Estuarine and Coastal Marine Science (1977) 5, 575–595

Deep Water Renewal of Loch Etive: A Three Basin Scottish Fjord

A. Edwards and D. J. Edelsten

Scottish Marine Biological Association, Dunstaffnage Marine Research Laboratory, P.O. Box 3, Oban, Argyll, Scotland

Received 7 May 1976 and in revised form 13 September 1976

Keywords: fjords, flushing time, bottom waters, salinity variations, runoff, sill depth, currents, Scotland coast

Loch Etive is a fjord with three basins. Innermost bottom water stagnates for months or years, with slowly changing temperature and salinity, falling deep oxygen concentration and with a secondary pycnocline below sill depth. A bottom water renewal is described and shown to be caused by low freshwater runoff. The renewal is a series of overflows of sill water during spring flood tides. During overflow, dense fluid forms a turbulent plume whose observed behaviour is similar to that expected from theory: an entrainment constant of 0·013 is found on a bottom slope of 6°.

Observations of salinity in the sill region show that the flushing time there is 4 weeks and that this is the response time of the renewal mechanism to changes in runoff. A model of the non-linear dependence of renewal upon runoff is made and used to hindcast during 1964–1975. The hindcast is verified and shows that renewal is aperiodic with a mean repetition time of 1⅓ years.

Introduction

Fjordic deep water renewal is often attributed to the arrival at the entrance sill of water sufficiently dense to replace that occupying the deep parts of the basin. After inflow, diffusion reduces deep water density and prepares the system for the next renewal. Renewals may be partial (Pickard, 1961), or where high sill density persists they may flush the deep basin thoroughly (Saelen, 1967). A model proposed by Welander (1974) neither allows for partial renewal nor accounts for the time scales but emphasizes both the non-linear nature of the process and the dependence of the time-mean properties of the bottom water upon the timing of high density excursions at the sill.

Several authors have described particular renewals, with various causes of the relatively high density of sill water. Extra-fjordic causes are usual: Anderson & Devol (1973) describe annual formation of high density water by coastal upwelling; Saelen (1947) discusses rare renewal in the Nordfjord as a consequence of lateral movement of coastal water: Dickson (1973) models the dependence of Skagerrak-Baltic overflow upon advection of high salinity water into the Skagerrak under the influence of changes in the Atlantic wind field. Intra-fjordic causes are rarer: Gilmartin (1962) reports a direct relation between freshwater runoff to Indian Arm and the salinity of the compensation current—consequently, renewal tends to occur at times of maximum runoff; the same mechanism is present in Howe Sound (Bell, 1973), augmented by down-fjord wind. Where sill depth is less, and tidal speeds higher, we imagine another mechanism in which not only momentum but also mass is strongly exchanged between the layers of the estuarine circulation: sill density is inversely related to runoff and renewals are initiated by drought. In this paper we describe such renewals and develop an empirically calibrated model which predicts bottom conditions as a function of freshwater runoff only.

Loch Etive

Loch Etive (Figure 1) is a three basin fjord, connected to the sea by a sill 300 m wide, 4 km long and 10 m deep. Severe shoaling on the sill chokes currents so that the internal tidal range is 2 m, compared with an external range of 4 m. Wood *et al.* (1973) establish the estuarine circulation in Airds Basin, and the possibility of a salinity control of the renewals of deep water in the inner basin is recognized by Gage (1972) and by Solorzano & Grantham (1975).

Runoff

The rainwater catchment of 1400 km^2 is larger than that of any other Scottish fjord and 7 times the mainland mean. Contrary to regional south-westerly drainage, water from the neighbouring Loch Awe catchment (area A) drains north westward to enter Loch Etive at Inverawe. The Awe flow is altered and controlled by a hydroelectric scheme which provides weekly figures after 1963 for runoff (n) into the Awe catchment and for discharge (j) of water at Inverawe. Because of proximity, similar topography, ground cover and height, we assume that the hydrologic responses of areas E and A are the same, and that the total weekly freshwater flow into Etive is

$$f = j + En/A.$$

The flow j, usually between 10 and 160 Mm^3 week^{-1}, is about 60% of the total f; it is buffered by 80 Mm^3 of storage in Loch Awe on time scales of a few days in wet weather to several weeks in dry weather.[a] We have shown elsewhere (Edwards & Edelsten, 1976) that this buffering has the potential to halve the frequency of renewal, but that its actual effect has been small.

A renewal in 1974

To examine renewal of the deep water of the innermost basin in 1974, we used the seven stations (5–11), shown in Figure 1. Temperature and salinity were measured with a profiling TSD (Bowers & Coghill, 1975). Recording current meters (Plessey type MO21, recording cycle 10 min, speed threshold about 5 cm s^{-1}) were moored at sites A, B, C and D for long periods, usually a few metres from the sea bed. We occasionally measured the vertical profile of currents (speed threshold 5 cm s^{-1}) at station 8, our principal deep water station. Much of the nature of renewal can be learnt by first considering results from only station 8 and Airds Bay, station 6. Figure 2 shows the time and depth variation of temperature, dissolved oxygen and salinity at station 8.

Temperature

At the beginning of April, water at sill depth (13 m) is at 7 °C, typical of coastal water, whose annual cycle is exemplified by Milne (1972). Near the surface there is an increase as surface

[a] Mm^3 = 10^6 m^3.

water warms in spring; deeper, a thermocline at 50 m separates the sill water from stagnant bottom water at 11·2 °C. If the bottom water is a relic of previous inflow of coastal water, then this temperature, which is exceeded in coastal water only during July–October, suggests that the inflow must have happened in a previous summer or early autumn. During April the bottom water erodes, the deep thermocline deepens and the temperature of sill water increases like that of coastal water.

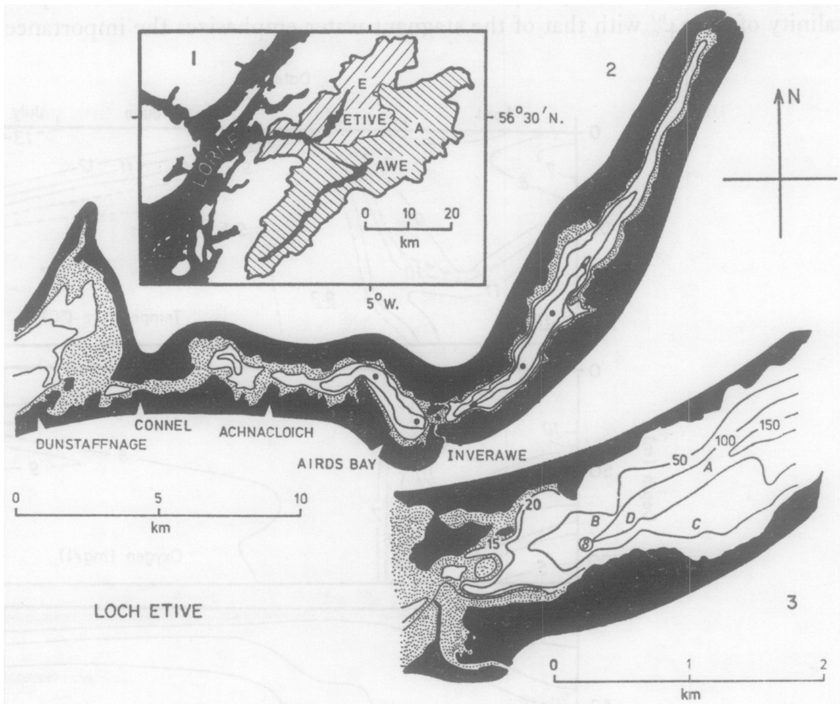

Figure 1. Loch Etive. 1, Rainfall catchments of Lochs Etive (marine) and Awe (fresh). 2, Bathymetry from Admiralty chart no. 2814 and recent echo sounding (1971) at Achnacloich. Isobaths at 20, 50 and 100 m., with stations 5 (west) to 11 (east) dotted. 3, Bathymetry east of Inverawe from recent echo sounding (1975). Isobaths at 10 m and deeper as shown, with station 8 and current meter sites A–D. Water less than 15 m deep is stippled.

At the beginning of May a mass of water at sill temperature appears below the warm water, which is rapidly lifted with decreasing temperature. By mid-May, there is a near uniform mass of sill water at all depths. Subsequently, bottom temperature changes little while sill water warms like coastal water and surface water warms more rapidly with terrestrial influence.

Dissolved oxygen

At the beginning of April, sill water is saturated with oxygen. There is a sharp gradient at about 50 m, below which there is stagnant water whose oxygen concentration falls to 40% saturation before rising slightly near the bottom. If this rise is real and if it is caused by recent partial overflow, then there should be a concomitant drop in temperature, unless the diffusion rate of heat is an order of magnitude greater than that of oxygen. We did not observe such a drop, and postpone discussion of this feature. During April the stagnant mass erodes until it disappears, leaving a well ventilated, near homogeneous water mass. There is little change thereafter.

Salinity

During April the salinity of the surface increases. Below the primary halocline the salinity of sill water also increases. The base of the sill water is initially at 50 m, marked by a secondary halocline which is usually a prominent feature of this basin. The comparison of coastal salinity of 33–34‰with that of the stagnant water emphasizes the importance of freshwater

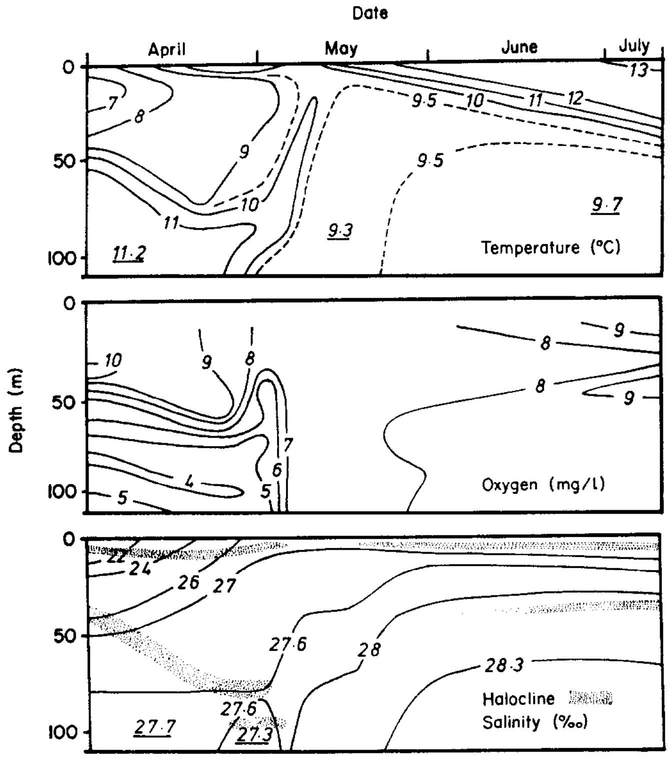

Figure 2. Change at station 8 in Spring 1974. Bottom water is stagnating in April, it is renewed in May, and it restagnates from June onwards. A secondary halocline is only found at the top of stagnant water.

in the fjord. The secondary halocline deepens until a third briefly appears to separate rising stagnant water from intruding cool water at the bottom. By mid-May all haloclines have disappeared. At the end of May the primary halocline returns, followed in June–July by the secondary one.

Currents

Figure 3 shows the mean current during successive ebbs and floods, measured at various sites and depths by the recording current meter. During April, the mean current at 40 m at site B is consistently landwards. We assume that the well ventilated water derives from the sill and flows landwards as part of the estuarine circulation. The speed is greatest in the centre of the record, during spring tides, suggesting either that the circulation is accelerated by springs or that the form of the velocity-depth profile changes from neaps to springs.

In mid-April the meter was moored deeper, at 75 m, at site C. There is dominant landwards flow with a neap-spring variation similar to site B, until mid-May when the meter was moved to site D. Here, in the last week of May, strong and diminishing landward flow continues until the end of the month when all activity above the meter threshold rapidly disappears. Afterwards, currents are negligible.

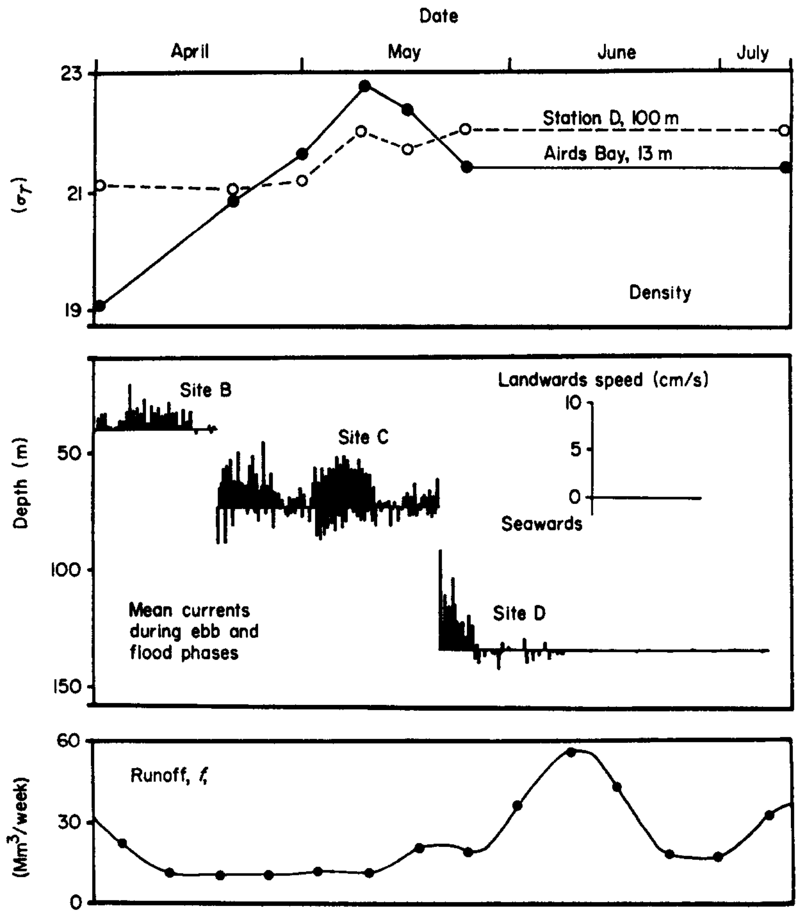

Figure 3. Variation during Spring 1974. Sill density, taken as that at 13 m depth in Airds Bay, exceeds bottom density, measured at 100 m at site D or station 8, only during May. The histograms of mean speed on successive ebbs and floods are drawn at the depth of operation of the recording current meter. For much of April and May, the runoff rate, f, is only 20% of its yearly average.

Density

The immediate cause of the above sequence of events is changing sill water density. Figure 3 shows that the density of water in Airds Bay increases during April while the top of the stagnant water sinks. Near the end of April, sill water density exceeds that of the stagnant water, and advection is possible from sill to the bottom of the deep basin. The consequences are the uplift of the stagnant water, the appearance of cold sill water deep in the basin, a gradual rise in bottom water density and near-homogeneity throughout the basin. After mid-May, sill density falls and soon is less than that of the newly formed bottom water; advection is no longer possible; currents at the bottom are negligible and sill water once more flows over stagnating bottom water.

Temperature variation only accounts for 10% of the sill density fluctuations, whose main cause is salinity variation. Figure 3 shows the weekly runoff during April–July. Falling runoff is associated with rising salinity, and conversely. The correlation of sill salinity with *weekly* runoff is not, however, the best possible (Figure 9) and we have not attempted it here.

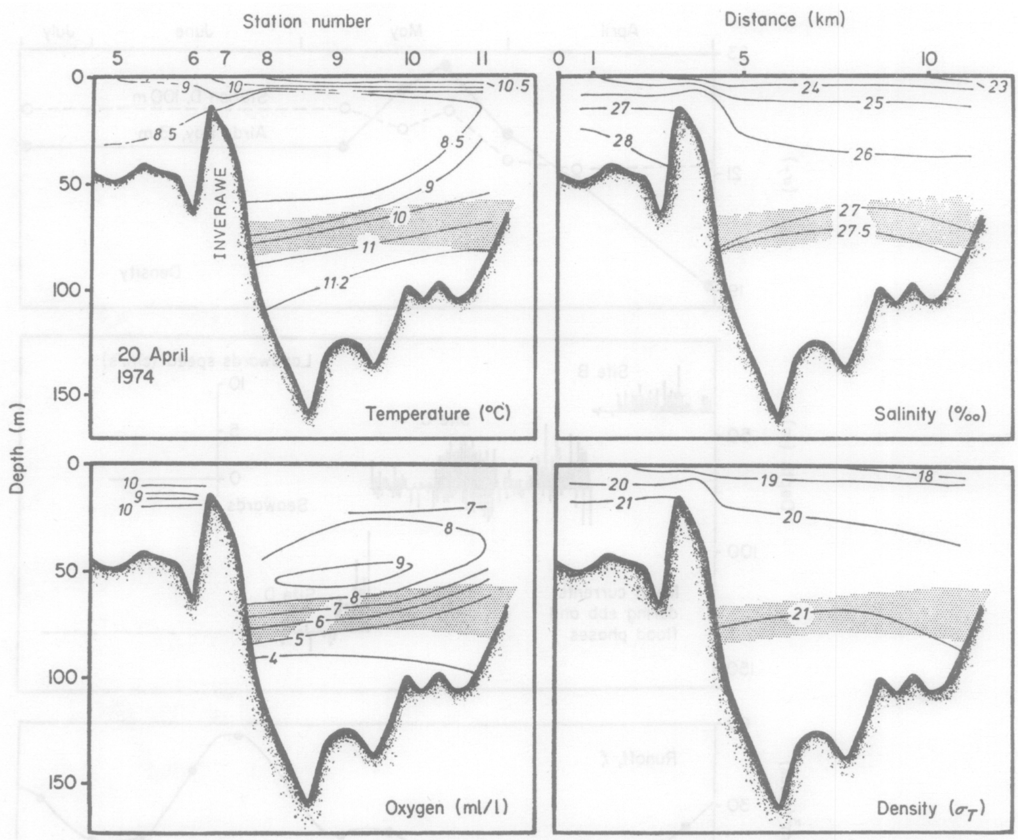

Figure 4. Stagnation. Warm, oxygen depleted water in the basin bottom is 1½ years old. It is covered by an intrusion of coastal water from Inverawe sill. There are strong vertical gradients of the water properties between the two types of water. The zone of density gradient, the pycnocline, is stippled.

There are three phases: stagnation of bottom water while its top is eroded by sill water, overflows of sill water, and restagnation of newly formed bottom water. Representative sections obtained during these phases are shown by Figures 4, 5 and 6 respectively.

Stagnation (Figure 4)

Below 70 m the water stagnates and above it there is a secondary pycnocline at all stations. There are associated sharp gradients of temperature, salinity and dissolved oxygen between the stagnant water and the water which lies between 10 and 60 m. This thick intrusion is continuous with sill water deriving from about 5–15 m in Airds Bay. The temperature of the intruded sill water increases landwards as its oxygen concentration falls, and this is consistent with our hypothesis that overflowing sill water erodes bottom water. The amount of microstructure (scale depth about 10–20 cm) in and around the secondary halocline seems, qualitatively, to decrease landwards as, we infer, the mixing decreases.

Above the sill water is the brackish surface layer whose salinity decreases landwards and whose temperature is high because of insolation and restricted vertical mixing. Where vertical mixing is greatest, at Inverawe, the horizontal salinity and temperature gradients increase, so that surface water is coolest and most saline in Airds Bay.

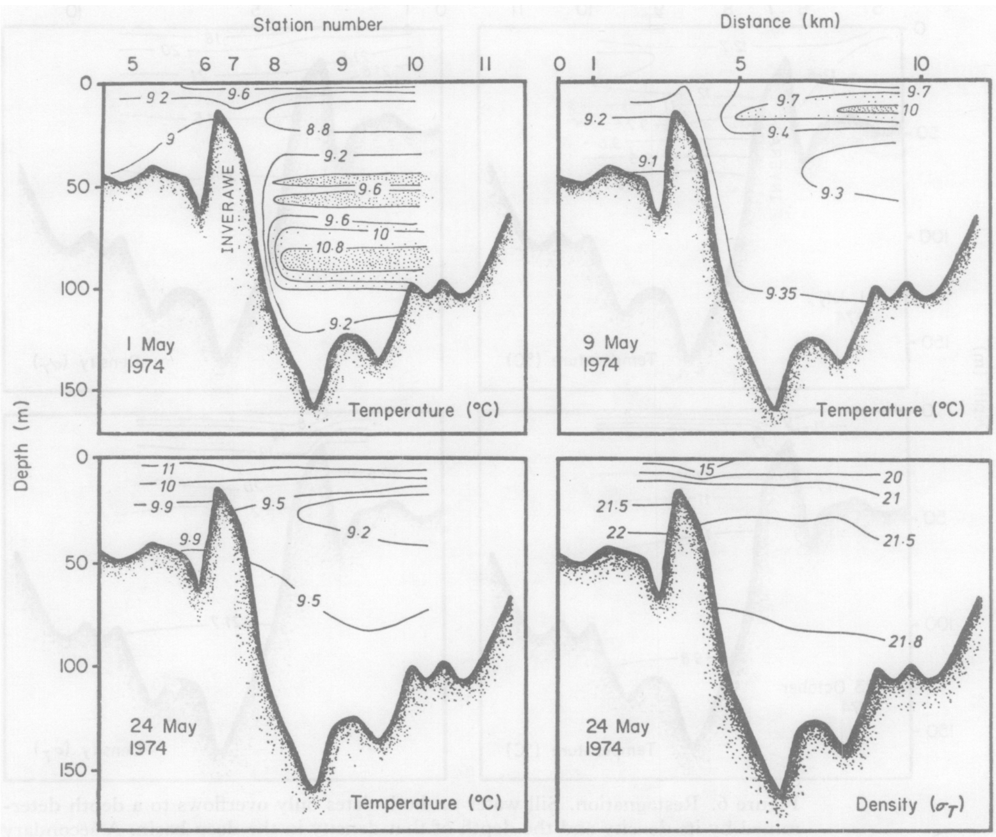

Figure 5. Renewal. Sill water is overflowing on May 1st and is underrunning old water (stippled). On 9 May the old water (stippled) has been raised to sill level. By 24 May the old water has gone; the section, obtained on an ebb tide, shows a possible source of overflow water just below sill level in Airds Bay. Bottom temperature increases all month, showing the frequent arrival of warming coastal water.

Overflows (Figure 5)

Conditions are shown on three dates. On 1 May and 9 May, sill density exceeds bottom density by more than 0·5 in σ_T and we believe that the sections are representative of overflows. On 1 May there is old water at all stations, its temperature has fallen relative to that of 20 April because of mixing with colder sill water which now flows down the slope. The two waters mix most rapidly near station 8—where slight density inversions throughout the water column were clearest.

On 9 May conditions are becoming more uniform and sill water, warmer than that of 1 May, continues to overflow. It has lifted the bottom water of 1 May. There is a vestige of old warm water at sill depth at stations 9 and 10. Because of heat loss to sill water, its temperature is now so low (10 °C) that we may have wrongly identified the effect of surface warming; this is improbable because water at sill depth does not generally reach 10 °C until after 24 May and because surface warming, identifiable on 1 May above 4 m at station 10, has reached only 9·7 °C.

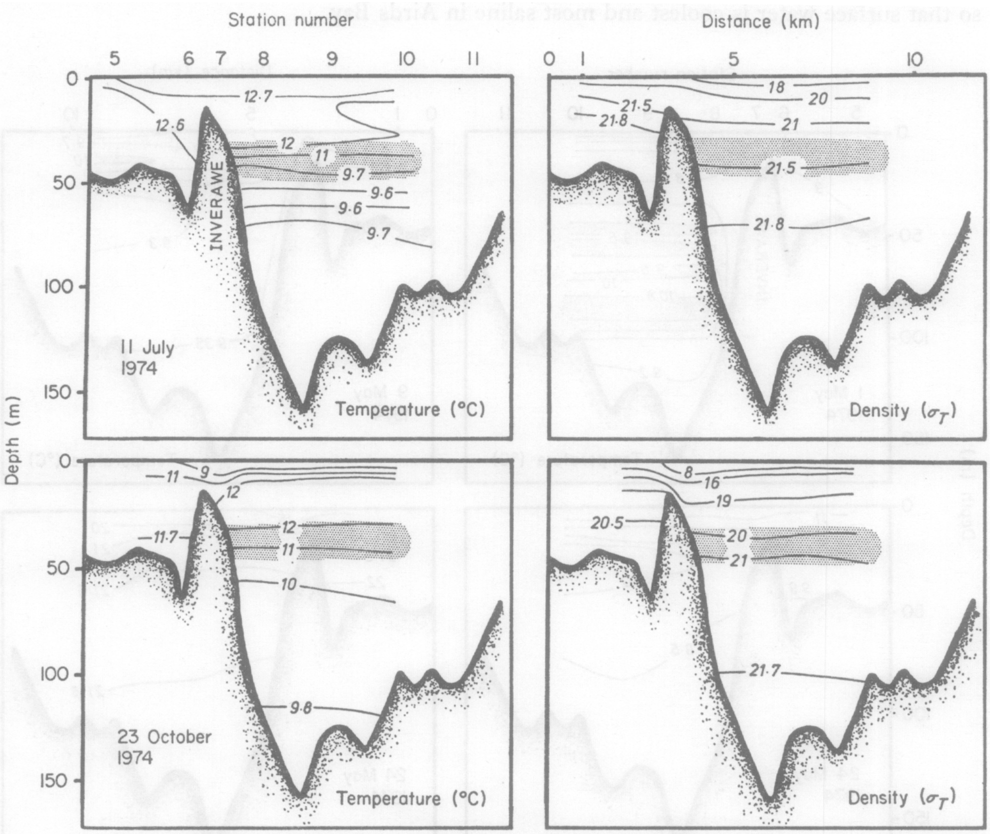

Figure 6. Restagnation. Sill water on both dates only overflows to a depth determined by its density and the depth of that density in the deep basin. A secondary pycnocline (stippled) reforms at the overflow depth and the water of the spring renewal stagnates below, with slowly increasing temperature and slowly decreasing density.

The uplift of old water between the two dates is from 90 to 13 m. The volume of the deep basin between these depths is about 480 Mm^3, whence the mean inflow is 30 Mm^3/tide. The mean tidal inflow during this period was 25 Mm^3/tide. From the near equality of these rates we conclude that the flushing rate is determined by the rate of supply of water by flooding tides and that there is a little modification of the overflowing water by entrainment of older water. The minimum time to flush the basin below sill level is one week at spring tides.

By 24 May there is no trace of old water. Sill density is low relative to deep density but because the section was obtained during an ebb tide we do not conclude that renewal has finished, only that it is not possible during the ebb. Current measurements at station 8 on 23 May support this; during the ebb there was outflow between the surface and 25 m but no inflow below, landwards inflow developed during the flood tide and reached speeds of 15 cm

s^{-1} over a range from 30 to 80 m. Readings were stopped 2 h after slack water because of shifting anchors, but the recording current meter showed (Figures 3 and 8) that overflows occurred until the end of May.

Restagnation (*Figure 6*)

The new bottom water is isolated on 11 July by the new deep thermocline and secondary pycnocline. The rates of transfer of heat and salt through the pycnocline are slow; by 23 October, bottom temperature has risen only 0·2 °C, and salinity has fallen about 0·2‰. These rates are typical of most stagnation periods. There is no longer longitudinal variation in the deep water. In July the warmest sill water is in Airds Bay and older colder water is landwards, whereas in October, when coastal sea temperature is falling, the Airds Bay water is colder than that landwards. Increasing runoff has lowered the salinity and density of all water in Airds Bay during October.

Currents during overflows

In spring 1971, Wood *et al.* (1973) observed a typically fjordic circulation (Saelen, 1967) near Achnacloich. Currents were also measured then at station 8 while deep water was stagnating below a secondary halocline at 40 m; surface outflow to 8 m changed to inflow which reached its maximum at 20 m and had vanished by 40 m. All currents below 40 m were below the threshold (5 cm s^{-1}) of the meter. We later moored meters near the bottom at site A in July–September 1973 and again at site D in July–October 1974; each time, the bottom water was stagnating, and speeds were usually below the threshold, only reaching a few cm s^{-1} for about 2 h in spring tides. We believe that these low bottom currents are typical of stagnation and that they are caused by semidiurnal internal oscillations of the stratified water of the deep basin.

Figure 7 shows profiles in a flood tide during overflow at station 8. There is surface outflow above 25 m and deep inflow which increases towards the bottom. Speed is variable in the deep inflow: 30 readings over 10 min at 100 m at the end of profile K gave a mean speed of 59 cm s^{-1} with a r.m.s. variation of 7·5 cm s^{-1} between extremes of 40 cm s^{-1} and 70 cm s^{-1}. The recording meter at site C shows lower speeds because either it is not central, or the sectional area at site C (4×10^4 m^2) is twice that at station 8, or both. Comparison of the two meters suggests that the main inflow at site C starts about an hour later than at station 8. When we repeated the experiment on 9 May, taking more profiles near the beginning of inflow, we found a delay of 50 min.

The spectrum of the current at site C is dominated by the semidiurnal period and its harmonics (Figure 8). The record is not long enough to resolve the 14-day period which is shown instead by histograms of landwards vector displacement during ebb, flood and whole tidal cycles at sites C and D. Inflow is much greater at spring tides than at neaps. It is non-linear with tidal height—almost vanishing at neaps. From 1 May to 9 May the mean displacement at site C is about 0·4 km/tide. If this existed through the section below the vestigial old water (Figure 5), the volume flow would be 16 Mm^3/tide. Because this is lower than the mean flooding volume (25 Mm^3/tide) or the flow necessary to lift the old water (30 Mm^3/tide), the main current was elsewhere, probably in the deepest part of the section. This conclusion is supported by the higher speeds found later at site D, which is at the deepest part of its section.

Entrainment

Overflows are turbulent plumes of dense fluid which start at the sill and flow downslope under relatively quiet fluid. Because the Reynolds number of the flows of Figure 7 is large (about 10^7), we describe them in the manner of Ellison & Turner (1959) and Turner (1971), although their theory applies to the two dimensional case and our flows were in the bottom of a channel whose cross-section varies from a wide shallow depression at Inverawe to a deep V-section at station 8.

At station 8, let

z = height above the bottom,
$a(z)$ = width of the section,
$v(z)$ = landwards velocity,
d = height at which $v(z)$ changes sign,
$h(t)$ = height of the sea surface at time t,
Q = landwards surface area of the fjord,

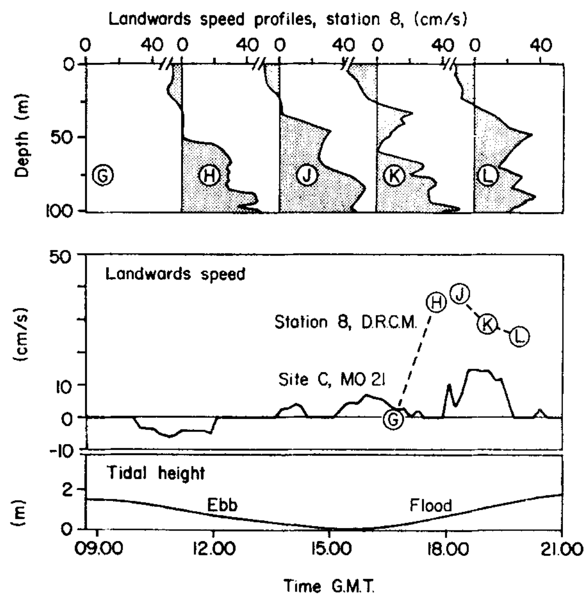

Figure 7. Overflow currents on 8 May 1974. Profiles G–L of current at station 8 during flood tide were measured with a direct reading current meter. Readings at 75 m in the profiles are compared with part of the recording meter record from Site C. Major landward flow occurs during the flood of the surface tide.

then convert the observations to an equivalent system of a near surface layer of cross-sectional area A_T and velocity V_T, and a bottom layer of similar A_B and V_B. This system carries the same landward and seaward flows of volume and momentum if

$$F_B = \int_0^d av\mathrm{d}z = A_B V_B; \qquad \int_0^d av^2\mathrm{d}z = A_B V_B^2$$

$$F_T = \int_d^h av\mathrm{d}z = A_T V_T; \qquad \int_d^h av^2\mathrm{d}z = A_T{}_2^T V.$$

The landward flow at Inverawe, F, is derived from the Inverawe tidal record by

$$F = Q\, \mathrm{d}h/\mathrm{d}t.$$

We assume that both the seaward flow above $z = d$ and the observed increase in landward flow from Inverawe to station 8 are caused by entrainment of ambient fluid into the top of the plume. To conserve mass, we should have

$$F = F_B + F_T.$$

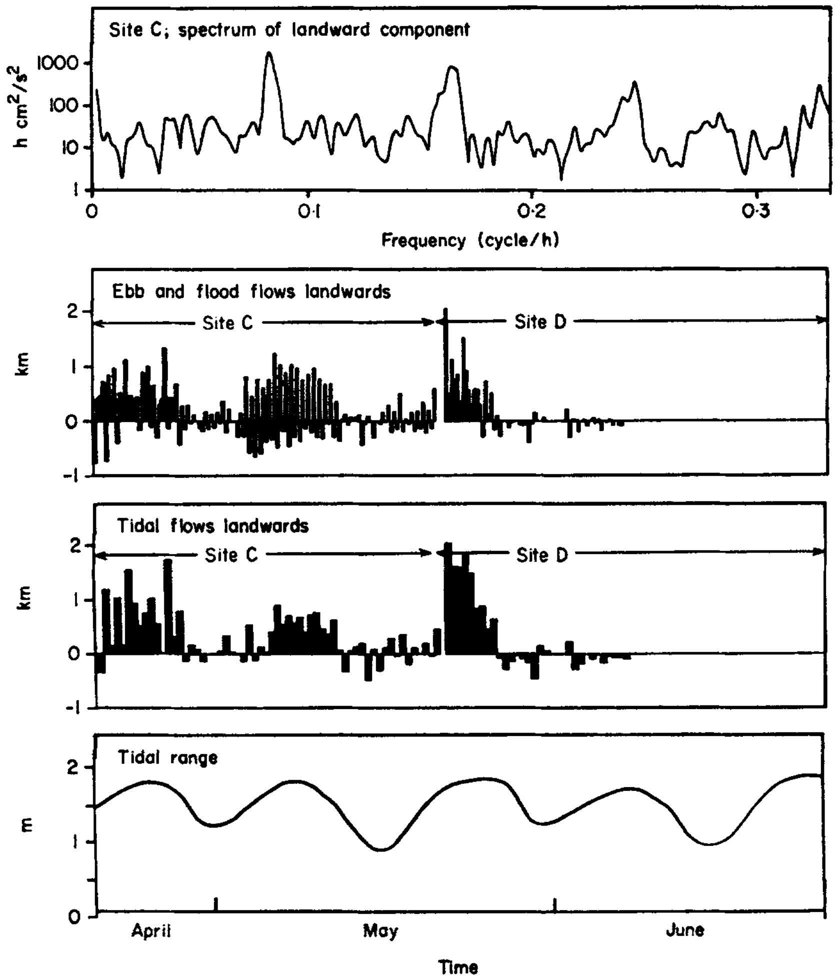

Figure 8. Time variation of current. Tidal frequencies predominate: there is a strong semidiurnal component in the Site C record, with greater landward flows on floods than on the ebbs. Nett landwards displacement at Site C occurs only on spring tides. At Site D, the last springs of May give strong nett landward flows, but overflow currents cease thereafter because of falling sill salinity.

The results of these and the following calculations are shown in Table 1, which shows that none of the profiles satisfies this equation.

The inequality in the balance is of the order of 15% of the contributing terms. It is not explained by error in F, which is accurate to $\pm 100\ \mathrm{m^3\,s^{-1}}$. There are bottom cliffs near station 8, and such rough topography may make our profiles unrepresentative of the cross-section in the deep water. It is more likely that the profiles are unrepresentative nearer the surface, where section width increases. The influence of boat motion is small—we used a taut three-anchor mooring—but makes near-surface measurement unreliable. For these reasons we prefer the estimate of the entrained flow,

$$F_e = F_B - F$$
$$\text{to} \quad F_e = -F_T.$$

The width W of the top of the plume at station 8 is defined by

$$\int_0^y a\,dz = A_B, \qquad W = a(y).$$

It is in the range 270–320 m. A surface convergence noticed just east of the sill is thought to be the intersection of the sea surface with the plume surface, whose width is that of the fjord there, 500 m. The distance between station 8 and the convergence is 1 km, so that the area over which entrainment occurs is

$$A_e \simeq 4 \times 10^5 \text{ m}^2.$$

The cross-sectional area at Inverawe, A_S, is 3500 m^2. The mean speed at the sill is

$$V_S = F/A_S.$$

The mean speed in the plume is

$$V_P = (V_S + V_B)/2.$$

The mean entrainment velocity is F_e/A_e. It is related to V_P by the entrainment constant,

$$E = F_e/(A_e V_P),$$

whose mean value is 0·013, over a mean bottom slope of 6°, considering only the deepest part of cross-sections between Inverawe and station 8. This value of E agrees with the prediction of Ellison and Turner for this slope and shows little more variability than their laboratory determinations did.

The speed of the nose of the plume can be estimated from the travel time from station 8 to site C. Because site C was not in the main inflow path, our previous estimate of 50 min may be too low. Over 1 km, this time implies a nose speed of 33 cm s^{-1}, the same as V_B and about 50% of the speed of the fastest fluid in the plume at station 8.

The flux of density difference

We estimated this twice, using $g = 10$ m s^{-2}.

(1) The difference in sill density and deep density $= \Delta\rho$. From Figure 3, $\Delta\rho \simeq 0{\cdot}6$ kg m^{-3}. The flux of density difference, M, is $M = g F\Delta\rho/\rho \simeq 10\text{m}^4\text{ s}^{-3}$.

(2) Salinity and temperature profiles obtained before profile G and after profile K show that density below 30 m increased by about 0·2 kg m^{-3}. If the increase at z is r (z), then

$$M = (1/\rho) \int_0^d gravdz = 9 \text{ m}^4\text{ s}^{-3}.$$

Both estimates are subject to error, but because of their similarity we have continued. The plume has a mean top width of 400 m, so that the total flux is equivalent to a line source of strength

TABLE 1. Calculation of the entrainment constant, E

Profile	Sill		Bottom Water				Surface Water			Entrainment			
	F ($m^3 s^{-1}$)	V_S ($m s^{-1}$)	V_B ($m s^{-1}$)	A_B ($1000 m^2$)	F_B ($m^3 s^{-1}$)	W (m)	V_T ($m s^{-1}$)	A_T ($1000 m^2$)	F_T ($m s^{-1}$)	F_e ($m^3 s^{-1}$)	V_P ($m s^{-1}$)	E	A/V_B^3
H	1400	0·4	0·38	7	2650	270	−0·07	11·8	−840	1250	0·39	0·008	0·41
J	1700	0·48	0·38	10·7	4100	290	−0·09	8·8	−800	2400	0·43	0·014	0·41
K	1700	0·48	0·25	10·9	2720	290	−0·18	10·8	−1900	1020	0·37	0·007	1·44
L	1700	0·48	0·29	13·5	3950	320	−0·09	11·5	−1080	2250	0·38	0·015	0·92

$$A = M/400 \simeq 2{\cdot}25\ 10^{-2}\ \mathrm{m^3\ s^{-3}}.$$

It is impossible to investigate the way in which A changes in time by using our observations. If we assume that A is constant during the time G–L then the ratio A/V_B^3, which should be constant for a fixed bottom slope, varies between 0·4 and 1·5. The ratio is very sensitive to errors in V_B and consequently the mean ratio $\overline{A/V_B^3}$, is 0·8 but the ratio of the means, $A/(\overline{V}_B)^3$, is 0·6—this is higher than our extrapolation of Ellison and Turner's results, perhaps because of the comparability of the small changes in density upon which our estimates of M are based with the possible instrumental error in determining density.

Momentum

Ignoring the small difference in integrated hydrostatic pressure on the two ends of the plume, an approximate momentum equation for the plume between Inverawe and station 8 may be written

$$FV_S - A_B V_B^2 + ML \sin 6°/V_P - C_D\, V_P^2\, A_c = 0$$

where C_D is the drag coeefficient relating bottom stress to water velocity and A_c is the area of the bottom in contact with the plume. The terms are the flux of momentum into the plume at Inverawe, the flux out at station 8, the force of gravity acting down the slope and the drag on the plume because of bottom friction. Inserting typical values for all quantities except C_D gives $C_D = 2{\cdot}8 \times 10^{-2}$. There are unknown errors in this estimate because our ignorance of the variation of many quantities both along the plume length and across the terminal sections forced us to use products of means, rather than means of products, to solve the equation.

A model of renewal

To quantify the association of overflow and low runoff we have examined 50 surveys made during 1971–73. We hypothesize that renewal occurs whenever sill density (ρ_s) is greater than bottom density (ρ_b); at all other times, sill water enters the return current above the secondary pycnocline and affects bottom water only by diffusion. To describe ρ_s and ρ_b we describe sill temperature (T_s) and salinity (S_s), bottom temperature (T_b) and salinity (S_b). With hydrologic data as input, the model must in particular account for the timing of the renewals observed in 1971–73, so as to hindcast to 1964, when the hydrologic data start, and to estimate the mean stagnation time.

Sill salinity

Figures 2 and 3 suggest that sill salinity, S_s, is negatively correlated with runoff in some preceding time. We seek a linear relation of the form

$$S_s(t) = S_0 - k\,R(t) \tag{1a}$$

where S_0 is a constant base salinity, k is a constant, and

$$R(t) = \sum_1^{\infty} a_i f_i(t) \tag{1b}$$

f_i being the runoff in the ith week preceding time t. The weights a_i must, to conserve flow over long periods, obey

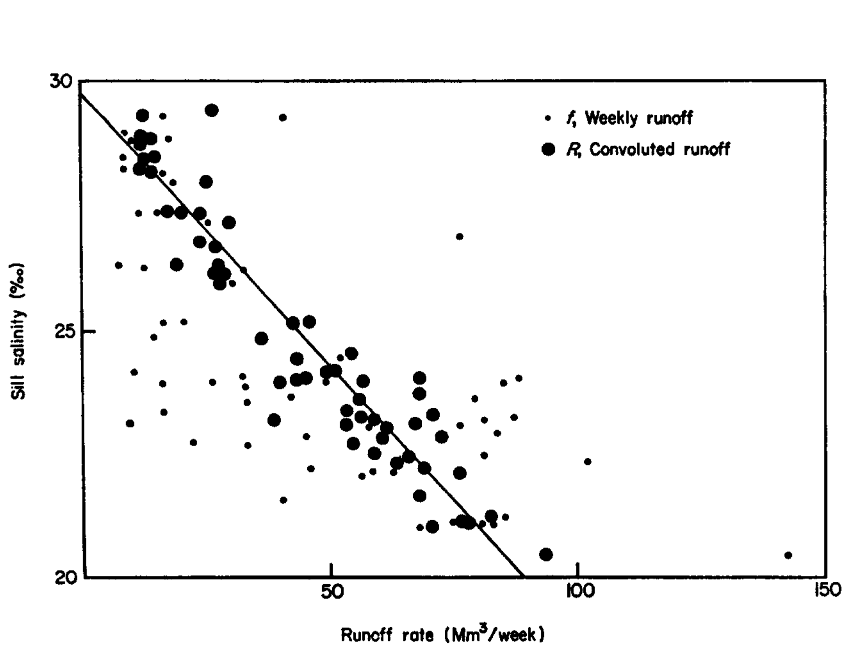

Figure 9. 1971–72. Correlation of sill salinity with runoff rate in a previous time. If the weekly rate f is used, there is much scatter, but use of a convoluted runoff rate R can linearize the relation. R is a weighted runoff, the sum of the product of the rates f in all previous weeks and a weight function which decreases exponentially with time before the salinity measurement. The standard error of the regression ($S_S = 29.75 - 0.11\,R \pm 0.9‰$) is minimized when the time scale of the exponential decrease is 4 weeks.

$$\sum_{1}^{\infty} a_i = 1.$$

The easiest way to solve this problem is to continually measure S_s and f and to compare the resultant time series. We did not do this. To determine the set a_i, which for reasonable confidence must be truncated for $i \ll 50$, we examined the 1971–73 surveys for 50 values of S_s. Rather than regress these values of S_s upon the accompanying 50 sets of f_i to obtain the best set a_i, we first find the nature of a_i in a well mixed box model of the sill region. We note that the weighted runoff R is a discrete form of convoluted runoff.

$$r(t) = \int_0^\infty f(t-T)a(T)\,\mathrm{d}T,$$

where

$$\int_0^\infty a(T)\,\mathrm{d}T = 1,$$

f is the instantaneous rate of runoff and $a(T)$ is the weight function at time T before t. Assume that the sill region is a box of unit volume, with fresh inflow g, seawater inflow $(h\text{-}g)$ at salinity S_0 and constant outflow h at salinity U. Conserving salt gives

$$\frac{dU}{\mathrm{d}t} + hU = (h\text{-}g)S_0$$

whence

$$U(t) = S_0\,(1 - \int g e^{ht} dt / e^{gt})$$

$$= S_0 \left(1 - \int_0^\infty e^{-hT} g\,(t-T)\, dT \right)$$

If $g \propto f$ and $h = 1/a$

$$a\,(T) = (e^{-t/\alpha})/a$$

or, in discrete form

$$a_i = e^{-(i-0.5)/\alpha}\, e^{-(1/2\alpha)}\, (e^{1/\alpha} - 1)$$

The set a_i is determined by a, chosen to minimize the standard error of the estimate (1) of S_s. We found $a \simeq 4$ weeks; it is the flushing time of the sill region. Values of S_s and R are shown in Figure 9; we have—with R in Mm^3 week^{-1}—

$$S_s = 29{\cdot}75 - 0{\cdot}11\, R \pm 0{\cdot}9‰ \text{ (standard error)} \tag{2a}$$

as the predictor of sill salinity. Much of the error of an estimate based on (2) comes from real fluctuations in S_s caused by internal oscillations in Airds Bay.

Sill temperature

Because of the turbulence associated with the sills at Connel (up to 10 m s^{-1} near to the tidal falls) and Achnacloich (up to 2 m s^{-1} mean speed in the section), sill water in Airds Bay is a mixture of Firth of Lorne water and brackish water from the surface layers of Etive. With weekly runoff reaching a maximum of 160 Mm^3, (2*a*) shows that as much as 50% of Inverawe sill water can be freshwater. Sill water consequently follows local sea temperature, modified towards higher summer and lower winter values by the terrestrially derived freshwater.

With a maximum error of 1·5 °C and a mean error of 0·5 °C, sill temperature is represented by

$$T_s = \{10{\cdot}50 - 3{\cdot}35 \cos\,[w\,(t-60)]\}\ ^\circ\text{C}. \tag{2b}$$
$w = (2\pi/365)$ day^{-1}.
$t = 0$ on 1 January and is measured in days.

The error in the estimation of ρ_s caused by (2*b*) is no more than 0·3 in σ_T. A typical error in ρ_s caused by the salinity predictor (1) is 0·8 in σ_T and it thus seems fruitless to improve the temperature predictor (2*b*).

Bottom salinity and temperature

At renewal time, ignoring the modification of downslope flow by turbulent entrainment, $(\rho_s \geq \rho_b)$, and

$$S_b = S_s;\ T_b = T_s \tag{3a-i}$$

The time needed to flush old water has been shown to be about one week; to allow for this and the entrainment we have used.

$$S_b = 0{\cdot}67\, S_s + 0{\cdot}33\, S_b' \tag{3a-ii}$$

—an equation which, similarly for temperature, describes new bottom water as a mixture of sill water and previous weeks bottom water (salinity S_b'). The difference between the two versions of (3*a*) is unimportant, consisting of a phase lag of about a week and a slight diminution of maximum bottom density when (3*a*-ii) is used.

At other times, when a secondary pycnocline inhibits the transfer of heat and salt we assume that the transfer rates are proportional to the differences between bottom and sill water. This is not the only hypothesis consistent with our observations which are however too noisy to support a more elaborate one, and ($\rho_s < \rho_b$).

$$\frac{\partial S_b}{\partial t} = -k_S(S_b - S_s)$$

$$\frac{\partial T_b}{\partial t} = -k_T(T_b - T_s) \qquad (3b)$$

Using the 1971–73 surveys,

$k_S \simeq 0{\cdot}2 \text{ year}^{-1}$

$k_T \simeq 0{\cdot}5 \text{ year}^{-1}$.

Lastly, the equation of state,

$$\rho = \rho(S, T) \qquad (3c)$$

has been used in the form given by Lafond (1951).

The set (3) is non-linear and in what follows we assert nothing about the future behaviour of the system under what will be different meteorologic conditions. As Welander (1974) has remarked, the time-mean properties of the bottom water in such a system do not depend in any simple way upon those of the sill water. In particular, the temporal ordering of sill density maxima is crucial to the frequency of overflow. In what follows, we determine the mean time between renewals in 1964–75, but can give no simple statistics of the hydrologic and meteorologic inputs which relate to it.

Hindcasting during 1974–75

Using the runoff data of 1964–75, equations (1–3) have been solved with a time step of 1 week. Because the values of the various constants were determined using surveys of 1971–72, the solution during that period agrees with reality, but other tests of the solution are offered by the present renewal and by the observations of B. E. Grantham (personal communication, 1970) and J. A. Marlow (personal communication, 1975). The satisfactory comparison of these tests with the model is shown in Figure 10.

Accepting the constants, Figure 11 shows 12 years of operation of the hydroelectric scheme. Renewal occurred 9 times. It was aperiodic, the interval ranging from a few weeks to 2½ years, and occurred most often in spring or summer thus often producing warm bottom water. The mean bottom temperature was not however high—it was 10 °C, little different from that of sill water—because of the persistence of two cold inflows in the winter of 1964 and spring of 1969. Winter renewal may occur even when precipitation is high, because of the storage of runoff as ice and snow in the mountainous catchment. The frozen period needs to be comparable to *a* if it is to allow sill salinities to rise sufficiently. Only in rare severe winters, with a period of sub-zero temperature lasting well over 4 weeks, can this be expected. The other cause of low runoff in winter is a long period of low precipitation; such winters also appear to be rare—the February 1964 example is of this sort.

We may now interpret Grantham's earlier observations of Loch Etive in 1967–69 (in Gage, 1972). There are discrepancies: the hindcast temperature in November 1967 is 12 °C, but Grantham found 9 °C. An increase of only 1 in σ_T during spring 1967 would however change our hindcast to an overflow, with bottom temperature about 9° as required. By February 1968, there had been little change in bottom temperature and oxygen concentration was 40% of saturation below 80 m. The year 1968 was unusual because two renewals are hindcast. One in March–April gave a spring bottom temperature of 8 °C, and another, in July, left a bottom temperature of 11–12 °C. One of Grantham's sections (18 August) looks as if it was obtained during an overflow in the second renewal. This and subsequent surveys agree with the hindcast.

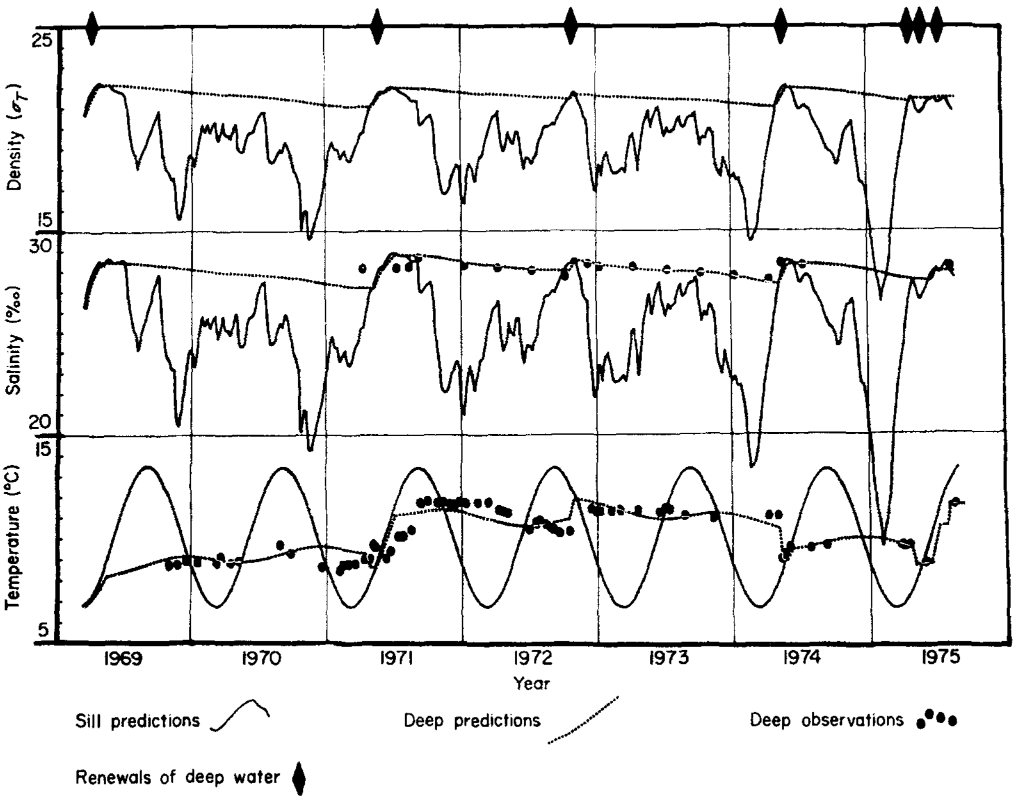

Figure 10. Calibration and verification of a model of renewal. Observations of the deep water in 1971–72 were used to calibrate the model, but others are a check on its accuracy.

We have already doubted partial overflow as the explanation of a slight increase of oxygen concentrations towards the bottom during stagnation in March 1974. The modelled sill density is much less than bottom density during the preceding autumn and winter; at the end of March 1974 there was no water at *any* depth in Airds Bay which could have sunk to the bottom of the deep basin. Therefore we discount partial renewal, and suggest instead that the upper parts of stagnating water may be depleted of oxygen more rapidly than the lower parts. Whether this is caused by the congregation of animals at the top of the water, or by the exhaustion of the oxygen demand of sediment before it settles, is not known.

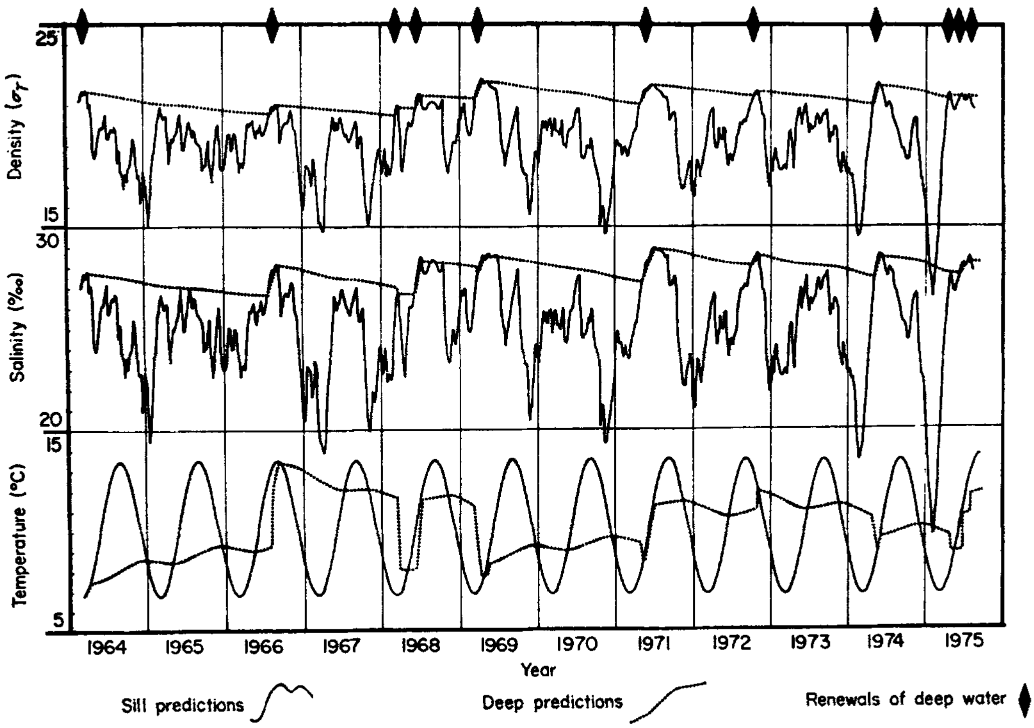

Figure 11. Solution of the model 1964–75. Although there is annual periodicity in the sill density, the year to year variation of the maximum is so great that in some years [1965, 1967 (but see text), 1970 and 1973] the peak is less than the density of the bottom water, formed in the previous year and renewal cannot happen.

Summary

Stagnation of the bottom water of Loch Etive is recognized by the presence of a secondary pycnocline at depths of 30–100 m. Below the pycnocline, temperature and salinity vary slowly, currents are small and oxygen concentration decreases with time. If the bottom water is to be renewed, it is necessary that runoff to the loch should be low. During the flood of spring tides, sill water then flows downslope as a turbulent plume. The penetration of the relatively light old water by the plume destroys the secondary pycnocline and rapidly changes the oceanographic properties, in particular the dissolved oxygen concentration which increases. Despite its greater length scale ($\times 500$) and buoyancy flux ($\times 40$), the plume is similar to those described by Ellison & Turner (1959). The difficulties of making adequate observations from one boat are however manifest.

Deep currents associated with inflow are fast and turbulent in the neighbourhood of the sill, but diminish landwards. This is important; it is only during overflow that high bottom speeds exist and then only at the sillward end of the basin. The cause of any persistent horizontal heterogeneity in the sediments or the benthos may be the strong horizontal gradients of current, temperature and oxygen found during the relatively rare periods of overflow rather than the slight variation of properties found during the long periods of stagnation.

A simple set of equations describes the dependence of renewal upon runoff. Various empirically determined quantities (a, k_S, k_T) relate to the flushing time of the sill water and to the diffusion rates of salt and heat from the bottom water; the set then successfully describes known observations. A frustrating aspect of the equations is their non-linearity, so that although output (prediction of bottom conditions) is well defined for any reasonable and particular input (runoff data) the statistics of outputs are not determined by any simple statistics of general inputs.

Among Scottish lochs, Loch Etive has an exceptionally high runoff, its tidal range is small and the ratio of supply of buoyancy to turbulent kinetic energy is unusually high. This is the cause of the strong stratification, slow diffusion, and consequent ease of stagnation in the loch. It seems unlikely that similarly long stagnation times will be found elsewhere in the north-west although, in the south-west, small tidal ranges may be conducive to long stagnation. Accepting that the inner basin of Loch Etive is exceptional, the possibility remains that shorter stagnations and more frequent renewals is the usual sequence in many Scottish fjords. In such a regime, where the turbulent plume injects mass and kinetic energy in a complicated fashion through time and depth, it becomes restrictive to describe diffusion only as a gradient-controlled Fickian process and we would prefer to describe its dependence upon the relative local fluxes of energy and buoyancy. With frequent convection from the sill regions, this is difficult and we have had to make do with two questionable 'constants', k_S and k_T, in order to make any progress.

Acknowledgements

We thank the officers of the North of Scotland Hydro Electric Board for their willing provision of the runoff data. We are grateful to Lucia Solorzano, H. T. Powell, the officers and crew of R. V. 'Calanus' and to all our friends who inspired and criticized.

It was a fortunate chance that the renewal of 1974 occurred soon after the start of a monitoring programme that was to have continued until renewal occurred. Such prompt renewal was however an *embarras de richesse*; we wish therefore to thank A. M. Souter and A. M. Souter of the R. V. 'Beaver' for their help and patience in the execution of hurriedly conceived plans; without them much of the detail would have been lost.

References

Anderson, J. J. & Devol, A. H. 1973 Deep water renewal in Saanich Inlet, an intermittently anoxic basin. *Estuarine & Coastal Marine Science* **1**, 1–10.

Bell, W. H. 1973 The exchange of deep water in Howe Sound basin *Marine Sciences Directorate, Pacific Region Environment Canada, Report* no. 73-13, 35 pp.

Bowers, R. & Coghill, G. G. 1975 A continuously profiling TSD system. *Journal of Physics E: Scientific Instruments* **8**, 150–152.

Dickson, R. R. 1973 The prediction of major Baltic inflows. *Deutsche Hydrographische Zeitschrift* **26**, 97–105.

Edwards, A. & Edelsten, D. J. 1976 Control of fjordic deep water renewal by runoff modification. *Hydrological Sciences Bulletin* **21** (3), 445–450.

Ellison, T. H. & Turner, J. S. 1959 Turbulent entrainment in stratified flows. *Journal of Fluid Mechanics* **6**, 423–448.

Gage, J. 1972 A preliminary survey of the benthic macrofauna and sediments in Lochs Etive and Creran, sea-lochs along the west coast of Scotland. *Journal of the Marine Biological Association of the U.K.* **52**, 237–276.

Gilmartin, M. 1962 Annual cyclic changes in the physical oceanography of a British Columbia fjord. *Journal of the Fisheries Research Board of Canada* **19**, 921–974.

Lafond, E. C. 1951 *Processing Oceanographic Data.* U.S. Navy Hydrographic Office, 114 pp.

Milne, P. H. 1972 Hydrography of Scottish west coast sea lochs. *Marine Research* No. 3, H.M.S.O. 50 pp.

Pickard, G. L. 1961 Oceanographic features of inlets in the British Columbia mainland coast. *Journal of the Fisheries Research Board of Canada* **18**, 907–999.

Saelen, O. H. 1947 Temperature variations and heat transport in the Nordfjord. *Bergens Museums Årbok, Naturvitenskapelig Rekke* No. 6, 28 pp.

Saelen, O. H. 1967 Some features of the hydrography of Norwegian fjords. In *Estuaries* (Lauff, K. H. ed.) American Association for the Advancement of Science Publication No. 83, 63–70.

Solorzano, L. & Grantham, B. E. 1975 Surface nutrients, chlorophyll *a* and phaeopigment in some Scottish sea lochs. *Journal of Experimental Marine Biology and Ecology* **20**, 63–76.

Turner, J. S. 1973 *Buoyancy Effects in Fluids*. Cambridge University Press, 367 pp.

Welander, P. 1974 Two layer exchange in an estuary basin, with special reference to the Baltic Sea. *Journal of Physical Oceanography* **4**, 542–556.

Wood, B. J. B., Tett, P. B. & Edwards, A. 1973 An introduction to the phytoplankton, primary production and relevant hydrography of Loch Etive. *Journal of Ecology* **61**, 569–585.