# WATER MOVEMENT STUDIES REQUIRED FOR PORT PLANNING

by

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## 1 INTRODUCTION

Some of the factors involved in the design of a programme of measurement and analysis of current, temperature and salinity data, required for the environmental assessment of an estuarine port, are considered in the context of a study carried out in the Port of Melbourne, Australia. The study was undertaken as part of the Port of Melbourne Environmental Study, 6 Webb Dock Marine Study which was aimed at assessing the present regime and the effects on the marine and coastal environments resulting from the construction of Berth 6, Webb Dock in Hobsons Bay (Figure 1). To this end, integrated investigations of water movement, water quality, coastal processes and marine ecology were conducted.

Although the results presented in this paper are specific to Hobsons Bay, the approach taken is of general applicability to the environmental assessment of proposed physical changes in complex estuaries and embayments. In such cases, the prediction of changed patterns of currents and density structure is a key element in assessing likely changes in other environmental factors such as water quality and the biota.

In general, an environmental study of water movement in an estuary will involve some measurements of the existing conditions of current, temperature and salinity, followed by appropriate analyses of these data to enable the likely changes to be predicted.

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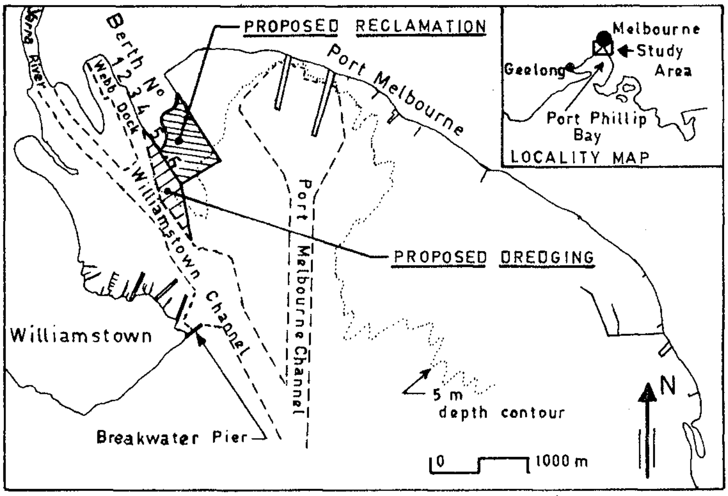


Figure 1. Hobsons Bay

The principal factors which must be considered in undertaking a study of water movement in a complex estuary are:

(i) The major forcing functions and their relative influence on currents (i.e. tide, wind, freshwater inflow, etc.)

(ii) The variability which exists in the processes under study, including time scales, range of variation and spatial scale.

(iii) The choice of instrumentation and methods of data analysis which could be used in the study.

(iv) The accuracy required in the predicted changes in flow regime.

(v) The methods which could be used to predict likely changes in the estuary as a result of proposed development works (e.g. are mathematical or physical models appropriate?)

The consideration of these factors in relation to the Port of Melbourne Study is described in this paper.

## 2 DESCRIPTION OF STUDY AREA

Hobsons Bay, at the northern end of Port Phillip Bay, is a tidal embayment containing the delta and outer estuary of the Yarra River (see Figure 1). It is bounded to the west by the Williamstown promontory, and to the east by the north-east Port Phillip Bay coastline. The bay is of varying depth, being typically 6 m deep but with shipping channels dredged to approximately 12 m.

The bay is subject to a tide with a dominant $M_2$ constituent of 0.46 m range and spring tides of over 1 m range. Freshwater inflow from the Yarra River is received throughout the year. The minimum mean monthly flow occurs during March (6.35 $m^3/s$) and the maximum occurs in October (47.8 $m^3/s$). This water reaches the bay via an estuarine section of the river system. The dilution of the sea water creates a density stratified system of varying character.

The bay is subject to direct meteorological influence, principally from the action of wind and barometric pressure. Winds are predominantly from the north in winter, whereas southerly winds tend to predominate in summer.

Hobsons Bay is a complex embayment, both because of its irregular geometry and because of the fact that the currents are quite weak and may be influenced at various times by tide, wind and/or fresh water influx from the Yarra River. The significant influence of meteorological factors, principally wind, means that the current regime is highly variable in time, in depth and in location in the bay.

## 3 FIELD PROGRAMME

Because of the complex flow regime known to exist in Hobsons Bay and time limitations on the study, the possible use of physical or mathematical models was not considered to be practicable. Instead, considerable effort was concentrated on the collection of a comprehensive set of field data which would form the basis for predicted changes in the physical regime.

The major forcing functions could not be identified *a priori* so the measurement programme had to embrace time scales appropriate to meteorological, hydrological and tidal phenomena. This was achieved by combining several intensive field exercises of short duration with continuous monitoring at a few locations over a 12 month period in order to cover as wide a range of conditions as possible.

The intensive field exercises provided detailed spatial resolution for relatively short periods, thus enabling overall flow patterns to be identified. The continuous monitoring, on the other hand, provided detailed time series information of currents at particular locations and thereby enabled statistical correlations of currents with external forcing factors to be carried out.

Current speeds were expected to be small, in general, hence current meters with a low threshold were required. The variability of the currents meant that net circulation had to be obtained by integrating over long periods of time. This variability also imposed severe demands on the accuracy of measurement.

The current meters selected had threshold speeds of 2.0 to 2.5 cm/s and were chosen on grounds of anticipated reliability, immediate availability and cost. To improve the measurement of net circulation, continuous recording current meters were used as described below. No special problems relating to salinity and temperature measurement were anticipated, however frequent calibration was necessary due to fouling of electrodes.

In essence, the field programme comprised the following acitivies:

(i) Four intensive field exercises, each of three days duration conducted over the whole of Hobsons Bay

(ii) Additional one day field exercises concentrated in areas of particular interest, namely Webb Dock and the Lower Yarra Estuary

(iii) Long term continuous recording of currents, temperature, salinity and water levels at selected locations.

The four intensive field exercises were held in June, August and December 1977 and in February 1978 in order to obtain a range of external influences and flow conditions in the bay. During each exercise, monitoring was carried out over a full tidal cycle on each of three consecutive days. Direct profile measurements of current speed and direction, temperature and salinity were made from five boats each anchored at a fixed location in the bay or alternating between two stations. In general, readings were taken at 0.5 m intervals to 2 m depth and then at 1 m intervals to the bottom. Complete profiles were repeated at approximately half hour intervals.

In conjunction with the profiling, direct Lagrangian measurements of the current field were conducted on six of the monitored tidal cycles. Methods used included tracing the movements of free drogues and of dye releases. The drogues were suspended at selected depths and were connected to surface buoys and targets. Up to 20 drogues were tracked at any one time from a field radar station. On selected days, dye was introduced into the near-surface waters and the movement and rate of spread of dye patches were monitored using radar fixes and aerial photography.

The one day field exercises conducted in Webb-Dock and the Lower Yarra Estuary were conducted in a similar manner to the bay-wide exercises but had a finer spatial focus. Two exercises were conducted in each of these locations.

To supplement the limited range of conditions which were covered in the intensive exercises, four automatic current recording instruments were deployed at selected locations in the bay. The meters used were Alexseev instruments which record current speed and direction at pre-set time intervals on paper tape. Each meter was deployed for a period ranging from one to six months at a particular location using a 15 minute recording interval. To record near-bottom currents, the meters were suspended from tripods which rested on the bay floor. Near-surface currents were recorded by suspending the meters from several floats which were free to move vertically with the rise and fall of the water level. In total, about 1166 days of useful data were recorded in this way.

Data from continuous temperature recorders at 8 locations in the bay were collected during the period of the field investigations. These had been installed by the State Electricity Commission of Victoria and provided records of three-hourly temperature readings dating back several years.

To provide information on the penetration of river water into the existing Webb Dock area, a continuous temperature/salinity recorder was installed in the dock for a period of two months.

The above field programme was complemented by the acquisition of suitable data by other agencies. These data included:

(i) Meteorological measurements such as wind speed and direction, barometric pressure, rainfall and air temperature

(ii) Freshwater inflow from the Yarra River System.

(iii) Water level data at Breakwater Pier, Williamstown.

## 4 DATA ANALYSIS AND RESULTS

### 4.1 Velocity and Salinity Data

The field data were edited and adjusted for calibration errors before being entered on to computer files. These, together with data obtained from other agencies, formed a comprehensive data base for analysis. A variety of analyses were carried out using computer programs written specifically for the purpose.

The data from intensive field exercises were processed to produce line printer plots of depth profiles at all stations. Density layers were defined by the occurrence of steep vertical density gradients in the profile. It was found that the bay was density stratified in most conditions. Vertical temperature gradients in the bay were found to be rather small, with most of the density variation being due to salinity differences between the fresher river water and the deeper bay water.

Usually two and sometimes three distinct density layers could be identified in water deeper than 4 metres, although the depth of the upper layer varied significantly in time and space. On occasions more complex layering occurred. Kinematic layers were identified by noting the change in the directional component of profiled current data.

The continuous current records were analysed to determine the relative importance of the various factors which influence currents in the bay. The current records were analysed using a tidal harmonic analysis to identify the tidal component. It was found that the $M_2$ tidal constituent accounted for about 25% of the variance in currents at each location. The non-tidal components of current were correlated with riverflow. wind speed, barometric pressure and rainfall in order to determine the relevant influence of these factors. It was found that wind, and principally its north-south component, had a major influence on currents in the bay. Riverflow had a significant effect on the currents at some locations and other parameters were of lesser importance. These results were substantiated by detailed examination of the results from the intensive field investigations.

4.2 Time Scales in Response to Wind Stress

There appear to be two time scales involved in the hydrodynamic response of Hobsons Bay to a change in the wind stress field. The first depends upon the rate of downward transport of the momentum imparted by the wind stress. The second relates to the time for establishment of flows driven by horizontal pressure gradients which arise due to the wind-induced set up (down) of water level near coastlines.

Neglecting the influence of lateral boundaries and in the absence of stratification, it is possible to make a rough estimate of the first time scale. It is assumed that, from an initial state of rest, a wind stress is imposed uniformly over the surface of the water. Empirical relationships allow an estimate of the surface shear stress, $\tau_w$, and the surface wind drift speed, $u_d$ (Spillane, Robinson and Hess, 1978). Application of the boundary layer momentum integral equation leads to an expression for the momentum thickness, $\theta$, as a function of $\tau_w$, $u_d$, $\rho$, the density of water, and t, the time elapsed:

$$\theta = \frac{\tau_w}{\rho u_d} t \qquad (1)$$

Assuming a wind speed of 5 m/s, we obtain $u_d \simeq 0.03\ u_w = .15$ m/s and $\tau_w = \rho k u_w^2 = .03\ N/m^2$. For $\theta = 1$ m, t = 1.5 hours; for $\theta = 2.5$ m, t = 3.8 hours.

Assuming a wind speed of 10 m/s, we obtain, for $\theta = 1$ m, t = 0.6 hours; for $\theta = 2.5$ m, t = 1.6 hours.

Drogues located from 0.5 - 2.5 m below the water surface were used to track upper layer water movement. It was possible to examine the response of drogue trajectories to sudden changes in wind direction. The response times varied between 45 minutes to approximately 3 hours. For example, on 23 February 1978, between 1200 and 1400 hours, drogue velocity vectors rotated about 45° in an anticlockwise direction. This appears to have been in response to the wind field which swung from west to south between 1000 and 1100 hours, while maintaining a low speed of 2 m/s, and then, maintaining direction, intensified to a speed of about 5 m/s during the period 1200-1400. A response time of about 3 hours seems in reasonable agreement with the above calculations.

Flows driven by pressure gradients become established as the pressure gradients become established. The latter require times in the order of $L/\sqrt{gy}$, where L is the fetch and y the depth. For L = 4 km and y = 10 m, the time is in the order of 7 minutes. If we say 5 to 30 minutes allowing for the approximate nature of the analysis, this is still less than the first time scale which then becomes the effective one.

## 5 TYPICAL FLOW PATTERNS

Information on the kinematic and density stratification of the bay was used to choose the most appropriate way of classifying and presenting the current field. In most cases, the movements of near-surface (0 - 2.5 m), mid (3 - 5 m) and deep (6 - 8 m) waters provided a useful division. Within each of these divisions, current vectors representative of each two hour period from all data sources were plotted on a single map; the two hour period being approximately equal to the response time of the bay to wind stress. The data sources included current profiles, drogue trajectories, dye patch trajectories, and recording current meters. Bay-wide plots of near-surface salinities were obtained for the same two hour periods. Temperature differences across the bay were small and had little influence on the flow patterns.

Typical current and salinity fields are shown in Figures 2 and 3. A detailed examination of these quasi-steady velocity and salinity fields indicated that certain flow patterns could be identified on the basis of wind speed and direction and river flow, with tidal influence being of minor importance.

Figure 2 shows the surface current and salinity fields on February 23, 1978, at 0800 to 1000 hours. During this time, the wind was from the north-west at 2 m/s, the river flow was 4.5 $m^3/s$ (low) and the tide was falling.

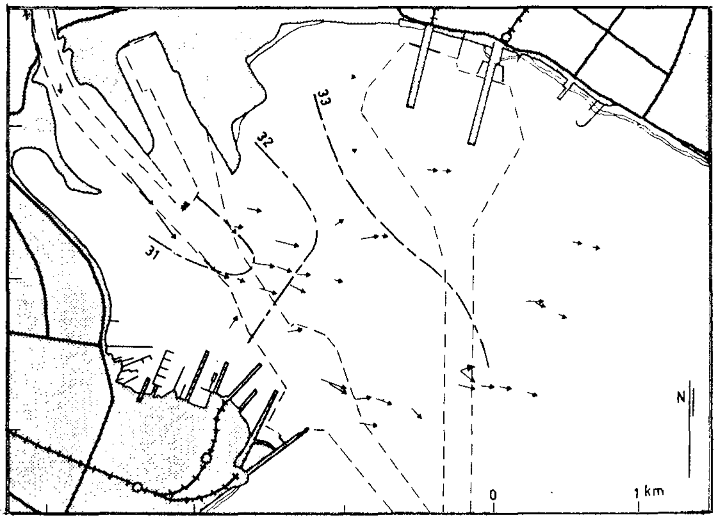


Figure 2. Surface Current and Salinity Fields on Feb. 23, 1978, at 0800-1000 hours

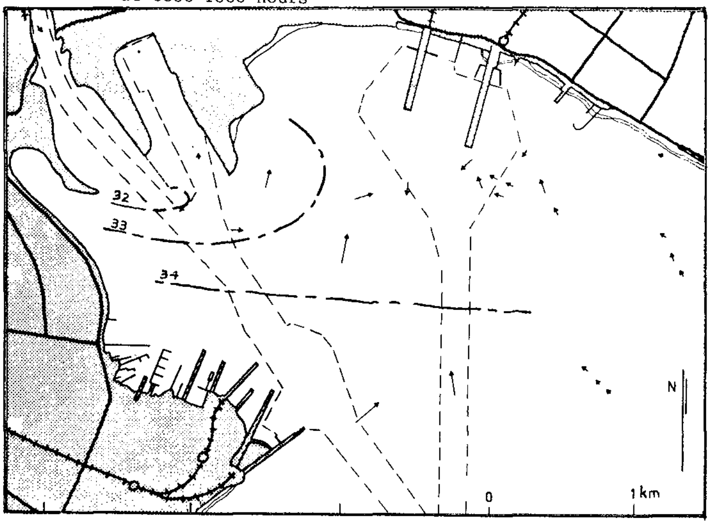


Figure 3. Surface Current and Salinity Fields on Feb. 23, 1978, at 1800-2000 hours

It can be seen from Figure 2 that the near-surface water adjacent to the Yarra mouth exhibits a generally south-easterly movement with speeds in the range of 0·1 to 0·2 m/s. Once beyond the line of the proposed Webb Dock 6 extension, the surface water spread to the north-east and then re-aligned itself with the south-east trending coastline.

Water movement at mid-depth was quite sluggish, particularly in locations of large total water depth. Its direction of movement tended not to differ significantly from that of near-surface water except where it was deflected by the direct effect of the bay's bathymetry. Deeper water appeared to flow northward in the vicinity of both shipping channels with maximum speeds of about 0·1 m/s. Much of this deep water flux must have been induced in order to compensate for the net efflux of near-surface waters southward out of Hobsons Bay.

The surface salinities recorded at this time are in the range 30-34 g/l (Figure 2). They indicate the existence of a plume of river water moving towards the south-east in response to the currents in that direction. The depth of the maximum salinity gradient was about 0·7 m for locations near the central axis of the plume and about 2 m for the more marginal stations.

A different set of conditions are illustrated in Figure 3 which shows the near-surface current field and surface salinity distribution observed on February 23, 1978, at 1800 to 2000 hours. During this period, the wind speed averaged 7 m/s from the south-south-east, the river flow as 4·5 $m^3$/s (low) and the tide was falling.

At this time, the near-surface currents throughout most of Hobsons Bay (except near the mouth of the Yarra River) exhibited a significant northward velocity component. Near-surface water on the east side of the Port Melbourne Channel moved to the north-west in conformity both with the direction of the wind and the coastal alignment. Water to the west of the channel moved north-north-east to north-east. There was a noticeable convergence of surface waters in the vicinity of the swinging basin located at the head of the Port Melbourne Channel.

The pattern of mid to deeper water movement was not well defined, with mid-depth water being essentially stagnant. The most unmistakable feature was a deeper-water movement to the south in the vicinity of the Port Melbourne Channel. Mass balance calculations indicated that this deep water flux to the south essentially balanced the near-surface flux to the north and the mass deficit due to the falling water level.

The near-surface salinity field (Figure 3) indicated a weak plume of less saline water extending into Hobsons Bay in an easterly direction from the Yarra mouth.

## 6 CLASSIFICATION OF FLOW PATTERNS

The detailed analysis of flow patterns in Hobsons Bay enabled the classification of these patterns into a limited number of representative conditions. Seven representative patterns were identified, each resulting from a different combination of high or low river flow and wind direction as shown in Table 1. It was found that tide made little difference to the basic flow patterns. The choice of 50 $m^3/s$ as a dividing point between high and low river flow was based on the measurements taken in the Lower Yarra Estuary which indicated the formation of a salt wedge for discharges greater than this figure. Below 50 $m^3/s$ the estuary was partially mixed.

The near-surface flow fields for two of the flow patterns are shown in Figures 4 and 5. Pattern A (Figure 4) corresponds to north to north-west winds and low river flow, while Pattern C (Figure 5) corresponds to south to south-east winds and low river flow. The tendency for the near-surface waters to converge in the vicinity of Station and Princes Piers under conditions of south to south-east winds should be noted.

The frequency of occurrence of each flow pattern was determined by analysing historical records of wind and river flow and determining the relative frequency of occurrence of each combination of these. These relative frequencies are included in Table 1 expressed in the form of the average number of days per year for which a particular pattern is expected to occur.

## 7. USE OF OBJECTIVE CLASSIFICATION SCHEMES

Attempts were made to put this descriptive classification into dynamic terms. Dynamic classification schemes relate the external forces or fluxes of energy which determine the water movement. The most complete of these schemes, that of Hansen and Rattray (1966), was applied successfully to the Lower Yarra estuary. However in the case of Hobsons Bay gross parameters used by Hansen and Rattray could not be measured with sufficient accuracy while the theoretical parameters contained products and ratios of diffusion parameters, which could only be inferred indirectly and then only for certain of the flow conditions.

Of the various energy ratio schemes, that of Ippen and Harleman (1961) is typical and has been well correlated with flow patterns through their model studies. Their scheme is based on the ratio of two parameters, one representing the rate of tidal energy dissipation per unit mass of water and the other the rate of gain of potential energy per unit mass of water. This scheme may be extended by considering also the energy input by the wind acting on the water surface and the inflow of kinetic energy to the bay from the river. A difficulty with all of these parameters is that the detailed information necessary to obtain exact numerical values is not available, so gross physical variables are used instead. Hence the quantities calculated are likely to suffer from errors ranging from perhaps 25% in the case of tidal and wind energy to perhaps 50% for the other two quantities (the potential energy term used is that of Ippen and Harleman (1961) and is not an actual energy change but it is a quantity indicative of the relative magnitude of the potential energy change as the river flow passes through an estuary).

TABLE 1. Flow Patterns in Hobsons Bay

| Pattern | Occurrence (days/year) | River Flow ($m^3/s$) | Wind Direction at Breakwater Pier | Flow Pattern |
|---|---|---|---|---|
| A | 95.8 | Low (< 50) | NW & N | Surface: SSE; mid and deep water: N and up channel at 0.1 m/s |
| B | 54.9 | Low | NE & E | Surface: S, SE; mid-depth: weak but similar; deep: up channel |
| C | 98.5 | Low | SE & S | Surface: generally NE, Yarra outflow swings E, inflow to N along Williamstown shore, convergence near Station Pier; mid: similar; deep: S in Pt. Melbourne Channel |
| D | 83.0 | Low | SW & W | Surface: generally NE, Yarra outflow swings E to NE, inflow to N along Williamstown shore; mid: similar to weak; deep: weak |
| E | 5.2 | High (≥ 50) | W | Surface: ESE with strong river plume extending into bay, N near Breakwater Pier; mid and deep: N to NW |
| F | 13.8 | High | NW to E | Surface: strong river plume following Williamstown Channel; deep: up channel |
| G | 14.0 | High | SE to SW | Surface: Strong river plume flowing S to Breakwater Pier then ESE; deep: up channel |

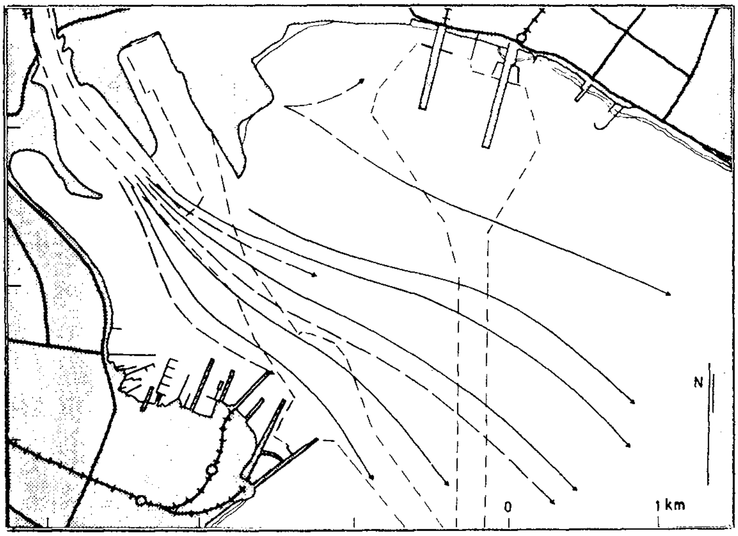


Figure 4. Flow Pattern A

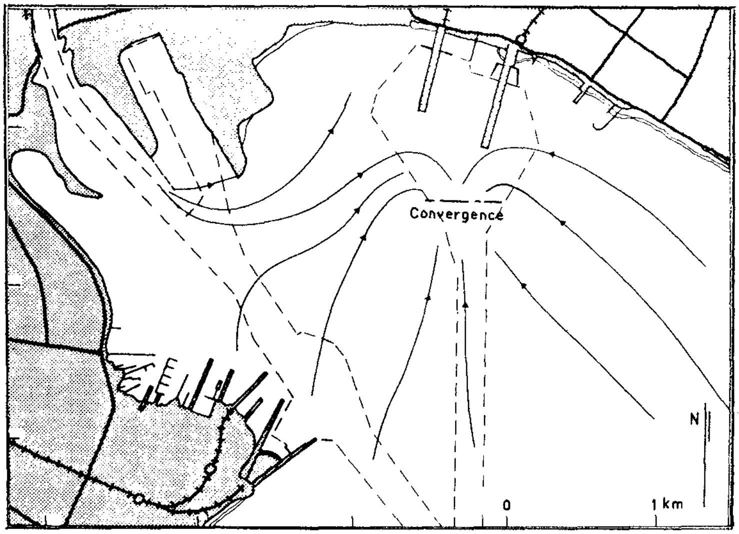


Figure 5. Flow Pattern C

The energy terms, calculated for an area of 8 $km^2$ of the bay for typical and high winds, for typical and high tidal currents and for typical and flood river flows, are given in Table 2. The most obvious feature of these results is the high energy input by the wind, and the small input by the tides. From this it may be inferred that mixing is primarily caused by the wind and hence in the absence of winds the bay is likely to be stratified, while wind is likely to be less important under high flow conditions. Both these features have been observed.

Under flood conditions, for the wind to impart sufficient power to negate the potential energy input of the river plume would require a very strong wind or a large area of bay surface. Thus the plume should persist as an identifiable feature for some distance. Using data from the flood of February 1973, a river plume with a well defined boundary covered an area of 3·6 $km^2$ on 7 February. The wind was relatively steady with a speed of 9 m/s and the river flow over the preceding 24 hours averaged 120 $m^3/s$. For these conditions, the power input to the plume from the wind was 197 kw and that from the river was 240 kw. This agreement, which is surprisingly close in view of the usually low efficiency of the mixing process, can possibly be accounted for by the fact that mixing is only partially complete just outside the plume, and weakly stratified water extends over tens of square kilometres.

TABLE 2. Rates of Energy Dissipation in Hobsons Bay.

| | | | | |
|---|---|---|---|---|
| Wind Speed (m/s) | 5 | | 10 | |
| Power Input by wind over 8 $km^2$ (kw) | 75 | | 600 | |
| Tidal Velocity (m/s) | 0·02 | 0·02 | 0·05 | 0·05 |
| Depth (m) | 10 | 6 | 10 | 6 |
| Tidal Power dissipated over 8 $km^2$ (kw) | 0·15 | 0.18 | 2·33 | 2.77 |
| River Flow ($m^3/s$) | 5 | | 150 | |
| Rate of Potential Energy Change (kw) | 1·50 | | 300 | |

## 8 USE OF LONG-TERM CHANGES FOR ENVIRONMENTAL PREDICTION

Predictions of changes in the long term average currents, salinities and water quality variables (nutrients and dissolved oxygen)

TABLE 3. Projected Changes in Salinity and Current Speed Following Construction of Berth No. 6.

| Pattern | Maximum Changes following Construction of Berth No. 6 [1] | | | | |
|---|---|---|---|---|---|
| | Existing Dock | Berth No. 6 | Within 300m E of No.6 | Williamstown | Other |
| A | Nil | V+ | Nil | Nil | (Bottom V+) |
| B | Nil | Nil | Nil | Nil | S – 0·2 at Parsons |
| C | Top layer 0·3 m thicker | Plume impinge on No. 6 | V–, S+1 | S+0·4 to 1 maximum V– | Flotsam South of No. 6 |
| D | S – 0·5 | Plume impinge on No. 6 | V–, S+0·5 | Nil | Flotsam South of No. 6 |
| E | S – 5 | Nil | S+2, V+ | Nil | Nil |
| F | Nil | Nil | Nil | Nil | Nil |
| G | Top S – 2·5, V+ Mid S ± 2 | Top S – 2·5, V+ Mid S ± 2 | Top S – 2·5 Mid S ± 1 | Nil | River Entrance: Mid S ± 1 |

1. Changes given are maxima in all cases and unless specified apply only to the top 1·5 m; + indicates an increase, – a fall. Changes of less than 0.05 g/l in salinity and 3 cm/s in current speed have not been given a numerical estimate. Changes in salinity (S) are in g/l and in current speed (V) are in cm/s.

TABLE 4. Estimated Changes in Long-Term Average Velocities and Salinities

| Location | Maximum change in average current speed (m/s) | Standard deviation of measured current speed (m/s) | Maximum change in average salinity of upper 1.5 m (g/l) | Standard deviation of measured salinity (g/l) |
|---|---|---|---|---|
| Existing Dock | Negligible | Not applicable | - 0.3 | 4.0 |
| Berth 6 Webb Dock | + .01 | .027 | - 0.1 | 3.9 |
| Within 300m to the east of Berth 6 | Negligible | Not applicable | + 0.4 OR - 0.1 | 4.0 |
| Williamstown Foreshore | - .01 | .04 | + 0.3 | 6.0 |
| Other Locations | Less than .01 | .03 to .04 | Less than 0.05 | 3.0 to 6.0 |

resulting from dock construction were required in order to assess the likely effects on the biota in the bay. Predictions of changes in the physical variables to an accuracy of one significant figure was deemed adequate for the subsequent biological assessment. It was decided therefore to use relatively simple methods for predicting these physical changes.

The expected change in each flow pattern was determined by a close examination of the streamlines and by applying judgement to assess the way in which these would change following dock construction. The equations of continuity and conservation of salt were then applied to determine the expected changes in the velocities and salinities resulting from the displacement of the streamlines. The predicted changes are given in Table 3. The expected changes are, in general, relatively small except for infrequent combinations of external factors, e.g. high river flow and westerly wind which is expected to occur only about 5 days per year on average.

The long term average changes in velocities and salinities were computed by combining the changes expected in each flow pattern with the relative frequency of occurrence of that pattern. These are shown in Table 4 together with estimated standard deviations of the parameters due to natural variability. In general, it was found that the expected long term average changes in currents and salinity were much less than the natural variability which occurs in these parameters.

## 9 CONCLUSIONS

(i) The investigation of water movement was central in assessing the environmental effects of port development works by enabling prediction of future water movements and environmental parameters. It was found that the proposed berth would not have a major effect on currents or salinity (or on other parameters) in Hobsons Bay.

(ii) Current patterns in Hobsons Bay are influenced by salinity stratification at all times and are determined principally by river flow and wind, with tide having a minor influence. Currents take up to two to three hours to respond to changes in the wind.

(iii) Published estuary classification schemes were not useful, but consideration of gross energy inputs by the different forcing processes provides a basis for understanding flow patterns.

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