SSF

SOUND OF MULL HYDROGRAPHY & ECE ESTIMATES

REPORT SOUND OF MULL 001

[redacted]

JANUARY 2013

For:
Scottish Sea Farms Ltd
[redacted]

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SUMMARY

This report outlines the hydrography of the general area of the Sound of Mull in west Scotland so as to estimate the effect of consented fish farms on local nutrient concentrations via the 'Equilibrium Concentration Enhancement' (ECE) approach.

There are six farm sites within the sound. Previous current measurements made at these sites for regulatory purposes relate to the farm sites but not directly to the circulation of the whole sound. Tidal and residual flows in the locality of the farms have been analysed by various methods including tide tables and analysis of the regulatory current records. The relevant flows in the sound are inferred in this report within the context of other knowledge of the sound.

Two-week current records at the sites reveal tidal and residual flows of amplitudes about 0.1 $m.s^{-1}$, largely aligned along the sound. The residual flows lie in either direction but also may have a very long term westward mean.

At worst case, with all direct inputs from the six consented sites at maximum tonnages of 2500, the conservatively predicted increase in site-local or whole-sound Nitrogen concentration is expected to be less than 2 μM.

These increases are small in comparison with OSPAR and Water Framework Directive criteria relating to permitted increases above reference concentrations of nitrogen, or with the previously used Environmental Quality Standard of 12 μM.

No significant adverse environmental effect from nitrogen enhancement predicted by the ECE model is therefore expected from presently foreseeable tonnages up to 2500 per site over either the local or whole-sound areas.

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TABLES

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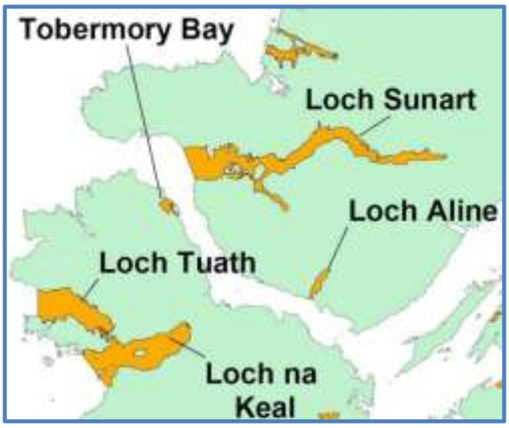
1 INTRODUCTION

1.1 SOUND OF MULL REGULATORY ISSUES

The Sound of Mull is not a categorized area within the Locational Guidelines (Marine Scotland, 2012); there are no category 2 areas adjacent to the sound, but three category 3 areas in Loch Sunart, Loch Aline and Tobermory Bay are contiguous (Figure 1). An assessment of nutrient enhancement for planning purposes or Environmental Impact Assessment is required, to include the cumulative effect of nutrients released from fish farms in the area.

This report relates conditions at the farms to an integrated view of the whole sound. It estimates the increases in nitrogen concentration in waters local to the sites and in the whole water body of the sound.

Figure 1: Sound of Mull: locational guidelines – category 3 (orange)



A relevant water body is one defined by the implementation of the Water Framework Directive in Scotland (the WEWS Act, 2003), shown in Figure 2, from http://www.scotland.gov.uk/Topics/marine/seamanagement/nmpihome/nmpi).

Figure 2: Sound of Mull water bodies (WFD)

1.2 THE ECE APPROACH

The ECE (Equilibrium Concentration Enhancement) equation was expressed by the then SEERAD Marine Laboratory in support of the Locational Guidelines for the Authorisation of Marine Fish Farms in Scottish Waters (see http://www.scotland.gov.uk/Topics/marine/science/Publications/publicationslatest/farmedfish/locationalfishfarms).

The equation estimates the enhancement of nitrogen above background levels resulting from aquaculture; it assumes that released nitrogen is conserved, mixed with surrounding waters and only removed by water flows. The ECE model is a simple dilution relation that considers dissolved nitrogen, particulate nitrogen and nitrogen that may have re-dissolved from the seabed. It takes no account of intrinsic biological or chemical processes. The model equation is described within www.scotland.gov.uk/Topics/marine/Fish-Shellfish/18716/environmentalimpact/models. The equation estimates the enhancement of nitrogen above background levels from aquaculture, assuming that released nitrogen is conserved and only removed by water flows.

ECE = ***S***.***M***/***Q*** (kgN.m^{-3})

Where:

S = Source Rate (kgN.tonne^{-1}.year^{-1})

M = Total Consented Biomass (tonne)

Q = Volume Flow Rate (m^{3} year^{-1})

The source rate ***S*** is conventionally taken as 60 kgN.tonne^{-1}.year^{-1}.

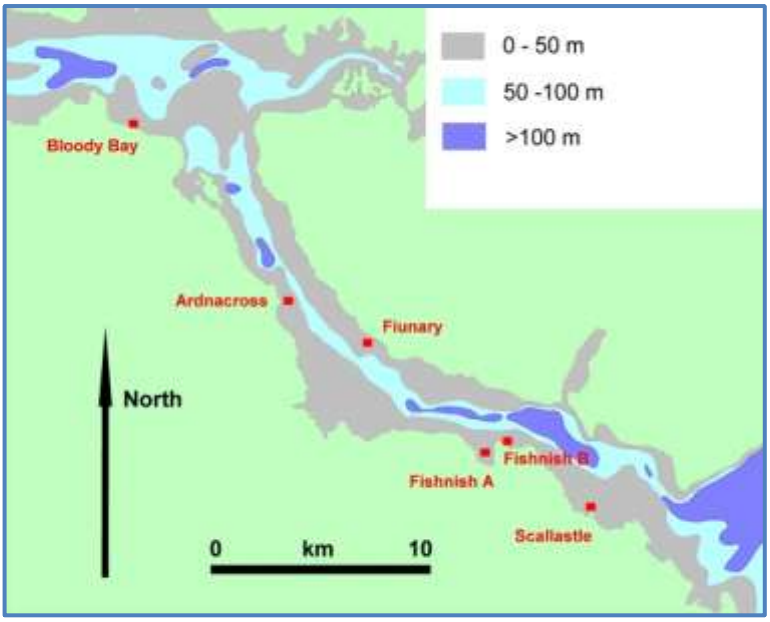
2 PHYSICAL BACKGROUND

2.1 GEOGRAPHY

The Sound of Mull is a post-glacial channel about thirty km long and two to three km wide with a maximum depth of about 130 m and a mean depth about 40 m. There are complex restrictive regions at the eastern and western ends that both inhibit and accelerate local flows. Between these restrictions the typical cross sectional area of the sound is about 10^5 m^2.

There are six relevant farm sites within the sound as shown in Figure 3.

Figure 3: SSF farms in the Sound of Mull



2.2 TIDES

2.2.1 Tidal Range

The tides at Tobermory are summarised in Table 1 (from National Tides & Sea Level Facility, http://www.pol.ac.uk/ntslf/hilo.php?port=tobermory).

Table 1: Tides at Tobermory

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

Typical tidal ranges in this area are thus about 1.4 (neap) to 4.0 (spring) metres, with an average of about 2.7 metres.

2.2.2 Tidal Streams

Tidal currents associated with the largely semidiurnal rise and fall of the tides are described roughly in the Admiralty Tidal Stream Atlas (2009), which is on too coarse a scale to show much detail. Table 2 shows the hourly summaries.

Table 2: Tidal Currents in the Sound of Mull

Time from HW Dover	**Neaps**		**Springs**	
Hours	**Speed $m.s^{-1}$**	**Direction**	**Speed $m.s^{-1}$**	**Direction**
-6	0	slack	0	slack
-5	0.1	eastward	0.2	eastward
-4	0.2	eastward	0.5	eastward
-3	0.2	eastward	0.6	eastward
-2	0.2	eastward	0.5	eastward
-1	0.1	eastward	0.4	eastward
0	0	slack	0	slack
1	0.1	westward	0.2	westward
2	0.2	westward	0.6	westward
3	0.2	westward	0.7	westward
4	0.2	westward	0.6	westward
5	0.1	westward	0.3	westward
6	0	slack	0	slack
Typical speed	0.13	-	0.38	-
Net Flow	0	-	0.02	Westward

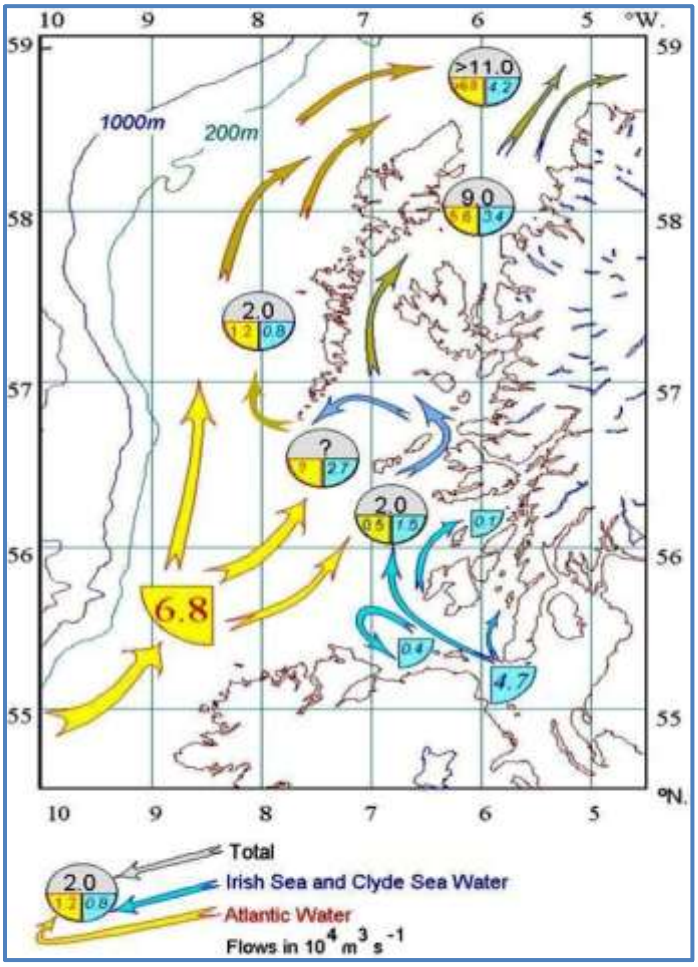
Typical speeds of flow are about 0.13 $m.s^{-1}$ (neaps), to 0.38 $m.s^{-1}$ (springs). The net flow in the sound appears to be slightly westward on springs (about 2 $cm.s^{-1}$) but in view of the crudely expressed summary chart speeds - given only for navigational purposes - little significance attaches either to these estimates of residual speed or direction.

2.3 EXTERNAL NON-TIDAL CIRCULATION

The main feature of the non-tidal circulation in the local coastal area around Mull is a northward residual drift along the Scottish west coast (Ellett, 1994). Ellett estimated the residual flow on the southern edge of Mull towards Loch Linnhe to be about 10^3 $m^3.s^{-1}$. With no other outlet to the North, this flow must then pass westward through the Sound of Mull, with a corresponding typical residual speed in the cross section (10^5 m^2) of 0.01 $m^3.s^{-1}$. Interestingly, this is very similar to the rough Admiralty Tide Table estimate in section 2.2.2. After leaving the sound, water re-joins the general westward and northwards coastal flows.

These flows were derived to some extent from considerations of the long term (many months or a year) fate and decay of Caesium-137 in west coast waters. From this viewpoint, they express long term patterns that are not necessarily to be expected in shorter term measurements such as the (typically) 15 day measurements made for regulatory purposes.

Figure 4: Flow partitions west of Scotland (after McKay et al., 1986)



3 MEASURED SITE FLOWS

Currents at sites in Figure 3 were previously measured over fifteen days at various intervals at each depth so as to support their consent applications.

The results of these surveys were reported in standard regulatory form by the hydrographic contractors quoted below for each site.

At all sites the data were supplied and handled to acceptable regulatory standards in spreadsheets and this report therefore does not deal with any uncertainties arising from the methods of measurement.

The data provided thereby for regulatory purposes have been re-presented to a common format in the following sections and figures.

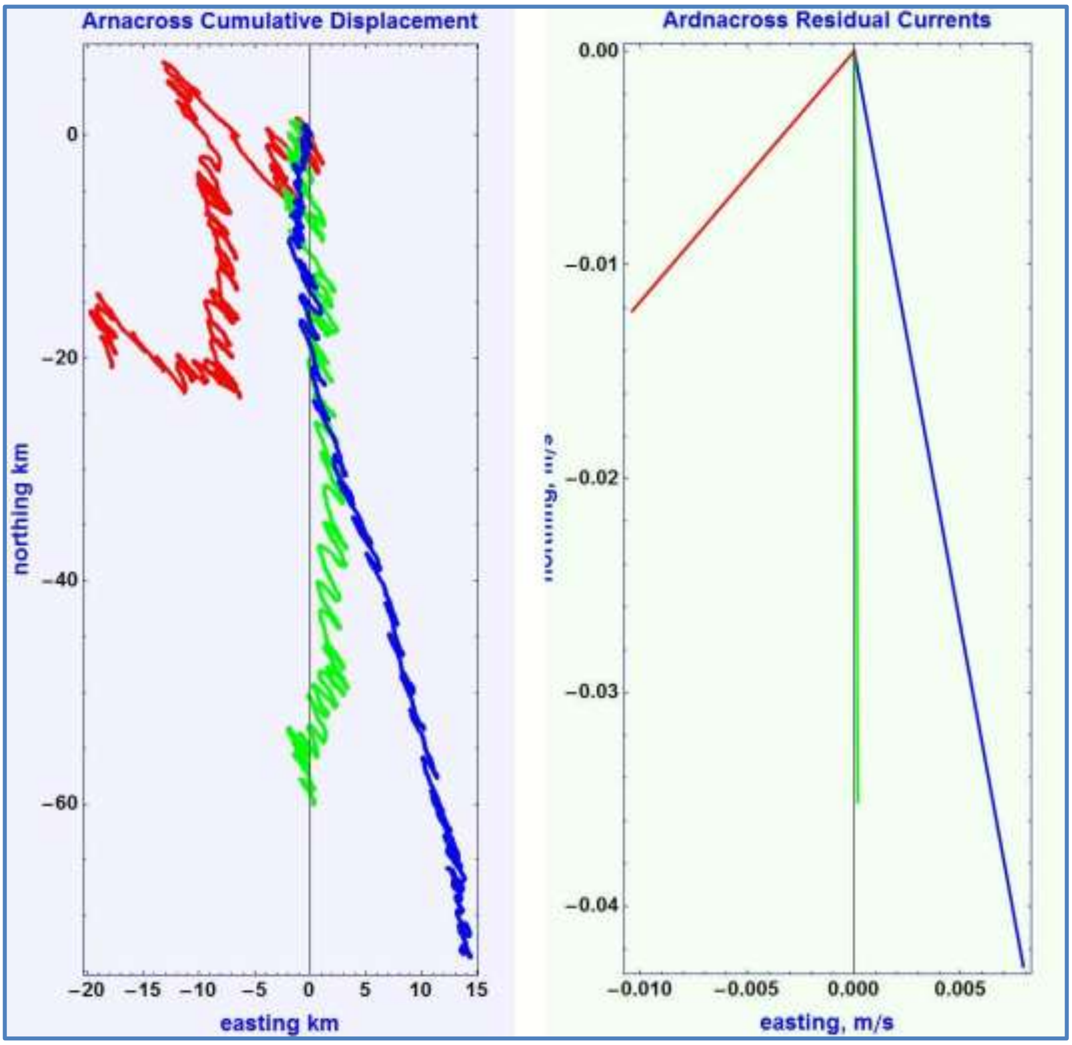
In the following figures of this section, near surface measurements are depicted in red, mid depth are green and near-bed are blue.

3.1 ARDNACROSS

This site was modelled by the Scottish Environment Protection Agency (SEPA) in 2002. The current data (Anon, 2002, supplied by SSF, 2012) have been re-analysed here. Winds were light to moderate.

The main features of the record are visible in Figure 5. Residual southward flows were modulated by semidiurnal oscillatory flow that produced tidal excursions of a few kilometres along the sound.

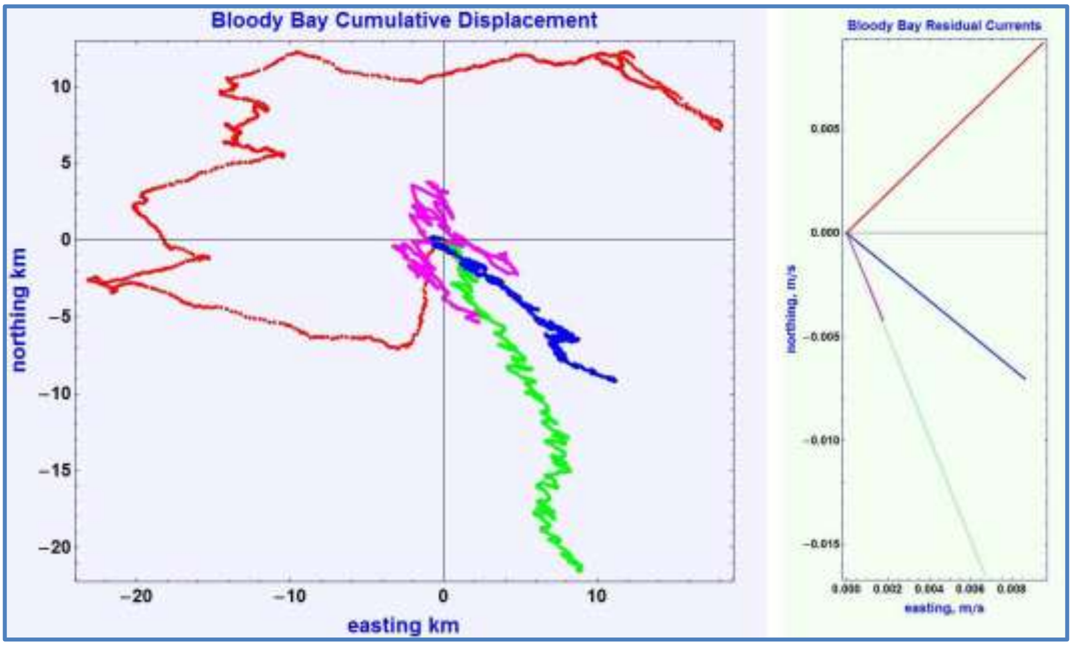
Figure 5: Ardnacross 19-Mar-2002 to 8-Apr-2002; vector diagrams and residual velocities



3.2 BLOODY BAY

Measurements were reported by Dalriada (2008). Important features are visible in Figure 6. The wind during the period was mainly moderate westerly. Residual flows near the surface were variable over time scales of days with little tidal modulation. Deeper residual currents were to the South-East and were modulated by tidal oscillatory excursions of a kilometre or so.

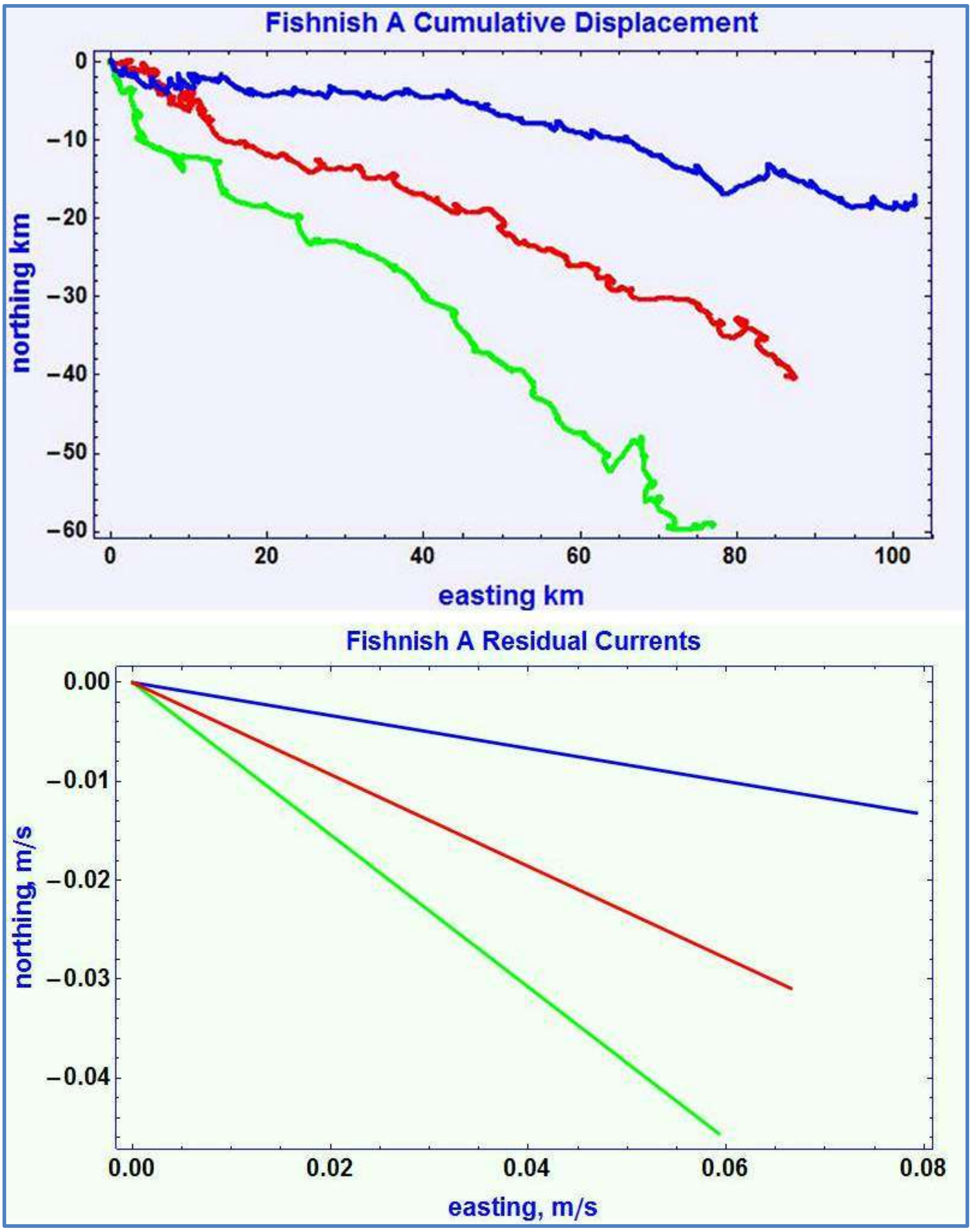
Figure 6: Bloody Bay 19-7-2001 to 3-8-2001; vector diagrams and residual velocities (magenta is from a near-bed rotor meter)



3.3 FISHNISH A

A series of 18-day measurements was described by Provost (2006). The main features are summarised in Figure 7. The wind during this period was mainly moderate south-westerly. Residual flows to the South-East were only weakly modulated by oscillatory excursions of about a kilometre or less.

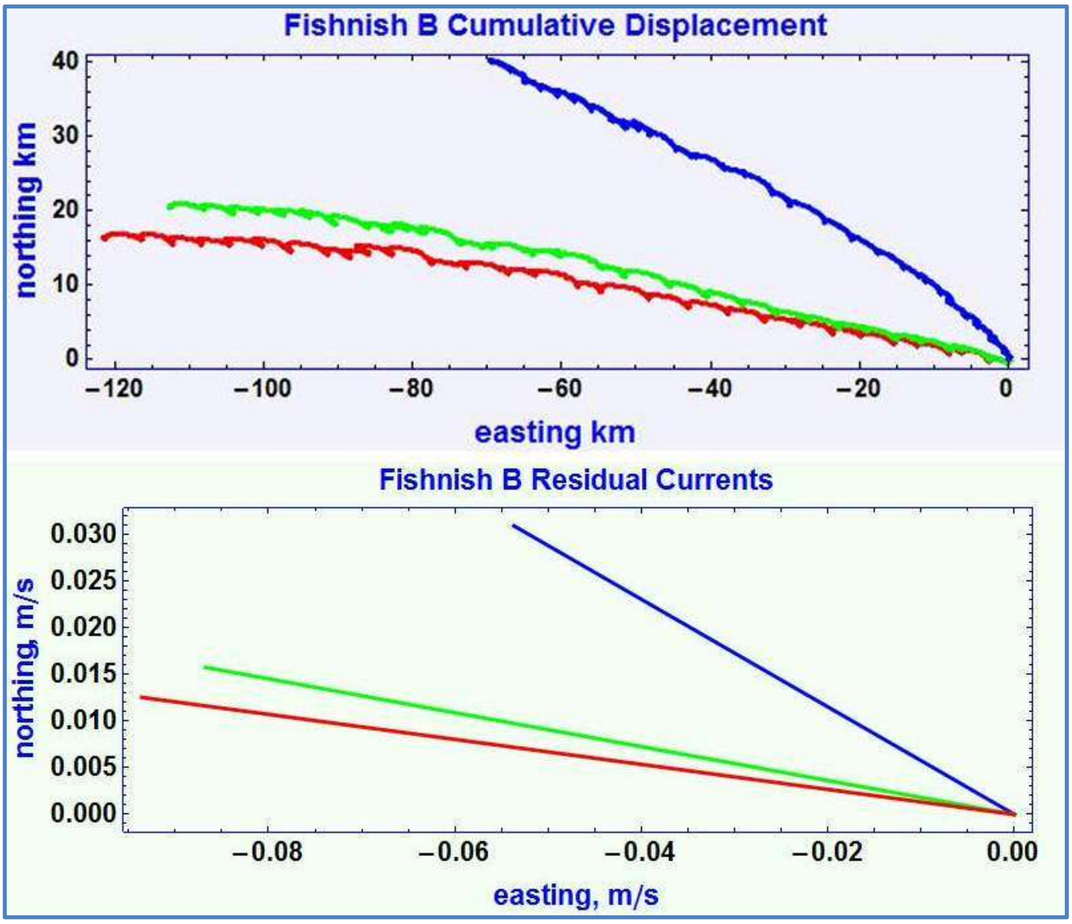
Figure 7: Fishnish A 6-10-2006 to 24-10-2006; vector diagrams and residual velocities



3.4 FISHNISH B

Measurements at this site were reported by Anderson Surveys (2008). The main features of the currents are summarized in Figure 8. Winds were moderate to light; no direction was reported. Residual flows to the North-West were modulated by oscillatory long-sound tidal excursions of about a kilometre.

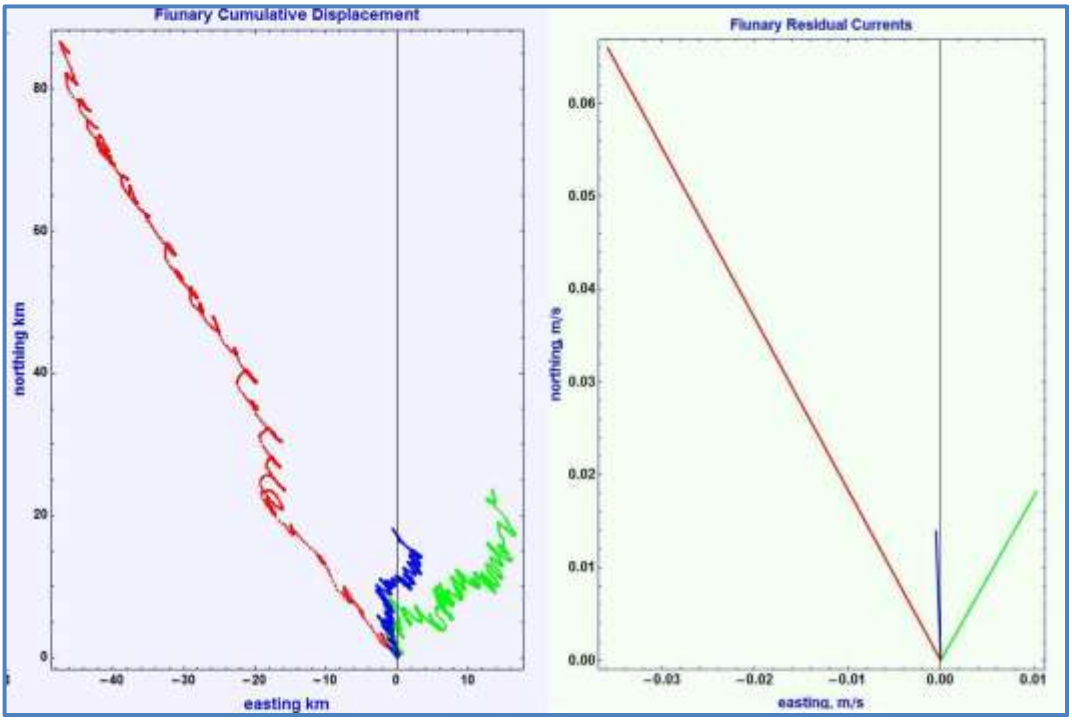
Figure 8: Fishnish B 6-10-2006 to 24-10-2006; vector diagrams and residual velocities



3.5 FIUNARY

Measurements at Fiunary were described by Anderson Surveys (2006) and are summarised in Figure 9. Residual flows to the North-West were modulated by oscillatory excursions of about two or three kilometres.

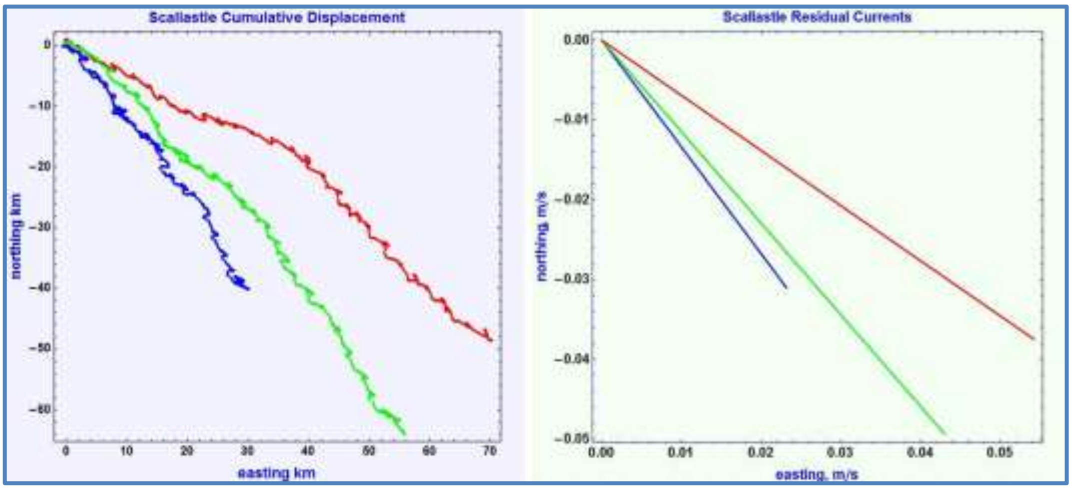
Figure 9; Fiunary 6-10-2006 to 24-10-2006 vector diagrams and residual velocities



3.6 SCALLASTLE

Currents at Scallastle were measured by Marine Harvest (2005). The wind over this period was light to moderate from variable directions. The measurements are summarised in Figure 10. Residual flows to the South-East were modulated by oscillatory excursions of about two kilometres.

Figure 10: Scallastle current vectors 9-9-2005 to 30-9-2005; vector diagrams and residual velocities



4 SUMMARY OF CURRENTS AT ALL SITES

4.1 THE EFFECT OF WIND

During these measurements the winds were mainly light to moderate, consistent with the requirements of the regulatory modelling process. Stratification in the Sound of Mull is very weak in the absence of strong freshwater sources and in the presence of enhanced mixing at the restricted western and eastern ends. Direct wind effects are therefore likely to penetrate to some depth, with correspondingly low speeds of wind-driven currents. The effect of wind is generally not clearly visible in the current measurements. In previous work in the Sound of Mull (Black et al., 2009), wind effects were found to be small. From these viewpoints, no further analysis of wind is therefore undertaken here.

4.2 TIDAL AND RESIDUAL CURRENTS

Although the records are variable in their nature and were obtained under different conditions, some general points come out of the preceding analysis.

The diagrams of section 3 generally show a pattern of long-sound residual flows modulated to various extents by semidiurnal tidal currents that also tend to align with the sound.

The oscillatory tidal current vectors within each record have been derived numerically from each record by subtracting the residual vector from the measured currents.

4.3 CURRENT STATISTICS

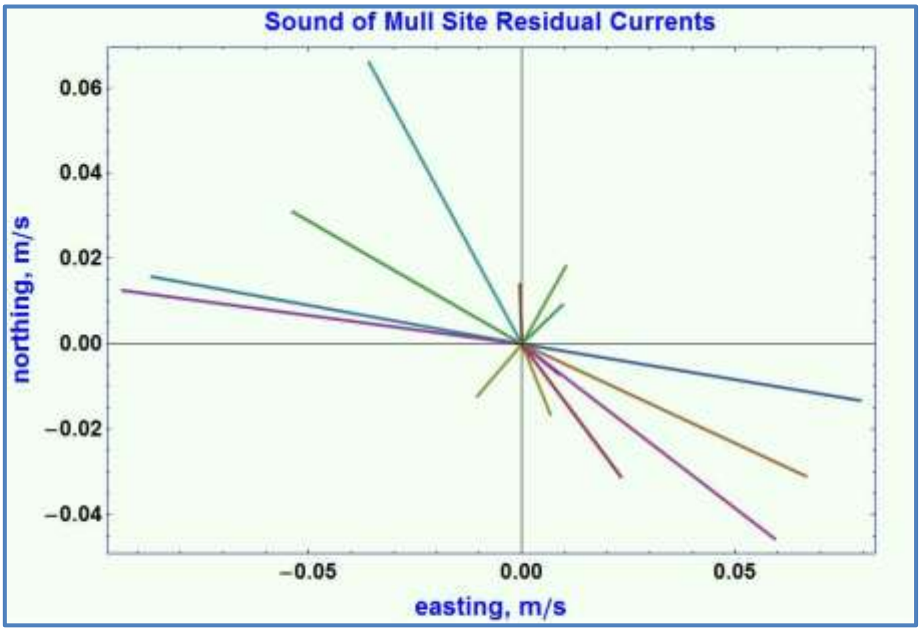
The main statistics (mean, maximum, root mean square, tidal, residual speeds and direction) of the currents are summarised in Table 3.

Table 3: Statistical summary of currents (yellow: residual to South-East; green to North-West)

Site	Mean, m/s	Maximum, m/s	RMS Speed, m/s	Mean Tidal Speed m/s	Residual, m/s	Direction, °N
Ardnacross Bed 25m	0.12	0.39	0.14	0.11	0.044	170.
Ardnacross Mid 11m	0.14	0.47	0.16	0.13	0.035	180.
Ardnacross Top 5m	0.16	0.53	0.18	0.16	0.016	221.
Bloody Bay Bed 23m	0.051	0.18	0.063	0.052	0.011	129.
Bloody Bay Bed Rotor 30m	0.053	0.24	0.078	0.055	0.0045	157.
Bloody Bay Mid 13m	0.06	0.2	0.073	0.06	0.018	158.
Bloody Bay Top 4m	0.1	0.4	0.13	0.1	0.013	46.
Fishnish A Bed 22m	0.12	0.41	0.15	0.11	0.08	99.5
Fishnish A Mid 11m	0.12	0.44	0.15	0.11	0.075	128.
Fishnish A Top 2m	0.13	0.49	0.16	0.12	0.073	115.
Fishnish B Bed 17m	0.09	0.32	0.12	0.086	0.062	300.
Fishnish B Mid 12m	0.13	0.39	0.16	0.12	0.088	280.
Fishnish B Top 6m	0.13	0.41	0.16	0.12	0.094	278.
Fiunary Bed 39m	0.081	0.36	0.1	0.082	0.014	358.
Fiunary Mid 16m	0.14	0.47	0.17	0.14	0.021	29.5
Fiunary Top 7m	0.17	0.61	0.21	0.17	0.075	331.
Scallastle Bed 14m	0.095	0.37	0.11	0.089	0.039	143.
Scallastle Mid 10m	0.11	0.36	0.13	0.099	0.065	139.
Scallastle Top 5m	0.11	0.38	0.14	0.1	0.066	125.

The estimates of residuals from this table are shown graphically in Figure 11.

Figure 11: Residuals at all sites in the Sound of Mull



4.4 TIDAL CURRENTS

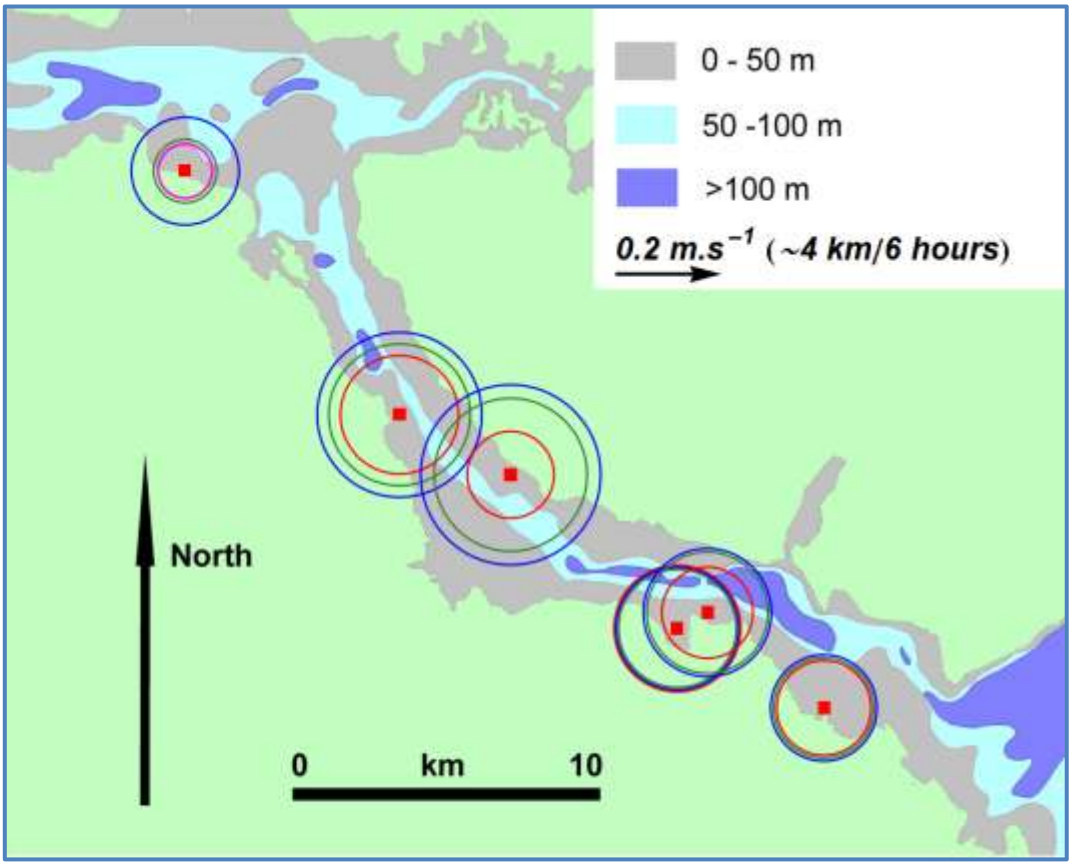
Table 3 shows that the typical size of the tidal currents is around their mean value of ±0.11 $m.s^{-1}$; these are rather less than the Admiralty tidal streams discussed in section 2.2.2; the difference probably owes to the frictional reduction of flows near the sides of the sound where the sites are situated, relative to the more central position of the admiralty flows.

The root mean square (RMS) speeds are slightly higher around a mean value of 0.14 $m.s^{-1}$, and mean residual speeds are around their mean value of 0.05 $m.s^{-1}$.

These tidal currents also tend to lie along the sound, as reported by the various contractors or as exemplified by the small scale embroidery of many of the vector diagrams in section 3. The deeper tidal currents at Bloody Bay are a little less (about 6 $cm.s^{-1}$) than the typical Sound values.

These tidal currents are depicted in Figure 12 by circles that represent both the mean tidal speed and also (on the scale of the map) the typical semi-diurnal tidal excursion associated with that speed over 6 hours. The scale of the excursions is a few kilometres, comparable with the width of the sound. With horizontal topographic eddying promoted by the irregular shores, and with higher currents (section 2.2.2) likely in the centre of the sound, promoting horizontal shear dispersion, it is likely that over a small number of excursions, effluent from any of the sites mixes across the sound.

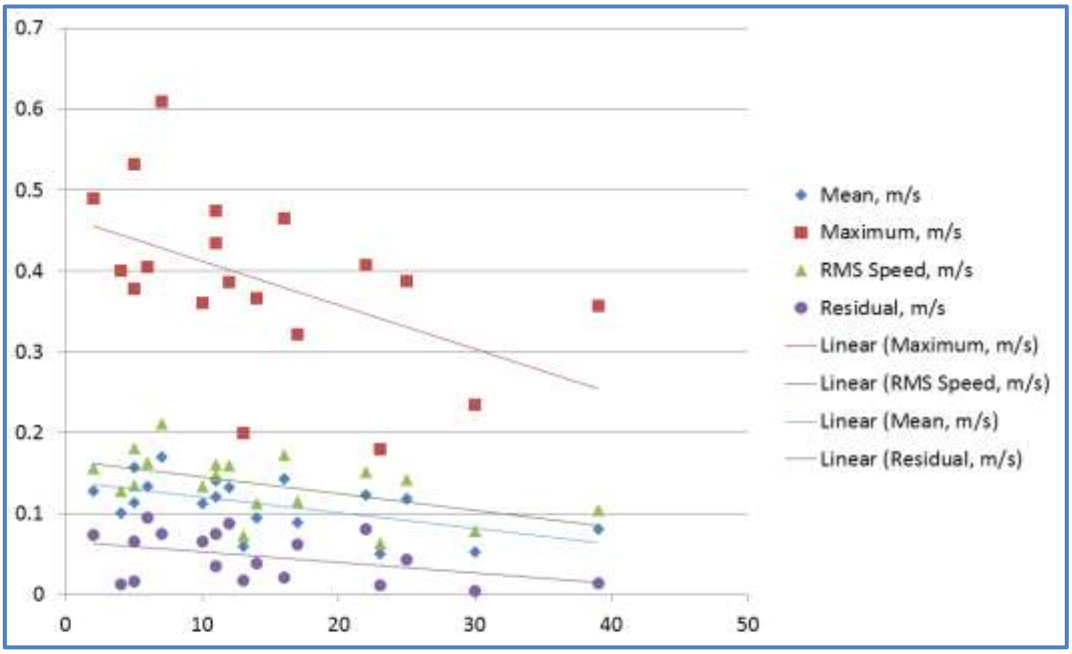
Figure 12: Tidal currents at sites in the Sound of Mull



4.5 VARIATION OF CURRENT WITH DEPTH

Figure 13 reveals a tendency for deeper currents in the sound to be weaker than surface currents in respect of maximal, mean, RMS and residual speeds.

Figure 13: Variation of currents with depth, all sites

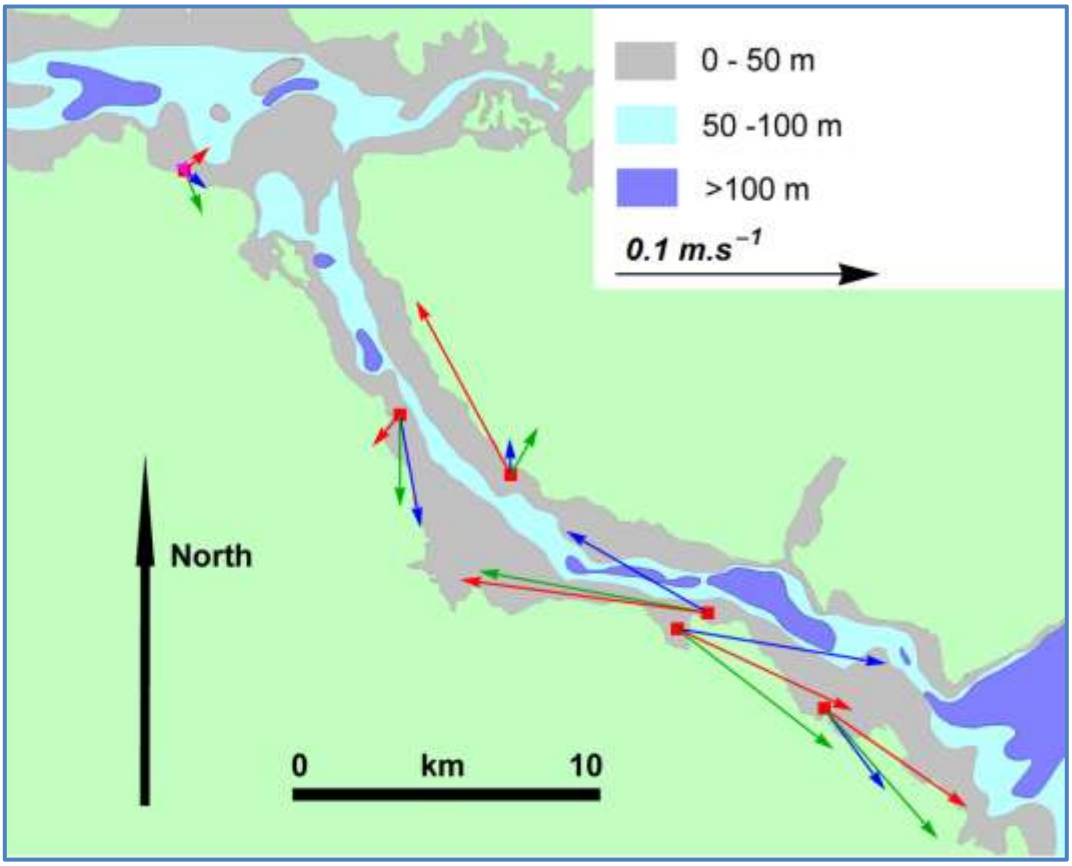


This decrease is trivial within ten metres of the water surface and may be reasonably be attributed to increased frictional and obstructive resistance to the flows near the bed and in the narrower deeper parts of the sound.

4.6 VARIATION OF RESIDUAL CURRENT WITH POSITION

Figure 13 shows the speed of the residual currents at all sites. The residuals tend to flow along the sound. The arrows also depict roughly (on the scale of the map) the distance that the residual would flow in a day. It is clear that these flows would flush the sound in a few days.

Figure 14: Residual currents at sites in the Sound of Mull



4.7 HYDROGRAPHIC SUMMARY

Sites in the Sound of Mull are characterized by a combination of semidiurnal oscillatory tidal flows of about 0.1 m.s^{-1} and two-week residual flows of about 0.1 m.s^{-1}. The flows diminish with depth and are probably greatest in the middle of the sound. The measured tidal and residual flows are largely directed along the direction of the sound. The tidal flows vary with neaps and springs; the residuals vary between east and west on time scales longer than those of these records.

A much weaker long term westward residual on timescales of months has been inferred from the work of Ellett (1994) and of McKay et al.(1986).

Conditions at any of these sites may be typified in this way, although the residuals at Bloody Bay are a little smaller than at sites within the sound proper.

5 PREDICTION OF NUTRIENT INCREASE

All sites lie to the side of the sound and it is instructive to examine both local and whole-loch aspects of the ECE argument.

5.1 SPREADING OF WATER FROM A CAGE GROUP

The band of water leaving a farm comes from a cage group width ***W***. It then disperses horizontally and vertically.

The horizontal spreading is related to the dispersion coefficient ***K***.

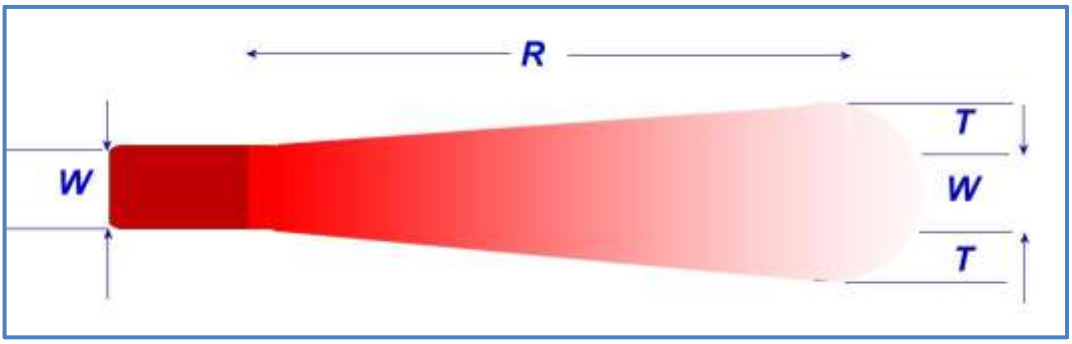
The horizontal scale ***T*** of spreading in a semidiurnal period ***t*** is of order $(2Kt)^{0.5}$.

Conservatively ignoring vertical spread, it may therefore be assumed that the typical width of the region influenced by the effluent after time ***t*** is around ***W***+***T***.

With a residual current speed ***U***, the residual displacement ***R***=***U***.***t***.

A simple view of this spreading is shown in Figure 15.

Figure 15: Spreading of effluent in a semidiurnal period, with residual flow



The area affected by the effluent water is about ***R***.***t***.(***W***+***T***). Over a depth ***H***, the affected volume ***V*** = ***R.t.H***.(***W***+***T***), or

$V = U.t.H.\ (W+(2Kt)^{0.5})$ … (1)

5.2 LOCAL NUTRIENT ENHANCEMENT

The source rate is ***S***

Tonnage is ***M***

In a semidiurnal period ***t***, the Nitrogen released = ***M***.***S***.***t***

And from equation (1), the local enhancement

$E = (M.S)/(U.H.\ (W+(2Kt)^{0.5}))$ … (2)

Typical parameter values over a range of circumstances at sites may be adopted:

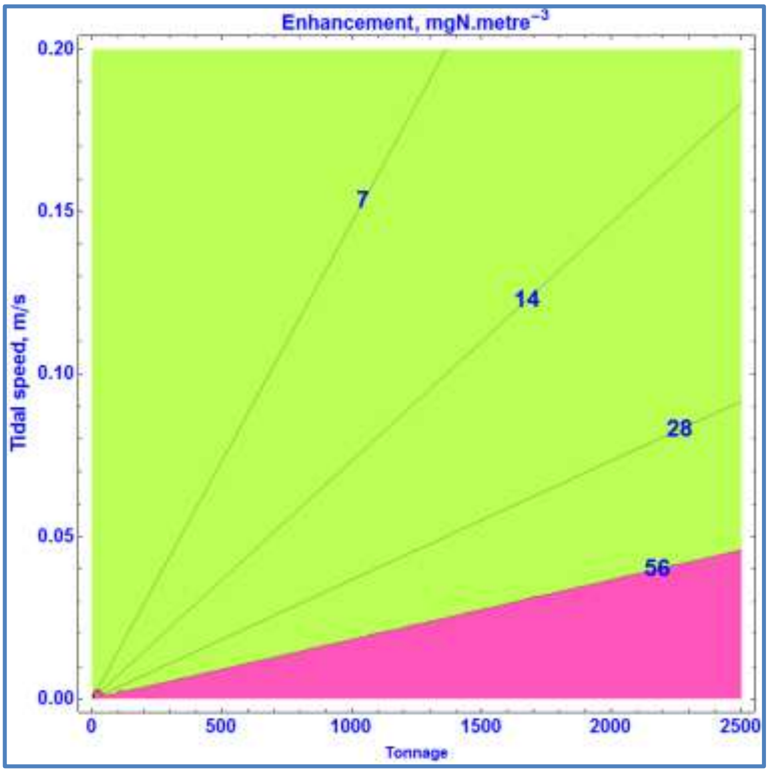
- Conservatively, a depth of ***H***=10 metres may be used, being close to cage depth and less than the depth of the entrances to the sound
- The semidiurnal period ***t*** is about 12.4 hours, or 4.5×10^4 seconds

- The dispersion coefficient ***K*** is usually taken in regulatory work to be about 0.1 $m^2.s^{-1}$. This is a conservative value, likely to be exceeded in energetic waters (see for example Lewis & Riddle, 2000).
- A typical cage group width ***W*** is around 100 metres
- ***S*** is usually taken to be 60 kgN.tonne^{-1}.year^{-1}.

Parameters that may vary from site to site are the current ***U*** and the tonnage ***F***. The corresponding ECE predictions from equation (2) over a range of typical values of ***U*** and ***F*** are shown in Figure 16.

- The residual current ***U*** is taken to be in the range 0 to 0.2 m.s^{-1}
- ***M*** is taken here to lie in the range 0 to 2500 tonnes.

Figure 16: Nutrient enhancement near a site within a semidiurnal period (12.5 hours)



The figure emphasizes the feature that local enhancement is higher in regions where the tidal flows are small and tonnage is high. However, for all reasonable circumstances in the Sound of Mull sites (tonnage less than 2500, tidal speeds above 0.05 m.s^{-1}), the local enhancement remains below 28 mgN.m^{-3}, or 2µM.

5.3 ECE WITHIN THE SOUND OF MULL WATERBODY

If the effluent is dispersed over the width of the sound (section 4.4) to a (conservatively estimated) depth of 10 metres, it will be diluted by the flows to that depth.

Over the timescale of the current records, typical site residual flows of section 4 are about 0.1 m.s^{-1}. The corresponding flows in the sound (cross sectional area about 10^5 m^2) are 10^4 m^3.s^{-1}, of which flow **Φ** in the near surface 10 metre depth zone is about 3.10^3 m^3.s^{-1}.

At any single site ***i***, the contribution to the ECE is:

$$\boldsymbol{E_i} = (\boldsymbol{F_i}.\boldsymbol{S}) / \boldsymbol{\Phi} \qquad \dots (4)$$

Assuming that water flows through the sound, picking up effluent from each site and losing none of its nitrogen to processes such as photosynthesis, the ECE within the sound may be found as the sum of all such contributions as in Table 4.

Table 4: Maximal site contributions to the ECE of the Sound of Mull residual flow

$Site_i$	**M_i tonnes**	**Enhancement E_i mgN.m^{-3}**
Ardnacross	2500	5
Bloody Bay	2500	5
Fishnish A	2500	5
Fishnish B	2500	5
Fiunary	2500	5
Scallastle	2500	5
Maximum total ECE	15000	30

It follows from the above arguments that, even with the most intensive use of all sites at a tonnage of 2500, the whole-sound ECE is very likely to remain within 30 mgN.m^{-3}, or 2 µM.

5.4 DISCUSSION OF ENHANCEMENT ESTIMATES

Sections 5.2 and 5.3 estimate conservatively the local and whole-sound nutrient enhancements over a range of site usage going up to 2500 tonnes. Lower enhancements would follow if vertical mixing below 10 metres were included. With lower tonnages, local or whole-sound enhancements reduce in direct proportion.

These estimates, up to 2 µM, may therefore be regarded as upper bounds on the local or whole-sound nutrient enhancements.

Inputs from aquaculture are assessed against OSPAR and UKTAG Water Framework Directive (WFD) reference/background levels. The calculated ECE from fish farms in the water body is added to the reference (background) level for that water and the result is then assessed as to whether it breaches the threshold, which is 50% above the reference value.

In coastal waters the reference DIN normalised to salinity of 32 is 13µM, with a 50% threshold breach of 6.5 µM. In offshore waters such as the Sound of Mull the reference DIN for salinity above 34 is 10µM with a 50% threshold breach of 5 µM.

On both local (site) and large (whole-sound) scales, maximum equilibrium concentration enhancements up to 2µM have been estimated as the ratio of nutrient inputs to water flows. This is well below the breach concentration.

These maximal and conservative ECE estimates are therefore small in comparison with the OSPAR and WFD criteria relating to the permitted increase above reference concentrations or with a previously used Environmental Quality Standard of 168 mgN.m^{-3} (12 µM).

6 CONCLUSION

Two-week current records at six sites in the Sound of Mull display tidal and residual flows of amplitudes about 0.1 $m.s^{-1}$, largely aligned along the sound. The residual flows may lie in either direction but may have a very long term westward mean.

At worst case, with all direct inputs from consented sites at maximum tonnages of 2500, the conservatively predicted increase in site-local or whole-sound Nitrogen concentration is expected to be less than 2 μM.

These increases are small in comparison with OSPAR and Water Framework Directive criteria relating to permitted increases above reference concentrations of nitrogen, or with the previously used Environmental Quality Standard of 12 μM.

In conclusion, representative maximum nitrogen concentration enhancement within the Sound of Mull predicted by the ECE model from all presently contemplated inputs is expected to be less than 2 μM and no significant adverse environmental effect from nitrogen enhancement is therefore to be expected from the modelled tonnages over either the local or whole-sound areas of this water body.

7 REFERENCES

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