SSF

LOCH LINNHE 2018
ECE ESTIMATES

REPORT LINNHE 2018

April 2018

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REPORT NO:

SUMMARY

This report updates an earlier report (Edwards, 2014) with new tonnage figures for the group of fish farms in and around Loch Linnhe, relative to OSPAR & Water Framework Directive Reference Conditions.

The report outlines the hydrography of the general area of Loch Linnhe in central west Scotland, to estimate the effect of fish farms on local nutrient concentrations via the Equilibrium Concentration Enhancement (ECE) approach.

Tidal and residual flows within the area have been estimated by various methods (tide tables, direct observation and water budgets). They are sufficient to dilute the nitrogen released from existing consented sites such that the conservatively estimated general ECE increase in nitrogen concentration is in the range 5 to less than 22 µgN.litre^{-1}, much lower than measured winter background concentrations, well below a previous Environmental Quality Standard of 168 µgN.litre^{-1}, and meeting OSPAR and Water Framework Directive constraints.

Large scale tidal dispersion and additional wind-driven water exchanges with the coastal sea cannot be quantified with the available data but their effect is to increase local and general dilution, correspondingly reducing the predicted increases in the ECE of nitrogen.

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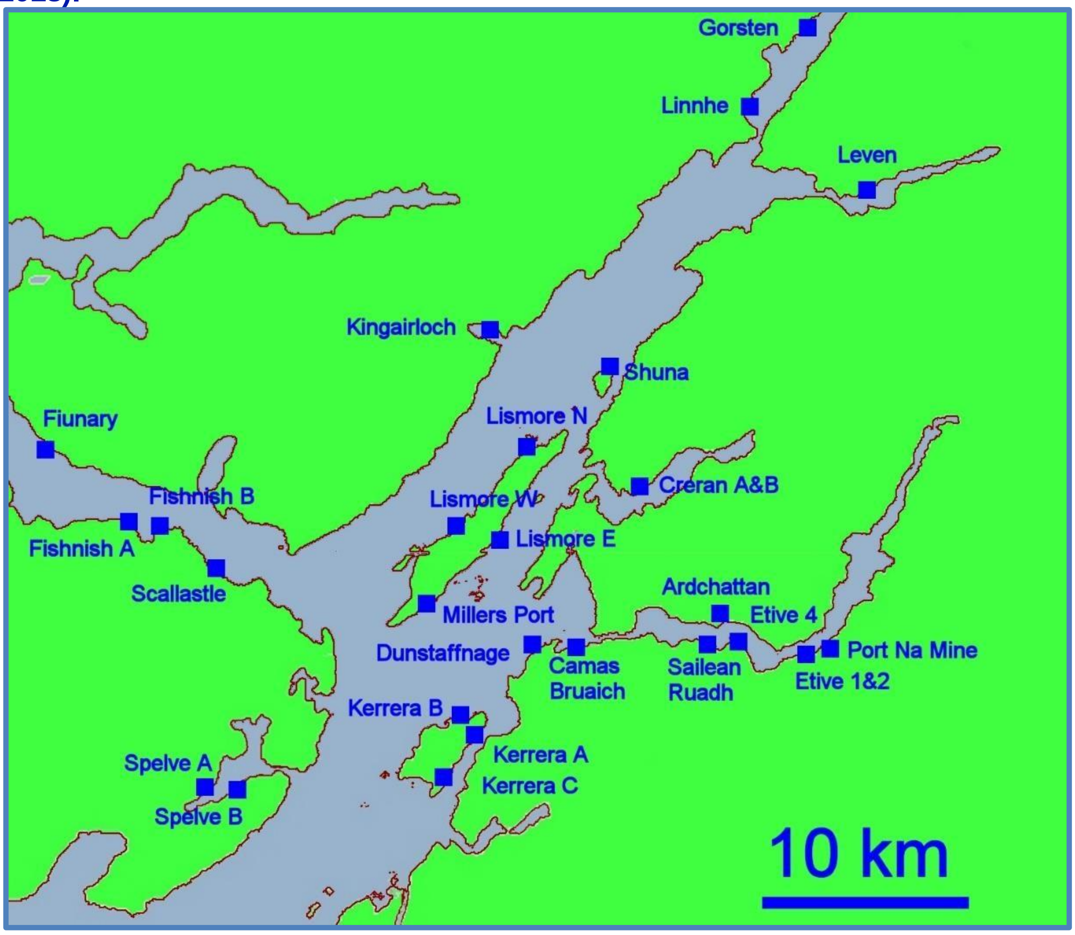
2 PHYSICAL BACKGROUND

2.1 Geography

The area of Loch Linnhe within the yellow area of Figure 1 and including the adjacent lochs Etive, Creran, Leven, upper Linnhe and Spelve is about 450 km^2. There are several relevant sites in the area of the applications. Figure 2 shows the locations listed as CAR (Controlled Activities Regulations) licensed, some of which are presently fallow or proposed to be fallow.

Figure 2: Farms in the Loch Linnhe area (from http://aquaculture.scotland.gov.uk , 2018).



2.2 Non-tidal circulation in the Mull area

The main feature of the non-tidal circulation in the area is a northward residual drift along the west Scottish coast (Figure 3) at typical rates of 10^5 $m^3.s^{-1}$ (Ellett, 1994). This flow is distributed over several paths and its partition is sketched in Figure 4.

The flow up the Firth of Lorne towards Loch Linnhe and the Sound of Mull is a small portion of the main flows, around 10^3 $m^3.s^{-1}$; in a channel of width 2 km and average depth 50 metres such as the Sound of Mull, such a flow corresponds to a westward residual current of only about 0.01 $m.s^{-1}$; in the wider Firth of Lorne it is even less. These are almost immeasurable speeds that cannot be expected to show in the analysis of short current records such as are made at farm sites in support of consent applications.

In the upper parts of the water column, this coastal circulation is enhanced by the upper outflows from Loch Linnhe, estimated as about 2000 $m^3.s^{-1}$ (section 2.3.7).

Figure 3: Current paths west of Scotland (after Ellett, 1994)

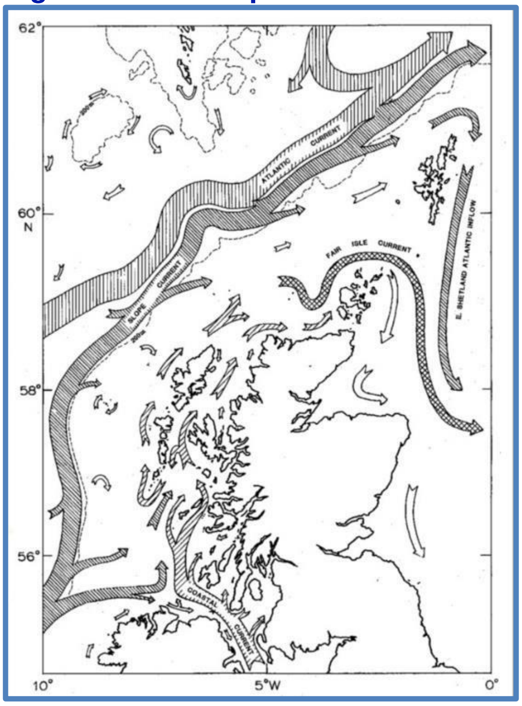
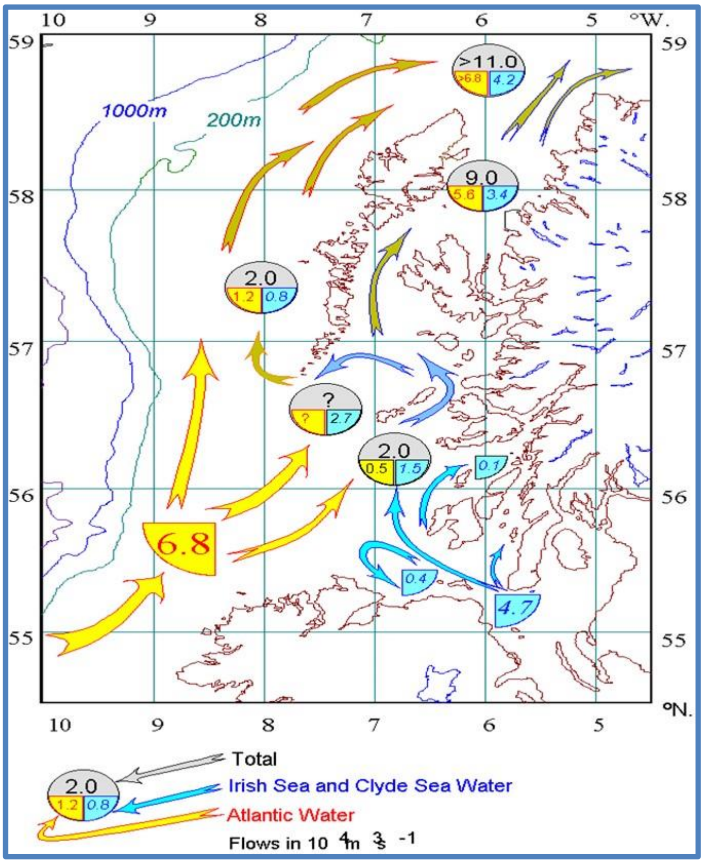


Figure 4: Flow partitions west of Scotland (after Ellett, 1994)



This general picture of residual flow is the context for the following analysis of sitespecific measurements from the fish farms. Because of the general westward flow in the Sound of Mull, the farms within the sound may be expected to have little effect on southern Loch Linnhe.

2.3 Tidal Currents

2.3.1 Tidal Range

The tides at Tobermory, the nearest and relevant national tide gauge, similar in range to the Firth of Lorne and Lower Loch Linnhe, are summarised in Table 1, (National Tides & Sea Level Facility, http://www.ntslf.org/tgi/portinfo?port=Tobermory). **Table 1: Tides at Tobermory**

Tide	Tobermory
Highest Astronomic Tide	5.23m
Lowest Astronomic Tide	0.16m
Mean High Water Spring	4.61m
Mean Low Water Spring	0.77m
Mean High Water Neap	3.42m
Mean Low Water Neap	1.94m

Typical tidal ranges in this area are thus about 1.5 (neap) to 3.9 (spring) metres, with an average of about 2.7 metres.

2.3.2 The Tidal Stream Atlas

Currents associated with the rise and fall of the tides are described roughly in the Admiralty Tidal Stream Atlas (2009). The atlas shows tidal streams every hour. Figure 5 shows an example of the hourly maps in the atlas for this area. **Figure 5: Tidal streams three hours after high water at Dover**

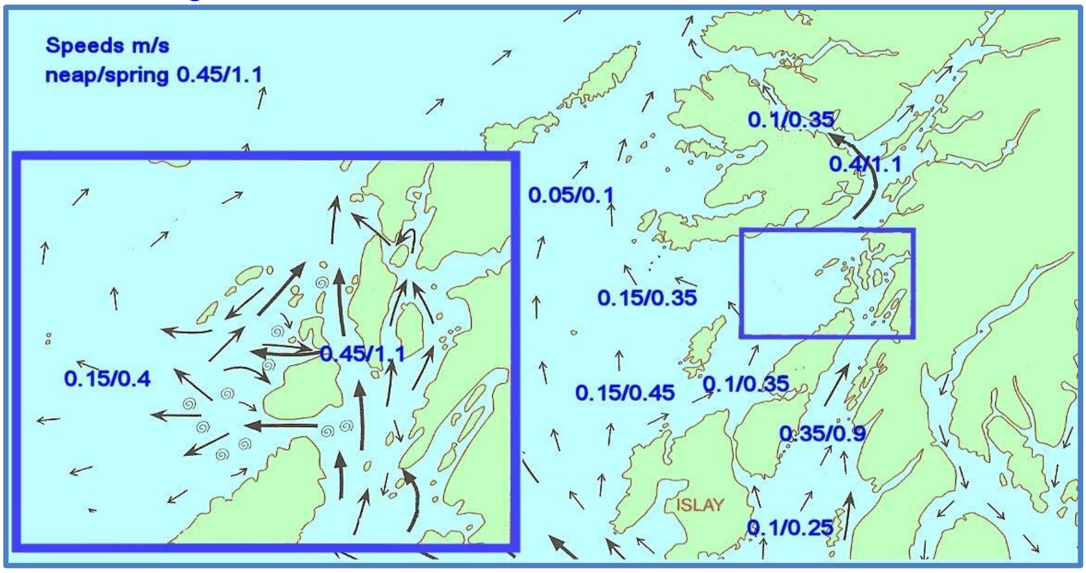


Table 2 summarizes the Tidal Atlas currents in the Sound of Mull and at the south end of Lismore. The calculated averages are also shown in this table: in the Sound of Mull, the average is weakly westward while at the south end of Lismore it is weakly southward. In Loch Linnhe, the currents are depicted only qualitatively. **Table 2: Tidal streams, Sound of Mull and south of Lismore**

Hours from high water Dover	Sound of Mull, $m.s^{-1}$		South Lismore, $m.s^{-1}$	
	Neap	**Spring**	**Neap**	**Spring**
-6	0	0	0.05	0.2
-5	0.05	0.1	0.25	0.65
-4	0.1	0.25	0.35	0.9
-3	0.1	0.3	0.35	1.05
-2	0.1	0.25	0.4	1.05
-1	0.05	0.2	0.35	0.95
0	0	0	0.2	0.55
1	0.05	0.1	0.05	0.15
2	0.1	0.3	0.2	0.55

3	0.1	0.35	0.4	1.1
4	0.1	0.3	0.55	1.5
5	0.05	0.15	0.4	1.15
6	0	0	0.15	0.4
Average	**0**	**0.01**	**0.02**	**0.06**

In view of the rough nature of the atlas and the critical dependence of currents on position in such an intricate area, little significance attaches to these averages.

2.3.3 Estimates of currents in the Sound of Mull

Apart from farm site measurements, no other current measurements have been found in the Sound of Mull in the British Oceanographic Data Centre (BODC) inventory. According to Ellett & Edwards (1983), currents in straits such as the Sound of Mull may be estimated from a simple dynamic balance of the sea-level difference along the strait against frictional resistance in the channel. If we assume that:

- gravitational acceleration **g** = 10 $m.s^{-2}$;
- typical spring tide height difference along the sound **d** = 0.1 m (Ellett & Edwards, 1983, Figure 1);
- typical depth of the Sound of Mull **h** = 50 m;
- length **L** = 40000 m;
- representative drag coefficient C_d = 0.003;

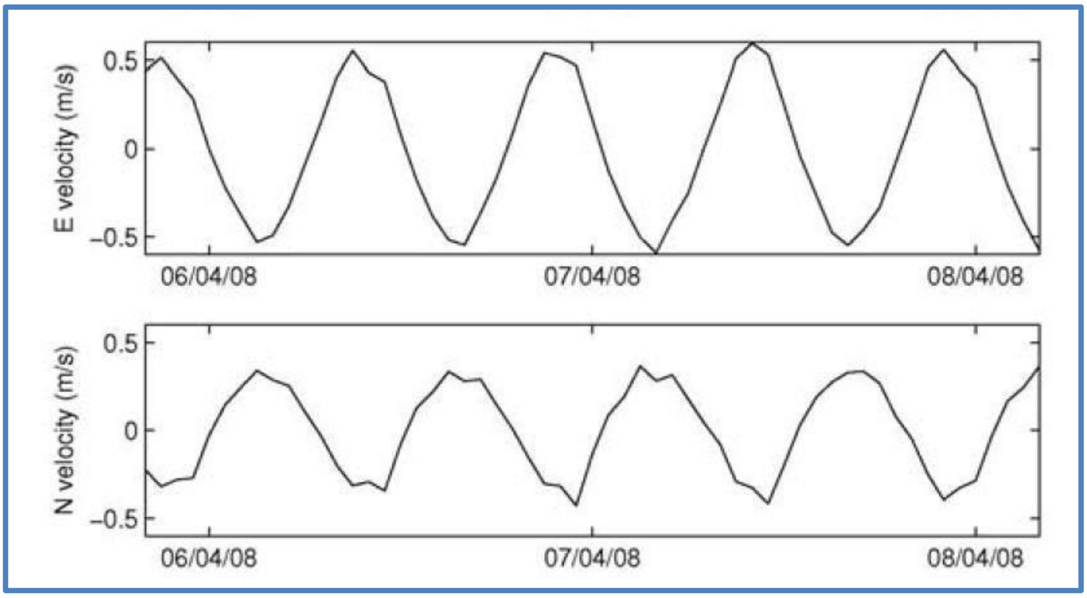
and balance the pressure gradient against the frictional forces, it follows that the typical speed **U** through the channel is given by $U = (g\ d\ h / (L\ C_d))^{0.5}\ m.s^{-1}$ = 0.65 $m.s^{1}$.

This estimate may be checked against information from an independent Scottish Salmon Producers Organisation (SSPO) study at Fiunary.

2.3.4 Currents in the Sound of Mull - the SSPO Large Site Study

Currents were measured in the Sound of Mull for a study of the Fiunary site for the SSPO (Black *et al.*, 2009) and used to calibrate a flow model for the sound. An example of modelled depth-averaged flows in spring tides is shown in Figure 6.

Figure 6: Sound of Mull, modelled depth-average current, tidal diamond 2390C



These modelled spring east and north components of current correspond to maximum channel flows about 0.6 $m.s^{-1}$. The agreement between this and the rough estimate of section 2.3.3 is reassuring of both.

Representative currents in the Sound of Mull may therefore be expected to be semidiurnally tidal, with speeds up to about 0.6 $m.s^{-1}$ at springs, and correspondingly less (~0.3 $m.s^{-1}$) at neaps.

2.3.5 Sound of Mull tidal exchanges

The area of the Sound of Mull is about 80 km^2. The lowest tidal range is about 2 metres. A conservative estimate of tidal inflow is therefore about $1.6.10^8$ m^3 per tide. If as much as half of this were recirculation of outflow, the tidal inflows of "new" water would be about $1.6.10^8$ m^3 per day, or about 2000 $m^3.s^{-1}$.

2.3.6 Loch Linnhe - the Marine Laboratory Lismore record

The Marine Laboratory Aberdeen measured currents at 56.5267º N, 5.55º E in 1991, to the west of Lismore in the southern end of Loch Linnhe (Edwards, 2014; from https://www.bodc.ac.uk/data/information_and_inventories/current_meters/search).

Currents were measured near the surface and bottom of the loch at a site that may be expected to represent conditions in the southern part of Loch Linnhe.

All records in Table 3 have been analysed (with kind permission from the Marine Laboratory), ignoring all measurements flagged by BODC as questionable.

Table 3: Data from the Marine Laboratory mooring north of Lismore, 1991

BODC Record	Ref.		Start	End	seabed	depth
b0437348	338/1	N338	19/01/1991 15:40	23/02/1991 09:20	68	13
b0437416	344/1	N344	23/02/1991 11:40	23/03/1991 12:30	70	15
b0437613	353/1	N353	24/03/1991 06:40	21/04/1991 09:20	69	17
b0437729	361/1	N361	21/04/1991 13:40	19/05/1991 05:50	69	15
b0437834	374/1	N374	19/05/1991 09:40	16/06/1991 07:30	69	17
b0437963	383/1	N383	16/06/1991 10:40	14/07/1991 06:10	69	15
b0438235	399/1	N399	11/08/1991 08:40	08/09/1991 09:30	69	15

b0438468	418/1	418/1	08/09/1991 18:40	06/10/1991 15:30	69	15
b0438573	433/1	N433	06/10/1991 09:40	08/11/1991 16:30	69	15
b0438733	444/1	N444	13/11/1991 10:40	15/12/1991 14:00	69	15
b0438837	450/1	N450	15/12/1991 15:50	11/02/1992 14:20	69	15
b0437361	338/2	N338	19/01/1991 15:40	31/01/1991 13:30	68	51
b0437428	344/2	N344	23/02/1991 11:40	23/03/1991 12:30	70	50
b0437625	353/2	N353	24/03/1991 06:40	21/04/1991 09:20	69	50
b0437975	383/2	N383	16/06/1991 10:40	14/07/1991 06:10	69	52
b0438106	391/2	N391	14/07/1991 08:40	11/08/1991 07:20	69	52
b0438247	399/2	N399	11/08/1991 08:40	08/09/1991 09:30	69	52
b0438481	418/2	418/2	08/09/1991 10:40	06/10/1991 07:30	69	52
b0438585	433/2	N433	06/10/1991 09:40	08/11/1991 16:30	69	52
b0438849	450/2	N450	15/12/1991 16:10	11/02/1992 14:40	69	52

Figure 7: Marine Laboratory mooring west of Lismore, depth 13 metres, 1991. Salinity, temperature (ºC.), 25-hour mean easterly current (cm.s^{-1}), speed (cm.s^{-1})

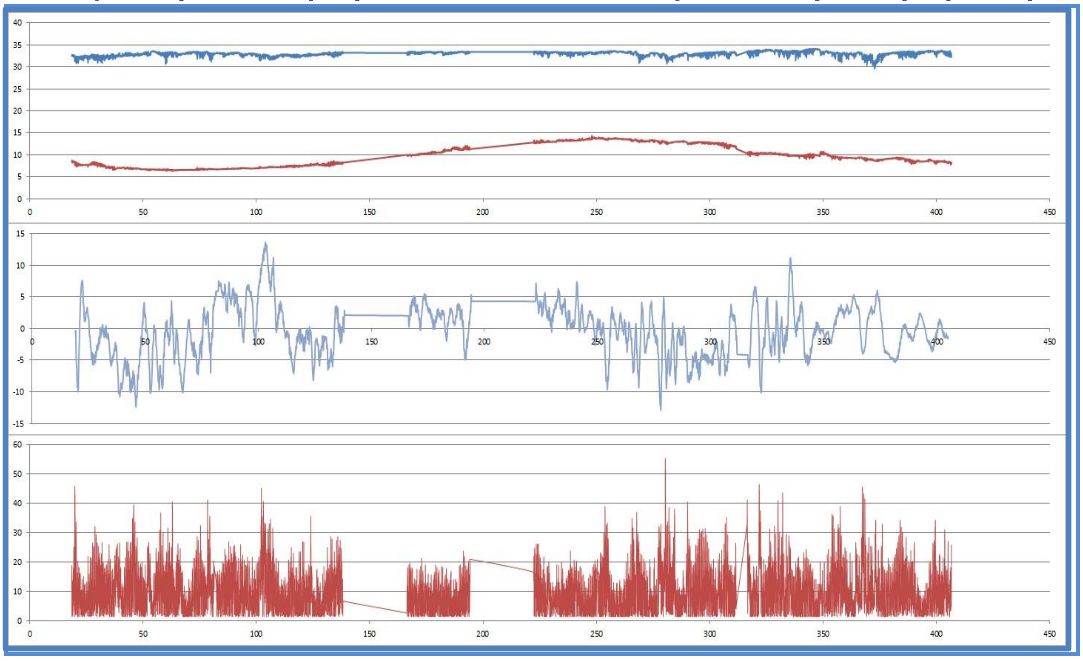
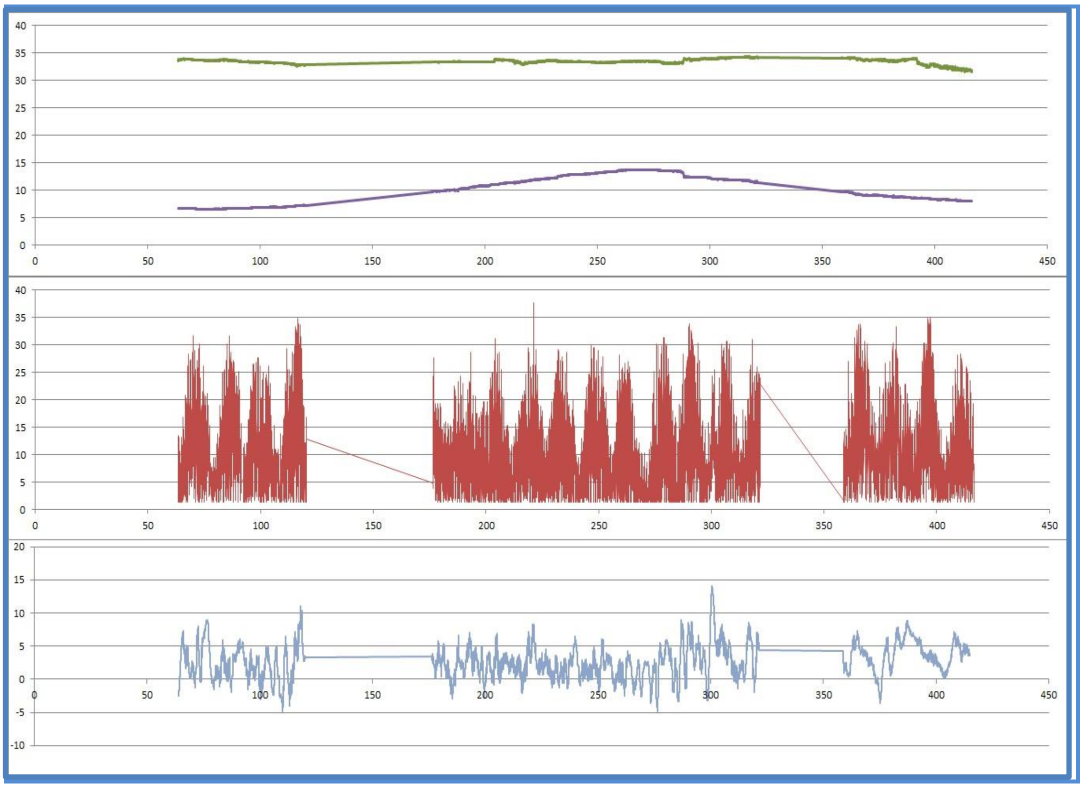


Figure 8: Marine Laboratory mooring west of Lismore, depth 51 metres, 1991. Salinity, temperature (ºC.), 25-hour mean easterly current (cm.s^{-1}), speed (cm.s^{-1})



These results show that speeds in the deep water of Loch Linnhe vary tidally whereas the upper water is clearly a mixture of tidal and wind driven (as seen most obviously in the 25-hour moving averages) currents.

Longer term averages over the whole year, although making no correction for missing data, are shown in Table 4 and reveal residual flows.

Table 4: Statistics from the Marine Laboratory mooring west of Lismore

Period, 1991	Depth 13 metres	Depth 52 metres
Average salinity	32.95	33.5
Average Speed, $m.s^{-1}$	0.10	11.09
Residual Easterly component, $m.s^{-1}$	-0.024	2.5
Residual Northerly component, $m.s^{-1}$	-0.006	5.5
Residual speed, $m.s^{-1}$	0.025	6
Residual Direction, ºN	256	25

Residual currents near the surface (13 m) tend to the west-southwest at speeds about 0.03 $m.s^{-1}$ whereas residual deep currents flow towards the east of north at about 0.06 $m.s^{-1}$. Such a flow pattern (outwards in the upper layers, landwards in the deep water) is consistent with a normal fjordic estuarine circulation.

2.3.7 Loch Linnhe - estimation of flows past Lismore

Although the Marine Laboratory measurements are limited to two depths, it is interesting to convert their residuals measured near Lismore to water flows. According to Ross *et al.* (1993), the daily freshwater flow to the system is about $0.035 \times V_s$ (a volume-related parameter, taken as the surface layer of the loch). The upstream sea area to the north is about 250 km^2, corresponding to a fresh flow rate of about 100 $m^3.s^{-1}$.

2.3.7.1 Flow from the Marine Laboratory record

Assuming on the basis of depth interpolation of the residual current that the outflow persists to depths to about 25 metres and that the width of Loch Linnhe is about 3500 m, the residual annual flow to the southwest is about 2500 $m^3.s^{-1}$.

The measured salinity of outflow is about 32.95, compared with measured salinity of deep inflow about 33.5 (Table 4). If outflow salinity pertained to near surface waters, it would imply a freshwater component of 1.6% (i.e. *{33.5 - 32.95}/33*) of the residual flow (2500 $m^3.s^{-1}$), implying outward freshwater flow about 40 $m^3.s^{-1}$.

The current meter is near the base of the 10-metre surface layer identified by Ross et al. (1993) so is likely to overestimate the typical salinity of surface waters and thus to underestimate the freshwater component. Applying a reasonable correction factor of two increases the estimate of fresh flow to about 80 $m^3.s^{-1}$.

2.3.7.2 Flow from a freshwater budget

The catchment of Loch Linnhe north of the site in Lismore is about 2500 km^2 and the annual rainfall above evaporation about 1 $m.year^{-1}$, corresponding to a freshwater discharge of about 80 $m^3.s^{-1}$.

2.3.7.3 Lismore flow summary

The rough equivalence of these three estimates of annual freshwater flows suggests that they represent the annual freshwater outflow in the Lismore region and that the corresponding observed residual near-surface total outflow past Lismore of about 2500 $m^3.s^{-1}$ is therefore a persistent feature, although it may be expected to vary seasonally and may occasionally be stalled by strong winds from the south-west or enhanced by wind from the north-east.

2.3.8 Estimates of tidal current in Loch Linnhe

Because Loch Linnhe is a short non-resonant closed system, tidal currents may be estimated by water budgets. On a tide of range **R** metres, the maximum typical speed at a section of depth **D** in a loch of length **L** is about $\mathbf{R}.10^{-4}.\mathbf{L}/\mathbf{D}$ $m.s^{-1}$ (for example, Edwards and Edelsten, 1976). Using values of **L** = 50 km; **D**=60 m and tidal ranges **R** from Table 1, this is about 0.3 $m.s^{-1}$ west of Lismore at spring tides and about half that value at neaps. These values compare well with the Marine Laboratory measurements of section 2.3.6.

2.4 SITE CURRENTS

Currents at all sites have been measured to support their consent applications. Some of the features of these measurements as reported by the various hydrographic contractors are repeated here.

2.4.1 Shuna

Currents at Shuna (Figure 9) are summarized in Table 5, based on re-analysis of the consent application current measurements in December 2015.

Figure 9: The site at Shuna

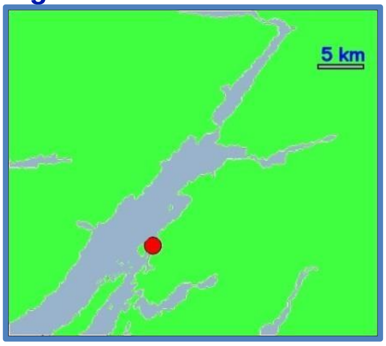


Table 5: Shuna, summary hydrographic statistics

9/12/15 to 29/4/15			
Speeds, m.s^{-1}	**Bed**	**Mid**	**Surface**
Mean velocity	0.057	0.069	0.082
Maximum velocity	0.176	0.295	0.266
Residual speed	0.005	0.013	0.026
Residual direction ºN	330	244	245
Tidal Amplitude (Parallel)	0.085	0.107	0.123
Tidal Amplitude (Normal)	0.027	0.040	0.039

Tidal and residual currents at this site diminish with depth. The residuals flow to the South-west at all depths.

2.4.2 Oban Bay current data

Figure 10: The site at Oban Bay

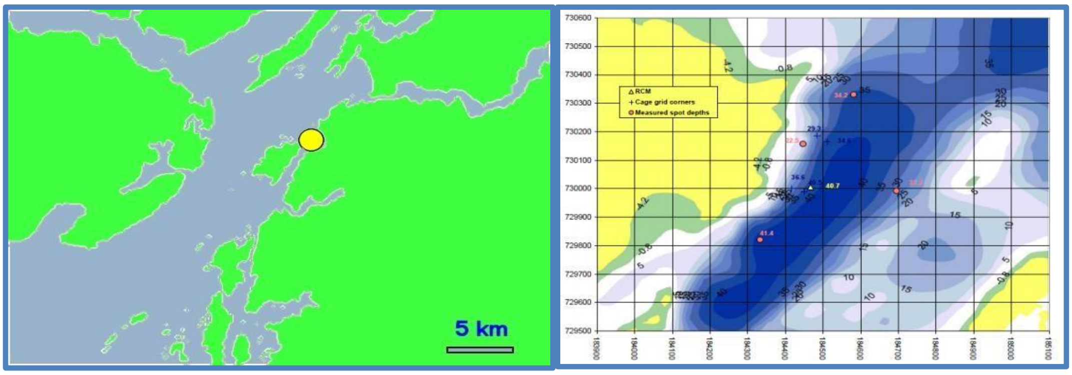


Table 6: Oban Bay, summary hydrographic statistics

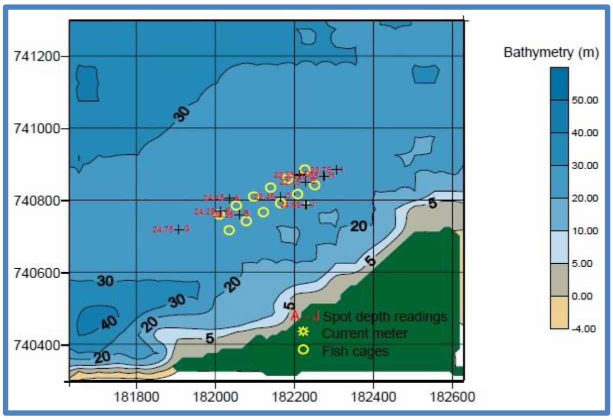
Speeds, m.s^{-1}	**Surface**	**Mid**	**Seabed**
Mean speed	0.064	0.057	0.027
Residual current speed	0.009	0.009	0.017
Residual current direction (°)	316	348	46

Major axis of tidal ellipse (°)	35	35	70
Residual Flow (Parallel)	0.002	0.002	0.015
Residual Flow (Normal)	-0.009	-0.007	-0.007
Tidal Amplitude (Parallel)	0.093	0.085	0.047
Tidal Amplitude (Normal)	0.039	0.033	0.021

Tidal currents at this site diminish with depth. Residuals present a confused picture, perhaps affected by complex topography near the site.

2.4.3 Lismore West

Figure 11: The site at Lismore West



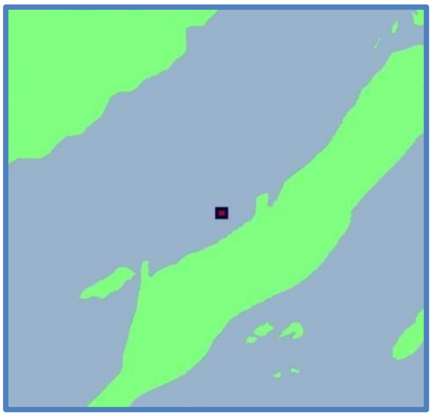


Table 7: Lismore West, summary hydrographic statistics

Speeds, m.s^{-1}	Surface	Mid	Seabed
Mean speed	0.068	0.040	0.030
Residual current speed	0.037	0.004	0.005
Residual current direction (°)	206	124	118
Major axis of tidal ellipse (°)	250	240	110
Residual Flow (Parallel)	-0.017	-0.003	-0.004
Residual Flow (Normal)	0.033	0.002	0.002
Tidal Amplitude (Parallel)	0.057	0.037	0.032
Tidal Amplitude (Normal)	0.092	0.066	0.047

Tidal currents at this site diminish with depth. The surface residual is strongest, to the SouthWest. This may be related to the general south-westward estuarine circulation to be expected in this freshwater-influenced Loch Linnhe system, in which near-surface layers move seawards as they carry freshwater to the coastal sea.

2.4.4 Lismore North, Port na Morlachd

Figure 12: The site at Lismore North – Port na Morlachd

Table 8: Lismore North – Port na Morlachd, summary hydrographic statistics

Speeds, m.s^{-1}	Surface	Mid	Seabed
Mean speed	0.024	0.021	0.026
Residual current speed	0.005	0.007	0.013
Residual current direction (°)	82	81	324
Major axis of tidal ellipse (°)	90	90	270
Residual Flow (Parallel)	0.033	0.025	0.036
Residual Flow (Normal)	0.024	0.025	0.023
Tidal Amplitude (Parallel)	0.005	0.005	0.007
Tidal Amplitude (Normal)	-0.001	-0.001	0.010

Tidal currents at this site are similar at all depths and residuals are varied in both speed and direction.

2.4.5 Lismore Dubh Sgeir

This site is very similar to Port na Morlachd but was surveyed separately.

Figure 13: The site at Lismore North – Dubh Sgeir

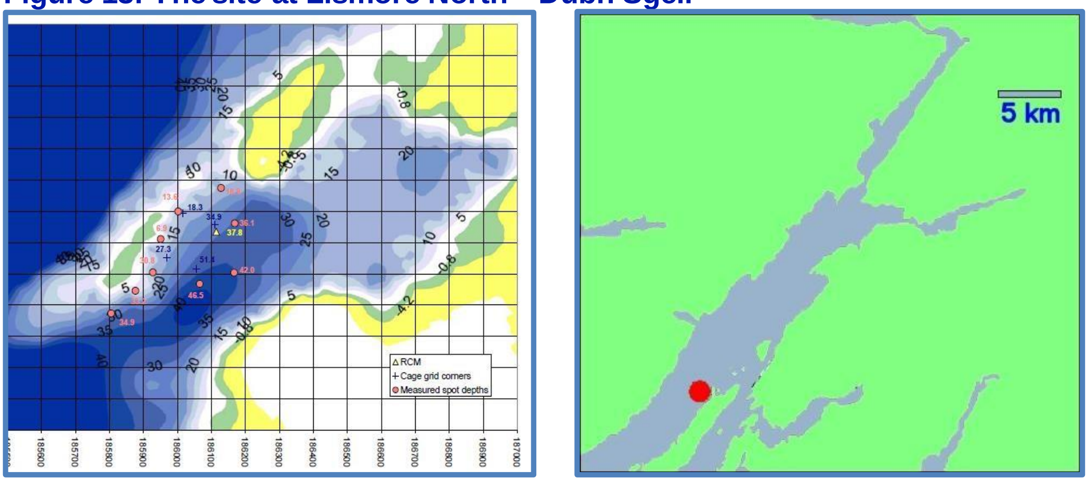


Table 9: Lismore North – Dubh Sgeir, summary hydrographic statistics

Speeds, m.s^{-1}	Surface	Mid	Seabed

Mean speed	0.025	0.024	0.009
Residual current speed	0.004	0.001	0.006
Residual current direction (°)	187	130	64
Major axis of tidal ellipse (°)	30	45	25
Residual Flow (Parallel)	-0.004	0	0.005
Residual Flow (Normal)	0.002	0.001	0.004
Tidal Amplitude (Parallel)	0.053	0.51	0.021
Tidal Amplitude (Normal)	0.022	0.024	0.015

2.4.6 Lismore East

Figure 14 The site at Lismore East

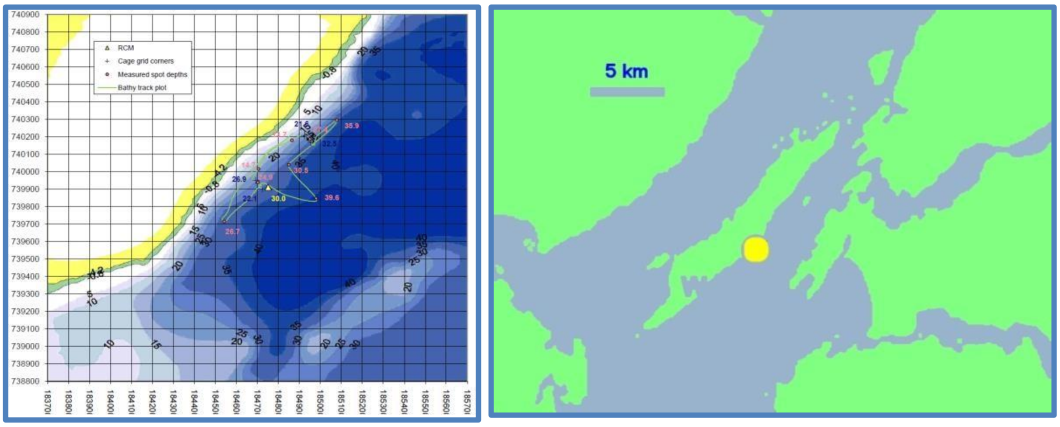


Table 10: Lismore East, summary hydrographic statistics

Speeds, m.s^{-1}	Surface	Mid	Seabed
Mean speed	0.082	0.079	0.049
Residual current speed	0.057	0.051	0.010
Residual current direction (°)	216	222	183
Major axis of tidal ellipse (°)	215	220	200
Residual Flow (Parallel)	0.057	0.051	0.009
Residual Flow (Normal)	0.001	0.002	-0.003
Tidal Amplitude (Parallel)	0.117	0.118	0.093
Tidal Amplitude (Normal)	0.019	0.022	0.26

2.4.7 Charlottes Bay

Figure 15: The site at Charlottes Bay

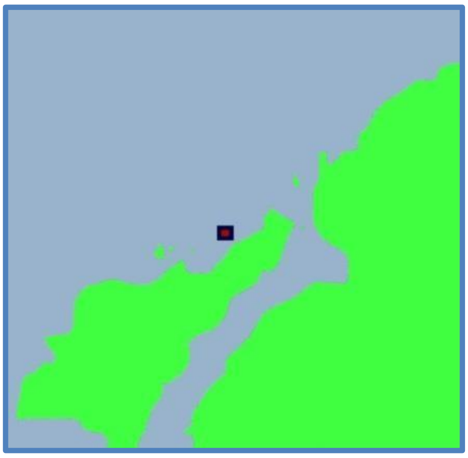


Table 11: Charlottes Bay, summary hydrographic statistics - surface

Current meter ID :	Charlottes Bay surface		
variation:	0		convergence:
Period of measurement :	9/11/05 13:40	to	24/11/05 13:40
Percentiles	Current Speed		
1%	0.004 m/s		percentile analysis
5%	0.013 m/s		
10%	0.020 m/s		
25%	0.035 m/s		
50%	0.062 m/s		
75%	0.107 m/s		
90%	0.164 m/s		
95%	0.214 m/s		
99%	0.433 m/s		
100%	1.020 m/s		
20%	0.030 m/s		threshold values
34%	0.045 m/s		
69%	0.095 m/s		
66%	0.086 m/s		mean
Major axis :	255 deg		0.138 m/s
Residual current :	0.019 m/s	at	233 deg
	Residual		**Tidal amplitude**
Longitudinal (U) :	0.018 m/s		0.138 m/s
Lateral (V) :	-0.007 m/s		0.114 m/s
Anisotropy (long'l/lat'l) :	2.45		1.21

2.4.8 Dunstaffnage

Figure 16: The site at Dunstaffnage

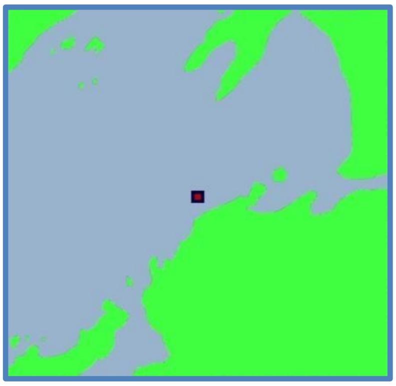


Table 12: Dunstaffnage, summary hydrographic statistics

Speeds, $m.s^{-1}$	Surface	Mid	Seabed
Mean speed	0.077	0.066	0.063
Residual current speed	0.042	0.40	0.065
Residual current direction (°)	89	68	46

2.4.9 Summary of Site Measurements

Currents at these sites are mainly semidiurnal tidal with speeds reaching a decimetre per second or so; there can be considerable difference between currents and residuals at various depths, suggesting strong topographic influences and the effects of some stratification.

The surface data residual current summaries, all made by site contractors to a common reporting procedure, are shown in Table 13.

Table 13: Near-surface site residual currents over 15 days of record

Site	Residual, $m.s^{-1}$	Direction, °N	Mean Current, $m.s^{-1}$
Shuna	0.026	245	0.082
Lismore Port na Morlachd	0.005	89	0.023
Lismore Dubh Sgeir	0.004	187	0.025
Lismore West	0.042	233	0.071
Charlottes Bay	0.019	233	0.086
Oban Bay	0.009	316	0.064
Lismore East	0.057	216	0.082
Dunstaffnage	0.048	48	0.072

There is a strong tendency for surface residuals of a few $cm.s^{-1}$ at these sites to direct to the South-West, consistent with a normal near-surface estuarine outflow in the Loch Linnhe system, described in section 2.3.7.

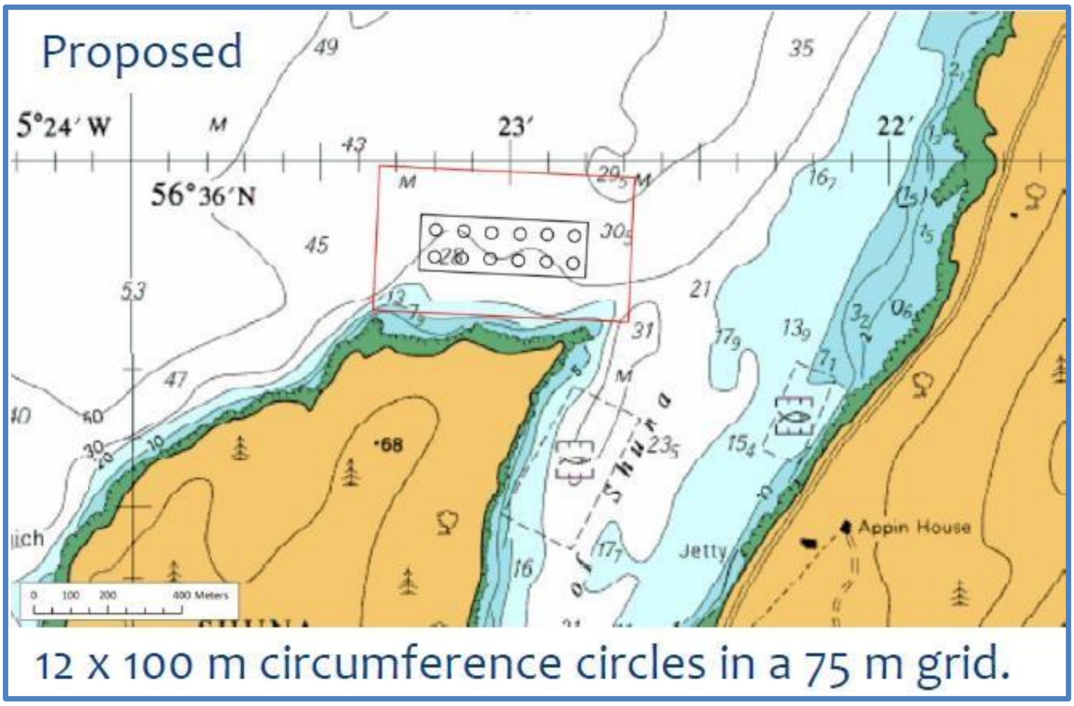
2.5 LOCAL RESIDUAL FLOW FROM A FARM

In view of the general and measured residual flows at these sites it is useful to attribute a notional local residual volume flow to each farm.

2.5.1 Scale of diluting flow

To typify a farm, it is reasonable to use a depth **H** of ten metres and a width **W**, say 200 metres (see for example, Figure 17).

Figure 17: Example of a proposed layout at Shuna



Additional to the physical width of the farms, the effects of horizontal dispersion act to create similar length scales of mixing across flows after release of nutrients.

2.5.2 Dispersion

In simple Fickian diffusion (Thorpe, 2005; Crank, 1980), the flow rate of dissolved material is proportional to the concentration gradient. The constant of proportionality (**K**, the diffusion coefficient) is intrinsic to the medium as in, for example, molecular diffusion in fluids or gases.

For regulatory purposes the dispersion coefficient **K** is usually taken conservatively in Scottish coastal aquacultural regulatory matters to be 0.1 $m^2.s^{-1}$ or more.

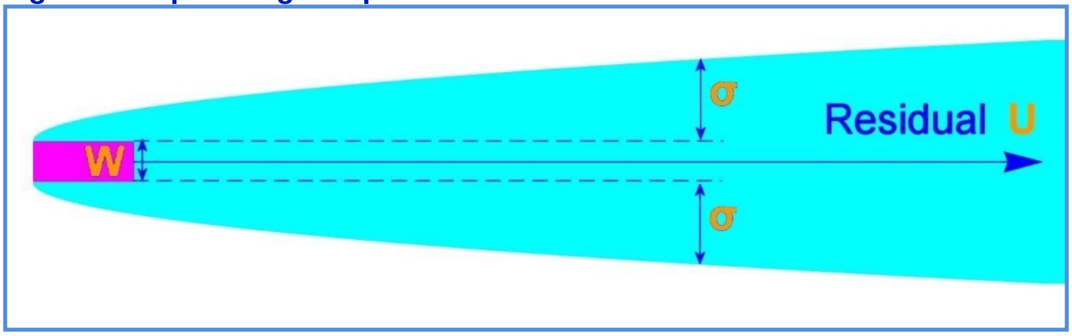
If the diffusion is isotropic (the same in all directions), a patch of material spreads radially, with a typical radius $\sigma(t)$ at time **t**, given (in two dimensions) by $\sigma(t)^2 = 4\,K.t$

The patch area increases at a constant rate and the variance σ^2 increases in direct proportion to the time.

Figure 18 sketches the effluent plume in a residual current **U**. At the time (**t**) shown the width **P** of the plume is roughly

$$P \approx W + 2\,\sigma(t) = W + 4\,(K.t)^{0.5}$$

Figure 18: Spreading of a plume from a farm site in a residual current at time t



The notional diluting flow over the depth **H** after a time **t** is therefore

Diluting flow = **H U P** = **H U** (**W** + 2 **σ**(**t**) = **W** + 4 (**K**.**t**)$^{0.5}$)

As an example, if the cage group has a width **W** about 200 metres, typical values for the plume width **P** are about 600 metres after a day and about 1600 metres after 15 days.

3 PREDICTION OF NUTRIENT INCREASE

Nutrients come from directly from active sites and indirectly from active sites in adjacent lochs. In all cases the nitrogen input to surrounding waters from the biomass at each site may be estimated from the source rate. The conventionally assumed source rate is 60 $kgN.tonne^{-1}.year^{-1}$, representing the direct input from excretion and the indirect inputs from decomposition of faeces and seabed inputs.

3.1 LOCAL NUTRIENT ENHANCEMENT ESTIMATES

The notional local residual flows of section 2.5.2 are available to receive and dilute the released nutrients from a farm. The diluting flows of Table 13 were derived over the regulatory-required time scale of 15 days ($t = 1.3.10^6$ seconds). Table 14 shows the predicted local enhancement for this time and for a much more conservative time scale of only 1 day ($t = 8.6.10^4$ seconds).

Table 13 also shows the estimated average enhancement of the outflow from Loch Spelve, on the assumption that both Spelve A and Spelve B farm sites are operative and that 50% of tidal outflow is recirculated. These assumptions are both very conservative (Edwards, 2018).

Table 14: SSF sites: local enhancement in residual current over relevant times

Site	Residual, $m.s^{-1}$	Proposed Biomass, tonne	Nitrogen input, $gmN.s^{-1}$	Time 1 day		Time 15 days	
				Notional residual Flow, $m^3.s^{-1}$	Enhancement, $\mu gN.litre^{-1}$	Notional residual Flow, $m^3.s^{-1}$	Enhancement, $\mu gN.litre^{-1}$
Shuna	0.026	2060	3.9	149	**26**	426	**9**
Lismore Port na Morlachd	0.005	680	1.3	29	**45**	82	**16**
Lismore Dubh Sgeir	0.004	1786	3.4	23	**149**	66	**52**
Lismore West	0.042	1900	3.6	240	**15**	689	**5**
Charlottes Bay	0.019	1063	2.0	109	**19**	312	**6**
Oban Bay	0.009	500	1.0	51	**18**	148	**6**
Kerrera C	0.016#	500	1.0	91	**10**	262	**4**
Lismore East	0.057	999	1.9	326	**6**	935	**2**
Dunstaffnage	0.048	2500	4.8	274	**17**	787	**6**
Total SSF		**11988**					

Site	Exchange, $m^3.s^{-1}$	Biomass, tonne	Nitrogen input, $gmN.s^{-1}$	Enhancement, $\mu gN.litre^{-1}$
Spelve	*231	1927	3.7	**16**

(Loch Spelve exchange flow conservatively estimated as 50% x two tidal volumes per day)*
(# Residual at Kerrera C surface calculated from *SEPA Finfish Current Data 30727Ffv5-s.xls 25-2-97 to 12-3-97)*

Mean currents of Table 13 are well in excess of the residuals and ensure that the local enhancement may be expected to be less than Table 14 shows. Such estimates are therefore a rough upper limit on local enhancement and, if diluting flows are sufficient in the whole Linnhe system, are an upper limit on possible enhancement within the waters of Loch Linnhe itself.

3.2 NUTRIENT INPUTS TO LOCH LINNHE

Potential nutrient inputs to Loch Linnhe (Figure 1, yellow area) come from SSF farms in Lochs Linnhe (Table 14) and Spelve, and indirectly from other CARlicensed farms in Linnhe, Leven, Creran and Etive, listed in Table 15 according to http://aquaculture.scotland.gov.uk/.

Table 15: Other listed sites in the Loch Linnhe region

Loch	Site	CAR Reference	Consented Biomass
Linnhe	Ardgour	CAR/L/1009970/C1/V4	2500 (Salmon)
Linnhe	Gorsten	CAR/L/1009968/C1/V6	2500 (Salmon)
Linnhe	Kingairloch	CAR/L/1003887/V8	1400 (Salmon)
Linnhe	**Total**		**6400 (Salmon)**
Etive	Camas Bruaich	WPC/W/22774(01)	250 (Salmon/Trout)
Etive	Ardchattan	CAR/L/1003325/V5	262.5 (Trout)
Etive	Sailean Ruadh	CAR/L/1042067/C1/V3	1500 (Trout)
Etive	Aird Point (Etive 4)	CAR/L/1018068/V5	1545.3 (Trout)
Etive	Inverawe (Etive 1&2)	CAR/L/1022266/V3	250 (Trout)
Etive	Etive 3 (Port na Mine)	CAR/L/1010366/V5	458.4 (Trout)
Etive	**Total**		**4266.2 (Mixed)**
Creran	Creran A	CAR/L/1000843/C1/V3	1500 (Salmon)
Creran	Creran B	CAR/L/1003492/V6	1500 (Salmon)
Creran	**Total**		**3000 (Salmon)**
Leven	Callert	CAR/L/1009962/V7	1607 (Salmon)
Leven	**Total**		**1607 (Salmon)**

Some of these sites are listed for trout; for the purposes of this report the nitrogen source rate has been assumed the same for trout as for salmon (Dosdat, 1996). The total listed trout biomass is less than 4300 tonnes, about 15% of the total listed biomass (29188 tonnes) in the system. Consequently, even a factor of two in the error of this trout assumption would only affect total nitrogen source rate by less than 15%, so has been ignored relative to all other sources of error.

3.3 LOCH OUTFLOW ENHANCEMENT ESTIMATES

It may be assumed that the outflows from sites within lochs adjacent to Loch Linnhe are thoroughly mixed with the outgoing tidal volumes as they traverse the lochs' energetic entrance sill systems. The amount of diluting tidal flow is the product of the area of loch and its tidal range. Assuming conservatively that only 50% of inflowing water is "new", the remainder being outflow water recirculated into the loch, Table 16 shows the enhancement to be expected in the outflowing water from each of those lochs when the semidiurnal tidal range is a typical range of two metres.

Table 16: Estimated nutrient enhancement of loch tidal flows

Loch	Area, km^2	Tidal flow per day, $m^3.s^{-1}$	Biomass, tonne	Nitrogen input, $gmN.s^{-1}$	Enhancement, $\mu gN.litre^{-1}$
Separate Lochs					
Leven	9	208	1607	3.1	15
Creran	15	347	3000	5.7	16
Etive	30	694	4266	8.1	12
Spelve (SSF)	10	231	1927	3.7	16

These concentrations are therefore a conservative upper limit on the enhancement of outflows from adjacent lochs of the waters of Loch Linnhe.

3.4 LOCH LINNHE NUTRIENT ENHANCEMENT ESTIMATES

The total listed potential biomass in the Linnhe system is 29188 tonnes. The corresponding potential source rate is 55.5 $gmN.s^{-1}$.

Three estimates of enhancement may be made according to the different flows that are present in the system.

3.4.1.1 Tidal dilution only

Similar to the local or loch-outflow enhancements discussed in sections 3.1 and 3.4, an overall budget may be constructed for the whole Loch Linnhe system. **Table 17: Estimated nutrient enhancement of Linnhe tidal flows**

Loch	Area, km^2	Tidal flow per day, $m^3.s^{-1}$	Total system biomass, tonne	Nitrogen input, $gmN.s^{-1}$	Enhancement, $\mu gN.litre^{-1}$
Loch Linnhe	450	10417	29188	55.5	5

The estimate of enhancement (5 $\mu gN.litre^{-1}$) after tidal dilution for Loch Linnhe using all the area of the system, tidal range 2 m, incorporating all listed farms and allowing for 50% recirculation is less than any of the adjacent lochs in Table 16.

3.4.1.2 Residual flow dilution only

The representative flow southward in the near-surface layers (section 2.3.7) is around 2500 $m^3.s^{-1}$. In the absence of any tidal exchanges, the corresponding enhancement from all farms in the Linnhe system would be about 22 µgN.$litre^{-1}$.

3.4.1.3 Sound of Mull flows only

In the area of the Sound of Mull, residual flow is expected to be around 1000 $m^3.s^{-1}$ (section 2.2). This adds to the Sound's tidal exchanges of about 2000 $m^3.s^{-1}$ (section 2.3.5) and the total flows are likely to be around 3000 $m^3.s^{-1}$. Ignoring any tidally driven dispersion within Loch Linnhe and upper outflows (section 2.3.7) from Loch Linnhe, this is a conservative estimate. The corresponding enhancement in this area to the south and west of Lismore is about 19 µgN.$litre^{-1}$ or less.

3.4.1.4 Summary

Each of these three enhancement estimates pertains to one process acting alone. On the scale of Loch Linnhe, all processes are at work and the enhancement will be correspondingly less than any of the estimates. The likely range of enhancement is therefore likely to be from about 5 to much less than about 22 µgN.$litre^{-1}$.

3.5 DISCUSSION OF ENHANCEMENT ESTIMATES

On the rather small scales local to a site, and allowing for dispersion within relevant time scales, the concentration enhancements in notional local residual site flows have been estimated (Section 3.1) as the ratio of nutrient inputs and water flows and are expected to be of order of tens of µgN.$litre^{-1}$.

On the medium (loch) scales the concentration enhancements in loch outflows have been conservatively estimated (Section 3.3) as the ratio of nutrient inputs and tidal volume exchanges and are expected to be about 15 to 20 µgN.$litre^{-1}$.

On the scale of Loch Linnhe (section 3.4) or the Sound of Mull, the ratio of nutrient inputs to residual flows is such that the concentration enhancement is expected to be in the range 5 to less than 22 µgN.$litre^{-1}$.

The effect of listed farms sites in the Sound of Mull has not been considered because of the westward flushing tendency of current in the Sound. Were the sound farms biomass of about 7000 tonnes to be included pessimistically in the Linnhe estimation, the enhancement would rise correspondingly by about 20%. This has no effect on the validity of the conclusions drawn here.

These estimates are all conservative, because they ignore large scale tidal dispersion and wind driven circulations, both of which may be expected to increase dilution both locally and generally in Loch Linnhe, reducing the estimated enhancements.

4 CONCLUSION

In conclusion, representative enhancement within the Loch Linnhe system from all inputs is expected to lie in the rough range 6 µgN.$litre^{-1}$ to less than about 22 µgN.$litre^{-1}$.

These predicted enhancements are very much less than any regulatory limits related to:

- background winter concentrations (90 µgN $litre^{-1}$ or 6 µM quoted by Ross *et al.* 1993)
- a previous Environmental Quality Standard for available nitrogen of 168 µgN.$litre^{-1}$

- OSPAR & Water Framework Directive Reference Conditions. In offshore waters such as these (salinity >34): the DIN reference value is 10 µM and the threshold 15 µM. Increases are therefore limited to 5 µM (70 µgN.litre^{-1}).

Despite the uncertainties in the estimation process, but noting the conservative nature of all assumptions, these predicted enhancements in the average nitrogen concentration of Loch Linnhe are small in relation to all regulatory standards.

The predicted enhancements therefore appear insignificant in their likely effects on the nutrient status of this water body.

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