ISSN 1039-3218

Literature Review of the Physics of Port Phillip Bay

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Technical Report No.3

CSIRO Port Phillip Bay Environmental Study
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August 1992

EXECUTIVE SUMMARY

Aim

A Literature Review of the "Physical Processes in Port Phillip Bay" has been undertaken. The review summarises our current understanding of the physics of Port Phillip Bay and notes deficiencies in our knowledge. Sources of useful and accessible data which would be relevant to proposed future studies of hydrodynamics, dispersal and sediment dynamics are identified. The review highlighted our broad understanding of the physics of the bay, although some gaps in our knowledge were noted.

Physics of Port Phillip Bay

Port Phillip Bay is a semi-enclosed, predominantly tidal embayment (surface area of 1.95x109 m2, tidal prism of 9.4x108 m3 and mean depth of 12.8 m) (MMBW & FOOD, 573). The Bay is linked to the ocean of Bass Strait by a narrow, rocky entrance (cross-sectional area of 3.84x104 m2) (Fig. l). The bay is located in a tectonically controlled depression or sunkland, bounded by two major faults (Bowler, 739).

The dynamics of Port Phillip Bay are complex. The Bay's nearly fully enclosed nature and the wide variability in currents, make the links between hydrodynamics, residence times and biological health difficult to define (MMBW & FOOD, 573; WILLIAMS, 1739). The ocean entrance is isolated from the large, deeper, "saucer-shaped" inner bay by an unusually narrow entrance and wide flood-tidal delta, characterised by a fan-shaped series of channels and banks. Very few bays have similar morphologies. For example, many studied estuaries are linear, rather than circular. Some quickly shoal upstream to become very shallow or are typified by narrow tidal channels separated by large inter-tidal deltas.

In the region of the Heads and the Port Phillip Sands, water movements primarily result from the regular astronomical and barometric induced water-level variations between Port Phillip Bay and Bass Strait. These influences are less significant north of the Sands flood-tidal delta where water movements and mixing are largely induced by sea-surface wind stress which creates a complex variety of surface currents and bottom/nearshore return flows.

Thus, the hydrodynamics are characterised by (i) an entrance region where fast (3 m.s-1) ebb and flood jets dominate the circulation, (ii) a large flood-tidal delta, known as the Sands region, where strong currents occur in the major channels and (iii) an "inner" zone where tidal flows are weak. Thus, a friction-dominated entrance links the ocean to a large saucer-shaped inner basin where frictional resistance ,s sometimes secondary to the balance between wind stress and associated pressure gradients.

The Bay is linked by its narrow entrance to Bass Strait, an approximately rectangular waterbody some 400 km by 200 km in extent. The Strait consists of a shallow platform, mostly about 70 m below mean sea level, flanked by 4-5 km deep ocean to the east and west and by land to the north and south. Tidal flows are strong through the cross- sections at the entrances to the strait but decrease by an order of magnitude in the central regions, e.g. near the entrance to Port Phillip Bay (FANDRY et. al., 1985; BLACK, 2426).

The water levels and circulation in Port Phillip Bay include a response to forcing from Bass Strait (HUGHES, 1611) and the Bay needs to be placed in the larger regional context (CHURCH and FREE.AND, 1987; MIDDLETON AND VIERA, 1991; BLACK, 2426) to specify its dynamics.

Oscillations due to local wind, barometric pressure and coastaltrapped waves enter Port Phillip Bay from the strait. Seiching, surface gravity waves, density gradients and ocean currents are present in the bay or near the en-trance.

Regional monthly mean air temperatures are 10-18.5°C. The winds are variable, although westerlies prevail in winter and south or southwesterlies in summer. Sunshine averages 45' for the year, but June has nearly 5 times as many cloudy days than clear days. Annual evaporation is approximately 1010 mm compared with an annual rainfall of about. 760 mm.

The evaporation typically exceeds the rainfall in summer and the converse occurs in winter (MMBW & FOOD? 573).

The largest single sources of freshwater are the Yarra River which has a median annual discharge of about 28 m3.s-1 emptying into northern Port Phillip Bay (HINWOOD et. al., 163) and the Werribee Treatment Complex which discharges 6 m3.s 1 of effluent into the northern bay. The total annual freshwater input from smaller rivers and creeks and numerous diffuse sources is much less than the total volume entering through the entrance due to the tides.

Strong vertical stratification is relatively rare except near the major freshwater sources such as the Yarra River. Monthly records of vertical salinity and temperature structure in the deepest (24 m) central region showed salinity differences through the depth of less than 0.1 ppt with one exception associated with exceptional rainfall (LONGMORE et. al., 1909). Vertical temperature differences were usually very small but occassionally reached 3°C (ROCHFORD, 740; LONGMORE et al., 1909; MICKELSON, et al., 40). However, horizontal temperature and salinity gradients are common (LONGMORE et al., 1909) due to depth dependent differential heating between Bass Strait and the Bay, and to freshwater inputs.

The vertical circulation patterns are characterised by shear with currents at the bed often being opposite to the wind. Vertical temperature stratification in the bay occurs in low wind conditions when air temperature exceeds the water temperature. Thus, vertical stratification is most common during the warming period from August to February. The wind climate of Port Phillip Bay is not as strong as generally perceived, with gentle breezes or less (i.e. < 10 knot) occurring more than half the time.

The size of the Bay and its shallowness constrain the rate and the length-scales at which lateral mixing can occur. Thus, spatial waterquality variations around the Bay will result. Energy levels for vertical mixing (wave action, wind currents and tidal currents) vary spatially. The residence times are likely to increase up-harbour as tidal currents decrease and the wave climate becomes less severe in the more sheltered Geelong Arm.

The mixing of Werribee Treatment Complex effluent is dependent on the density structure of the water near Werribee compared with the density of the discharged fluid. Tidal currents are small in the Werribee sector of the Bay. Thus, a gradual spreading of the WTC effluent to form local stratification occurs in light wind conditions. Such local stratification persists until wind-induced mixing occurs, i.e. winds exceed about 10 knots.

For winds from 5-15 knots, the WTC effluent travels significant distances before its buoyancy is eroded by vertical mixing. Under these conditions, the direction of effluent travel is dependent on the prevailing wind direction which drives the surface flows.

For contaminants associated with particulates, initial settling may occur in the Werribee vicinity in liyht wind conditions. However, measurements of sediment transport near Portarlington have shown that these particulates are likely to be resuspended and transported to other areas. Their ultimate destination is presently unknown, although sediment grain size maps show large areas of fine deposition in the central Bay and in the Geelong Arm towards and within Corio Bay. Some of the material must be lost through the entrance but the volumes retained are unknown.

The likelihood of resuspension is a function of the particle size and density, sedin,ent cohesiveness, and the bottom turbulence (due to waves and currents), which vary with location and particularly with water depth. The bed sediment grain sizes in Port Phillip Bay are highly correlated with these relative energy levels. Sandy bottoms in the Sands and around the shallow margins (BIRD, 445) reflect tidal current strength ar,d local wave activity respectively. Fine muds are deposited in the deeper and more sheltered regions (SEEDSMAN and MARSDEN, 178; BUCKLEY, 61).

Winds above approximately 15 knots are sufficient to cause good local vertical mixing. The nett movement of the northern Bay waters is determined by the prevailing winds in such conditions but verticallyaveraged current directions are modified by pressure gradients against the shorelines.

State of our understanding

Prior investigations have provided a good understanding of many of the processes in the bay. For example,

* tidal currents
* sea level oscillations
* wind-driven circulation
* sediment characteristics
* exchange coefficients at the entrance
* the extent of temperature and salinity stratification
* local-scale mixing of WTC effluent
* wave climate
* bed orbital motion
* sea bed morphology

are broadly understood. Some limited additional experiments aiming at specific details in the above categories may be needed. However, we have a very good broad understanding of the above matters.

* Numerical hydrodynamic models of the bay have been developed and thoroughly tested.

* Dispersal models have also been applied.

The major weaknesses are associated with

* a lack of data to support detailed investigations of vertical eddy viscosity and diffusivity

* a lack of data to fully characterise the sediment pathways

* a lack of knowledge about the exchange rates across the Sands

* insufficient experiments treating the relationship between shallow water dynamics and biological productivity (e.g. sea grass) in the nearshore zone

In addition,

* no large-scale studies have been undertaken to specify annual residence times in the bay. The simplest case of a conservative tracer has not been analysed. Regional mixing experiments have been undertaken but these could not provide bay-wide results. Numerical techniques are clearly needed to address this question.

PORT PHILLIP BAY ENVIRONMENTAL STUDY

LITERATURE REVIEW OF THE PHYSICS OF PORT PHILLIP BAY

Victorian Institute of Marine Sciences

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Table of Contents

INTRODUCTION

On the 11th of June, 1991, the Minister for Conservation and Environment, Mr Steve Crabb, announced a major environmental study of Port Phillip Bay which is expected to set the agenda for environmental management of the Port Phillip Bay catchment for the next 20 years.

In July, 1991, Melbourne Water Corporation, on behalf of the Management Committee (representing Melbourne Water, Department of Conservation and Environment, Environment Protection Authority, Port of Melbourne Authority), commissioned CSIRO to prepare a Study Design.

A draft version of the Study Design was presented to the committee and public interest groups in January, 1992. The design considered the opinions of local and national experts but, in the available time, it could not incorporate all of the prior research. Thus, to finalise the draft Study Design, a series of Literature Reviews were commissioned which would identify the state of our understanding of the Bay, identify key groups and individuals who have undertaken studies of the Eay and highlight any serious deficiencies in our present knowledge.

The Victorian Institute of Marine Sciences (VIMS) was requested by CSIRO on 8 July, 1992, to provide a "Literature Review of the Physics of the Port Phillip Bay". This was one of several reviews; the others considered matters such as the weather, chemistry and biology.

The structure of the report and the information categories listed below reflect the requirements of the brief. No new work or analysis was required or undertaken. The review aimed to identify existing knowledge and sources of useful data.

As part of the Review, we collected the relevant papers and now hold copies in the VIMS library. Copies of the key publications were also provided to CSIRO.

We were fortunate that a detailed data base of publications relevant to Port Phillip Bay had been prepared by VIMS for Melbourne Water prior to our investigation (BALL et al., 1992). The data base provided an invaluable source of information as a basis for this report. Similarly, a prior study by COLMAN et al., (147) on the physical processes in the Bay was very helpful.

STRUCTURE OF THE REPORT

The physical processes were categorised as follows:

* Hydrodynamics
* Stratification
* Mixing and flushing
* Wave climate
* Physical inputs
* Sediments
* Numerical models

A number of sub-categories occur within each of these major groups.

The report examines each sue-category individually under the following headings:

* References
* Data
* Summary of our knowledge
* Deficiencies in our knowledge

The references are listed using the same code number as in the Port Phillip Bay reference database (BALL, et al.. 1992) and are identifiable in this report by bold-faced numbers. A star next to a code number indicates a key reference.

Some references use the date of publication rather than the database code number. Dates are not in bold print. These references are separately listed in the "Literature Cited" section.

The sub-set of references relative to the physics of the Bay are listed in this report as Appendix 1, in numerical order and in

Appendix 2, in alphabetical order. A few additional references were found as part of our study and these are numbered as 999x.

In the data category, we note existing data and its source. Unlike the publications, no attempt was made to collect the actual data sets. This category is meant to provide an overview of existing data so that any measurement deemed to be useful can be sought during the study.

The key results from the papers are summarised. We were primarily interested in constructing a broad view of the physical dynamics and to identify limitations in our knowledge.

1. HYDRODYNAMICS

1.1 Tidal Elevations

Reports- 88, 109, 163, 217, 282, 447, 573 , 1203, 1611, 1859, 2378, 2423 9992, 9999

Data- 88, 109, 163, 217, 282, 573, 914, 945, 965, 966, 1094, 1203, 1323, 1611, 1741 , 1747, 1749, 1750, 1752, 1859, 2423 , 9992, 9993, 9996, 9999

The major sources of sea level data are (i) the permanent tide stations primarily maintained by the Port Authorities and stored at the National Tidal Facility (Flinders University of South Australia) (Appendix 4); (ii) a three-year field program conducted by VIMS from 1987 to 1989 (ROSENBERG et al., 2423); and (iii) the Phase 1 Studies of Port Phillip Bay (MMBW & FOOD, 573).

Tide gauge deployments were made by VIMS in the period from November 1987 to March 1989 (ROSENBERG et al., 2423) at 9 locations to supplement the data from the permanent tide stations (Fig. 1). One tide gauge was maintained throughout the fie'd program at Site T2 in the south of the inner Bay to provide an extra reference sea level to be used to relate the shorter-duration deployments. Tides were recorded with high-resolution Aanderaa WLR5 and lG3A digital quartz pressure sensors. The meters recorded sea level, temperature and conductivity for a total of 882 current-meter-days (2.4 years).

Tides in Port Phillip Bay are semi-diurnal, exhibit a diurnal inequality and are characterised by rapid modification of tidal phase and amplitude through the entrance and over the Sands. M2 amplitudes of 0.7 m outside the entrance reduce to 0.44 m at Pt Lonsdale, 0.19 m after the Sands and rise again to 0.27 m at Geelong (Fig. 1). Thus, 37% of the total attenuation of the M2 constituent occurrs in the

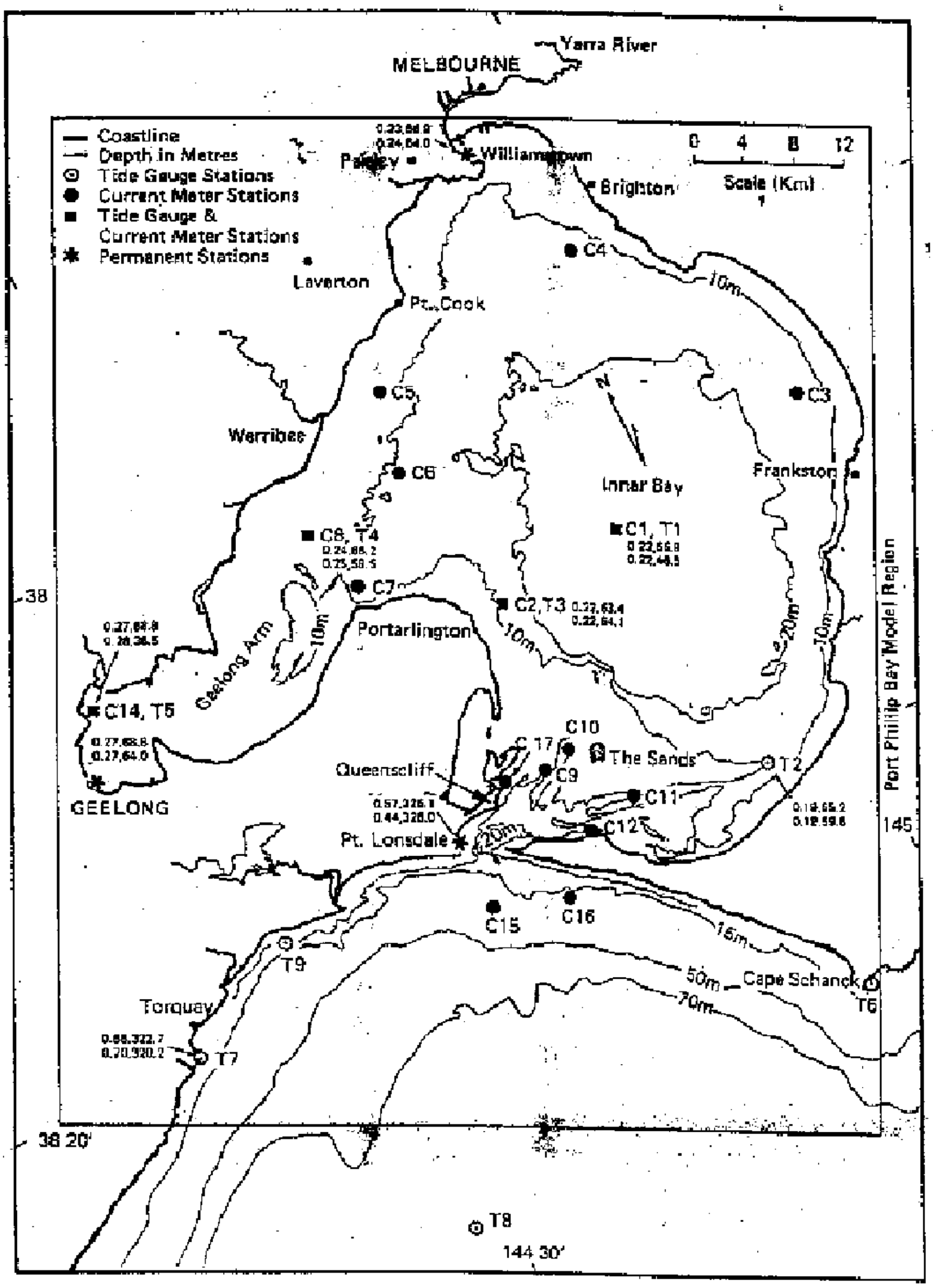

Figure 1: Current meter and tide gauge sites wherz measurements were made by the Victorian Institute of Marine Sciences (after ROSENBERG et al., 2423)

immediate vicinity of the entrance while the remainder occurs over the Sands. M2 tidal phases change by an average of 104° or 3.6 hours over a distance of approximately 20 km.

Tidal phase in the inner Bay is nearly constant although some data suggested the possibility of a rapid change in high tide times around the shoreline. Investigating this possibility, a numerical model of the M2 c¢nstituent showed that the tidal phase increased by only 2° (or 4 minutes) anti-clockwise around the perimeter of the Bay (BLACK et al., 9999).

When all of the tidal constituents and other currents were included in a numerical model, the M2 amplitude reduced by about 0.01 m (4%) at Williamstown, compared with the case of M2 alone. Thus, non-linear interaction in the entrance and over the Sands has a small, noteworthy effect on the tidal amplitude attenuation.

A recurring feature of the Bay is the frequency dependence of attenuation through the entrance and across the Sands. The cross spectrum between sea levels in Bass Strait and in northern Port Phillip Bay was coherent at periods greater than 8-12 hours only. The damping increased as the pericd shortened with the gain factor being 0.45 for the diurnal tidal constituents and 0.32 for the semi-diurnal. The phase shift also varied as a function of frequency (Fig. 5).

Deficiencies in our knowledqe

Tidal sea levels are regularly recorded at a number of locations. There are no serious deficiencies in our knowledge.

1.2 Tidal Currents

Reports- 163, 217, 447, 573, 899, 2361, 2378, 9999

Data- 163, 573 , 1751, 1752, 1998, 2361, 2423 , 9999

The major sources of current data have arisen out of (i) a three- year field program conducted by VIMS from 1987 to 1989 (ROSENBERG et al., 2423); and (ii) the Phase 1 Studies of Port Phillip Bay (MMBW & FOOD, 573), and measurements by CALDWELL CONNELL ENGINEERS (2361) near Poirt Wilson in 1981; (iii) measurements by the Coastal Investigations Unit, Port of Melbourne Authority.

Deployments of current meters at 17 sites were made by VIMS in the period from November 1987 to March 1989 (Fig. 1). Current meters were moored for an average of 43 days for each deployment. Multiple deployments at these locations and multiple levels in the water column were sampled to examine seasonal variations and 3-dimensional circulation respectively.

Currents were recorded in most cases using Aanderaa impellor-type RCM4/5 meters. Vector-averaging Neil Brown acoustic or S4 electromagnetic current meters, more suitable for locations with surface waves, were deployed at one Bass Strait site, and at three Port Phillip Bay sites. The meters recorded current speed and direction, temperature and conductivity for a total cf 1258 currentmeter-days (3.5 years).

The Port of Melbourne Authority Coastal Investigations Unit holds unpublished current data and a study was corducted near Point Wilson by CALDWELL CONNELL ENGINEERS (23613) in 1981 during which currents were recorded with Aanderaa RCM-4 current meters and using drogues.

A number of instantaneous velocity profile measurements were made during the Port Phillip Bay Phase 1 Study (573)

Previous circulation experiments involving the deployment of current meters and tide gauges had been conducted in Bass Strait (HODGKINSON et al., 1990).

Using their measurements, VIMS developed a calibrated 2- dimensional numerical model of the Bay which predicted tidal currents with a high degree of accuracy (BLACK et al., 9999). This model provides a detailed view of the horizontal tidal ciculation and when combined with the field measurements provides a good understanding of tidal circulation.

The semi-diurnal tidal circulation in Port Phillip-Bay at high, midebb, low and mid-flood tides is shown in Fig. 2. The maximum currents occur near the time of high and low tide in the entrance (Fig. 2a,c). Within the Bay, the maximum currents occur near mid-tide, in response to the 3- hour sea level phase shift through the entrance and across the Sands. Large eddies some 15 km across flank the ebb tidal jet (Fig. 2b, d). Flood currents near the shoreline persist for much of the cycle. Notably, sea level phase or amplitude variations around the model boundary were neglected and the circulation in Bass Strait away from the Bay entrance may not be well predicted. Maximum currents in the entrance were nearly 3 m.s 1 (Fig. 2a) while tidal currents within Port Phillip Bay were much slower, e.g. maximum spring tidal currents were 0.06 m.s-1 at Site C6 at the entrance to the Geelong Arm near the Werribee Treatment Complex.

Thus, tidal circulation in Port Phillip Bay is primarily governed by volume continuity with the tidal prism decreasing and depths increasing sharply in the inner Bay beyond the Sands where the currents diminish. Through the central regions of the Bay, the currents are faster on the western shore due to the larger downstream prism in the Geelong Arm.

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Currents measured at multiple levels above the bed within Port Phillip Bay showed that the inclination of the major tidal axis was nearly constant through the vertical for the dominant M2 component. Indeed, the variability in the measured inclination at common levels was greater than any changes between levels. The tidal currents mostly increased with distance from the bed, although scatter was sometimes evident as the surface was approached.

The phases indicated that near-bed flows reversed somewhat earlier than those higher in the water column, due to bed friction. The near bed and upper level reversal times differed by up to 15° or 30 minutes.

Deficiencies in our knowledqe

Tidal currents have been recorded at an exceptionally large number of locations for such a small bay. This data has been utilised to create a calibrated numerical model of the flow. There are no serious deficiencies in our knowledge of tidal circulation.

1.3 Wind-Driven and Low Frequency Currents

Reports- 163, 217, 472, 573 , 2351, 2373, 9999

Data- 163, 573 , 2361, 2378, 2423, 9999

Low-frequency currents are predominantly wind-driven in inner Port Phillip Bay (9999, Fig. 4). Over the Sands, however, low-frequency currents are better correlated with the passage of low frequency oscillations in Bass Strait. These current.s from Bass Strait decrease with the reduction in prism and the increase in depth and are therefore less important in the inner 6ay (9999).

Two-dimensional numerical simulations showed currents directed downwind along the shallow margins of the inner basin where the vertically- averaged wind stress was greatest (573, 9999). A return upwind current across central Port Phillip Bay, driven by the pressure gradient associated with coastal surge on the downwind shoreline, maintained the volume continuity. Notably, this pattern of two oppositely-rotating "cells" in central Port Phillip Bay characterised simulations of all wind directions and is the classic case for an enclosed water body described by CSANADY (1973). Only the location of

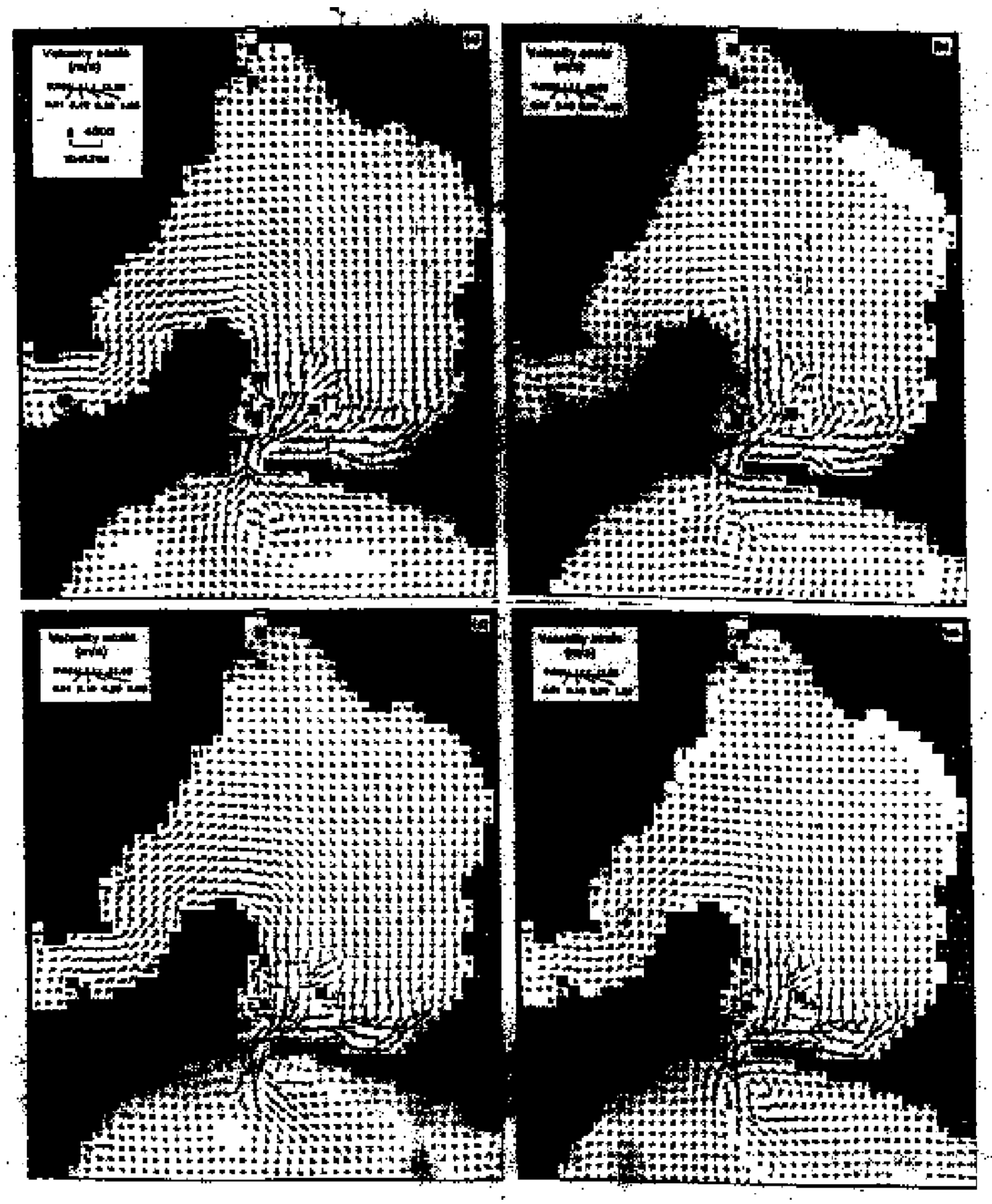


Figure 2: Tidal currents in Port Phillip Bay (after BLACK et al., 9999).

the centres of the gyres moved with changes in wind direction in Port Phillip Bay.

Significant offsets evident in averaged currents recorded in the Sands or near the ebb jet in Bass Strait are tidal current residuals generated by the interaction with local topography (9999). For example, the ebb jet, which extends at least 10 km offshore, was depicted by a strong southward residual in the measured currents.

At low frequency, currents at different levels above the bed were often oppositely directed and typically different. Near-bed currents in the inner bay vary in strength and orientation relative to the wind direction. Horizontal measurements suggest that upwelling and downwelling may occur at the shorelines. The near-bed currents then conserve mass associated with the downwelling at the windward coastlines.

Vertical shear was always present with curren-ts near the surface being different in magnitude and direction to currents at middle or bottom levels (Fig. 3). A logarithmic vertical velocity profile was not evident at low frequencies.

Upwelling and downwelling within the irregular semi-enclosed water body mostly obscured any simple relationship between the vertical levels. However, in the central Bay at Site C1, the vertical shear was found to be well correlated with wind (9999). The regression equations were,

$$\frac{\partial u}{\partial z} = (3.54 \, Wew - 4.32 \, Wns - 2.22) \times 10\text{-}4 \quad r2=0.66$$

$$\frac{\partial v}{\partial z} = (5.28 \, Wew - 2.03 \, Wns - 7.92) \times 1C\text{-}4 \quad r2=0.49$$

where U and V are daily-averaged east/west and north/south velocitiesmeasured at 2.2 and 17.5 m above the bed in 24 m depth and measured by two current meters (Fig. 3), Wew and Wns are the daily-averaged components of the Point Cook wind. Typical values of ∂U/ax and ∂V/∂x were 2x10-3. The correlation coefficient diminished when the wind stress was used in the analysis.

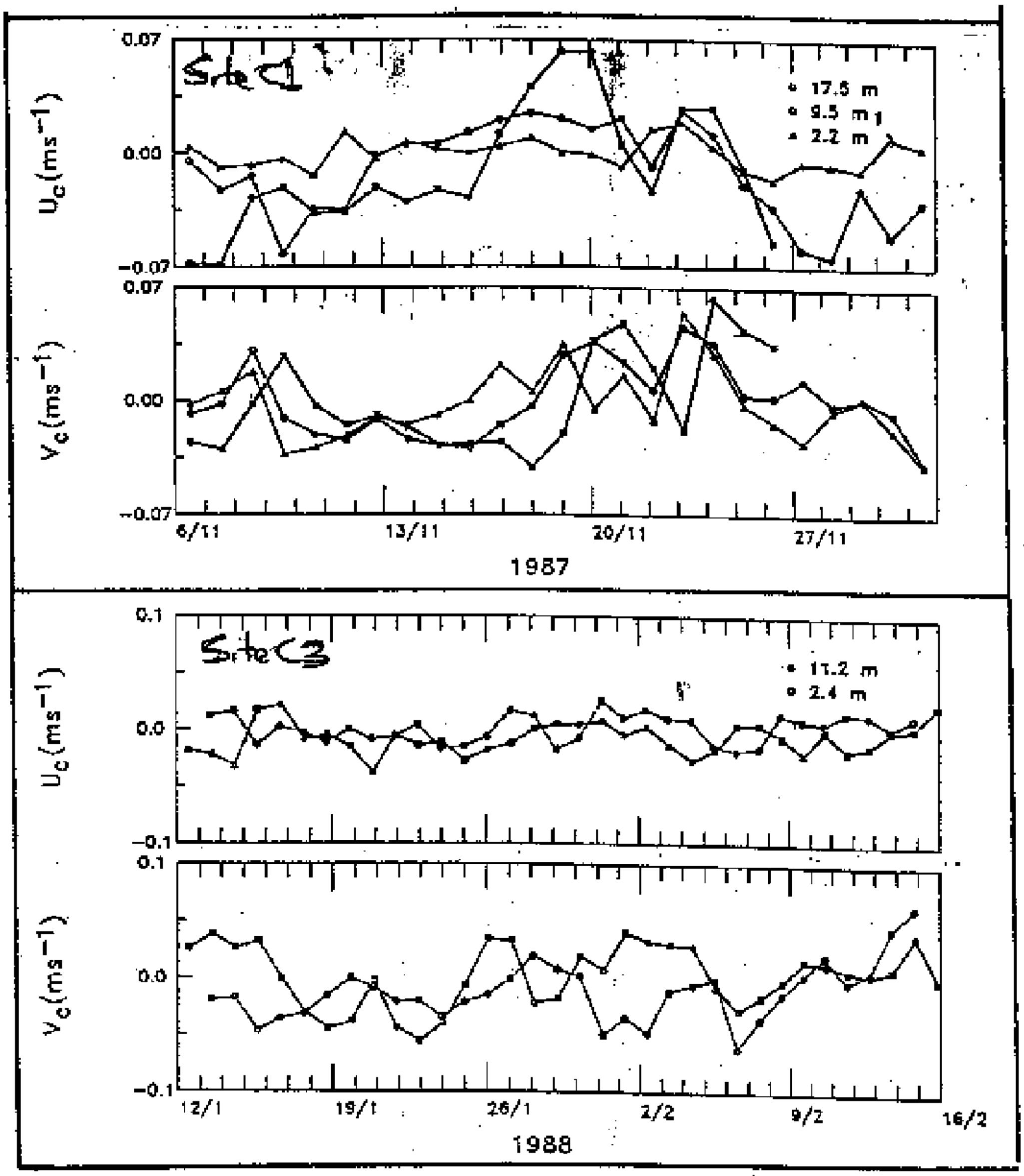


Figure 3: Low frequency currents measured at various levels above the bed at Sites C1 and C3 (after BLACK et al, 2378).

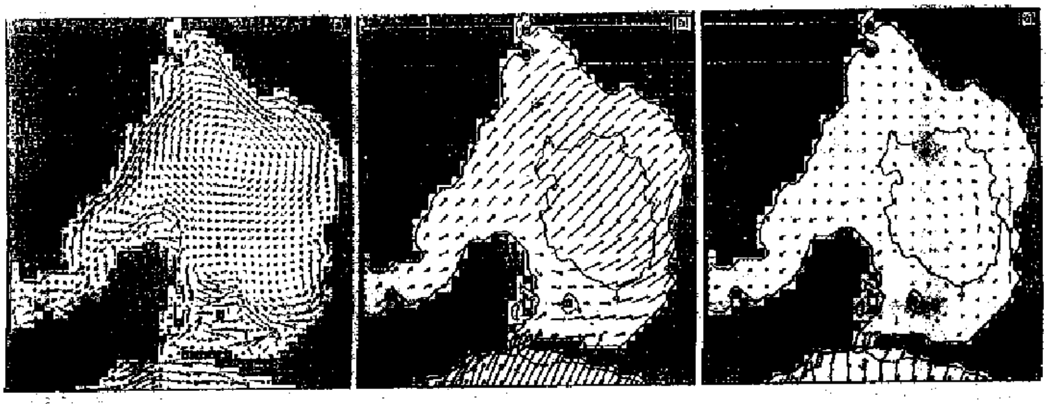


Figure 4: Currents in Port Phillip Bay for a 22 m.s 1 west wind: (a) vertically-averaged (b) 0-1.5 m below the surface and (c) 4.5 to 7.5 m below the surface (after BLACK et al., 9999).

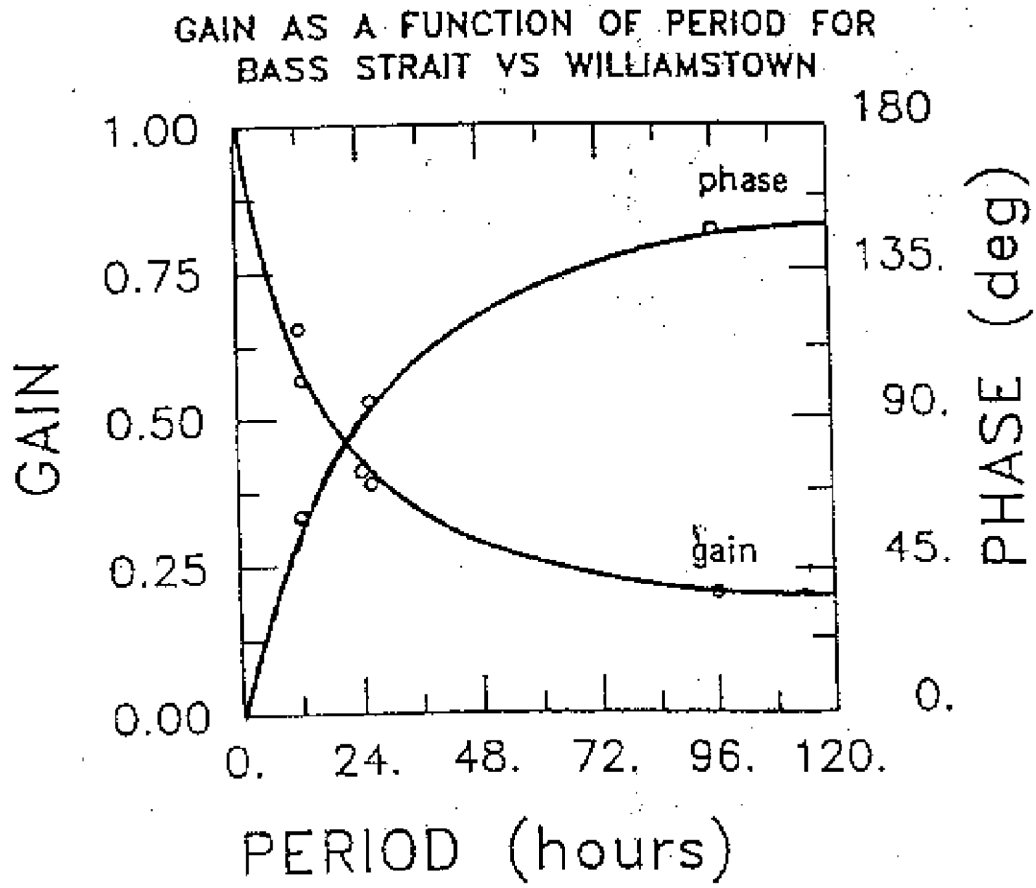


Figure 5: Gain and phase shift of sea level oscillations between Bass Strait and Williamstown as a function of period (after BLACK et al., 9999).

Deficiencies in our knowledge

The long-term observations made by VIMS have limited vertical resolution, although measurements were made at a wide variety of levels. As such, a preliminary assessment of vertical structure only, could be made. More data collection and analysis is required to properly determine the vertical shear, eddy diffusivity and the overall structure of the circulation throughout the Bay. Further work which relates the vertical mixing to the wind stress is needed to fully specify the wind-driven and low frequency circulation in 3 dimensions.

1.4 Low Frequency Sea Level and Atmospheric Pressure Response

Reports- 88, 163, 282, 573 , 1611, 1859, 2378, 9999*

Data- 163, 573, 2378, 9993

Regression analyses by BLACK et al., (9999) showed that the pressure factor relating atmospheric pressure to sea level (Pf) was 0.011 at Point Lonsdale (near the entrance) and Williamstown (in northern Port Phillip Bay). However, lags, r, of 14 and 22 hours at Pt Lonsdale and Williamstown respectively were noted between pressure and sea level with pressure always leading. The lags at other sites exhibited a general increase from about 5 hours in Bass Strait to more than 20 hours within the Bay.

CHURCH and FREELAND (1987) found Pf to be 0.014 and they did not consider any lag. Hughes (535) noted that extreme sea levels at Williamstown could be predicted from the pressure alone using Pf=0.023 and r=24 hrs.

Outside the entrance, BLACK et al., (9999) used a numerical model to eliminate the correlation between wind and atmospheric pressure in order to test the response to pressure alone. They demonstrated an isostatic response in Bass Strait with pressure factor Pf=0.00997.

A lag of 12 hours between Point Lonsdale and Williamstown was confirmed numerically and shown to be associated with the non- linear interaction of low frequency and tidal components. The response to barometric pressure was therefore non-isostatic.

BLACK et al., (9999) provided the following best fit equation relating Williamstown residual levels (after removing the tides) to those at the entrance,

$$Zw = 0.884\ Z1 + 0.00767\ rx + 0.0167\ T - 0.450$$

where Zw is the Williamstown residual sea level, Z1 the Pt Lonsdale residual level measured 6 hours earlier, Tx the Point Cook wind stress along 29°T and T the monthly-smoothed air temperature at Laverton (°C) measured 44.75 days earlier. The lateral wind stress was insignificant and does not appear in the above equation. No barometric pressure correction was needed because the effects were contained within the Pt Lonsdale levels. The regression demonstrates that the levels in the Bay are related to levels at the entrance, local wind stress and horizontal density gradients.

Removal of the tides from the Will,amstown record reduced the time series variance to 27% of its initial value. Only (% of the initial variance remained after the linear re5ression. The residual was primarily associated with seiches in the Bay which were not specifically treated.

The Pt Lonsdale levels accounted for 63% of the non-tidal variance which means that most of the sea level energy at Williamstown comes from Bass Strait. The regression showed that the amplitude of nontidal sea level oscillations reduced between Pt Lonsdale and Williamstown by 11.6% . However, the frequency dependence of the attenuation is not treated by the linear regression model in the time domain.

In summary, approximately 98% of the sea level variance in the nearby Strait and 96% within the Bay was found to be predictable using empirical and numerical techniques to describe the tides, coastaltrapped waves, barometric pressure, local wind-forcing and horizontal temperature gradients. Over a complete year, coastal- trapped waves arriving from the west accounted for 3% of the total variance.

ADAMS (88) listed all extreme sea levels which were greater than 0.85 m above Australian Height Datum (AHD) at Williamstown from 1874-1939 and from 1944-1985. The largest of these was 1.33 m above AHD and was calculated to have a return period of 109 years. A 0.89 m level above AHD has a 1 year return period.

BLACK et al.' (2378) showed that the extremes coincided with very low pressures, as expected, and with winds from the westerly quadrant (not southerly). The west wind creates longshore currents in Bass Strait near the entrance which set up the water level.

For the strongest westerly wind recorded at Laverton, the sea level rose by about 0.32 m within Port Phillip Bay alone and by an additional 0.52 m in Bass Strait near the entrance.

Deficiencies in our knowledge

A high percentage of the low frequency sea level could be predicted. Some further study of the annual cycle in level between the entrance and Williamstown may be warranted.

2. STRATIFICATION

2.1 Salinity and Temperature

Reports- 40, 113, 142, 163 , 340, 525 , 573, 653, 740*, 899, 1040, 1049, 1909 , 2130, 2361, 9999

Data- 40 , 113 , 142, 163, 340, 472, 525, 740, 1063, 1067, 1069, 1155, 1232, 1435*, 1736, 1738, 1748, 1752 , 1753, 1909 , 1930, 2130,2361, 2423 , 2597, 9994

Generally' Bay temperature varies from 9–25 deg C with an inter-annual variation of about 2-4 degrees:

Year	Reference	Temperature Range (°C)
1952	740	9.4-21.3
1980-82	113	9–25
1985-86	1909, 1155	10-21
1988	1156	10.6-21.5

Longmore et al., (1909) reports that water temperature is lowest in August (10-11.5 °C) and highest in February (18-21 °C). Hobsons Bay was generally the warmest area.

Salinity measurements in the Bay show no clear seasonal pattern (EPA, 113). Mean salinities in 1980-82 ranged from 32.3 to 34 ppt.

The monitoring program conducted by the EPA (113) between June 1980 and May 1982 sub-divided the Bay into sixteen sampling strata (Fig. 6) on the basis of regions most likely to be affected by 'external' influences (river inputs, WTC, Bass Strait etc).

There did not appear to be a systematic difference in stratum temperatures and because stratum mean temperatures were similar, it was concluded that "no segment was being influenced to a determinable degree by any source of heat other than the natural." (See Fig. 7).

Salinity measurements (Fig. 8) show that the strata with the highest variation from the mean value were: Swan Bay, North-eastern South, Corio Industrial, Werribee Remainder and North-eastern North. The lowest variation were by Corio Remainder, Geelong, Corio Urban, Central and Altona Remainder. These variations are influenced by proximity to freshwater inputs and by strata geometry.

A more detailed listing of temperature and salinity values between 1980 and 1984 for specific Bay locations is given by Cowdell et al., (1435).

2.2 Vertical Structure

Reports-40* , 163, 573, 653, 740* , 1049, 1203,
1909* , 2130, 2361, 3740, 9999

Data- 40, 142, 163, 573, 653, 1067, 1203, 1909

Vertical temperature stratification, as reported by ROCHFORD (740) between 1947 and 1952, was most pronounced in the centre, segment in the Bay during the vernal-summer warming of surface waters (Fig. 10). The temperature differential reached 3°C over a depth of 20 metres. Vertical temperature stratification was usually very small during the cooling period from March to August. As the development of vertical stratification is highly correlated with periods when air temperature exceeds water temperature (Fig. 11), the stratification is most common when water temperature is rising between August and February.

"Chlorinity" measurements by ROCHFORD (740) showed that the chlorinity structure in the middle of the Bay was nearly homogeneous at a 20 metre deep water column. This was in contrast to the chlorinity stratification found in the Hobsons Bay area at a depth of 5 metres, associated with the Yarra plume. The chlorinity of bottom waters in this area fluctuated seasonally in the same fashion as those in the centre of the Bay with minimum values around September-October and maximum values around February of each year of the measurement period.

2.3 Horizontal Structure and Density Fronts

Reports- 40, 163, 378, 573, 653, 899, 1049, 1203, 1909* , 2361, 9994, 9999

Data- 40, 142, 163, 573, 653, 1203, 1909*

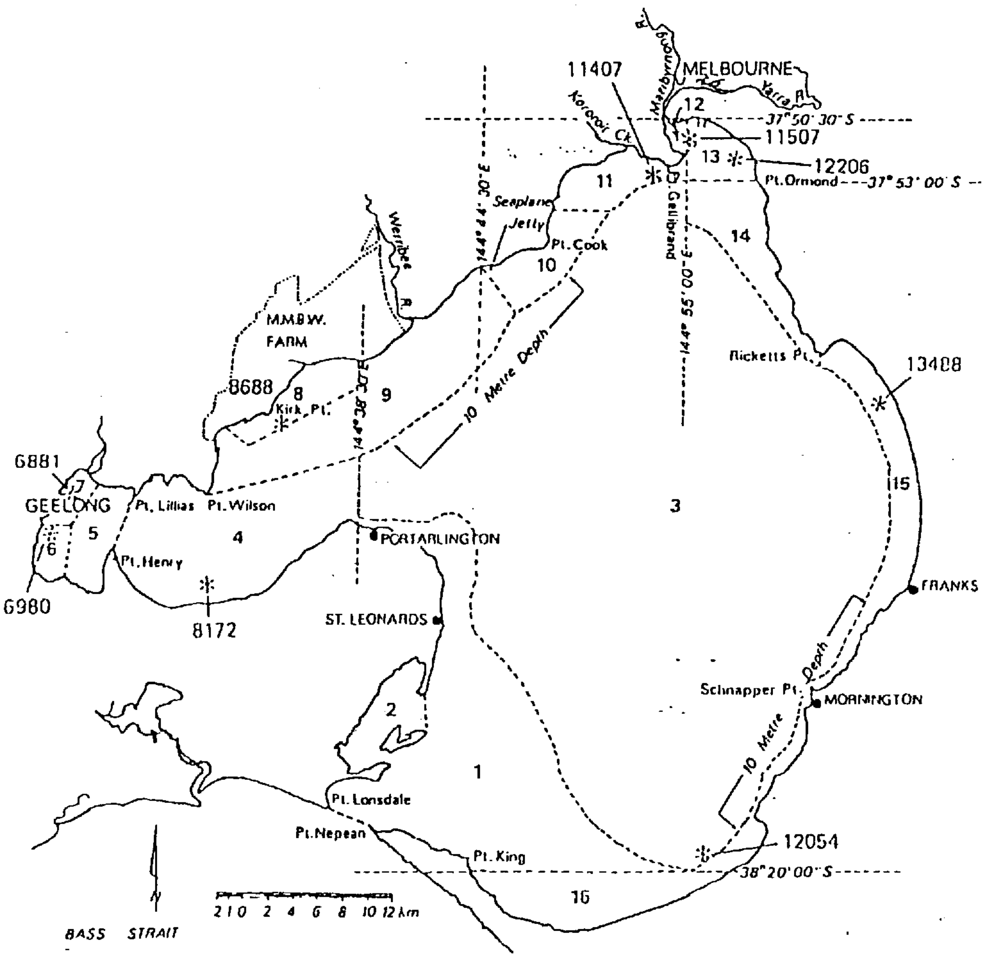
Horizontal temperature and salinity gradients are always present in the Bay and are determined by the rainfall, evaporation, freshwater input and mixing of ocean waters through the entrance.

Differential heating as a function of depth create horizontal temperature gradients between the entrance and the inner Bay. Ihe Bay is colder in winter and warmer in summer than the adjacent ocean.

Freshwater inputs from the Yarra, WTC and some of the larger rivers (e.g. Patterson River) usually characterise the salinity contours (LONGMORE et al., 1909) (Fig. 9).

Generally, Corio Bay is more saline tnan the adjacent waters, probably indicating that evaporation outweighs freshwater input to Corio Bay. In February 1985, measurements showed that Corio Bay salinity was 36.4 ppt as compared to 35.7 ppt for the rest of the Bay (LONGMORE et al.,1909).

Horizontal density fronts associated with river discharge are common. For example, a density difference of 26 kg.m~3 between the Bay and the head of the Patterson River estuary causes the lighter freshwater to



KEY TO SAMPLING STRATA

1 EXCHANGE REMAINDER
2 SWAN BAY
3 CENTRAL
4 GEELONG
5 CORIO REMAINDER
6 CORIO URBAN
7 CORIO INDUSTRIAL
8 WERRIBEE FARM
9 WERRIBEE REMAINDER
10 ALTONA REMAINDER
11 ALTONA URBAN
12 YARRA MOUTH
13 HOBSON REMAINDER
14 N.E. NORTH
15 N.E. SOUTH
16 SOUTH-EASTERN

Figure 6: Location of Port Phillip Eay sampling strata (after EPA, 113).

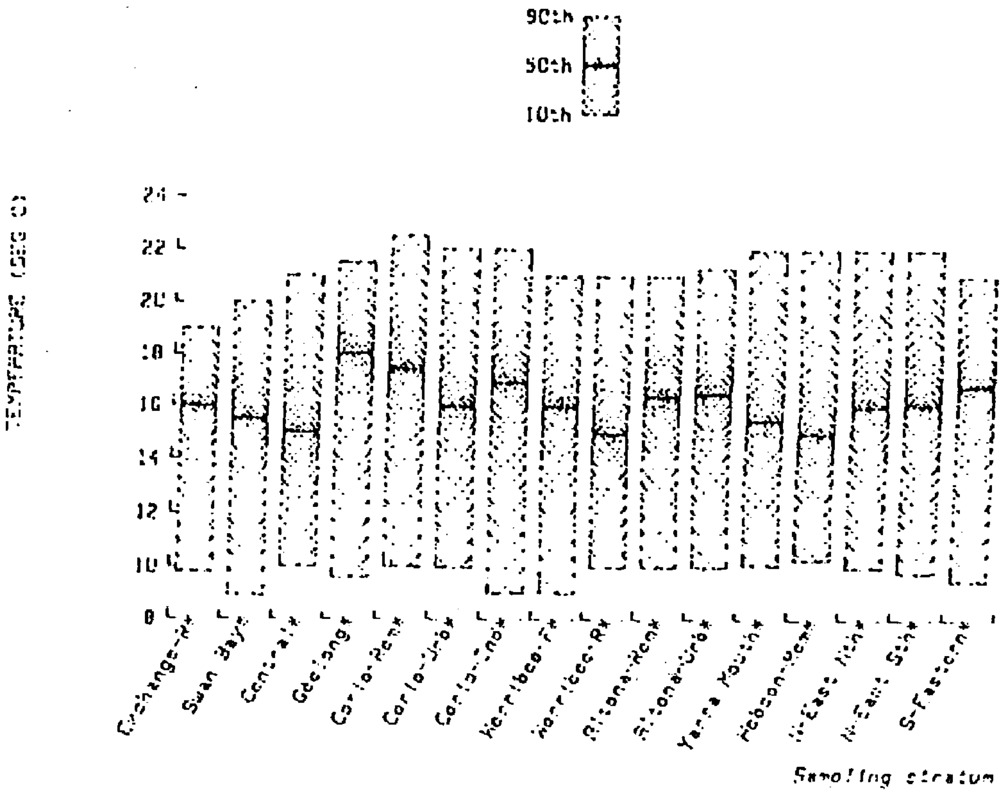


Figure 7: Percentile yraph of temperature versus sampling stratum (after EPA, 113).

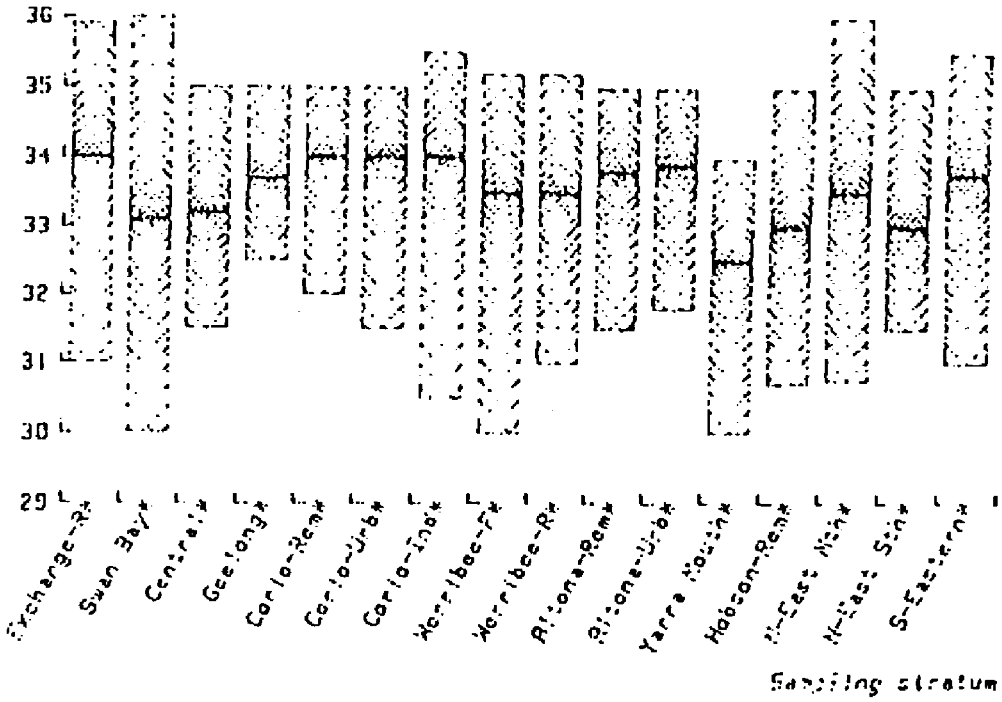


Figure 8: Percentile graph of salinity versus sampling stratum (after EPA, 113).

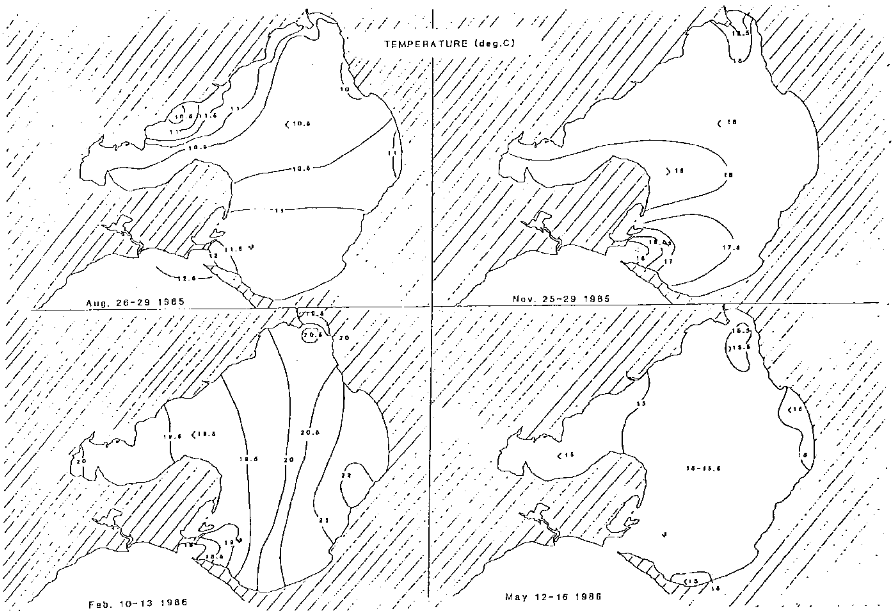


Figure 9a: Temperature contours in Port Phillip Bay (after I,ONGMGRE et al., 1909).

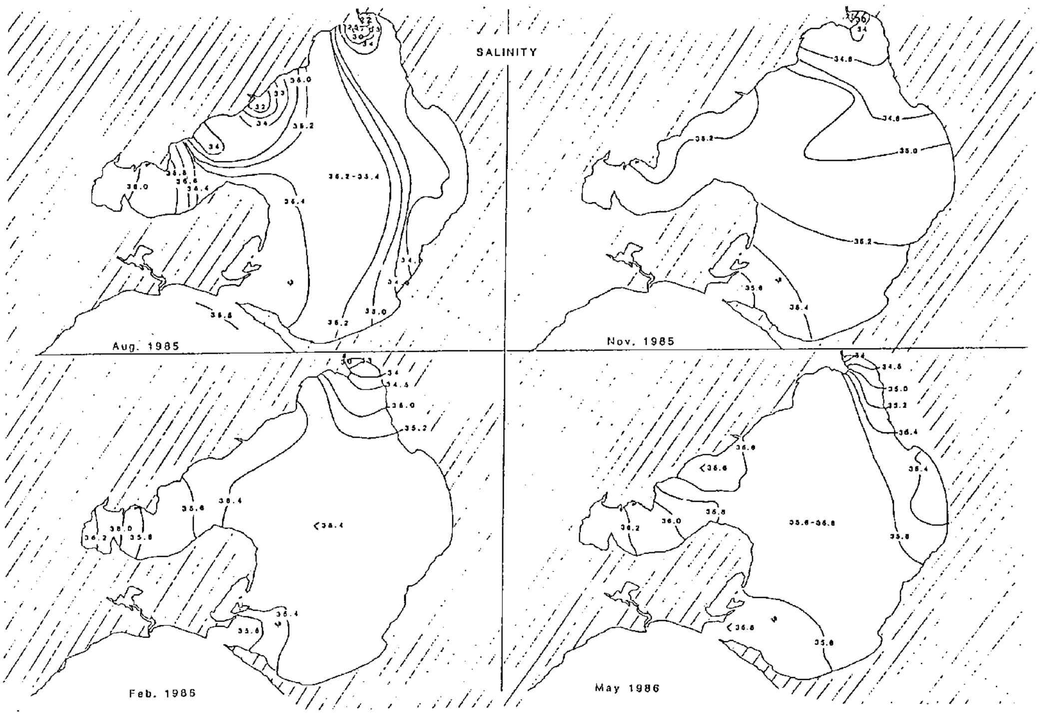


Figure 9b Salinity contours in Port Phillip Bay (after LGNGMORE et al., 1909)

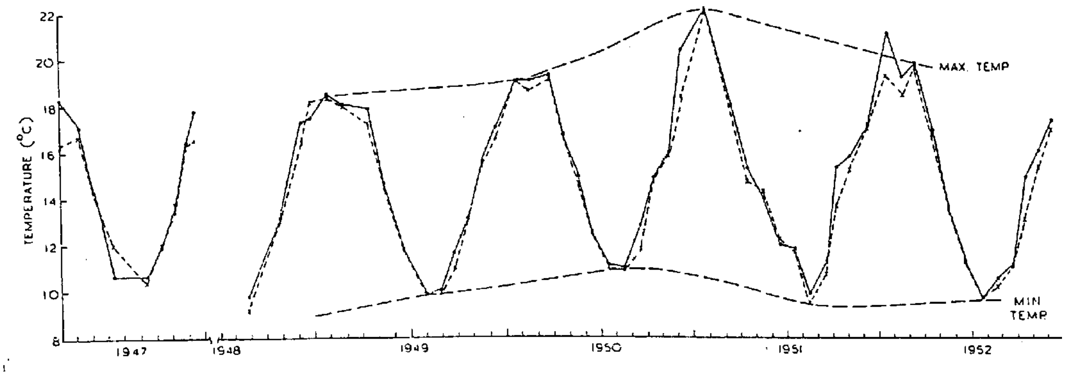


Figure 10: Vertical temperatures at surface (solid line) and at 20 m depth (dashed line) in central Port Phillip Bay (after ROCHFORD, 740).

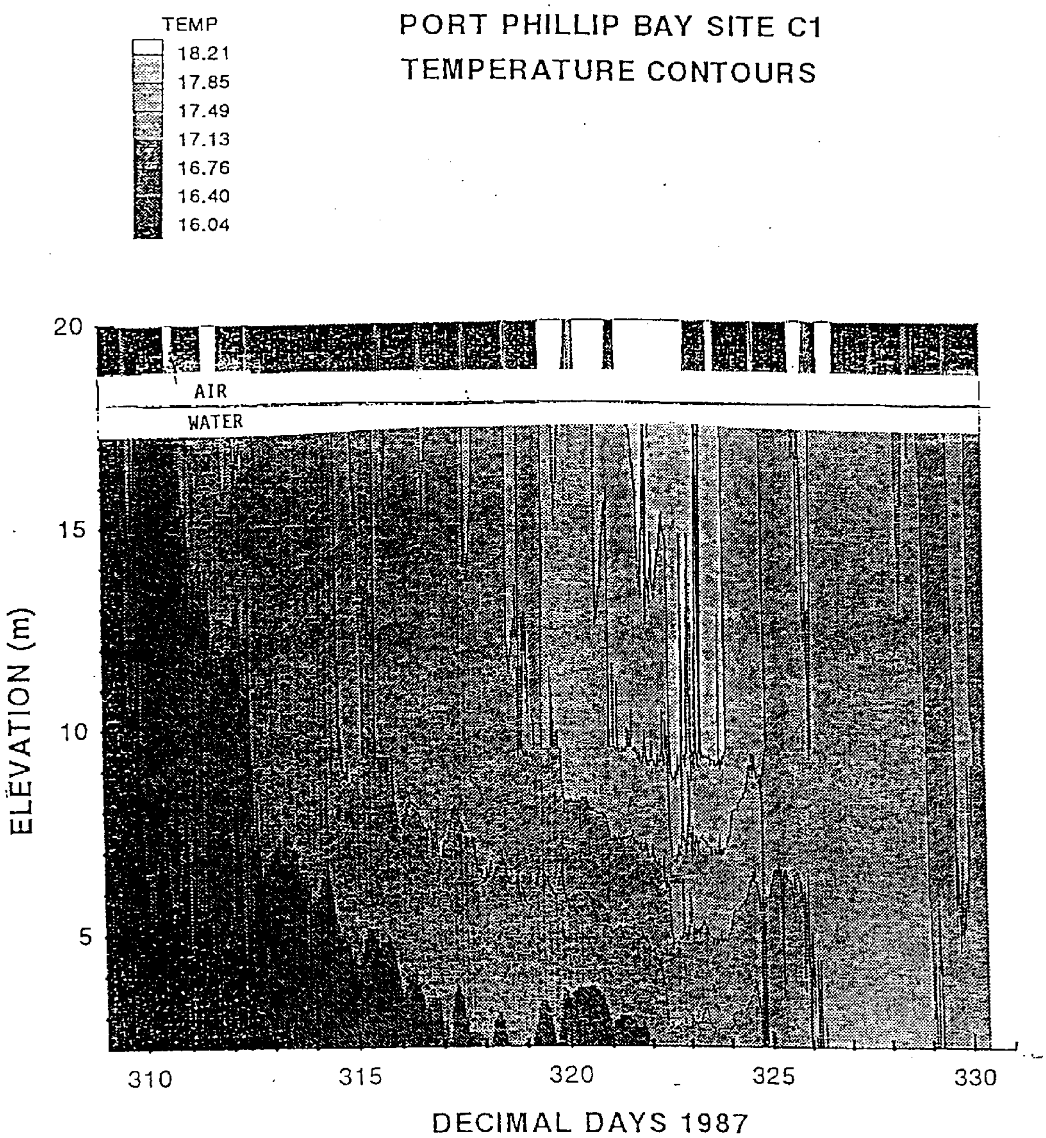


Figure 11: Temperature structure at a site in central Port Phillip Bav. The water column becomes mildly stratified when the air temperature exceeds the water temperature (after BLACK et al., 2426)

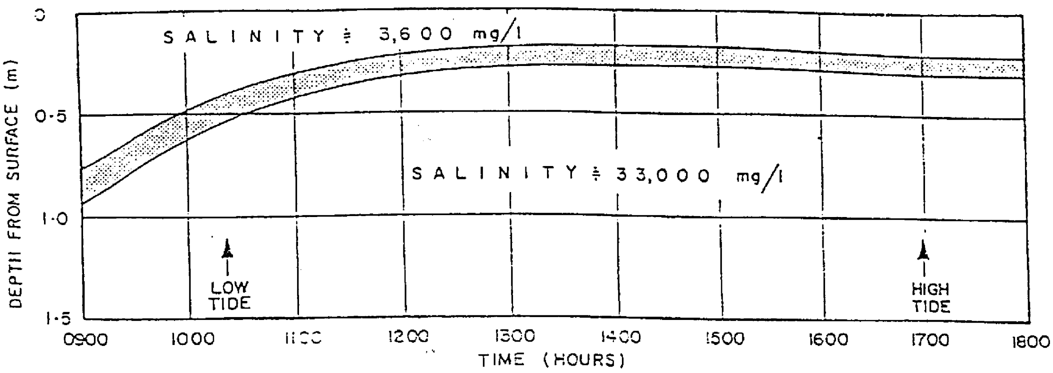


Figure 12: Salinity stratification measured at the mouth of Patterson River on 27 May 1975 (after CALDWELL CONNELL ENGINEERS, 1203).

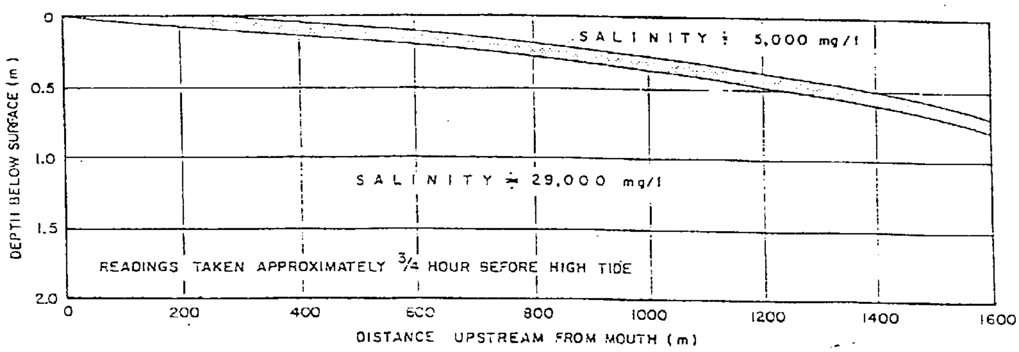


Figure 13: Density stratification measured in Patterson River on 5 June 1974 (after CALDWELL CONNELL ENGINEERS, 1203).

remain as a distinct layer on top of the denser saline Bay water, except at times of very high mixing. The stratified layer was measured to be about 0.25 m below the surface (CALDWELL CONNELL ENGINEERS, 1203) (See Fig. 12). Salinity profiles made just before high tide on 5 June 1974 show a saline wedge with the freshwater layer increasing in depth from zero at the mouth of the estuary to 0.7 m at a distance 1.6 km upstream from the mouth (Fig. 13).

Appendix C of Hinwood et al., (163) gives a detailed account of density stratification of the Yarra/Maribyrnong River system and Hobsons Bay. High river flows (>50 m3s-1) typically cause the river plume to extend across the whole of Hobsons Bay, where horizontal density gradients transverse to the plume axis may be significant.

Annual average surface salinities (1977-1978) show that salinity (density) values were lowest near the river mouth and rise towards the south and the east. Except during floods, water below 1.5 m is essentially bay water and below 3 m is pure bay water of mean salinity 33-34 gl-1. During floods, salinity minima are reached through the upper half of the water column, with salinities in the 1 m thick river plume falling below 15 gl-1, and in the upper 3 m falling to about 2591- 1.

Density fronts have been very occassionally observed in the Sands region (personal observations).

2.4 Remote Sensing

Reports- 419* , 2423

Data

Remote sensing has recently been utilized by VIMS (1986) and by the Board of Works (1987) to monitor various water quality characteristics of Port Phillip Bay.

ROSENBERG et al., (Appendix 5 of 2423) used imagery from the AVHRR (Advanced Very High Resolution Radiometer) onboard the NOAA 9 polar orbiting satellite to measure sea surface temperatures. They compared the predictions of sea surface temperature from the satellite with a series of measurements simultaneously made in the bay from boats and jetties. Both sets of measurements showed highest temperature in the central region of the Bay, and lower temperatures in the Geelong Arm, in the southern part of the Bay, and in the extreme north of the Bay.

HOWARD et al., (419) of the Remote Sensing Unit of the MMBW undertook to assess the viability of using remote sensing to augment traditional methods of monitoring Port Phillip Bay. The most suitable images of the Bay (22 in all) were obtained by the Coastal Zone Colour Scanner (CZCS) onboard the Nimbus 7 polar orbiting satellite between 24 November 1978 to 24 June 1986.

The analysis of the radiance images provided some useful information. River flow, suspended sediments and bathymetry could be identified in the observed radiance patterns. However, the potential influence of gelbstoff and/or non-uniform aerosol reduced the value of some images.

Measurements of depths between O and 25 metres and gelbstoff of O.1 m~ 1 were recorded. Seston values (suspended sediment) were found to be from 3 to 259 dry wt. m~3 as compared to 4-12g dry wt. m~3 from the Phase 1 Study (573).

The complex interaction between these parameters and other variables such as aerosol is thought to limit the capability of remote sensing technology in accurately mapping Port Phillip Bay waters (HOWARD et al., 419).

PARSLOW (9997) gives consideration to this problem and to the development of algorithms that model the CZCS data. He suggests that a greater amount of theoretical and empirical study to improve algorithm performance coupled with suitable in-situ data collection will see this technology given higher priority in future monitoring programs.

3. MIXING AND FLUSHING

Analysis of the mixing and horizontal advection across the Sands flood-tidal delta is a pre-requisite to an understanding of Bay-wide residence times. In deeper water within the inner Bay, the interaction of horizontal and vertical mixing is important.

Mixing is generally separately considered in both the vertical and horizontal because of the differing influences in each dimension. However, horizontal eddy diffusivities are strongly related to the rate of vertical mixing, particularly if vertical shear is present.

3.1 Werribee Treatment Complex effluent

Reports- 378* , 424* , 541, 1716

Data- 424, 541, 1716

The rates at which the buoyant WTC effluent mixes vertically is determined by the density structure of the Bay waters near Werribee, the density differences between the effluent and the Bay waters, the energies available to overcome these stabilizing influences and a range of second order interactions.

Studies have been carried out to assess the characteristics of the transport and mixing of the effluent, but all have been confined to short time and length scales (eg. PEARSON, 541; PEARSON, 1716; PATTIARATCHI, 424).

The effluent remains as a buoyant plume (less than 1 metre thick) for a considerable time under light wind conditions because the energy regime is insufficient to promote complete effluent/seawater mixing (Fig. 14). Further, the 'jet' discharge velocity from the outlet structure partly dictates the size of the mixing field. PEARSON (1716) found that an increasing jet velocity decreased the mixing efficiency, and created a broader dispersion field as the effluent is effectively pushed out into the Bay as a thin buoyant sheet.

For wind speeds less than about 3 m.s-1 (PEARSON, 1716) (or 5 m.s-1, PATTIARATCHI et al., 424) the effluent forms a thin surface plume with minimal vertical mixing. With stronger winds, the behaviour of the plume depends on the wind direction which determines wave height and local current intensity. Onshore or alongshore winds cause the effluent to be mixed throughout the water column more easily than offshore winds. Increased sediment contact results when the plume is well mixed, although fine sediment is always found in the water column during rough conditions in the Bay. Underground seepage is also thought to contribute to effuent entering nearshore sediments (PEARSON, 541; HICKMAN, 378). However, these authors did not quantify the likely rate of this process.

Measurements suggest that effluent dilution is essentially complete within about 1.5-8 km offshore from the drains, depending upon the discharge volumes and weather conditions. The effluent does not significantly affect salinity, temperature or pH outside these mixing regions.

The recent study by PATTIARATCHI et al., (424) used measurements of salinity as an effluent plume indicator. This study assumed the depression of salinity was indicative of the path of the plume and the degree of effluent mixing. Spatial salinity monitoring was used to track the effluent plume in different wind conditions over a period of 5 days. The study also measured pH levels in the discharge area. The effluent was measured at a pH of 7.7, with pH values in the plume itself ranging between pH 8.4 to 8.6. These values are similar to -the natural levels and so pH was not a reliable indicator of the plume at the resolution used in the study.

Based on salinity measurement and wind monitoring, the interface shear that operates between layers in a stratified water column was found to dominate mixing over simple wind stirr-ing (PATTIARATCHI et al., 424). A number of algorithms were given to describe the rate of mixing under the conditions observed.

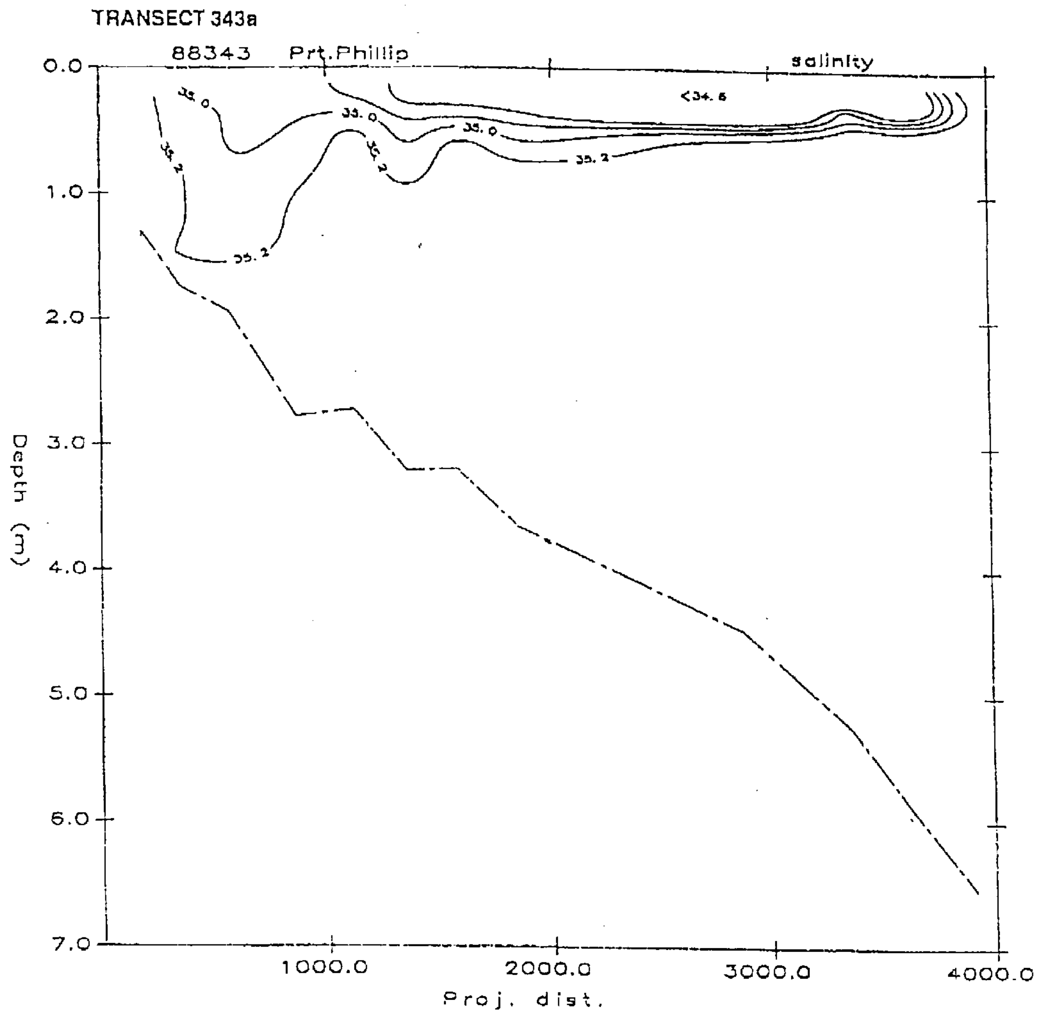


Figure 14: Cross-section of the WTC plume during a period of calm weather. The wind strength increased at the end of the measurment period, causing the inshore contours to dip downwards (after PATTIARATCHI et al., 424).

Initial mixing of the plume is also affected by the water-level of the Bay. The outlet structures are such that at low tide' the mouth of the outlet is often above Bay sea level (COLMAN, 147). Under these conditions, the effluent falls into the Bay, promoting initial mixing and reducing the intensity of stratification in the surrounding waters. At high tide, however, the WTC outfall and Bay water levels are similar.

HICKMAN (378) used the fluorescence of 'black liquor' (a waste product from the paper pulping industry which is discharged from the Werribee Complex) as a tracer of the effluent. This study concentrated on evaluating the fluorescence of the effluent as a plume tracing technique rather than actually monitoring plume movement. The Werribee effluent fluoresces at 430 nm as opposed to ambient seawater fluorescence of 410 nm. The fluorescence level of the effluent decays with time approaching the ambient level of seawater. Hence, the report suggests that this property could be used to determine the age of the discharge waste particles in Bay sediments and waters.

The discharge of WTC effluent occurs at the shoreline, and in well mixed conditions the effluent can be assumed to follow any prevailing currents. The direction of vertically-averaged currents in the Werribee region is complex and varies with the wind direction (Fig. 4).

Deficiencies in our knowledge

Data and investigations specifically relevent to the tracing of WTC effluent have largely relied on salinity monitoring and drogue tracking. Thus, these investigations only give information relevant to short time-scales (ie. less than 24 hours generally).

3.2 Vertical Eddy Viscosity

Reports- 424, 573, 1716, 9994, 9995

Data- 424

There have been very few studies of the vertical eddy viscosity, although a number of indirect measurements have been made. PATTIARATCHI et. al., (424) used fine scale measurements of vertical temperature and salinity structure to examine the WTC discharge plume. They found that vertical mixing ensued after the wind speed exceeded 5 knots.

Vertical profile measurements were made during the Phase 1 Study (573). These haven't been analysed for bed roughess ler,gths or friction velocities.

The field investigations by VIMS and the numerical model studies have both provided indirect measures of the vertical mixing but detailed studies have not been undertaken.

Deficiencies in our _nowledge

A lack of data and prior effort limits our knowledge of the magnitudes of vertical eddy viscosity.

3.3 Horizontal Eddy Viscosity

Reports- 1049, 1716, 2130, 2361, 9994, 9995

Data

Dye releases by CALDWELL CONNELL ENGINEERS (2361) near Point Wilson suggested horizontal eddy viscosities of about 1 m2.s-1 in the top 3 m of the water column over a 3 hour period. A moderate wind across the predominant current direction was present. A slight thermocline (0.2°C

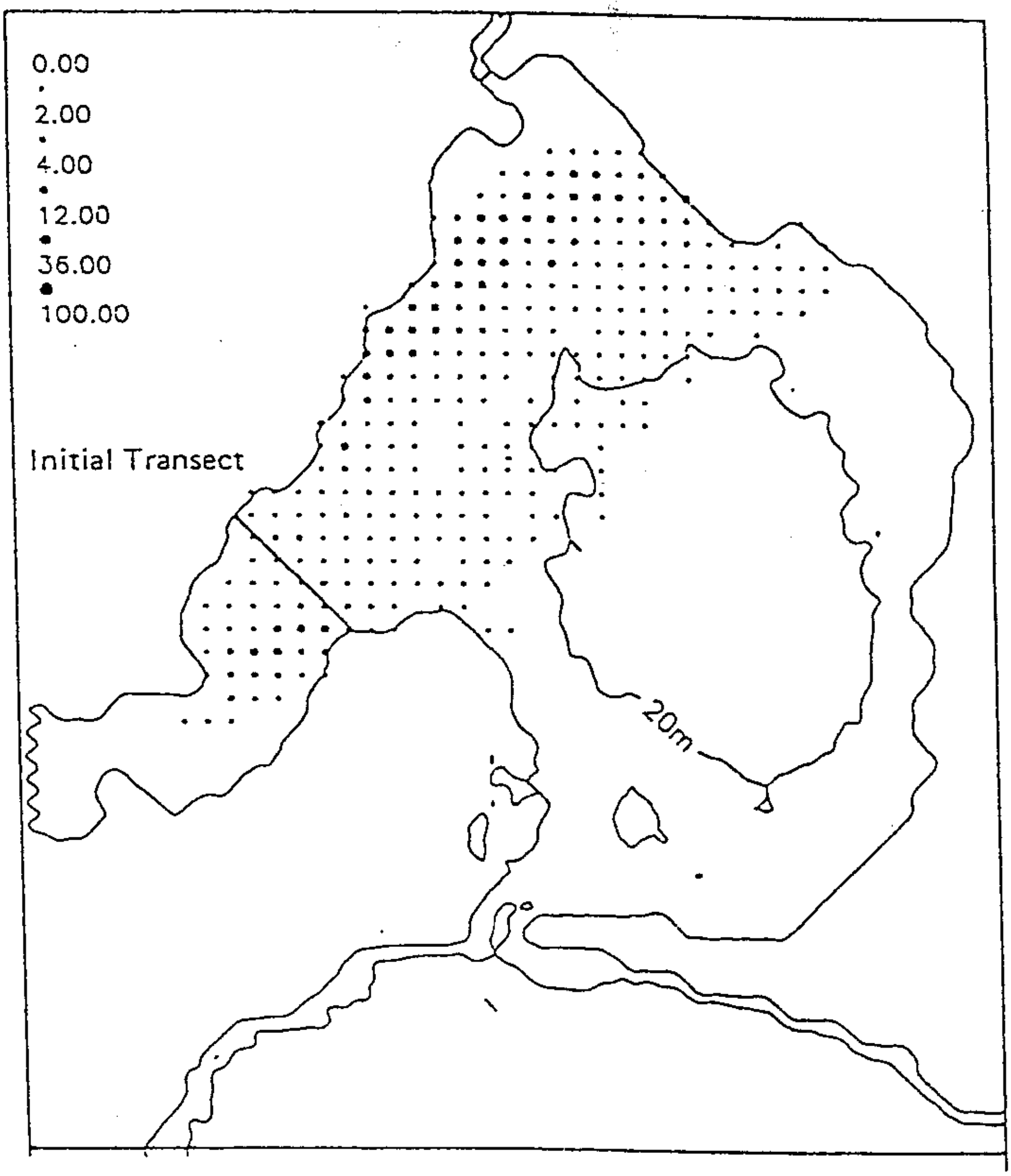


Figure 15: Location after 1 day of neutrally buoyant vertically well mixed material released from the transect linking Werribee to Portarlington for the case of a steady 22 m.s west wind. Flow patterns from the 3-dimensional model were used (after BLACK et al., 9999).

temperature difference) was recorded at 3 m but no measurements of dye concentration were made below 3 m due to instrument limitations. Thus, these experiments mostly neglected the shear diffusion associated with vertical velocity gradients because measurements were made in the top 3 m only and for a time which was much less than the period of the tidal cycle.

Deficiencies in our knowledge

Very few studies of horizontal mixing have been undertaken, although existing Bay-wide salinity measurements could be analysed to estimate a global value. The horizontal dispersion is limited by the physical size of the Bay and is dependent on the vertical shear dispersion.

3.4 Shear
Dispersion

Reports- 378, 1203, 1716, 2130, 9995

Data- 1909

Current strength and orientation can vary with depth in the inner Bay. Measurements show that near-bed currents can be opposite to those at the surface. However, orientations vary in response to changing topography.

Tidal currents are slow and have a near-zero residual in the inner basin, while correlation between wind and current is high. Thus, wind primarily determines inner Bay flushing and tidal currents play a secondary role by enhancing vertical shear dispersion.

1 mixing and creating some vertical

Numerical 3-dimensional dispersal patterns have depicted effective horizontal eddy diffusivities as great as KH = 325 m2.s-1 which is an order of magnitude larger than typical values due to random turbulence (Fig. 15). The high values are related to the horizontal shear dispersion associated with the complex vertical velocity structure.

Deficiencies in our knowledge

The model simulations were meant to provide a qualitative view of the dispersal as they had limited information available about vertical eddy diffusivity and were not calibrated. As the shear depends on the vertical eddy viscosity in the model, predictions of horizontal eddy diffusivity are ultimately determined by the vertical structure. Further work is needed to fully specify the vertical shear and resulting shear dispersion.

3.5 Exchange through the Heads

Reports- 573, 1362

Data- 573

The exchange coefficient at the entrance will be very large (MMBW & FOOD, 573), as returning water primarily comes from the coastal margins adjacent to the ebb jet. Drogue experiments indicated that more than 90% of the ebbing water is exchanged in Bass Strait each cycle (MMBW & FWD, 573) (Fig. 16). However, no experiments have been undertaken to determine the probability that this water will cross the Sands. The tidal excursions on the flood-tidal delta are of order 10 km, approximately half the width of the Sands. Mixing across the Sands may more directly determine inner Bay residence times, rather than the exchange rate at the entrance.

Deficiencies in our knowledge

Numerical model studies are needed to quantify the exchange rate across the Sands. Exchange through the entrance is very high due to the presence of the strong ebb jet and the common occurrence of longshore currents passing the entrance in Bass Strait. Thus, further studies of the exchange coefficient may not be warranted. However, the inner and outer Bay are separated by the Sands, a physically large region with variable topography. The exchange across this important region is not well understood. Notably, the vertical flow structure in the Sands is likely to be logarithmic, due to the presence of the fast tidal currents, and a 2-dimensional model may be a useful aid.

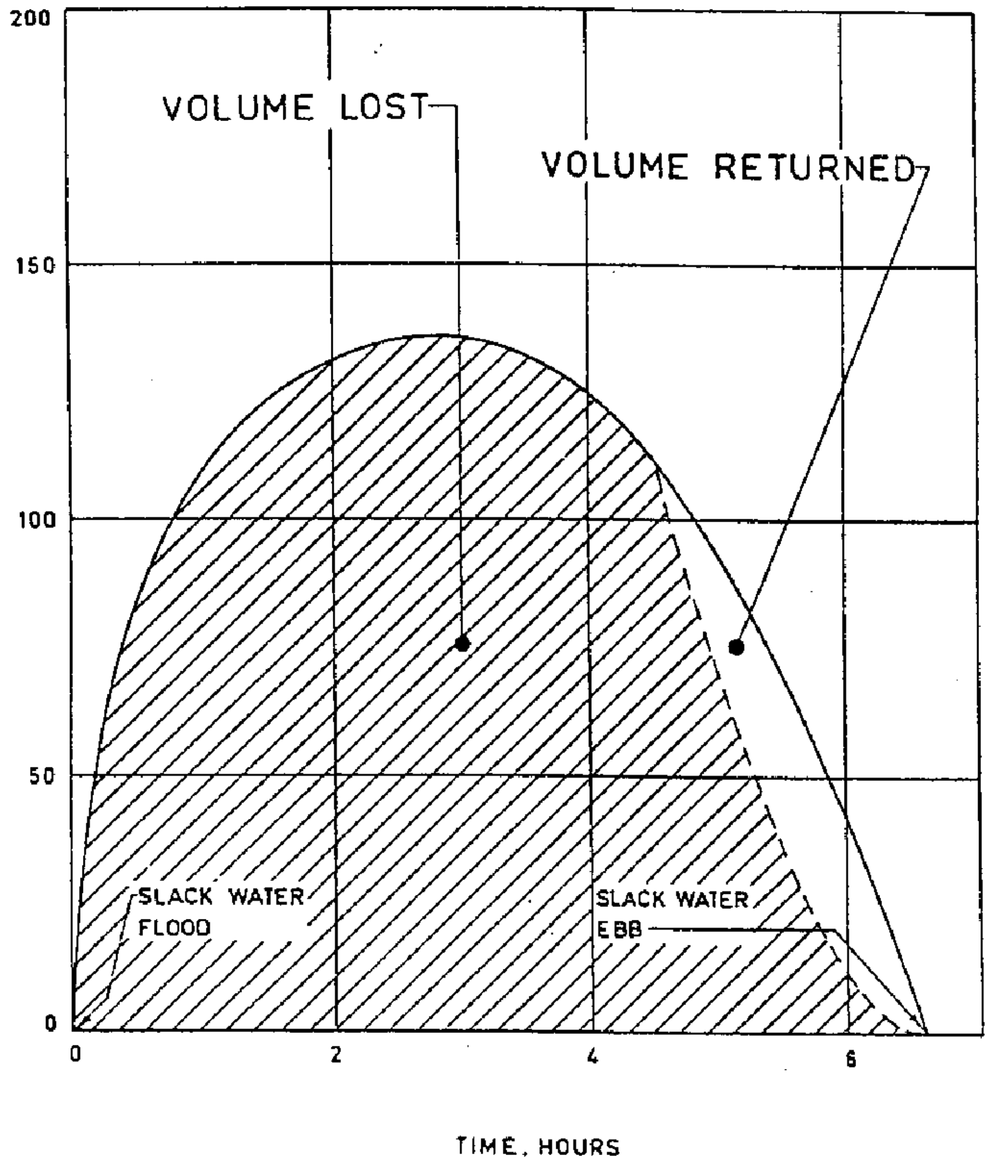


Figure 16: Exchange of water through the entrance (after MMBW & FWD, 573).

4. WAVE CLIMATE

4.1 Surface Wave Climate

Reports- 109, 115* , 163, 217, 280, 573, 945, 1324, 2128, 2320, 2361, 9991, 9999

Data- 59* , 115, 163, 217, 500, 514, 966, 1063, 1990, 2361, 9999

WILSON (2320) tested three empirical models for the prediction of wave height and period within Port Phillip Bay due to local winds. He tested a deep water wave model and separately treated shoaling, and the SMB model (SHORE PROTECTION MANUAL, 1975), with 2 different parameterisations of the depth. The SMB model directly treats shallow water processes including shoaling and bottom friction.

Adequate predictions of wave height and period were achieved with the simple empirical formulae, but WILSON (2320) found that the variation in depth along the fetch needed special treatment.

The model was confirmed using wave-rider buoy measurements made by the Marine Models Laboratory (Port of Melbourne Authority) at a number of sites around the Bay (Fig. 17).

Notably, the time for full arousal in fetch limited Port Phillip Bay is typically 1-3 hours. Moreover, 3-5 second period waves are common in the Bay and these take 1-3 hours to travel across the largest fetches. Thus, the response of the sea surface to wind is at time scales of a few hours, and a full spectral model would not be warranted.

CALDWELL CONNELL ENGINEERS (2361) analysed wave height records made by the Port of Melbourne Authority at Altona and St Leonards. Nearly 1 year of data at each site was available. The 1 year return period wave heights were 2.4 and 2.7 m at St Leonards and Altona respectively.

FALCONER (115) computed the deep water wave heights and periods of waves which arrive at the entrance. Swell comes from a restricted range of directions between 193 and 232°T. Wave heights in excess of 20 ft (6 m) were noted.

Deficiencies in our knowledge

The measurements used to confirm the wave height predictions were made with wave rider buoys. In short period swells, such as those common to Port Phillip Bay, these instruments tend to damp out the short period oscillations and to trim the wave crests. As such, further measurements of wave height may be justified. Any new surface wave measurements should be supplemented with measurements of bed orbital motion (see below).

4.2 Bed Orbital Motion

Reports-163

Data-2423

BLACK et al. (in prep.) have recently completed analyses which extend the work of WILSON (2320) to develop predictions of the bottom orbital motion for sediment transport studies. They found that the JONSWAP spectrum provided a good prediction of wave heights. However, the linear response function relating surface heights to sea bed orbital motion under-estimated the measured variance in deep water, for short period swells. They developed a correction which was a function of the water depth and peak spectral period and achieved good results (Fig. 18). A Port Phillip Bay wave climate for both the sea surface conditions and the bed orbital motion was produced.

The relationship between the nature of the sea bed sediments versus the wave and current intensities was quantified using the above techniques to specify the wave action and a 2-dimensional hydrodynamic model for the tidal currents.

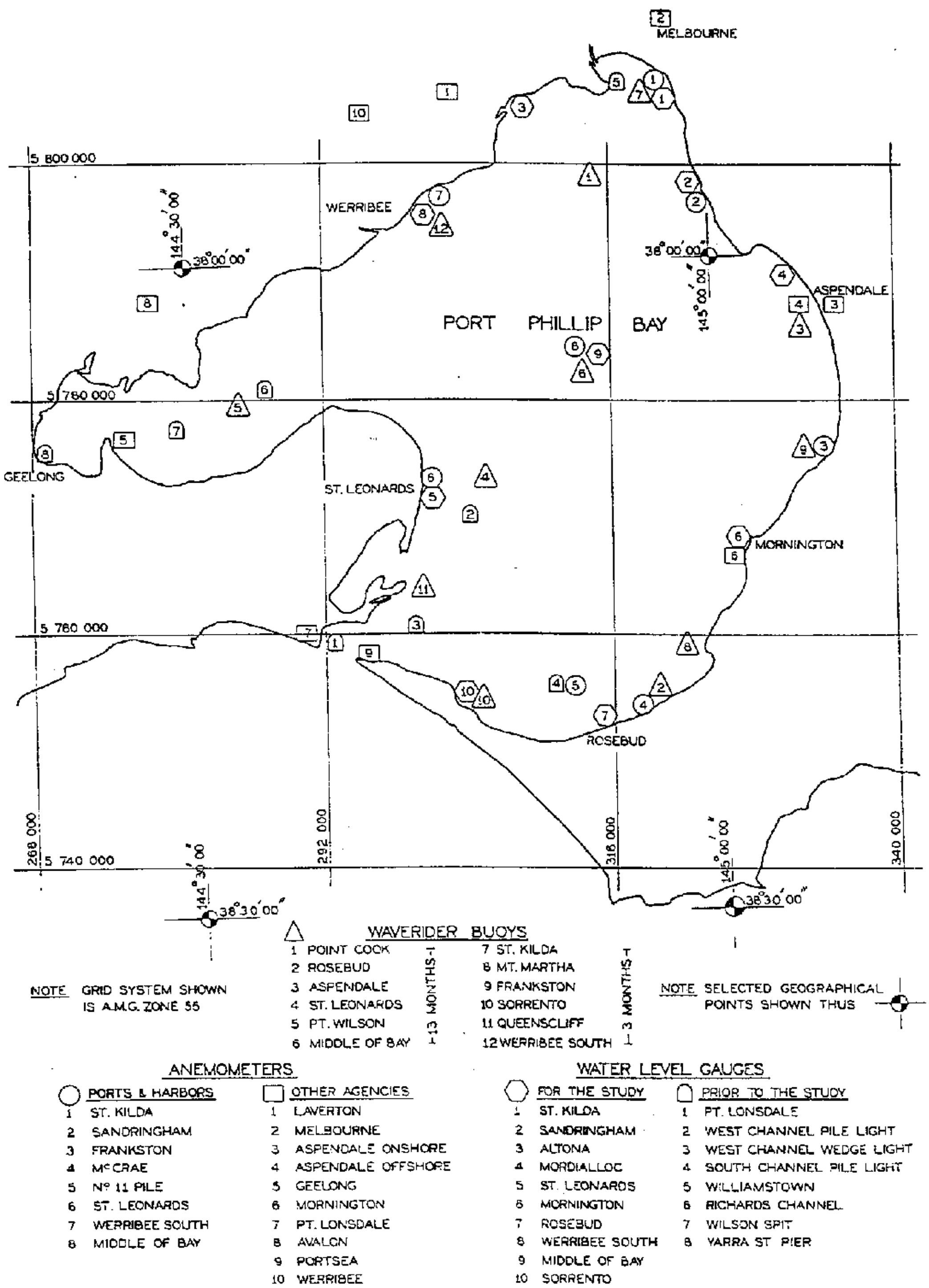


Figure 17: Wave measurement, anenometer and water level sites (after JONES et al., 945).

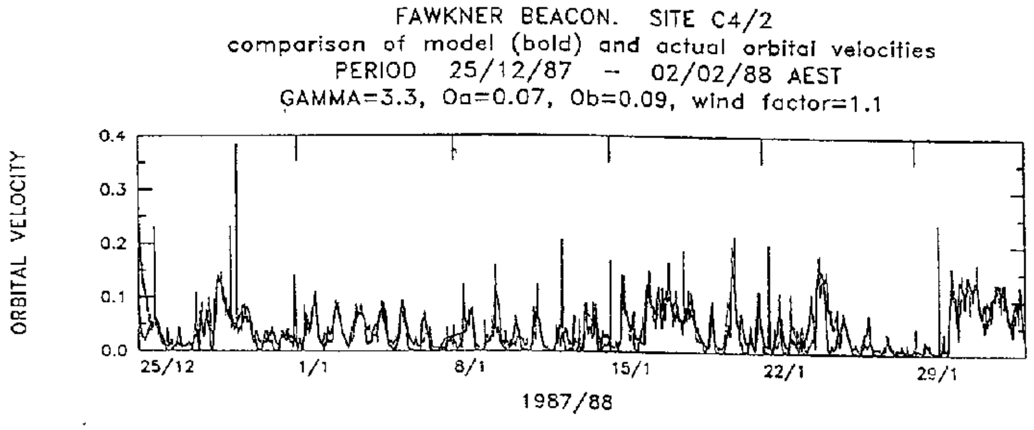


Figure 18: Comparison of measured and predicted bottom orbital velocities in Port Phillip Bay (after BLACK, GREILACH and PARRY, unpublished).

Deficiencies in our knowledge

The work of BLACK, GREILACH and PARRY (in prep.) has demonstrated that useful predictions of bed orbital motion can be obtained from the wind records alone. Some further current meter deployments to record orbital motion in the deepest central segment of Port Phillip Bay would be warranted.

5. PHYSICAL INPUTS

5.1 Werribee Treatment Complex

Reports- 110, 142, 143, 378, 472, 554, 530, 1435, 1716

Data- 142, 1743, 1748, 1909

The Werribee Treatment Complex is a major source of effluent to the Werribee segment of the Bay. The plant disposes more than 178,000 megalitres (5.6 m^3s^{-1}) of raw sewage each year into the Bay via four main drains- 15E, 145W, Borrie and Murtcain. The Bay receives the effluent in the shallow waters of the Werribee coastline and locally around the main drains.

The Werribee effluent concentrations in the Bay have been examined in studies carried out by or for Melbourne Water (DORSEY, 110; BROWN et al., 472; MITCHELL, 554; PEARSON, 1716), the Marine Pollution Studies Group (or the Marine Science Laboratories) (RAINER et al., 530; LONGMORE et al., 1909; COWDELL et. al., 1435), and the Environmental Protection Authority (EPA, 1748). The discharge contributes a significant proportion of the nutrient input to Port Phillip Bay and may contain a number of other contaminants of varying levels of toxicity HICKMAN (378).

A number of studies have been conducted to temporally and spatially define the effluent plume using one, or a number of these effluent characteristics as tracers. Studies have been confined to contaminants dissolved in the effluent and which remain dissolved once they mix with Bay waters. No consideration has been given to the contaminants which are particulates or are attached to particulates within the effluent, or to dissolved contaminant which may attach to particulates once the effluent is mixed with Bay waters, although the nearby benthic environment has been investigated (DORSEY, 110; BROWN et. al., 472) .

Nutrients are biologically utilised and can be chemically transformed. They are also constituents of the sediment load which is periodically resuspended. Thus, nutrient concentrations in the water column can be highly variable and may not fully identify the extent of the WTC effluent transport or quantify the mixing processes. Indeed, PEARSON (541) suggests that benthic plants and animals in the vicinity of the WTC outfall, dominate the nutrient uptake process. LONGMORE et al., (1909) have measured the concentrations of non-conservative components of the plume waters, such as dissolved oxygen levels, nitrate and nitrite concentrations and total organic carbon. They also measured conservative tracers such as salinty.

PEARSON (541, 1716) measured total N, P and C1 concentrations in the effluent and monitored dilution of these components with time, subsequent to mixing with Bay waters. Sampling stations at the weir mouth gave indications of the initial concentration of these elements. However, significant variations in tracer concentration were measured within the outlet structure itself. PEARSON (541) suggests that possible causes for this variation were a "better quality effluent flowing over the weir" or "better mixing with salt-water in the outlet structure downstream of the weir".

Deficiencies in our knowledge

Apparently, no investigations have been undertaken into particulate material that is discharged from the WTC nor of the fate of WTC contaminants that adsorb to particulates once they mix with Bay waters.

Moreover, the tracers used to track the effluent from the WTC are unable to fully characterise the plume behaviour and the flushing of the Bay. Combined field investigations and numerical models may be needed to fully characterise Bay flushing at longer time scales.

5.2 Rivers/Creeks/Large Drains

Reports- 143, 163, 419, 573* , 653, 852, 1049,
1203, 2041

Data- 142, 163, 340* , 400, 419, 573* , 653, 1063,
1069, 1203, 1228, 1356, 1748* , 1749, 2063,
2589, 2591, 2597, 2605

The peripheral catchment includes a series of rivers and more than 300 creeks which provides freshwater into the Bay. The total run-off from the catchment area yields an average inflow to the Bay of 1.4 x 1012 m3.year-1 (MMBW & FWD, 573).

Fresh-water inputs can be sub-divided into a number of different segments :

* Altona segment contains the catchments of Skeleton and Kororoit Creeks and Maribyrnong River;

* Werribee segment contains the catchments of the Werribee and Little Rivers and part of the Hovells Creek catchment;

* Corio Bay segment contains Hovells Creek as the only significant stream discharge;

* Bellarine/Nepean Peninsula segment contains no surface streams of note. This segment includes the Port Phillip Sands which function as a barrier to the exchange of water and pollutants between the Bay and Bass Strait;

* Northern/Eastern segment contains Mordialloc Creek, Patterson River and Kananook Creek as well as many small drains;

* Hobsons Bay segment is predominantly influenced by the Yarra River; (LEONARD, 1362).

The Yarra River accounts for at least 52% of the freshwater discharge into the north-eastern part of the Bay (LEONARD, 1362).

Mean value flow measurements by the Floods and Mitigation Division of Melbourne Water are given below for the Yarra catchment:

* Yarra River at Fairfield- 1054 megalitres/day (12.2 m3s~1) * Maribyrnong River- 285 megalitres/day (3.3 m3s~l) * Kororoit Creek- 104 megalitres/day (1.2 m3s~l) * Gardiners Creek- 69 megalitres/day (0.8 m3s-l)

Mean daily flow data for Patterson River and Mordialloc Creek catchments are recorded by the Dandenong Division of Melbourne Water.

Deficiencies in our knowledge

River flows are regularly monitored by the relevant authorities.

5.3 Diffuse Sources

Reports-143, 202, 340, 508, 573

Data-340, 573

Diffuse inputs introduce lower volumes into the Bay than the rivers and creeks. Urban runoff comes through 3000 kms of stormwater drainage and waterways networks. These may have a significant local impact at the discharge site on water quality.

Deficiencies in our knowledge

To our knowledge, limited quantification of the nature of the effluent and the volume of diffuse sources has been undertaken.

5.4 Particulates

Yarra River

Reports-142, 340, 419, 573, 2041

Data-340* , 573, 1155, 1156, 1435, 1748, 1909, 2041

The Yarra River is one of the major sources of particulates and suspended solids. With an average annual flow of 9x108 m3 per year the its tributaries introduce a sediment load of usually 500 kg/m3 of suspended solids (LAMMERTS, 2041) contributing to mud and sand deposits in the Bay (Fig. 19).

An investigation of turbidity and sediment transport in the Yarra River by LAMMERTS (2041) identified a "good relationship" between turbidity and suspended solid concentrations, but the relationship varied on a seasonal basis (Fig. 19). The r2 value for all data combined was 0.78. Thus, regular water samples may provide a more accurate measure of the actual mass transported than turbidity records, although the turbidity provides a useful estimate. The largest suspended solid concentrations noted were about 130C mg.l-l. The relationship between suspended solid and river discharge was very scattered (Fig. 19).

The clay component varied from 10-45% of the mass. The organic component varied from 5-60% with highest percentages occurring at low total load.

Particulates coming from the other rivers, creeks and large drains measured by EPA (340) are summarised in Fig. 20. Up to 350 mg.l-1 of suspended solids was measured.

The Phase 1 Report (573) tabulates suspended solid inputs of up to nearly 200 mg.l-1 in drains serving residential and industrial areas and at the Werribee Treatment Complex (Tables 6.2, 6.3, 6.4, 6.6 and 6.8, 573).

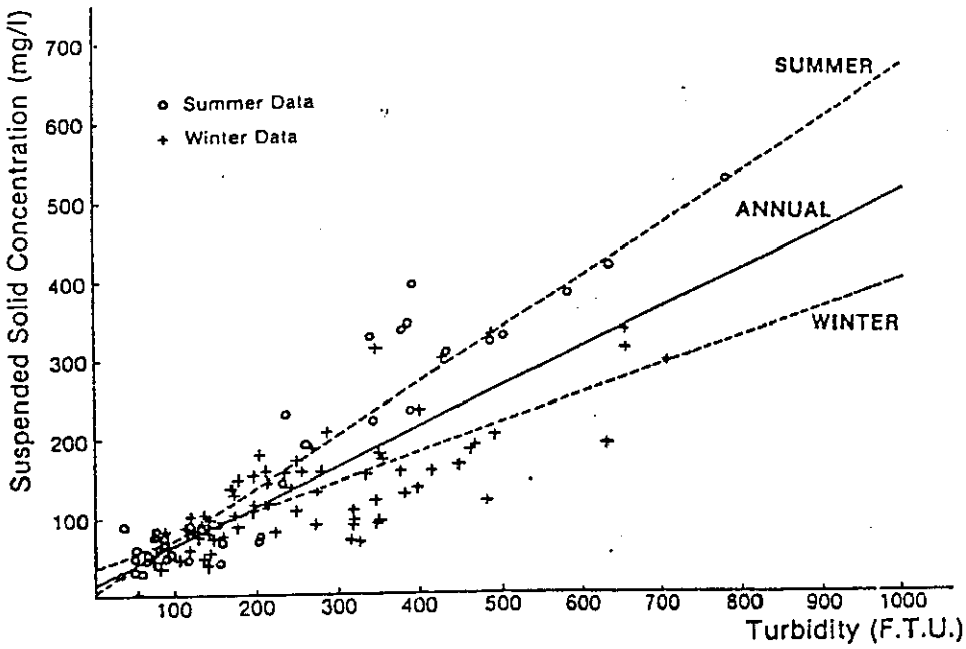


Figure I9: suspended solid concentration versus turbidity in the Yarra River (after LAMMERTS, 2041).

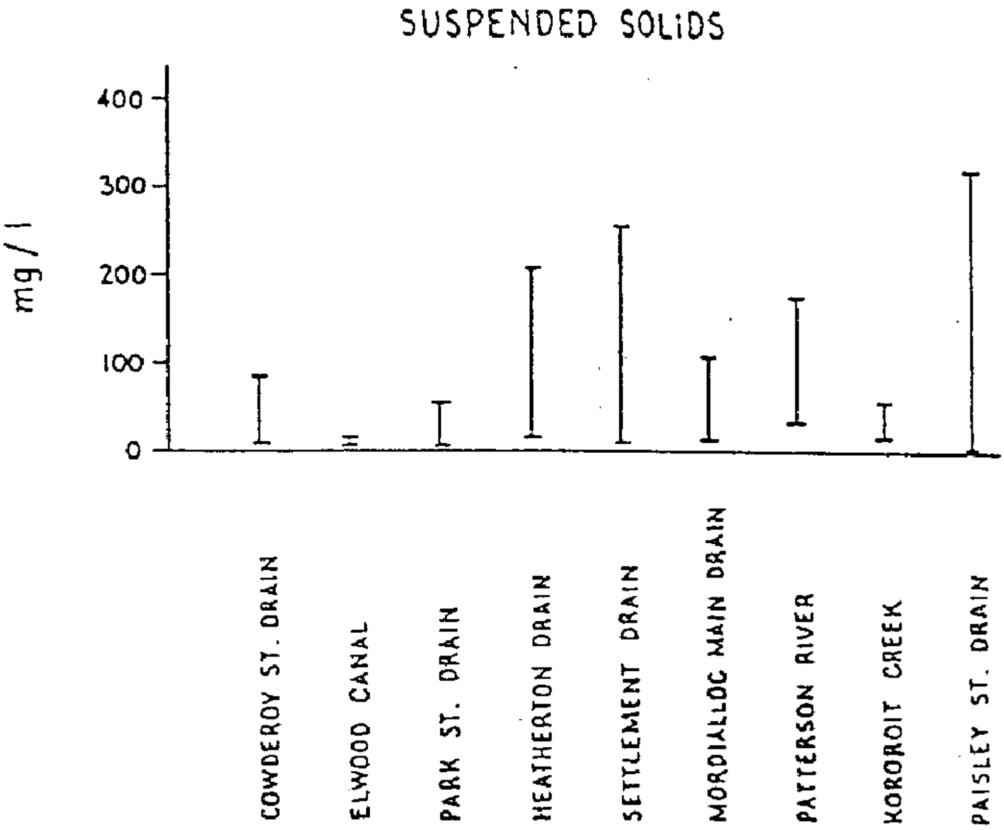


Figure 20: Suspended solids in a number of rivers and drains (after EPA, 113).

Deficiencies in our knowledge

The studies by LAMMERTS (2041) show the typical concentrations of particulates in the Yarra River. Some monitoring data is available from the sources noted above.

5.5 Coastal
Erosion/Beaches

Reports- 109, 151, 163, 170, 332, 333, 444, 445, 446, 739, 1049, 1203, 1634, 2027, 2373 2374, 2375

Data- 2373

Erosion of the coastline around the Bay is caused by a combination of wind and wave action. Wind generated waves erode coastal cliffs and transport sand along and across the beach and sub-tidal platform. Any set up in water level due to wind, waves or other factors exacerbate the erosion. Future greenhouse sea level rises are therefore expected to be important and may need to be considered.

Cliffs

Rock types outcropping around the coast of Port Phillip Bay vary from east to west (BOWLER, 739). On the east coast, Palaeozoic granitic rocks outcrop on the Mornington Peninsula at Mt. Eliza, Mt. Martha and Arthur's Seat. Between Balcombe Bay and Frankston, the coastal sections are composed mainly of Tertiary Older Basalt, Tertiary calcareous clays and Upper Tertiary sandstones and one small occurrence of Mesozoic sandstone. Upper Tertiary sandstones also outcrop on the cliffed sections and foreshores further north from Beaumaris to Brighton. Between Beaumaris and Frankston, Quaternary alluvium has accumulated in an area of local subsidence.

The western coastline of Port Phillip Bay lies close to the edge of the extensive Newer Basalt flows, which extend west to the South Australian border. Basalt is continuous from Williamstown to 5 km north of the Werribee River where low cliffs are cut in Quaternary alluvium. These extend 3 km south of the river mouth to the basaltic plain which continues along the coast to Corio Bay.

Relatively high cliffs alternate with sandy beaches along much of the eastern coast of Port Phillip Bay. The most active cliffs are developed on headlands, and often alternate with vegetated cliffs backing sandy beaches. Comparatively few cliffs occur on the western coast, particularly between Williamstown and Geelong. East along the Bellarine Peninsula, low cliffs are developed in tilted Tertiary clays and limestone.

Beaches

The cliffs or bluffs are fronted by shore platforms, and alternate with low-lying sandy plains and marshy areas. Narrow beaches of sand and gravel (including shell grit) run intermittently along all coastlines. Along the east coast' the beaches widen in coves where the shore platforms are interrupted. BIRD (445) notes that the beaches are largely of local derivation. They consist mostly of quartzose sand with some ferrugnous gravel, eroded from cliff, foreshore and sea floor outcrops of Tertiary sandstone. To the south, the beaches are dominated by calcareous sand and gravel derived from Pleistocene dune calcarenites, which in turn came from biogenic sands washed and blown in from the adjacent continental shelf. The few inflowing rivers and creeks carry mainly silt and clay, and have contributed little to the modern beach sediments.

Broad sandy beaches occur in two main regions on the eastern coastline; one from Mordiallic to Frankston, the other from Dromana to Portsea. On the west coast, narrow sandy beaches extend continuously from Williamstown to Corio Bay. The sands are usually poorly sorted and often include whole shell and shell grit.

Offshore Platforms

Shallow sand bars characterise both the east and west coast sub-aerial and inter-tidal nearshore platforms (BOWLER, 739). These features are often long-crested and parallel with the shoreline and extend as a series of sand bars across the nearshore platform. Cuspate forms are also common in some locations. These features are easily identified in aerial photographs, particularly at low tide.

Nearshore topographic profiles show that the depth immediately offshore of the shelf break (i.e. the position where the platform drops away towards the floor of the bay) is approximately 24 feet in both the Mordialloc-Frankston and Dromana-Rosebud areas. On the west coast, the offshore depths are approximately 14 feet, with some variations along the coast depending on local bedrock outcrops. The depth off the shelf break on the natural floor of the bay is a measure of the local topography and the wave energy.

Nett Sand Movement

On the Bay's western shores, sand generally moves northward (BIRD, 445). Beaches at Mentone and Frankston, Sorrento and Safety Beach and Point Lonsdale and St. Leonards appear to have a stable relationship between the entry and removal of sand (BIRD, 445).

BLACK et al., (446) undertook numerical simulations of the wave climate and longshore sediment transport to demonstrate that, although beach orientations vary considerably, east and south coast beaches have mostly developed an alignment which is in equilibrium with the prevailing weather patterns and the shape of the Bay. The latter determines wave fetch.

Transfer of material still occurs between beaches. BAKER (2374, 2375) conducted tracer experiments from two beaches near Sandringham to show the movement of sediment over 3 months. Large excursions of several kilometres were identified. However, much of the coarser sediments remained on the beach where they were initially deposited. The coarser grain size was similar to the grain size of natural sediments. Natural grain size sorting is occurring around the Bay (BUCKLEY, 61; LINK, 174, 915).

Sediment Supplies

Eroding cliffs around the Bay are thought to provide very limited supplies of sediment for the beaches. Beaches have been eroding since the Phase 1 study of Port Phillip Bay and beach renourishment has been required (BUCKLEY, 61; BIRD, 445). Early attempts to trap beach sediment with groynes or jetties were generally unsuccessful. Sediment is probably lost off the edge of the nearshore platform during storms and is not being replaced from land sources. Shellfish abundance has also diminished in the Geelong Arm. The shells and shell grit provide a natural sediment supply. Aerial photographs show a tendency for sediment depletion in the nearshore zone since the 1940's.

Beach Process Studies

The most detailed beach process studies were done by HINWOOD et al., (Appendix C of 163), BLACK et al., (2373) and BAKER (2374, 2375). HINWOOD et al., 163) studied the sediment transport at Sandridge Beach in northern Port Phillip Bay. They found that gross movements were many times the nett movements, and that onshore/offshore movements were appreciable (Fig. 21). They observed a natural realignment of the beach after construction at one end.

BLACK et al., (2373) measured the currents, waves, tides and bedforms at Safety Beach near Dromana. Numerical models of the wind-driven currents and of the wave-driven longshore transport supplemented the field measurements to examine sediment dynamics. They identified cross- shelf and longshore sediment transport mechanisms and predicted large longshore transport but a near zero nett transport.

An experiment by PARRY et al., (576) at Rye Beach demonstrated that the growth of sea grass was related to the abundance of mobile sediments.

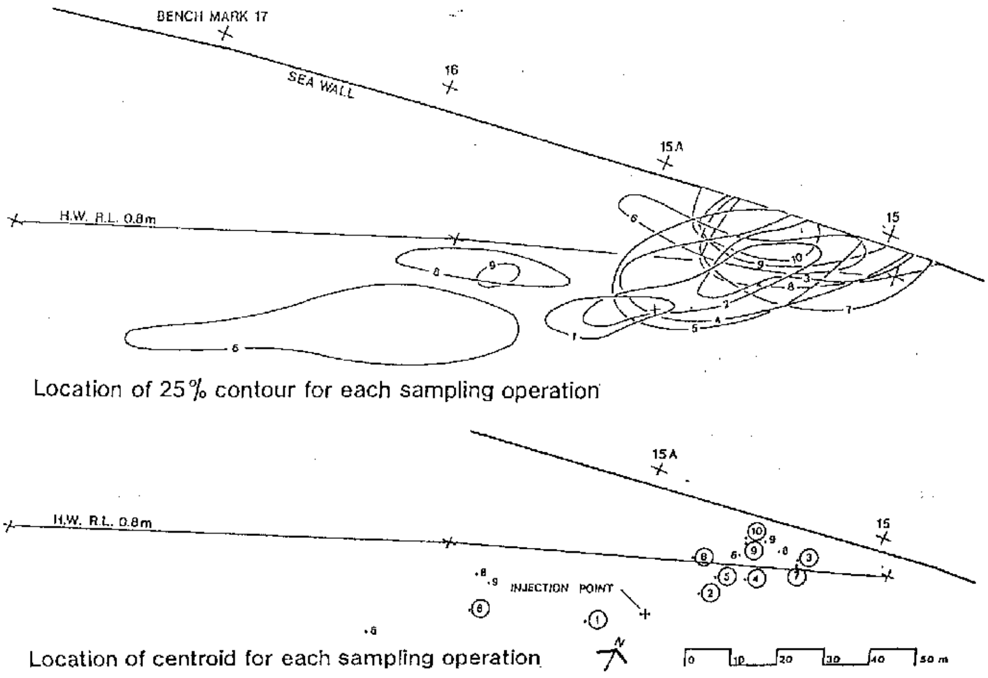


Figure 21: sediment tracing results in Hobsons Bay (after HINWOOD et al., 163)

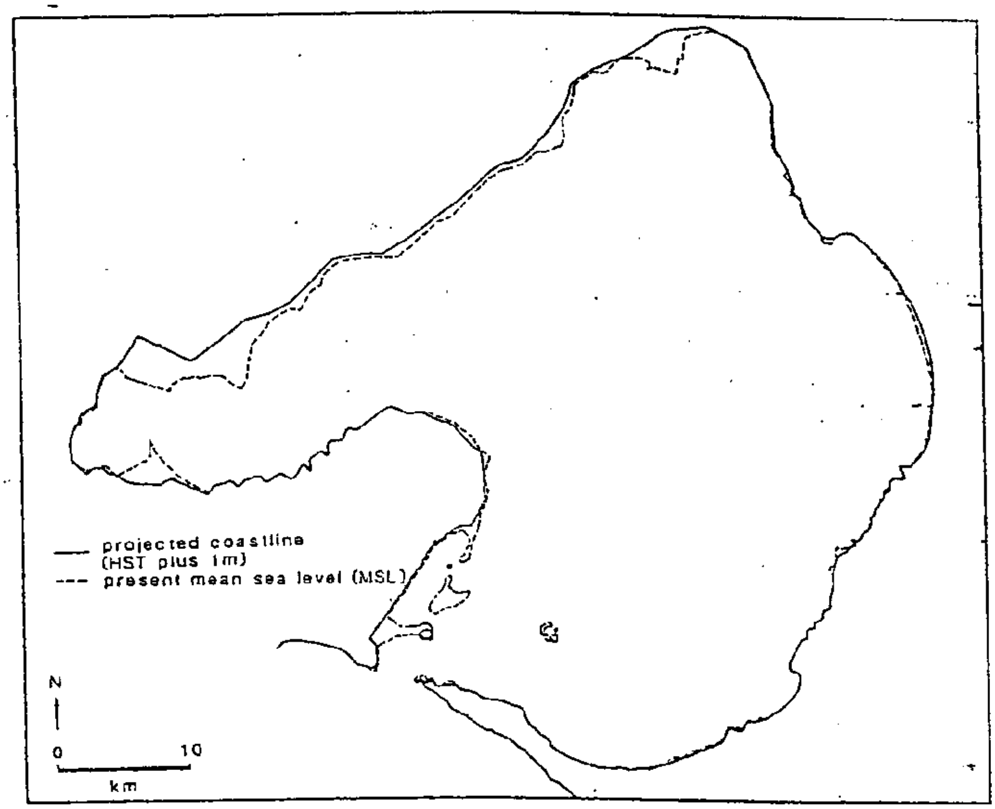


Figure 22 Possible inundation due to "Greenhouse" sea level rises (after BONE, 280).

Deficiencies in our knowledge

Good descriptions of the beaches and their sediments (see below) are present in the literature. However, there are very few physical process studies which have measured wave, current and sediment dynamics simultaneously. A qualitative link between the beach, the sub- aerial platform, and the growth of sea grass has been identified, but no rigorous relationships have been developed. The importance of sea grass for the nutrient balance (and for a fish nursery) may warrant further studies of sediment dynamics and sea grass growth. In particular, the width of the platforms, depth at the edge and the sediment and sea grass abundance may serve as good indicators of the health and importance of the nearshore zone and may help to quantify the nutrient balance.

5.6 Coastal
Inundation

Reports-280, 1173, 2378

Data

BONE (280) specified potential coastal inundation for a series of sea level rise scenarios (Fig. 22). Greater depths at the entrance and on the Sands will allow a greater volume of water into the Bay causing a small increase in the tidal range (BLACK et al., 2378). Contrary to this, the wind set-up will be smaller in the deeper water. However, PITTOCK (1991) suggests that storms may become more frequent due to `'Greenhouse" changes in weather patterns.

A similar unpublished study was undertaken by CRAPPER (1173) which showed the potential inundation levels around metropolitan Melbourne.

Deficiencies in our knowledge

In view of the uncertainty in sea level rise and changing weather patterns and, as precise data is available about present sea level and land elevations, there appears to be no serious deficiencies worth considering.

6. SEDIMENTS

As contaminants adsorb to either organic or mineral particulates, a knowledge of the movement of these (mostly sedimentary) particulates will also specify the path of the contaminants attached to them.

Organic contaminants are known to readily attach to organic particulates in an effluent, likewise high toxicity metals have an affinity for mineral particulates. After discharge, particulates settle out at rates dependent on the size/density of the particles and the local water turbulence and currents. Material is transported during periodic resuspension events by waves and currents. Coarser sediments will not move as far or be resuspended as easily. This sorting process will continue until the particulates either pass through the Heads; aggregate to become more sedimentary; are transported to a low energy bottom environment; or become trapped in a depression where turbulence is lower than the surrounding sea bed. Such a destination, which may be well away from the discharge site, might constitute an area of accumulating contamination for persistent contaminants attached to the particulates.

6.1 Sea-bed
Description/Morphology

Reports- 109, 163, 170, 192, 280, 302, 330, 332, 333, 444, 573, 915, 1203, 1633, 2361

Data- 163, 573

The most comprehensive studies of the sea bed were conducted by BEASLEY (332) and more recently by PARRY and collaborators (personal communication). BEASLEY (332) used divers to take bed samples from a number of sites. The divers were asked to describe bed morphology and these descriptions were tabuluted. For example, rippled sites were noted.

CALDWELL CONNELL ENGINEERS (2361) conducted sea bed surveys in the vicinity of Point Wilson. The sea bed to the north was mostly a thin veneer of shell grit and sand over basalt within 1 m of the sea bed at all stations. To the west, the bed was rocky and shell beds were common.

BLACK (217) took some grain size samples from sites around Point Wilson and Kirk Point and noted the character of the sea bed.

<u>Deficiencies in our knowledge</u>

See the next section.

6.2 Sediment Description/Sampling/Observations

Reports- 61* , 109, 163, 170, 174, 192, 217, 330, 332, 378, 444, 505, 573, 915 , 945, 1362, 1775

Data- 61, 163, 174, 330, 332, 505, 573, 915

6.3 Grain sizes

Reports- 61* , 163, 174, 330, 333, 915, 1775

Data- 61, 330, 333, 915

6.4 Mud Contents

Reports- 61, 174, 192, 332, 915

Data-332, 915

The most detailed study of bed sediments throughout the Bay was undertaken by BEASLEY (332). More recently, BUCKLEY (61) supplemented these with a series of grain size analyses of beach and offshore sediments.

The bottom sediments of the Bay are chiefly sands, silty sands, silty clays and clays (Fig. 23). The floor of the extensive area enclosed within the 6 m line in the central part of the Bay consists of mainly silty clay in its northern half and of clay in the southern half. Off the eastern shore of the Bay, out to the 3 m line and over the Sands, the bottom is mainly sand. The bottom sediments of Corio Bay are chiefly silty clay and clay.

Marine skeletal material constitutes a large portion of the sediments in some localities; high prevalence being associated with coarsergrained sediments and shallow water.

The predominant detrital material is quartz. The bottom sediments are considered to have been derived in part from the reworking of detritus originally deposited by rivers before the Bay was flooded by the sea about 7000 years ago, and in part from detritus derived since that time from the rivers discharging into the Bay and from coastal and bottom erosion.

A highly detailed study of sediments in northern Port Phillip Bay was undertaken by LINK (915). Identification of the deposition associated with the Yarra River was a feature of his results.

A series of grain size analyses, including fall velocity analyses of both the sands and the muds, have been made recently by PARRY and BLACK (personal observations). Although very detailed, these measurements are restricted to 3 locations.

Some samples have also been collected recently by the consultants Dames and Moore at 8 sites around the Bay (unpublished).

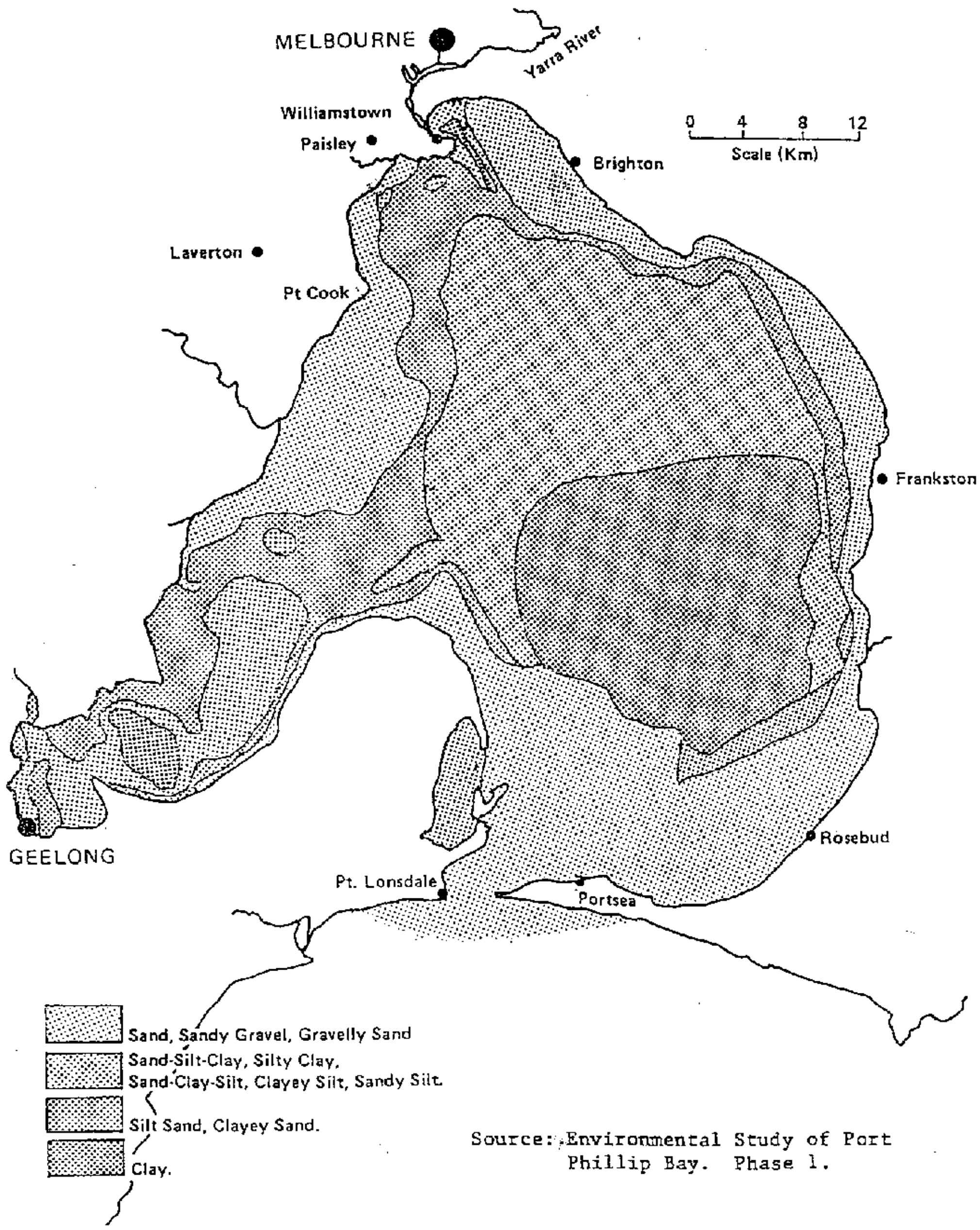


Figure 23 Distribution of sediment types (after MMBW & FWD, 573).

Deficiencies in our knowledge

As the Bay is continuing to receive fine material from the rivers and other factors such as scallop dredging are disturbing bottom sediments, a survey of the bed for comparison with the prior studies may be warranted. Moreover, BEASLEY (333) analysed the samples (at class interval resolution) by drying and sieving which destroys the structure of the fines. Wet fall velocity analyses are more appropriate. The analysis techniques should more appropriately reflect the sediment transport nature of the studies and so fall velocity techniques should be applied.

6.5 Suspended Load/Turbidity/Particulates

Reports- 163, 419, 573, 2041* , 2379

Data- 163, 573, 1063, 1748, 2041, 2379

A series of turbidity measurements have been made recently by ROSENBERG et al., (2379) for investigations of the environmental impact of scallop dredging. These are measurements of suspended sediment load under a variety of natural conditions including storms using instruments attached to a bottom-mounted aluminium frame. An underwater video camera simultaneously monitored the sea bed.

The measurements are being applied to relate wave orbital motion and other currents to the suspended sediment concentrations. Measurements have been made at 3 sites characterised by very different bed sediments. These are Dromana, St. Leonards and Portarlington.

Other measurements (analysis of pumped water samples and with Secchi Discs, 573, 1909) have been made during relatively calmer conditions. Longmore et al. (1909) show suspended solid concentrations of up to nearly 20 mg.l-l and secchi disc depths of up to 10.5 m. The correlation with prevailing weather was not considered. Spatially, the highest concentrations varied with the season, but these variations may be more appropriately related to prevailing weather.

Deficiencies in our knowledge

Although several months of measurements of suspended load have been made, further long-term measurements would expand the data base. In particular, long deployments are needed to ensure that a number of storms are sampled. The bed sediments are suspended fairly rarely in the deeper regions of the Bay.

7. NUMERICAL MODELS

The first numerical models of the bay were established by Brown Caldwell - John Connell (573, Appendix C) . They developed a hydrodynamic and dispersal model on a network of 110 triangular elements. The models were depth-averaged.

WILLIAMS (1739) applied a suite of models to simulate the hydrodynamics, dispersal and phytoplankton growth. These were linked

to create a general approach for the management of waste water systems. Williams also developed an optimizaton model which determined "best" solutions in terms of minimum discounted cost over the planning period for a particular constraint on the effluent load from the WTC. He found that proposed regulations on nutrient inputs into the Bay were too stringent and would require very high treatment plant costs.

VIMS used their data (2423) to examine bay dynamics and to develop numerical hydrodynamic and dispersal models of Bass Strait and Port Phillip Bay. Similar previously-developed models (e.g. WILLIAMS, (1739); FANDRY, 1981; FANDRY et al., 1985; BLACK, (2526); MMBW & FWD (Appendix C of 573)) provided descriptions of the tidal and/or wind driven dynamics, but these studies could not aim to calibrate all aspects of model behaviour. WILLIAMS (1739) concluded that existing circulation data were insufficient to verify models of the Bay and recommended further data acquisition programs, as subsequently undertaken by VIMS.

Bass Strait models have a grid resolution which cannot satisfactorily resolve Port Phillip Bay dynamics. FANDRY et al. (1985) were concerned with tidal circulation in Bass Strait only, while BLACK (2526) examined the relationship between modern sediments and tidal currents only. HUBBERT et al., (1168) developed a storm surge model of Bass Strait to support daily weather forecasting operations, but no attempt was made to use the model to understand the dynamics of the Bay.

7 1 Two and Three Dimensional Hydrodynamic Models

Reports- 217, 280, 447, 573* , 1203, 1739* , 2093, 2320, 2378, 2526, 2601, 9992, 9995, 9998, 9999*

Data- 217, 2378, 9999

The Phase 1 Port Phillip Bay model (MMBW & FWD, 573) described the Bay as a network of 110 triangular shaped elements formed by a series of 77 nodes and 195 channels. Each node was physically defined by its surface area, its depth and its volume (calculated with a weighted mean depth). Consideration was not given to vertical motion. Instead the entire depth of the water column was treated as a single unit.

Calculations of water surface elevations and directions were made for successive real-time intervals of four minutes throughout a full tidal cycle of twenty-five hours. The model was run for at most six tidal cycles to reach dynamic equilibrium.

Three separate scenarios were tested by the model. Simulation of a westerly wind blowing continuously at five miles per hour (seemingly representing equivalent annual conditions) resulted in slow clockwise movement (3-6 months for a complete circuit) of Bay waters. Stronger winds (10 miles per hour) resulted in separate circulation cells off the eastern and western shores of the Bay. With a southerly, the western cell rotates clockwise and the eastern cell anti- clockwise. Nett movement for the water column as a whole in the central region is towards the south. A northerly produces directions of rotation and of nett movement opposite to those just described.

The VIMS Bass Strait model covered the region from South Australia to Sydney in NSW and from southern Tasmania. Nested within was the Port Phillip Bay and adjoining waters model. The WILLIAMS (1739) model of the Bay used a similar location for the southern boundary and consisted of 2-km square cells.

The VIMS Port Phillip Bay numerical model consists of 43 by 56 cells each 1500 m square, with a nested finer grid of the Geelong Arm (500 m grid size). Using the data set recorded by VIMS (2423), the model simulated M2 sea level amplitudes with an average error of 1.2% and M2 phases with an error of 3.8%, both of which were well within the scatter in the field data. The predicted and measured tidal currents had a correlation coefficient of 0.98. There was a 13% average deviation between predictions and measurements of low frequency wind driven currents within inner Port Phillip Bay but a wind factor of 1.07 applied to the wind speeds eliminated this deviation.

The only three-dimensional simulations have been undertaken by VIMS (2378). These showed a complex vertical structure in the inner bay in

accordance with velocity measurements. Upwelling and downwelling at the shorelines characterised the results.

Deficiencies in our knowledge

A more accurate 3-dimensional model could be developed with more information about vertical eddy viscosity, wave action and vertical shear stress. No models of Port Phillip Bay which couple the circulation with the density-driven dynamics have been attempted.

7.2 Dispersion Models

Reports- 573, 1739, 9999

Data- 573, 9999

Dispersion models have been developed by MMBW & FWD (573), by WILLIAMS (1739) and by VIMS (BLACK et al., 9999). The latter two use Lagrangian particle tracking techniques.

The Phase 1 dispersion model (573) simulated the movement of a selected constituent added in specific amounts as defined by a specific case of the Phase 1 hydrodynamic model discussed above. Calibration of the model showed that a dispersion coefficient of 0.48 gave "reasonably accurate" results.

WILLIAMS (1739) applied the ELDER (1959) expressions for the longitudinal and lateral dispersion coefficients (Ex, Ey) i.e.

$$EX=0.236hU^*$$
$$Ey= 5.9hU^*$$

where h is water depth and U* the friction velocity. A variety of dispersion coefficients have been tested with the VIMS model.

Both 2 and 3-dimensional versions of VIMS dispersal models have been applied to a number of applications. These include dispersal of pollutants and larvae from northern Port Phillip Bay (BLACK, 217; KEOUGH and BLACK, in press), the entry of fish larvae through the Heads (JENKINS and BLACK, in prep.), and the dispersal of material suspended by scallop dredging (BLACK and PARRY, in prep.).

<u>Deficiencies in our knowledge</u>

The VIMS 3-dimensional model and field measurements have shown that dispersal in the inner basin is strongly influenced by vertical shear. As such, the two-dimensional models are not able to fully simulate dispersal in the inner Bay. The 3-dimensional models could be refined with further information about vertical eddy viscosity and eddy diffusivity.

7.3 Sediment Transport Models

Reports

Data

Using the measurements described by ROSENBERG et al. (2379), BLACK and PARRY (in prep.) have established a sediment model for the dispersal of material suspended by natural storms versus suspension by scallop dredging. A dredge spoil dispersal model is being applied by Lawson and Treloar for the Port of Geelong Authority. No results have been published at this stage from these studies.

Deficiencies in our knowledge

All of the individual components necessary for a full sediment model have been examined. These include measurements and analysis of suspended loads and the establishment of 3 dimensional hydrodynamic and pollution models. A wave climate has also been developed for the bay, both for the surface wave heights and bottom orbital motions. The components, however, have not yet been brought together to create a unified computer simulation of sediment transport for all of Port Phillip Bay.

LITERATURE CITED

BALL, D., STEERE, C., MOURTIKAS, S., NOYES-FITZSIMMONS, R., 1992. Port Phillip Bay Bibliographic Database Study (Report to VIMS to Melbourne Water)

BLACK, K.P. and PARRY, G.D., 1992. Sediment disturbance and dispersal in Port Phillip Bay: The effect of scallop dredging versus natural events. Victorian Institute of Marine Sciences Technical Report (in prep.)

BLACK, K.P., GREILACH, P. and PARRY, G., 1992. Prediction of bottom orbital motion in a semi-enclosed bay and the relationship to bed sediment grain size. Australian Journal of Marine and Freshwater Research (in prep.)

CSANADY, G.T., 1973. Wind-induced barotropic motions in long lakes. *Journa1 of Physica1 Oceanography, 3,* 429-438.

CHURCH, J.A. and FREELAND, H.J., 1987. The energy source for the coastal-trapped waves in the Australian Coastal Experiment region. *Journa1 of Physica1 Oceanography,* 17, 289-300.

ELDER, J.W., 1959. The dispersion of marked fluid in turbulent shear flow. *Journa1 of Fluid Mechanics,* 5, 544-550.

FANDRY, C.B., 1981. Development of a numerical model of tidal and wind-driven circulation in Bass Strait. *Australian Journa1 of Marine and Freshwater Research,* 32, 9-29.

FANDRY, C.B., HUBBERT, G.D. and McINTOSH, P.C., 1985. Comparison of predictions of a numerical model and observations of tides in Sass Strait. *Australian Journa1 of Marine and Freshwater Research, 36,* 737-752.

HODGKINSON, R. et al., 1990. *Current meter observations in Bass Strait.* Victorian Institute of Marine Sciences Technical Report, (in press).

JENKINS, G and BLACK, K.P., In Preparation. Hydrodynamics determines the timing and location of fish settlement in Port Phillip Bay. *Limnology and Oceanography*

KEOUGH, M.J. and BLACK, K.P., 1992. Predicting the scale of marine impacts: understanding planktonic links between populations. *Ecology Applications.* Volume 3, Number 2., In press.

MIDDLETON, J.F. and VIERA, F., 1991. The forcing of low frequency motions within Bass Strait. *Journal of Physical Oceanography,* 21, 695-708.

PARSLOW, J.S., 1990. A Theoretical Analysis of the Factors Affecting the Interpretation of Coastal Zone Colour Scanner Data in Port Phillip Bay. (Final Report). CSIRO Division of Fisheries.

PITTOCK, A.B., FOWLER, A.M., 'WHETTON, P.H., 1991. Probable Changes in Rainfall Regimes Due to the Enhanced Greenhouse Effect. *Proceedings of International Hydrology and Water Symposium.* Perth 2-4 October.

U.S ARMY COASTAL ENGINEERING RESEARCH CENTRE, 1975. Shore Protection Manual, Volume 1 (2nd Edition)