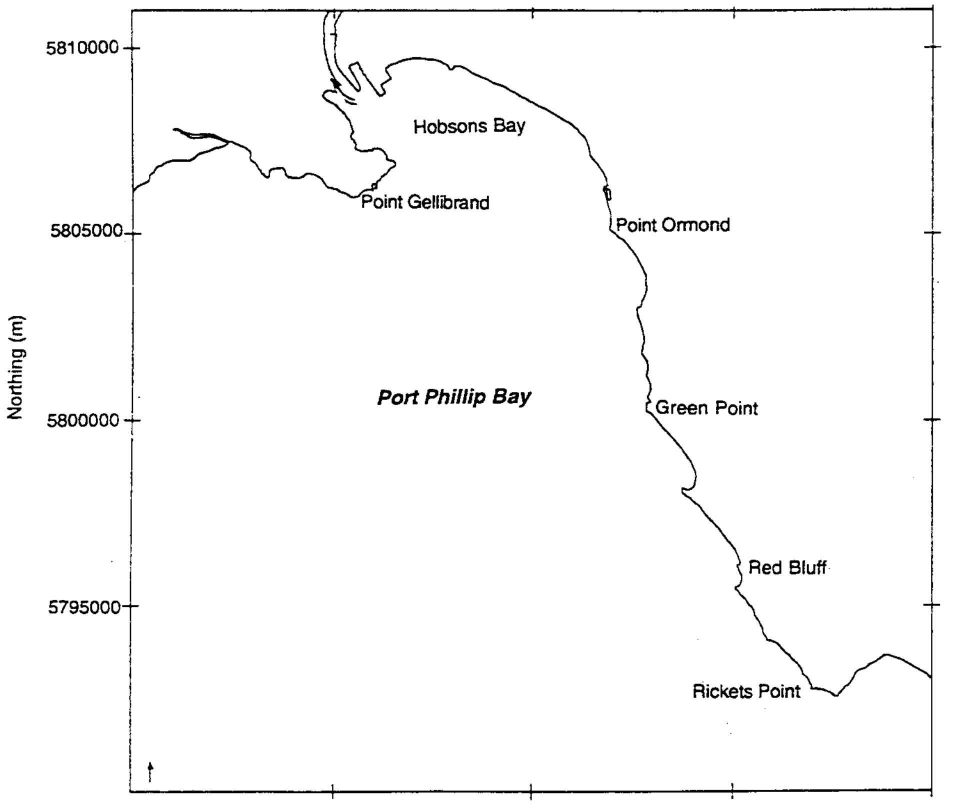

Figure 1.2(a): The Yarra Plume experiment study area.

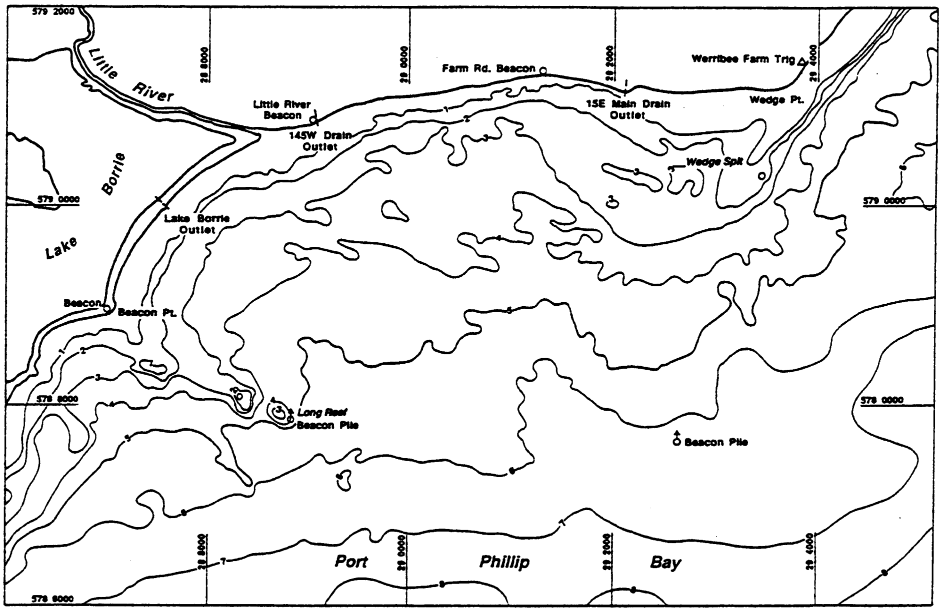

Figure 1.2(b): The Werribee Plume experiment study area.

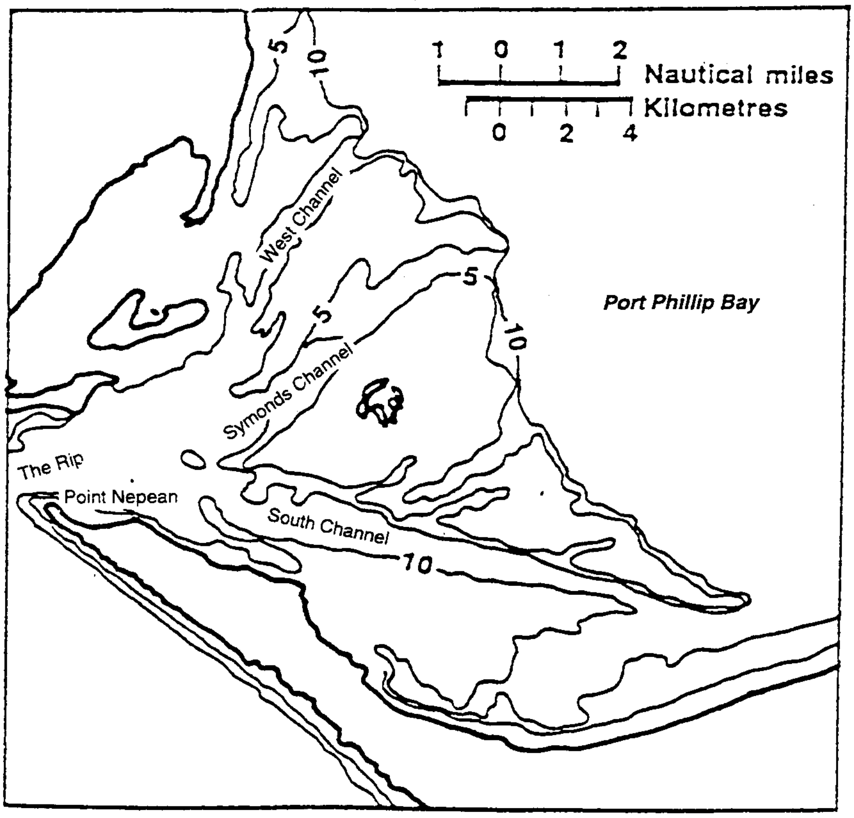

Figure 1.2(c): The Sands Flushing experiment study area.

2. INSTRUMENTATION

The field Program used two instruments designed and developed at the Centre for Water Research specifically for mixing investigations:

- the fine-scale CTD (conductivity-temperature-depth) probe and
- the microstructure profiler.

2.1. Fine-scale profiling CTD

The fine-scale profiler is an "intelligent" CTD designed to study mixing and dispersion in lakes, reservoirs and coastal seas. Mixing and dispersion processes act over scales ranging from millimetres to kilometres. The profiler is specifically designed to resolve both fine-scale motions (of order centimetres) and basin-scale motions (of order kilometres). The instrument is a component of a total field measurement system integrating real time data analysis and presentation, boat position fixing, instrument calibration, and fine-scale and microstructure data acquisition and processing. The real time data display gives the user the flexibility to alter the sampling strategy in the field and thereby optimise the resolution of the particular process of interest.

The profiler is equipped with depth, temperature and conductivity sensors with oxygen and turbidity sensors as additional options :

Sensor	Range	Resolution
Depth	0-60 m	0.001 m
Temperature	-1° - 31°C	0.001°C
Conductivity	0 - 5 Sm^{-1}	10^{-4} Sm^{-1}

All sensors have been selected for their accuracy, long term stability and short response times. Signal enhancement software is provided to correct for the different response times of the various sensors. The communications link uses a twisted pair cable with RS485 signals, allowing long cables to be reliably driven at high rates. In the present study, the profiler was used in the free-fall mode. Here the profiler is ballasted to fall at a constant rate of 1 m/s With 50 Hz sampling at this speed the vertical spatial resolution is 2 cm.

2.1.1. Preparation and calibration of the CTD

Calibration of the temperature, conductivity and pressure sensors was undertaken using an automated interface and a PC based system. The interface, connected to standard sensors, reports directly to the PC simultaneously with input signals from the probe which is under calibration. This allows real time calibration from which third-order polynomial curve fitting may be derived for application to the sensors under calibration.

2.1.2. Deployment and position fixing

For each survey, profiling was undertaken on a pre-defined grid. Stations within this grid were sampled repeatedly to obtain temporal as well as spatial variability. Specific details on station locations and sampling routines are given in the chapters describing each survey.

In each case, the CTD profiler was deployed, from the stern of the vessel, in free fall mode. The sampling rate was set at 50 Hz and the GPS (Global Positioning System) was used for fixing positions.

2.1.3. Recording and display of CTD data

The measured data were directly transmitted to a portable PC and displayed on the screen. The data were then recorded on the hard disk of a portable computer and backups onto floppy discs made. Upon return to CWR, the data was transferred to a SUN Microsystems computer for analysis.

2.1.4. Processing and analysis of CTD data

After the application of pre-processing routines (sharpening, filtering, salinity and density calculations, etc.), the data was presented as contour plots showing the horizontal and vertical distributions of temperature, salinity and turbidity.

2.2. Microstructure profiler

The microstructure profiler is a portable instrument designed to measure extremely small scale fluctuations in the temperature and conductivity of water bodies. These data are used to infer the turbulent kinetic energy levels and the in situ fluxes and diffusivities. The profiler can be used as a stand-alone instrument or may be used as part of a total field measurement system integrating boat position fixing, instrument calibration, fine-scale and microstructure data acquisition and processing, and real time analysis and presentation.

The microstructure profiler is equipped with a depth sensor and two temperature and conductivity sensors:

Sensor	Range	Resolution
Depth	0 - 90 m	0.003 m
Temperature	0 - 40°C	0.001°C
Conductivity	0 - 5 Sm^{-1}	10^{-4} Sm^{-1}

The sensors are specially selected for their accuracy, resolution and short response times rather than long-term stability. The profiler can measure two temperature and conductivity signals and derive the gradients of each. Electronics within the probe include pre-amplifiers for the sensors and a weight release motor. The deck unit houses a laptop PC, a battery powered printer and an electronics interface. This interface contains a 16 bit A-D card and buffers, amplifiers, differentiators and filters for the analogue signals. The front panel houses an instrument depth display, manual gain and offset switches for the signal amplifiers, and switches for the power supply and weight release.

The profiler is designed to measure mixing motions down to scales of millimetres. It is deployed with a disposable ballast and descends at 45° to the vertical. The ballast is released by the operator and the probe, being positively buoyant, then ascends vertically at a constant rate of 0.1 m/s. By sampling all channels at 100 Hz the vertical resolution of the sensors is 1 mm.

2.2.1. Preparation and calibration of the microstructure profiler

Calibration of the temperature, conductivity and pressure sensors was undertaken using an automated interface and a PC based system. The interface, connected to standard sensors, reports directly to the PC simultaneously with input signals from the probe which is under calibration. This allows real time calibration from which third-order polynomial curve fitting may be derived for application to the sensors under calibration.

2.2.2. Deployment Program and position fixing

The microstructure probe was deployed at different locations to obtain time-series measurements of the turbulence levels under different wind, tide and inflow conditions. The selection of the locations was dependent upon the CTD surveys on that particular day. Details are given in following chapters. Position fixing was via GPS.

The instrument, with a disposable weight attached, was deployed from the side of the vessel. A wing on the instrument caused it to sink at 45°; this ensures that when the weight was triggered to release at the desired depth, the probe rose vertically through an undisturbed water column.

2.2.3. Recording and display of microstructure data

The data were directly transmitted to a portable PC, displayed on the screen and then recorded on the hard disk of the portable computer. Backups onto floppy discs were made. Upon return to CWR, the data were transferred to a SUN Microsystems computer for analysis.

2.2.4. Processing and analysis of microstructure data

After the application of pre-processing routines (sharpening, filtering, salinity and density calculations etc.) the data are plotted as vertical profiles of temperature, salinity density and temperature gradient. The buoyancy frequency, a measure of the density stratification, is also calculated from the density profiles.

The temperature, salinity and density profiles reveal layering and billowing events; the temperature gradient signal allows estimation of the dissipation of turbulent kinetic energy. The frequency distribution of the gradient signal is analysed by Fast Fourier Transform and compared with the theoretical frequency distribution of turbulence, known as the Batchelor spectrum. The measured spectrum is fitted to the Batchelor spectrum, and the dissipation is estimated from the fit. This analysis is done over windows of 256 samples, which is assumed to be small enough to ensure stationarity of the gradient signal. A detailed description of this analysis is given in Imberger and Boashash (1996) and Imberger and Ivey (1991).

Given the dissipation of turbulent kinetic energy, ε, and the buoyancy frequency, N, the eddy diffusivity, K_ρ, was calculated using the following formula given by Osborne (1980).

$$K_\rho < 0.2 \frac{\varepsilon}{N^2}$$

We therefore have an upper boundary of eddy diffusivity. This calculation has been performed on many profiles giving the range of diffusivities and therefore mixing rates which occur over a range of tidal and meteorological conditions.

3. BAY WIDE CTD SURVEYS

This section describes the bay-wide CTD surveys undertaken over four different periods in May and September, 1994.

3.1. Methods

The fine scale CTD profiler was used to measure temperature, conductivity and turbidity in the water column. Measurements were made using the Melbourne Water vessel R.V. Proteus over 4 periods:

3-4 May 1994
12-16 May 1994
14 -15 September 1994
29 September to 3 October 1994

Summaries of the survey operations for these periods are presented in the table below.

Table 3.1: Survey operation details

	3 May 1994	**4 May 1994**	**12 May 1994**	**13 May 1994**	**16 May 1994**
Weather conditions	*Sunny, calm seas, no wind*	*Sunny, calm seas, no wind*	*SE winds, overcast*	*Sunny, 0.5m sea stormy change*	*Overcast, 0.5-1 m seas*
Start Time	0733	0816	0702	0750	0754
Number of Sites	45	40	49	5	35
Finish Time	1758	1750	1719	0843	1414
	14 Sep 1994	**15 Sep 1994**	**29 Sep 1994**	**30 Sep 1994**	**3 Oct 1994**
Weather conditions	*Overcast, 5 kn westerly, deteriorated.*	*Sunny, 1 to 1.5 m seas*	*Seas calm, little wind.*	*Sunny, winds to 5 kn, deteriorated.*	*Slight cloud, winds 5 to 10 kn.*
Start Time	0701	0618	0624	0737	0635
Number of Sites	33	41	51	10	29
Finish Time	1329	1530	1702	1038	1351

3.2. Results

Survey 1: 3-4 May 1994

Figures 3.1 to 3.3 show the surface distribution of temperature, salinity and turbidity, respectively.

The Surface temperature data indicate colder water along the shallow perimeter (nearshore) of PPB with warmer water in the centre of the bay. The surface temperature ranged from 14 C (adjacent to Werribee) to 16.2°C at the centre of the bay. This structure was maintained to 5m depth. From the surface salinity distribution, the Yarra plume may be identified extending approximately 1 km into the bay. The salinity values increase towards the Heads where a maximum salinity value of 35.4 pss was recorded. The salinity structure is vertically homogenous except in the vicinity of the Yarra River where there is strong vertical stratification (Figure 3.4) The turbidity distribution indicates that the western and southern sections of PPB consists of clear water (< 3.0 NTU). In contrast the eastern end of the bay has very high levels of turbidity. The source of the turbidity does not appear to be the Yarra River. The higher turbidity patch along the eastern shore is found in the top 5m of the water column.

Survey 2: 12-16 May 1994

Figure 3.5 and 3.6 show the surface distribution of temperature and salinity respectively.

Surface temperature distribution shows a similar pattern to the previous survey: colder water along the shallow perimeter of PPB with warmer at the centre of the bay. However, the surface temperature has decreased by approximately 1°C : the surface temperature ranges from 13.2°C (adjacent to Werribee) to 15.2°C at the centre of the bay. Again, the water column was unstratified. The surface salinity distribution is again similar to the previous survey except that the Yarra plume may be identified extending further into the bay. Again the salinity structure is vertically homogenous except in the vicinity of the Yarra River where there is strong vertical stratification (Figure 3.7).

Survey 3: 14-15 September 1994

Figure 3.8 to 3.10 show the surface distribution of temperature, salinity and turbidity, respectively.

Surface temperature data indicate warmer water along the shallow perimeter (nearshore) of PPB with cooler water in the centre of the bay. The surface temperature ranged between 12.2°C (adjacent to Werribee River and the Yarra outflow) and

11.4°C at the centre of the bay. This structure was maintained to 5m depth except near the Sands region where an influx of warmer (12.2°C) water from Bass Strait at depths greater than 2 metres may be identified. From the salinity distribution, the Yarra plume may be identified extending approximately 5 km into PPB along the eastern shore. Lower salinity values are also present along the eastern shoreline and adjacent to the Werribee River. The salinity values increased towards the Heads where a maximum salinity value of 35.0 pss was recorded. The salinity structure is vertically homogenous except in the vicinity of the Yarra River where there is strong vertical stratification (Figure 3.11). The horizontal turbidity distribution in the surface waters of the bay varies between 0 and 2 NTU, decreasing to < 1 NTU at most measurement sites below 2 m depth. The turbidity of the Yarra Plume varies from 2-3 NTU at the surface to 1-2 NTU at 5 m depth.

Survey 4: 29 September to 3 October 1994

Figure 3.12 to 3.14 show the surface distribution of temperature, salinity and turbidity, respectively.

Surface temperature distribution now shows a gradient, from < 11.0°C near the Werribee River to > 12.4°C at the Heads. The surface salinity distribution is similar to the previous survey except that it has decreased by 0.2 pss over most of the bay, and the Yarra plume has extended more than 10 km into PPB. The salinity of the Yarra Plume has decreased markedly from 33.6 pss at the mouth to 31 pss. This survey was undertaken after some heavy rainfall events. The data indicate that the salinity of the bay reflects the effects of freshwater input with very little time lag (order of days). Again the salinity structure is vertically homogenous except in the vicinity of the Yarra River where there is strong vertical stratification (Figure 3.15). The turbidity in the northern and eastern parts of the bay has increased substantially since the previous survey. Values at the surface are patchy, varying from 13 NTU at the mouth of the Yarra to 1 NTU in Corio Bay and at the Heads. There is a small patch of high (7-9 NTU) about 20 km from Melbourne on the eastern shore. The turbidity decreases with depth and becomes more uniform. At 5 m depth there is a fairly sharp demarcation between the north and east with 2 NTU and the remainder of the bay with < 1 NTU.

3.3. Summary and Conclusions

Measurements of salinity, temperature and turbidity were taken over the whole Bay in four separate surveys carried out during two periods in May and September/October 1994, respectively. The distribution of salinity and temperature over the two periods show distinct seasonal variation. Between the May and September/October surveys, temperature decreased by about 5°C in the centre of PPB and by 2°C at the periphery; salinities were 0.2 to 0.4 pss higher throughout PPB. Turbidity levels are related to the freshwater input to the bay. In the first May survey there was a region of high turbidity near the eastern shoreline. This was absent for the first survey in September but was evident during the second.

Salinity is the principal conservative parameter and plays the major role in dictating density and, hence, mixing characteristics. Its horizontal distribution is determined by the inputs to the bay, therefore, the salinity reduces towards the coastline. Evaporation is also likely to play a significant role in the distribution. The largest gradients are associated with the Yarra Estuary at one end of PPB and the Sands region at the other. In the vertical, the water column is well mixed over the bay except in the vicinity of the Yarra Estuary where there is strong vertical stratification.

The response of PPB to periods of rainfall (therefore discharge) is demonstrated by the salinity distributions obtained during Surveys 3 and 4. Although the surveys were undertaken 14-15 days apart there is a marked change in salinity distribution between them, particularly in the Yarra Plume region. Survey 3, which was undertaken when the Yarra River discharge was 10-12 m^3/s indicates that the plume, defined as water <34.0 pss (Section 5.1.3) is limited to Hobsons Bay and extends up to 5 km along the eastern shoreline. In contrast, during Survey 4, when the Yarra discharge had increased to 45 m^3/s, the 34.0 pss contour extended along the whole length of PPB. There was considerable amount of rainfall between the two surveys and therefore, this feature is not due to the Yarra Plume alone. These results (Surveys 3 and 4) provide a data set to verify the performance of the transport model for the Bay.

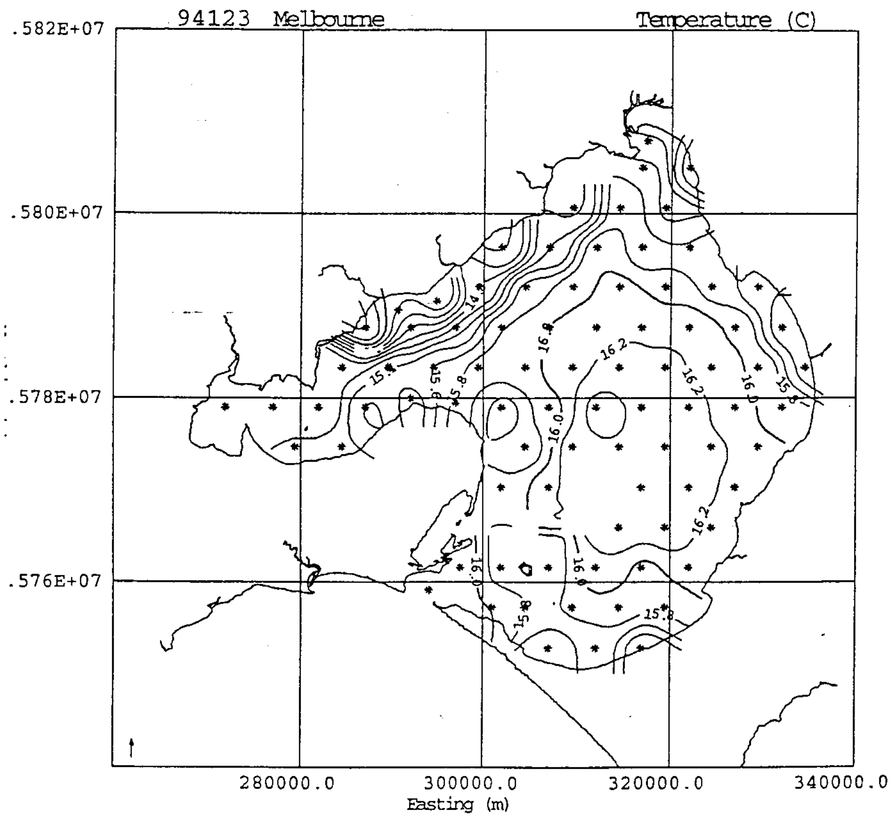

Figure 3.1: Distribution of surface temperature over the whole Bay measured in Survey 1 (3 and 4 May, 1994)

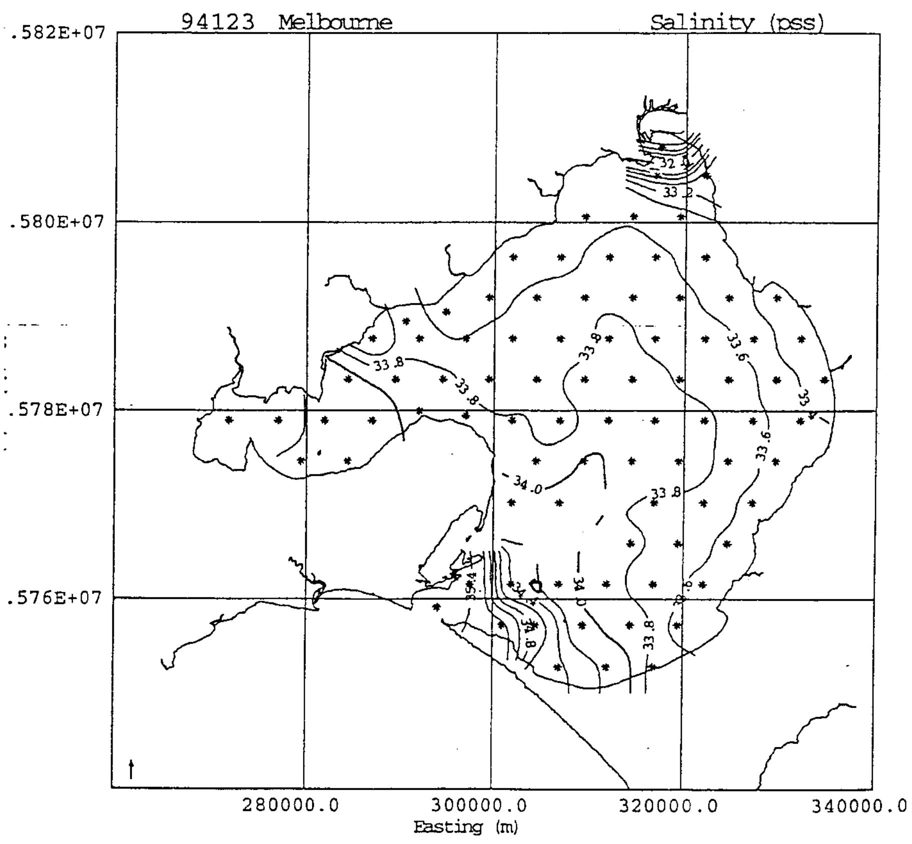

Figure 3.2: Distribution of surface salinity over the whole Bay measured in Survey 1 (3and 4 May, 1994)

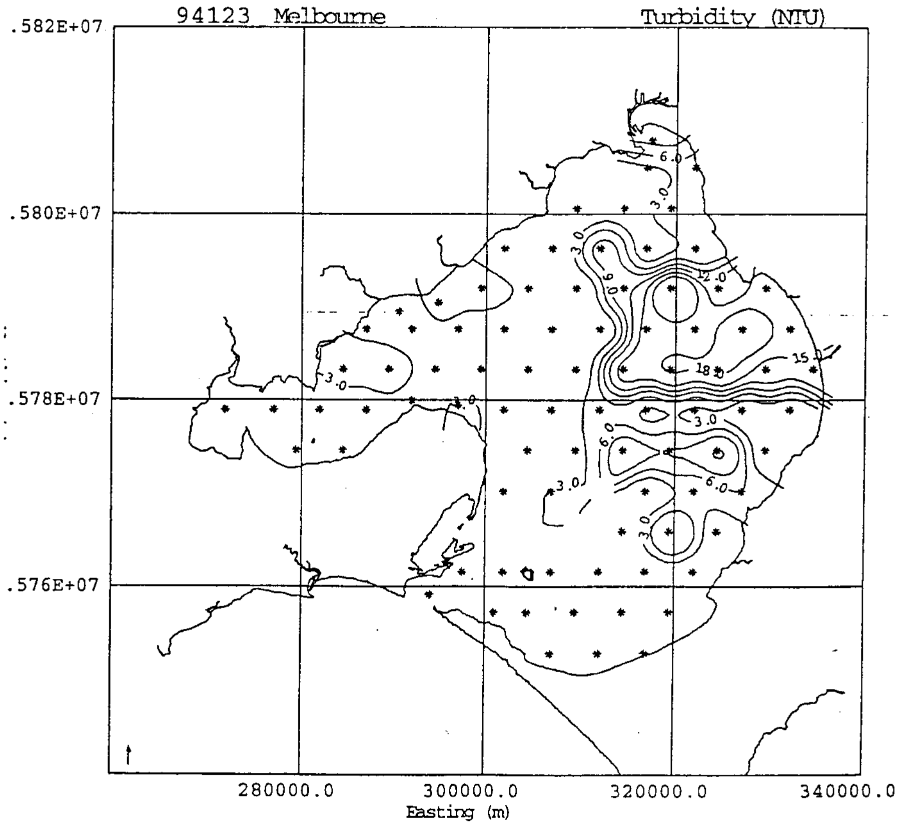

Figure 3.3: Distribution of surface turbidity over the whole Bay measured in Survey 1 (3 and 4 May, 1994)

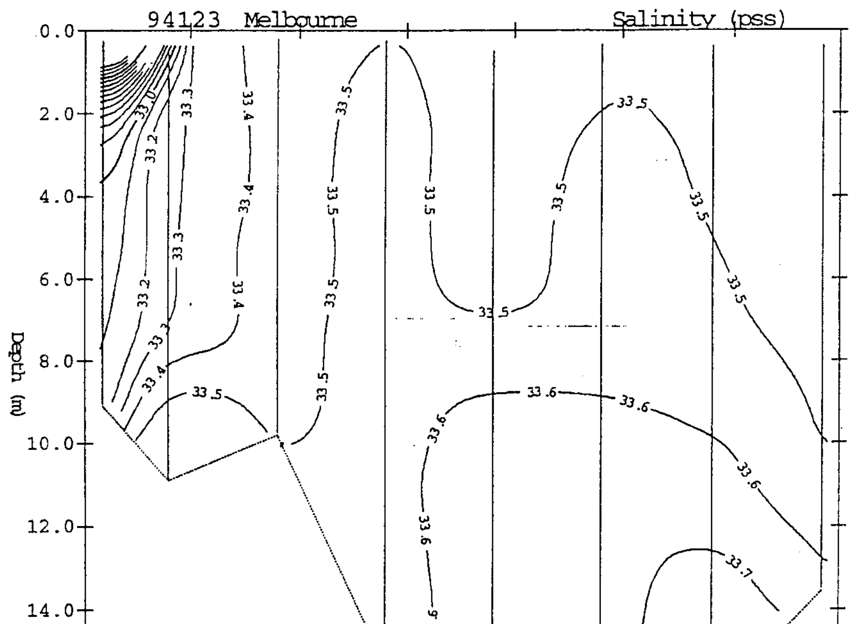

Figure 3.4: Vertical distribution of salinity along the eastern coastline and through the Yarra Plume in Survey 1 (3 and 4 May, 1994)

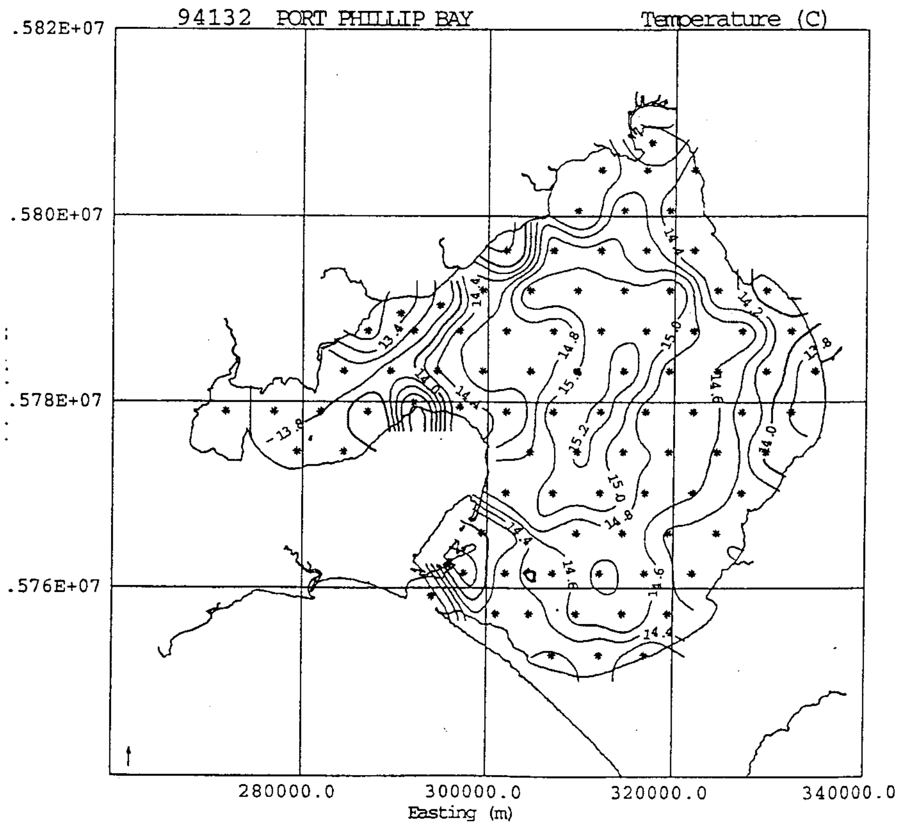

Figure 3.5: Distribution of surface temperature over the whole Bay measured in Survey 2 (12 to 16 May, 1994))

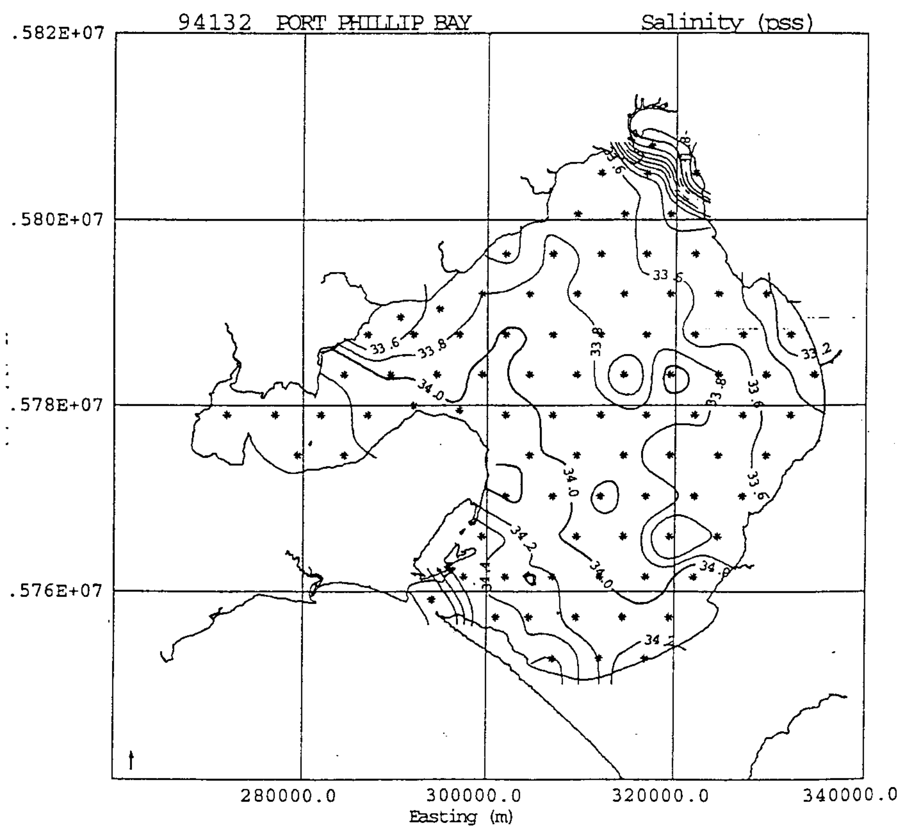

Figure 3.6: Distribution of surface salinity over the whole Bay measured in Survey 2 (12 to 16 May, 1994)

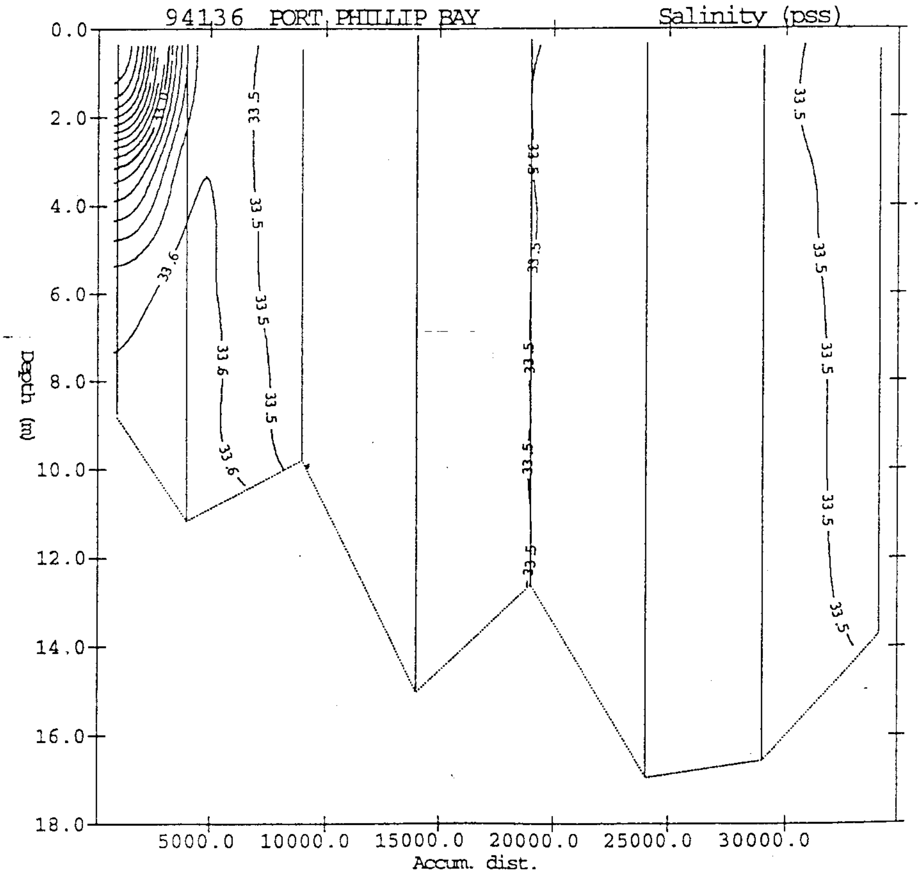

Figure 3.7: Vertical distribution of salinity along the eastern coastline and through the Yarra Plume in Survey 2 (12 to 16 May, 1994)

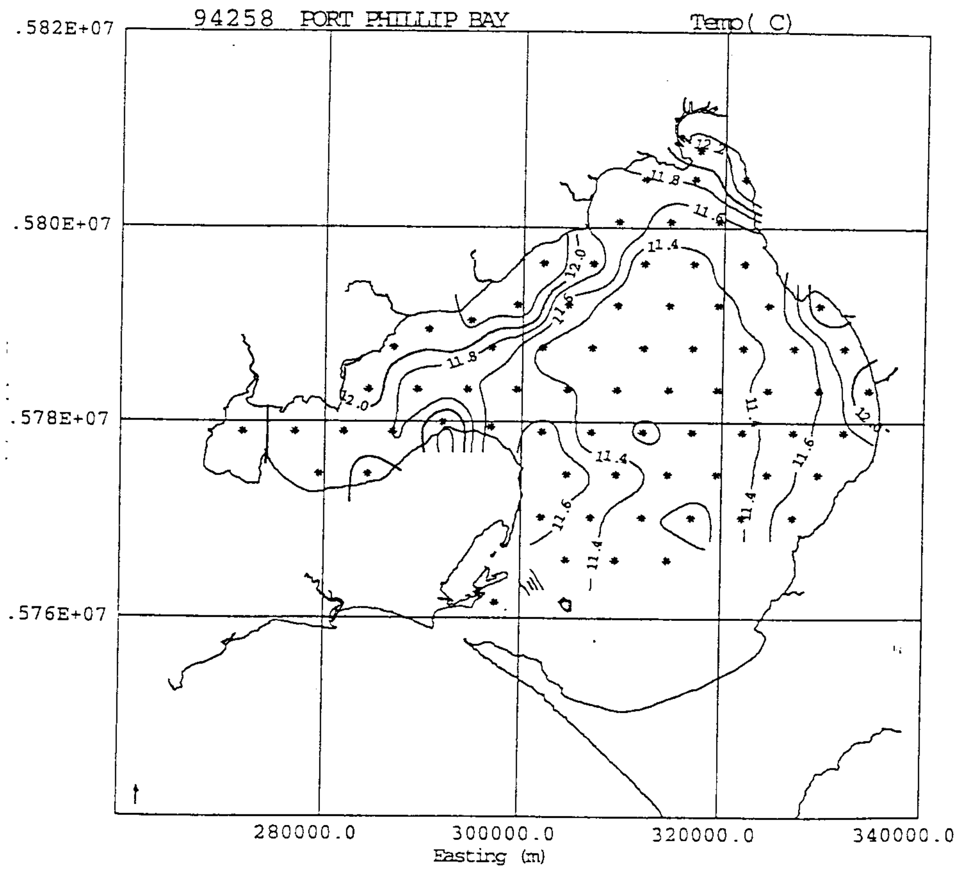

Figure 3.8: Distribution of surface temperature over the whole Bay measured in Survey 3 (14 and 15 September, 1994)

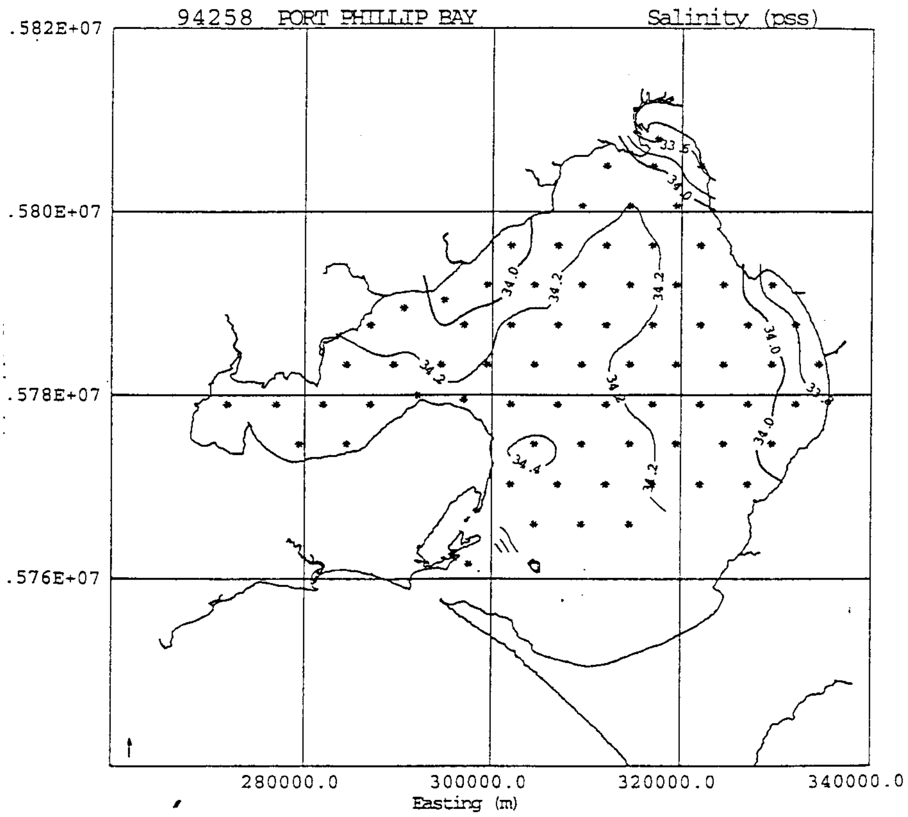

Figure 3.9: Distribution of surface salinity over the whole Bay measured in Survey 3 (14and 15 September, 1994)

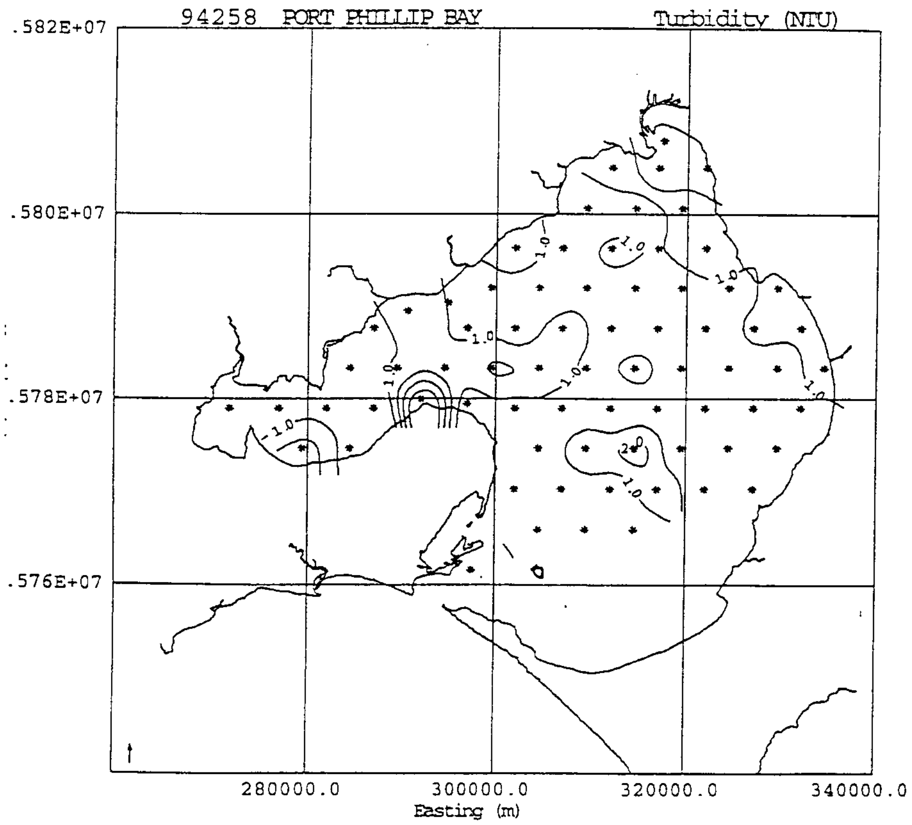

Figure 3.10: Distribution of surface turbidity over the whole Bay measured in Survey 3 (14 and 15 September, 1994)

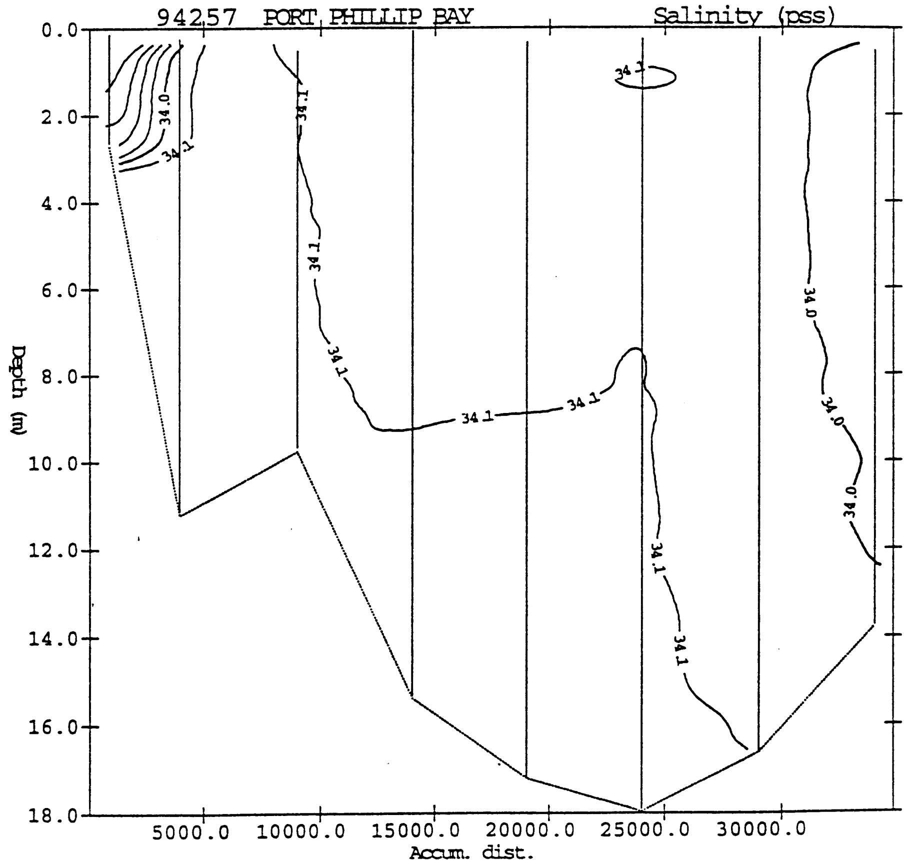

Figure 3.11: Vertical distribution of salinity along the eastern coastline and through the Yarra Plume in Survey 3 (14 and 15 September, 1994)

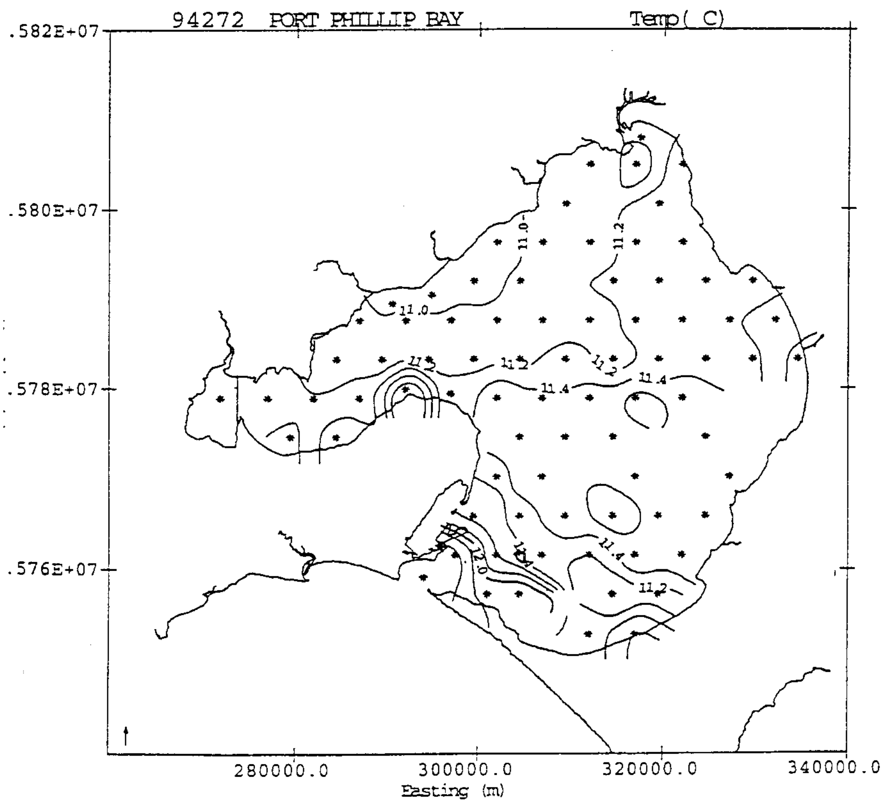

Figure 3.12: Distribution of surface temperature over the whole Bay measured in Survey 4 (29 September to 3 October, 1994)

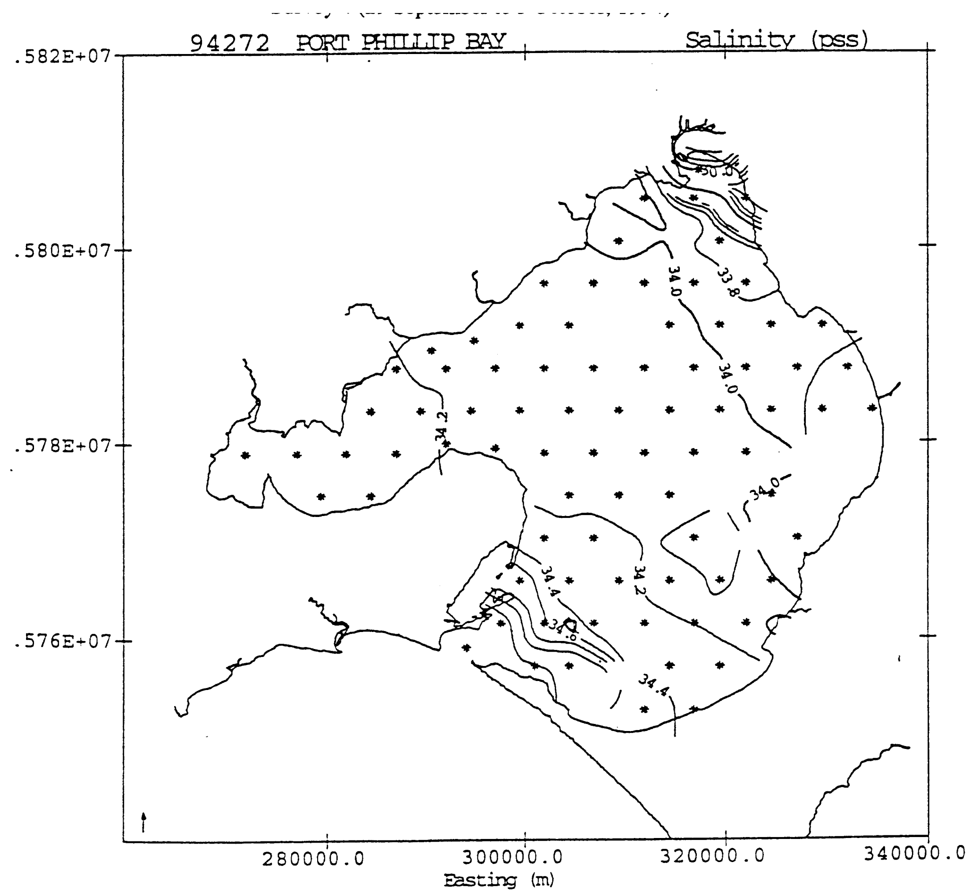

Figure 3.13: Distribution of surface salinity over the whole Bay measured in Survey 4 (29 September to 3 October, 1994)

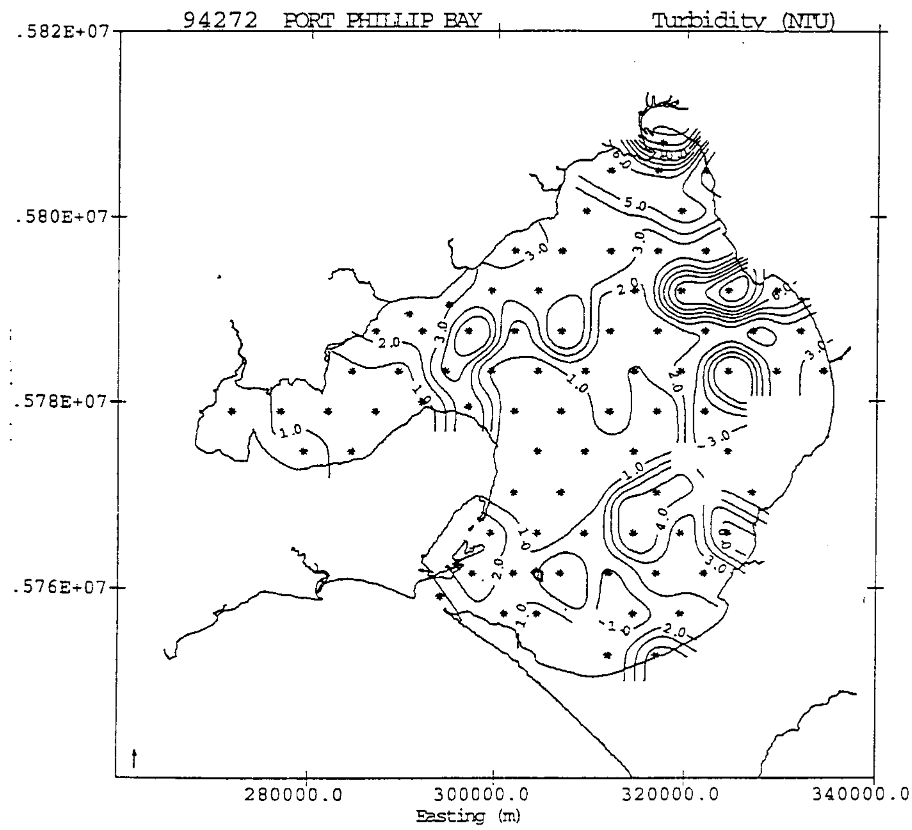

Figure 3.14: Distribution of surface turbidity over the whole Bay measured in Survey 4 (29 September to 3 October, 1994)

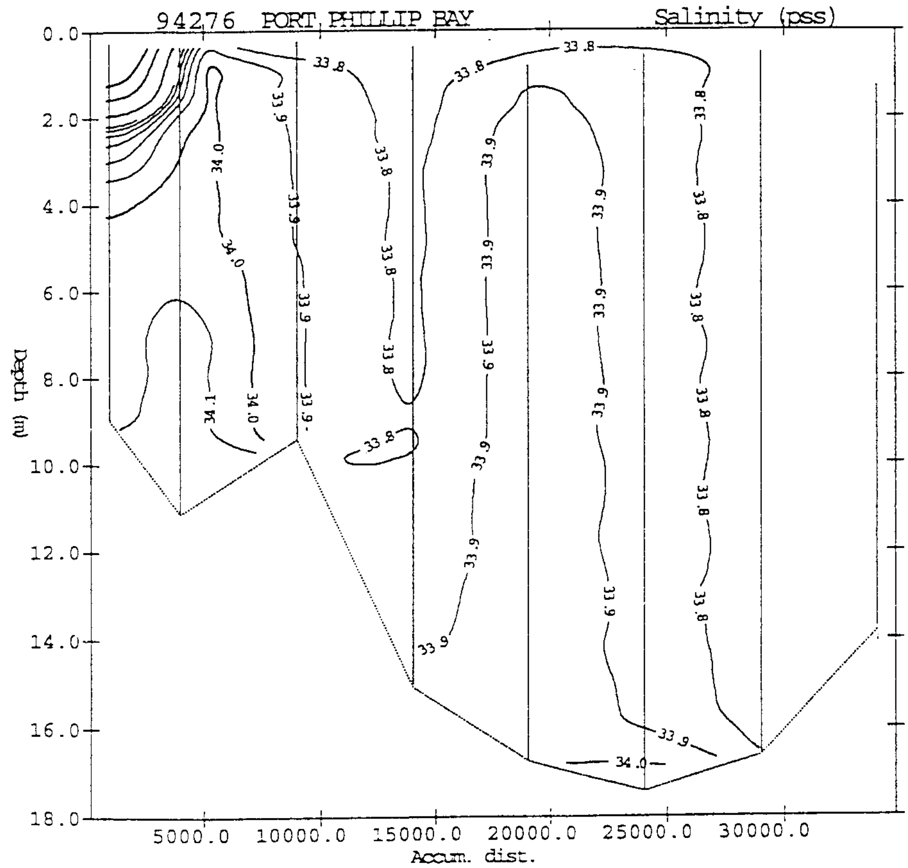

Figure 3.15: Vertical distribution of salinity along the eastern coastline and through the Yarra Plume in Survey 4 (29 September to 3 October, 1994)

4. THE SANDS FLUSHING EXPERIMENT

The objectives of the Sands Flushing Experiment was to examine the mixing between the Bass Strait and the Port Phillip Bay waters; and to quantify the tidal exchange ratio and the flushing time for the Bay

CTD and ADCP surveys were carried out in the region between the 7th and 12th of May, 1994. These surveys are described and the results presented below. Section 4.3 presents the calculations for the tidal exchange ratio and flushing time for PPB.

4.1. CTD Surveys

4.1.1. Survey Procedures

Field data was collected on 7 to 11 May 1994 using the Melbourne Water vessels R.V. *Proteus* and R.V. *Mokera* and the Department of Conservation vessel *Gratis*. Profiles were collected using the fine scale CTD profiler at stations along five main transects over the Sands region. These are shown in Figure 4.1 (a) and (b) and include:

(1)	The 'Entrance' transect:	This transect with 9 stations was located across the entrance to Port Phillip Bay and was performed to coincide with the Acoustic Doppler Current Profiler surveys. 14 repeat transects were completed.
(2)	The 'West Channel' transect:	This transect with 9 stations was located along the axis of the West Channel. 8 repeat transects were completed.
(3)	The 'Symonds Channel' transect:	This transect with 9 stations was located along the axis of the Symonds Channel. 8 repeat transects were completed.
(4)	The 'South Channel' transect:	This transect with 11 stations was located along the axis of the South Channel. 8 repeat transects were completed.
(5)	The 'Bayward Edge' transect:	This transect with 9 stations was located along the northern end of the Sands region. 9 repeat transects were completed.

The aim of the surveys was to complete as many transects as possible to define the spatial and temporal variation along the transects over a tidal cycle. A summary of the data collected over the 5 day period is presented in Table 4.1.

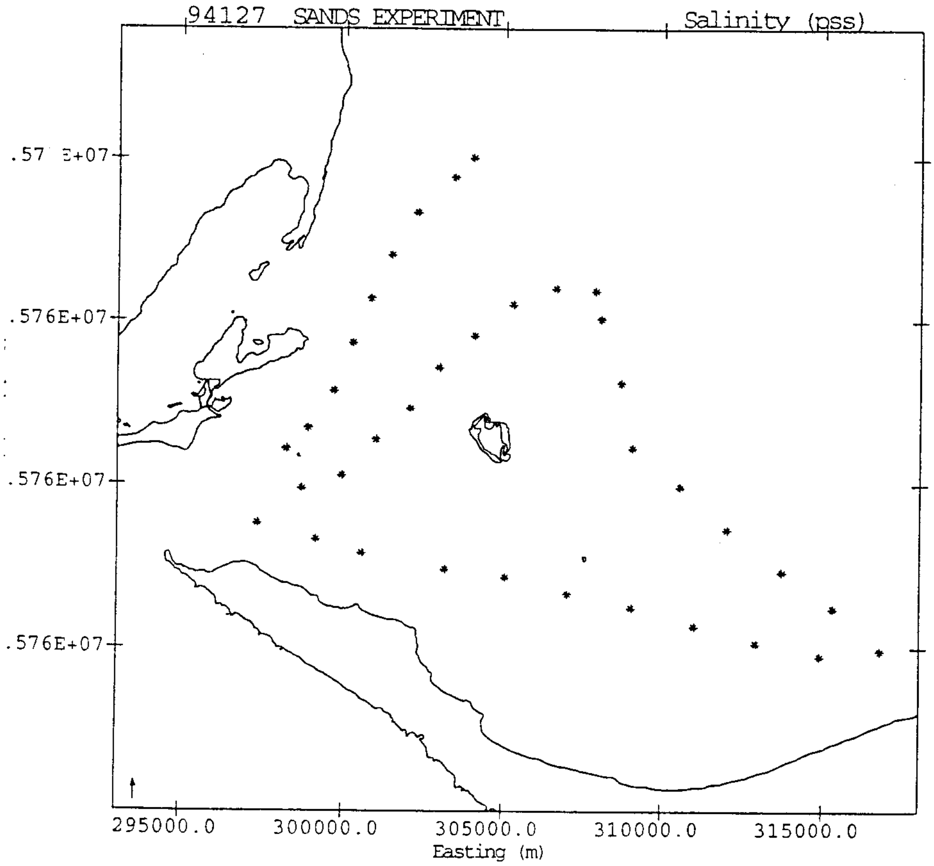

Figure 4.1(a): Site locations for channel transects

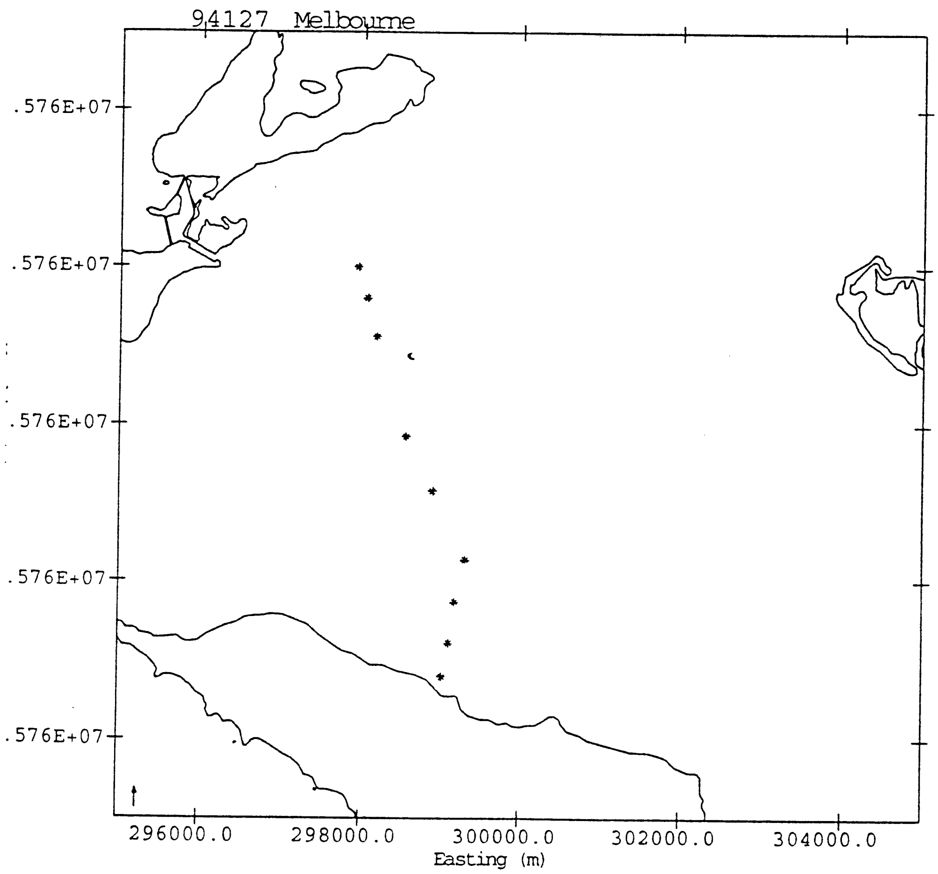

Figure 4.1(b): Site locations for entrance transects

Table 4.1: Summary of field data collection for the Sands experiment.

Transect Location, Date, and Probe	Start Time	End Time	Direction of Stream	Tide Age (hours)	Comments
7 May 1994					Very cloudy, little wind
Melbourne Water F-Probe					
South Channel	759	856	Flood	3	
Bayward Edge of Sands	856	948		4	South section
Symonds Channel	948	1034		5	
West Channel	1039	1119		5	
Bayward Edge of Sands	1119	1230	Ebb	0	Whole transect
South Channel	1230	1334		1	
Symonds Channel	1341	1431		2	
Bayward Edge of Sands	1431	1454		3	North section
West Channel	1454	1530		3	
South Channel	1547	1701		5	
CWR F-Probe					
Entrance	818	900	Flood	3	
Entrance	1005	1036		5	
Entrance	1143	1214	Ebb	0	
Entrance	1314	1343		2	
Entrance	1501	1542		4	
Entrance	1644	1711		5	
8 May 1994					Partly cloudy, light winds
Melbourne Water F-Probe					
West Channel	808	854	Flood	2	
Bayward Edge of Sands	854	932		2	North section
Symonds Channel	932	1022		3	
South Channel	1036	1152		5	
CWR F-Probe					
West Channel	1023	1111		4	
9 May 1994					
Melbourne Water F-Probe					
South Channel	1255	1407		6	
Bayward Edge of Sands	1407	1454	Ebb tide	0	South section
Symonds Channel	1454	1529		1	
Entrance	1627	1651		3	
Entrance	1749	1827		4	
CWR F-Probe					
Entrance	1300	1332		6	
Entrance	1428	1445		0	

Table 4.1 (cont.)

Transect Location, Date and Probe	Start Time	End Time	Direction of Stream	Tide Age (hours)	Comments
10 May 1994					
Melbourne Water F-Probe					
Entrance	655	731	Ebb	5	
Symonds Channel	740	820		5	
Bayward Edge of Sands	820	846		6	North section
West Channel	846	927	Flood	0	
Entrance	932	1002		1	
Symonds Channel	1013	1054		2	
Bayward Edge of Sands	1054	1121		2	North section
West Channel	1121	1201		3	
Entrance	1207	1238		4	
Symonds Channel	1249	1328		4	
Bayward Edge of Sands	1328	1354		5	North section
West Channel	1354	1435		6	
Entrance	1440	1506	Ebb	0	
Symonds Channel	1516	1553		0	
Bayward Edge of Sands	1553	1617		1	North section
West Channel	1617	1653		2	
Entrance	1658	1726		2	
11 May 1994					1 to 2 m seas wind to 20 knots
Melbourne Water F-Probe					
Entrance	0737	835	Ebb	5	
South Channel	0843	915		6	Aborted
South Channel	1301	1358	Flood	4	
South Channel	1451	1553		6	

4.1.2. Results

Plots showing the distribution of surface salinity through the tidal cycle are shown in Figures 4.2 (a) - (e). Corresponding vertical transects through the West Channel are shown in Figures 4.3 (a) - (h).

Three main water masses are identified: The Bass Strait water, defined as water having a salinity > 35.3 pss and temperature > 15.5°C. The Port Phillip Bay water defined as having a salinity < 34.0 pss and temperature < 15.5°C. There is also a 'mixed' water mass situated mainly in the Sands region which varies in salinity between 34.0 and 35.3 pss.

The vertical distribution of salinity and temperature indicate that although the area is vertically homogenous there are horizontal changes associated with the different water masses present in the area. This may be identified from both the horizontal and vertical contour plots. Firstly, the surface salinity distribution during the period at the start of the flood tide (Figure 4.2(a)) shows no evidence of Bass Strait water as the 35.0 pss contour is only present along the eastern end of the Heads. At the eastern edge of South Channel, the Port Phillip Bay water (salinity < 34.0 pss) is identified. It is also possible that Port Phillip Bay water is present along the northern edge of the Sands region. The 'mixed' water mass covers the region seaward of Mud Island and extends almost 10 km into the South Channel. Three hours into the flood (Figure 4.2(b)) the intrusion of Bass strait water into the Bay may be identified with Port Phillip Bay water still present along the eastern edge of the Sands region. An hour later (Figure 4.2(c)), the Bass Strait water extends up to Mud Island with Port Phillip Bay water still present along the eastern edge of the Sands region. At the end of the flood tide (Figure 4.2(d)) the Bass Strait water extends beyond Mud Island.

The vertical transects indicate that the water column in the sands region is vertically mixed. The movement of the frontal system formed between the intruding Bass Strait water and the mixed water mass is clearly identified in the transects. A good example of this process is shown in Figures 4.3 (a) - (h) for the West Channel. At the start of the flood tide (Figure 4.3 (a): Flood tide: 0.5 hours), the channel consists of water with salinity < 34.2 pss and the 34.2 pss contour located at the seaward end of the channel. Two hours after the start of the flood (Figure 4.3 (b) Flood tide: 2 hours), the 34.2 pss contour has migrated 5 km along the channel and the maximum salinity at the channel entrance is 34.5 pss. Another hour later (Figure 4.3 (c)), the 34.2 pss contour has migrated a further 4 km along the channel and the maximum salinity at the channel entrance is 35.25 pss corresponding to the Bass Strait water. Hence, it has taken almost 3 hours before the Bass Strait water enters the Channel. Two hours later, (Figure 4.3 (d) Flood tide: 5 hours) the position of the 34.2 contour has moved a further 2 km. At the end of the flood tide (Figure 4.3 (e) Flood tide: 6 hours) up to 6 km of the seaward end of the channel consists of Bass Strait water (> 35.3 pss) whilst the bay end of the channel consists of the 'mixed' water mass. After the start of the ebb tide (Figure 4.3 (f-h)) the higher salinity water is moved out of the channel. The other channel transects: Symonds Channel and South Channel also indicate a similar process. All the transects indicate that the presence of Bass Strait water in the channels occur approximately 3 hours after the beginning of the flood tide and that the maximum excursion of this water mass along the channel is about 6 km.

From the above observations it is apparent that whilst on the flood tide a high proportion of Bass Strait Water enters the channels only a small proportion actually reaches the bay. Similarly, on the ebb tide, only a small proportion of the PPB water actually reaches the Bass Strait. This demonstrates the limited tidal exchange over the Sands Region.

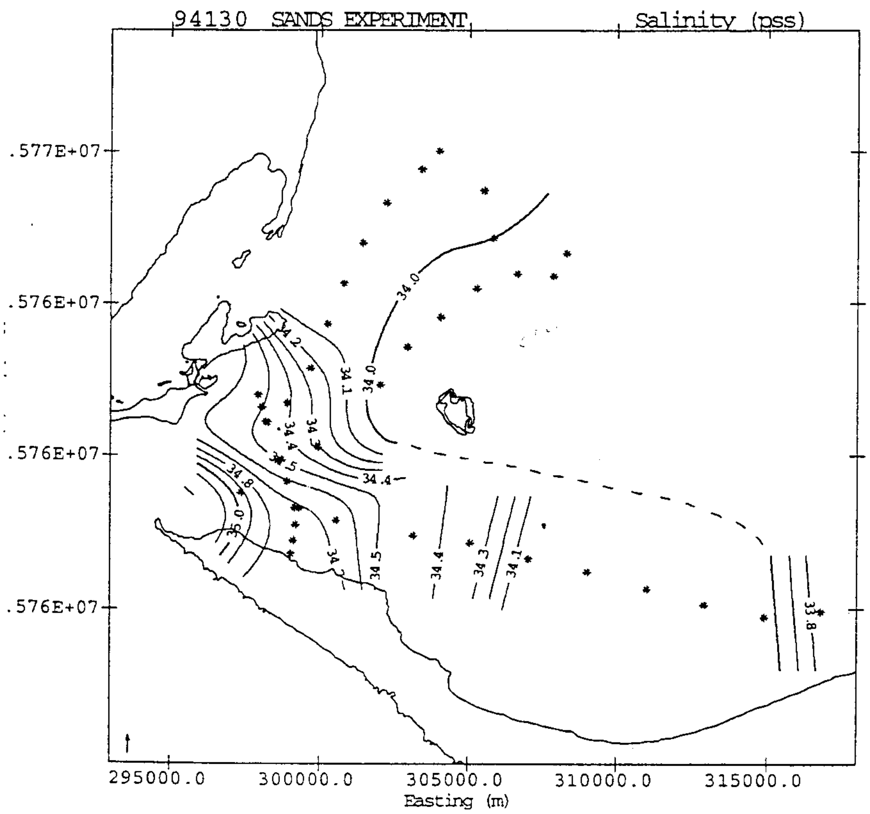

Figure 4.2(a): Surface Distribution of salinity for the Sands Experiment surface to 1m depth Ebb tide:5 hours to Flood tide: 0.5 hours

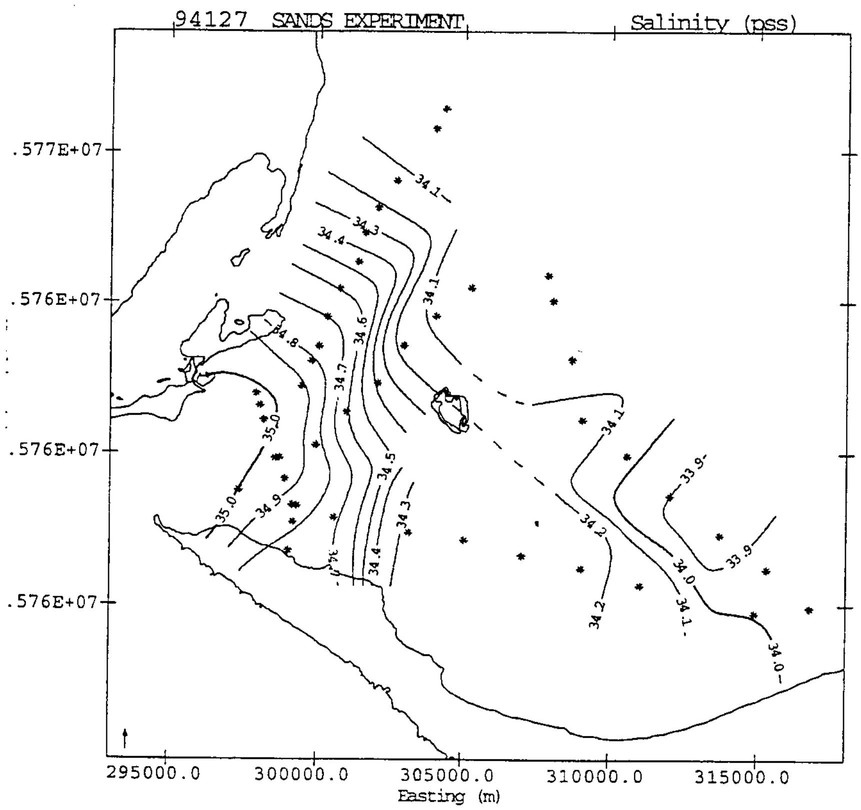

Figure 4.2(b): Surface Distribution of salinity for the Sands Experiment surface to 1m depth Flood tide: 3 to 4 hours

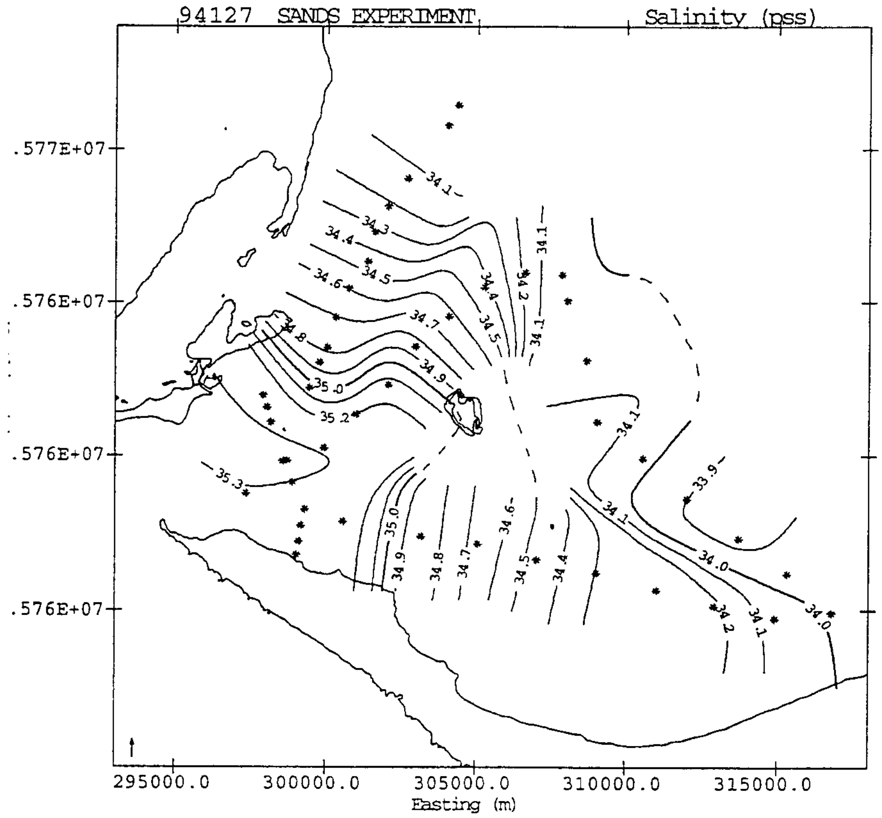

Figure 4.2(c): Surface Distribution of salinity for the Sands Experiment surface to 1m depth Flood tide: 4 hours

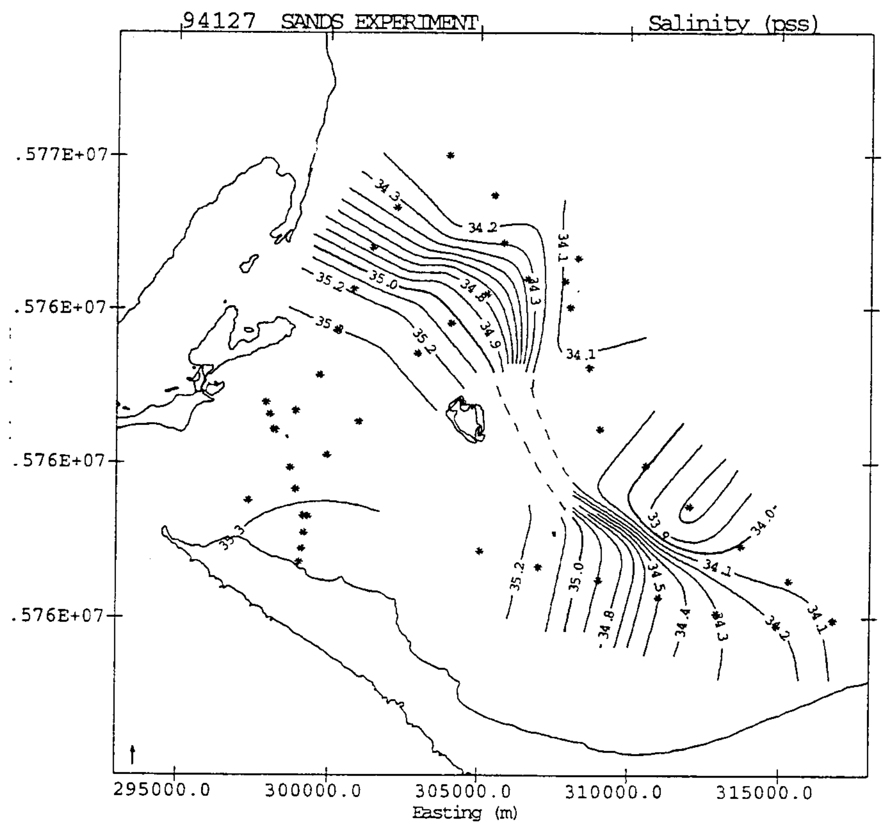

Figure 4.2(d): Surface Distribution of salinity for the Sands Experiment surface to 1m depth Flood tide: 6 hours to Ebb tide: 0.5 hours

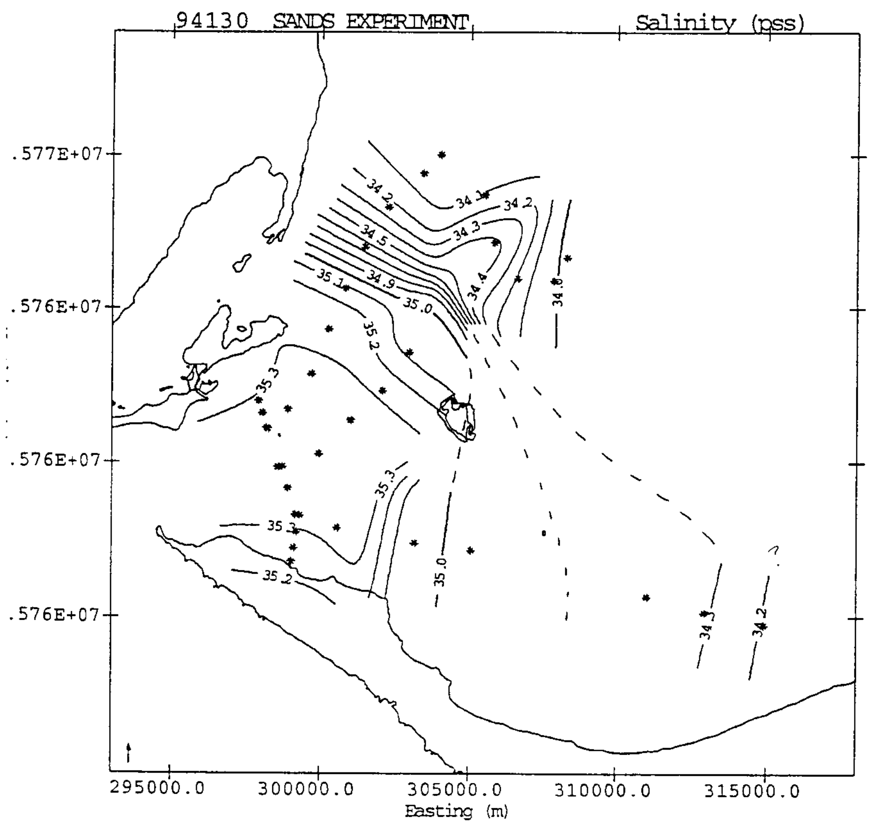

Figure 4.2(e): Surface Distribution of salinity for the Sands Experiment
surface to 1m depth Ebb tide: 1 to 2 hours

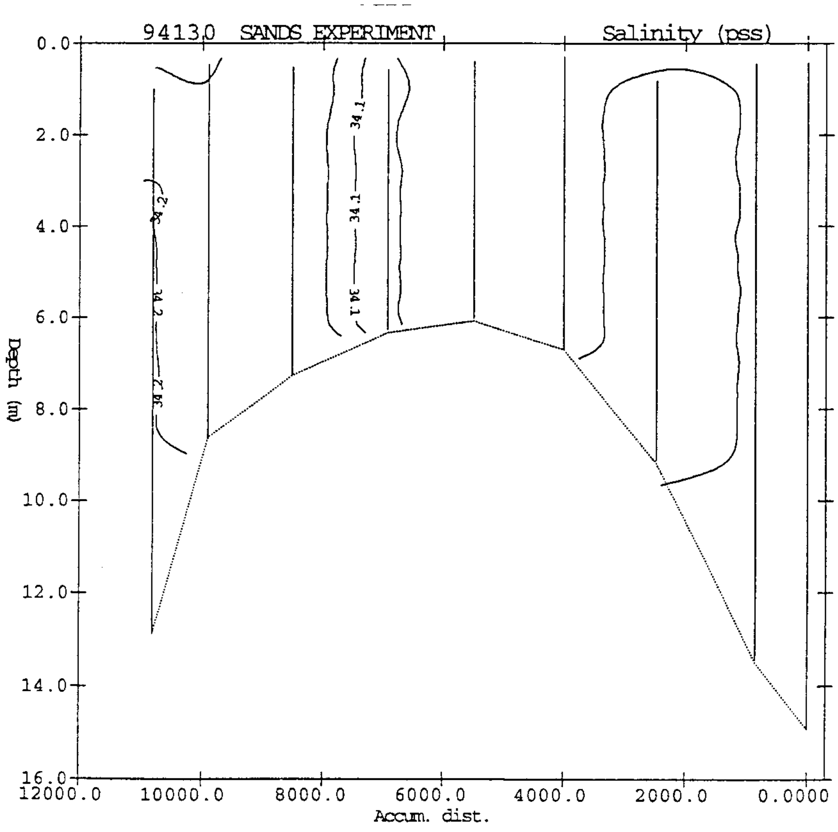

Figure 4.3 (a): Vertical distribution of salinity through the West Channel for the Sands Experiment
846 to 927, 10 May 1994 Flood tide: 0.5 hours

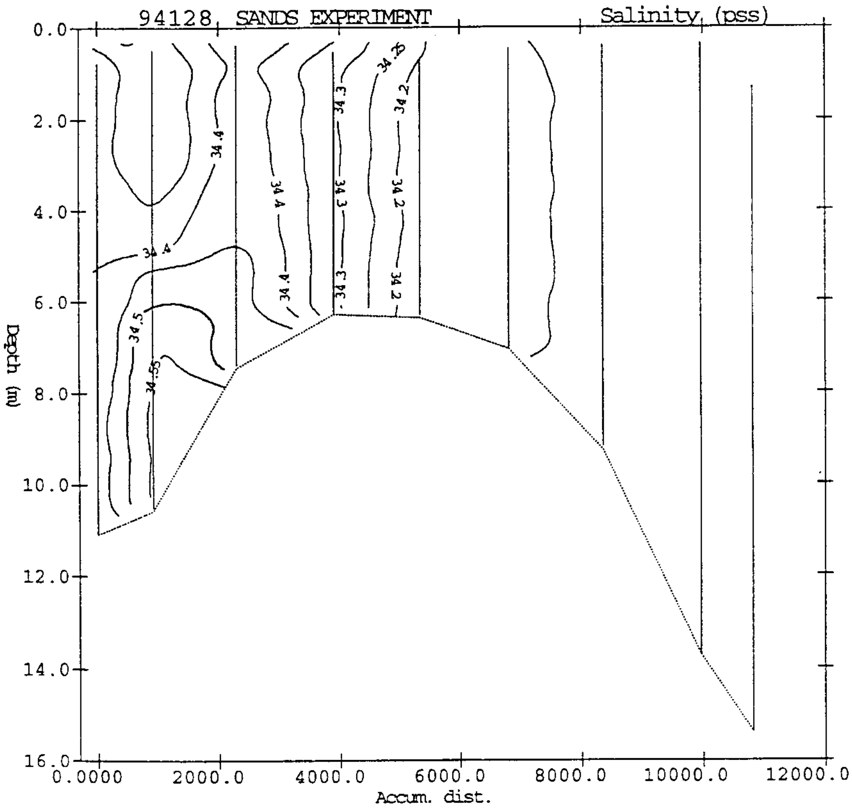

Figure 4.3 (b): Vertical distribution of salinity through the West Channel for the Sands Experiment 808 to 854, 8 May 1994 Flood tide: 2 hours

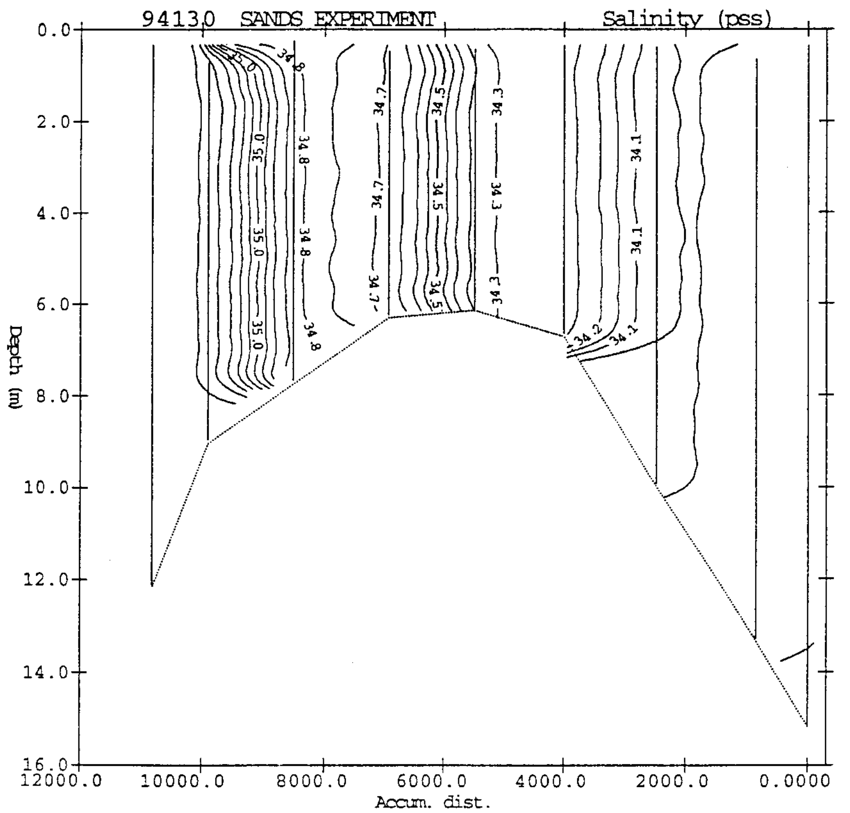

Figure 4.3 (c): Vertical distribution of salinity through the West Channel for the Sands Experiment 1121 to 1201, 10 May 1994 Flood tide: 3 hours

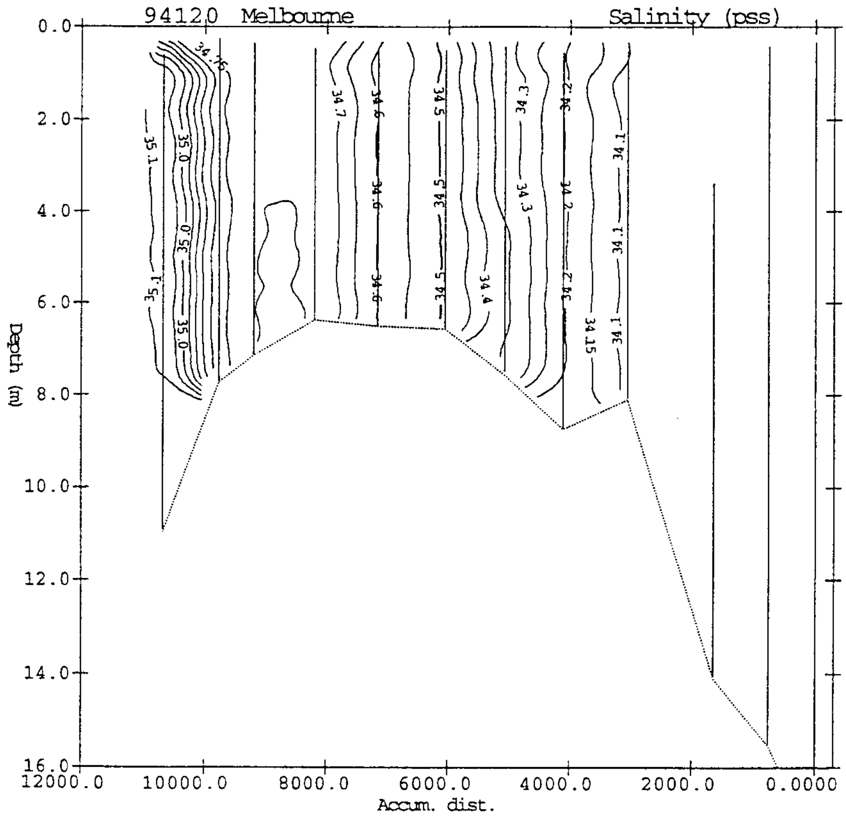

Figure 4.3 (d): Vertical distribution of salinity through the West Channel for the Sands Experiment
1023 to 1111, 8 May 1994 Flood tide: 4 hours

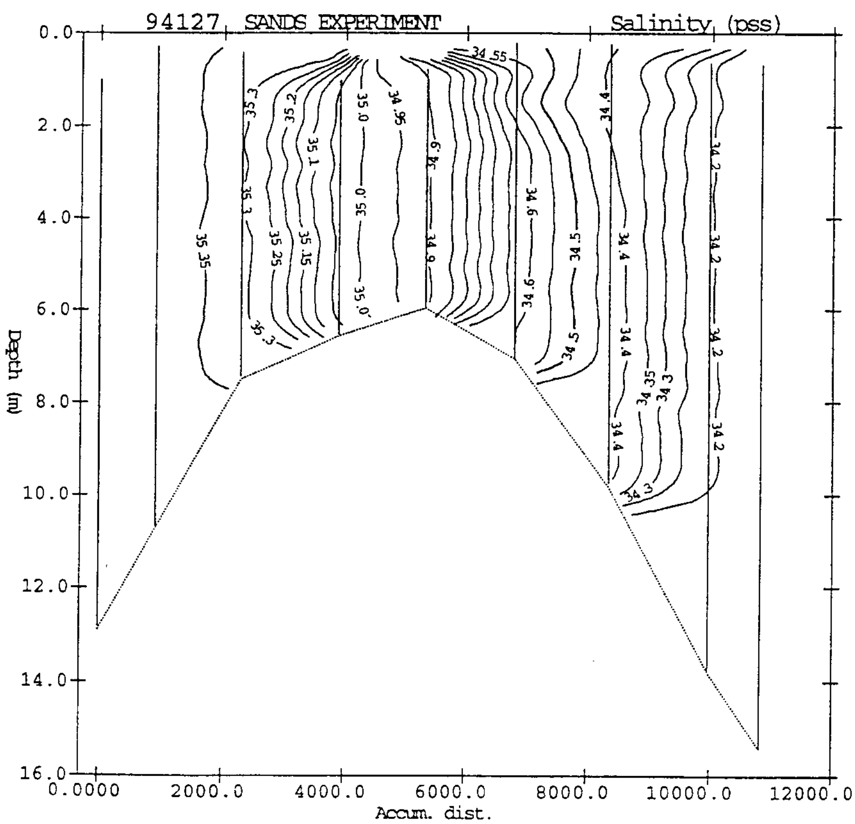

Figure 4.3 (e): Vertical distribution of salinity through the West Channel for the Sands Experiment
1039 to 1119, 7 May 1994 Flood tide: 5 hours

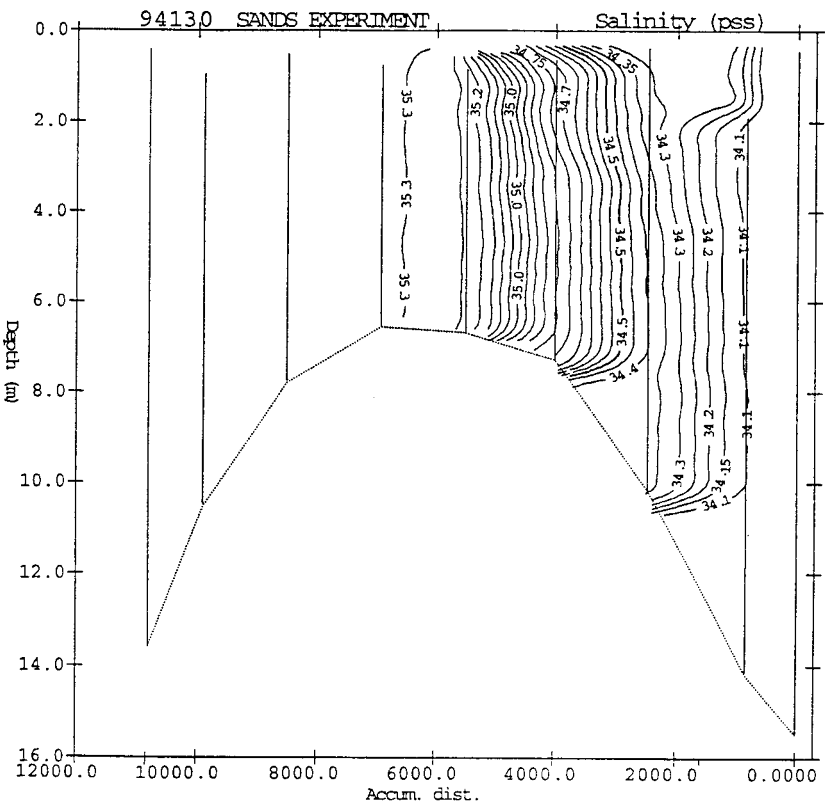

Figure 4.3 (f): Vertical distribution of salinity through the West Channel for the Sands Experiment
1354 to 1435, 10 May 1994 Flood tide: 6 hours

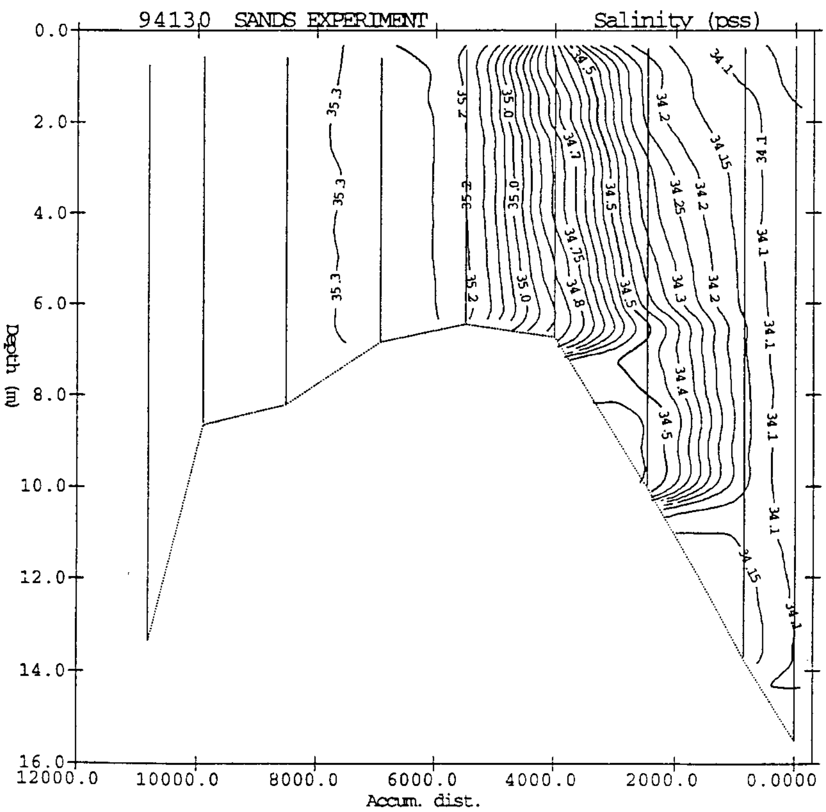

Figure 4.3 (g): Vertical distribution of salinity through the West Channel for the Sands Experiment
1617 to 1653, 10 May 1994 Ebb tide: 2 hours

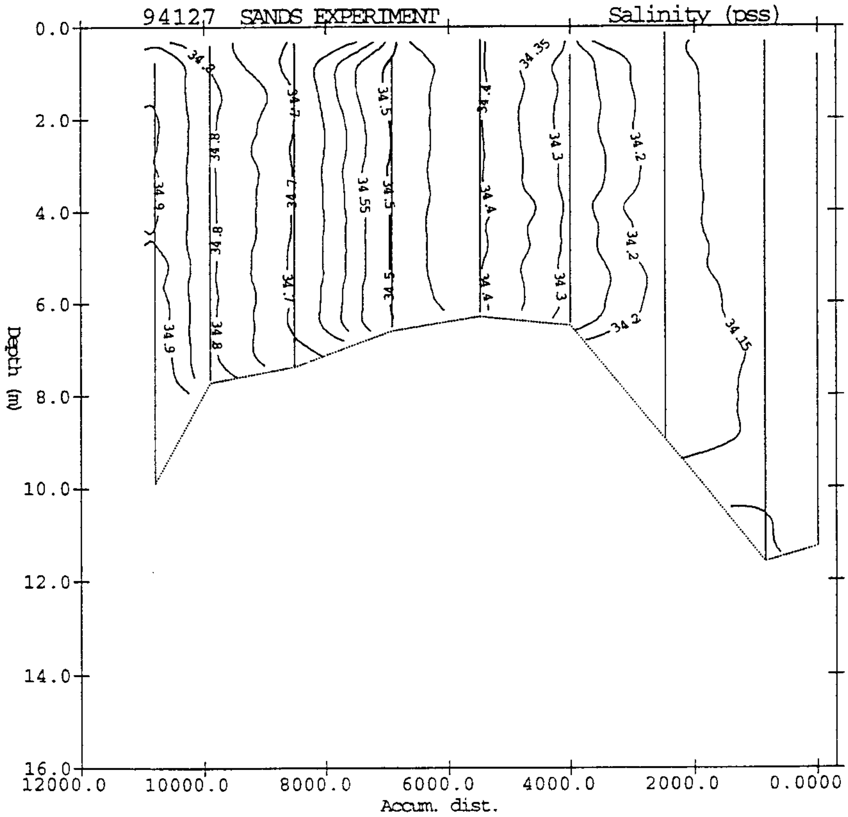

Figure 4.3 (h): Vertical distribution of salinity through the West Channel for the Sands Experiment
1454 to 1530, 7 May 1994 Ebb tide: 3 hours

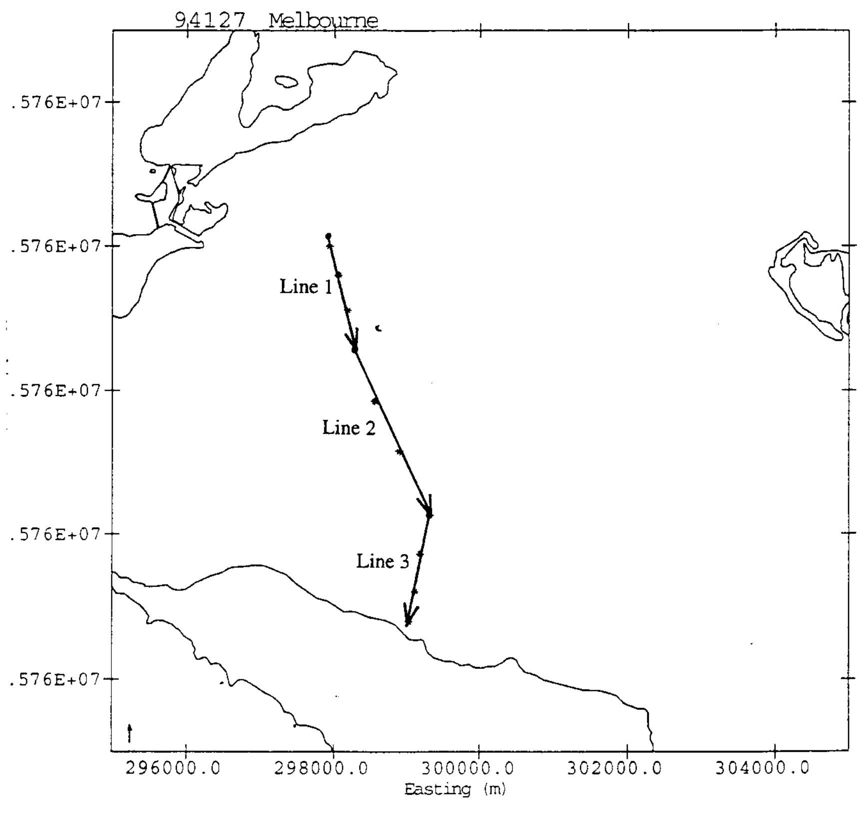

Figure 4.4: Locations of ADCP transects across channel

4.2. ADCP Survey

An ADCP survey was carried out, in conjunction with the CTD survey along the 'entrance' transect. Data was collected mainly along a transect at the entrance to each channel (Figure 4.4). Data along other lines were also collected but have not been used in the present study.

The results from this survey have been provided as cross sectional flows at various times through the tidal cycle. To facilitate integration (below), a smooth line has been drawn through these data points to enable values to be extracted at regular intervals. These are shown for the 7th and 10 May in Figures 4.5 (a) and (b), respectively.

On 10 May, maximum flows are seen in the South Channel on mid flood at 23,250 m^3/s compared with 19,600 m^3/s in the Symonds Channel and 16,000 m^3/s in the West Channel. Due to the diurnal inequality ebb flows are smaller. On 7 May, mid flood flows in the south channel are 19,000 m^3/s compared with 16,800 m^3/s in the Symonds Channel and 12,800 m^3/s in the West Channel. Again, flows are less on the ebb.

Integrating the flows over the ebb and flood tides gives the volumes of water passing through each channel. Table 4.2 compares these with the predicted tidal ranges at the Heads which shows that, to within about 10%, the volumes are proportional to the tidal range. Moreover, the flood volume is equivalent to the tidal prism given in MMBW/FWD (1973).

These flows are used, in conjunction with the salinities from the CTD surveys, to calculate the tidal exchange ratios and the flushing time for PPB.

Table 4.2: Predicted tidal ranges at the Heads compared with volume of flow on the flood and ebb tides

	Ebb tidal range	Flood tidal range	Ebb volume	Flood Volume
7-May-94	0.81	0.95	7.35×10^8	9.52×10^8
10-May-94	0.53	0.66	5.73×10^8	7.45×10^8

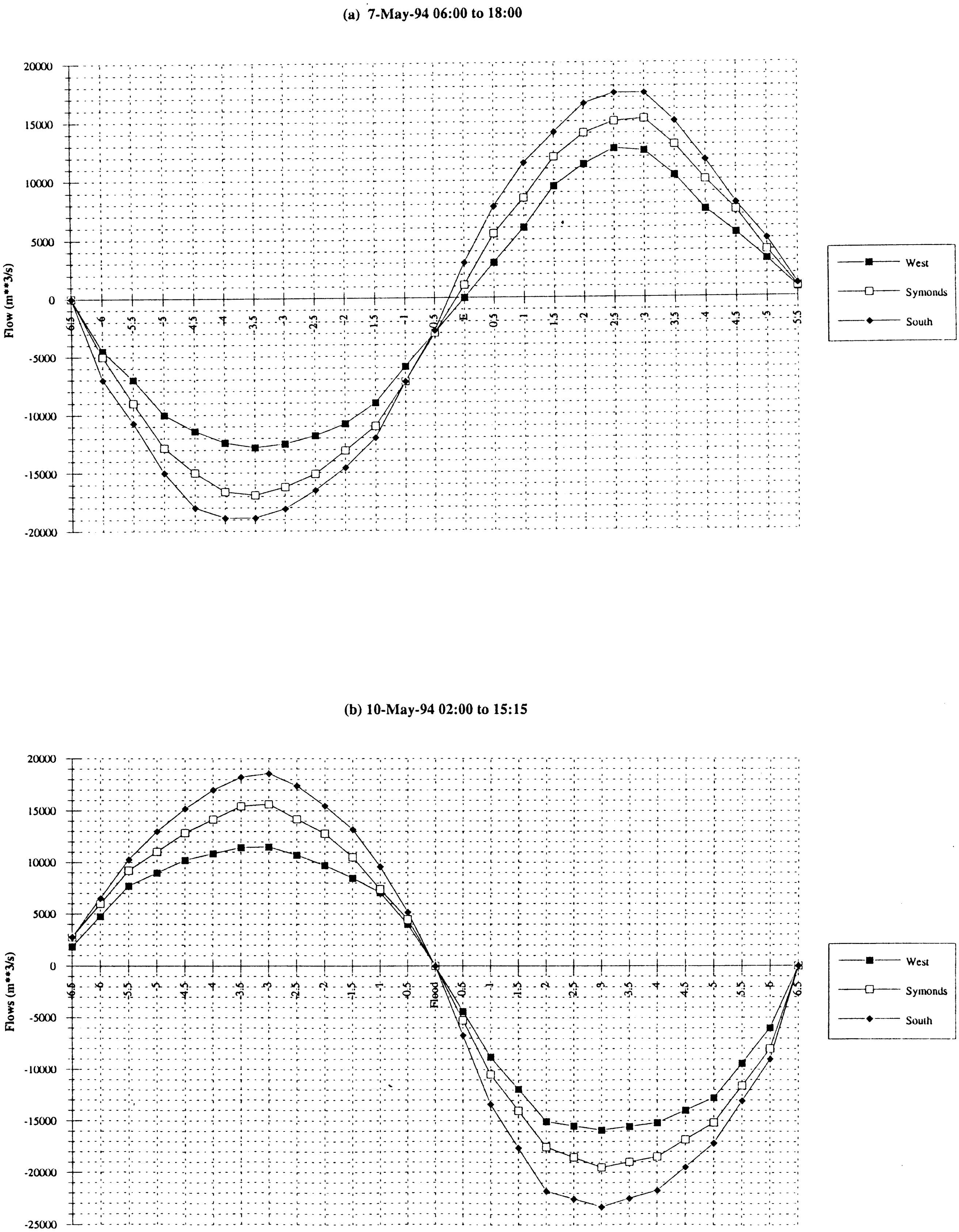

Figure 4.5: Current flows through the West, Symonds and South channels as measured by ADCP on 7 May 1994 and 10 May 1994.

Table 4.3 (a) Flows, salinities and fraction of PPBW in each sample (F) for the West Channel on 7 May 1994.

Tide Age	Flow (m3/s)	Salinity (pss)	F
-6.5	0	34.62	0.49
-6	-4500	34.62	0.49
-5.5	-7000	34.64	0.47
-5	-10000	34.67	0.45
-4.5	-11400	34.74	0.40
-4	-12400	34.80	0.36
-3.5	-12800	34.95	0.25
-3	-12500	35.12	0.13
-2.5	-11800	35.20	0.07
-2	-10800	35.26	0.03
-1.5	-9000	35.30	0.00
-1	-5900	35.30	0.00
-0.5	-2950	35.30	0.00
ebb	0	35.30	0.00
0.5	3000	35.30	0.00
1	6000	35.30	0.00
1.5	9500	35.26	0.03
2	11350	35.16	0.10
2.5	12700	35.00	0.21
3	12500	34.90	0.29
3.5	10400	34.80	0.36
4	7500	34.73	0.41
4.5	5500	34.66	0.46
5	3200	34.63	0.48
5.5	800	34.61	0.49

Table 4.3 (b) Flows, salinities and fraction of PPBW in each sample (F) for the Symonds Channel on 7 May 1994.

Tide Age	Flow (m3/s)	Salinity (pss)	F
-6.5	0	34.63	0.48
-6	-5000	34.63	0.48
-5.5	-9000	34.64	0.47
-5	-12850	34.67	0.45
-4.5	-15000	34.74	0.40
-4	-16600	34.80	0.36
-3.5	-16900	34.95	0.25
-3	-16200	35.12	0.13
-2.5	-15100	35.20	0.07
-2	-13100	35.26	0.03
-1.5	-11000	35.30	0.00
-1	-7200	35.30	0.00
-0.5	-3000	35.30	0.00
Ebb	1100	35.30	0.00
0.5	5500	35.30	0.00
1	8500	35.30	0.00
1.5	12000	35.29	0.01
2	14000	35.22	0.06
2.5	15000	35.13	0.12
3	15200	35.00	0.21
3.5	13000	34.87	0.31
4	10000	34.75	0.39
4.5	7400	34.71	0.42
5	4000	34.67	0.45
5.5	900	34.64	0.47

Table 4.3 (c) Flows, salinities and fraction of PPBW in each sample (F) for the South Channel on 7 May 1994.

Tide Age	Flow (m3/s)	Salinity (pss)	F
-6.5	0	34.77	0.38
-6	-7000	34.77	0.38
-5.5	-10700	34.78	0.37
-5	-15000	34.79	0.36
-4.5	-18000	34.81	0.35
-4	-18850	34.90	0.29
-3.5	-18850	35.08	0.16
-3	-18100	35.20	0.07
-2.5	-16500	35.27	0.02
-2	-14550	35.30	0.00
-1.5	-12000	35.30	0.00
-1	-7200	35.30	0.00
-0.5	-2800	35.30	0.00
Ebb	3000	35.30	0.00
0.5	7800	35.30	0.00
1	11500	35.30	0.00
1.5	14100	35.30	0.00
2	16500	35.28	0.01
2.5	17400	35.22	0.06
3	17400	35.16	0.10
3.5	15000	35.05	0.18
4	11700	34.93	0.26
4.5	8000	34.79	0.36
5	5000	34.75	0.39
5.5	1100	34.74	0.40

Table 4.3: Salinities, flows and factors for the proportion of PPBW in each sample at the entrance to the West, Symonds and the South channels on the 7 May 1994.

4.3. Tidal Exchange Ratio and "Flushing Time" Calculation

The most important physical influence on the water quality of an inlet is its "flushing time". This is the time it takes for the water in a system to be replaced through repeated exchange of the intertidal volume with the open ocean. Water entering the inlet on the flood tide fills the intertidal volume and mixes with the existing water until high tide is reached. As the tide ebbs the mixed water in the intertidal volume flows out of the inlet. A proportion of this water is lost to the open ocean by advection or mixing whilst the remainder will return to the inlet on the following flood tide. The tidal exchange ratio is defined as the proportion of water in the ebb tide which does not return on the following flood.

The tidal exchange ratio and flushing time for PPB are calculated using the salinity and flow data measured at the entrances of the three main channels to the Bay.

4.3.1. Tidal exchange ratio

In the following derivation of an expression (Fisher *et al.* 1979) for the tidal exchange ratio (R), let:

V_e be the total volume of water leaving the channel on the ebb tide,

V_f be the total volume of water entering the channel on the flood tide,

V_eF_e be the volume of PPB water leaving the channel on the ebb tide,

V_fF_f be the volume of the PPB water entering the channel on the flood tide

V_{fe} be the proportion of PPB water in V_e lost to the Bass Strait on the ebb tide

Using the above notation, the tidal exchange ratio is defined as:

$$R = V_{fe}/V_e$$

The volume of PPB water lost to the Bass Strait, V_{fe}, is given by the difference between the volumes of PPB water leaving the bay on the ebb tide and that returning on the flood, i.e. $V_{fe} = (V_eF_e - V_fF_f)$. Therefore:

$$R = (V_eF_e - V_fF_f)/V_e$$

To obtain these variables, we examine the variation in the salinities and the flows, at the entrance to the channels, over a tidal cycle. Integrating the flows (Q_i) over the ebb and flood duration gives the total volume of water leaving and entering the channels. Also, since the salinities of the Bass Strait water (S_o) and the PPB water (S_b) are known (S_o=35.3 pss; S_b=33.9 pss) the fraction of PPB water contained in each sample (F) can be calculated from:

$$F = (S_o - S_i)/(S_o - S_b)$$

where, S_i is the average salinity in the sample.

Multiplying F by the volume of water passing through the channel in time dt (Q_i.dt) gives the proportion of PPB water in that volume. Integrating this over each tide gives the volume of PPB water entering and leaving the channel.

Assuming that the ebb and flood volumes are equal, these integrations can be performed as follows:

$$V_e F_e = \int_0^{T_e} Q_i F_i dt \approx \Delta t \sum_{i=1}^{T_e/\Delta t} Q_i F_i$$

$$V_f F_f = \int_0^{T_f} Q_j F_j dt \approx \Delta t \sum_{j=1}^{T_f/\Delta t} Q_j F_j$$

$$V_e = \int_0^{T_e} Q_i dt \approx \Delta t \sum_{i=1}^{T_e/\Delta t} Q_i$$

$$V_f = \int_0^{T_f} Q_j dt \approx \Delta t \sum_{j=1}^{T_f/\Delta t} Q_j$$

where: T_e and T_f are the durations of the ebb and flood tides,

Q_i is the flow during the ith hour of the ebb tide,

Q_j is the flow during the jth hour of the flood tide and

F_i and F_j are the fractions of PPB water in the water during the ith and jth hour of the ebb and flood tides respectively.

These values enable the tidal exchange ratio to be calculated.

The measurements from the 7th and 10th May were examined in detail as, on these two days, concurrent data on flows and salinities over a tidal cycle were collected. Due to adverse weather conditions on the 8th, 9th and 11th May there are some gaps that do not enable the calculation of a tidal exchange ratio.

4.3.2. Results - 7 May 1994

To facilitate integration, values of salinity and flow at half hour intervals were obtained by drawing a smooth line through the data measured on the 7th May, 1994. These values are presented, along with F (the fraction of PPB water in each sample), for each channel in Table 4.3 (a) to (c). The salinities and flows are shown graphically in Figure 4.6 (a) to (c).

The flood and ebb volume integrations over the ebb and flood tides, respectively, show that the volume of water entering PPB on the flood is greater than that leaving on the ebb (Table 4.2). The underlying assumption in the method for calculating the tidal exchange ratio given above is that the flood and ebb volumes are equal. This method can still be applied, however, if the calculations are undertaken for a period over which the volume of the bay does not change. Analysis of tide gauge data indicate that this is the case from HW-4:15 to LW. The integrations are therefore carried out for the whole of the ebb tide and from HW-4:15 to HW for the flood tides. The resulting values as well as the calculation of V_{fe} are presented in Table 4.4. The sum for all of the channels is also given.

Table 4.4: Values of variables for the calculation of the tidal exchange ratio on the 7 May 1994

	West Channel	Symonds Channel	South Channel	TOTAL
Ve (m^3)	1.49×10^8	1.92×10^8	2.31×10^8	5.72×10^8
Vf (m^3)	1.49×10^8	1.92×10^8	2.31×10^8	5.72×10^8
VeFe (m^3)	3.39×10^7	3.46×10^7	2.53×10^7	9.38×10^8
VfFf (m^3)	2.17×10^7	3.00×10^7	2.37×10^7	7.54×10^8
Vfe (v)	1.22×10^7	4.57×10^6	1.65×10^6	1.84×10^7
Tidal exchange ratio (R)	0.08	0.02	0.007	0.032

Sum of all the Channels

The tidal exchange ratio for all three entrance channels is given as:

$$R = 1.84 \times 10^7 / 5.27 \times 10^8 = 0.032$$

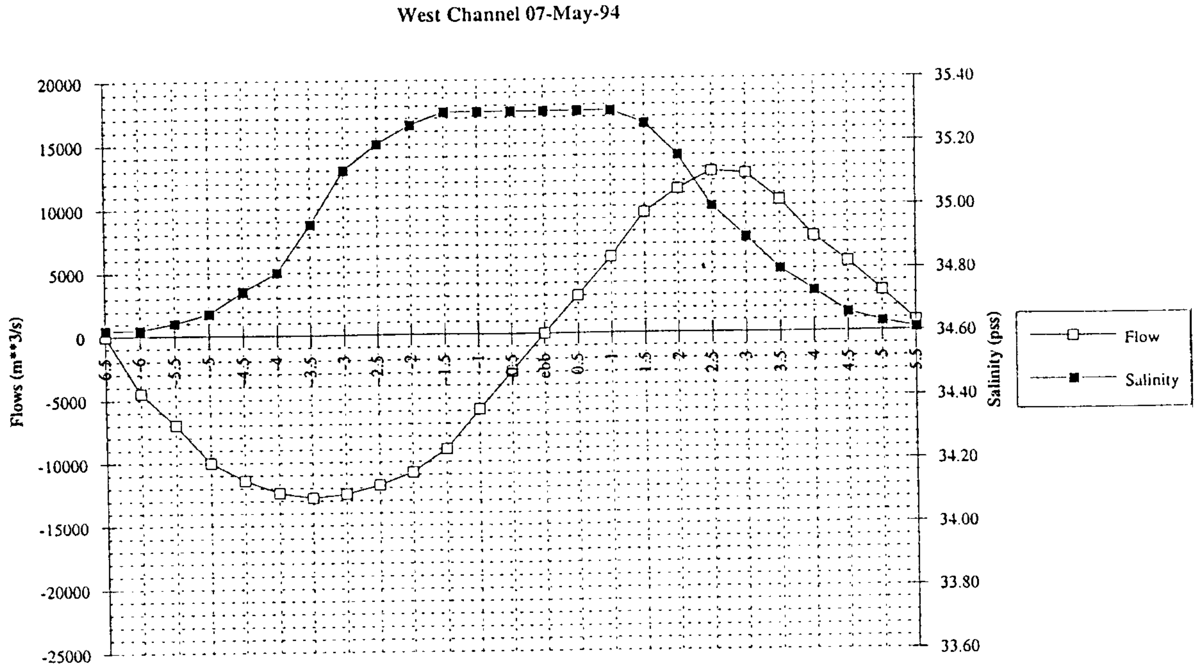

Figure 4.6 (a): Time series of salinity and flow over a tidal cycle at the entrance to the West, Symonds and South channels on 7 May 1994

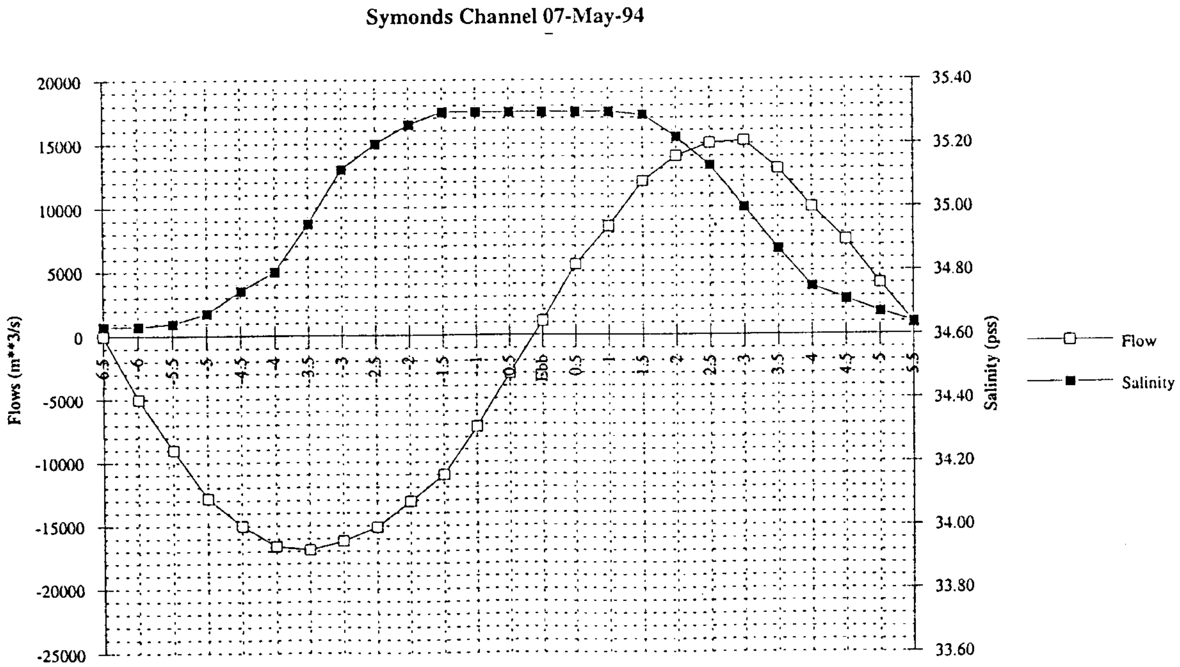

Figure 4.6 (b): Time series of salinity and flow over a tidal cycle at the entrance to the West, Symonds and South channels on 7 May 1994

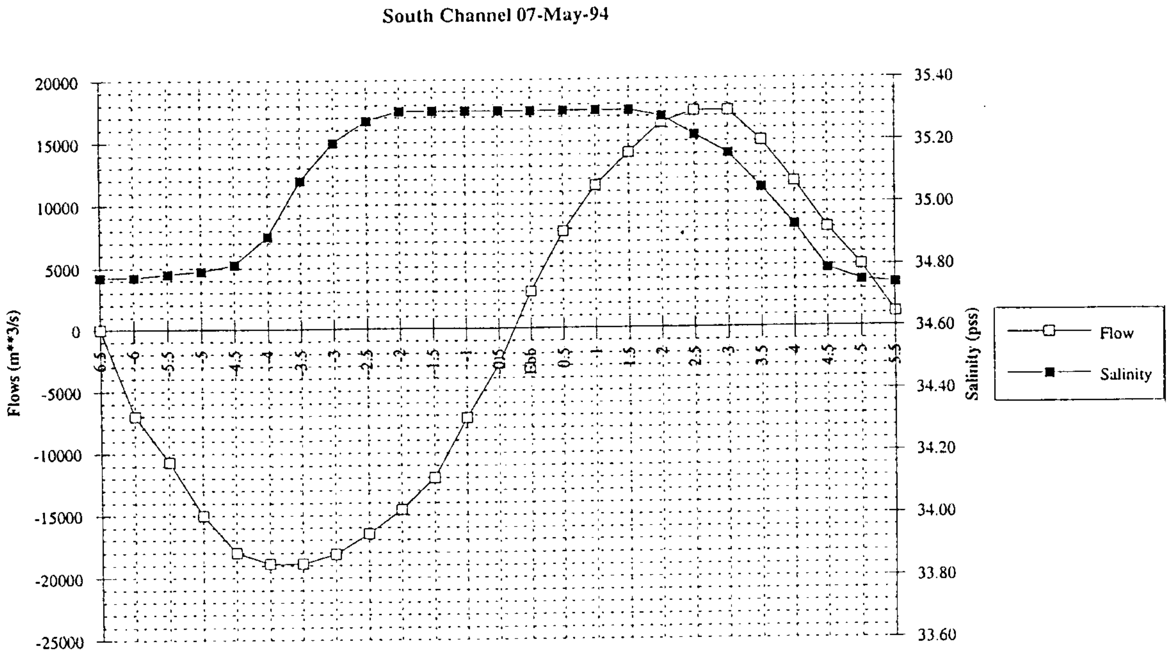

Figure 4.6 (c): Time series of salinity and flow over a tidal cycle at the entrance to the West, Symonds and South channels on 7 May 1994

4.3.3. Results - 10 May 1994

Table 4.5 (a) to (c) presents, for each channel, the salinities, flows and fractions of PPB water in each sample for the intermediate tide on the 10th May, 1994. The salinities and flows are shown as time series in Figure 4.7 (a) to (c).

As for the 7 May 1994, the flood tide volume is greater than the ebb and it is necessary to undertake the integrations for the flood tide over a period for which the volume entering the Bay is the same as that leaving. The resulting integration values as well as the calculations for V_{fe} are presented in Tables 4.6. The sum for all of the channels is also given.

Table 4.6: Values of variables for the calculation of the tidal exchange ratio on the 10 May 1994

	West Channel	Symonds Channel	South Channel	TOTAL
Ve (m^3)	1.94×10^8	2.47×10^8	2.94×10^8	7.35×10^8
Vf (m^3)	1.94×10^8	2.47×10^8	2.94×10^8	7.35×10^8
VeFe (m^3)	5.26×10^7	6.93×10^7	6.80×10^7	1.90×10^8
VfFf (m^3)	3.62×10^7	5.15×10^7	6.56×10^7	1.53×10^8
Vfe (v)	1.64×10^7	1.78×10^7	2.40×10^6	3.66×10^7
Tidal exchange ratio (R)	0.085	0.072	0.008	0.05

The largest exchange occurs through the Symonds and the West Channels. This is in agreement with observations and particle tracking results from the HF radar surface currents survey which was carried out at the same time as the CTD and ADCP measurements (Prytz and Heron, 1994). This shows large currents to the west of Mud Island flowing through the two channels suggesting that these channels are most effective in transporting material from PPB to the Bass Strait. This conclusions is corroborated by particle tracking results.

Sum of all the Channels

The tidal exchange ratio for all three entrance channels is given as:

$$R = 3.66 \times 10^7 / 7.35 \times 10^8 = 0.05$$

Table 4.5 (a) Flows, salinities and fraction of PPBW in each sample (F) for the West Channel on 10 May 1994.

Tide Age	Flow (m3/s)	Salinity (pss)	F
-6.5	1841	35.30	0.00
-6	4784	35.30	0.00
-5.5	7728	35.30	0.00
-5	8975	35.30	0.00
-4.5	10222	35.30	0.00
-4	10837	35.28	0.01
-3.5	11453	35.20	0.07
-3	11506	34.96	0.24
-2.5	10700	34.72	0.41
-2	9700	34.43	0.62
-1.5	8500	34.29	0.72
-1	7100	34.20	0.79
-0.5	4000	34.15	0.82
Flood	0	34.14	0.83
0.5	-4400	34.18	0.80
1	-8800	34.35	0.68
1.5	-11925	34.68	0.44
2	-15050	34.94	0.26
2.5	-15475	35.19	0.08
3	-15900	35.28	0.01
3.5	-15550	35.30	0.00
4	-15200	35.30	0.00
4.5	-14000	35.30	0.00
5	-12800	35.30	0.00
5.5	-9400	35.30	0.00
6	-6000	35.30	0.00
6.5	0	35.30	0.00

Table 4.5 (b) Flows, salinities and fraction of PPBW in each sample (F) for the Symonds Channel on 10 May 1994.

Tide Age	Flow (m3/s)	Salinity (pss)	F
-6.5	2762	35.30	0.00
-6	5983	35.30	0.00
-5.5	9205	35.30	0.00
-5	11025	35.30	0.00
-4.5	12844	35.30	0.00
-4	14155	35.28	0.01
-3.5	15467	35.20	0.07
-3	15649	35.02	0.20
-2.5	14200	34.74	0.40
-2	12800	34.34	0.69
-1.5	10500	34.14	0.83
-1	7400	34.09	0.86
-0.5	4500	34.08	0.87
Flood	0	34.08	0.87
0.5	-5250	34.11	0.85
1	-10500	34.23	0.76
1.5	-14000	34.56	0.53
2	-17500	34.90	0.29
2.5	-18500	35.12	0.13
3	-19500	35.24	0.04
3.5	-19000	35.30	0.00
4	-18500	35.30	0.00
4.5	-16850	35.30	0.00
5	-15200	35.30	0.00
5.5	-11600	35.30	0.00
6	-8000	35.30	0.00
6.5	0	35.30	0.00

Table 4.5 (c) Flows, salinities and fraction of PPBW in each sample (F) for the South Channel on 10 May 1994.

Tide Age	Flow (m3/s)	Salinity (pss)	F
-6.5	2762	35.30	0.00
-6	6518	35.30	0.00
-5.5	10275	35.30	0.00
-5	13000	35.30	0.00
-4.5	15200	35.30	0.00
-4	17000	35.28	0.01
-3.5	18228	35.25	0.04
-3	18592	35.05	0.18
-2.5	17400	34.80	0.36
-2	15500	34.56	0.53
-1.5	13200	34.41	0.64
-1	9600	34.35	0.68
-0.5	5200	34.33	0.69
Flood	0	34.32	0.70
0.5	-6700	34.34	0.69
1	-13400	34.40	0.64
1.5	-17600	34.54	0.54
2	-21800	34.84	0.33
2.5	-22550	35.06	0.17
3	-23300	35.20	0.07
3.5	-22550	35.27	0.02
4	-21800	35.30	0.00
4.5	-19500	35.30	0.00
5	-17200	35.30	0.00
5.5	-13100	35.30	0.00
6	-9000	35.30	0.00
6.5	0	35.30	0.00

Table 4.5: Salinities, flows and factors for the proportion of PPBW in each sample at the entrance to the West, Symonds and the South channels on the 10 May 1994.

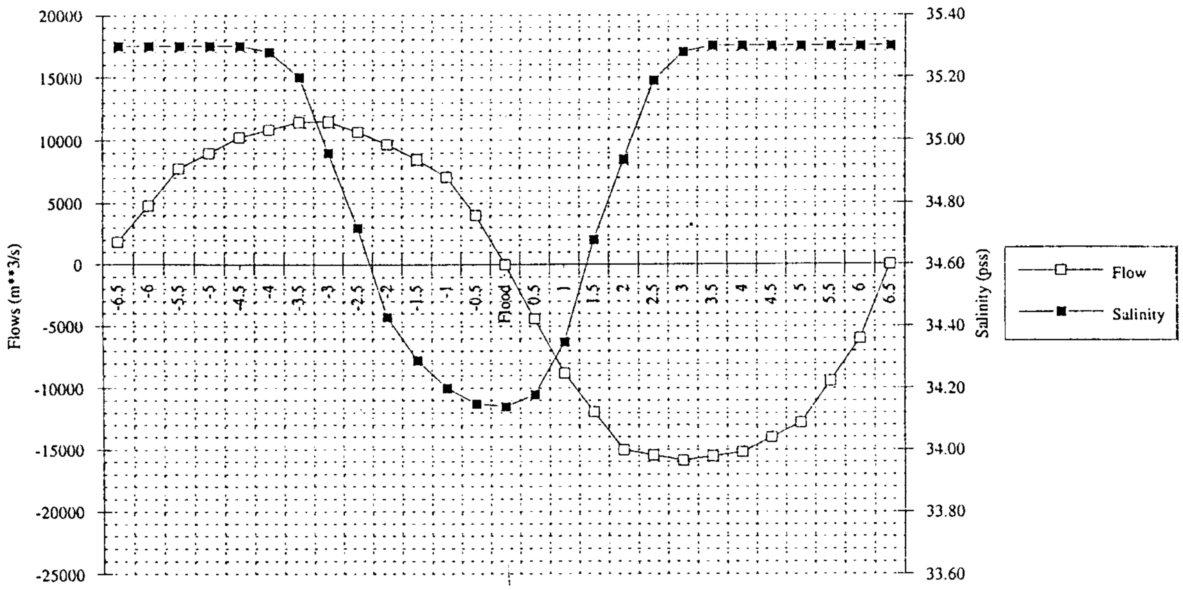

Figure 4.7 (a): Time series of salinity and flow over a tidal cycle at the entrance to the West, Symonds and the South channels on 10 May 1994

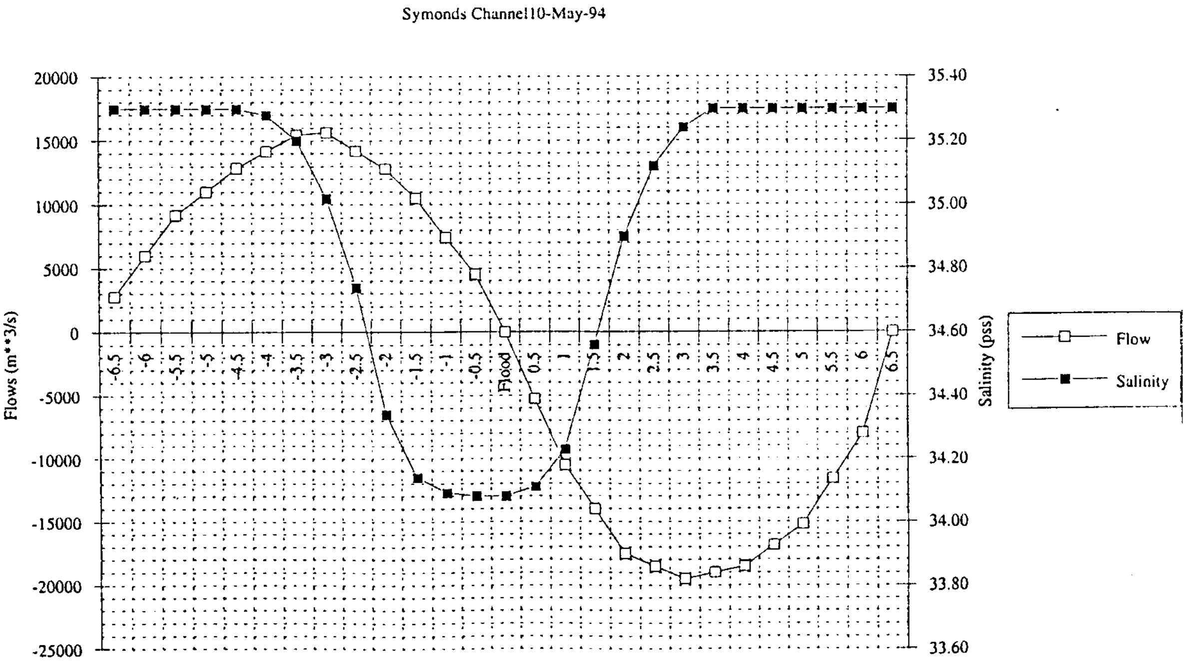

Figure 4.7 (b): Time series of salinity and flow over a tidal cycle at the entrance to the West, Symonds and the South channels on 10 May 1994

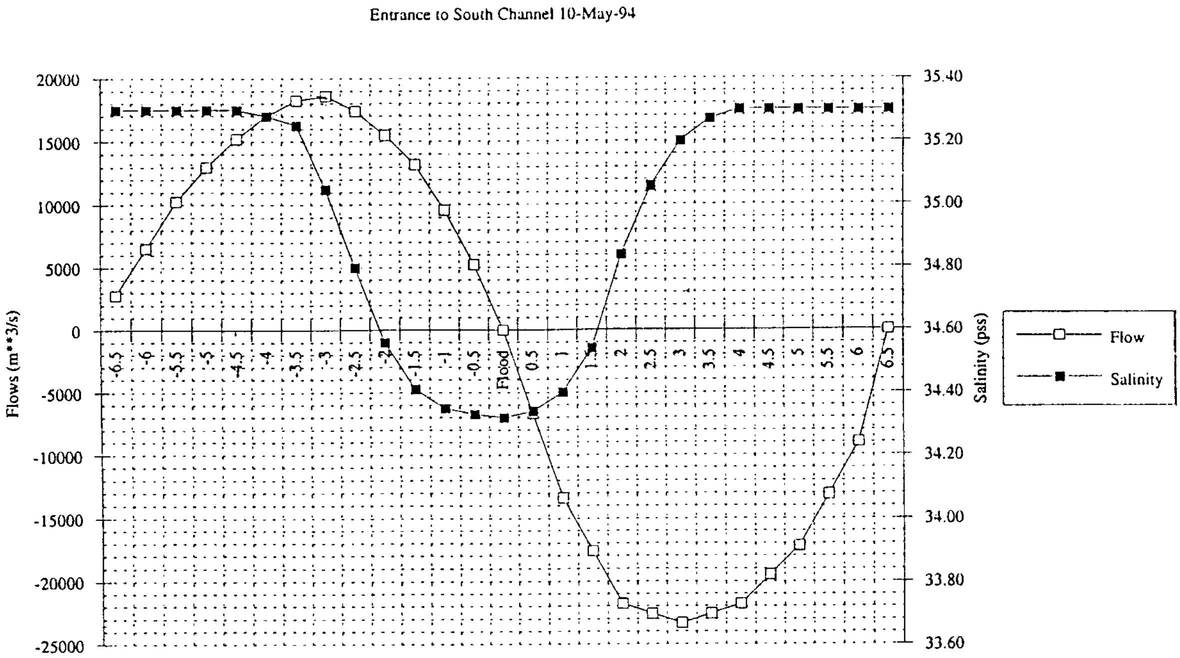

Figure 4.7 (c): Time series of salinity and flow over a tidal cycle at the entrance to the West, Symonds and the South channels on 10 May 1994

4.3.4. 'Flushing Time' for PPB

The "flushing time" for PPB is computed by comparing the total volume of the bay (2.5×10^{10} m^3) with the volume of PPB water being lost to the Bass Strait on the ebb tide. This latter volume has been calculated for two tides: the neap on the 7 May and intermediate on the 10 May. From these it is apparent that the flushing is greater for higher tidal ranges. Consequently, taking an average of the two volumes would skew the result towards a neap tide value thereby underestimating the flushing time. For the purpose of calculating a more long term average value it is deemed appropriate to use just the data from the intermediate tide measured on the 10 May.

The source and the destination of the various water masses making up the ebb and flood volumes on the 10 May are shown in Figures 4.8 (a) and (b), respectively.

On the ebb tide, approximately, 74% of the water is BSW discharging from its intrusion into the channels on the flood tide. PPBW makes up the remaining 26%, of which, 21% will return on the flood tide and 5% will be lost to the Bass Strait.

On the flood tide, 84% of the water is BSW and the remaining 16% is PPBW returning from the ebb. Of the BSW, 4% can be attributed to replacement for the water lost to the Bass Strait and 23% to the extra water flowing into the bay due to the diurnal inequality. The remaining 57% may also be though of as new, however, it may have entered and discharged from the bay previously but not have mixed with PPBW.

Using the value of 3.66×10^7 m^3 for the volume of PPBW being lost to the Bass Strait, the "flushing time" for the bay works out to be ($2.5 \times 10^{10}/3.66 \times 10^7$) 683 tidal cycles. If it is assumed that the same volume of PPBW is lost to Bass Strait on each tidal cycle then the flushing time works out to be around 353 days.

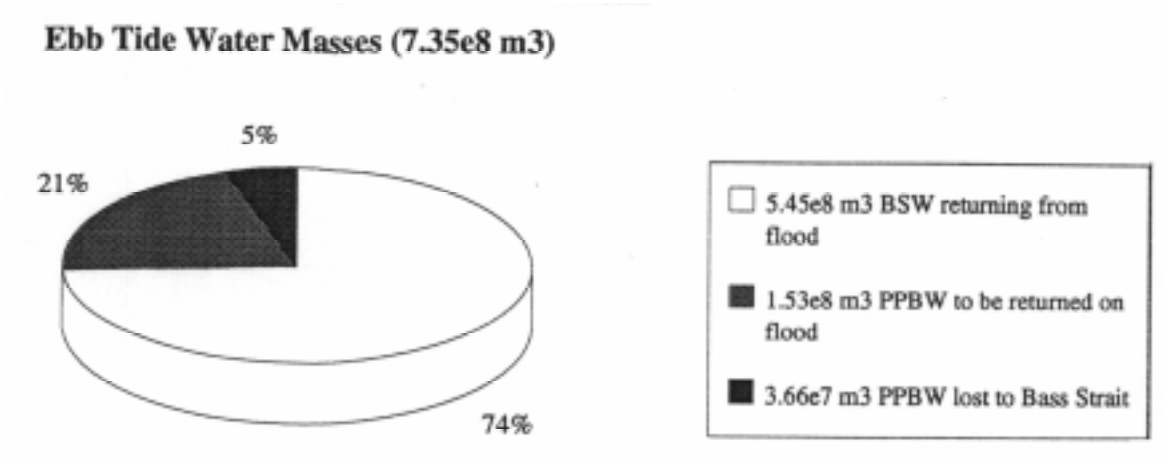

Figure 4.8 (a): Constituent proportions of the ebb water volume

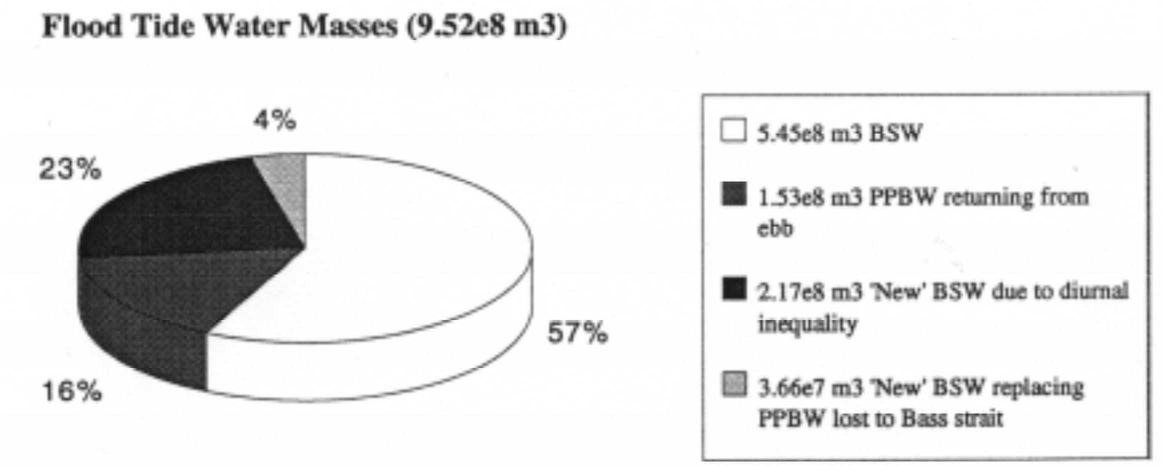

Figure 4.8 (b): Constituent proportions of the flood water volume

4.4. Discussion

The values for the tidal exchange ratio for PPB are valid only on the tides for which they were calculated. Furthermore, the calculation for flushing time assumes that the same volume of PPB water is lost to Bass Strait on each tidal cycle; this is clearly not the case. A number of factors affect the tidal exchange. These include the:

- diurnal inequality over two tidal cycles;
- tidal range;
- wind;
- fresh water input; and
- long-period water level changes

The affect of each of these factors is considered below.

Diurnal inequality

Due to the diurnal inequality, the water returns to its original level in two semi-diurnal cycles. The sequence goes from lower high water (LHW) through lower low water (LLW) to higher high water (HHW) to higher low water (HLW) before returning back to LHW. The intertidal movement of the saline fronts vary according to the ranges for these tides and will affect the tidal exchange. This is demonstrated using the predicted tides at the Heads over the measuring period on the 10 May, 1994 (Table 4.5).

The maximum proportion of PPB water is likely to be lost to the Bass Strait on the first ebb tide between LHW and LLW (the tide over which measurements were taken) as this is preceded by a small flood. Similarly, maximum Bass Strait Water is likely to enter the bay on the flood to HHW as it has a large tidal range and is followed by a small ebb to HLW (Ebb II). This second ebb is likely to discharge mainly the BSW from the first flood. The second flood to LHW is also small meaning that BSW will not penetrate far into the channels which, in turn, means that more PPB water is likely to be discharged on the following ebb. This completes the cycle. It may be concluded that the maximum tidal exchange occurs on the first tidal cycle and that it is likely to be small on the second.

Tidal range

The tidal range is proportional to the volume of water that passes in and out of the Bass Strait. Therefore, the larger the tidal range the higher the tidal exchange. The tide on the 10th May was an intermediate tide (range 0.9 m) and thus the exchange calculated may be considered to be an average value.

Wind

One of the most important factors in determining tidal exchange is the longshore transport in the Bass Strait. Longshore currents are induced by wind and have the effect of sweeping the outgoing plume of Bay water away and allowing only a small amount to return on the following flood. Conversely, they may tend to hold the outgoing plume against the shore and cause a relatively large percentage to return. MMBW/FWD (1973) assume that maximum exchange is associated with a northerly wind as offshore currents would be more pronounced; minimum exchange ratio is associated with a southerly wind and an intermediate value is suggested for westerly winds.

In addition to this, the Victorian Tide Tables report that west to south-west winds cause a rise in sea level outside Port Phillip and a consequent increase both in rate and duration of the ingoing stream and a corresponding decrease in the outgoing stream. On the winds ceasing, sea level outside falls to normal, causing the outgoing stream to increase both in duration and rate until each level in Port Phillip has fallen to normal and the levels outside and inside are equal again. It is assumed that events such as these would significantly increase tidal exchange.

When estimating an average flushing time for the bay the wind has not been considered as, over a long time period, the cumulative effects of different wind directions are assumed to be negligible.

Fresh water input

Increased fresh water input will increase the residual flow seawards which acts to augment the flushing of the bay.

4.5. Summary and conclusions

Measurements of temperature, salinity and current flows were carried out over the Great Sands region between the 7th and 12th of May, 1994. These observations demonstrate the mixing between the Bass Strait water and Port Phillip Bay water and provide a comprehensive data set for model validation.

Using the data sets for the 7 and 10 May, the tidal exchange ratios have been calculated at the entrances to the three main channels as follows:

Channel	R (7 May-94)	R (10-May-94)
West channel	0.08	0.085
Symonds Channel	0.02	0.072
South Channel	0.007	0.008

From these it is apparent that tidal exchange is greater for higher tidal ranges and that the largest exchange occurs in the West and Symonds Channel. This latter observation is in agreement with results from the HF radar survey of surface currents and is attributed to the short length of these channels relative to the South Channel and their large current flow.

The combined tidal exchange for the three channels is computed as 0.032 for May 7 and 0.05 for May 10. For the flushing time calculation it is deemed most appropriate to use the data for the 10 May as it is an intermediate tide and most likely to yield a long term average value. A value of 353 days was calculated. This is of the same order as estimates given in Hunter (1992) which, based on different methods, range between 300-450 days. It should be realised, however, that the value given in this study is based on a single tidal cycle. It is recommended that the proposed transport model be calibrated against the measured salinity data and then used to calculate a more definitive value for the flushing time.

5. YARRA PLUME EXPERIMENT

The objective of the Yarra Plume experiment was to gain an insight into the transport and mixing characteristics of the water discharging from the Yarra Estuary. CTD profiling and microstructure surveys were undertaken in this region between the 17th and 22nd September, 1994 and the 5th and 6th October, 1994.

5.1. CTD Profiling

CTD profiling, utilising salinity, temperature and turbidity as tracers, was undertaken to define the extent and the length scales of the plume discharging from the Yarra Estuary.

The CTD survey was undertaken over two periods between September 17 and 22 and October 5 and 6, 1994. Profiles were collected on a pre-defined grid using the fine-scale profiling CTD. The grid contained 82 stations covering the mouth of the Yarra Estuary, Hobsons Bay and the north east of Port Phillip Bay. A location map and easting and northing co-ordinates are given in Appendix A.1. Sampling of the grid commenced at the station closest to the river (Y01) and continued eastwards and westwards whilst moving south through the grid. Each run took approximately 3 hours. Due to adverse weather conditions on the 18th, 20th and 22nd of September profiling could only be undertaken in Hobsons Bay and, on the 19th, in the Yarra Estuary. A summary of data collected over the 8 days is presented in Table 5.1.

Table 5.1: Summary of field data collection for the Yarra Plume experiment.

Date	Start Time	End Time	Tide Age (hours)
17 September 1994	08:43	12:53	HW-3.5 to HW+0.5
	13:30	16:17	HW+1.0 to HW+4.0
18 September 1994	07:54	09:36	HW-4.5
	10:30	12:21	HW-2.0
	12:30	14:55	HW
19 September 1994	09:47	10:38	HW-4
	11:07	11:54	HW-3
	12:26	13:21	HW-1.5
	13:55	14:38	HW
20 September 1994	07:52	09:14	LW-0.75
	09:38	11:31	LW+1.25
21 September 1994	08:03	13:51	LW-2 to HW-4.5
	14:25	16:59	HW-1.5 to HW+1.0
22 September 1994	09:19	11:59	LW
	12:12	13:22	HW-3.5
5 October 1994	06:56	11:51	LW-1.25 to LW+3.5
	12:25	17:02	HW-2 to HW+2.75
6 October 1994	06:46	09:42	LW-2.5 to LW+0.5
	10:16	12:37	LW+1 to LW+3.25

TABLE 5.2 Length scales of buoyant surface jet and measued and calculated vertical dispersion coefficients under different conditions of wind, river flow and tide.

Day	Time	Tide Age	Wind Speed (m/s)	Wind Direction	River Flow (m^3/s)	Surface Salinity at the mouth of the estuary (pss)	Salinity at the base of the halocline (pss)	Depth of halocline (m)	Vertical Salinity Gradient (pss/m)	Length of jet (km)	Area of jet (km^2)	Measured surface Kz (m^2/s)	Calculated Kz (N & K, 1987)
Day 260 (17-Sep-94)	08:43 to 12:53	HW-3.5 to HW+0.5	7.5	NW	10.9	28	33	3	1.67	4	2.97		1.10E-05
	13:30 to 16:17	HW+1.0 to HW+4.0	8	NW	10.9	31.8	33.2	2.5	0.56	3	3.52		7.74E-06
Day 261 (18-Sep-94)	07:54 to 09:36	HW-4.5	5 to 6	NW-W	9.75	28	33	1.8	2.78	3.5	2.97		5.91E-06
	10:30 to 12:21	HW-2.0	6 to 9	W	9.75	31.4	33	2.2	0.73	1.8	1.63		1.32E-05
	12:30 to 14:55	HW	9	W	9.75	31.4	33	2	0.80	1	0.71		2.75E-05
Day 263 (20-Sep-94)	07:52 to 09:14	LW-0.75	5 to 11	W	12.9	29.6	32	2.3	1.04	2.4	3.26	1.12E-03	9.10E-06
	09:38 to 11:31	LW+1.25	12	W	12.9	29.6	33	3	1.13	2	2.62		1.48E-05
Day 264 (21-Sep-94)	08:03 to 13:51	LW-2 to HW-4.5	6 to 4	SE-S	20	30.8	33	5	0.44	1.3	1.7	1.00E-04	5.88E-05
	14:25 to 16:59	HW-1.5 to HW+1	4 to 3	S-SE	20	25.5	32	2.3	2.83	1.9	4.25	1.00E-05	1.08E-05
Day 265 (22-Sep-94)	09:19 to 11:59	LW	11 to 9	N	23.2	27.7	33	4	1.33	5.3	8.5	1.00E-05	1.09E-05
	12:12 to 13:22	HW-3.5	9 to 7	N	23.2	26.9	33	4	1.53	5.5	8.7	1.00E-05	1.07E-05
Day 278 (05-Oct-94)	06:56 to 11:51	LW-1.25 to LW+3.5	5	W	23	28	33	1.8	2.78	6.00	15		2.76E-06
	12:25 to 17:02	HW-2 to HW+2.75	5 to 3	W-SE	23	29	33	2.5	1.60	2.70	5.1		1.13E-05
Day 279 06-Oct-94)	06:46 to 09:42	LW-2.5 to LW+0.5	6 to12	N	21.1	23.8	33	3.8	2.42	6.3	19		4.22E-06
	10:16 to 12:37	LW+1 to LW+3.25	12	N	21.1	20	33	3	4.33	3	5.51		1.15E-05

Table 5.2: Length scales of buoyant surface plumes under different wind and flow conditions.

Results

Data was plotted as surface contours showing salinity distribution in the horizontal and cross sections gave the distribution of salinity, temperature and turbidity in the vertical.

Both temperature and salinity data can be used to define the extent of the plumes. However, in this study, salinity was used as it is the principal conservative parameter and plays the major role in dictating density and, hence, the mixing characteristics. The salinity values recorded during the survey ranged from 21.0 to 34.2 pss. It is considered that any measurements above 34.0 pss represents the ambient PPB water as this value was measured during the bay wide CTD survey (Figure 3.10). Measurements below 34.0 pss indicate the presence of the Yarra Plume in this region.

5.2. Discussion

The Yarra estuary discharges into Hobsons Bay as a buoyant surface jet. Entrainment at the base of this buoyant surface layer and mixing within the bay forms a well mixed plume. During the time of measurement, this could be distinguished from the ambient PPB water by the 34.0 pss isohaline and used as a tracer to define the extent of the Yarra derived water.

The mixing and transport characteristics of the buoyant jet depend critically on the river flow and the wind speed and direction. Tidal currents are small and variable and hence their influence on the transport can be neglected. Table 5.2 summarises, for each day, the length scales and salinity gradients of the buoyant surface plume under the different wind and flow regimes.

River discharge increases the extent of the plume and inputs buoyancy to the system. During low river discharge (10.9 m^3/s) on day 260, the plume was seen to extend approximately 4 km into the bay. However, after a period of intense river discharge (Figures 5.2 (a) and (b)) on day 278 the extent, the width and the stratification of the plume increased substantially.

The following summarises the transport and mixing characteristics of the plume under each wind direction (Figures 5.1 (a) and (b)).

(a) Northerly component

Winds with a northerly component were experienced on days 265 and 279. On both days the buoyant plume was forced offshore against the western headland. The plumes also remained stratified for 5 and 6 km, respectively, into the bay. This is a result of the enhanced river flows for these periods. Dominant mixing processes appear to be due to interfacial shear as shown by the microstructure data.

(b) Westerly component

Winds with a westerly component were experienced on days 260, 261, 263 and 278. On these days the buoyant plume appeared to discharge fairly uniformly about a south-east axis. The offshore extent of the plume varies over these days and depends, firstly, on the buoyancy flux input and on the wind speed. For example during low river flow (e.g. day 260) it extends approximately 3 to 4 km into the bay whilst, during high river flows (e.g. day 279) it extends to over 6 km.

(c) Southerly and easterly components

Winds from the south are onshore and have a large fetch . Consequently they have the largest capacity for wind stirring. Winds with a southerly and an easterly component were experienced on days 264 and 278. On day 264 the wind was strong in the morning and arrested the discharge of the buoyant plume into the bay. However, in the afternoon the wind relaxed and it discharged to a distance of 3.5 km. The onset of stratification in the water column is demonstrated by the microstructure data at Station Y03. This shows that stratification occurred at 0951 which coincided with a wind speed of about 5 m/s. On day 278, the wind backed from the west to the south east. During the westerly wind the water column was stratified, however, this appeared to break down as the wind shifted to the south east.

The microstructure data indicate that there are primarily three types of mixing processes operating within the study area:

- Wind stirring (Kraus and Turner, 1967);
- interfacial shear (Pollard *et al.*, 1973); and
- bottom boundary shear.

Wind stirring and interfacial shear are most important for energising entrainment at the base of the buoyant surface layer. Wind stirring uses the turbulent kinetic energy at or near the surface transferred from external energy inputs originating from the wind. This results in the downward mixing of water and a deepening of the mixed layer.

Interfacial shear uses the locally produced kinetic energy contained in the shear across the interface between the surface and higher density layers. This results in entrainment of water from one layer to the other and a further deepening of the mixed layer.

Bottom boundary shear utilises the turbulent kinetic energy derived from the water column moving across the sea bed. The resulting turbulence propagates upwards in the water column.

Interfacial shear between the two layers requires a wind stress at the surface to build up the shear. Stirring dominates the mixing whenever the wind stress is too weak, the duration too brief or the fetch too short to allow this to occur. Often wind stirring and interfacial shear processes combine; the stirring motion from the surface sharpens the interface sufficiently to allow shear instability to mix the two fluids.

Vertical eddy diffusivity (K_Z) was found to range between $1x10^{-3}$ and $1x10^{-6}$ m^2s^{-1}. This is related to the stratification of the water column which, in turn, is related to the wind speed. For example on day 263 (20 September, 1994) when wind speeds were high and the water column well mixed, the K_Z was of the order $1x10^{-3}$ m^2s^{-1}. In contrast, on day 264 (21 September, 1994) the wind speed decreased and the water column became stratified; under these conditions the K_Z decreased by three orders of magnitude to $1x10^{-6}$ m^2s^{-1}.

K_Z has also been calculated using the formula:

$$K_z = \frac{\bar{Q} S_c}{\bar{C} A} \qquad (5.1)$$

where $\bar{Q}$ is the mean flow rate over the residence time of fluid above the isohaline, S_C is the salinity at the chosen isohaline $\bar{C}$ is the salinity gradient perpendicular to the isohaline and A is the area of the isohaline.

The computed values for each day are shown in Table 5.2. These range between $1x10^{-5}$ and $2x10^{-6}$ m^2s^{-1}. Comparisons with those measured on days 264 and 265 show that they are of the same order of magnitude, however, on day 263, the calculated value is much less. This is probably due to the fact that the microstructure profile was taken in the well mixed plume.

Pattiaratchi (1995) outlines the method of energy dissipation for calculating the horizontal eddy diffusivity from ε; the pertinent equation being

$$K_X = 0.1\, \varepsilon^{1/3} L_x^{4/3}$$

where ε is the dissipation of turbulent kinetic energy (measured in the microstructure survey) and L_x is the length scale of diffusion. This method was attempted using the data collected in the present study using the dissipation measured in the surface layer for ε and the jet length as the scale of diffusion (Table 5.3). The results show that K_x varies between 10 and $25m^2s^{-1}$. This range is higher than the 1 - 5 m^2s^{-1} given in Pattiaratchi et al. (1989). These values are contradictory and it is recommended that the horizontal diffusion coefficient be found in model calibration by matching the predicted results with the field data presented in this report.

Table 5.3: Calculations for horizontal eddy diffusivity (K_x)

Day	Tide Age	Dissipation of TKE (m^2/s)	Length of jet (m)	K_x (m^2/s)
263	LW -1	1×10^{-6}	2000	25
264	LW-2 to HW-4.5	1×10^{-6}	1300	14
	HW	1×10^{-7}	1900	10
265	HW-3.5	1×10^{-8}	5500	20

5.3. Summary and Conclusions

The waters from the Yarra estuary discharge into Hobsons Bay as a buoyant surface jet. The dimensions of this vary considerably depending upon river discharge and wind regime. The extent of the plume is largest during high river discharges and with offshore winds. Plume depth increases as a result of onshore winds and/or high river discharge. Entrainment at the base of the surface jet forms a well mixed plume which becomes dispersed into the bay. The microstructure data show the three primary mixing processes operating within the study area to be wind stirring and interfacial and bottom boundary shear. The well-mixed plume can be distinguished from the ambient PPB water and can, therefore, be used as a tracer to define the long term fate of the Yarra derived water. Vertical eddy diffusivity ranges from 1×10^{-3} m^2s^{-1} for a well mixed water column to 1×10^{-6} m^2s^{-1} under stratified conditions.

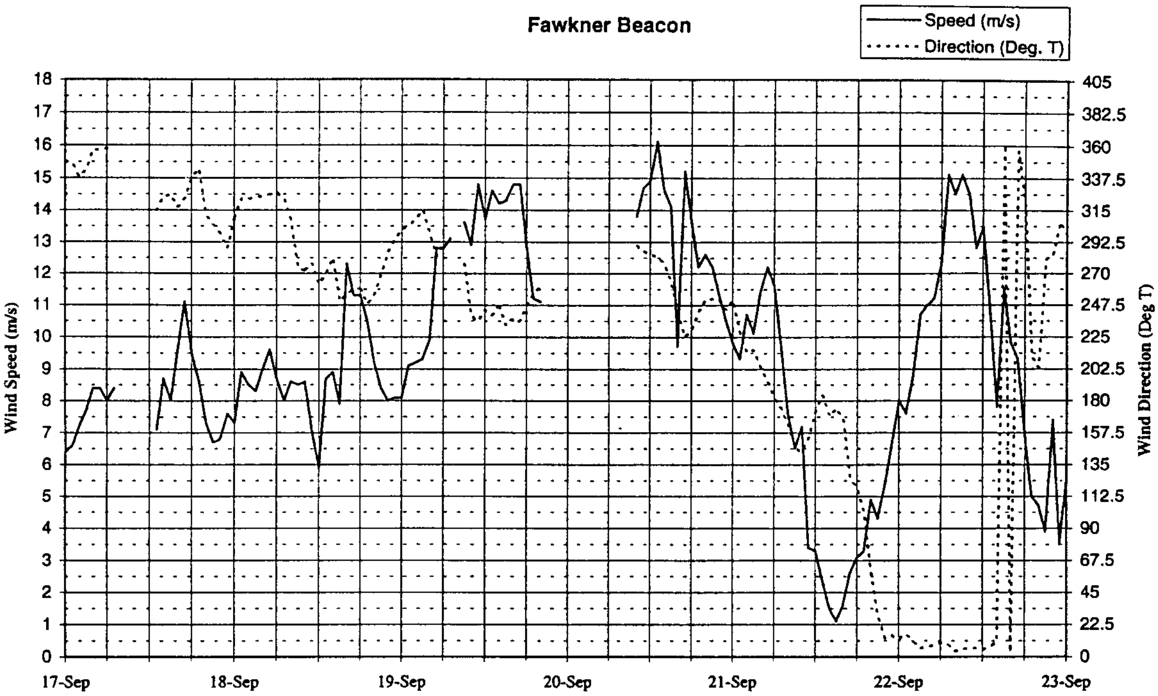

Figure 5.1 (a): Wind speed and direction measured at Fawkner Beacon during the Yarra plume experiment between 17 Sep 94 00:00 and 23 Sep 94 00:00.

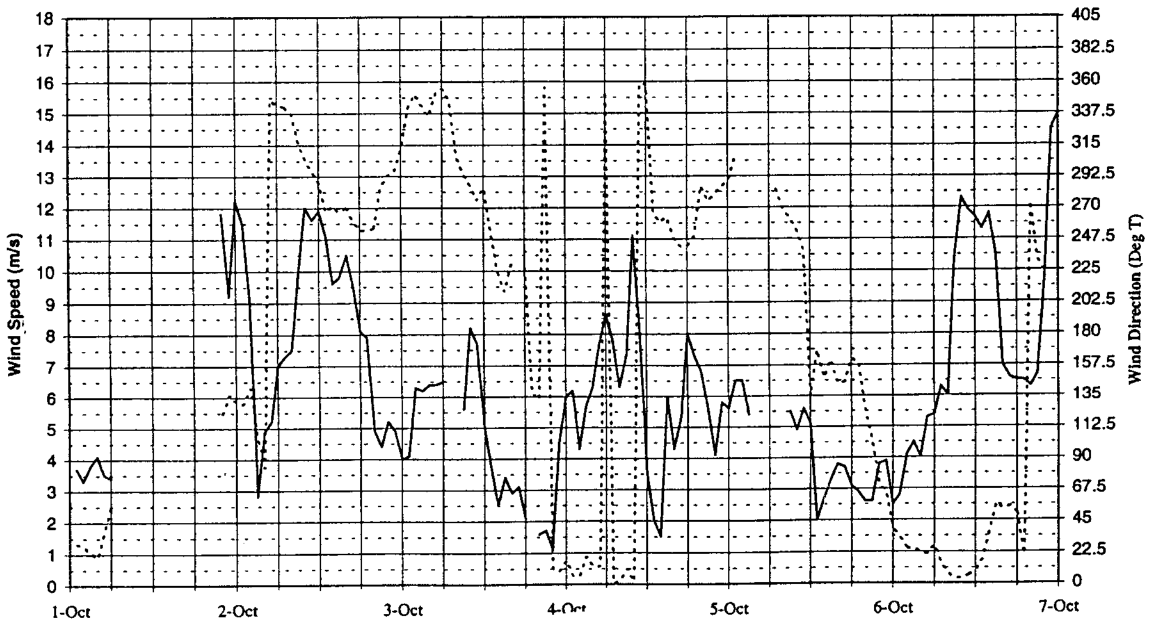

Figure 5.1 (b): Wind speed and direction measured at Fawkner Beacon during the Yarra plume experiment between 01 Oct 94 00:00 and 07 Oct 94 00:00.

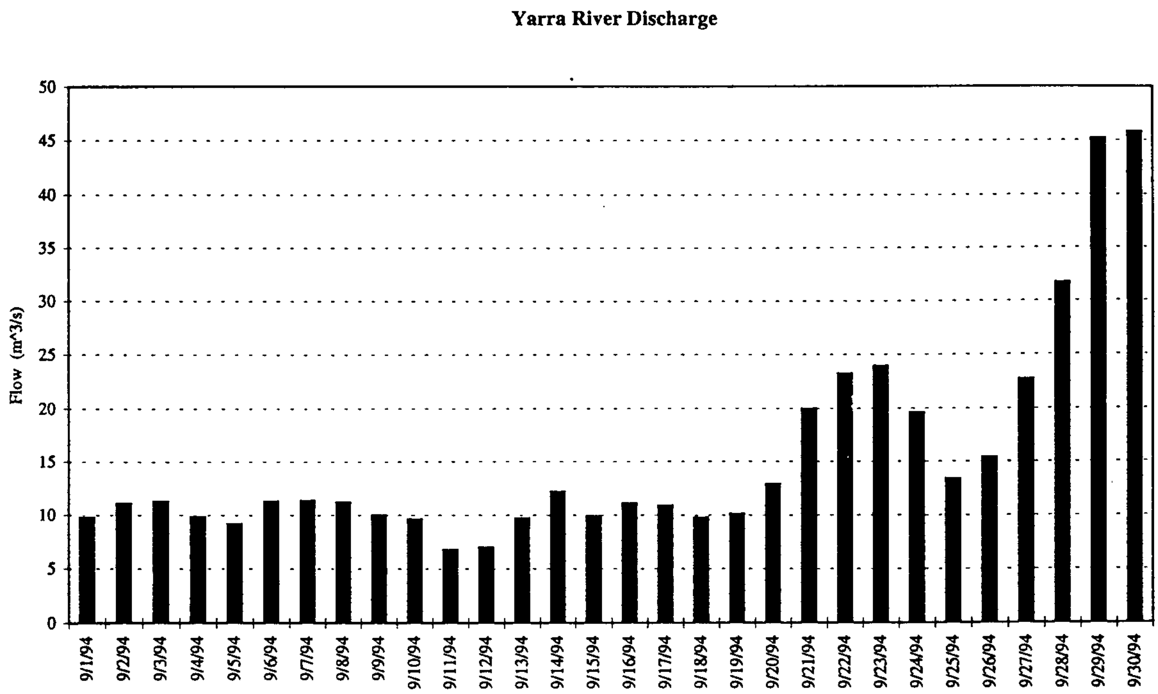

Figure 5.2 (a): Daily Yarra River discharge for September 1994

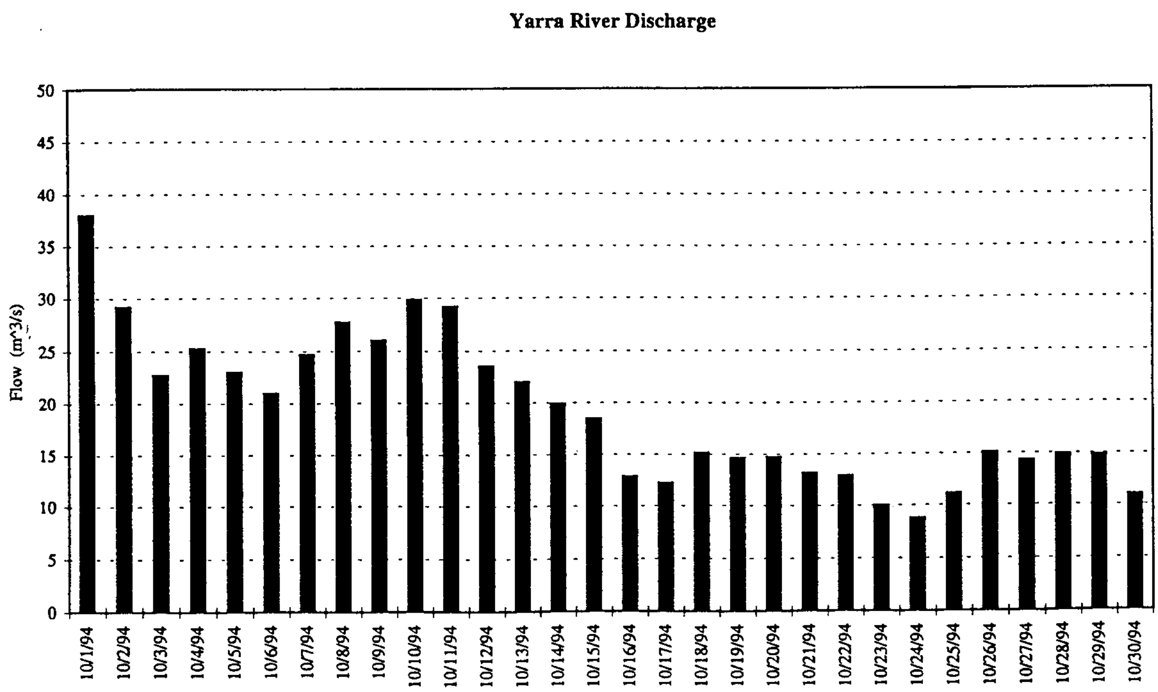

Figure 5.2 (b): Daily Yarra River discharge for October 1994

6. WERRIBEE PLUME EXPERIMENT

The objective of the Werribee Plume experiment was to gain an insight into the transport and mixing characteristics of the water discharging from the Western Treatment Plant. CTD profiling and microstructure surveys were undertaken in this region between the 23rd and 26th September, 1994.

6.1. CTD Profiling

CTD profiling surveys were undertaken to define the extent and the length scales of the plumes discharging from the WTP. Profiles were collected on a pre-defined grid using the fine-scale profiling CTD. A location map, easting and northing co-ordinates and transect locations are given in Appendix C.1. Due to sea conditions on certain days it was not possible to profile all stations. A summary of data collected over the 5 days is presented in Table 6.1.

Table 6.1: Summary of field data collection for the Werribee Plume experiment.

Date	Start Time	End Time	Tide Age (hours)
23 September 1994	08:45 14:10	13:49 17:14	LW-2.75 to LW+2.5 LW+2.75 to LW+5.75
24 September 1994	08:11	09:47	LW-3.0
25 September 1994	08:44 14:25	13:50 16:09	LW-3.75 to LW+1.25 LW+2 to LW+3.75
26 September 1994	08:17	12:38	LW-5 to LW+0.5

6.2. Summary and Conclusions

The effluent from the WTP main drains discharge into PPB as buoyant surface jets. The tide currents in the area are low and advective transport and mixing characteristics are dominated by surface wind stress. Observations were undertaken mostly during westerly winds of >5 m/s (Figure 6.1). During such periods the plumes were well mixed and flowed eastwards around Wedge Point towards the mouth of the Werribee River. Whilst flowing past the Point, the plume is forced offshore by the Wedge Spit. This is contrary to the conclusion in Pattiaratchi *et al.* (1989) which assumes that Wedge Spit constrains the transport to the east.

The vertical eddy diffusivity ranges between 1×10^{-4} and 1×10^{-6} m^2/s. As found in the Yarra plume experiment this is related to stratification and wind speed.

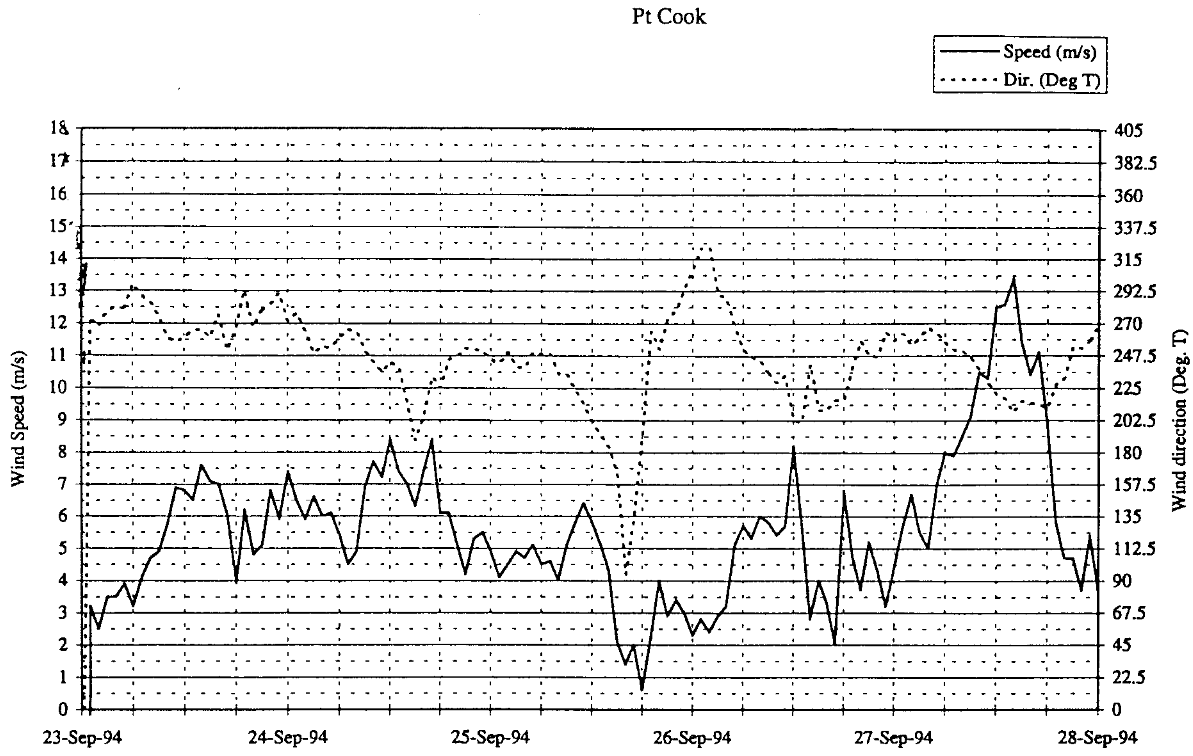

Figure 6.1: Wind speed and direction measured at Point Cook during the Werribee plume experiment between 23 Sep 94 00:00 and 28 Sep 94 00:00

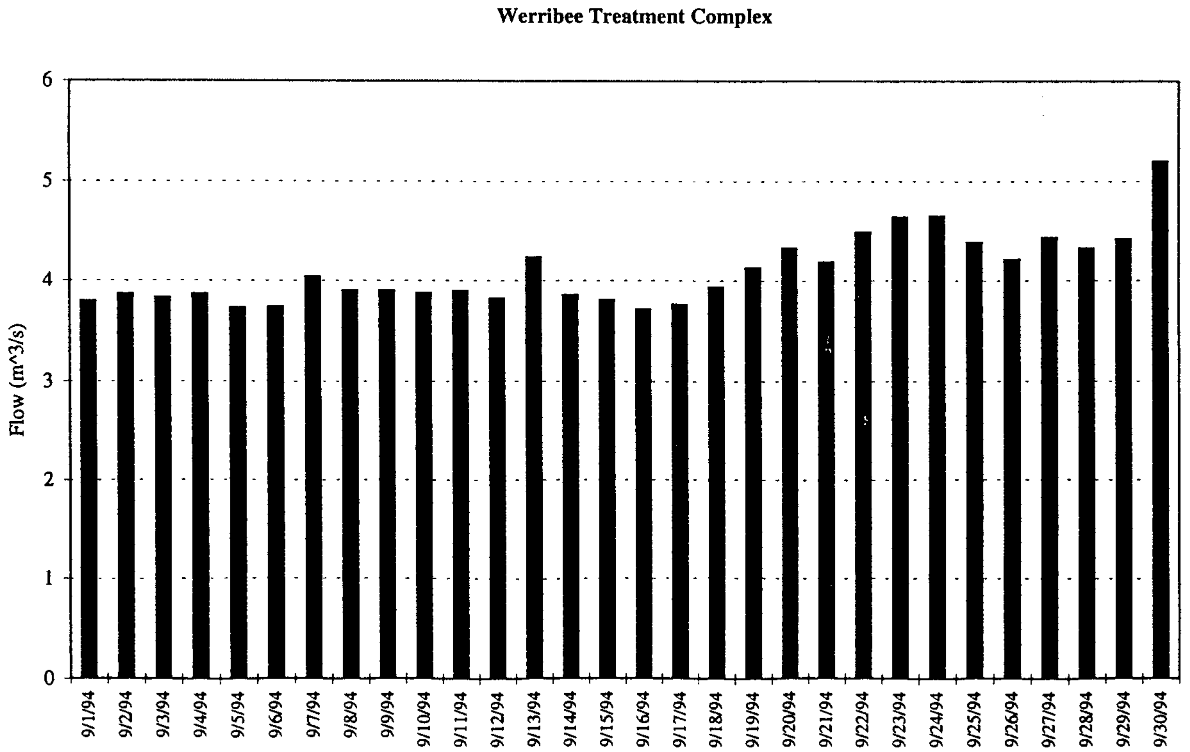

Figure 6.2: Daily WTP discharge for September 1994

7. CONCLUSIONS

The water quality in Port Phillip Bay depends critically on inputs from the Yarra River and the Western Treatment Plant and also the exchange of water between the Bay and the Bass Strait. Intensive CTD and microstructure surveys in these areas, together with the Bay-wide CTD surveys, provide a comprehensive data base for calibration and verification of the proposed transport model for the Bay.

The Bay-wide CTD surveys have revealed the horizontal and vertical distribution and also the seasonal variability of the measured parameters (salinity, temperature and turbidity). Salinity is the principal conservative parameter and plays the major role in defining density and therefore mixing characteristics. Largest horizontal gradients are associated with the Yarra River discharge in the north of the Bay and over Great Sands region. In the vertical, the water column is well mixed over the Bay except in the vicinity of the Yarra discharge where there is strong stratification.

The Yarra River discharges into the Bay as a buoyant surface jet, the extent of which depends on the river flow and wind regime. River flow determines the volume of the less saline water and the wind determines its shape. Turbulent mixing, generated by wind stirring and interfacial shear between the buoyant surface layer and the receiving waters forms a well mixed plume which disperses into the Bay. This can be distinguished from the ambient Port Phillip Bay Water and provides a long term tracer indicating the extent of its influence in the Bay. During periods of high river discharge the region of lower salinity extended along the eastern margin of the Bay. However, this is due to a combination of inputs from smaller freshwater discharges as well as the Yarra.

The flows from the Werribee treatment plant are significantly lower than those from the Yarra and the discharge becomes readily mixed with the receiving water. The tidal currents are low in the area and advective transport and mixing phenomena are dominated by surface wind stress. During the periods of observation, wind speeds were consistently greater than 5 m/s. Under such conditions, the discharged plumes were well mixed and flowed, along the coast, eastwards around Wedge point and towards the mouth of the Werribee River. This is contrary to Pattiaratchi *et al.* (1989) in which it is concluded that under such wind conditions the plumes are constrained by Wedge Spit.

Observations over the Sands region demonstrate the mixing and the limited exchange between the Bass Strait and the Bay waters. The water column is well mixed and frontal systems between the two water masses are clearly identified. It is apparent that whilst on the flood tide a high proportion of Bass Strait water enters the three channels only a small proportion actually reaches the Bay. Similarly on the ebb tide, only a small proportion of the PPB water actually reaches the Bass Strait. The tidal exchange across the entrance to the three channels was calculated as 0.032 for May 7 and 0.05 for May 10.

An estimate of the flushing time for the Bay is given as 353 days. This is based on data from only one of the tides and is considered a lower limit; for reasons given, it may be up to a factor of two greater. To obtain a more accurate value it is recommended that the proposed numerical model be calibrated against the measured observations over the Sands Region and then run over an extended period, using a conservative tracer, to estimate the flushing time.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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10. APPENDICES

A 1

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xfv1520.278	xfv1530.278	xfv1535.2
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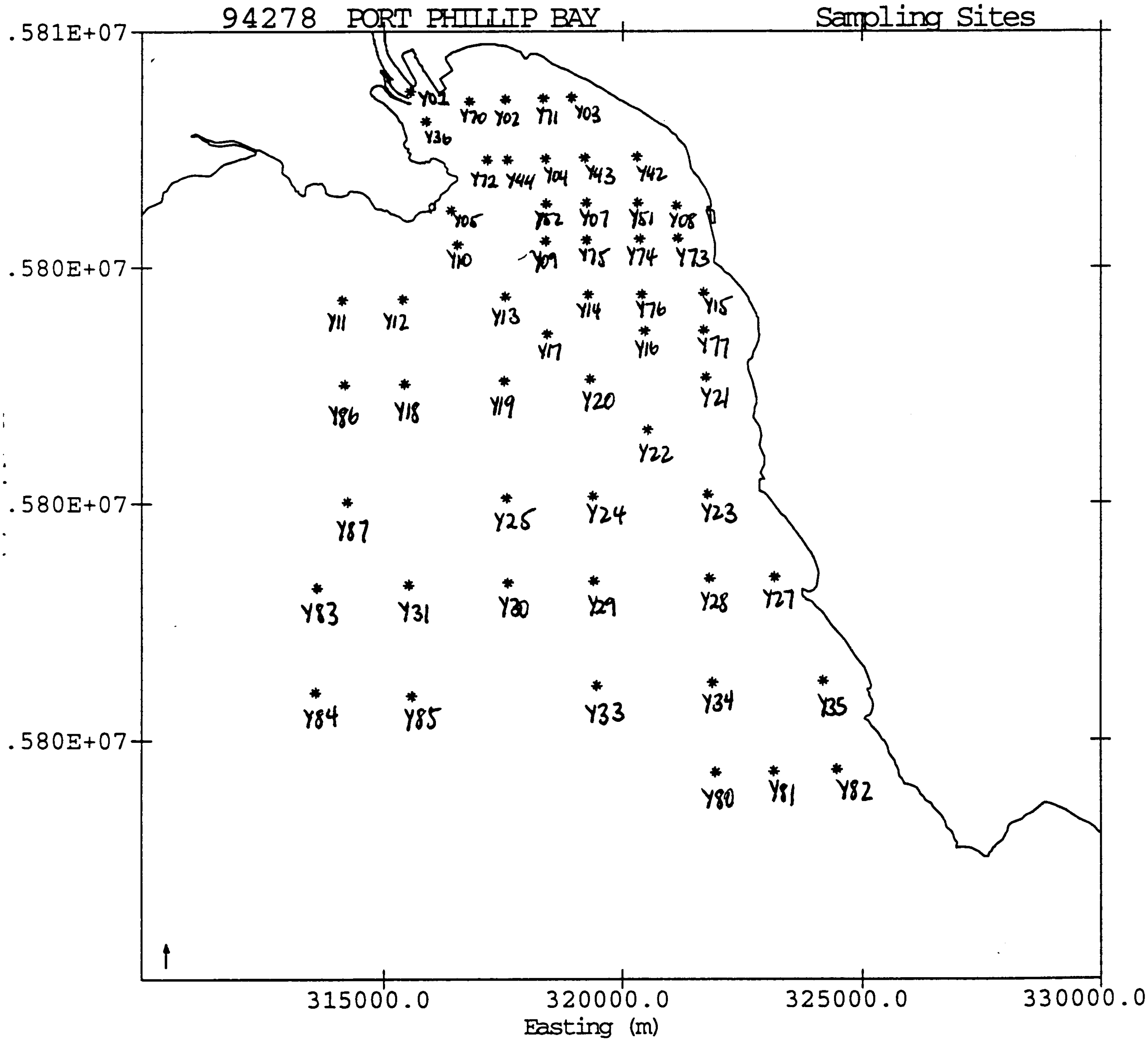

A1

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xfv1225.278	xfv1304.278	xfv1557.2
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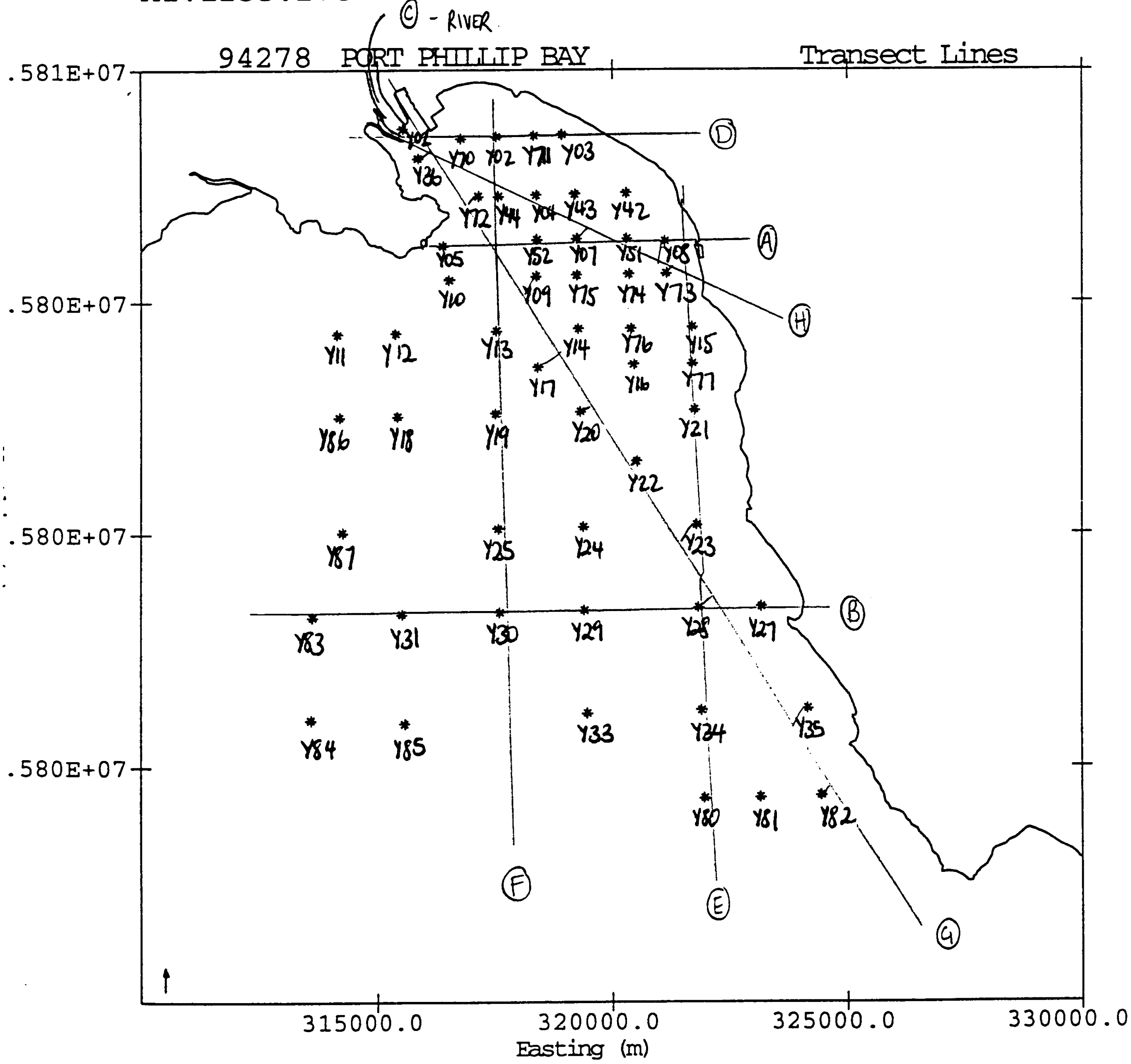

Coordinates for Yarra Plume Experiment

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C1

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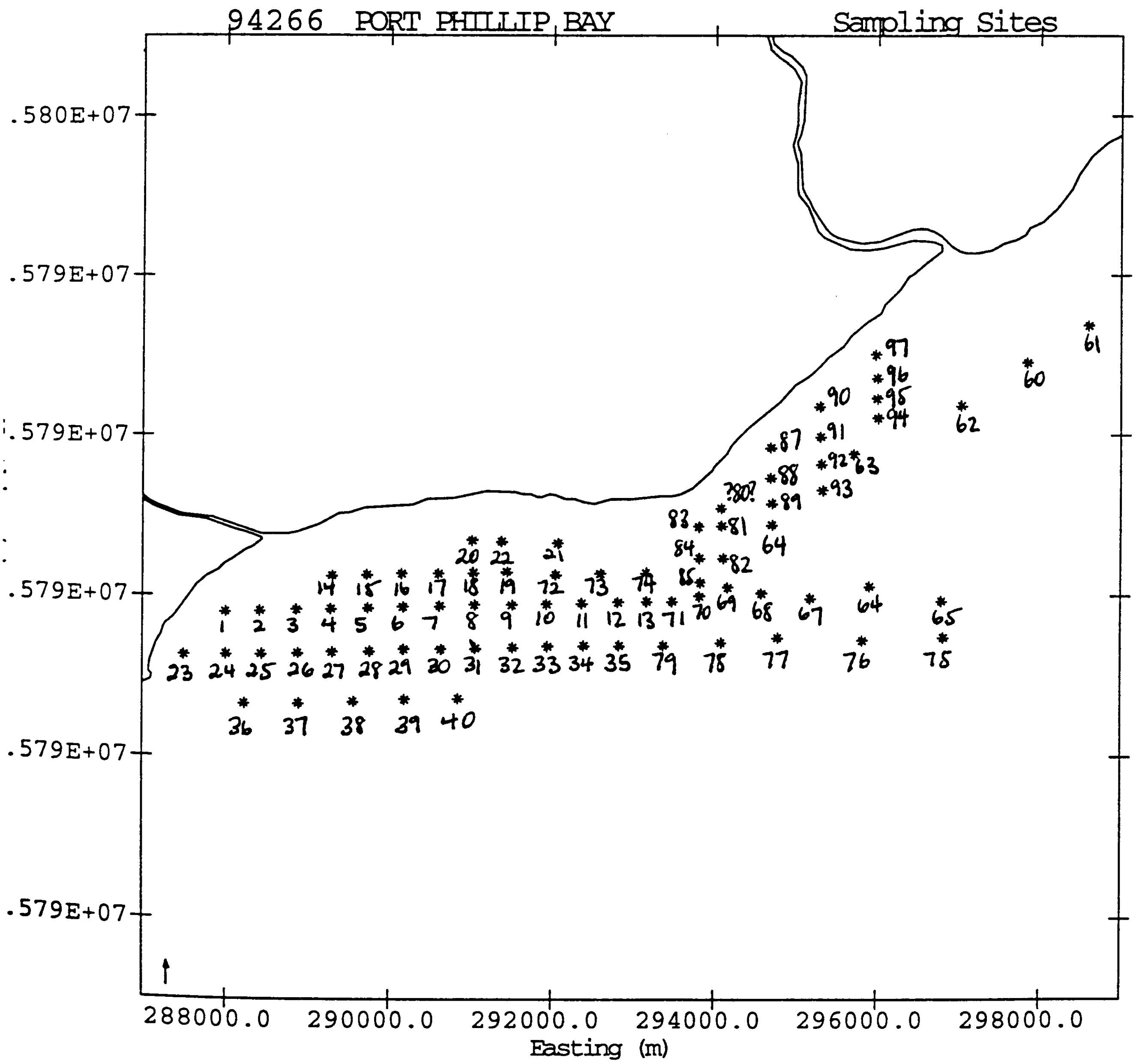

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xfv1138.266

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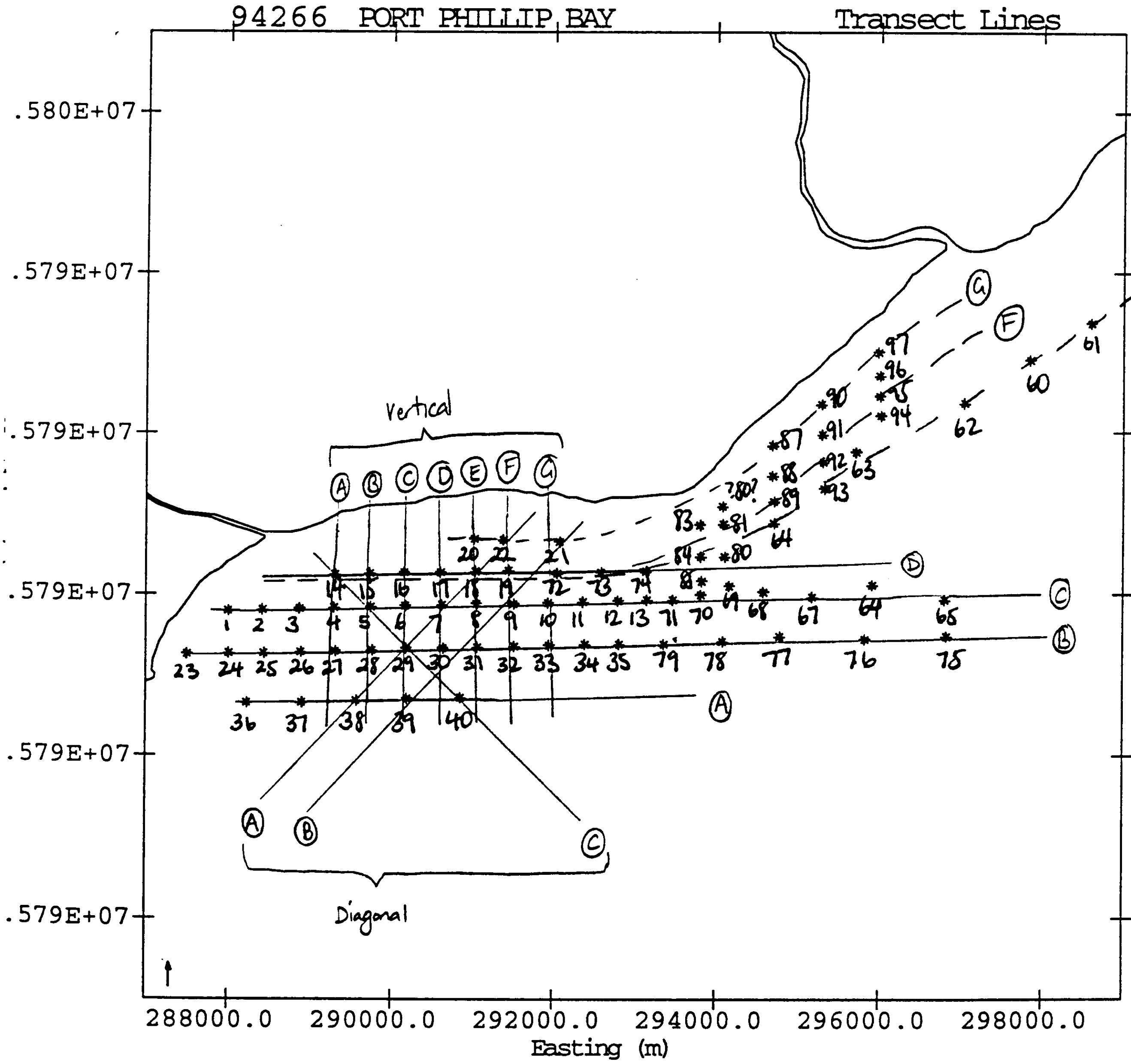

C 1

Coordinates for Werribee Plume Experiment

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w03	288883.2	5789824.7
w04	289297.3	5789835.4
w05	289745.1	5789847.0
w06	290176.8	5789858.1
w07	290624.6	5789869.6
w08	291056.2	5789880.6
w09	291505.5	5789892.1
w10	291935.7	5789903.1
w11	292367.4	5789914.1
w12	292797.6	5789925.0
w13	293160.5	5789934.2
w14	289304.2	5790248.3
w15	289734.5	5790259.4
test	289734.5	5790259.4
w16	290166.2	5790270.5
w17	290614.0	5790282.0
w18	291045.7	5790293.1
w19	291442.3	5790303.2
w20	291035.6	5790687.0
w21	292068.7	5790661.6
w22	291381.4	5790679.2
w23	287501.0	5789255.8
w24	288017.6	5789269.3
w25	288449.2	5789280.5
w26	288897.0	5789292.1
w27	289311.1	5789302.7
w28	289758.8	5789314.3
w29	290190.5	5789325.4
w30	290638.2	5789336.9
w31	291069.9	5789347.9
w32	291519.1	5789359.4
w33	291949.3	5789370.4
w34	292380.9	5789381.4
w35	292811.1	5789392.3
w36	288241.4	5788656.9
w37	288912.9	5788674.3
w38	289568.4	5788691.2
w39	290206.3	5788707.6
w40	290861.8	5788724.4
w41	291534.9	5788741.7
w42	292241.6	5788759.7
w43	292826.8	5788774.5
w44	293464.7	5788790.7

w94	295985.8	5793012.7
w95	295993.1	5792720.4
w96	295999.5	5792463.4
w97	296005.5	5792222.9
w98	296679.2	5793579.6
w99	296688.6	5793202.3
w100	292209.0	5790615.2
w101	291771.0	5790448.6
w102	291191.5	5790433.8
w103	290671.7	5790488.9
w104	290173.1	5790513.2
w105	289689.2	5790537.7
w106	289277.9	5790305.0
w107	289037.8	5790243.3
w108	289556.1	5790589.8
w109	289667.1	5790259.5
w45	293318.0	5788167.0
w46	289584.4	5788071.6
w47	290222.3	5788088.0
w48	290877.7	5788104.8
w49	291550.7	5788122.0
w50	292257.3	5788140.1
w51	292842.5	5788154.9
w52	293480.4	5788171.1
w62	297034.5	5792367.0
w60	297853.0	5792907.3
w61	298616.1	5793385.1
w63	295721.1	5791766.1
w64	294707.8	5790881.9
w65	296790.3	5789936.5
w66	295908.7	5790119.9
w67	295177.3	5789973.9
w68	294577.0	5790029.2
w69	294168.2	5790096.6
w70	293819.4	5789991.6
w71	293470.7	5789942.0
w72	292049.6	5790261.3
w73	292585.2	5790274.9
w74	293138.4	5790289.0
w75	296812.0	5789476.2
w76	295830.6	5789435.1
w77	294776.8	5789477.1
w78	294087.1	5789424.6
w79	293363.2	5789389.6
w80	294090.5	5791262.5

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w81	294100.4	5790868.5
w82	294110.4	5790472.7
w83	293806.3	5790861.1
w84	293816.3	5790465.3
w85	293824.1	5790156.4
w86	292872.7	5790545.0
w87	294686.6	5791845.6
w88	294696.1	5791466.5
w89	294703.8	5791157.6
w90	295294.7	5792358.8
w91	295304.1	5791981.4
w92	295312.8	5791637.4
w93	295320.9	5791311.9
MOKERA	293763.7	5790808.2
?W80?	294083.1	5791093.9