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OBSERVATIONS AND MODEL SIMULATIONS OF WATER CIRCULATION AND TRANSPORT IN LOCH FYNE, A SCOTTISH FJORD

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ABSTRACT

A non-linear, two-dimensional laterally-integrated, baroclinic numerical model was applied to investigate the water circulation and transport of pollutants in a Scottish fjord, Loch Fyne. The model was calibrated against current meter, Acoustic Doppler Current Profiler (ADCP), and salinity data collected from November 1994 - February 1995, and is shown to reproduce the tidal constituent characteristics, and the main features of the measured current and salinity data. Tidal currents across the sill were found to be dominated by the M2 tide, with little vertical variability in amplitude or phase. The circulation in the upper basin was also strongly tidal, but also exhibited strong fluctuations in response to wind forcing and river runoff.

The model was employed to investigate water circulation and transport processes in the loch. Calculations of volume flux through three lateral cross-sections showed that variability in the total transport through the sections was dominated by low-frequency fluctuations in water level. Variance in the transport of buoyancy through the cross-sections, however, was dominated by local wind forcing, with 97% of the variance in buoyancy transport through the mouth of the fjord being related to wind speed and direction.

Simulations using a passive tracer to investigate the transport, accumulation and removal of discharged contaminants within the loch are described. Simulations of a continuous source of tracer into the surface layer (where most contaminants are likely to be discharged) showed that at the end of the 94-day simulation, 75.5% of the discharged tracer had been exported from the system. A small proportion of the released tracer, 3.8%, had entered the deep water behind the sill. The remainder was located in the loch waters above sill depth. A follow-on 94-day simulation, with the tracer source switched off, demonstrated the relatively slow exchange of the deeper water behind the sill compared to the water above sill depth. The turnover time for the basin water behind the sill was estimated at 52 days. However, the deepest water in the basin had a turnover time greater than 94 days.

Complete advective renewal of the deep water behind the sill did not occur during the observation period. Model results suggest that although water of sufficient density to replace the basin water was often present in the outer fjord, mixing during transit across the sill reduced the density sufficiently to inhibit renewal.
1. INTRODUCTION

The fjordic sea lochs on the western seaboard of Scotland have long been considered as pristine environments, with minimal anthropogenic impact and exhibiting exceptional water quality amongst European coastal waters. In recent years, concern has grown over the increase of pollutants discharged into this environment. The growth of the mariculture industry, which is concentrated in the sea lochs of the west coast, has caused particular concern. In Loch Fyne, one of the largest Scottish lochs, the industry has expanded to a total licenced salmon production of about 6,000 tonnes per annum. To understand and predict the dispersion of discharged pollutants, it is first necessary to understand the water circulation and transport mechanisms of the system. To this end, a two-dimensional, laterally integrated numerical model, suitable for simulating the water circulation in fjords (Elliott et al., 1992; Gillibrand et al., 1995) has been applied to Loch Fyne and used to investigate the water circulation and exchange of the system.

Loch Fyne is situated in the southwest of Scotland and extends 64 km northwards from its mouth on the Firth of Clyde to its head, with an average width of almost 3 km (Fig. 1). In the upper reaches above the outer sill, the width is generally less than 2 km. The loch has two sills, the first is 36 m deep and located about 24 km from the mouth, the second 42 m deep about 36 km from the mouth. The two basins behind these sills have maximum depths of 64 m and 135 m respectively. Between the outer sill and the mouth, water depths reach up to 200 m. The tide in Loch Fyne is predominantly semi-diurnal with a mean spring range of 3.1 m and a mean neap range of 1 m. The catchment area of the loch is 894 km² which results in a mean annual freshwater runoff of 1340.4 x 10⁶ m³ (Edwards and Sharples, 1986). Much of this freshwater comes from surrounding hills to the north and east, where the response to rainfall is very rapid and the river flow therefore very variable.

2. OBSERVATIONS

Data on currents, water level and water properties in Loch Fyne were collected in late 1994 and early 1995. Two Aanderaa RCM-7 current meters and an RDI upward-looking, narrow band, self-contained acoustic doppler current profiler (SC-ADCP) were deployed in Loch Fyne from November 1994 to February 1995. The current meters were deployed on a U-type mooring in the upper basin of the loch (Fig. 1), with the meters lying at depths of 9 m and 50 m below mean sea level in a water depth of 60 m. The current meters were suspended below sub-surface buoyancy to minimise wave effects on the data. At 30 minute intervals, the RCM-7s recorded orthogonal horizontal components of velocity, which were subsequently resolved to along- and across-channel flow, temperature and conductivity (which were used to calculate salinity based on the Practical Salinity Scale 1978). The 300 kHz SC-ADCP was deployed in 56 m of water between the two sills (Fig. 1) and measured velocity in 11 bins, each 4 m high, every 15 minutes. The velocity bins were centred at heights above the seabed ranging from approximately 6 m to 46 m. The measured north and east components of velocity were also resolved into along- and across-channel flows. Details of the current data are given in Table 1.

Following manual inspection for erroneous data values, analysis of the current data, from both the RCM-7s and the SC-ADCP, consisted of tidal analysis and low-pass filtering. The former was performed using Fourier techniques described by Jenkins and Watts (1968) to determine amplitudes and phases for 13 tidal constituents (Table 2). The data were low-pass filtered using a digital filter described by Godin (1967), with a half-power point at 30 hours. The measured and low-pass filtered data were resolved into along- and across-channel flows.
Surveys of temperature and salinity were conducted using a Neil Brown Instrument Systems ‘Smart’ Conductivity Temperature Depth (CTD) probe during the deployment and recovery cruises on 20-21 November 1994 and 21-22 February 1995. Depth profiles were made at 17 stations spaced regularly along the axis of the loch (Fig. 1). Transverse sections were also made which confirmed the lateral homogeneity of the water column. Water samples were collected for salinity analysis for CTD calibration. Temperature and salinity profiles were taken from the downcast of each station. Processing of the data included the application of a median filter (Sy, 1985) and, where necessary, manual editing of spikes.

Wind data for the period were obtained from the Meteorological Office for the station at Machrihanish (Fig. 1). An Aanderaa Meteorological Buoy was deployed adjacent to the SC-ADCP mooring but the instrument failed midway through the deployment. Comparisons of the surviving data show a reasonable correlation between the locally measured wind and the Machrihanish data that were used to drive the model (r² = 0.44 and 0.59 for North and East wind velocity components respectively). River flow data were obtained from the Scottish Environment Protection Agency for the River Falloch, which flows into the nearby Loch Lomond, and were converted into values suitable for Loch Fyne by weighting the data according to the relative catchment areas. An Aanderaa WLR-5 water level recorder was deployed with the current meter mooring and provided data for the surface oscillation. Following recovery, the data were regressed against data measured at Tarbert from a previous deployment, and the regression applied to provide surface oscillation data suitable for the mouth of the fjord. This was done, rather than using tidally -predicted water level, to ensure that low-frequency fluctuations in water level were included in the boundary condition.

3. MODEL DESCRIPTION AND IMPLEMENTATION

The model used in this study is a two-dimensional, laterally integrated numerical model. Because most sea lochs are very narrow relative to their length, water movements across the loch are considered to be of secondary importance (the Rossby radius of deformation is much greater than the width of the loch). In such cases, two-dimensional models which resolve longitudinally and vertically are able to simulate the most important features of the circulation. Two-dimensional models have been widely used to investigate circulation in fjordic estuaries (eg Dunbar and Burling, 1987; Lavelle et al., 1991; Stacey et al., 1991, 1995; Stacey and Pond, 1992). The basic model used in this study has been described previously by Elliott et al. (1992) and Gillibrand et al. (1995). The non-linear, laterally integrated governing equations are:

Equation of Continuity:

\[ \frac{\partial}{\partial x} (uB) + \frac{\partial}{\partial z} (wB) = 0 \]  \hspace{1cm} (1)

\[ \frac{\partial}{\partial t} (B\eta) + \frac{\partial}{\partial x} \int_{-h}^{h} (uB) \, dz = 0 \]  \hspace{1cm} (2)
Momentum Balance:

\[
\frac{\partial}{\partial t} (uB) + \frac{\partial}{\partial x} (u\nu) + \frac{\partial}{\partial z} (uwB) - \frac{\partial}{\partial x} \left( BN, \frac{\partial u}{\partial x} \right) - \frac{\partial}{\partial z} \left( BN, \frac{\partial u}{\partial z} \right) + ku |u| \left( 1 + \left( \frac{\partial B}{\partial z} \right)^2 \right)^{1/2} + Bg \frac{\partial \eta}{\partial x} + \frac{Bg}{\rho_0} \frac{\partial}{\partial x} \int_0^z \rho d\zeta' = 0
\]

(3)

Salt Balance:

\[
\frac{\partial}{\partial t} (SB) + \frac{\partial}{\partial x} (uSB) + \frac{\partial}{\partial z} (wSB) - \frac{\partial}{\partial x} \left( BK, \frac{\partial S}{\partial x} \right) - \frac{\partial}{\partial z} \left( BK, \frac{\partial S}{\partial z} \right) = 0
\]

(4)

Equation of State:

\[
\rho = \rho_0 (\alpha + \beta S)
\]

(5)

where \(x, z\) are the longitudinal and vertical coordinates respectively, with \(z\) positive downward; \(u, w\) are the corresponding velocity components; \(S\) is the salinity; \(\eta\) the surface elevation (positive upwards); \(B(x, z)\) the width of the channel; \(H\) the undisturbed depth; \(K_x, K_z\) are the horizontal and vertical eddy diffusivity coefficients; \(N_x, N_z\) the horizontal and vertical eddy viscosity coefficients; \(k\) is the boundary friction coefficient; \(g\) the acceleration due to gravity; \(\rho\) and \(\rho_0\) are the density and a reference density respectively; and \(\alpha\) and \(\beta\) are constants (Wang and Kravitz, 1980).

The model employed in this study was fully non-linear, unlike that employed by Gillibrand et al. (1995) which had the non-linear advection terms removed. The vertical eddy viscosity and diffusion coefficients are determined using the level 2.5 turbulence closure sub-model of Mellor and Yamada (1982), but with the length scale, \(l\), specified following the method of Stacey et al. (1995) i.e.

\[
l = 0.105 (H + \eta) \text{erf} \left[ \frac{\kappa}{0.105} \sqrt{\Pi} \left( \frac{H - \eta}{2 (H + \eta)} \right) \right] x \text{erf} \left[ \frac{\kappa}{0.105} \sqrt{\Pi} \left( \frac{H - \eta}{2 (H + \eta)} \right) \right]
\]

(6)

where \(\kappa = 0.4\) is von Karman’s constant. The vertical diffusion coefficients are calculated from the length scale, turbulent kinetic energy and stability functions as described by Mellor and Yamada (1982). Following Stacey et al. (1995), lower bounds were placed on the vertical diffusion coefficients. These bounds were dependent on the local stratification, with the minimum vertical diffusivity set by

\[
K_v = a_0 N^{-1.5}
\]

(7)

where \(N\) is the local Brunt-Väisälä frequency and \(a_0\) is a constant (Stacey et al., 1995). A series of calibration simulations resulted in a value of \(a_0\) of \(1.8 \times 10^{-5}\) cm \(^2\) s \(^{-5/2}\). This gave minimum values of \(K_v\) of about \(1.0\) cm \(^2\) s \(^{-1}\) in the deep basin and \(0.005\) cm \(^2\) s \(^{-1}\) in the strongly stratified surface layer.

Horizontal diffusion coefficients were held constant and specified to be \(10^2\) m\(^2\) s\(^{-1}\). Horizontal advection of salinity was simulated using the hybrid advection scheme described by James...
(1986), which modifies the centred differencing by introducing an increasing element of upwind differencing as the salinity gradients sharpen.

**Passive Tracer Simulation**

In this paper, some simulations illustrating the transport of a passive tracer are described. The advection and diffusion of the tracer concentration, \( C \), was treated analogously to that of salinity ie:

\[
\frac{\partial CB}{\partial t} + \frac{\partial u CB}{\partial x} + \frac{\partial w CB}{\partial z} + \frac{\partial}{\partial x} \left( BK_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial z} \left( BK_z \frac{\partial C}{\partial z} \right) = P_s
\]

(8)

where \( P_s \) is a tracer source. The values of the diffusion coefficients, \( K_z \) and \( K_x \), were the same as those used for the diffusion of salinity.

**Boundary Conditions**

The model was forced by time series of observed along-channel wind stress (resolved from the Machrihanish data), river runoff and surface tide. At the open boundary, salt input from the adjacent coastal ocean was estimated by linear interpolation between the salinity profiles measured at the mouth of the fjord during the two field surveys. During flood currents, the measured salinity values are prescribed with a linear adjustment period of one hour. During ebb currents, an upstream advection scheme is implemented. The initial salinity distribution within the loch was specified based on the field data of 20-21 November 1994.

At the seabed, bottom stress \( \tau_b \) was made quadratic in velocity ie

\[
\tau_b = \rho k |u_b|
\]

(9)

where \( u_b \) is the velocity at the grid point closest to the seabed. The friction coefficient, \( k \), was set to 2.5\( \times \)10^{-3}. At the sea surface, the wind stress was defined by

\[
\tau_w = \rho_a C_D U_w |U_w|
\]

(10)

were \( \rho_a \) is the air density (1.2 kg m^{-3}), \( U_w \) is the along-loch wind velocity (m s^{-1}) and the wind drag coefficient, \( C_D \), was made dependent on wind speed and defined by (Lavelle et al., 1991):

\[
C_D = \begin{cases} 
1.1 \times 10^{-3}, & 0 < |U_w| < 6 \text{ m/s} \\
(0.72 + 0.063 |U_w|) \times 10^{-3}, & 6 \text{ m/s} \leq |U_w| \leq 22 \text{ m/s}
\end{cases}
\]

(11)
Model Grid

The equations are solved on a cartesian grid using finite difference approximations (Elliott, 1976; Wang and Kravitz, 1980). In the present case, Loch Fyne is modelled using a grid consisting of 17 columns and a maximum of 19 rows (Fig. 2a). The horizontal grid spacing is 2 km. The vertical spacing between grid rows can be varied, thus allowing good vertical resolution near the surface without necessitating an excessive number of grid points to cover the deep basins. The water surface is allowed to pass through the surface grid rows (Hamilton, 1975; Gillibrand et al., 1995), so that the tide can be simulated without having to increase the spacing of the near surface rows. Thus, the grid itself is a variable and grid points are included and excluded from the grid as the water surface rises and falls. In the present model, the vertical spacing increases from 2 m near the surface to 20 m in the deeper water. The model incorporates real bottom topography through the specification of the channel width at each grid point. The model used a time increment of 60 seconds.

4. MODEL CALIBRATION

The model was calibrated against the velocity and salinity data obtained from Loch Fyne between November 1994 and February 1995. To initialize the simulations, the initial salinity field was held fixed while the velocity field was “spun-up” for the 3-day period 18-21 November. The salinity was then allowed to evolve over the 94 day simulation from 21 November to 23 February. The initial salinity field of 20-21 November, as measured and interpolated onto the model grid, is shown in Figure 2b. The boundary forcing time series of wind vectors, surface oscillation and freshwater runoff are shown in Figure 3.

Axial Salinity Distribution

The model was first tested by comparing the predicted salinity field at the end of the simulation with the observed field in February 1995. Both simulated and observed fields are presented in Figure 4. The agreement is generally good. The model has maintained the brackish surface layer, although the simulated layer is slightly shallower than that observed, and has simulated the freshening of the deep basin water behind the sill that had occurred since the initial survey (Fig. 2b). The root-mean-square (RMS) error between the observed and predicted salinity fields is 0.67, which is acceptable given the range of salinity simulated (20-33.2) and the strength of the vertical gradients, which can introduce significant errors for relatively minor discrepancies in model performance.

Tidal Current Analysis

The performance of the model in simulating the tidal circulation was then assessed. The observed and simulated current data were harmonically analysed for the 13 constituents listed in Table 2. In this paper, results for the six largest constituents (O₁, K₁, M₂, S₂, N₂ and M₄) are presented. Vertical profiles of the observed and simulated profiles of constituent amplitude and phase at the SC-ADCP position are shown, and results are also compared for the current meter locations. All the velocity data discussed in the following are the along-loch components.

Vertical profiles of the measured and modelled amplitude of the six tidal constituents are presented in Figure 5a. The model profiles extend from 5 m depth to 47 m, whereas the observed profiles extend from 10 m - 50 m. This is because the vertical locations of the model grid points and SC-ADCP bins are not coincident. The M₂ and S₂ modelled profiles show good agreement with the observations, although there is some deviation in the lower part of the M₂ amplitude profile. The simulated amplitudes for N₂ and O₁ are of the correct
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magnitude, but again there is some deviation from observed values near the surface and bottom of the N2 profile. The comparison between modelled and observed K1 and M4 again shows good agreement for the constituent amplitudes.

The profiles of phase also show generally good agreement between model predictions and the observations (Fig. 5b). The profiles of M2 and S2, the dominant constituents, show very good agreement. There is some discrepancy for the O1 phase, although the comparison is good for the N2 profile. The agreement for the K1 profile is variable, with the model exhibiting more depth variability than observed. The simulated M4 profile agrees well with data in the upper part of the water column but drifts away from the data in the lower part.

The amplitude profiles in Figure 5 demonstrate that the tidal currents over the sill in Loch Fyne are dominated by the semi-diurnal components, and in particular by the M2 tide which is a factor 3-4 greater than the next largest constituent (S2). The ratios of tidal current amplitudes are in direct proportion to the tidal height constituents, suggesting that the flow over the sill is dominated by the linear barotropic tide. This is also indicated by the vertical homogeneity of the amplitude and phase profiles.

The data from the current meters deployed in the upper basin and the model output from the corresponding positions were also analysed for tidal constituents. These results are presented in Table 3. The agreement is less good than the comparison with the SC-ADCP data, with observed M2 amplitudes at both depths being 30-50% greater than the simulated amplitudes. This is probably caused by greater spatial variability of velocity in the basin than over the sill, where the constriction is likely to produce more vertical and lateral homogeneity. It is interesting to note that the semi-diurnal constituents in the deep water had amplitudes more than 50% greater than the near-surface values. The model successfully reproduced this amplified signal, albeit at the reduced simulated amplitudes.

Time Series of Velocity and Salinity

Finally, the performance of the model compared to the time series of along-channel velocity and salinity in the upper basin was examined (Fig. 6). The time series reveal that the model showed fairly good agreement with both the near-surface and near-bed velocity data, and reproduced most of the major velocity events. Some of the higher frequency fluctuations were not captured by the model, but given the difficulties of comparing laterally integrated model results against the point measurements of current meter data, and the relatively coarse model grid used in this study, the velocity time series from surface and bottom compare satisfactorily. The aim of this study is to investigate the non-tidal transport and flushing of contaminants from Loch Fyne, and for this purpose it is of greater importance to reproduce the lower-frequency velocity signal, which the model does. With regard to salinity, the model simulation reproduced the main features of the evolution of the near-surface and near-bed salinity and, as shown earlier, the final predicted salinity field compared well with the observed field. Again, however, the model appears to miss much of the higher frequency in the salinity time series, where strong tidal fluctuations were apparent in the data. This is again likely to be due to the fairly coarse resolution of the model, but since the long-term evolution of salinity is reproduced, the important events in contaminant dispersion should be simulated.

Simulations of Water Exchange and Transport

Volume and buoyancy transport

One of the motivations for this study was to investigate the transport of waste materials from Loch Fyne. The model was therefore used to examine the volume transport through the
mouth of the fjord and across the two internal sills (Fig. 1). During the 94-day calibration simulation described above, hourly means of the volume transport across the sills and through the mouth were recorded and the results then low-pass filtered to investigate the mechanisms affecting the residual (ie non-tidal) flux of water. By altering the boundary forcing of the model (ie the wind stress, fresh water runoff and surface oscillation) and rerunning the simulation, the contribution of each forcing mechanism to the transport was evaluated. Four initial simulations were performed: 1) a baseline run, ie the full calibration simulation; 2) a simulation with constant runoff; 3) a simulation with constant wind stress; and 4) a simulation with tidally predicted surface oscillation, ie without low-frequency fluctuations in water level. The values chosen for the constant runoff and constant wind forcing simulations were the mean values of those variables over the period of the simulations ie 21 November 1994 - 23 February 1995. The tidally predicted surface oscillation time series was generated by inserting the results of the tidal analysis of water level (Table 2) into a tidal prediction software package (Foreman, 1978).

The variances of the low-pass filtered along-channel volume transport across the three sections were calculated for each simulation. By holding individual forcing mechanisms constant, the variability introduced into the simulation by that mechanism is removed from the resultant time series of transport. The reduction in variance in the resulting time series gives an indication of the importance of the mechanism to the transport. The percentage reduction in variance, $R$, is calculated simply by:

$$R = \frac{\sigma_B^2 - \sigma_S^2}{\sigma_B^2} \times 100$$

(12)

where $\sigma_B$ and $\sigma_S$ are the calculated standard deviations for the baseline simulation and the test simulation respectively. This approach neglects non-linear interactions between the various forcing mechanisms, but should give a broad indication of the relative importance of wind, runoff and tidal forcing to volume transport in the loch.

The results of the volume transport simulations are given in Table 4. The mean transport for each simulation through the mouth and across each sill was typically 43 m$^3$s$^{-1}$, which corresponded well with the mean river flow into the system over the simulation period (42 m$^3$s$^{-1}$), showing the the model is conserving volume well. Table 4 shows that the variance in depth-integrated volume transport was dominated by low-frequency fluctuations in the water level. At the inner sill, the simulation with a constant river flow reduced the variance by about 25%, indicating that variability in the freshwater input had a tangible effect on volume transport variance in the upper part of the loch. However, the effect gradually diminished further seaward and reduced the transport variance by only 2% at the mouth of the loch. Wind forcing had only a small effect on volume transport at all three crossections. The strong surface flows induced by wind forcing are compensated by deeper flows in the opposite direction, so that the net transport remains small. Removing the low-frequency fluctuations in water level reduced the variance by 74%, 90% and 98% at the inner sill, outer sill and the mouth respectively, indicating that the variance in volume transport through the mouth and across the sills of Loch Fyne was dominated by external fluctuations in water level (eg due to storm surges) propagating into the fjord.

Since much of the soluble waste material discharged into Loch Fyne (and coastal water in general) is discharged into the near surface layers, further simulations were performed using freshwater as a tracer. The buoyancy transport, $Q_F$, through the mouth and across the sills was calculated by
\[ Q_F = \int_0^H Bu \left( S_o - S \right) \frac{dz}{S_o} \quad (13) \]

where \( H \) is the water depth, \( S(z) \) is the salinity and \( S_o \) is the ocean salinity, specified for these calculations as the salinity at the deepest grid point at the mouth of the estuary. The same simulations as described above were performed and the results are shown in Table 5.

Variability in the buoyancy transport was dominated by wind forcing. The baseline variance was reduced by 97%, 87% and 87% respectively through the mouth and across the outer and inner sills when the wind stress was held constant. A constant freshwater input also had a significant effect on the variance at the two sills (reduced by 21% and 18% at the outer and inner sill respectively), but was still much less important than the wind stress. The low-frequency variability in the water level had a negligible effect on the buoyancy transport. In fact, the variance across the two sills was greater with the predicted tide than for the baseline run. This was because on certain occasions during the baseline simulation, the small transport due to the surface oscillation opposed and therefore reduced the wind-driven flux. When that small transport was removed in Simulation 8, the variance in the transport increased.

These simulations of the buoyancy transport suggest that dispersion and removal of contaminants discharged into the surface layer of the fjord, and thereby associated closely with the brackish water, will be dominated by the wind-driven circulation. A contour map of the daily-mean buoyancy transport through the mouth of Loch Fyne, plotted against components of the daily-mean wind velocity for the 94-day baseline simulation described above, is presented in Figure 7. The zero transport contour occurs when the wind is generally weakly northward and therefore opposing the baroclinic circulation. However, if the eastward component of wind forcing is greater than about 5 m s\(^{-1}\), the model suggests the northward component has much less influence on the positive (eastward) buoyancy transport and can increase considerably without reversing the transport. The strongest seaward transport occurs when winds are from the northwest, and the strongest landward when the winds are from the southeast. Southwesterly winds are predominant in the southwest of Scotland, and these have variable effects on the transport through the mouth, depending on the precise strength and direction of the wind.

**Effect of wind direction on water circulation**

The simulations described above show that wind forcing dominates the transport of freshwater and associated material across the sills and through the mouth of the loch. The model was therefore used to examine the effect of different wind direction on the non-tidal circulation in the loch. For these simulations, the model was initialised with the salinity distribution shown in Figure 2b and spun-up as described previously. The runoff and water level boundary forcing for the baseline simulation were maintained, but the wind speed was kept constant at 4.5 m s\(^{-1}\), corresponding to the mean speed over the 94-day measurement period. Four such simulations were performed, with wind directions from the south-west, south-east, north-east and north-west respectively. These directions were chosen to be most closely aligned with the orientation of the main axis of the loch. The wind forcing was maintained for two days (50 hours) only, since in reality a steady wind direction is rarely maintained for longer. Current velocities at each grid point were averaged over the final 25 hours of the simulation to remove the M2 tidal oscillations and provide approximate non-tidal current vectors. These results are presented in Figure 8.

Not unexpectedly, the different wind direction induced different circulation patterns, particularly in the near-surface layers. Both north-westerly and north-easterly winds, blowing seaward along the two arms of the loch, produced a strong surface outflow, and a relatively strong compensating inflow at mid-depth over the sills. The surface currents in the upper
basin of the loch were significantly stronger under the influence of the north-easterly wind, which was most closely aligned to the longitudinal axis of the upper loch. The stronger surface currents rapidly advected surface brackish water seawards, resulting in higher surface salinities than under north-westerly winds. Both northerly wind directions produced a strong surface outflow in the outer part of the loch and a fairly strong inflow across the sill at mid-depth. The buoyancy flux through the mouth of the loch was strongest under north-westerly winds (Fig. 7), which is demonstrated here by the very strong near surface currents at the mouth of the loch.

The near-surface circulation patterns resulting from southerly wind forcing are markedly different from those described above. South-westerly winds reversed the residual surface currents along almost the entire length of the loch, so that at the surface currents were landward and the seaward circulation had been forced deeper. The landward currents in the surface layer prevented brackish water from leaving the upper basin, and salinities were very low (S~18) at the head of the loch. South-easterly winds also produced a reversal of the typical estuarine circulation in outer basin of the loch, but in the upper basin, where south-easterly winds are approximately normal to the main axis of the loch, the surface currents were seaward and the normal estuarine circulation was reestablished. At the outer sill, this surface outflow dived below the inflowing surface waters in the outer loch. In the upper basin, the brackish surface layer was clearly defined along the length of the basin, but salinities were higher than predicted under north-westerly winds. Figure 7 suggests that south-easterly winds with a speed greater than about 2-4 m s\(^{-1}\) produced a negative (ie landward) buoyancy flux through the mouth of the loch. This is supported here, where the residual currents in the surface 10 m layer at the mouth of the loch are strongly landward. Figure 7 suggests that the situation is more ambiguous for south-westerly winds with speeds of about 4 m s\(^{-1}\), with either seaward and landward buoyancy fluxes possible depending on the strength of the eastward component of the wind. As shown in Figure 8, predicted residual currents at the mouth of the loch are much weaker under the simulated south-westerly winds, but in this simulation appear to have produced a landward buoyancy flux.

The surface circulation in Loch Fyne appears to respond relatively quickly to wind forcing. However, it is noticeable from Figure 8, that the deeper circulation remains the same under all four wind forcing conditions. The deeper circulation shows a weak residual circulation in the outer basin, an inflow across the sill, and a vertical gyre in the upper basin, with downwelling inside the sill and upwelling at the head of the loch. The short simulations presented here, probably corresponding to real time scales of fluctuations in wind forcing, do not allow sufficient time for the deeper circulation to respond to the development of the surface slope set up by the wind. The deep water circulation does indeed vary, as will be seen in the next section, but it clearly varies on longer times scales than the surface circulation and wind forcing.

**Contaminant accumulation**

Much of the contaminant material entering Loch Fyne will be discharged into the near-surface layer. A set of simulations were performed to investigate the retention of contaminants discharged continuously into the surface water along the length of the loch. The 94-day simulation described earlier was repeated, with real wind, tide and river boundary conditions, and with a steady source of tracer into the surface 10 m from the head of the loch to the mouth. Such a source represents diffuse inputs to the surface layer along the entire length of the system. The total rate of input was 80 kg hr\(^{-1}\), distributed evenly over the upper 5 grid rows (ie 10 m). During the simulation, the mass of tracer retained within each basin and the cumulative mass exported through the mouth were calculated and recorded daily. In addition, the mass accumulating within the deep water behind the sill was also calculated and recorded separately. Conservation of the mass of tracer within the model over the 94-day simulation was tested and found to be 99.2%.
The calculated time series of tracer mass retained in each basin are presented in Figure 9. The total released mass increased steadily during the simulation, with a final total of 180.5 tonnes of material having been released. The mass of tracer within each basin also increased as the simulation progressed, but the rates of increase were variable and included periods when the mass of tracer decreased, illustrating the variability of the exchange of the upper layers in each basin. The mass of tracer declined when material was being exported from the loch basin faster than it was being input, i.e., when exchange was very effective. The exchange of the upper water column varied in response to fluctuations in the freshwater discharge and particularly the wind forcing of the system.

The sharp decrease in retained mass at about day 40 (31 December 1994) was associated with the onset of strong north-westerly winds (Fig. 3), which forced surface water, with high tracer content, out of the fjord. Over this two-day period, the mass of tracer in the loch decreased by about 50%. The tracer distribution and 25-hour mean velocity vectors at this stage of the simulation are presented in Figure 10. On day 40, a large proportion of the tracer was still concentrated within the surface layer and was being rapidly transported seaward by the strong residual near-surface currents generated by the north-westerly wind. Inflowing water at intermediate depths created upwelling at the head of the loch and immediately seaward of the outer sill. The upwelling retained the majority of the tracer in the upper water column, from where it was advected seaward. Thus, north-westerly winds appear to induce the most rapid exchange of material from the upper layers of the system (as suggested by Fig. 7). For the remainder of the simulation, under variable wind and runoff forcing, the mass of tracer in each basin steadily increased.

At the end of the simulation 136.3 tonnes of tracer, i.e., 75.5% of the total mass released, had been exported from the system. The water column above sill depth contained 37.9 tonnes (21.0% of the mass released), most of which was located in the upper basin. The distribution of tracer at the end of the 94-day simulation is shown in Figure 11. The highest concentrations, which exceeded 22.0 µg l⁻¹, were at the head of the loch, where the tracer was accumulating due to the strong south-westerlies prevalent toward the end of the simulation (Fig. 3).

By the end of the simulation, a significant proportion of the tracer had penetrated into the deep water of the upper basin. The rate of accumulation of tracer within that deep water (i.e., below the sill depth of 42 m) is shown in Figure 9. The mass increased steadily, but not at a uniform rate. A period of relatively rapid increase occurred during Days 57-58. The tracer distributions and 25-hourly averaged velocity vectors from that time (Fig. 10) show that the strong southerly/southwesterly winds at the time (17-18 January 1995, Fig. 3) produced a strong landward flow in the surface layer and downwelling at the head of the fjord. The downwelling carried a mass of tracer from the surface layer into the deeper water, some of which penetrated below sill depth. The fluctuating nature of the time series of deep water mass demonstrates that the deep water is not exchanged purely by diffusive exchange but is subject to some advective exchange, at least in the waters closest to sill depth.

At the end of the simulation, 6.8 tonnes of tracer, 3.8% of the total released mass, was located in the upper basin below sill depth. From Figure 11 it is apparent that the bulk of the tracer left in the system remained in the water column above sill depth, but a significant quantity had penetrated into the deep water in the basin. The deep water outside the sill was effectively free of tracer. These simulations indicate that a small proportion of contaminants released into the surface 10 m of the water column in Loch Fyne may eventually reach the deep basin, particularly when periods of strong southerly winds induce downwelling at the head of the loch. Conversely, however, a large proportion of any contaminant released into the surface layer will be removed from the system fairly rapidly.
Contaminant removal

In order to examine the removal of contaminants from the system, the 94-day simulation described in the previous section was repeated with the tracer sources switched off, and using the final tracer distribution from the above simulation (Fig. 11) as the initial tracer field for the new simulation. The removal simulation, therefore, commenced with 35.1 tonnes of tracer within the system initially. The mass retained within the system, and the cumulative mass exported, were again calculated and recorded daily. The mass within the deep water of the upper basin was again recorded separately. This simulation was performed for the full 94 days. The simulated time series are presented in Figure 12.

During the simulation, the retained mass dropped rapidly as material was removed from the system. The strong north-westerly wind event noted previously accelerated the decrease in tracer mass appreciably around day 40. As time progressed, the rate of removal slowed as an increasing proportion of the retained mass was located within the deep water of the upper basin. Advection then began to play a lesser role in tracer removal and diffusive processes became more important. As shown in Figure 13, at the end of the simulation the vast majority of the remaining tracer was trapped in the deep water behind the sill. In total, 2.6 tonnes remained in the system, 7.4% of the initial mass. From the decrease in retained mass (Fig. 12), the turnover time of the loch, defined as the time taken for the tracer mass to fall to a factor $e^{-1}$ of its initial value (Prandle, 1984; Luff and Pohlmann, 1995), for this ‘realistic’ initial distribution of mass, was estimated at 28 days (i.e when the tracer mass became less than 13.0 tonnes). This is significantly greater than the turnover times estimated by Gillibrand (2001) using uniform initial distributions.

The time series of deep water mass showed an initial rise, as tracer continued to enter the deep water from the upper water column despite the cessation of the tracer source at the surface. From Day 19, however, the mass in the deep water dropped steadily. The strong southerly wind event at Day 57-58 discussed above increased the removal rate perceptibly, this time by lifting tracer out of the basin on the strong deep seaward currents (Fig. 10). By the end of the simulation, the deep water mass had fallen to 1.91 tonnes, 28.1% of its initial value. This formed 73% of the mass remaining in the whole loch, and 5.4% of the total initial mass.

Deep water exchange

In order to estimate the exchange of the deep water in greater detail, the 94-day simulation was performed again, with initial contaminant concentrations of 1.0 in the water below sill depth in the upper basin and zero elsewhere throughout the loch. The deep water was therefore being exchanged initially with tracer-free water, unlike the simulation described in the previous section. However, any tracer removed from the deep water into the upper water column was allowed to return to the deep water by advective or diffusive processes. The time taken for the tracer concentration at each grid cell in the deep basin to fall to 0.37 (i.e a factor $e^{-1}$ of the initial concentration) during the simulation was recorded. The results are presented in Figure 13b.

The turnover times for the basin water varied from 2 days at the upper surface behind the sill to over 94 days for the deepest part of the basin (i.e the concentration did not reach 0.37 during the simulation period). There is also considerable variability along the length of the basin, with turnover times of 14 days at sill depth at the head of the loch. This may well be a facet of the simulation, since the first few weeks were dominated by southerly winds which accumulated material at the head of the loch and inhibited dispersion there, increasing turnover times. As might be expected, turnover times increased rapidly with depth, as the basin water becomes more isolated from the general circulation in the loch.
For the basin as a whole, the turnover time given by this simulation was 54 days, five times greater than the mean turnover time calculated for the water column above sill depth in the upper basin (Gillibrand, 2001).

This simulation was repeated 15 times to investigate the variability of the deep water exchange rate, with the start time of the tracer dispersion being moved forward in 3-day steps between simulations. The tracer was thereby dispersed under the differing wind and runoff conditions prevalent when the tracer was released. This methodology follows Luff and Pohlmann (1995) and is described in more detail for the Loch Fyne simulations by Gillibrand (2001). For each simulation, the turnover time for the basin (i.e., the time for the total tracer mass in the basin to fall to \( e^{-1} \) of the initial mass) was recorded. Over the 16 simulations, the basin turnover time varied from 46-55 days, and had a mean value of 52 days. This latter value is probably the best estimate for the turnover time of the upper basin deep water in Loch Fyne, under the conditions of vertical diffusion and weak advection discussed earlier. Strong advective renewal of the deep water is discussed later. Like the surface layers (Gillibrand, 2001) but to a lesser extent, the exchange of the deep basin water exhibited significant variability in response to varying meteorological conditions.

**Freshwater fraction method**

The flushing time of each basin was also estimated using the freshwater fraction method, whereby

\[
T_F = \frac{V_f}{Q_R}
\]

where \( V_f \) is the volume of freshwater in the basin and \( Q_R \) is the riverine flux of freshwater to the basin. The value of \( T_F \) for each basin was calculated on a daily basis, by integrating the freshwater content along the length of each basin and dividing by the river runoff. The results are presented in Figure 14.

The results reflect the high variability in the freshwater inflow to the loch which varied from almost zero to 380 m\(^3\)s\(^{-1}\). Flushing times for the whole loch based on this method varied from 9 to 1151 days. The flushing times for the upper and middle basins were proportionately shorter than for the whole loch as less freshwater is contained in those basins but all the freshwater input is discharged at the head of the loch. However, the results for all basins were consistently higher than the flushing times given by the tracer dispersion simulations described by Gillibrand (2001) and indicate that exchange of the upper layers by freshwater input is a secondary process compared to the tidal- and wind-driven exchange processes.

### 5. DISCUSSION

The current data discussed in this paper have been used principally to calibrate the numerical model, but also reveal some information about the hydrodynamics of this fjord. The observed flow across the sill was strongly barotropic, dominated by the M\(_2\) tide, and exhibited relatively little vertical variability in amplitude or phase. The phase of the M\(_2\) velocity constituent led the phase of the M\(^4\) water level constituent (Table 2) by about 110\(^\circ\) (252\(^\circ\) compared to 001\(^\circ\)), consistent with the tide acting largely as a standing wave with a small progressive element. The current amplitudes of the other constituents were generally proportional to the water level constituent amplitudes (Table 2).
In the upper basin, the results from the tidal analysis of the deep current meter data also conformed to an essentially linear model of the tide, with the velocity amplitudes proportional to the water level constituent amplitudes (Tables 2, 3). However, there was some evidence that energy was being transferred from $M_2$ into the $M_4$ tide, which had a larger current amplitude than would be expected from the water elevation constituent. This energy transfer from the $M_2$ tide into its harmonics often occurs in the presence of non-linear internal tides. There was also a phase lag of 65º between the near-surface and deeper $M_2$ currents. These data suggest that a fairly weak internal tide is generated over the sill in Loch Fyne, although this aspect of the circulation has not yet been investigated fully. The analysis of the model output shows that the model reproduced the relative enhancement of the $M_4$ amplitude and consequent reduction of the $M_2$ amplitude, although underpredicting both. The phase of the near-surface $M_2$ constituent is also predicted less well than the other constituents, suggesting that the model is not fully reproducing all aspects of the internal tide.

The observations of salinity along the axis of the loch presented in this report do not exhibit major differences, even though the measurements were taken 3 months apart. The outer basin of the loch appeared to be dominated by conditions in the Firth of Clyde, which vary relatively slowly. A near surface brackish layer was not strongly evident. In the upper basin, however, salinity distributions were more typically fjordic, with a brackish layer 10-20 m deep and relatively homogeneous water in the deep basin. Baroclinic flows are likely to be significantly stronger in this upper basin than in the outer, where the horizontal density gradients were weak, and the upper basin is more likely to exhibit variability on a time scale of days in response to fluctuations in rainfall and river flow. The interaction between these two differing hydrodynamic regimes across the long sill has not been the focus of this study, but would be of interest as it is likely to affect the advective exchange of the deep water in the upper basin.

The model results described in this paper demonstrated that wind forcing dominates the transport of buoyancy through the mouth and across the sills in Loch Fyne. Removing the variance of the wind forcing reduced the variance of the buoyancy transport through the mouth of the fjord by 97%. It can be presumed that transport of contaminants in the surface layer will be similarly dependent on meteorological conditions. The residual circulation (ie with $M_2$ tidal currents removed as calculated by the model) in the upper part of the water column was found to respond rapidly to wind forcing conditions. Not unexpectedly, given the orientation of the loch, northerly winds produced the strongest seaward surface currents and the most rapid exchange of the near surface layer, with north-westerly winds producing the strongest buoyancy transport through the mouth of the loch. Southerly winds were capable of reversing the surface circulation and blocking the transport of buoyancy from the loch. At mid-depths and deeper, however, the predicted circulation did not respond to the simulated two days of constant wind forcing. The deeper circulation probably fluctuates on much longer time scales than the surface circulation in response to the barotropic pressure gradients created by wind forcing or to fluctuations in density at the mouth of the loch.

The enhanced exchange induced by northerly winds may be of limited effect on contaminant dispersion in Loch Fyne given the dominance of southerly winds over the UK. During this simulation period, winds with a negative northward component (ie southward) were prevalent for only 23.4% of the time. This might suggest that exchange would be blocked on a frequent basis, but the tracer release and removal simulations suggest that exchange of contaminants continues throughout these conditions, albeit at a reduced rate. By the end of the 94-day tracer release simulation, 75% of the discharged tracer had been removed from the system. Previous simulations of surface layer exchange (Gillibrand, 2001) found that the water column above sill depth for the whole loch had a mean turnover time of 10.6 days. A small proportion of the remaining mass (3.8% of the total released mass) had penetrated the deep water of the upper basin. It should be noted from Figure 9, however, that the mass of tracer in the deep water was still increasing at the end of the simulation; a steady state had
Observations and Model Simulations of Water Circulation

not been reached. It is unclear from the present study when a steady deep water concentration would be reached and what proportion of the released mass would eventually enter the deep water.

The tracer removal study also demonstrated that exchange of the system continues, at a variable rate, despite the fluctuations in wind forcing. The underlying exchange mechanism is tidal mixing, which steadily removed tracer from the loch throughout all prevalent wind conditions. Tracer removal was clearly greatest when tidal mixing and wind-driven transport were complementary, which was best demonstrated on days 40-42 (Fig. 12).

**Deep Water Renewal**

Advective renewal of the deep water in Loch Fyne did not occur during the observation period discussed in this paper. Deep water renewal in several other Scottish sea lochs has been shown to be driven largely by wind-enhanced baroclinic circulation during periods of low runoff (eg Edwards and Edelsten, 1977; Gillibrand *et al.*, 1995), with the tidal excursion sometimes a factor (eg Edwards *et al.*, 1980; Allen and Simpson, 1998). Loch Fyne has a deeper sill than most of the sea lochs discussed by previous authors and the mechanisms driving replenishment of the deep water may differ. For example, the influence of freshwater runoff may be less due to the depth of the sill and the smaller tidal range. In shallow-silled fjords with large tidal ranges, intense mixing above the sill means that water emerging from the sill region only remains dense enough to replace the bottom water during periods of low river flow. Renewal events can be closely tied to low freshwater discharge (eg Edwards and Edelsten, 1977; Gillibrand *et al.*, 1995). The deeper sill in Loch Fyne may reduce the influence the surface brackish layer has on deeper inflowing seawater.

Time series of predicted low-pass filtered salinity from four locations, A-D (Fig. 2a), within Loch Fyne, both inside and outside the sill, are presented in Figure 15. The time series are taken from the calibration simulation discussed above. The figure illustrates how the salinity of the water outside the sill (A) is modified as it traverses the sill. The near-surface salinity (C) fluctuated strongly in response to river discharge. The basin water salinity (D) remained steady, gradually decreasing from 32.65 to 32.50. The low-pass filtered salinity at the outer edge of the sill fluctuated between 32.0-33.0, responding both to fluctuations in river flow and wind forcing (eg the strong northwesterly wind event beginning on 31 December produced high salinities outside the sill as the estuarine circulation increased). At times, the salinity (and therefore density) of the water outside the sill exceeded that in the basin by 0.35. However, throughout the simulation, the water emerging from the sill region (B) had a salinity less than that in the basin (Fig. 15) and renewal did not occur. Mixing above the sill seemed to prevent renewal occurring, although there did not appear to be a direct correlation between the dilution of the inflowing water (as indicated by the salinity difference between A and B) and the salinity fluctuation at the surface (C). The density of the water emerging from the sill region appears to be related to other factors in addition to the recent rainfall and river runoff conditions.

The density of the water in the Firth of Clyde at the mouth of Loch Fyne reaches its maximum during late winter/early spring (Rippeth *et al.*, 1995; Rippeth and Simpson, 1996; Midgeley *et al.*, 2001). It is possible that deep water renewal of Loch Fyne may be an annual event, occurring in response to this density maximum of the water entering the fjord from the Clyde. However, without direct observations and modelling of renewal events in the loch, it is not possible to draw further conclusions about the adjective exchange of the deep water in the upper basin of Loch Fyne.
6. ACKNOWLEDGEMENTS

The Scottish Environment Protection Agency provided the runoff data from the River Falloch. Wind data from Machrihanish were purchased from the Meteorological Office, Edinburgh.

7. REFERENCES


Observations and Model Simulations of Water Circulation


TABLE 1

<table>
<thead>
<tr>
<th>Instrument type</th>
<th>Position</th>
<th>Instrument depth (m)</th>
<th>Water Depth (m)</th>
<th>Deployment Duration</th>
<th>Recording interval (min)</th>
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<tr>
<td>SC-ADCP</td>
<td>56 03.30 N 05 17.40 W</td>
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<td>1600 20/11/94 - 1100 25/02/95</td>
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<td>30</td>
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<tr>
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<td>30</td>
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<td>60</td>
<td>1200 20/11/94 - 0900 25/02/95</td>
<td>15</td>
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</tbody>
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TABLE 2
Tidal constituents resolved by the tidal analysis procedure. The amplitudes (m) and phases (º) for the water level data measured in the upper basin are included. The highlighted constituents are presented later for model calibration purposes.

<table>
<thead>
<tr>
<th>Name</th>
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<th>Water Level</th>
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<td>Phase (º)</td>
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<tr>
<td>Q1</td>
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<td>O1</td>
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<tr>
<td>S1</td>
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<td>0.11</td>
<td>196</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K1</td>
<td>23.934</td>
<td>0.11</td>
<td>190</td>
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<td>U2</td>
<td>12.872</td>
<td>0.06</td>
<td>183</td>
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<tr>
<td>N2</td>
<td>12.658</td>
<td>0.24</td>
<td>003</td>
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<tr>
<td>V2</td>
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<td>0.18</td>
<td>052</td>
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<td></td>
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<tr>
<td>M2</td>
<td>12.421</td>
<td>1.18</td>
<td>001</td>
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<tr>
<td>L2</td>
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<td>0.14</td>
<td>078</td>
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<td>K2</td>
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<td>MS4</td>
<td>6.103</td>
<td>0.10</td>
<td>149</td>
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TABLE 3A

Results from the tidal analysis of the observed and simulated near-surface current data in the upper basin. Amplitudes (cm s⁻¹) and phases (°) for the six constituents shown in Figure 5 are presented.

<table>
<thead>
<tr>
<th>Name</th>
<th>Observed</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude (cm s⁻¹)</td>
<td>Phase (°)</td>
</tr>
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<td>O1</td>
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<td>046</td>
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<td>K1</td>
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<tr>
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<td>M4</td>
<td>1.79</td>
<td>016</td>
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</table>

TABLE 3B

Results from the tidal analysis of the observed and simulated near-bottom current data in the upper basin. Amplitudes (cm s⁻¹) and phases (°) for the six constituents shown in Figure 5 are presented.

<table>
<thead>
<tr>
<th>Name</th>
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<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude (cm s⁻¹)</td>
<td>Phase (°)</td>
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<tr>
<td>O1</td>
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<tr>
<td>K1</td>
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<td>6.56</td>
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<tr>
<td>S2</td>
<td>1.50</td>
<td>306</td>
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<tr>
<td>M4</td>
<td>1.01</td>
<td>048</td>
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## TABLE 4

Details and results of the simulations investigating the volume fluxes across the sills and through the mouth of Loch Fyne. The standard deviation (m³ s⁻¹) of the time series of volume transport across each cross-section is given for four simulations. The baseline simulation corresponds to the calibration simulation. The values for constant runoff and constant wind velocity correspond to the mean values for the simulation period. The predicted tide was generated from the tidal constituent data in Table 2. The derivation of the parameter R is given in the text.

<table>
<thead>
<tr>
<th>Run Number and Description</th>
<th>Standard Deviation, m³ s⁻¹, (R%)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Mouth</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>1. Baseline - volume transport</td>
<td>281</td>
</tr>
<tr>
<td>2. Constant Runoff: Q = 42 m³ s⁻¹</td>
<td>278</td>
</tr>
<tr>
<td>3. Constant wind: U = 3.0 m s⁻¹, V = 3.3 m s⁻¹</td>
<td>272</td>
</tr>
<tr>
<td>4. Predicted tide</td>
<td>43 (97.7)</td>
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</tbody>
</table>

## TABLE 5

Details and results of the simulations investigating the buoyancy fluxes across the sills and through the mouth of Loch Fyne. The standard deviation (m³ s⁻¹) of the time series of buoyancy transport across each cross-section is given for four simulations. The baseline simulation corresponds to the calibration simulation. The values for constant runoff and constant wind velocity correspond to the mean values for the simulation period. The predicted tide was generated from the tidal constituent data in Table 2. The derivation of the parameter R is given in the text.

<table>
<thead>
<tr>
<th>Run Number and Description</th>
<th>Standard Deviation, m³ s⁻¹, (R%)</th>
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<tbody>
<tr>
<td></td>
<td>Mouth</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>5. Baseline - buoyancy transport</td>
<td>167</td>
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<tr>
<td>6. Constant Runoff: Q = 42 m³ s⁻¹</td>
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<tr>
<td>7. Constant wind: U = 3.0 m s⁻¹, V = 3.3 m s⁻¹</td>
<td>31</td>
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<td>8. Predicted tide</td>
<td>165</td>
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Figure 1. Map of Loch Fyne showing the locations of sills, CTD stations (M), RCM mooring location (G) and the ADCP deployment position (ε).
Figure 2. (a) The model grid of Loch Fyne, with salinity and velocity grid point locations marked. The letters A-D are referred to in Figure 15. (b) Observed salinity distribution along the longitudinal axis of the loch on 21 November 1994. The contour interval is 1. The approximation of the bottom topography used by the model (—) is shown along with the real along-channel bathymetry (— - -).
Figure 3. Boundary forcing data used by the model: (a) water level (expressed as bottom pressure in dbar); (b) wind vectors from Machrihanish; (c) total freshwater runoff into Loch Fyne from the rivers shown in Figure 1.
Figure 4. Observed (a) and model-predicted (b) along-channel distribution of salinity on 21 February 1995. The contour interval is 1.
Figure 5. Observed (——) and model-predicted (– –) profiles of amplitude and phase for the six major tidal constituents above the sill. The observed results come from the moored ADCP data. Each sub-plot displays results from two constituents.
Figure 6a. Observed (——) and model-predicted (– –) time series of near-surface (upper panel) and near-bottom (lower panel) along-channel velocity for the period 21 November 1994 – 23 February 1995.
Figure 6b. Observed (-----) and model-predicted (– –) time series of near-surface (upper panel) and near-bottom (lower panel) salinity for the period 21 November 1994 – 23 February 1995.
Figure 7. Contoured values of buoyancy transport (10³ m³ s⁻¹, positive seaward) through the mouth of the loch during the baseline simulation, plotted for corresponding values of easterly and northerly wind velocity components.
Figure 8. Model-predicted “residual” velocity fields under constant wind forcing from the northwest (NW), northeast (NE), southwest (SW) and southeast (SE). The wind speed for these simulations was 4.5 m s$^{-1}$. The velocity vectors were calculated by averaging over the second 25-hour period of a 50-hour simulation. The mean salinity distributions over the second 25-hour period are also shown.
Figure 9. Results from the tracer release simulation. The upper plot shows the mass of tracer (tonnes) in the upper basin (1), the loch landward of the outer sill (2) and the whole loch (3). The cumulative mass of tracer exported from the system (— −) and the total mass of tracer released (— −) are also shown. In the lower plot, the mass of tracer in the deep water below sill depth in the upper basin is shown.
Figure 10. Predicted “residual” current vectors and tracer distributions from Day 40 (upper panel) and Day 57-58 (lower panel) of the tracer release simulation. “Residual” current vectors are calculated by taking an average over a 25-hour period to remove the M2 tidal signal. The tracer contour intervals are 1.0 µg l⁻¹.
Figure 11. Distribution of tracer at the end of the 94-day tracer release simulation. The contour interval is 2.0 µg l\(^{-1}\).
Figure 12. Results from the tracer removal simulation. The upper panel shows the mass of tracer (tonnes) remaining in the system (—) and the mass exported through the mouth of the loch (— –). The lower panel shows the mass of tracer in the deep water below sill depth in the upper basin.
Figure 13. (a) Tracer distribution at the end of the 94-day removal simulation. The contour interval is 0.05 µg l\(^{-1}\). (b) Calculated deep water turnover times (days) based on the time taken for the tracer concentration to fall to a factor of e\(^{-1}\) of the initial concentration.
Figure 14. Calculated flushing times (days) based on the freshwater fraction method, for the whole loch (°), the loch landward of the outer sill (♠), and the upper basin (□), plotted against daily freshwater input.
Figure 15. Predicted low-pass filtered time series of salinity from the baseline simulation at four locations, A (-----), B(----), C(---) and D(-----) within Loch Fyne (Figure 2a).