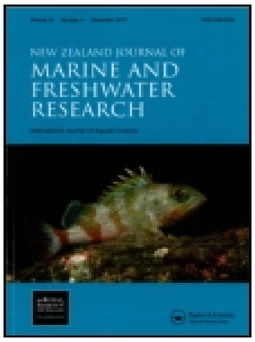

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# Hydrology of Okarito Lagoon and the inferred effects of selective logging in Okarito Forest

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Okarito Lagoon (43° 11′S, 170° 14′E) is a small (20 km$^2$) shore-parallel, predominantly subtidal estuary, deepest near the landward end, and linked to the sea by two subtidal channels incised through shallow subtidal and intertidal flats which occupy the southern third of the lagoon. Tides at sea vary from 2.1 m (spring) to 1.2 m (neap), but in the lagoon the tidal range is constant through the lunar cycle and varies from 0.80 m at the entrance to 0.17 m in the upper lagoon. Tidal water level and flow asymmetries in the subtidal channels are separated by a 1.7 h phase difference. Variations in the net discharge through the inlet result from changing flow cross-sections rather than from variations in current velocities. Both the tidal-averaged volume and the tidal compartment of the lagoon vary through the lunar cycle, from maxima at spring tides to minima at neap tides.

Freshwater inflows vary from less than 11 m$^3$.s$^{-1}$ to more than 750 m$^3$.s$^{-1}$. During storms, water level in the lagoon rises rapidly by 2–3 m, then declines to normal over several days. Three water masses, two with salinity and turbidity largely controlled by antecedent rainfall, normally occur in the lagoon. Suspended sediment concentrations in both freshwater inflows and lagoon waters are normally low but increase during floods. Most sediment is supplied by the Waitangi-taona River or by erosion of tidal channel margins. The lagoon is floored with organic-rich mud and sandy mud, deposited predominantly from suspension. Surface sediment is consistently muddier than subsurface sediment, probably reflecting an increase in the mud supply since diversion of the Waitangi-taona River in 1967.

Comparisons of the estimated sediment yield and water inflow effects of the 1967 river diversion with short-term observations during selective logging suggest that the effects of logging on sediment yield, water balance of the lagoon, and dissolved solids inputs will be small compared with changes caused by diversion of the Waitangi-taona River.

**Keywords:** Okarito Lagoon; bathymetry; tidal currents; sediment distribution; (freshwater inputs); (podocarp forests); (selective logging); (river diversion).

## INTRODUCTION

Much recent attention has been focused on Okarito Lagoon and the surrounding region, largely as a result of highly publicised conflicts between conservation interests who seek to preserve stands of podocarp terrace forests, and forest industry interests, who seek to manage parts of these forests as a productive resource.

Okarito Lagoon (43° 11′S, 170° 14′E) is one of the largest estuarine inlets on the west coast of the South Island, New Zealand (Fig. 1). This paper outlines the bathymetry of the lagoon, water salinity, turbidity, and temperature data, tidal current velocities, and tidal level and volume variations. Freshwater inflow data and surface and subsurface sediment characteristics are also reported. These data, together with interpretation of aerial photographs, are used to infer relationships between physical processes and sedimentation and to assess the likely physical impacts on Okarito Lagoon of the natural diversion of the Waitangi-taona River in 1967. In conjunction with other short-term studies of the effects of selective logging in Okarito Forest, this work attempts to assess the relative impact of selective logging and the Waitangi-taona River diversion on Okarito Lagoon.

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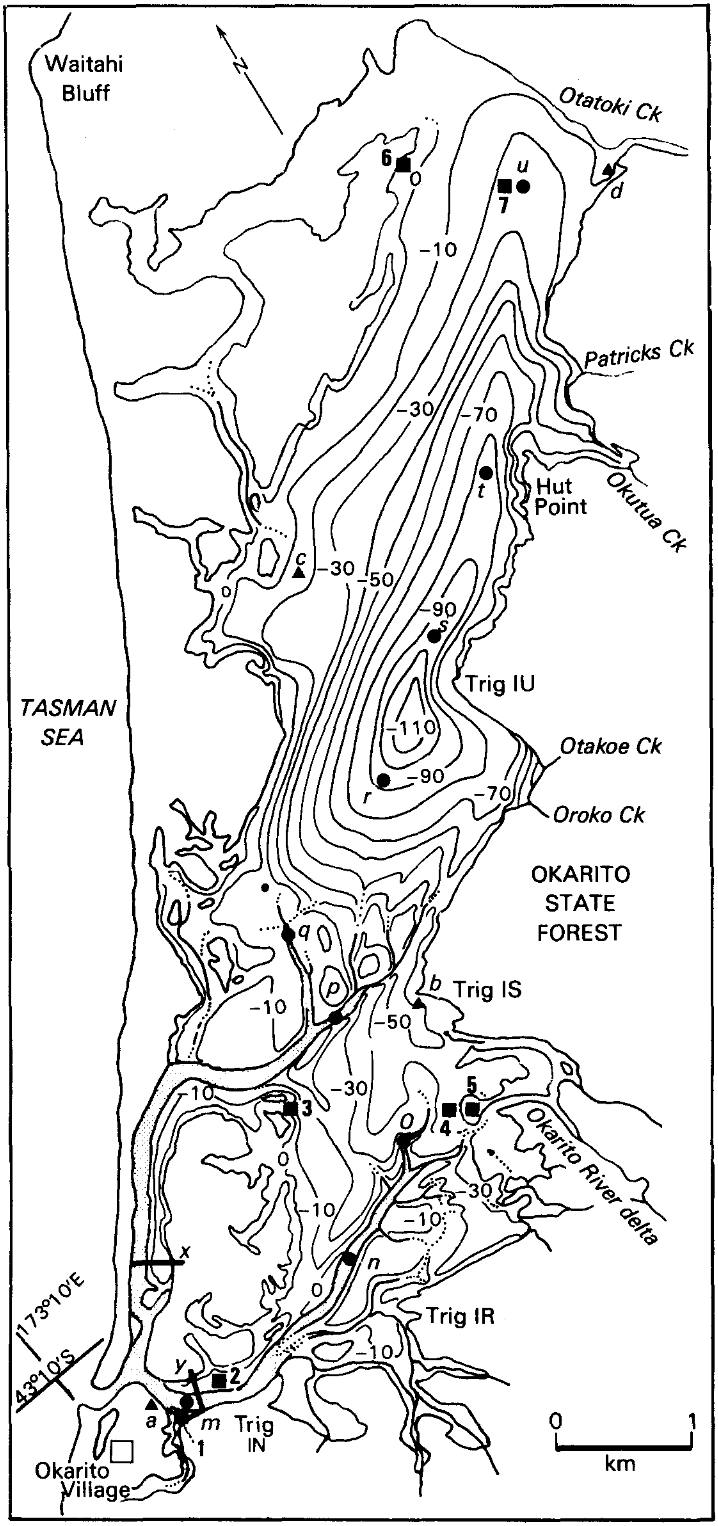

Fig. 1 Bathymetry and location details of Okarito Lagoon (bathymetric contours in centimetres, relative to local datum (nominally M.S.L.); principal subtidal channels shaded; *m–u*, tide gauge sites; *a–d*, water sample stations; location of Sections *x* and *y* (Fig. 2) and Cores 1–7 (Fig. 11) shown).

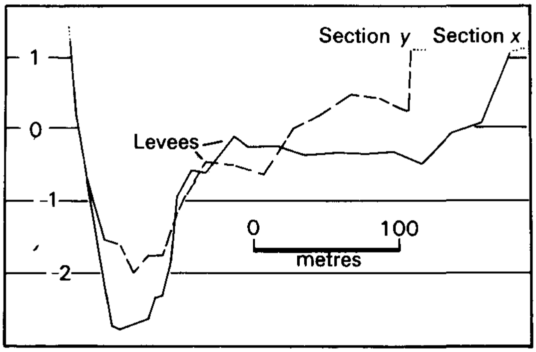

**Fig. 2** Representative bathymorphic sections across the seaward ends of the 2 principal subtidal channels of Okarito Lagoon (vertical scale in metres relative to local datum).

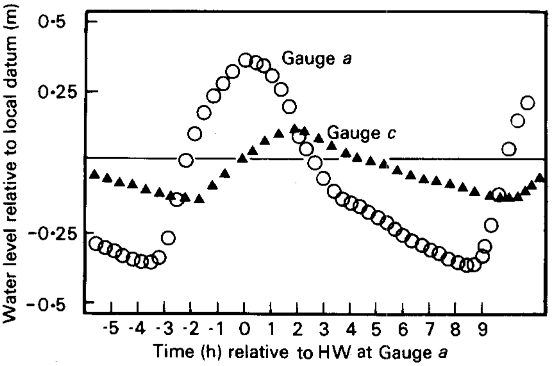

**Fig. 3** Simultaneous tide curves from gauges at Sites *a* & *c*, Okarito Lagoon (data points are 20 min (*a*) or 30 min (*c*) apart; recorded 8 Mar 1978; zero time about 1050 h).

## BATHYMETRY

### METHODS

Aerial photographs were used to map the outlines of the lagoon (Fig. 1). Water depths were measured by sounding from a small dinghy and referred to mean sea level (M.S.L.) (the local survey datum). Temporary survey stations were established at five locations in the lagoon: on a pile at the derelict Okarito Wharf (Site *a*, Fig. 1); in the subtidal channel below Trig IN; in shallow water off Trig IS (*b*, Fig. 1); in shallow water off Trig IU; and at Site *c* (Fig. 1). The stations were surveyed into Trig IN and their levels established. During sounding runs, tide gauges were set up adjacent to Site *a*, and adjacent to piles at Sites *b* or *c*. The resulting tide curves and stage measurements were used to correct measured depths to survey datum.

### RESULTS

The bathymetric map (Fig. 1) shows that Okarito Lagoon is a shallow, predominantly subtidal, estuary, 10 km long and from 1.1 to 2.7 km wide. The surface area at high water is 19.64 km$^2$, and the mean elevation of the floor of the lagoon is 0.33 m below M.S.L. The northern part of the lagoon is a 6 km long basin which deepens to the south and east. Mean water depth ranges from 10 to 110 cm. Shallow intertidal flats (10–50 cm mean depth) to the south of this upper basin are cut by two, steep-sided, 1–3 m deep subtidal channels (Fig. 2) bordered by low levees, which are up to 0.3 m above the adjacent flats and from 20 to 100 m wide. The two channels are deepest (2–3 m) near their junction just inside the lagoon entrance, and the short entrance channel then shallows to a subtidal gravel bar—analogous to a small ebb-tidal delta.

## TIDES

### TIDAL RANGES

The mean tidal range (at sea) at Okarito varies from 2.1 m (spring) to 1.2 m (neap). Tidal curves from gauges set up at sites within the lagoon showed that at Site *a* the tidal range was consistently about 0.8 m. Towards the heads of the two channels the range decreased to 0.6 m. At the other sites (*b*, *c*, and *d*), all effectively within the upper basin, the tidal range was consistently between 0.16 and 0.18 m. At mean high water, then, water depths in the upper basin range from 20 to 120 cm. On the only occasion that gauges were installed and running simultaneously at Sites *c* and *d* in the upper basin the range was the same at both sites (0.175 ± 0.005 m), although there was a mean delay of 66 min between high water at *c* and at *d*, and a mean delay of 40 min between low water at *c* and at *d* (means of 11 tides). Site *c* was not included in the survey network, and so differences in mean water levels between the two sites could not be estimated.

### TIDAL ASYMMETRIES

Fig. 3 shows that there are pronounced tidal asymmetries in the channels and in the upper basin of the lagoon. Immediately after low water the water level rises rapidly at Okarito Wharf, reaching high water 4.0–4.5 h later. The water level then falls for 8.5–9.0 h — rapidly at first, but at a slower, nearly constant rate for the final 4–5 h. In the upper basin (at Site *c* for example) high water occurs about 1.8 h later than at the wharf, and the water level rises for 3.7 h and falls for 8.8 h, both at fairly uniform rates.

In the two principal subtidal channels, tidal currents change direction at high water and at low water some time after levels have begun to fall from

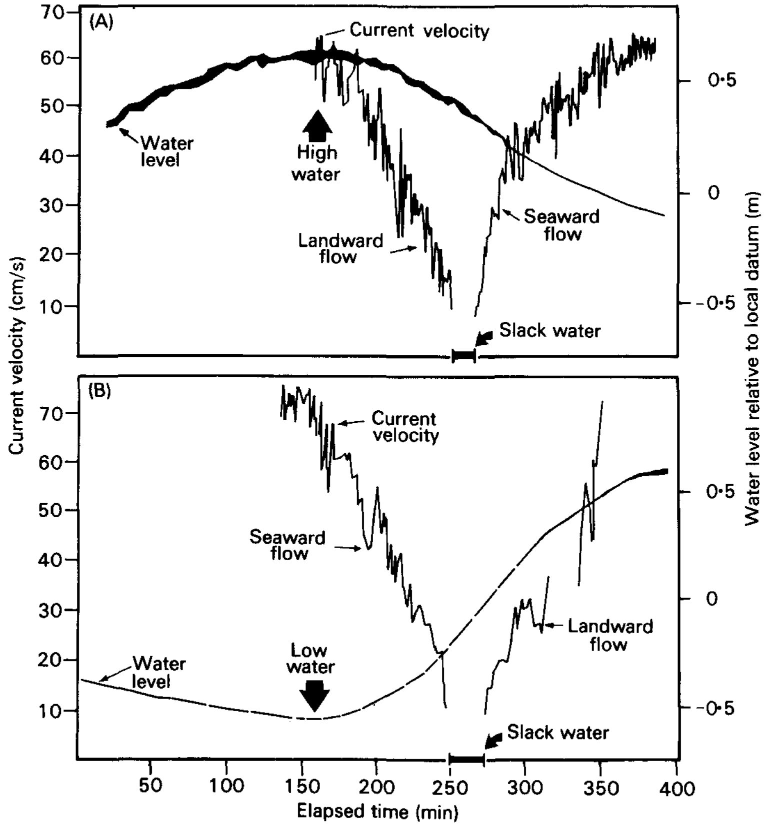

**Fig. 4** Simultaneous time-series records of water levels and current velocities at Okarito Wharf. (**A**), high water at 1123 h, 7 May 1978; (**B**), low water at 0835 h, 9 May 1978. (Water level data from a Belfort FW 1 water-level recorder running on 24-h rotation; thick trace near high water due to waves surging through lagoon entrance. Current velocities recorded with Ott model C1/10.152 current meter in centre of subtidal channel off wharf at 0.6 of water depth. Current velocities are 30 s means, spaced from 30 s to 2 min apart; time bases are from arbitrary points).

high water, or rise from low water. For example, at the wharf maximum current velocities (of 0.72 $m.s^{-1}$) occur shortly before low water on the ebbing tide, and the current continues to ebb, but at decreasing velocities, as the water level rises from low water. Slack water occurs about 100 min after low water and lasts for 10–15 min, by which time the water level has risen 0.40–0.45 m (Fig. 4). Water then begins to flow into the lagoon as the level continues to rise towards high water. The inflowing water reaches peak velocities (0.65 $m.s^{-1}$) shortly before high water, and then velocities decrease as the level falls from high water. Water continues to flow into the lagoon until about 110 min after high water, slack water lasts 4 or 5 min, and then water begins to flow out, by which time the level has fallen 0.30 m.

The asymmetries outlined above are due largely to the shallow gravel bar which partly obstructs the lagoon entrance. This bar appears to act as a broad-crested weir, effectively isolating the lagoon from the sea for a period of several hours around low tide (Fig. 5).

At mean high water the flow cross-sectional area of the two subtidal channels is 420 $m^2$ (calculated from data summarised in Figs 2–4). A velocity of 0.70 $m.s^{-1}$ (Fig. 4) is considered a reasonable estimate of the high water mean inflow velocity, since width : depth ratios are large (of the order of 1 : 100, Fig. 3) in the subtidal channels. At mean high water, marine water flows into the lagoon at a rate of about 294 $m^3.s^{-1}$. Similarly, a mean low water cross-sectional area of 179 $m^2$ and an assumed mean outflow velocity of 0.60 $m.s^{-1}$ produces an outflow of about 107 $m^3.s^{-1}$. Thus in broad tidal-averaged terms, water flowed into this lagoon at about twice the rate that it flowed out when these data were collected, and water flowed in for about half as long as it flowed out.

### TIDAL VOLUMES

A comparison of predicted tides at Westport (from the N.Z. Nautical Almanac 1978) and recorded tides at Okarito Wharf shows that, during spring tides, mid-tide levels at the wharf are high and, as neap tides approach, mid-tide levels at the wharf decrease. Tidal range, however, remains almost the same (Fig. 6). This effect is probably also due to the influence of the entrance bar; as high water levels increase at sea, the flow cross-section at high water in the entrance channels also increases, but the low water cross-

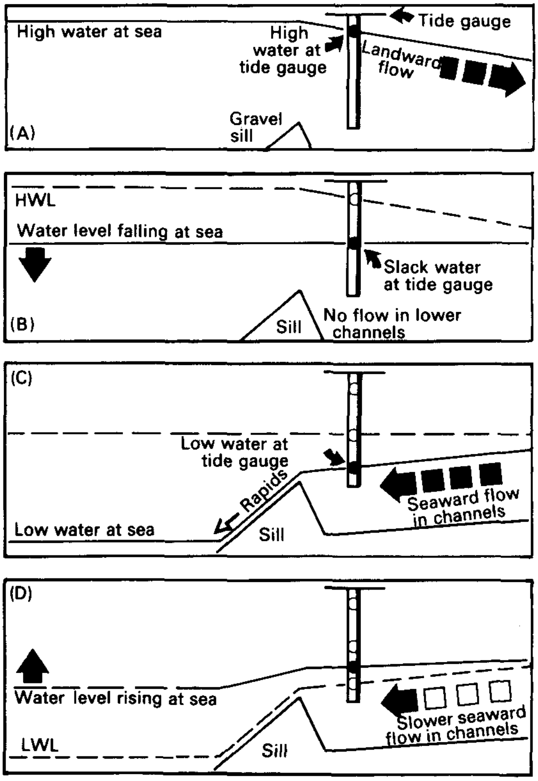

**Fig. 5** Diagrammatic explanation of tidal water level and flow asymmetries in subtidal channels of Okarito Lagoon. (**A**), high water at sea; (**B**), 100 min after high water at sea, slack water at tide gauge (which represents Okarito Wharf, Gauge *a*); (**C**), low water at sea; (**D**), 80 min after low water at sea, approaching slack water at tide gauge.

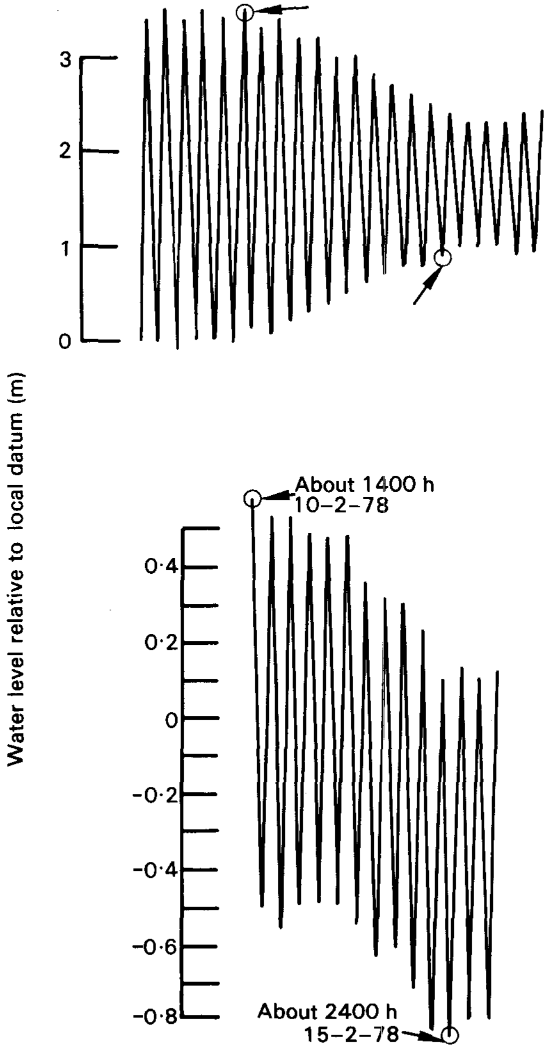

**Fig. 6** Predicted heights of high water and low water at Westport (*upper series*), and recorded heights of the same tides at Okarito Wharf (*lower series*), early February 1978.

section remains the same. Thus, duing spring tides there is a net landward flow of water and tidal-averaged water levels rise.

As tidal-averaged water levels rise at Okarito Wharf, levels also rise in the upper basin, and again the tidal range remains almost the same. Thus, during spring tides the tidal-averaged volume of water in the lagoon reaches a maximum, and minimum volumes occur during neap tides (Fig. 7). In the example in Fig. 7c, the maximum tidal-averaged volume of water in the lagoon during spring tides was 10.44 × $10^6$ $m^3$ (mean depth 53 cm), and during neaps the minimum tidal-averaged volume was 5.39 × $10^6$ $m^3$ (mean depth 27 cm). The mean tidal-averaged volume of the lagoon is about 7.91 × $10^6$ $m^3$ (mean depth 40 cm).

During spring tides, tidal-averaged water levels reach +0.13 m at Okarito Wharf and +0.163 m in the upper basin of the lagoon. The spring tidal compartment (the amount of water in the lagoon at high water minus the amount that remains at low water) is 3.002 × $10^6$ $m^3$. During neap tides, tidal-averaged water levels decrease to -0.30 m at the wharf, and to -0.126 m in the upper basin. The neap tidal compartment is 2.386 × $10^6$ $m^3$. During spring tides very little of the lagoon is intertidal, and only areas which are above the zero contour (Fig. 1) are exposed at low water. During neap tides all areas above -0.15 m to -0.20 m are exposed at low water.

During spring tides, the channel levees are covered with 0.5–0.6 m of water at high water, and are only briefly exposed at low water. During neap tides the levees are barely covered at high water. At low water, water level in the lower subtidal channels may be as

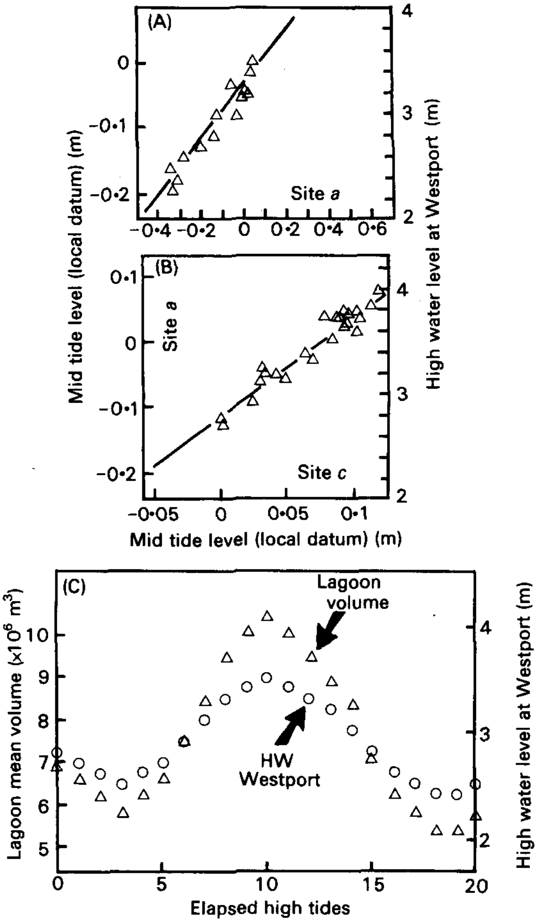

**Fig. 7** Relationships between water levels at sea, at Okarito Wharf, and in the upper basin of Okarito Lagoon. (**A**), scatter plot of mid-tide levels at Okarito Wharf against predicted levels of same high tides at Westport, for 10–17 Feb 1978; coefficient of determination for the linear regression 0.94; (**B**), scatter plot of mid-tide levels at Okarito Wharf against mid-tide levels — for same tides — at Site *c* (upper basin) for 3–9 May 1978; coefficient of determination for the linear regression 0.80; (**C**), synthetic example of relationship between high water at Westport and tidal mean volume of water in Okarito Lagoon, from (**A**) and (**B**) above, based on spring tides of early July 1978.

much as 1 m below the adjacent levee crests, and water from the surrounding shallow flats drains via numerous small tributaries and waterfalls into the channels.

In late July 1978, when the lagoon entrance had migrated several tens of metres to the south, the tidal range at Site *a* was 0.49 m (compared to 0.80 m earlier in 1978). At Site *c* in the upper basin the tidal range was 0.198 m (average of seven ranges), compared to 0.17–0.18 m earlier. These observations suggest that the tidal range in the upper basin is almost independent of the tidal range in the subtidal channels (over the ranges involved), and that the levees which separate the upper basin from the subtidal channels act as broad-crested weirs, isolating the upper basin from low water levels in the subtidal channels. The tidal range in the upper basin is influenced largely by the heights of high water levels in the subtidal channels. The reduced tidal range in the subtidal channels in July 1978 appears to be related to increased height of the gravel bar at the lagoon entrance, which maintains greater low water levels in the lagoon without affecting high water levels.

## FRESHWATER INFLOWS

Three distinct catchment areas supply fresh water to Okarito Lagoon. The Okarito Forest area (9700 ha) is undulating and low-lying, and is underlain by compacted, impermeable till and outwash (Okarito Formation, Warren (1967)). Five small streams with apparently stable gravel-bed channels drain this area. Channel sizes suggest maximum flood flows are about 3–4 $m^3.s^{-1}$. The Mapourika catchment area (9000 ha) mainly drains lower slopes of the Southern Alps into Lake Mapourika, and thence into the Okarito River. The Waitangi-taona catchment area (8300 ha) extends well towards the main divide of the Southern Alps and is predominantly steep and mountainous, rising to almost 2000 m at Mt Downe. Before 1967 this river flowed north of Okarito Forest and entered the sea near the mouth of the Whataroa River. In 1967 the river breached stopbanks near the State highway bridge, and diverted permanently into Lake Wahapo. The Lake Wahapo outflow is joined by Zalas Creek, and then joins the Okarito River at The Forks, 1 km below the lake. Addition of the Waitangi-taona River to the Okarito River system increased the catchment area of Okarito Lagoon by 44%.

Low-flow inputs of fresh water to Okarito Lagoon were estimated for two periods. In February 1978, after an unusually long period of fine weather (about 3.5 weeks), flow in Okarito River about 1 km below The Forks was 10.6 $m^3.s^{-1}$. Okarito Forest streams were either dry or too low to measure thus about 11 $m^3.s^{-1}$ of fresh water enters the lagoon during dry spells. On 5–6 May 1978, after a period of average rainfall, flow measurements at a number of stations (Table 1) indicated a total inflow of 15.665 $m^3.s^{-1}$. The flow rate of Waitangi-taona River at this time was about 70% of its mean discharge (8.5 $m^3.s^{-1}$, unpubl. M. W. D. report 1968). The mean tidal compartment of Okarito Lagoon is $2.694 \times 10^6$ $m^3$, and this volume is added to the lagoon in about 4.5 h as the tide flows in. During 4.5 h a freshwater inflow of 15.665 $m^3.s^{-1}$ adds $2.5 \times 10^5$ $m^3$ to the volume of the lagoon, or 9.3% of the mean tidal compartment.

**Table 1** Freshwater contributions to Okarito Lagoon, 5-6 May 1978 (all forest catchment area discharges measured with a small Ott current meter (model Cl/10.152) or a velocity head-rod).

| | Discharge ($m^3.s^{-1}$) |
|---|---|
| Mapourika and Waitangi-taona catchments | |
| Estimated discharge at Lake Wahapo weir (stage height at WL recorder about 0.9 m)* | 6.00 |
| Okarito River (near junction of State Highway 8 and road to Okarito) (Velocity head-rod measurement) | 9.00 |
| Zalas Creek (at State Highway 8 culvert) (Ott current meter measurement) | 0.151 |
| Forest catchment areas | |
| Oroko Creek | 0.209 |
| Otakoe Creek | 0.018 |
| Okutua Creek | 0.186 |
| Patricks Creek | 0.025 |
| Otatoki Creek | 0.076 |
| **Total** | **15.665** |

*Unpubl. data of M. Duncan (M.W.D., Christchurch) (pers. comm.)

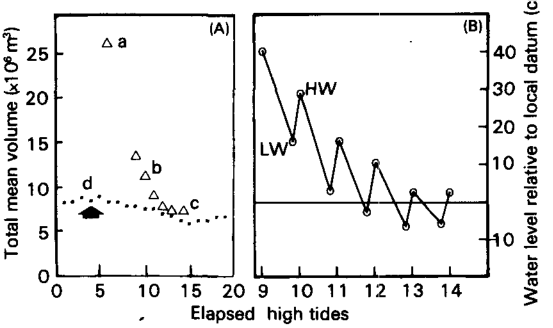

**Fig. 8** Response of Okarito Lagoon to flood of Easter 1978. (**A**), total volume of water in lagoon when water level peaked at 1.04 m above datum at about 0100 h, 28 March (a), and high water volumes 29 Mar - 1 Apr, beginning three high tides after peak volume was reached (b & c). Normal volumes (d above) predicted from Fig. 8. (**B**), heights of high water and low water at Site *c* in upper basin of lagoon for same period; arbitary time base runs from high water at Westport of 2257 h on 25 Mar 1978.

During the 12.5 h of a complete tidal cycle, an inflow of 15.665 $m^3.s^{-1}$ contributes 7.0 × $10^5$ $m^3$ of water to the lagoon, or 26.0% of the mean tidal compartment.

### FLOOD INFLOWS, EASTER 1978

Heavy rain fell in South Westland during Easter 1978, with heaviest falls occurring between 1900 h on 26 March and 0200 h on 27 March. The 24 h total for 26-27 March at Haast was 370 mm (N.Z. Meteorological Service 1978), and at The Forks the 48 h total was 97 mm. Widespread flooding occurred throughout South Westland, and the Waitangi-taona River peaked at about noon on 27 March (R. Meltzer, pers. comm.). Peak flow at the new Okarito Forest bridge at The Forks was estimated (from high-water marks on the bridge piles) to have a flow cross-section of 140 $m^2$, and the sectional mean velocity was probably about 2.5 $m.s^{-1}$, giving a peak discharge of 350 $m^3.s^{-1}$. It is reasonable to assume that the Mapourika catchment area contributed similar flows, and that the peak discharge from the two river catchments approached 700 $m^3.s^{-1}$ — about 50 times their mean discharge. If the peak discharge from the Okarito Forest catchment area increased by two orders of magnitude (to about 50 $m^3.s^{-1}$), then the total peak flow of fresh water into the lagoon may have reached 750 $m^3.s^{-1}$. Maintained for 5 h, this flow would have contributed 13.5 × $10^6$ $m^3$ of water — almost twice the mean volume of the lagoon.

Water level recorders were installed at Sites *a* and *c* (Fig. 1) in the lagoon on 29 March, 2 days after peak flood flows; the recorders ran for 3 days and were then removed. High-water marks around the edges of the lagoon and at the wharf indicated that maximum water levels, corresponding to a high tide at about midnight on 28 March, were 1.04 m above datum. At this stage the lagoon contained 26 × $10^6$ $m^3$ of water, about three times the normal tidal-averaged volume. The recorders were installed three high tides later, when the high water level was +0.40 m. Normal high water levels were not reached until seven high tides after the highest high water (Fig. 8), by which time river inflows had also returned to about normal volumes.

## SALINITY, TURBIDITY, AND TEMPERATURE OF LAGOON WATER AND INFLOWS

### METHODS

Water samples were collected from nine sites (*m-u*, Fig. 1) in the lagoon, and from sites in the Waitangi-taona and Mapourika catchment areas, on several dates in 1978. Water temperatures were recorded at the time of collection. Densities were measured in the laboratory by hydrometer and converted to salinities with standard tables (American Public Health Association 1975). Turbidities (filterable suspended solids concentrations) were measured by filtering 1 L of each sample through two pre-weighed GFC paper filters, which were dried at 80°C and reweighed.

Samples of lagoon waters were collected from the surface 10-15 cm of water. Except in the subtidal channels, the lagoon is sufficiently shallow (mean depth 40 cm) and sufficiently exposed to strong prevailing westerly winds that near-complete vertical mixing of the water profile can be assumed. The profile data of Knox *et al.* (1976), obtained when the entrance was closed and freshwater inflows had raised water levels to about 2 m above normal, show that, even under relatively unfavourable conditions for mixing, salinity gradients are slight. Except for one site, next to the closed entrance, their salinity gradients ranged from -0.5‰ per metre to 5.5‰ per metre with a mean of 2.8‰ per metre. If these gradients persisted under open-entrance conditions with much smaller water depths, a salinity difference of 1‰ between surface and bottom water would be expected at the mean depth of the lagoon. Knox *et al.* (1976) noted a thermocline at 1-2 m depth, with bottom waters 1-3°C warmer than surface water. At water depths typical of open-entrance conditions, temperature differences are likely to be much smaller than those observed by Knox *et al.* A difference of 0.5°C between surface and bottom water would be expected at mean lagoon depth, if the gradients found by Knox *et al.* persisted in open-entrance conditions.

## RESULTS

Three separate water masses are usually observed in the lagoon. Each water mass has distinctive combinations of salinity, turbidity, colour, and temperature. The boundaries between them are commonly sharply defined by lines of floating debris — foam, weed, leaves, and bird feathers.

1. The upper basin contains 10-110 cm of clear, amber water of low to moderate salinity (4-15‰). Except for its salinity, this water mass appears similar to the amber waters characteristic of many Westland lakes and streams. In summer this water body is warmer than the marine water in the subtidal channels; in winter the upper basin water is cooler (Table 2).
2. Clear, uncoloured, or slightly amber non-saline water enters the lagoon from the three mouths of the Okarito River. During incoming tides Okarito River water flows north-west across the deepest (50 cm) part of the southern flats of the lagoon, and around Trig IS Point as far up the eastern side of the upper basin as Oroko Creek. After high water, the mass of river water in the upper basin drains into the western channel and out to sea, whereas water entering the lagoon from the river mouths after high water drains across the southern flats, and into the head of the southern subtidal channel.
3. Cloudy, blue, marine water begins to flow up the subtidal channels of the lagoon about 15 min after flood-tide slack water. At high tide this saline water mass fills the channels (Fig. 9a, c), and may have flooded as far as 1 km up the western shore of the upper basin. By half-tide on the ebb, most blue water has either flowed back out to sea, or been mixed with turbid channel water (Fig. 9).

**Table 2** Surface water temperature in Okarito Lagoon, early and mid 1978

| Station | Surface water temperature (°C)<br>13 Feb | 4 May | 17 July |
|---|---|---|---|
| *m* | 20.0 | 15.0 | 12.0 |
| *n* | 20.0 | 14.8 | 10.5 |
| *o* | 20.0 | 14.6 | 9.3 |
| *p* | 20.0 | 13.0 | 9.0 |
| *q* | 21.5 | 14.8 | 7.8 |
| *r* | 21.0 | 13.0 | 8.1 |
| *s* | 21.4 | 13.0 | 8.0 |
| *t* | 21.5 | 13.0 | 7.3 |
| *u* | 22.2 | 12.5 | 7.6 |

During periods of low rainfall the mean salinity of the upper basin water is higher than during wetter periods. For example, on 13 February 1978, after zero rainfall in the preceding 25 days, the mean surface water salinity at Stns *r* to *u* (Fig. 1; mean depth of the four stations is 73 cm) was 15.35‰ (Fig. 9a). Similarly, on 19 July 1978, after a period of low to moderate rainfall (87 mm at The Forks during the preceding 10 days), the mean surface salinity at the same stations was 14.75‰.

Heavy rain and flooding reduce the salinity of upper basin water. On 4 May 1978, after 112 mm of rain at The Forks during the preceding 10 days, the mean salinity of water at Stns *r* to *u* was only 4.1‰ (Fig. 9c), and on 29 March, 2 days after the peak of the Easter flood (when 167 mm of rain fell at The Forks during the preceding 10 days), the mean salinity of the four stations was 6.3‰ (Fig. 9b). During floods the southern end of the lagoon fills with turbid river water, and sea water may penetrate only a short distance up the channels during incoming tides (as shown in Fig. 9b).

When low to moderate volumes of fresh water flow into the lagoon, the Okarito Forest streams and Okarito River contribute water of very low turbidity (less than 1 part per million (ppm) of suspended solids). During floods the turbidity of Okarito River water increases to between 40 and 50 ppm, but the turbidity of amber water in the upper basin does not increase above normal values (1-3 ppm), indicating that very little suspended sediment enters the lagoon from the Okarito Forest catchments. During floods the turbidity of water in the subtidal channels during ebb tides also increases, and on 29 March 1978, after the Easter flood, 110 ppm was recorded from a sample collected at Stn *m* (Fig. 2), whereas samples collected upstream gave values of 32 ppm (at *n*), 28 ppm (at *o*), 11 ppm (at *p*), and 12 ppm (at *q*). Stns *r* to *u* gave values of 1-2 ppm.

Turbid water in the Okarito River system during floods is contributed predominantly by the Waitangitaona River. On 29 March 1978, for example, 2 days after the Easter flood peak, water entering Lake

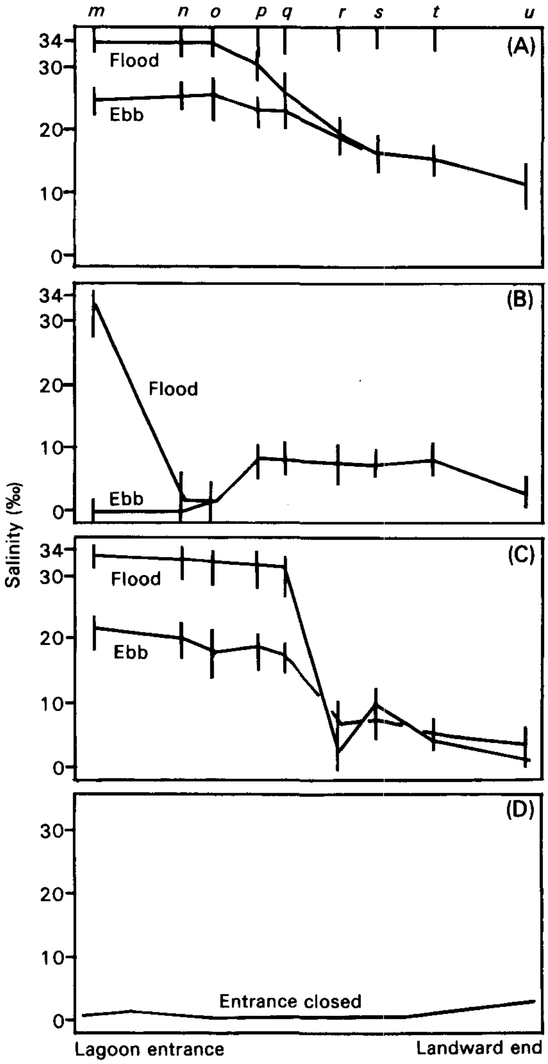

**Fig. 9** Longitudinal variations in the surface salinity of Okarito Lagoon. (**A**), surface salinity after a period of dry weather (sampled 13 Feb 1978); (**B**), 2 days after peak of Easter 1978 flood (29 Mar 1978); (**C**), after period of normal rainfall (sampled 5 May 1978); (**D**), surface salinity after entrance of lagoon had been closed for some time (sampled 3-6 May 1976; from Knox *et al.* (1976)). (Locations of Stns *m*-*u* shown in Fig. 1).

Wahapo from the Waitangi-taona had a turbidity of 46 ppm and water leaving the lake at the outlet weir had a turbidity of 44 ppm, whereas the Okarito River at The Forks turnoff from State Highway 6 had a turbidity of only 2 ppm. Sediment concentrations during peak flow were almost certainly greater than these values.

Water temperatures recorded at Stns *m* to *u* on 13 February, 4 May, and 17 July 1978 are shown in Table 2. In February (summer), sea water entering the lagoon was slightly cooler than water in the upper basin, where the mean temperature was 21.5 °C (mean of Stns *r*-*u*). In May (early winter) the incoming water was 5 °C cooler than in February, but warmer than water in the upper basin (where the mean temperature was 12.9 °C). By mid July (mid-winter, but a mild winter) the temperature of incoming sea water was 12 °C, and the mean upper basin temperature was 7.75 °C.

## SEDIMENTS

### METHODS

Surface sediment was sampled by scraping a 1-5 mm thick layer of sediment from an area of about 10 cm$^2$ at each sample site. Standard sedimentological procedures (Folk 1974) were used in the laboratory, except that a Woods Hole-type Rapid Sediment Analyser (RSA) (Pelagic Instruments Inc., Model 8010 at the Department of Geography, University of Canterbury) was used for routine size analyses of sand fractions of all samples which contained more than a small percentage of sand. Output from the instrument consists of a cumulative pressure/time curve, traced on to squared paper as sand grains settle past a transducer port, 1 m below the top of the tube. Sedimentation rates were converted to sedimentation diameters using the data of Gibbs *et al.* (1971), and replotted on cumulative probability paper. Percentiles required for the calculation of Folk and Ward graphic statistics (Folk & Ward 1957) were read from the resulting curves.

Size analyses of mud (material finer than 0.0625 mm) were not attempted, mainly because reliable measurements of the 'sizes' of particles in organic-rich mud are difficult to achieve. Fine particles are almost always aggregated into larger, composite particles in nature (Drake 1976), and on deposition individual aggregates will probably lose their identity; when sampled and subjected to normal laboratory procedures they certainly will (Kranck 1975).

Mud fractions of most samples were split into two subsamples. One was heated to 555 °C, and percentage losses were calculated. These data provide an indication of the organic content of the mud. The second subsample was made up to a 1 L suspension with distilled water, allowed to stand for 2 h, and 50 ml of the suspension was removed from a depth of 10 cm providing a sample of clay-sized particles (finer than 2 μm, +9 phi). The 50 ml subsamples were evaporated almost to dryness, spread on glass slides, and oven dried. Clay-sized mineral species were identified by X-ray diffraction methods at the Department of Geology, University of Canterbury.

### RESULTS

Graphic mean diameters of the coarse fractions (coarser than 0.0625 mm) of all samples, sediment muddiness (%), and weight losses on combustion are shown in Fig. 10. Sediment in the north and east of the upper basin is predominantly mud, with small amounts of fine and very fine sand. Muddiness generally increases and sand mean size generally decreases towards the deepest water (off Trig IU). The muddiest sediment contains the highest percentage of organic material, with the most organic-rich material also occurring in the deepest (1.1 m) part of the basin off Trig IU. On the southern flats, mean grain sizes tend to increase and muddiness tends to decrease towards the lagoon entrance, although there also appears to be a separate trend towards coarser, cleaner sediment in shallow water. Sediment on the southern flats contains less organic material than sediment in the upper basin.

Clean sand (with less than 5% mud) occurs only on the intertidal flats less than 800 m from the lagoon entrance and at the central and southern mouths of the Okarito River in the delta area. Gravel and gravelly sand occur seaward of Okarito Wharf in the southern subtidal channel, and extend 600 m up the northern channel. Parts of the Okarito River subaerial deltas are gravelly, and the river channels are armoured with coarse gravel and boulders. Bouldery bars run about 50 m off Trig IS, Trig IU, and Hut points, on the eastern shores of the lagoon.

The sediment pattern in the upper basin, with decreasing grain size and increasing muddiness in deeper water, suggests that wave energy in the shallower water winnows mud from the bottom sediment. Most of the muddy sediment recently deposited beneath deeper (1 m) water in the upper basin was probably transported in suspension and distributed by advection throughout the basin by slow tidal and wind-driven currents. Density and thermal currents seem unlikely to be important for sediment transport in these very shallow waters which are well mixed vertically by wind-generated waves. In the shallowest water around the edge of the upper basin, wave- and current-induced grain saltation may also be an important transporter of sand-sized sediment. In contrast to the upper basin, the lack of clear sediment distribution patterns on the southern flats suggests that no single sedimentary process exerts a dominant influence on the surface sediment of that part of the lagoon.

Rippled clean sand and gravelly sand are deposited only where river or tidal currents are sufficiently strong, i.e., on river deltas and at the seaward ends of the subtidal channels. Bouldery areas in this lagoon appear to be mainly lag deposits, where waves or currents have removed all finer material.

X-ray diffraction results indicate that clay-sized particles in mud from this lagoon consist of a simple assemblage of quartz, muscovite, biotite, chlorite, and albite; clay minerals such as illite, kaolinite, and montmorillonite are absent. This simple mineral assemblage occurs throughout the lagoon, in both surface and subsurface sediments, indicating that fine particles entering the lagoon are derived predominantly from erosion of fresh rock or from unweathered fluvial, glaciofluvial, or glacial deposits. The partly weathered nature of the extensive till and outwash deposits of the Okarito Formation suggests that they are not the source of the fine sediment. Recently eroded material from steeper sections of the Waitangi-taona and Mapourika catchments, east of the Alpine Fault, are the probable principal sources of fine sediment in Okarito Lagoon.

## SUBSURFACE SEDIMENT

### METHODS

Cores of subsurface sediment were collected from intertidal flats near Okarito Wharf, from the northern end of the southern large island, from the central Okarito River delta, and from the northern end of the upper basin (Fig. 1 shows core locations). Coring was done by driving short (0.7–1.5 m) lengths of plastic drain pipe (60 mm o.d.) into the bottom of the lagoon and then digging them out. Filled tubes were sealed with plastic bags and returned intact to the laboratory. Samples from individual sedimentation units within each core were studied by the same methods as surface sediment samples.

### RESULTS

Graphic logs and summary sediment properties (Fig. 12) show that the uppermost subsurface sediment from the southern flats consists of interbedded units of moderately layered and massive (unstratified), slightly muddy, fine and very fine sand. Both mean grain size and sediment muddiness are fairly uniform throughout the upper few tens of centimetres of sediment (Cores 1–3). Flats along the western margins of the upper basin are underlain by moderately layered and massive, very fine sand (Core 6) and massive, very fine, sandy mud (Core 7).

Core 5, from the centre of the central subaerial delta of the Okarito River, shows that the stratified clean sand and gravelly sand of this delta overlie burrowed, unstratified, slightly muddy medium sand, and that the flats adjacent to the delta are similarly composed of layered gravelly sediment overlying burrowed medium and fine sand (Core 4). Aerial photographs taken in 1948 (N.Z. Aerial Mapping Ltd, S.N. 508, photographs 1545/4 and 1545/5) show that a delta did not then exist at the sites of Cores 4 and 5, and there is no evidence of any

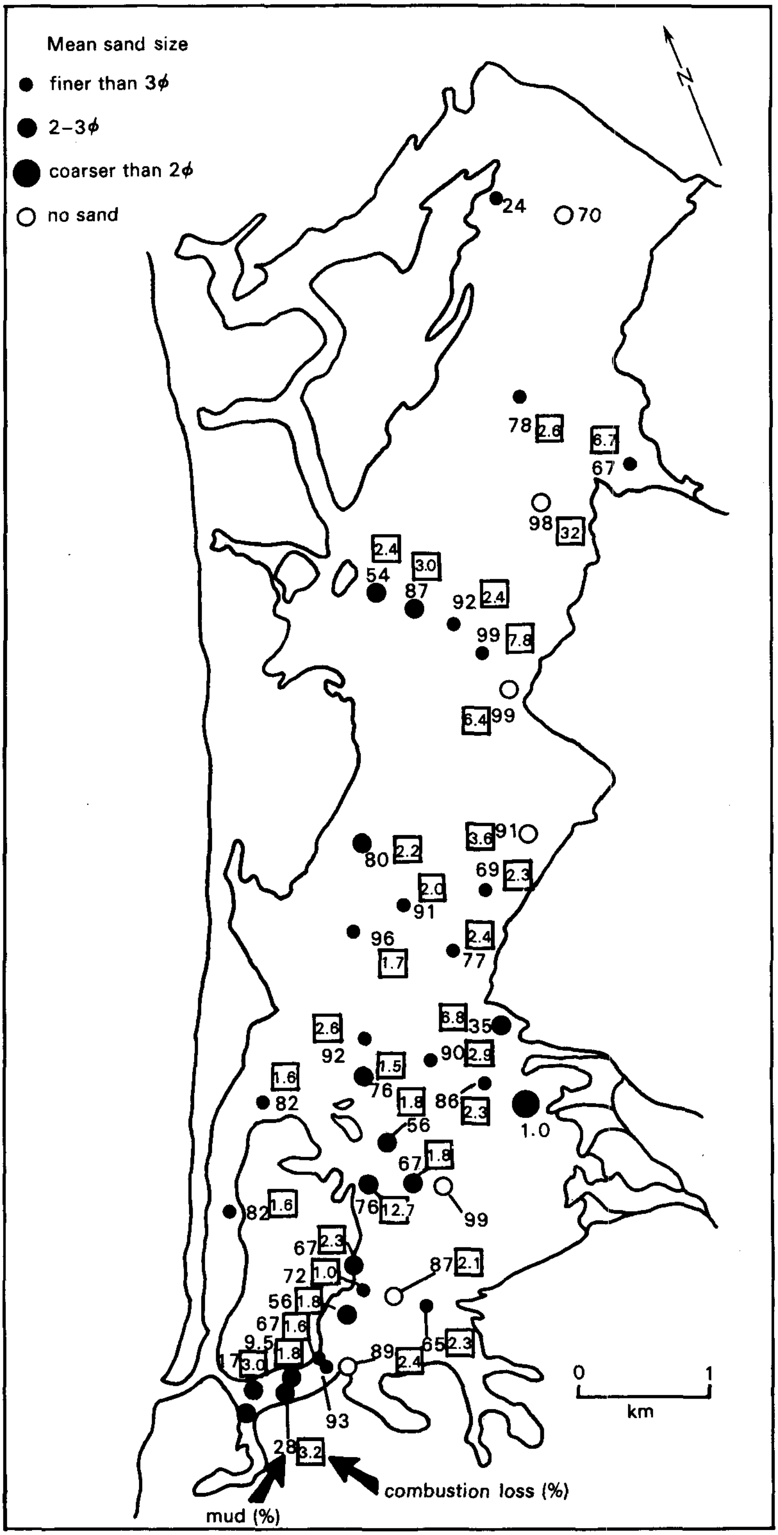

**Fig. 10** Coarse fraction phi mean diameter, percentage mud, and percentage weight loss on combustion of surface sediment samples from Okarito Lagoon.

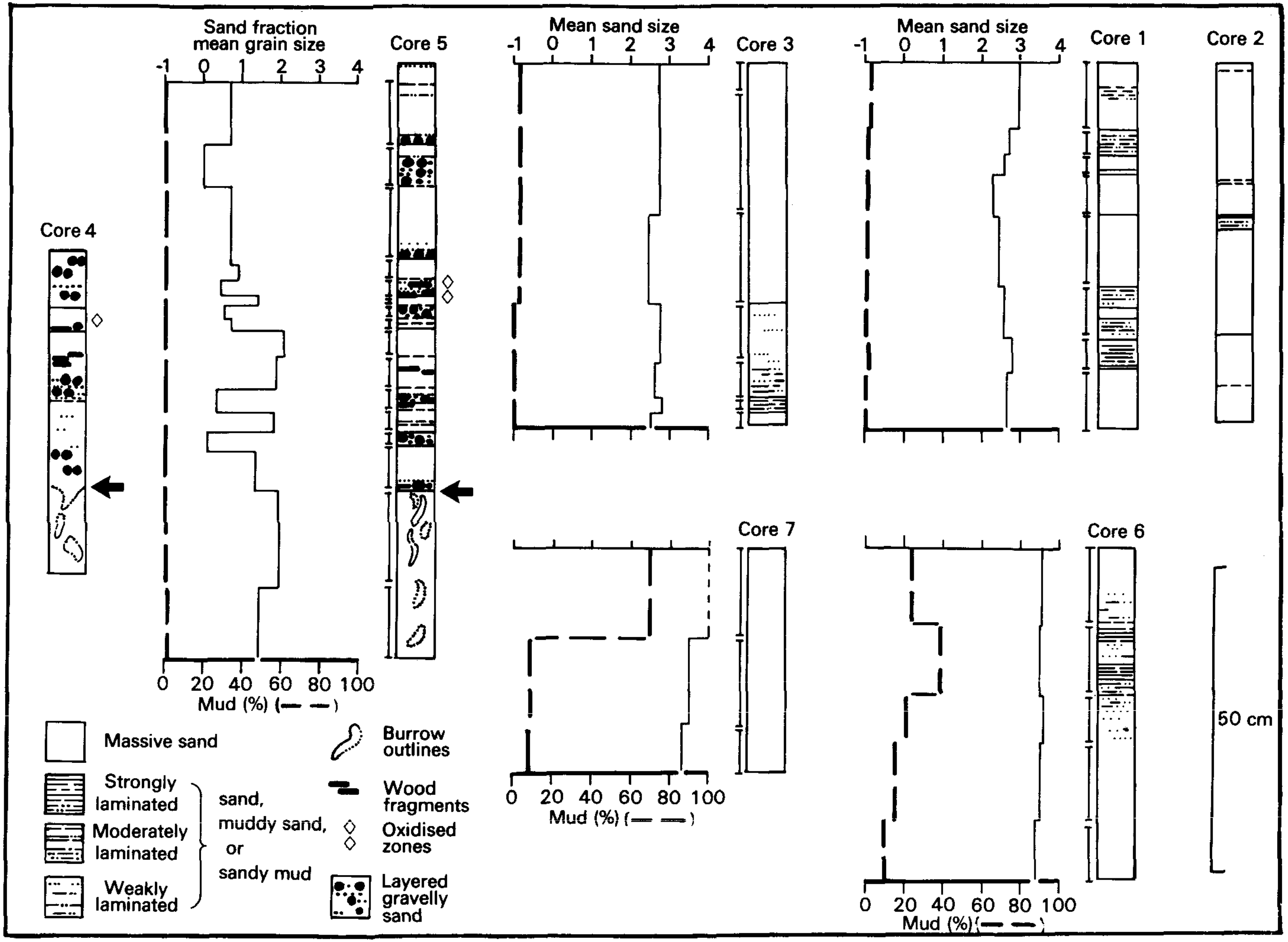

**Fig. 11** Summary logs of cores from Okarito Lagoon, sand fraction phi mean diameters, and sediment muddiness of samples from the cores. Properties of Cores 2 & 4 were similar to those of adjacent Cores 1 & 5; arrows indicate equivalent stratigraphic horizons in Cores 4 & 5; subsurface sediment sampling units shown by bars beside core sections (Fig. 1 shows core locations).

change between then and 1963 (N.Z. Aerial Mapping, S.N. 1542, photographs 3678/6 and 3678/7). The delta does appear in photographs taken in 1969, 2 years after diversion of the Waitangi-taona River into Lake Wahapo, and has remained almost unchanged since (N.Z. Aerial Mapping, S.N. 3208, photographs 4299/3 and 4299/4; S.N. 3602, photographs A/8 and A/9), indicating that the diversion may have caused the growth of the delta. The arrows adjacent to Cores 4 and 5 in Fig. 11 indicate the probable pre-1967 position of the lagoon bottom, beneath the present delta.

Core samples are consistently less muddy than nearby surface sediment samples, especially on the southern flats. This may be a normal feature of very shallow waters, or it may be a result of greatly increased deposition of mud since diversion of the Waitangi-taona in 1967. The writer favours the second possibility — suspended sediment concentrations in water entering the lagoon have increased since diversion of the Waitangi-taona, and increasing amounts of river water flowing through the southern subtidal channel have led to erosion of the banks, and higher local suspended sediment concentrations.

## RECENT NATURAL CHANGES IN THE LAGOON

Comparisons of air photographs taken in 1948, 1963, 1969, and 1972, and sparse documentary records (Anon. 1976, Bishop & Walker 1977) indicate that a number of natural changes are occurring in Okarito Lagoon. Some of the most visible are at the lagoon inlet, which in historical times has occupied various positions along a 0.8 km section of the coast west of Okarito village. The entrance appears to migrate southward periodically at rates of several tens of metres per month, and is returned to a more direct northern position when artificially opened after a blockage. The entrance has closed less frequently since diversion of the Waitangi-taona River (Anon. 1967) and it is likely, because of higher inflow rates (especially in floods), that since this diversion the entrance remains closed for shorter periods when it does block.

A comparison of the 1948 and 1972 aerial photographs shows a number of changes in the southern subtidal channel, and on the adjacent southern flats. Several long, narrow (2–5 m wide), tributary channels which meandered across the shallow south-eastern flats have been infilled. In contrast, the principal subtidal channel has been undergoing active headward and lateral migration. The channel head has migrated north-east by 45 ± 8 m over the 24 years. Headward and lateral erosion is still active; during neap low tides, water flowing across the headward scarp and cascading down into the channel rapidly erodes the unconsolidated sediment, and chunks up to 1 $m^3$ in volume can be seen calving off the walls and slumping into the centre of the channel. A pole placed 1.5 m from the channel edge at Stn *n* (Fig. 1) in early February 1978 had slumped into the channel (along with a 100 m length of the channel wall) by early May, indicating a lateral erosion rate of about 1.6 cm. $day^{-1}$. From this 100 m length of channel alone, lateral erosion during the period February–May 1978 produced 300 $m^3$ of sediment.

Changes have also occurred at the lower end of this southern channel. The wharf is no longer usable because the principal subtidal channel migrated northwards by about 30 m between 1948 and 1963, and has remained in about that position since 1963. Layered supratidal marsh deposits along the south-western margin of the large southern island extended laterally by up to 10 m in places between 1948 and 1969, but were eroded by about 5 m in other places over the same period.

The delta sediments sampled in Cores 4 and 5 at the central principal distributary of the Okarito River are not evident in the 1963 aerial photographs. By 1969 deposition over an area of about 30 000 $m^2$ (± *ca* 5000 $m^2$) had occurred, and by 1972 the area had expanded slightly (to *ca* 35 000 $m^2$). The central distributary prograded 150–200 m into the lagoon between 1963 and 1972. Core stratigraphy reveals 40 cm (Core 4) and 70 cm (Core 5) of mud-free, sand and gravelly sand deposited over burrowed, muddy medium and fine sand. The coarser deposits are inferred to result from diversion of the Waitangi-taona River in 1967. The locations of the cores on the recent deposits suggest a mean thickness of at least 30 cm of coarse sediment, indicating that perhaps 10 000 $m^3$ or more of sediment have been deposited since diversion of the Waitangi-taona River.

## INFERRED RELATIVE IMPACTS OF WAITANGI-TAONA RIVER DIVERSION AND SELECTIVE LOGGING IN OKARITO FOREST

The 1967 diversion of the Waitangi-taona River increased the catchment area of the lagoon by 44% of the pre-diversion area. Much of the additional area is steep high country with higher rainfall than the rest of the catchment area. The diversion must have caused at least a 44% increase in the annual inflow of fresh water (assuming, conservatively, that despite its higher rainfall, the additional catchment area has the same runoff yield as the other catchment areas). Large increases in the input of suspended solids, dissolved cations, and nutrients must also have occurred.

Land-derived sediment inputs to the lagoon are now completely dominated by sediment from the Waitangi-taona River - Lake Wahapo catchment.

The sediment concentration and flow-estimate data outlined earlier indicate that, at low flows, at least 75% of sediment input to the lagoon derives from the Waitangi-taona catchment (Lake Wahapo outlet 10 $g.m^{-3}$ or greater, other inflows *ca* 2 $g.m^{-3}$; flows as in Table 1). Conservative estimates of flood-flow sediment inputs suggest that at least 80% of sediment derives from the Waitangi-taona catchment (L. Wahapo outlet 50 $g.m^{-3}$ or greater, other inflows about 10 $g.m^{-3}$; flows as discussed on p. 31). The similarity of Lake Wahapo inflow and outflow sediment concentrations (p. 31) indicates that nearly all the sediment outflow derives from upstream of the lake. The natural diversion of the Waitangi-taona River has probably caused at least a three-fold and perhaps a 10-fold increase in sediment input to Okarito Lagoon.

Short-term studies of the effects of 25% selective logging on the physical water quality of some Okarito Forest streams (Pearce & Griffiths 1980) showed no detectable change in suspended solids, pH, temperature, or dissolved solids (estimated by electrical conductivity). Pearce & Griffiths also concluded that, even allowing for very substantial increases in sediment concentration on the rising limb of flood hydrographs unsampled in their study, logging-related changes in sediment yield were likely to be between 1% and 10% of the sediment yield change caused by diversion of the Waitangi-taona River.

The Okarito Forest catchment is 36% of the present catchment area of the lagoon (52% of the pre-diversion area). If 25% selective logging over the whole Okarito Forest area caused an equivalent 25% increase in runoff, annual freshwater inflow to the lagoon could be increased by about 9% of present inflows or about 13% of pre-1967 inflows (assuming, to maximise the estimated impact, that all three major catchment areas have equal annual runoff). This runoff increase would be less than one-third of the estimated increase caused by the Waitangi-taona diversion (based on the same runoff assumptions). The actual increase in runoff caused by logging as proposed is likely to be considerably less than 13% of pre-diversion inflows because of the following.

1. Not all of the 9700 ha of the Okarito Forest catchment area will be selectively logged.
2. Any increase in runoff will decline with time, and will not be constant over the 15–20 years of logging in Okarito Forest. The areas logged first are likely to have returned to normal runoff yields by the time the last areas are logged (20–25 years for runoff to return to normal after clearfelling are typically reported, e.g., U.S. Forest Service (1975)).
3. The increase in runoff yield following 25% selective logging is unlikely to be as great as 25%. Complete clearfelling and slash-burning on steep hill country in north Westland produced a 68% increase in runoff yield, and felling and burning of 80% of a second catchment produced a 57% increase in runoff yield (Pearce *et al.* 1980).

Pearce & Griffiths (1980) found no detectable change in total dissolved ionic constituents of stream water during or after logging in Okarito Forest, suggesting that logging-related changes in chemical inputs to the lagoon will be controlled primarily by the change in runoff yield.

Two important conclusions emerge from the above discussion. First, the effect of the Waitangi-taona River diversion in 1967 on freshwater inputs (and indirectly on salinity), on sediment inputs, and on dissolved solid inputs to Okarito Lagoon was several times larger (and perhaps an order of magnitude larger) than the maximum likely impact of 25% selective logging in Okarito Forest on those aspects of the hydrology of the lagoon. Second, it is clear that if studies of the ecological impact of physical changes in the lagoon and its catchment are undertaken in the future, assessment of the effects of the 1967 diversion should be the primary objective, and the impact of selective logging should be only a secondary concern.

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## REFERENCES

American Public Health Association 1975: Standard methods for the examination of water and wastewater, Washington D.C., American Public Health Association.

Anonymous 1976: Okarito Lagoon scheme deferred. *Soil and water 13(1)*: 24.

Bishop, J.; Walker, M. 1977: Westland County: a centennial album. Westland County Council.

Drake, D. E. 1976: Suspended sediment transport and mud deposition on continental shelves. *In*: Stanley, D. J. & Swift, D. J. P. *eds*, Marine sediment transport and environmental management. New York, Wiley. p. 127–158.

Folk, R. L. 1974: Petrology of sedimentary rocks. Austin, Hemphill.

Folk, R. L.; Ward, W. C. 1957: Brazos River bar: a study in the significance of grain-size parameters. *Journal of sedimentary petrology 27*: 3–26.

Gibbs, R. J.; Mathews, M. D.; Link, D. A. 1971: The relationship between sphere size and settling velocity. *Journal of sedimentary petrology 41*: 7–18.

Knox, G. A. et al. 1976: Report on a preliminary investigation of Okarito Lagoon, Westland. Unpublished report of the Estuarine Research Unit, Department of Zoology, University of Canterbury, Christchurch, New Zealand.

Kranck, K., 1975: Sediment deposition from flocculated suspensions. *Sedimentology 22*: 111-123.

New Zealand Meteorological Service 1978: Notes on the weather for March 1978. *New Zealand gazette 39*: 1382.

Pearce, A. J.; Griffiths, A. D. 1980: Effects of selective logging on physical water quality in small streams, Okarito Forest. *Journal of hydrology (New Zealand) 19(1)*: 60-67.

Pearce, A. J.; Rowe, L. K.; O'Loughlin, C. L. 1980: Effects of clear-felling and slash-burning on water yield and storm hydrographs in evergreen mixed forests, western New Zealand. *In*: The influence of man on the hydrological regime with special reference to representative and experimental basins. (Proceedings of the Helsinki symposium.) International Association of Hydrological Sciences [Washington D.C.]. p. 119-128.

United States Forest Service 1975. Municipal watershed management symposium. *United States Department of Agriculture Forest Service general technical report NE-13*.

Warren, G. 1967: Sheet 17—Hokitika (1st edn) Geological Map of New Zealand 1:250 000. Wellington, New Zealand Department of Scientific and Industrial Research.