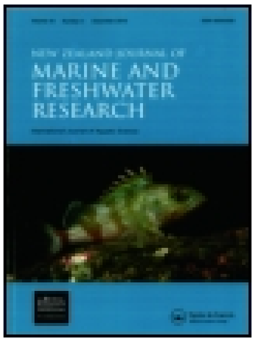

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Hydrodynamic and water column properties at six stations associated with mussel farming in Pelorus Sound, 1984–85

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Abstract Mussel farming places a benthic organism in a pelagic environment; it is therefore important to understand the driving force that transports the food to the mussels. The hydrodynamic regimes in the sidearms and embayments in Pelorus Sound are dominated by the lunar tide, and a net estuarine circulation in the main channel flowing inwards along the bottom and outwards along the top. Salinity gradients extend throughout the sound from the river inflows, with strongest density stratification in the sidearms and embayments nearest the head of the sound. There, the water column is separated at the pycnocline into upper and lower layers which tend to move in different directions or at different velocities. Local circulation patterns modify tidal flushing patterns, producing extended residence times in some embayments, whereas other embayments off the side of the main channel tend to be flushed more rapidly by through-flow water and have shorter residence times than would otherwise be expected. The changing inflow of fresh water modifies the local hydraulic regimes in the inner sounds, especially during flood conditions.

Keywords Pelorus Sound; hydrology; water column properties; mussel farming

INTRODUCTION

As well as being a major marine recreational area, the Marlborough Sounds are commercially important as the largest area of aquaculture in New Zealand, farming the green-lipped mussel, *Perna canaliculus*. There are at present about 330 licences issued for mussel farming in the sounds and a further 300 applications to develop new farms. However, the number of mussel farms that the sounds can sustain is unknown and already periodic shortages of mussel food, phytoplankton, have been indicated (Meredyth-Young 1983). There are also indications that some areas of the sounds are better than others for mussel culture in terms of growth and condition (Hickman & Illingworth 1980).

Although the factors influencing phytoplankton growth are of great importance to the food supply, it is obvious that the transport of food to the mussel will be of prime importance. In a concurrent study on mussel feeding, Waite (1989) found that water movement through a mussel farm was attenuated to about 30% of the velocity of the water approaching the farm, with the remainder being forced below or around the farm. Thus, with mussels being cultivated in a pelagic situation, knowledge of the open water movement would be helpful when siting a mussel farm within an embayment so that the best use is made of natural currents.

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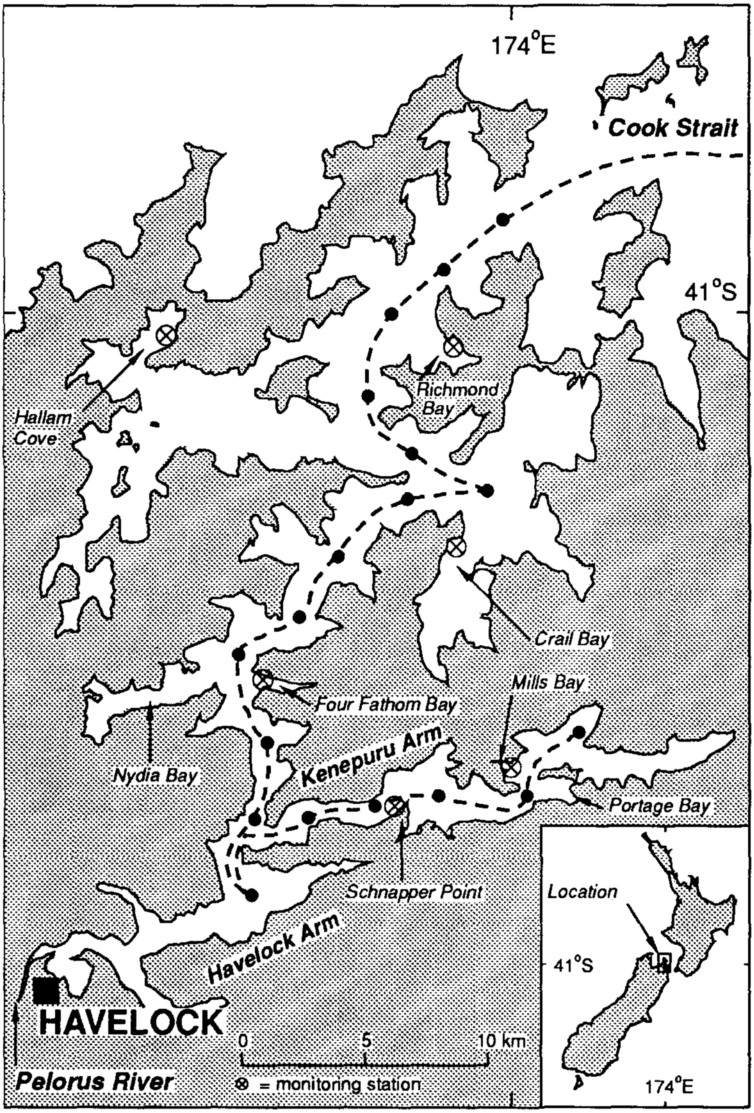


Fig. 1 Location map of the Pelorus Sound showing the transect line (broken line) and fixed monitoring stations: Mills Bay, Schnapper Point, Four Fathom Bay, Crail Bay, Hallam Cove, and Richmond Bay.

Water movement and hydrodynamics in the main channel of Pelorus Sound are described in detail by Heath (1974, 1976a, 1976b, 1982) and Carter (1976), and are summarised by Heath (1985). Although water movements in the Kenepuru arm were inferred from salinity and temperature measurements (Bradford et al. 1987), no detailed hydrological data are available in the sidearms and embayments off the main channel where the mussels are cultivated. The present study examines the water movement and water column properties within those sidearms and embayments as part of a larger study on nutrient cycling and availability in the water column associated with green-lipped mussel farming in the sounds. Other water quality parameters measured simultaneously will be reported elsewhere.

STUDY SITES AND SAMPLING METHODS

Sampling was carried out from FRV *Kaharoa* at six stations within Pelorus Sound (Fig. 1) on seven occasions: 3–10 April, 5–12 June, 4–11 August, 22–29 September, 13–20 December 1984; and 9–17 February and 18–25 April 1985. Sampling stations (Fig. 2–5) were positioned about 25 m from adjacent mussel farms selected in the inner (Mills Bay, Schnapper Point), middle (Four Fathom Bay, Crail Bay) and outer sounds (Hallam Cove, Richmond Bay). These stations covered shallow, deep, sheltered, and exposed locations in side embayments and re-entrants off the main channel (Table 1). Each station was occupied for 12 h (Mills Bay, Four Fathom Bay, Crail Bay, Hallam Cove) or 24 h (Schnapper Point, Richmond Bay) on each sampling occasion. Water column properties were measured hourly and chemical and biological variables were measured 2-hourly while on station, from depths of 1, 4, 7, and 10 m at all stations plus samples from 20 m and 30 m at deep stations. A transect line of 18 stations in the main channel through the Kenepuru arm to Cook Strait was sampled (within 6 h) on the outward journey of each visit (Fig. 1).

Current velocity and direction profiles were measured hourly, when possible, at each monitoring station using a manual Hydro Products 460 current meter and 465 direction sensor lowered through the water column from the stern of the ship. In situ recording Hydro Products Seatrak current meters were deployed once at each monitoring station for several weeks during the study period. The long-term measurements included monitoring positions within, below, and outside a mussel farm in Crail Bay and Richmond Bay (see Fig. 4 and 5).

Salinity was determined on freshly pumped samples using a conductivity meter and conversion equation. Temperature was measured on the same sample using a calibrated glass mercury thermometer. In situ temperature was measured simultaneously with dissolved oxygen (DO) using a Yellow Springs Instrument model 54A oxygen meter fitted with a 70 m cable with stirrer unit.

Daily rainfall data in the Pelorus catchment were provided by the NZ Meteorological Service, Wellington. River flows from TIDEDA discharge data, measured at Bryants gauging station on the Pelorus River and expressed as daily means, were provided by the Hydrology Section of Ministry of Works and Development, Nelson.

Bathymetric data were taken from charts by Irwin & Main (1987a, 1987b). Hypsographic areas were estimated by cutting out and weighing the area enclosed by selected depth contours relative to the weight of a measured area cut from the same map. The volume of a specific layer was calculated as the mean of the areas of the upper and lower surfaces multiplied by the depth of that layer (Table 1).

RESULTS

Current measurements

Current meter data for each station were incomplete owing to instrument fouling and failure, or the wind causing excessive ship movement. The data obtained are presented as progressive current vector plots (Fig. 2–5). The tidal cycle was dominant at each station but water movement was modified by the shape and depth of each embayment and the degree of density stratification. The estuarine circulation in the main channel also influenced water movement in the sidearms and embayments which were deep enough for the bottom water intrusion layer to enter.

With the exception of Crail Bay (Fig. 5), current vectors at each station varied in both direction and magnitude with depth and often had surface water moving in the opposite direction to water at 10 m.

Table 1 Morphometric and hydrological data for Pelorus Sound.

Sound/station	Location	Length (km)	Area (km^2)	Mean depth, HT (m)	Volume, HT (×10^6 m^3)	Tidal compartment (×10^6 m^3)	Ratio volume/tidal compartment
Havelock Arm		11	18	5.7	103	33	3.1
Kenepuru Arm		22	39	13.0	463	72	6.4
Whole system		56	290	39.6	11475	535	21.4
Mills Bay	173°59.5′E, 41°11.0′S		1.08	9	7.2	2.0	3.6
Schnapper Pt	173°55.8′E, 41°12.3′S		*	14	*	*	*
Four Fathom Bay	173°52.5′E, 41°09.1′S		1.14	12	10.4	2.1	5.0
Crail Bay	173°58.4′E, 41°05.5′S		13.06	32	198	24	8.3
Hallam Cove	173°49.4′E, 41°00.0′S		3.42	28	71	6.3	11.3
Richmond Bay	173°58.4′E, 41°00.3′S		3.68	24	90	6.8	13.2

*see Kenepuru arm

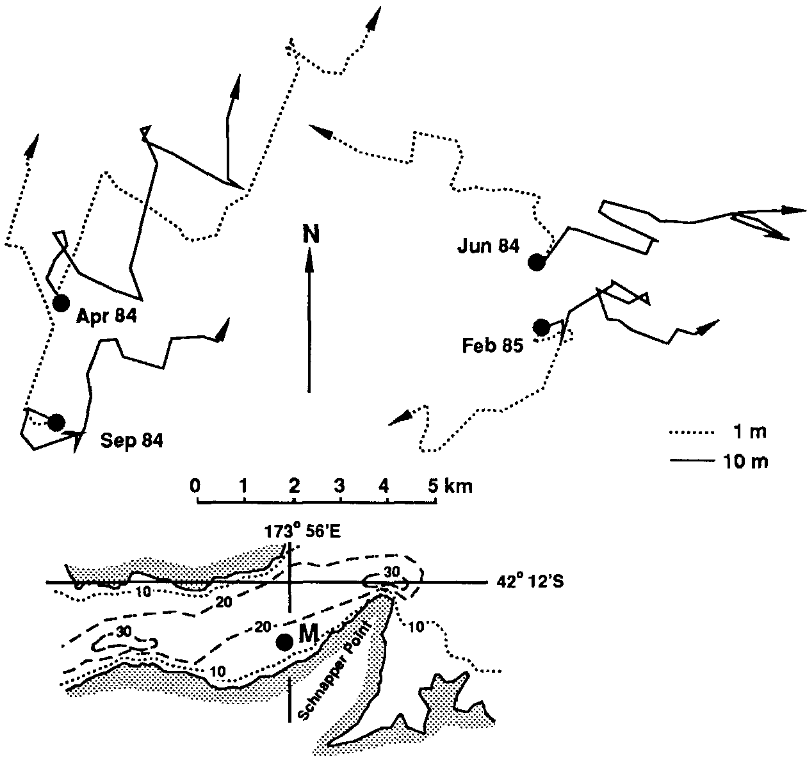
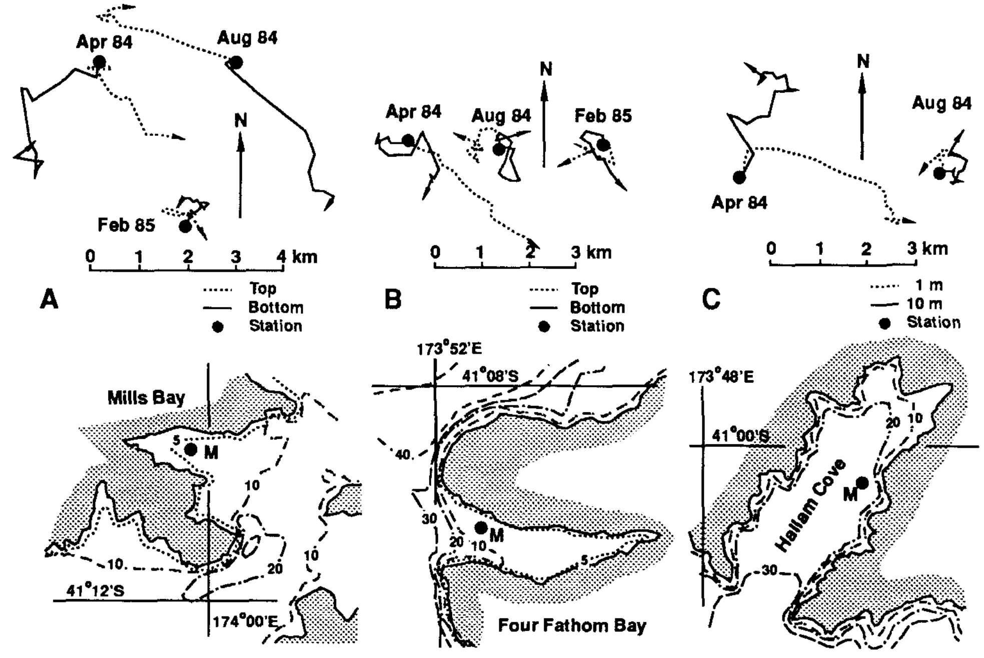


Fig. 2 Site map of Schnapper Point with fixed monitoring station (M). Progressive current vector plots at 1 m and 10 m show water column separation and the distance a theoretical parcel of water from each depth would have moved from the sampling station during the sampling period: April 1984, 25 h; June 1984, 28 h; September 1984, 20 h; February 1985, 17 h.

Fig. 3 (*Below*) Site maps and water movement plots of Mills Bay (A), Four Fathom Bay (B), and Hallam Cove (C). The sampling period for the progressive current vector plots were:
Mills Bay—April 1984, 12 h; August 1984, 10 h; February 1985, 13 h.
Four Fathom Bay—April 1984, 10 h; August 1984, 12 h; February 1985, 7 h.
Hallam Cove—April 1984, 12 h; August 1984, 14 h.



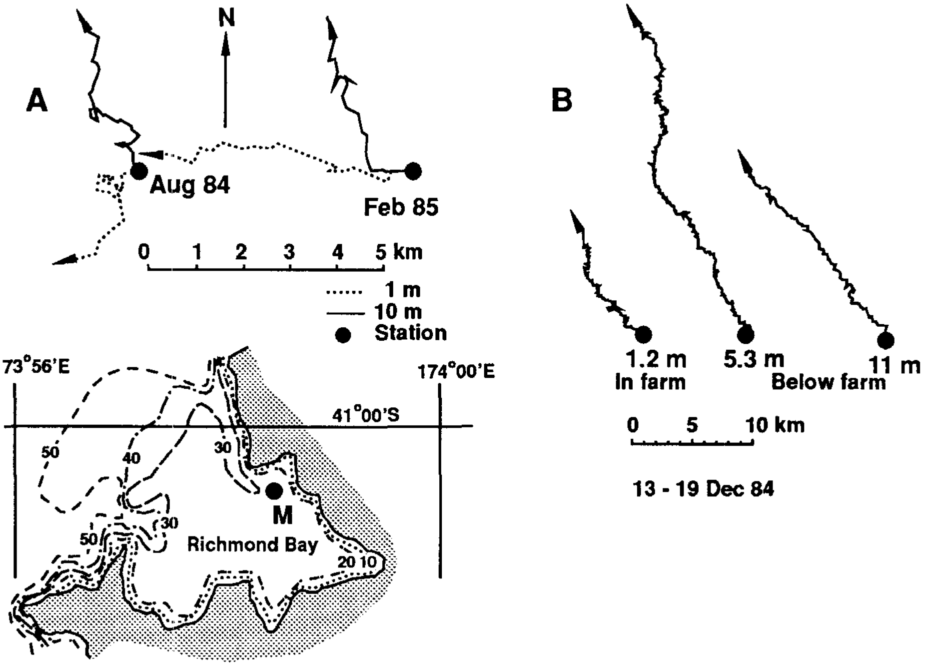


Fig. 4 A, Site map of Richmond Bay with progressive current vector plots showing water column separation of 1 m and 10 m water. Sampling period: August 1984, 25 h; February 1985, 22 h. B, In situ current vector data from within a mussel farm (1.2 m), just below the mussel ropes (5.3 m), and 5 m below the mussel farm (11 m) during December 1984. Sampling period 6 d.

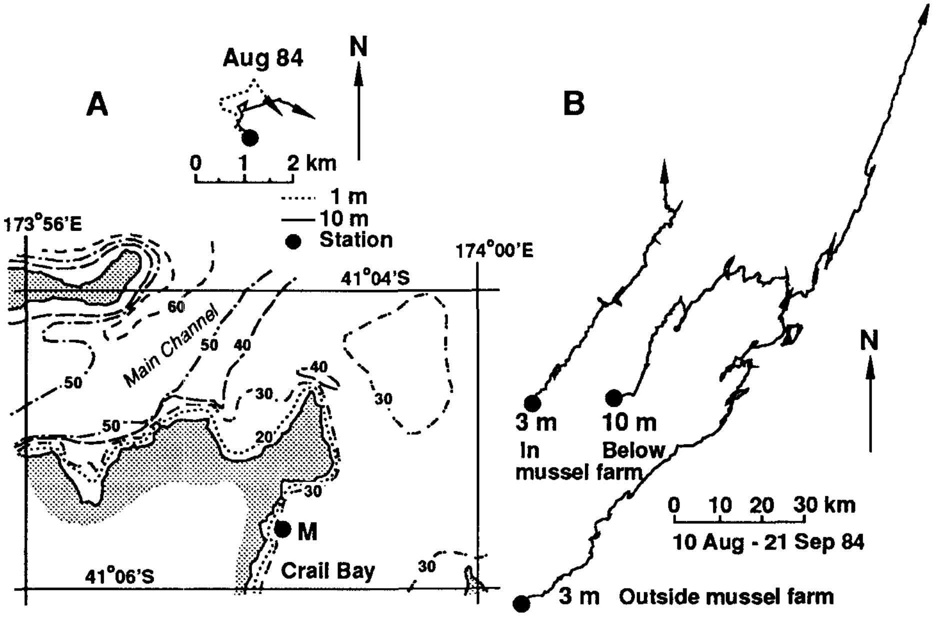


Fig. 5 A, Site map of Crail Bay with a progressive current vector plot from August 1984 (8 h). B, In situ current vector data within a mussel farm (3 m), below the mussel farm (10 m) and at 3 m depth outside the farm (3 m outside) during August and September 1984. Sampling period 48 d.

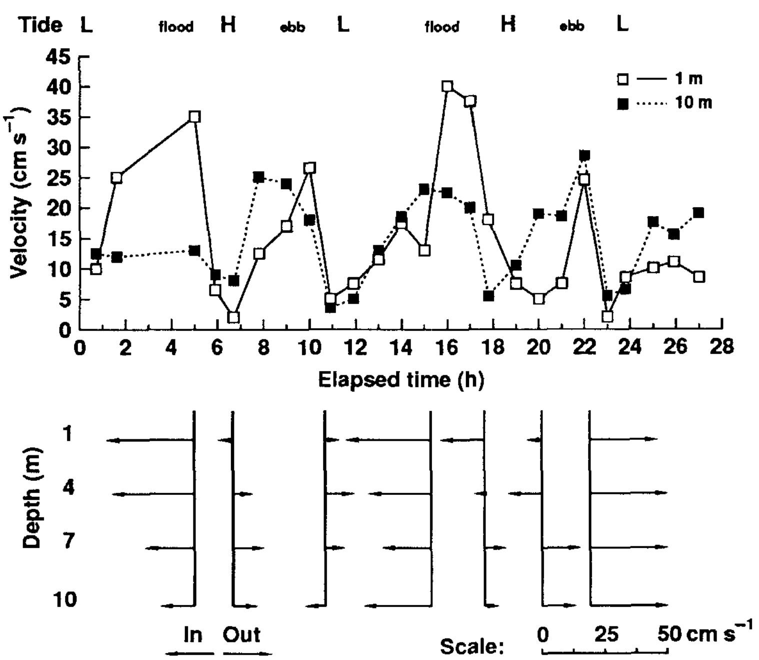


Fig. 6 Sequential velocity measurements at Schnapper Point (April 1984) showing water column separation with velocity and phase differences between 1 m and 10 m (upper) and flow direction for selected profiles (lower) at different stages of the tide. The vertical axis of the flow direction plots (lower) align with their sampling times on the axis immediately above.

The largest velocity difference between surface and bottom waters was found at Schnapper Point (Fig. 2 and 6). Mean velocities there varied from 10 cm s^{-1} to 15 cm s^{-1}, peaked at more than 40 cm s^{-1} (April 1984), and frequently exceeded 25–30 cm s^{-1}. These ranges occurred on most sampling occasions. The difference was greatest in June 1984 when theoretically water movement could have separated initially adjacent parcels of surface water and 10 m water by more than 10 km in 28 h (Fig. 2). As a general trend, bottom water moved eastwards up the southern side of Kenepuru arm at Schnapper Point. The surface water either moved up the Kenepuru arm at a rate similar to, although not necessarily in phase with, the bottom water (e.g., April 1984: Fig. 2) or moved down the Kenepuru arm in the opposite direction to the bottom water (e.g., June 1984, February 1985: Fig. 2). When both surface and bottom water moved up the southern side of the Kenepuru arm, slick lines and debris were observed moving down the Kenepuru arm on the northern side of the channel. This flow pattern implied a counter-clockwise circulation within the Kenepuru arm extending well beyond Schnapper Point and possibly as far as Mills Bay (see below). This regime would probably result in very slow flushing rates and the potential for long residence times within the Kenepuru arm. When surface and bottom waters moved in opposite directions (e.g., June 1984: Fig. 2) the whole surface layer appeared to move in unison. This flow pattern implies a "conveyor-belt" circulation, with the bottom water moving inwards, then upwell-ing beyond Schnapper Point before flowing outwards in the upper water column. The fast currents with this regime would probably result in a faster flushing rate as the surface water was displaced from the arm by the intrusion of higher salinity oceanic water along the bottom. Persistent bands of chlorophyll between Schnapper Point and Mills Bay were consistent with an upwelling region in that area of the Kenepuru arm.

At Mills Bay, Four Fathom Bay, and Hallam Cove (Fig. 3A, 3B, 3C) separation of surface and bottom water was also found but to a lesser degree. Mean velocities were generally lower than at Schnapper Point, ranging from 7.5 cm s^{-1} to 10.5 cm s^{-1} and peaking at 20–25 cm s^{-1}. At each of these stations, however, conditions were occasionally observed with virtually no movement of water at any depth and maximum velocities of c. 4 cm s^{-1} prevailing for only short periods during the 12-hour sampling.

The circulation pattern in Mills Bay was not consistent between visits (Fig. 3A) although it appeared to be an extension of the flows in the Kenepuru arm. This implies an exchange of water with the Kenepuru arm and probably a very rapid flushing of the bay over the tidal cycle. However, the periods of little water movement imply either a breakdown of that hydraulic coupling from time to time, isolating Mills Bay from the flows in the Kenepuru arm, or that the circulation pattern in the Kenepuru arm did not extend as far as Mills Bay on those occasions. The result was essentially stagnant water in Mills Bay.

At Four Fathom Bay the inferred circulation pattern was of opposing upper and lower water column flows which reversed between flood and ebb tide. The bottom water flowed into the bay on the flood tide consistent with the intrusion of the higher-salinity oceanic water moving inwards along the bottom of the main channel of Pelorus Sound. Consequently Four Fathom Bay was rapidly flushed over the tidal cycle. Under the prevailing westerly winds, a surface ($\approx$1 m) layer appeared to be held in Four Fathom Bay and moved in a clockwise direction independently of the water movements below.

At Hallam Cove the implied circulation pattern was a slow persistent clockwise movement of the upper water column with a sometimes opposing but much slower flow below 10 m. Although the surface water movement was consistent in direction, the velocity was variable with periods of near-stagnation. This regime results in very slow flushing rates and potentially long residence times within the bay.

Water movement at 10 m in Richmond Bay (Fig. 4) was found to have a consistent northerly component. However, the surface ($\approx$1 m) layer showed considerable separation in response to wind, even to flowing in the opposite direction (Fig. 4A). Mean velocities through the rest of the water column were 6–8 cm s^{-1}, peaking at 12–15 cm s^{-1}. Thus the implied flow pattern was of a persistent counter-clockwise circulation within Richmond Bay, involving the whole water column except for a wind-induced circulation of the surface water layer. This circulation pattern is consistent with the outwards moving surface water in the main channel flowing through Richmond Bay.

The pattern of current vectors and velocities measured at Crail Bay (Fig. 5) were similar to those at Richmond Bay but with a mean velocity at the ship of 8 cm s^{-1}. Peak velocities of 12–15 cm s^{-1} were frequently recorded whereas velocities below 4–5 cm s^{-1} were uncommon. Although separation of surface and 10 m water appeared to be minimal (Fig. 5A), occasionally reverse flows were measured below 20 m (Fig. 7A). This bottom flow is consistent with an intrusion into Crail Bay of higher-salinity oceanic water from the main channel about high tide.

Mussel farm influence

Current vector measurements taken from the ship by necessity were well away (c. 25 m) from the mussel farms. In situ recording current meters suspended within 2 m of the curtain of mussels of a mussel farm at Richmond Bay (Fig. 4B) gave the same consistent northerly vector as was recorded from the ship at 10 m (Fig. 4A). However, the magnitude of the current was much lower at the farm and appeared to be influenced by the farm structure. Beside the mussel ropes the mean velocity was 1.3 cm s^{-1} whereas at 11 m, well below the mussel farm, the mean velocity was 2.5 cm s^{-1}. Just below the mussel curtain, however, the mean velocity was 4 cm s^{-1} (Fig. 4B). The progressive current vector plots show a persistent flow to the north-west with few deviations or reverse flows in the 6-day period (Fig. 4B).

Inside the mussel farm in Crail Bay, at 3 m deep and 2 m from the mussel curtain, the mean velocity was also about 1.5 cm s^{-1} (Fig. 5B) and seldom exceeded 5 cm s^{-1}. The progressive current vector plots from the in situ current meters show a consistent long-term movement to the north-east. They also show that short periods of reverse flow occurred at irregular intervals (Fig. 5B). These flow patterns indicate a marked current attenuation to c. 30% of the flow entering the structure of a mussel farm with the rest of the flow being forced below the farm or around it.

Water column properties

A summary of the water column property data is presented in Table 2. Temperature, dissolved oxygen, and salinity profiles showed vertical gradients between top and bottom with the largest changes usually being measured between 7 and 10 m (Fig. 7). At all stations the water column remained well oxygenated although dissolved oxygen profiles showed a decrease in concentration with increasing depth. Conversely, salinity increased down the water column. Temperature profiles, however, frequently showed small increases towards the bottom in winter and decreases in summer. The annual temperature range was from 10.1 to 20.6°C and a strong seasonal pattern was found at all stations (Table 2). The highest temperatures occurred in Mills Bay in February and coincided with a period of minimal water movement in that bay.

There was no obvious difference between oxygen profiles measured between the mussel curtains and profiles measured in the open water of the bay, which is consistent with the continuous movement of water

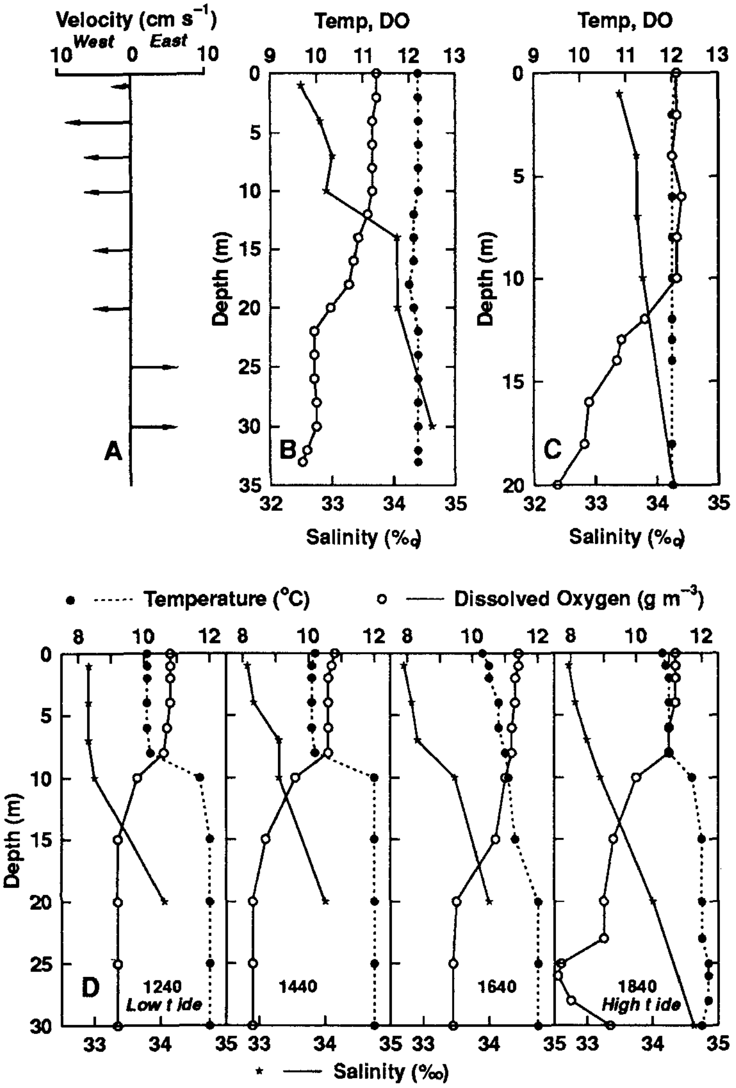


Fig. 7 A, Velocity-direction profile at Crail Bay (September) showing a reverse flow direction below 20 m about high tide.

Temperature (solid circle), dissolved oxygen (open circle), and salinity (star) profiles in September at B, Crail Bay, and C, Hallam Cove, show dissolved oxygen and salinity gradients with nearly isothermal conditions.

D, Sequential temperature, dissolved oxygen, and salinity profiles in Crail Bay in August between low and high tide show stronger gradients and a sudden discontinuity in the bottom water about high tide.

through the mussel farm. However, lower oxygen concentrations were occasionally measured close to the sediments beneath the mussel farm and the salmon farm which was also sited in Mills Bay during the study period. Profiles from both Crail Bay and Hallam Cove frequently showed a change in oxygen concentration whereas temperature profiles indicated near-isothermal conditions (Fig. 7B, 7C). However, profiles in August 1984 at Crail Bay showed consistent strong gradients for both temperature and oxygen (Fig. 7D). The marked discontinuity in the DO profile below 20 m about high tide and the change in temperature gradient before high tide (Fig. 7D) both indicate water column movements involving large water masses within the bay. The movement of water below 20 m is consistent with the intrusion of the oceanic water from the main channel along the bottom of the bay. Weak seasonal patterns of mean dissolved oxygen concentration appeared to follow an inverse relationship with mean temperature at all stations (Table 2); however, the DO maximum occurred almost 2 months after the minimum temperature.

Salinity data were limited to the surface 10 m except for isolated profiles in the outer sounds. The maximum gradient of the salinity profile always coincided with the change in oxygen concentration. The salinity gradient was generally small, being much less than 1‰ in Hallam Cove (Fig. 7C), Crail Bay, and Richmond Bay although stronger gradients were observed in Crail Bay in August (Fig. 7D). A salinity and temperature profile taken in the main channel near the entrance to Crail Bay subsequent to the 1984–85 study period showed colder, higher-salinity water below 40 m (Fig. 8).

In Four Fathom Bay, Schnapper Point, and Mills Bay, small salinity gradients were replaced with large gradients of up to 20‰ following rain. Freshwater input from the Pelorus River system was 5.8 m^3 s^{-1} at low flow and 54 m^3 s^{-1} at mean flow with an annual flood flow of 250 m^3 s^{-1} (Heath 1976b). Transect data also showed patches of lower-salinity surface water along the main channel after periods of moderate to heavy rain (Fig. 9).

After very heavy rain, flood water moved rapidly through the sound as a low-salinity surface layer initially c. 2 m thick but mixing downwards as it

Table 2 Annual physical variability at the top (t) and bottom (b) of the water column; – measurement not made.

		Apr 84	Jun 84	Aug 84	Sep 84	Dec 84	Feb 85	Apr 85
Mills Bay								
Temp.	t	17.4–18.0	11.1–11.5	10.8–10.9	11.7	17.5–18.8	19.0–20.6	15.9–16.6
(°C)	b	17.2–17.8	11.7–11.8	10.9–11.1	12.0	17.1	18.5–18.8	15.8–16.2
Oxygen	t	8.4–9.5	10.2–10.9	10.7–11.7	11.2	9.4–10.0	–	9.0–9.2
(g m^{-3})	b	7.6–8.9	8.6–9.6	9.9–10.5	10.4	8.0–8.2	–	8.4–8.7
Salinity	t	32.5–32.7	33.9–34.2	30.1–30.7	30.9–32.0	27.5–31.4	30.8–31.2	32.3–33.3
(‰)	b	32.5–32.8	33.6–34.4	30.4–30.6	32.0–33.4	28.1–32.0	31.5–31.9	33.5–33.6
Schnapper Point								
Temp.	t	17.2–17.7	11.5–12.2	11.0–11.6	11.4–11.8	15.8–18.5	18.8–19.6	16.2–16.8
(°C)	b	17.1–17.4	12.0–12.6	11.4–11.8	11.9–12.0	16.1–16.8	18.3–18.8	16.2–16.8
Oxygen	t	8.8–9.4	9.2–10.7	9.3–10.5	10.7–11.4	9.6–11.1	7.6–9.0	9.1–9.6
(g m^{-3})	b	7.6–8.4	8.6–9.7	7.5–8.8	9.2–9.8	8.4–8.7	6.4–7.2	8.7–9.8
Salinity	t	30.8–32.4	28.1–32.9	29.4–30.6	31.0–32.3	20.8–30.1	31.1–31.6	33.3–33.8
(‰)	b	32.3–33.1	32.0–33.1	30.4–32.6	32.9–33.9	24.2–32.6	31.2–32.6	33.5–33.9
Four Fathom Bay								
Temp.	t	16.7–17.3	12.2–12.7	10.5–11.2	12.3–13.1	17.0	18.0–18.3	15.5–16.6
(°C)	b	17.0	13.0–13.3	11.8–12.4	12.2–12.6	15.5	17.5–17.6	16.1–16.5
Oxygen	t	8.8–9.3	9.4–9.9	10.9–11.2	11.2–11.3	9.6	–	9.7
(g m^{-3})	b	8.0–8.6	8.7–8.9	9.4–10.2	10.8–11.2	8.5	–	9.8
Salinity	t	32.4–32.6	33.2–33.6	29.8–31.3	32.5–33.0	27.8–29.9	32.9–33.0	11.9–16.8
(‰)	b	32.9–33.8	33.5–34.0	31.9–33.3	32.8–34.1	30.8–33.6	33.0–33.9	33.2–34.3
Crail Bay								
Temp.	t	16.8–17.1	12.8–13.2	10.1–10.3	12.2	16.5	18.5–19.5	16.0
(°C)	b	16.4–16.8	13.3–13.4	12.0	12.2	15.9	16.5–16.6	16.7
Oxygen	t	9.4–10.2	9.7–9.9	10.8–11.4	11.3	9.5	–	9.5
(g m^{-3})	b	6.1–6.6	8.6–9.0	8.3–9.4	9.7–9.8	8.4	–	8.3
Salinity	t	33.7–33.9	34.0–34.2	32.1–32.5	32.3–32.9	32.8–33.2	33.1–33.3	31.9–33.4
(‰)	b	33.4–33.9	34.0–34.2	32.8–33.5	33.0–34.6	33.0–33.4	33.9–34.2	34.0–34.4
Hallam Cove								
Temp.	t	16.5–17.0	13.1–13.2	10.8–11.3	11.9–12.3	16.2	18.1–18.5	16.0
(°C)	b	16.4–17.0	13.2	11.6–11.8	12.0	15.5	16.6–16.9	16.0
Oxygen	t	8.1–9.0	9.5–9.9	11.0–11.5	12.1–12.2	9.5	–	9.9
(g m^{-3})	b	6.7–7.1	9.0–9.3	8.5–9.0	9.5–10.3	8.5	–	8.2
Salinity	t	34.1–34.4	34.2–34.3	33.0–33.1	33.5–33.7	33.3–34.4	33.7–33.9	33.3–33.6
(‰)	b	34.2–34.4	34.2–34.3	33.1	33.8–34.3	34.2–34.5	34.1–34.3	34.2–34.5
Richmond Bay								
Temp.	t	16.8	13.2	10.8–11.8	12.2–13.0	16.5	17.4–18.0	16.5
(°C)	b	16.8	13.1–13.2	12.0	12.0–12.5	15.8	16.5–16.9	16.1
Oxygen	t	9.3	9.6–9.9	10.0–10.8	10.8–11.6	9.8	–	9.6
(g m^{-3})	b	8.8	9.4–9.5	9.6–10.2	10.4–11.1	9.4	–	8.4
Salinity	t	34.1–34.4	33.9–34.6	33.7–34.3	33.9–34.3	33.2–34.2	33.9–34.3	34.3–34.6
(‰)	b	34.1–34.4	34.5–34.6	33.8–34.3	34.1–34.5	33.6–34.6	34.2–34.6	34.4–34.6

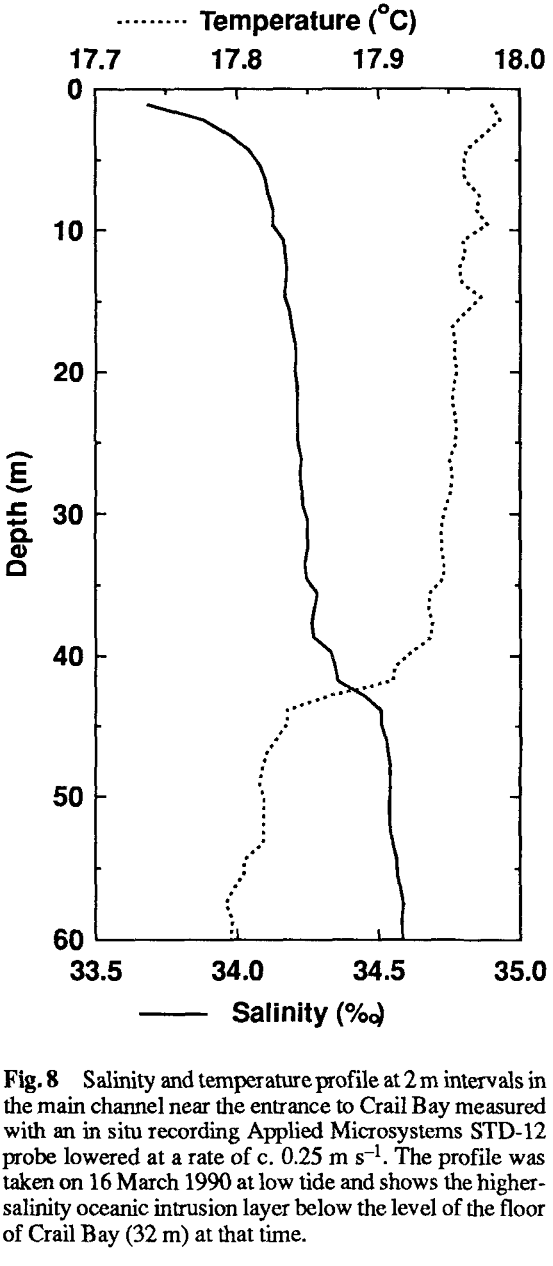


Fig. 8 Salinity and temperature profile at 2 m intervals in the main channel near the entrance to Crail Bay measured with an in situ recording Applied Microsystems STD-12 probe lowered at a rate of c. 0.25 m s^{-1}. The profile was taken on 16 March 1990 at low tide and shows the higher-salinity oceanic intrusion layer below the level of the floor of Crail Bay (32 m) at that time.

moved seawards. The low-salinity layer from the April 1985 flood event (Fig. 10) had not reached Hallam Cove at the time that bay was sampled, but was detected in Richmond Bay. The propagation time for the 50 km from Havelock to Richmond Bay was estimated to be 82 h giving a mean flow rate of 0.17 m s^{-1}.

Water movement indications

Although current meters gave a direct measurement of water movement, changes in the depth distribution of some chemical and biological variables over the 12 or 24 h sampling period on station gave indirect evidence of the way the water masses in the upper and lower layers moved in relation to each other within the embayments over the tidal cycle. These changes were much slower than, but superimposed on, the current flows and often indicated a displacement of one water mass with another or a change in water velocity.

In Mills Bay and Four Fathom Bay the suspended solids concentrations increased in the bottom waters on the ebb tide through sediment resuspension (Fig. 11). This erosion indicates faster-moving water on the ebb than flood tide. At Crail Bay, successive in vivo fluorescence profiles in September showed that the phytoplankton biomass peak on the pycnocline (Fig. 12) changed depth over the tidal cycle, moving closer to the surface at low tide. As all depths were measured from the surface downwards, this change in depth indicates that more water moved out of the upper than the lower water column on the ebb tide, reducing the thickness of the upper water layer. The same effect was seen with the nutrient concentration data at Hallam Cove in April 1985 (Fig. 13A). There, the boundary between the high-concentration bottom water layer and the low-concentration upper water layer moved up and down over the tidal cycle in the opposite direction to the tide and at more than twice the tidal amplitude. The movement of that boundary coincided with the 34.4‰ isohaline. This pattern of water movement was not consistent and in Crail Bay in August, changes in nutrient concentrations indicated that water moved into the upper water column on the ebb tide, increasing the thickness of the upper layer (Fig. 13B) on that occasion. Boundary oscillations were observed on most sampling occasions. At Hallam Cove in February, synchronous changes in nutrient concen-trations at all depths indicated that the whole water column was being moved in unison over the tidal cycle.

The existence of concentration gradients at both Crail Bay and Hallam Cove (Fig. 14) indicate that the whole water column was not mixed. However, uniform concentrations in the upper water column indicate that the surface layer was well mixed. Strong gradients in the bottom water column are consistent with poor mixing and slow water movement. At Richmond Bay uniform concentrations through the water column indicate that the whole water column

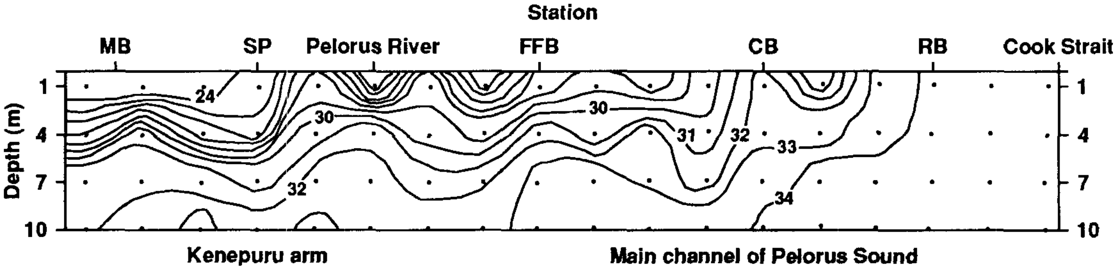


Fig. 9 Sequential transect data along the Kenepuru arm and main channel of Pelorus Sound (Fig. 1) to the sea for salinity (‰), 5 days after the April 1985 flood event. The approximate positions of the fixed sampling stations are marked by initials; "Pelorus River" indicates the position of the freshwater inflow from the Havelock arm.

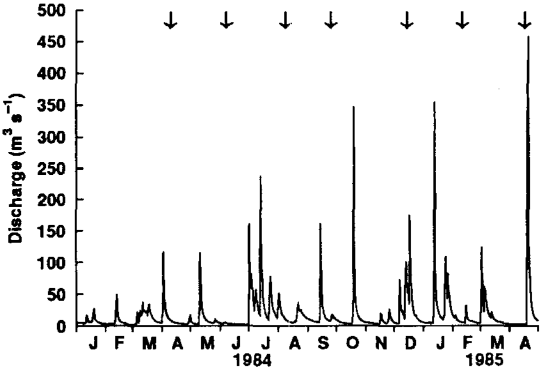


Fig. 10 Flow measurements at Bryants gauging station on the Pelorus River for the study period. Sampling occasions are indicated by arrows. Note that the discharge into the Havelock arm is c. 2.5 × greater than the flow at Bryants for low and medium flows (Shearer 1989).

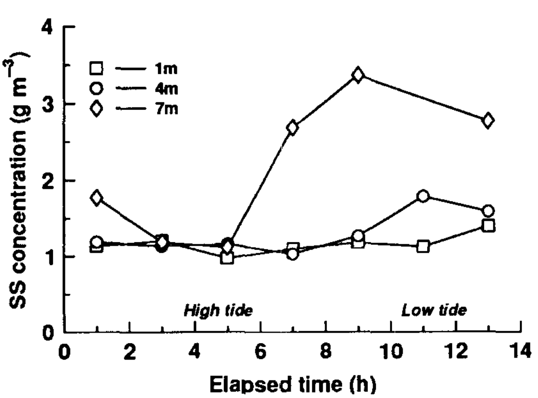


Fig. 11 Sequential suspended solids profiles in Mills Bay showing the increased concentrations in the bottom water associated with sediment erosion and resuspension on the ebb tide.

was well mixed (Fig. 15) whereas synchronous changes in concentration indicated that the whole water column moved in unison on almost every occasion. On most occasions the water movement was in phase with the tide (Fig. 15A) suggesting tidal flushing was rapid in the bay. However, water movements out of phase with the tidal cycle, as indicated by the chlorophyll *a* data (Fig. 15B), suggest that Richmond Bay may become partially isolated from the main channel from time to time; or these data (Fig. 15B) indicate a narrow band of suspensoids moving rapidly through the bay, suggesting very short residence times within Richmond Bay.

At Schnapper Point the separation of the upper and lower water column was seen in chemistry concentration profiles (Fig. 16) as a phase difference between 10 m data and data from the water column above. In this example the water at 10 m was c. 4 h ahead of the overlying water. The intrusion of the flood front into the Kenepuru arm in April 1985 was rapid and the changes in water column chemistry at that time (Fig. 17) indicate that the whole water column moved in unison; they also suggest that the whole water column was well mixed as the flood front moved past the sampling station.

DISCUSSION

The hydrological data presented here, coupled with the indications of water mass movement from the chemistry profiling data, suggest that the local water movements within the sidearms and embayments are primarily driven by the lunar tide and are essentially extensions of water movements found in the main channel of Pelorus Sound (Heath 1985) modified by the bathymetry, morphometry, and the hydraulic capacity of the bay. Of particular importance to most hydraulic regimes was the density stratification

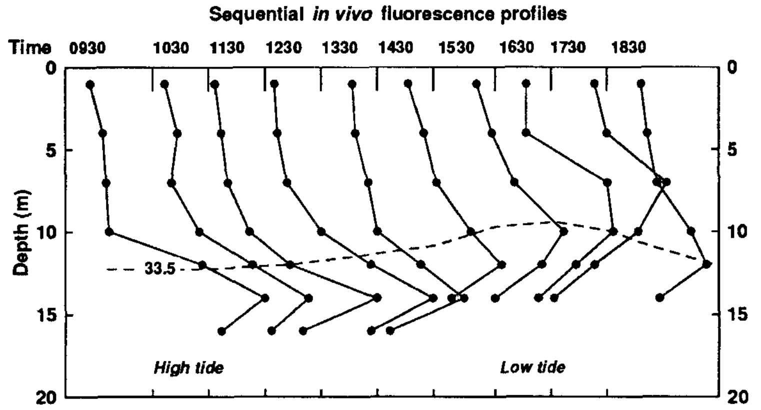


Fig. 12 Sequential in vivo fluorescence profiles obtained with a flow-through cell on a Turner Designs Field Fluorometer in Crail Bay in September showing the change in depth of the chlorophyll maxima towards low tide indicating water movement in the upper water column. Units are arbitrary fluorescence values relative to zero at the profile time on the x axis. Depths are measured relative to the surface. The 33.5‰ isohaline is indicated by a broken line.

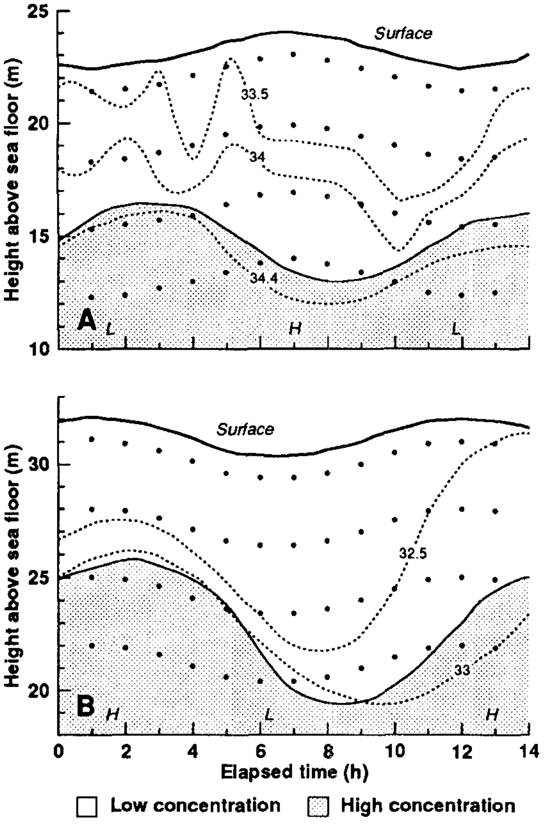


Fig. 13 Temporal movement of the boundary between high and low nutrient concentration water at **A**, Hallam Cove (April 1985), and **B**, Crail Bay (August 1984) showing the occurrence of internal waves. Water heights are referenced to the sea floor. Dots indicate the sampling position. Salinity (‰) isohalines are indicated by broken lines.

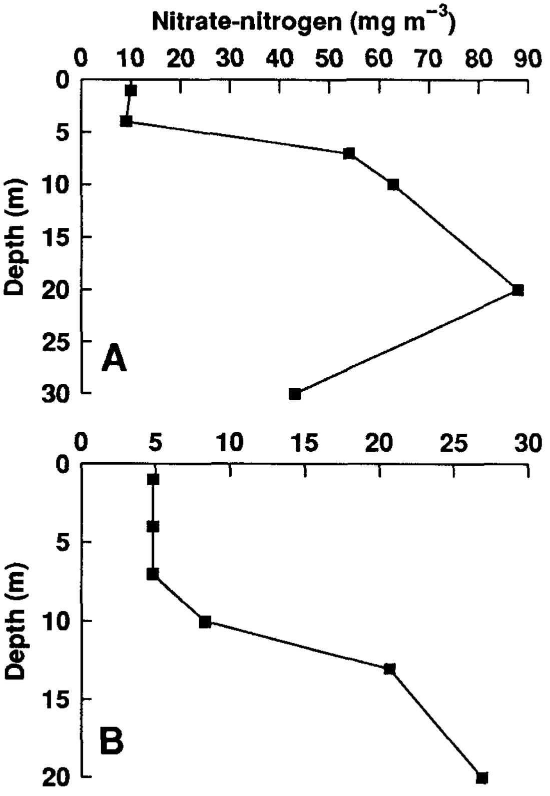


Fig. 14 Nitrate-nitrogen profiles in **A**, Crail Bay (August 1984), and **B**, Hallam Cove (December 1984), indicating the degree of mixing within the upper water column but lack of mixing in the lower water column.

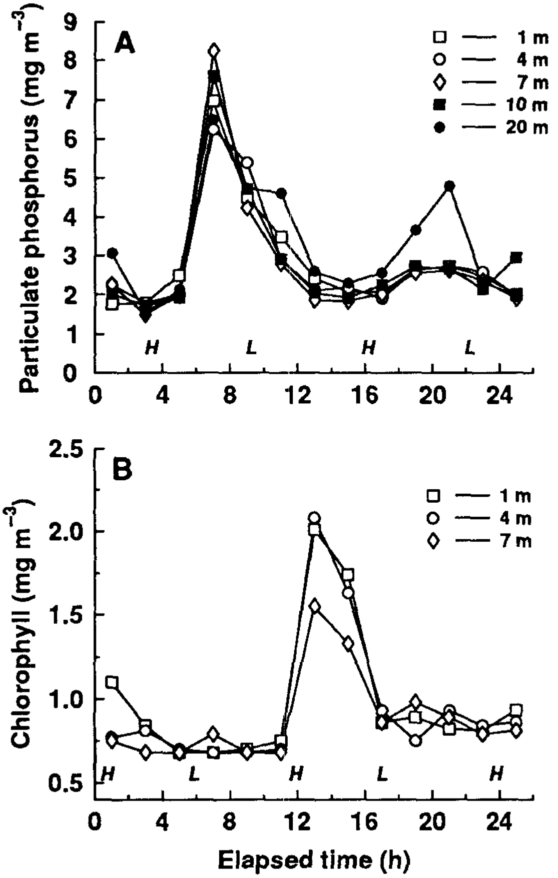


Fig. 15 Sequential chemistry profiles at Richmond Bay indicating a well-mixed water column, **A**, with changes in phase with the tidal cycle, and **B**, the movement of a parcel of higher concentration chlorophyll water through the bay indicating rapid flushing.

associated with the salinity gradient. This allowed the separation of the upper and lower water columns and their independent movement in both velocity and direction within the bay. A similar hydraulic regime was described in the main channel of the sound (Heath 1976a) where a phase difference of up to 4.5 h was found between upper and lower water column movement. This is consistent with observations in the Kenepuru arm where a phase difference of c. 4 h was found between upper and lower water column movement at Schnapper Point. Heath (1976a) assumed that the bottom water was leading the surface flow, which is consistent with the water movement pattern indicated by changes in the chemistry profiles with time (Fig. 16).

Velocity differences between upper and lower water columns were more pronounced in the inner than outer sounds embayments. The asymmetrical tide caused by the 1.25 h propagation delay for the lunar tide to reach the head of the sound (Heath 1976a) resulted in faster ebb than flood flows, with ebb flows reaching velocities sufficient to erode and resuspend sediments (Carter 1976). Observations in both Four Fathom Bay and Mills Bay found marked sediment resuspension only on the ebb tide, which is consistent with the above.

Separation of the upper and lower water columns altered the flushing of most embayments studied. Estuarine circulation in the main channel (Heath 1982) was reflected in the lower water column moving inwards, while the upper water column moved outwards—particularly in the inner sounds. This was most pronounced in Four Fathom Bay although there the tidal cycle allowed the flow direction in each layer to reverse on the ebb tide. The higher-salinity oceanic water layer was found at the bottom of the main channel near Crail Bay (Fig. 8), with the upper level at c. 40 m at low tide and the floor of Crail Bay at 32 m, but it is unlikely that the oceanic water would enter Crail Bay except at high tide. However, there are insufficient data to determine what depth the oceanic water reaches under different tides and degrees of stratification.

The slow counter-clockwise circulation pattern found in the Kenepuru arm may on occasion extend as far in as Mills Bay, allowing flushing of that bay. Without this, Mills Bay became essentially stagnant in summer resulting in water temperatures above 20°C, 1–2°C higher than at Schnapper Point (Table 2). The slow circulation pattern in the Kenepuru arm was also consistent with Heath's (1982) assumption that the Kenepuru arm behaved like a damping chamber, holding a large reservoir of high-salinity water with which the low-salinity water from the Havelock arm must mix on the outgoing tide. The replacement for that high-salinity water was derived from the intrusion of high-salinity oceanic water along the bottom of the sound. This flow pattern was the opposite to that suggested by Bradford et al. (1987).

During a flood event, low-salinity water was forced into the Kenepuru arm and retained until after the flood had passed. The intrusion of higher-salinity bottom water then displaced part of the lower-salinity surface water out of the Kenepuru arm into the main channel on each subsequent ebb tide. This resulted in the pattern of low-salinity patches found on the transects in the main channel on some occasions (Fig. 9).

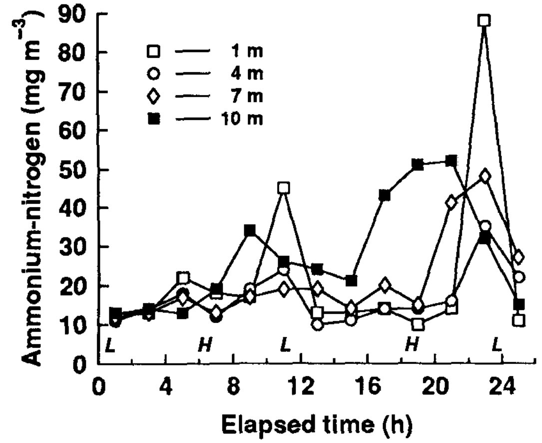


Fig. 16 Sequential chemistry profiles at Schnapper Point showing an apparent phase difference between water at 10 m and overlying water with the water at 10 m leading by c. 4 h.

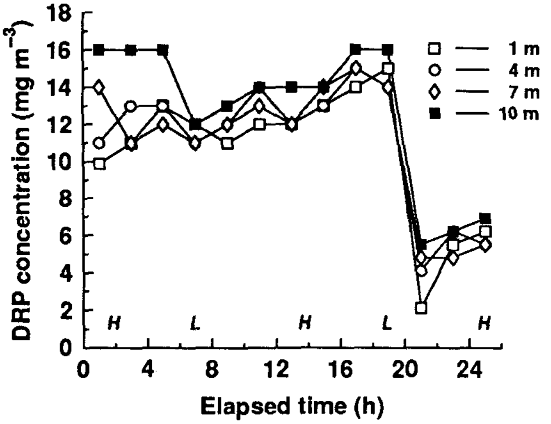


Fig. 17 Sequential phosphorus profiles at Schnapper Point showing a sudden and uniform change through the depth of the water column as flood water moved into the Kenepuru arm in April 1985. Salinity began decreasing at all depths from the 20 h sampling.

Water movement and circulation patterns in Crail Bay and Hallam Cove suggest a potentially three-layered system in those embayments. While the upper water column was continuously moving around the bay and apparently exchanging with other water masses over the tidal cycle, as indicated by the current vector data (Fig. 3C and 5B), the water column below the pycnocline was often almost stagnant, as indicated by the accumulation of nutrients and the strong nutrient gradients associated with poor mixing (Fig. 14). The third layer in these embayments was formed when the oceanic intrusion layer (Fig. 8) reached the level of the floor of those embayments and flowed into the bays near high tide. Periodic intrusions of short duration did not disturb the overall structure of the water column and were seen only as a bottom water discontinuity in one or more variables when profiling. The marked DO decrease below 25 m coupled with a slight temperature increase in Crail Bay in August (Fig. 7D) is an example of the bottom water intrusion, as is the decrease in nitrate-nitrogen concentration below 25 m (Fig. 14A). The extent of the intrusion appeared to vary from minimal intrusions which had the above effects, to massive intrusions which flushed out or mixed the entire water column between visits.

The apparent oscillation of the boundary between the upper and lower layers in both Hallam Cove and Crail Bay (Fig. 13) is consistent with the occurrence of an internal wave on the pycnocline as described by Heath (1976a) in the main channel. However, the shift in timing of these oscillations relative to the stage of the tide, between sampling occasions, indicates that they might be caused by seiching as was found in the Kenepuru arm where the half-wavelength period was calculated to be 5 h (Heath 1982). The amplitude of the internal wave at 4–6 m is much greater than either the mean tidal amplitude at 1.85 m or the amplitude of the seiche in the Kenepuru arm at 2.75 m (Heath 1982). While the boundary between high- and low-concentration water coincided with an isohaline, other salinity changes showed greater vertical movement within the water column than was indicated by the changes in nutrient concentration (Fig. 13).

Estimation of the theoretical mean residence times of most embayments in Pelorus Sound is difficult because of the changing hydraulic regimes within the embayments and the main channel. As a conceptual model, the theoretical mean residence time might be estimated as the ratio of the volume of the embayment to the volume of the tidal compartment in that bay (Table 1). Applied to the whole sound, the volume to tidal compartment ratio is 21.4 tidal cycles; the residence time estimated by Heath (1976b) is c. 20 d, suggesting a flushing efficiency of c. 50%. Allowing for this level of flushing efficiency produces a theoretical residence time of c. 6 d for the Kenepuru arm. A similar calculation for Mills Bay gives a value of c. 3.6 d which is unrealistic because Mills Bay is also flushed by part of the volume of the tidal compartment of the Kenepuru arm beyond the entrance to Mills Bay. If all of that water flowed through Mills Bay, the residence time would be c. 0.2 d. A more likely value would be somewhere between these extremes and would be variable as water movement in Mills Bay has been shown to almost stop for more than 12 h from time to time.

Applying this conceptual model to embayments like Four Fathom Bay and Richmond Bay gives theoretical residence times in the range of 0.1–4 and 0.2–13 d, respectively. In both of those embayments water movements indicate large amounts of through-flow water, suggesting that residence times are likely to be at the lower end of the range.

In contrast both Hallam Cove and Crail Bay form the ends of sidearms and probably receive little or no through-flow water. Hence, their estimated residence times of c. 11 and 8 d, respectively, are probably realistic in terms of the whole bay. However, stratification and water column separation has shown that the lower water column moves slower than the upper water column and consequently different residence times will apply to each part of that water column. A further complication for estimating theoretical mean residence times is the flood event which sees the rapid passage of fresh water through the sound. The mean flow of 0.17 m s^{-1} implies a much faster flow near the freshwater source and Carter (1976) found surface flows of 0.9 m s^{-1} near the head of the sound during flood conditions. The changing salinity gradients accompanying different river inflows will almost certainly modify the movement of water throughout the sound. Hence the hydraulic regime in each embayment will be continually changing in response to the varying freshwater inflows, especially during flood conditions.

The location of mussel farms in the sidearms and embayments appeared to have little effect on the overall water movement beyond the immediate area of the farm. The major effect of the farm structure was a 70% reduction of the water velocity through the farm with a serious implication for the mass transport of food to the mussels in the farm. Feeding studies (Waite 1989) indicated that mussels filter at different rates with different food concentrations to obtain their daily food ration. They reach a minimum filtering rate when the food concentration is high but only remove up to 60% of the food passing through a farm. Consequently anything reducing the food supply reduces the efficiency of mussel feeding within the farm. There will be a relationship between mass transport, the food requirements of the mussels in a farm, and the food production within the sounds which will determine the suitability of an area for mussel farming and, ultimately, how many mussel farms the area can sustain.

The effect of extended residence times is to allow the same water to pass through a farm more than once and implies there is a potential for food production within the embayment. Conversely, short flushing times imply an externally produced source of food which may be removed from the area before it reaches the mussels.

The design of mussel farms would need to be modified to improve the mass transport of food to the mussels. This includes positioning the mussels deeper in the water column to take advantage of the vertical water movement associated with the internal waves in some embayments.

CONCLUSION

Water movement in Pelorus Sound is dominated by a complex hydrodynamic regime which is being continuously modified by the effects of the lunar tide and estuarine circulation in the main channel, and the varying freshwater inflows. This results in variable residence times and flushing rates of embayments depending on their location, bathymetry, morphometry, hydraulic capacity, and the amount of freshwater inflow to the sound. The larger sidearms have the most consistent water circulation patterns while flow patterns in embayments off the main channel are very variable, changing from day to day and even over the tidal cycle. Although mussel farms have little effect on water movements beyond their immediate area, the circulation patterns, residence times, and flushing rate all affect the mass transport of food to the mussels in the farms.

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