Hydrological Sciences–Bulletin–des Sciences Hydrologiques, XXI, 3 9/1976

CONTROL OF FJORDIC DEEP WATER RENEWAL BY RUNOFF MODIFICATION

A. EDWARDS and D.J. EDELSTEN

Dunstaffnage Marine Research Laboratory, PO Box 3, Oban, Argyll, Scotland

Abstract. Loch Etive is a Scottish fjord subject to fresh-water runoff which renders it markedly brackish. This paper considers the frequency of deep water renewal, developing a model which relates the timing of all such renewals to runoff records. Using the model one can examine the effect of changes caused by interference with the natural runoff pattern.

Réglage du renouvellement des eaux profondes des fjords en utilisant un modèle qui effectue une modification du régime de l'écoulement

Résumé. Le Loch Etive est un fjord écossais qui subit un écoulement d'eaux douces, ce qui le rend fortement saumâtre. Le document qui suit étudie la fréquence de renouvellement des eaux profondes et développe un modèle permettant d'établir un rapport entre les périodes de renouvellement et les écoulements. En utilisant ce modèle, on peut étudier l'effet des changements apportés par toute interférence dans le rythme naturel d'écoulement.

INTRODUCTION

Because of their high precipitation and mountainous terrain, the fjordic areas of the world are attractive as sources of hydroelectric power. Most efficient use of hydroelectric resources is made when fluctuations in water supply are smoothed by storage. In temperate regions we do not expect evaporative losses from a catchment to be drastically altered by such time-shifting of runoff. Consequently, any part of a river-estuary system whose behaviour is linear with respect to runoff will preserve its time-mean properties despite any smoothing. Even in such a linear system the magnitude and timing of deviations from the mean may greatly alter the biological and sedimentary estuarine processes, as suggested by Neu in this symposium. When the system is nonlinear, even mean estuarine conditions are changed by runoff alterations and its behaviour becomes very sensitive to small changes in the pattern of runoff. In this paper we describe such a nonlinear estuary—a Scottish fjord—and develop a model which allows one to examine the effect of any changes caused by interference with the natural runoff pattern.

LOCH ETIVE

This fjord is about 30 km long and 1 km wide, with a shallow entrance sill that reduced tidal range from an external 4 m to 2 m. Two more sills at 13 m split the fjord into three basins of which the innermost is the longest (18 km) and deepest (150 m). The land draining into Loch Etive is nearly 1400 km^2 with a mean annual rainfall of 2400 mm, peaked so that 75 per cent of it occurs in the months from September to February. There is little prolonged storage of precipitation as snow or ice. Almost 60 per cent of the catchment discharges at the innermost sill through a lake, Loch Awe, which provides a working storage of about 80×10^6 m^3 for hydroelectric schemes operated by the North of Scotland Hydro-electric

Board. It is assumed that the hydrological response of the ungauged catchment (area E) is similar to that of the gauged Awe catchment (area A) and that the runoff to Etive is thus

$$f = j + En/A \quad 10^6\ \mathrm{m}^3 \text{ per week},$$

where j = gauged Loch Awe outflow, and n = gauged Loch Awe inflow.

WATER MASSES DURING DEEP STAGNATION

Over much of the fjord, the rivers feed a brackish layer of very variable low salinity (see, for example, Gage, 1972) which has a mean seawards motion as shown by Wood *et al.* (1973). At the base of this layer is the primary halocline, below which a return layer of intermediate salinity moves landwards replacing salt entrained into the brackish layer. The base of the return layer is marked by a secondary halocline, below which stagnating water of slowly varying salinity and temperature normally shows slowly decreasing dissolved oxygen levels, and currents of the order of a few centimetres per second. The salinity of the brackish and return layers is inversely related to runoff; the salinity of the bottom water is usually near 28 ‰, falling by 1‰ per year and is apparently unrelated to runoff.

The relation between salinity, S, in the brackish and return layers may be linearized by using the time-varying runoff $f(t)$ convoluted with a temporal weight function $a(T)$:

$$S = S_0 - k \int_0^\infty a(T)\, f(t-T)\, \mathrm{d}T \qquad (1)$$

with

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

The variables S_0 and k are functions of position only. The use of this equation is implicit, for example, in the work of Ketchum *et al.* (1951) who, in the New York Bight, examined a box function

$$a = 1/30\ \mathrm{d}^{-1}; \qquad 0 < T \leqslant 30\ \mathrm{d}$$
$$a = 0; \qquad T > 30\ \mathrm{d}$$

In Etive, as in the Bight, a function of such simple step shape fails to linearize the relation between runoff and salinity. Assuming that any part of the system, excluding the bottom water, may be treated as a well mixed box with constant outflow, varying inflow of fresh water proportional to runoff, and the remainder of inflow as sea water of some constant salinity, leads directly to the generality that $a(T)$ must be an exponentially decaying function of T. In particular, at the saddle of the innermost sill, it was found from 50 surveys of the fjord in 1971-1972 that (1) is a good predictor of S when

$$S_0 = 29.75‰$$
$$a(T) = 0.25 \exp(-T/4); \ T \text{ in weeks}$$
$$k = 0.1‰ \text{ per } 10^6\ \mathrm{m}^3$$

so that

$$S_s = 29.75 - 0.025 \int_0^\infty f(t-T) \exp(-T/4)\, \mathrm{d}T \ \pm 0.9‰ \qquad (2)$$

The temperature of the return flow varies approximately sinusoidally between 7° and 14°, following local coastal sea conditions. In the brackish layer this cycle is modified towards an earlier lower winter minimum and earlier summer maximum. Cooling is never sufficient to drive a convective overturning to erode the primary halocline, which in winter usually shows about 10‰ change in salinity. In the deep water of the inner basin the temperature is nearly constant during stagnation, showing no seasonal progression. At the sill saddle during 1971-1972, the survey data may be approximated by

$$T_s = 10.15 - 3.35 \cos(2\Pi(t-60)/365) \pm 1\,^\circ\mathrm{C} \tag{3}$$

where t is in days after 1 January.

RENEWAL OF DEEP WATER

The slow variation of deep water salinity and temperature is occasionally interrupted by rapid change. At such time bottom currents increase to tens of centimetres per second, oxygen levels rise to saturation, phosphate and nitrate levels fall to coastal levels, the secondary halocline disappears and bottom density rises. The temperature and salinity of the water which has apparently flushed the basin are close to those (T_S and S_S) of the return water found at the innermost sill and we thus infer a density driven flow of new water from the sill into the deep basin. The cause of this dense water flow is a period of low runoff; its effects are important in determining bottom conditions for months or years afterwards. If low runoff occurs in winter or spring the overflowing water will be cold; if, as is usual, the period of low runoff occurs in summer or autumn, the new water will be warm. If the overflows are rare then some benthic life cycles may be completed in the deep water; if the overflows become more frequent the same life cycles may be disrupted by the high speeds (70 cm/s is the maximum observed near the bottom) found in the density current, by the fluctuations of temperature and salinity, and by sediment transport. If the temperatures of the new and old waters are very different then the rapid changes which accompany mixing may disturb pelagic or planktonic stages of plants and animals found in the bottom water.

A MODEL OF RENEWAL

Following Welander (1974) the following set of equations has been adopted and called a model.

Let bottom salinity be S_B, temperature T_B, density R_B. Then, in stagnation, diffusion changes bottom water towards sill water, so that

$$\left.\begin{aligned} \frac{\partial S_B}{\partial t} &= -k_S(S_B - S_s) \\ \frac{\partial T_B}{\partial t} &= -k_T(T_B - T_s) \end{aligned}\right\} R_s \le R_B \tag{4}$$

At renewal ($R_S > R_B$), ignoring the entrainment of old water by new water,

$$\begin{aligned} S_B &= S_s \\ T_B &= T_s \end{aligned} \tag{5}$$

The equation of state,

$$R = R(S, T) \qquad (6)$$

has been used in the form given by Lafond (1951). Lastly (2) and (3) have been used applied to the runoff data of 1964-1975. Part of the solution of this set (2)-(6) is shown in Fig. 1. The figure also shows some of the data of 1971-1972 from which the empirically determined constants k, k_T and k_S have been found:

$$k_T = 0.5 \text{ year}^{-1}; \qquad k_S = 0.2 \text{ year}^{-1}$$

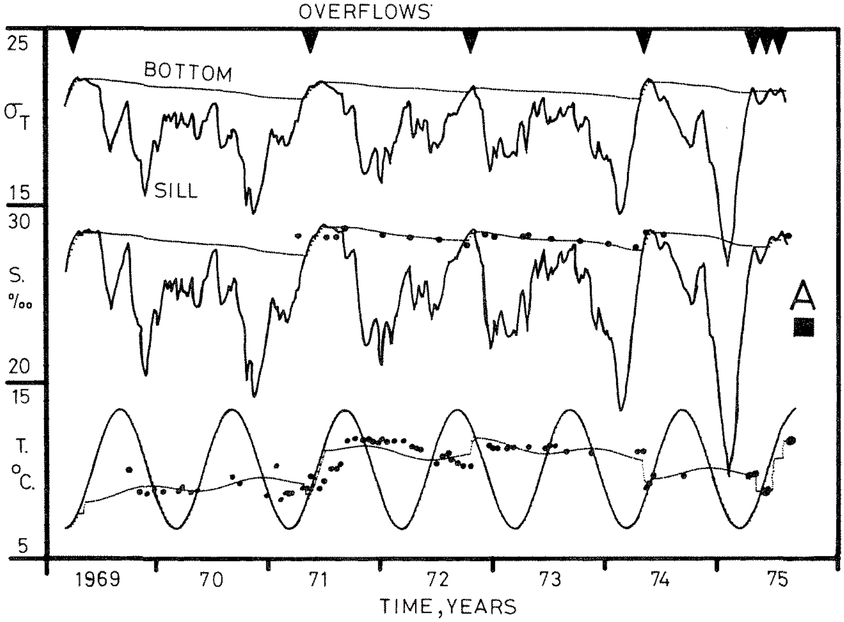

Fig. 1 – The modelling of salinity (S), temperature (T) and density (σ_T) at the inner sill and in the bottom water of the inner basin during 1969-1975. The model was calibrated using 1971-1972 data. Field data (some shown by spots) verify the model during the rest of the period. Renewal is by overflow of dense water at the times shown.

Outside 1971-1972, the model agrees well with observations and thus there is some confidence in extending the hindcasting to 1964 so as to examine all renewals which occurred during the period of operation of the hydroelectric schemes. The mean time between renewals is 1 year and 4 months, with a range from a few months to 2½ years.

SENSITIVITY TO CHANGES IN RUNOFF PATTERN

The primary influence on density in the fjord is salinity, so that in what follows temperature is ignored; its variation is in any case beyond the influence of hydroelectric schemes. Equation (2) shows that the sensitivity of sill salinity to the convoluted runoff is 0.1‰ per 10^6 m^3 per week, so that the potential effect of the 80 × 10^6 m^3 Awe storage is 8‰ weeks. This means that sill salinity could by appropriate discharge of stored water be reduced by 1‰ for 8 weeks or 2‰ for 4 weeks or by any reduction (r) for some period (dt) such that the integral $I = \int^{t} r \, \mathrm{d}t \leqslant 8‰$ weeks. The area A in Fig. 1 shows the maximum value of the integral I. The maximum extent of alteration of sill salinity may thus be related to storage capacity in the runoff system once k has been found.

The effect of releasing stored runoff during a dry period is shown in Fig. 2. Sill salinity may be depressed so much that renewal does not occur. This behaviour could be imagined for the salinity-time curve of Fig. 1. By using A, the peaks of sill salinity on some occasions could be removed sufficiently to prevent renewal. If this is done, the maximum possible mean time between renewals increases to 3 years. Conversely, if one imagines area A used to accentuate sill salinity peaks, one obtains a minimum possible mean time of 1 year. In practice runoff control is not closely correlated with sill salinity, and if the equations (2)-(6) are solved using

$$f = n + En/A \quad 10^{6}\ \mathrm{m}^{3}\ \text{per week}$$

as an estimate of the runoff which would exist in the absence of hydroelectric schemes, one extra renewal is found in the period 1964-1975, and the mean time decreases to 1.2 years.

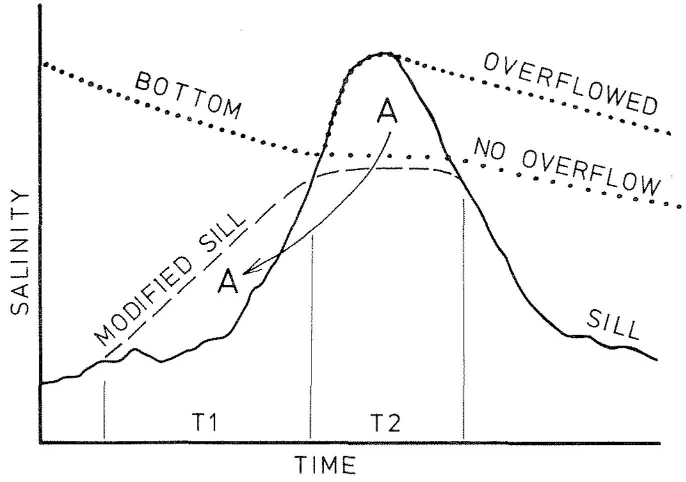

Fig. 2 – Prevention of renewal by runoff shifting. Runoff stored during time $T1$ may be released during $T2$ so as to depress sill salinity and hence prevent overflow. The maximum possible area A is determined by the storage B available and the (salinity/runoff rate) sensitivity k. $A \leqslant Bk$.

In conclusion, the estuary-river system is very sensitive to changes in runoff pattern, but the magnitude and timing of man's interference have to date been sufficient only to increase the mean time between renewals by an insignificant amount. Where larger modifications of a similar fjord system are planned, or where precipitation and hydroelectric cycles are well correlated, the nonlinearities should be very noticeable and the model is expected to be useful once the empirical constants, k, k_{S} and k_{T} have been determined.

Acknowledgement. The officers of the North of Scotland Hydro-electric Board are acknowledged for their constant and willing provision of data.

REFERENCES

Gage, J. (1972) Community structure of the Benthos in Scottish sea-lochs. I. Introduction and species diversity. *Mar. Biol.* **14**, 281-297.

Ketchum, B.H., Redfield, A.C. and Ayers, J.C. (1951) The oceanography of the New York Bight. *Pap. phys. Oceanogr. Meteorol.* **12**(1), 46 pp.

Lafond, E.C. (1951) Processing oceanographic data. *H.O. Publ. no. 614,* US Navy Hydrographic Office, Washington, D.C., USA.

Welander, P. (1974) Two layer exchange in an estuary basin, with special reference to the Baltic Sea. *J. Phys. Oceanogr.* **4**(4), 542-556.

Wood, B.J.B., Tett, P.B. and Edwards, A. (1973) An introduction to the phytoplankton, primary production and relevant hydrography of Loch Etive. *J. Ecol.* **61**, 569-585.