SSF

SCAPA FLOW
ECE ESTIMATES AND HYDROGRAPHY

Report No. Scapa 2021 004

[redacted]

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SUMMARY

This report outlines the hydrography of the area of Scapa Flow in the Orkney Islands to estimate the effect of all existing and two proposed (at Bring Head and Toyness) fish farms on local nutrient concentrations via the *Equilibrium Concentration Enhancement* (ECE) approach. The report is based on an analysis of measurements and on various pieces of literature relating to the general Orkney sea area and to Scapa Flow in particular.

Tidal and residual flows to Scapa Flow and at farms have been estimated by various methods (tide tables, direct measurement and water budgets).

A conservative (from the regulatory perspective) aspect of the analysis is that recirculation of tidal flows into Scapa Flow up to 90% has been considered but is believed to be much less. More realistic and lower values of recirculation increase the diluting effect of tidal flows and correspondingly reduce the predicted Nitrogen ECE below the estimated values, making them insignificant in relation to winter background concentrations or to a regulatory standard of 168 µgN.litre^{-1}.

A generally anticlockwise circulation in Scapa Flow is inferred from all relevant sites, consistent with other modelling done in support of ballast water operations. Wind measurements made in support of licence application at Westerbister in the east of Scapa Flow have been compared with long term conditions. From this perspective, the measurements are believed to be typical of long-term conditions. The current measurements reveal a northward flow at Westerbister, consistent with the eddy being a long-term feature of Scapa Flow.

The circulation time based on the inferred anticlockwise circulation in Scapa Flow is comparable with the flushing time of Scapa Flow estimated from a tidal flow budget. This agreement suggests that eastern waters are reasonably well connected and mixed into the general circulation of Scapa Flow. Flows in the West are relatively strong, flushing the sites at Bring Head and Toyness.

Conclusion

Flows in Scapa Flow are sufficient to dilute the nitrogen released from existing consented sites and proposed sites such that the size of the ECE increase in nitrogen concentration over the whole of Scapa Flow is a few (1.8 to 5) µgN.litre^{-1}, much lower than winter background concentrations and well below a regulatory standard of 168 µgN.litre^{-1}. Increases in concentration local to farms are restricted to small areas near the farms and similarly present no significant impact within one tidal cycle of emission.

The large precautionary margin between these conservative estimates and the regulatory standards means that more detailed modelling of dissolved nutrient enhancements is not needed.

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TABLES

FIGURES

1 INTRODUCTION

1.1 Scapa Flow: The regulatory context

Water bodies have been identified around the Scottish coast for the purposes of the Water Framework Directive, as implemented by the Water Environment and Water Services (Scotland) Act 2003. Those public agencies responsible for identifying water bodies in the United Kingdom have done so in a transparent and consultative manner, having regard, amongst other things, to the oceanographic and administrative realities of coastal waters.

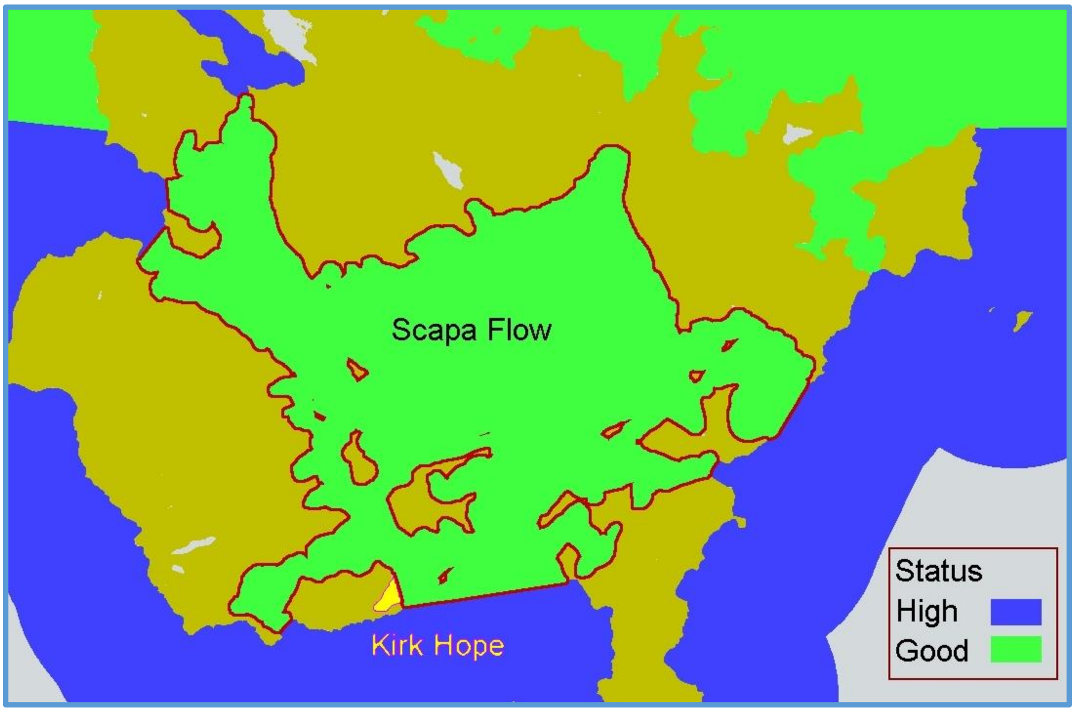
Although Scapa Flow is not a categorised area within the Locational Guidelines (Marine Scotland, 2020), an assessment of nutrient enhancement for regulatory and planning purposes is nevertheless required. The nearest categorised area is at Kirk Hope (category 3; Figure 1).

An assessment of the cumulative effect of nutrients released from all sites within Scapa Flow may be deemed most appropriate when based upon the defined administrative water body of the Water Framework Directive (WFD, Directive 2000/60/EC).

The directive's definition of a Water Body is *"…a discrete and significant element of surface water such as a lake, a reservoir, a stream, river or canal, part of a stream, river or canal, a transitional water or a stretch of coastal water.*"

The relevant Scapa Flow water body for the purposes of the WFD is shown in Figure 1, taken from Marine Scotland - National Marine Plan Interactive (atkinsgeospatial.com)

Figure 1: Scapa Flow Water Framework Directive water body & Kirk Hope categorised area



A similar map is shown (2021) in Water Classification Hub (sepa.org.uk), which also summarises the corresponding WFD classification results for the year 2018 (Table 1). All Scapa Flow features are in good or high condition and the overall status is Good. Other local marine waterbodies and the categorised area at Kirk Hope have High status.

Table 1: WFD Classification of the Scapa Flow Water Body

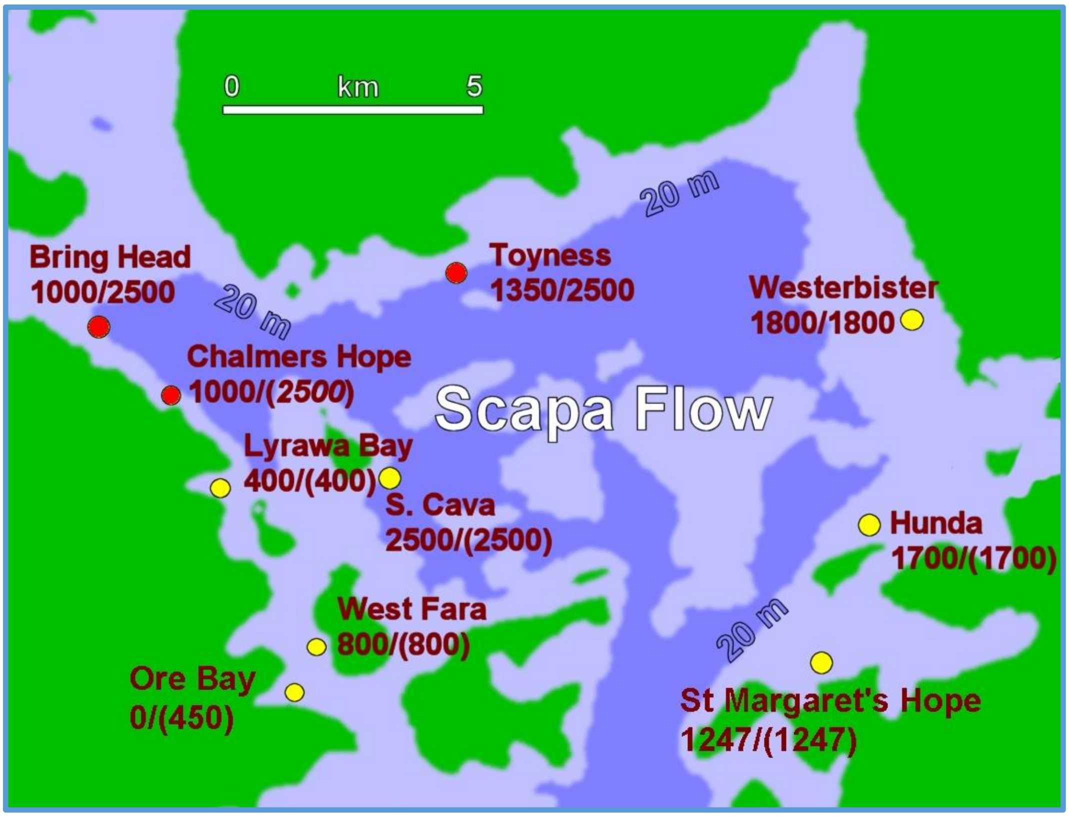
Feature	Class
Overall Ecology	High
Dissolved Oxygen	High
Dissolved Inorganic Nitrogen	Good
Biological Elements	Good
Invertebrate animals	Good
Imposex Assessment	High
Benthic invertebrates (IQI)	High
Macroalgae (FSL)	High
Macroalgae (RSL)	Good
Phytoplankton	High
Overall status	Good

This report therefore estimates the increase in nitrogen concentration in the WFD water body of Scapa Flow, a body containing several existing and proposed fish farms.

1.2 FISH FARMS IN SCAPA FLOW

There are several active licensed sites in the area of the applications. Figure 2 shows the bathymetry, locations and existing/proposed tonnages.

Figure 2: Farms in Scapa Flow, with existing/proposed SSF and (other) tonnages (yellow)



1.3 THE ECE APPROACH

The ECE equation was developed by SEERAD Marine Laboratory for the Locational Guidelines for the Authorisation of Marine Fish Farms in Scottish Waters as an extension of the sea-loch budgeting outlined in *The Sea Lochs Catalogue* (Edwards & Sharples, 1986). 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 biological or chemical processes. The equation estimates the enhancement of nitrogen above background levels from aquaculture, assuming that released nitrogen is conserved and only removed by water flows:

$ECE = S\ M\ /Q$

Where:

S = Source Rate	(kgN.tonne production^{-1}.year^{-1})
M = Total Consented Biomass	(tonne)
Q = Volume Flow Rate	(m^3 year^{-1})

Predicted ECE scales in direct proportion to the source rate S, which in this report is taken conservatively (and for comparison with earlier work when feed efficiencies were less) as 60 kgN.tonne^{-1}.year^{-1}.

Lower values have reasonably been used elsewhere (48.2 kgN.tonne^{-1}.year^{-1}: Greenwood, 2020; Davies, 2000; Xodus, 2103; and 35.6 kgN.tonne^{-1} year^{-1}, Intertek, 2018).

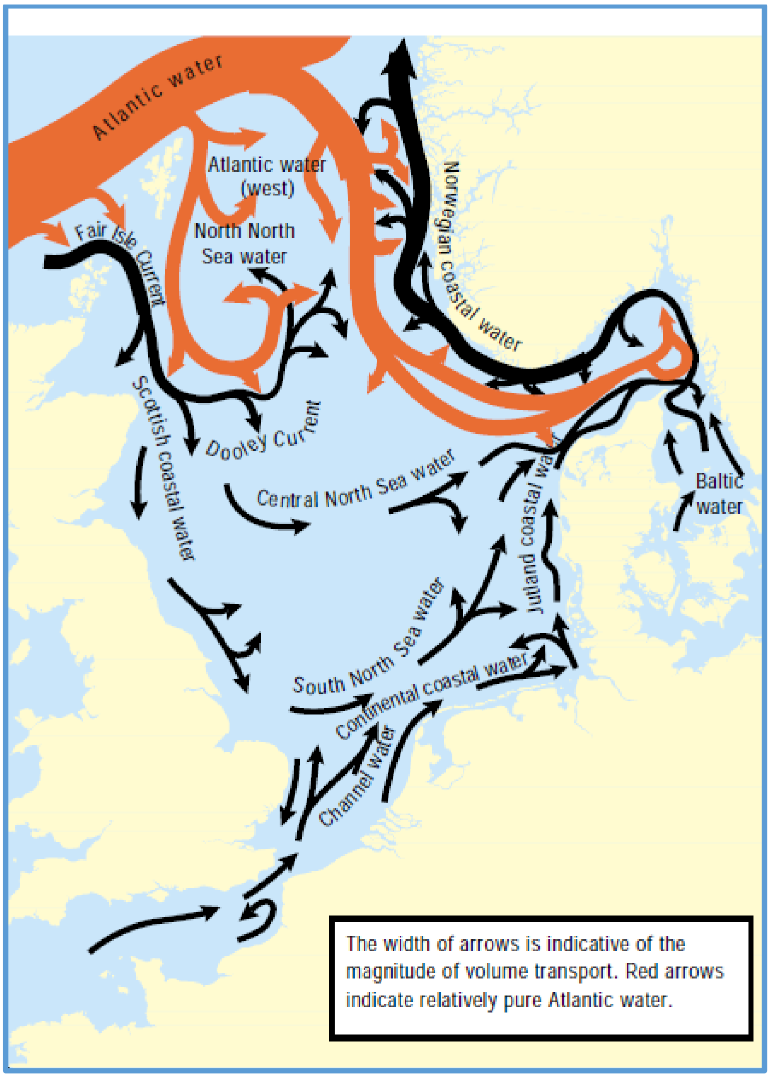
In consequence, all values of ECE calculated in this report would be 20% less were the lower value of 48.2 kgN.tonne^{-1}.year^{-1} used.

2 PHYSICAL BACKGROUND

2.1 NON-TIDAL CIRCULATION AND THE FAIR ISLE CURRENT

The main feature of the non-tidal circulation in the area is the Fair Isle current and the general residual flow from the west or north-west into the North Sea (Figure 3).

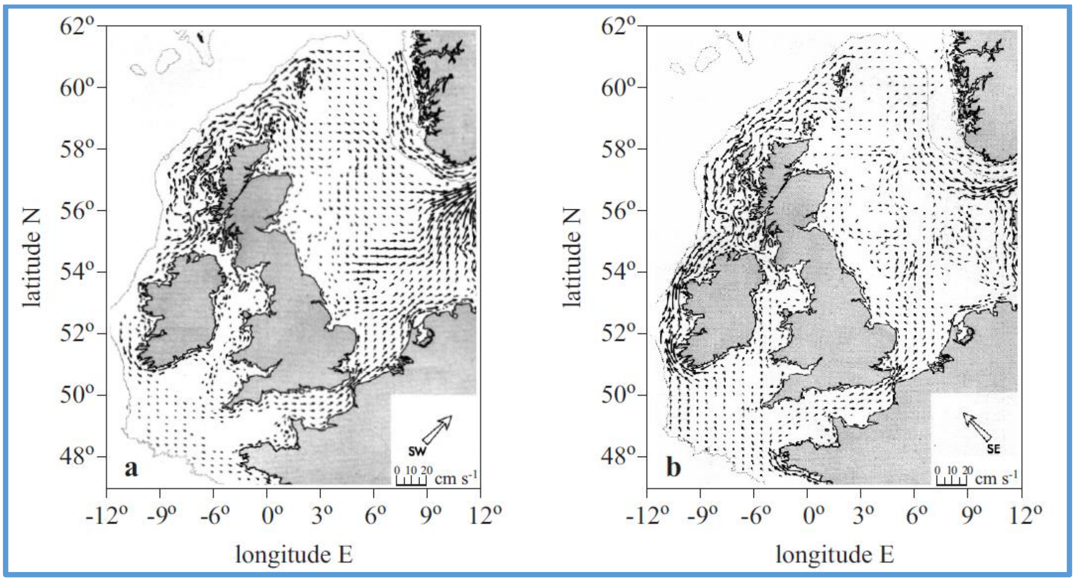
Figure 3: Schematic diagram of general circulation in the North Sea (after Turrell et al. 1992)



Dooley and MacKay (1975) noted residual speeds of about 0.1 m.s^{-1} west of Orkney. Dooley (1974) estimated a flow of about 10^{4} km^{3}.year^{-1} in the Fair Isle current; over the gap between Shetland and north Scotland, this translates into a residual current past and through Orkney of a few cm.s^{-1} to the South-South-East.

Large scale modelling of the shelf seas (Leterme *et al*. 2008, see Figure 4) reveals the same picture; Figure 4 shows the generally south-eastward, if wind-variable, nature of the flows.

Figure 4: Modelled currents under south-westerly and south-easterly wind; scale as shown

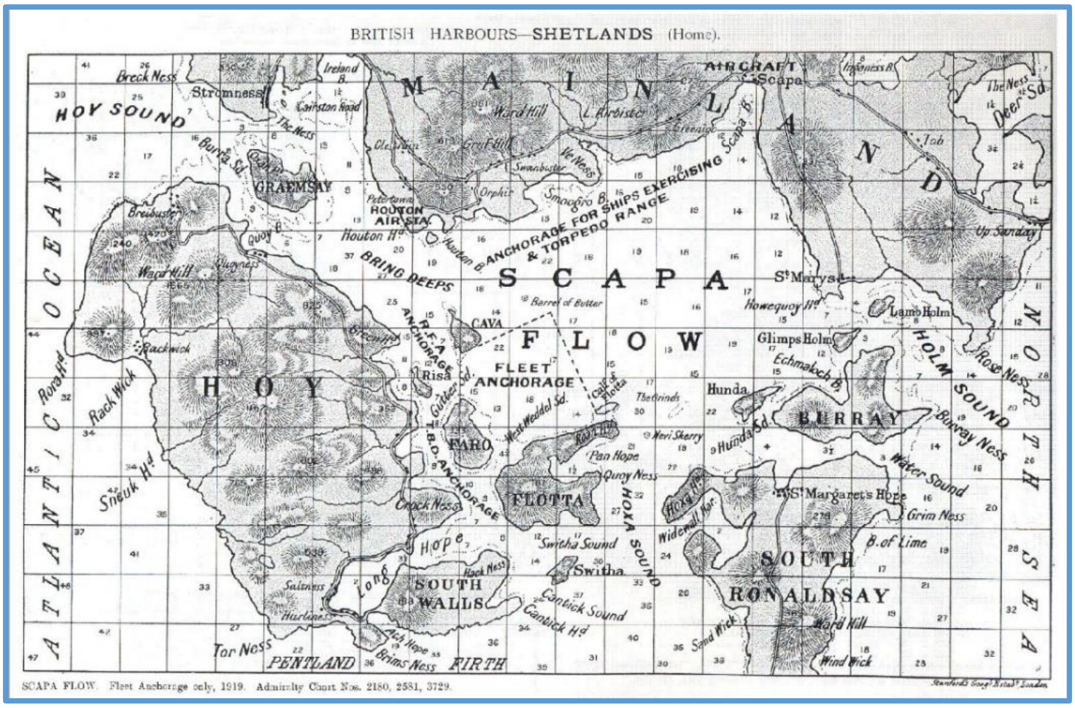


This general picture of residual flow is the context within which the following site-specific measurements from the fish farms should be seen.

2.2 GEOGRAPHY

Figure 5 shows an early bathymetry before the construction of causeways linked some islands and blocked shallow eastern entrance channels to Scapa Flow.

Figure 5: Scapa Flow bathymetry before causeway construction (depths in fathoms)



The causeways and main islands are sketched in Figure 6.

Figure 6: Scapa Flow – roads, causeways (red) and islands

The principal flushing flows to and from Scapa Flow therefore take place via the Sounds of Hoy and Hoxa.

2.3 TIDAL CURRENTS

2.3.1 Tidal Range

The tides at Wick, similar in range to the Scapa Flow area, are summarised in Table 2 (National Tides & Sea Level Facility, http://www.ntslf.org/tides/hilo?port=Wick).

Table 2: Tides at Wick

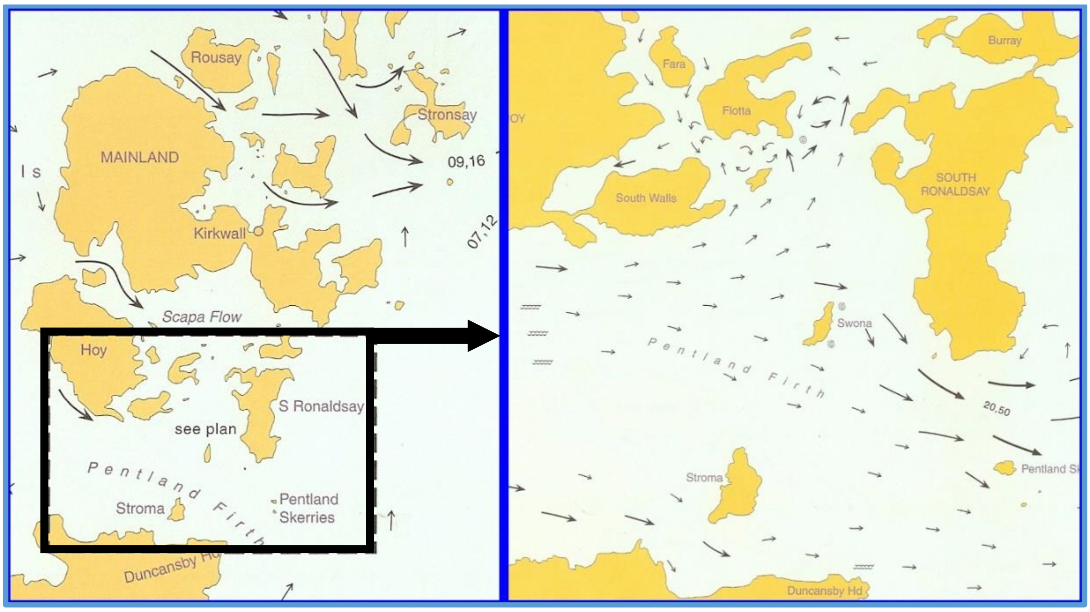
Tide	Wick
Highest Astronomic Tide	3.97 m
Lowest Astronomic Tide	0.06 m
Mean High Water Spring	3.51 m
Mean Low Water Spring	0.63 m
Mean High Water Neap	2.78 m
Mean Low Water Neap	1.43 m

Typical tidal ranges in the Orkney region thus reach about 3 to 4 metres, with an average of about 2 metres.

2.3.2 Tidal Streams

Currents associated with the rise and fall of the tides are described very roughly in the Admiralty Tidal Stream Atlas (2006). The atlas shows tidal streams every hour. Figure 7 shows examples of the hourly maps in the atlas for this area.

Figure 7: Tidal streams five hours before high water Dover; neap and spring (tenths of a knot)



From this set of maps it is possible to derive tables of estimated representative flows in Hoy and Hoxa Sounds, through which the main water flows enter and leave Scapa Flow (Table 3). The representation of flows on the maps is both variable and qualitative, so such estimates are necessarily rough.

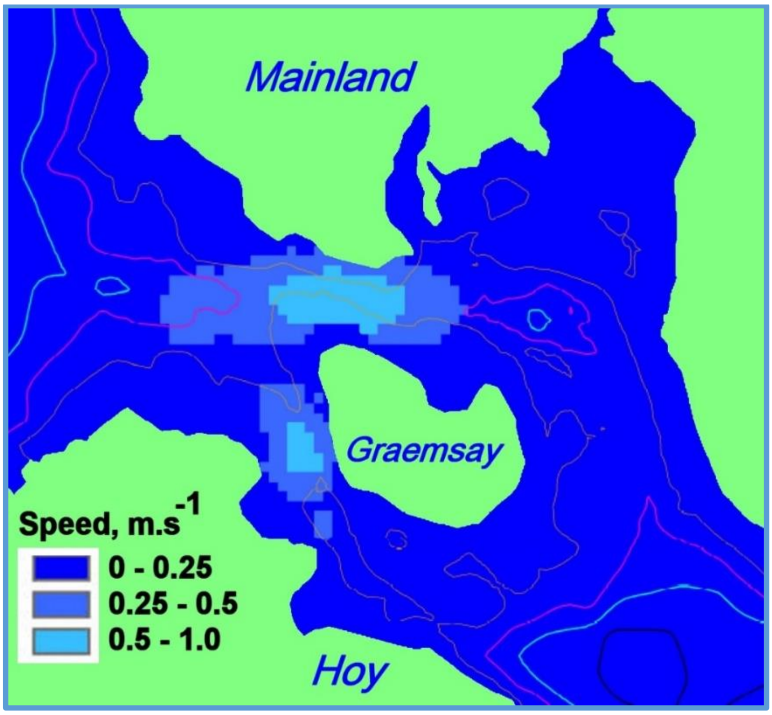
Table 3: Tidal flows in Hoy and Hoxa Sounds

Time from HW Dover	Hoy Sound Neap and spring (undifferentiated)		Hoxa Sound Neap and spring (undifferentiated)	
Hours	**Speed m.s^{-1}**	**Direction**	**Speed m.s^{-1}**	**Direction**
-6	~1	South-eastward	~0.5	Northward & eddying anticlockwise
-5	~1	South-eastward	~0.5	Northward & eddying anticlockwise
-4	~1	South-eastward	~0.5	Northward & eddying anticlockwise
-3	~1	South-eastward	~0.5	Northward
-2	~0.8	South-eastward	~0.3	Northward
-1	0.6	South-eastward	Weak	Variable
0	0.6	North-westward	Weak	Variable
1	Weak	North-westward	Weak	Southward
2	~1	North-westward	~0.3	Southward
3	~1.2	North-westward	~0.3	Southward
4	~1	North-westward	~0.3	Northward
5	~0.8	North-westward	~0.3	Northward
6	~0.5	South-eastward	~0.5	Northward eddying
Typical (average)	~0.8	Inflow/outflow	~0.3	Inflow/outflow

2.3.3 Currents near Graemsay

Average currents in Hoy Sound reach about 1 m.s^{-1} (Figure 8) although spring currents near Graemsay may reach as 4 m.s^{-1} in the most restricted parts (Marine Scotland, 2010; (previously quoted in http://www.scotland.gov.uk/Resource/Doc/295194/0096885.pdf (Edwards, 2015)). In Hoxa Sound, spring currents are weaker at about 1 m.s^{-1}.

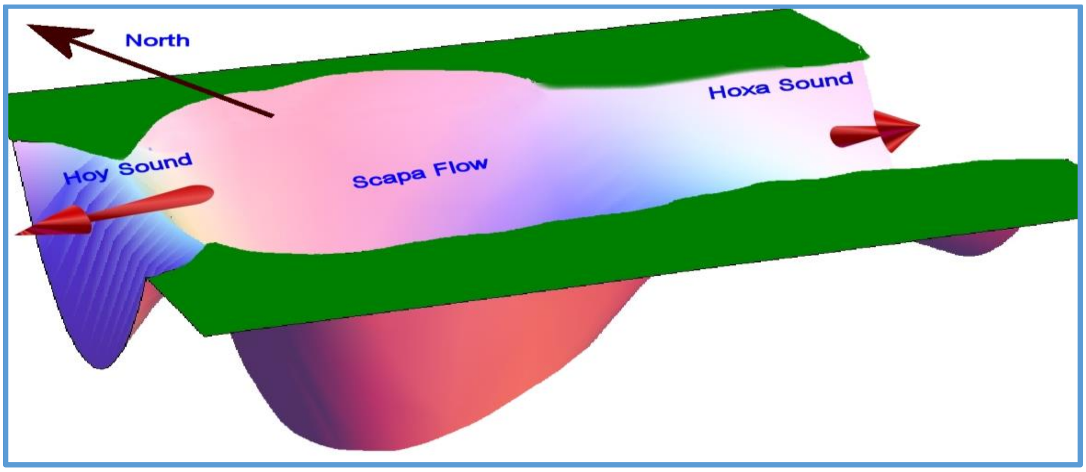
Figure 8: Average currents in Hoy Sound (adapted from Marine Scotland 2010)



2.3.4 Flows in the Sounds

The tidal flows in Hoy and Hoxa Sounds tend to oppose each other (section 2.3.2), so that Scapa Flow may fill or drain through the two sounds, as in the sketch of Figure 9.

Figure 9: Cartoon of ebb tide Scapa Flow (currents reverse on the flood tide)



The volume flows associated with these flows may be estimated according to the cross-sectional areas of the sounds: West of Graemsay in the area of the strong currents of Figure 8 the cross section of Hoy Sound (average depth 10 m, width 2 km) is about

2×10^4 m^2; the cross sectional area of Hoxa Sound east of Flotta (average depth 30 m; width 2 km) is about 6×10^4 m^2. From Table 3, typical speeds are: Hoy, 0.8 m.s^{-1}; Hoxa, 0.3 m.s^{-1}. Typical flows in these sounds may therefore be estimated as in Table 4.

Table 4: Typical tidal flow estimates in Hoxa and Hoy Sounds

	Hoy	**Hoxa**
Cross Section, m^2	2×10^4	6×10^4
Typical speed, m.s^{-1}	0.8	0.3
Typical Flow, m^3.s^{-1}	1.6×10^4	1.8×10^4
Typical Total Flow, m^3.s^{-1}	3.4×10^4	

From this analysis it appears that the volume flows of Figure 9 may be of similar size in each sound. Such estimates are averages over all tidal conditions; neaps will be a little lower; springs a little higher.

2.3.5 A Flow Budget

In view of the approximate nature of the flow estimates in section 2.3.4 it is reassuring to estimate them independently.

The rates of fall of sea level in a typical tide of range 2 metres (section 2.3.1) are about 10^{-4} m.s^{-1}. The area of Scapa Flow including the sounds is about 260 km^2. A typical tidal outflow or inflow rate is therefore about 260 km^2 x 10^{-4} m.s^{-1}, or 2.6×10^4 m^3.s^{-1}.

This compares well with the combined flows (3.4×10^4 m^3.s^{-1}) of Table 4, reinforcing the view that the main flows to Scapa Flow may be explained mainly by tidal draining and filling through Hoxa and Hoy Sounds.

Apart from farm site measurements, no current measurements were found in the BODC national database at https://www.bodc.ac.uk/data/bodc_database/currents/search/ Unattributed modelling of flows in the absence of wind reported to Orkney Islands Council by Intertek Metoc (2012, p31 fig 6.2) is generally consistent with the description of flows in this section 2.3 but adds no observational data. Other web-based resources are dominated by merely qualitative diving surveys.

3 CURRENTS MEASUREMENTS WITHIN SCAPA FLOW

3.1 DATA SETS

Bring Head and Toyness

Long new acoustic Doppler meter series of measurements were made at Bring Head (SSF, 2018, September 24 – December 9) and at Toyness (SSF, 2018, July 11 – September 18). These are analysed below.

Other Measurements

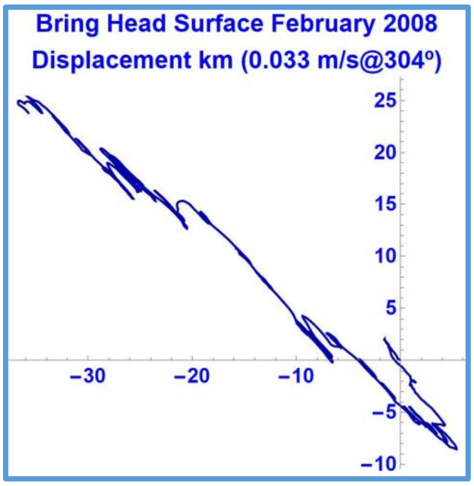
Prior to the present application, currents at all fish farm sites (Figure 2) were measured to support previous consent applications. Detail have been previously given (Edwards, 2015) but are brought together here.

3.1.1 Bring Head 2008

Currents over 15 days at Bring Head in 2008 are summarized in Table 5. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 5: Bring Head February 2008 summary statistics, near surface displacement

Speeds, m.s^{-1}	Surface	Net depth	Seabed
Mean speed	0.168	0.166	0.14
Residual current speed	0.033	0.034	0.027
Residual direction (°)	304	293	292
Major axis of tidal ellipse (°)	315	315	320
Tidal Amplitude (Parallel)	0.208	0.204	0.222
Tidal Amplitude (Normal)	0.195	0.191	0.052
Tidal Amplitude m.s^{-1}	0.29	0.28	0.23



Currents are similar at all depths, with only a slight decrease near the bottom through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing is correspondingly uninhibited.

The tidal amplitude at Bring Head is about 0.3 m.s^{-1}, aligned at 315º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 4 km.

The residual is about 0.03 m.s^{-1} at 300º N, corresponding to a tidal (12.5 hours) displacement of about 1.4 km north-eastward.

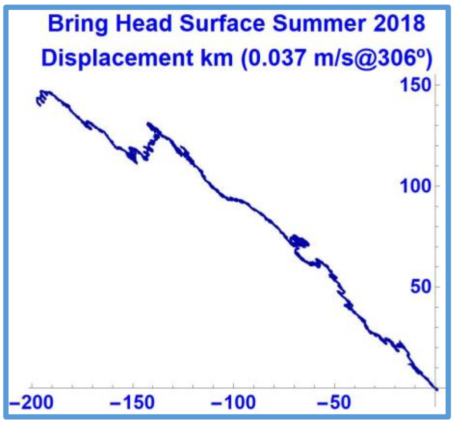
A near surface example from Bring Head of the record of the corresponding displacements over the measurement period is shown in Table 6. Tidal flows in the record here are often obscured by the residual flow.

3.1.2 Bring Head 2018 September 24 – December 9

Currents over ten weeks at Bring Head in 2008 are summarized in Table 6. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 6: Bring Head summary statistics & near surface displacements

Bring Head	Near Surface (32 m)	Middle (24 m)	Above Bed (3 m)
Mean Speed $m.s^{-1}$	0.156	0.154	0.135
Major Axis	315	315	315
Residual speed $m.s^{-1}$	0.037	0.048	0.051
Residual Direction	306	301	318
Amplitude parallel $m.s^{1}$	0.23	0.23	0.19
Amplitude normal $m.s^{-1}$	0.08	0.07	0.07
Tidal Amplitude $m.s^{-1}$	0.24	0.24	0.20



The tidal amplitude at Bring Head is about 0.25 $m.s^{-1}$, aligned at 315º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 3.5 km. The residual is about 0.045 $m.s^{-1}$ at 300º N, corresponding to a tidal displacement of about 2 km north-eastward.

Currents are similar at all depths, with a slight decrease near the bottom through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

These measurements are similar to the 2008 results, albeit that the tidal flow is a little weaker, the residuals a little stronger.

3.1.3 Bring Head Summary

The residual current typical of both periods of measurement was about 0.04 $m.s^{-1}$ to 310º. Were such a residual to apply to the whole cross section off Bring Head (10^5 m^2, see Figure 2) of the sound, this would represent an outflow of about 4000 $m^3.s^{-1}$, or about one fifth of the tidal flows estimated in Table 4.

3.1.4 Chalmers Hope

Measurements from 2003 at Chalmers Hope reside in the SEPA current database (*Chalmer's Hydrographic Data update_mm_20 mins1.xls*). They are summarised in Table 7.

Table 7: Chalmers Hope summary statistics

Chalmers Hope	Surface	Net depth	Seabed
Mean speed	0.13	0.12	0.11
Residual current speed	0.012	0.027	0.026
Residual direction (°)	218	276	290
Major axis tidal ellipse (°)	310	315	310

Currents are similar at all depths, with a slight decrease near the bottom through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

3.1.5 Hunda North

Currents at Hunda North were measured by Xodus (2011b) and are summarised in Table 8. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 8: Hunda North, summary statistics

Hunda North, Speeds, m.s^{-1}	Surface	Net depth	Seabed
Mean speed	0.044	0.040	0.037
Residual current speed	0.016	0.006	0.005
Residual direction (°)	88	100	232
Major axis tidal ellipse (°)	80	80	255
Tidal Amplitude (Parallel)	0.070	0.067	0.058
Tidal Amplitude (Normal)	0.023	0.020	0.019
Tidal Amplitude m.s^{-1}	0.074	0.069	0.06

Currents are similar at all depths, with a slight decrease near the bottom, through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

The tidal amplitude at Hunda North is about 0.07 m.s^{-1}, aligned at 80º/240º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 1 km. The residual well above the sea bed is about 0.01 m.s^{-1} to the east, corresponding to a tidal displacement of about 0.5 km eastward.

3.1.6 Roo Point

Currents at Roo Point were measured by Xodus (2011c) when the site was a possible new farm. The site has since been withdrawn from the planning process but the current data are informative and useful more generally. They are summarised in Table 9. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 9: Roo Point, summary statistics

Roo Point, Speeds, m.s^{-1}	Surface	Net depth	Seabed
Mean speed	0.052	0.047	0.048
Residual current speed	0.017	0.020	0.031
Residual direction (°)	211	229	260
Major axis of tidal ellipse (°)	265	260	245
Tidal Amplitude (Parallel)	0.075	0.070	0.054
Tidal Amplitude (Normal)	0.032	0.027	0.032
Tidal Amplitude m.s^{-1}	0.082	0.075	0.063

Currents are similar at all depths, with only a slight decrease near the bottom, perhaps through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

The tidal amplitude at Roo Point is about 0.07 m.s^{-1}, aligned at 250º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 1 km. The residual is about 0.02 m.s^{-1} to the south-west, corresponding to a tidal displacement of about 1 km southward.

3.1.7 South Cava

Informative measurements from 2008 at South Cava reside in the SEPA current database (*SouthCava_Surface_HGdatav2_v7.xls* etc). They are summarised in Table 10. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 10: South Cava, summary statistics, October 2003

South Cava, Speeds, m.s^{-1}	Surface	Net depth	Seabed
Mean speed	0.066	0.061	0.041
Residual current speed	0.054	0.052	0.025
Residual direction (°)	228	237	239
Major axis of tidal ellipse (°)	230	240	240
Tidal Amplitude (Parallel)	0.066	0.057	0.051
Tidal Amplitude (Normal)	0.035	0.031	0.030
Tidal Amplitude m.s^{-1}	0.075	0.065	0.059

Currents are similar at all depths, with only a slight decrease near the bottom, through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

The tidal amplitude at South Cava is about 0.07 m.s^{-1}, aligned at 240º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 1 km. The residual is about 0.05 m.s^{-1} to the south-west, corresponding to a tidal displacement of about 2.2 km south-westward.

3.1.8 St Margaret’s Hope

Currents at St Margaret’s Hope were measured by Xodus (2011d) and are summarised in Table 11. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 11: St Margaret’s Hope, summary statistics

St Margaret’s Hope, Speeds, m.s^{-1}	Surface	Net depth	Seabed
Mean speed	0.035	0.036	0.036
Residual current speed	0.011	0.017	0.019
Residual direction (°)	77	73	354
Major axis of tidal ellipse (°)	65	70	75
Tidal Amplitude (Parallel)	0.051	0.049	0.044
Tidal Amplitude (Normal)	0.021	0.022	0.027
Tidal Amplitude m.s^{-1}	0.055	0.054	0.052

Currents are similar at all depths. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

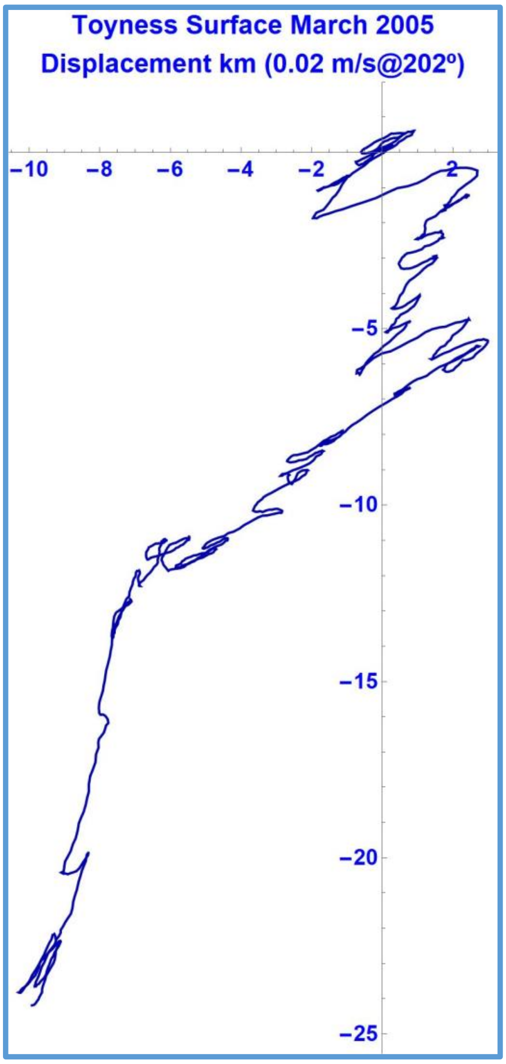
The tidal amplitude at St Margaret’s Hope is about 0.05 m.s^{-1}, aligned at 70º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 0.7 km. The residual in surface and middle is about 0.015 m.s^{-1} to the North-East, corresponding to a tidal displacement of about 0.7 km.

3.1.9 Toyness 2005

Currents at Toyness (from *ToyNess_Surface/Midwater/Bottom-V2_HGdata_v7.xls*) in 2005 are summarised in Table 12. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 12: Toyness 2005, summary statistics & near surface displacements

Toyness, Speeds, m.s^{-1}	Surface	Net depth	Seabed
Mean speed	0.076	0.073	0.07
Residual current speed	0.020	0.023	0.027
Residual direction (°)	202	241	251
Major axis of tidal ellipse (°)	235	235	230
Tidal Amplitude (Parallel)	0.113	0.106	0.093
Tidal Amplitude (Normal)	0.046	0.04	0.047
Tidal Amplitude m.s^{-1}	0.12	0.12	0.10



Currents are similar at all depths, with a trivial decrease near the bottom through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

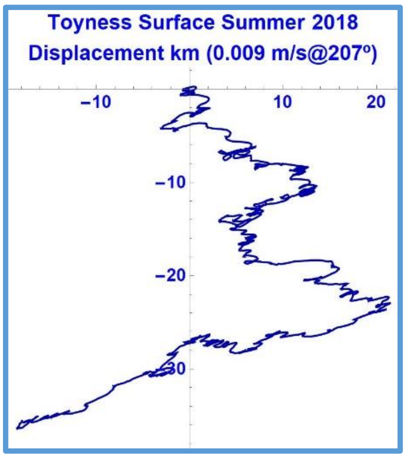
The tidal amplitude at Toyness is about 0.11 m.s^{-1}, aligned at 230º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 1.1 km. The residual is about 0.025 m.s^{-1} to the south-west, corresponding to a tidal displacement of about 1.6 km southward.

3.1.10 Toyness 2018 July - September

Currents over two months at Toyness Head in 2018 are summarized in Table 13. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 13: Toyness 2018, summary statistics & near surface displacements

July 11 – September 18			
Toyness	Near Surface (27 m)	Middle (19 m)	Above Bed (3 m)
Mean Speed m.s^{-1}	0.071	0.069	0.063
Major Axis	255	255	250
Residual speed m.s^{-1}	0.009	0.016	0.024
Residual Direction	207	251	261
Amplitude parallel m.s^{-1}	0.109	0.105	0.088
Amplitude normal m.s^{-1}	0.035	0.031	0.040
Tidal Amplitude m.s^{-1}	0.115	0.109	0.097



Currents are similar at all depths, with a trivial decrease near the bottom through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

The tidal amplitude at Toyness in 2018 is about 0.1 m.s^{-1}, aligned at 250º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 1.4 km. The residual is about 0.02 m.s^{-1} to the south-west, corresponding to a tidal displacement of about 0.9 km southward.

3.1.11 Toyness Summary

The long-term results at Toyness are similar in magnitude and direction to those from the shorter 2005 measurements.

In both sets of measurements, the residuals near surface show a south-south-west offshore movement while there is stronger movement in the deeper water, to the west-south-west towards Hoy Sound.

3.1.12 Westerbister

Currents at Westerbister were measured by Xodus (2011a) and are summarised here in Table 14. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 14: Westerbister, summary statistics

Westerbister, Speeds, m.s^{-1}	Surface (8 m)	Net depth (10 m)	Seabed (24 m)
Mean speed	0.043	0.035	0.036
Residual current speed	0.024	0.020	0.005
Residual direction (°)	7	3	121
Major axis of tidal ellipse (°)	10	10	185
Tidal Amplitude (Parallel)	0.055	0.041	0.048
Tidal Amplitude (Normal)	0.027	0.026	0.032
Tidal Amplitude m.s^{-1}	0.061	0.049	0.058

Currents are similar at all depths. This suggests that stratification is weak or non-existent at Westerbister and that vertical mixing is correspondingly uninhibited.

The tidal amplitude at Westerbister is about 0.05 $m.s^{-1}$, aligned roughly north-south, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 0.7 km. The relatively small residual is about 0.02 $m.s^{-1}$ to the north and almost non-existent east-west, corresponding to a tidal displacement of about 0.9 km northward.

3.1.13 West Fara

Informative measurements from 2003 at West Fara reside in the SEPA current database (*West Fara Surface Ffv5.xls* etc). They are summarised in Table 15. The last row (blue) is the Pythagorean addition of the two tidal amplitudes.

Table 15: West Fara, summary statistics, October 2003

West Fara, Speeds, $m.s^{-1}$	Surface	Net depth	Seabed
Mean speed	0.129	0.154	0.183
Residual current speed	0.117	0.109	0.092
Residual direction (°)	169	176	181
Major axis of tidal ellipse (°)	11	8	16
Tidal Amplitude (Parallel)	0.171	0.207	0.243
Tidal Amplitude (Normal)	0.032	0.029	0.072
Tidal Amplitude $m.s^{-1}$	0.174	0.209	0.253

Currents are similar at all depths, with only a slight decrease near the bottom, perhaps through frictional effects. This suggests that stratification is weak or non-existent and that vertical mixing will be correspondingly uninhibited.

The tidal amplitudes at West Fara are about 0.2 $m.s^{-1}$, aligned about 10º N, corresponding to a tidal excursion in one cycle of a semi-diurnal tide of about 2.9 km. The residual is about 0.11 $m.s^{-1}$ to the South, corresponding to a tidal displacement of about 5 km southward.

These residuals are some of the fastest in the system but because the channel is small (cross-section ~10^4 m^2) the associated flow is small, around 10^3 $m^3.s^{-1}$.

3.2 A Gyre in Scapa Flow

A new synthesis of all available current measurements in Scapa Flow is made in Figure 10. The tidal ellipses and residual currents from the eleven sets of measurements at the nine sites are shown.

At all sites, the tidal currents lie parallel to the local coast. The lateral (right angles to the coast) currents are much smaller than along-coast. The tidal ellipses thus extend along the coast. This picture is consistent with a hydrodynamic argument based on flow continuity in which flows at right angles near a coastline are necessarily small relative to the unconstrained parallel flows.

Figure 10: Residual displacements (red) in 12.5 hours, and tidal ellipses (blue)

This figure is very suggestive of the residual circulation. In the East, residuals at Toyness, Roo Point, Westerbister, Hunda and St Margaret's Hope are consistent with an anticlockwise gyre in Scapa Flow. At these sites the typical speeds of residuals near surface and middle depths are around 0.02 $m.s^{-1}$ (about 2 $km.day^{-1}$). This implies a transit time around the eastern periphery (~20 km) of Scapa Flow of about ten days.

In the West, stronger residuals at Bring Head and Chalmers Hope imply discharge of Scapa Flow water to the North-West. Residual flows in the narrow sound near West Fara are strong to the south, discharging to external waters.

The discharges near Bring Head and West Fara may be balanced by inflows on the north side of Hoy Sound and the west side of Hoxa Sound but there are no measurements to support or refute this hypothesis.

4 WIND DRIVEN CURRENTS

4.1 GENERAL

Wind plays a significant role in coastal circulation, often driving currents exceeding the tidal ones. The relation of wind to current was recognised in the Intertek Metoc (2012) description of the circulation of Scapa Flow.

Some of the detail of the vector diagrams of flow (section 3.1) is clearly non-tidal and owes to wind. Wind data are not available for many of the current records and the correlation has not been further examined here, apart from the following Westerbister record.

4.2 WIND-DRIVEN CURRENT AT WESTERBISTER

The relation of Westerbister currents and wind (Sandy Hill) within the original Xodus data set (Xodus, 2011) was analysed by Edwards (2015). The main conclusion of this work was that the most important feature at Westerbister is a northward current. Because of the similarity of the long-term average wind conditions and the wind condition in the Xodus record, the Xodus record seems representative of the long-term conditions at the site. A northward flow is therefore likely to be persistent.

In rare conditions of no wind modelled overall variance of current dropped only by 25%. Without wind, mean flow to the North dropped to 0.014 $m.s^{-1}$ (1.2 $km.day^{-1}$).

Flow at Westerbister is therefore typically northward at speeds about 2 $km.day^{-1}$, with small modelled reductions during infrequent calm weather, and with presumed augmentations during the stronger winds that are necessarily excluded by SEPA from any licence application data sets.

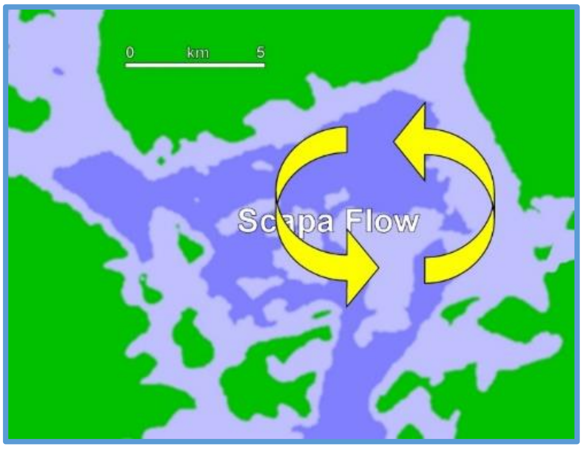
If the northward Westerbister residual is an indicator of the anticlockwise gyre, its persistence points to the persistence of the gyre (section 3.2) in Scapa Flow.

4.3 SCAPA FLOW CIRCULATION AND MIXING

4.3.1 Circulation time

A persistent large-scale circulation may therefore be inferred from the foregoing sections. The imagined circulation is shown in Figure 11.

Figure 11: Schematic of the scale of possible circulation



The typical circumference of such a large-scale eddy feature in Scapa Flow is about 20 km. With flows of about 2 km.day^{-1}, the circulation time is thus about 10 days.

4.3.2 Flushing time

Outflows from Scapa Flow estimated in sections 2.3.4 and 2.3.5 are about 3×10^4 $m^3.s^{-1}$. Scapa Flow including the sounds has a volume of about 5×10^9 m^3 (note that Wikipedia quotes an erroneous volume of 10^9 m^3). The time scale of flushing is thus ($5 \times 10^9 / 3 \times 10^4$ seconds), about 2×10^5 seconds, or 2 to 3 days.

This is a low estimate, based on complete flushing. In practice, recirculation of ejected water on each tide will increase the flushing time. For example, 50% recirculation would increase the flushing time to about 5 days. It is expected to be slightly more at neap tides and slightly less at springs.

4.3.3 Connection of East Scapa Flow

The likely circulation time (~10 days) derived from measurement and modelling is therefore comparable with the likely flushing time derived from volume flow considerations (~5 days). This comparison suggests that the eastern part of Scapa Flow is reasonably well connected and mixed to the overall circulation and energetic flows through the Sounds of Hoy and Hoxa.

4.3.4 Intertek Modelling

The circulation of Scapa Flow was modelled by Intertek (2018). When nutrient inputs were switched on, there was a rapid rise towards equilibrium at sites in the west, consistent with the rapid residuals and strong site flushing measured here.

In the East, the rise to equilibrium took about ten days (Intertek, 2018, Figure 3.1).

This Intertek modelling is therefore consistent with the present observational picture of rapid flushing in the West and a circulation time of a few days for the eddy that flushes the East.

5 DISPERSION FROM FARMS

5.1 INTRODUCTION

This section examines the likely range of dispersion to be expected in Scapa Flow.

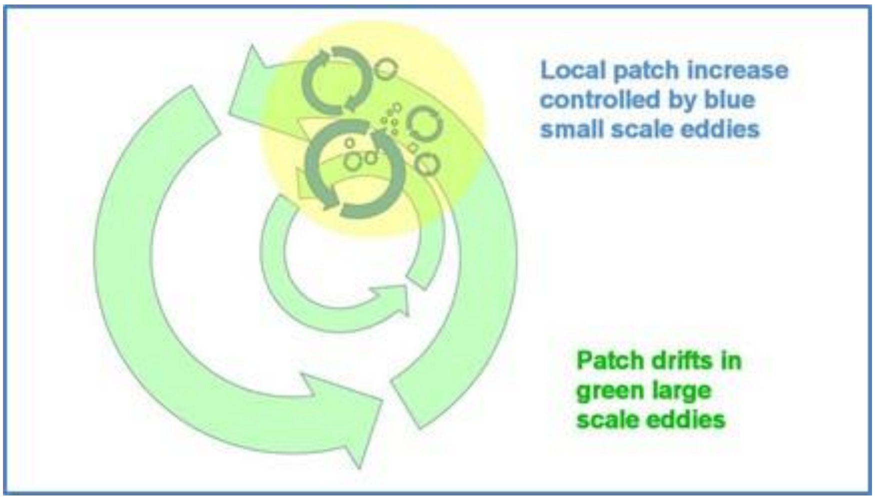
The spread of dissolved material is termed dispersion; it is caused by many mixing processes controlled by the input of energy to the fluid and by the details of the flow. Energy and motion are injected into the sea in heterogeneous ways by wind, tide and other forces. The consequent motions are modified by topography, mixing and various interactions between small- and large-scale fluid processes.

5.2 VARIABLE DISPERSION COEFFICIENTS

Any patch of discharged material is influenced by eddies on various scales. It is mixed internally by eddies smaller than the patch, is mixed into its surroundings by eddies on scales similar to the patch and is moved around bodily by eddies much larger than the patch. As the patch expands, the rate of mixing increases as ever larger eddies enter the mixing process.

Figure 12 is a sketch of these effects on patch scale. The yellow patch expands locally by small scale mixing; it is carried around by large scale eddies. As it gets larger, more of the larger eddies influence the local mixing and the dispersion increases.

Figure 12: A patch drifts with large eddies and is mixed by small eddies



5.2.1 The Okubo Review

Okubo (1971) reviewed many measurements of near-surface layer oceanic dispersion coefficients. The conditions for the original experiments ranged from estuarine through coastal to oceanic. The time scales of the experiments were from two hours to one month and the space scales ranged from 30 m to 100 km. Figure 13 summarises Okubo's conclusions. The "apparent diffusion coefficient" K for 2-dimensional horizontal dispersion is related to the variance $\sigma^2(t)$ by

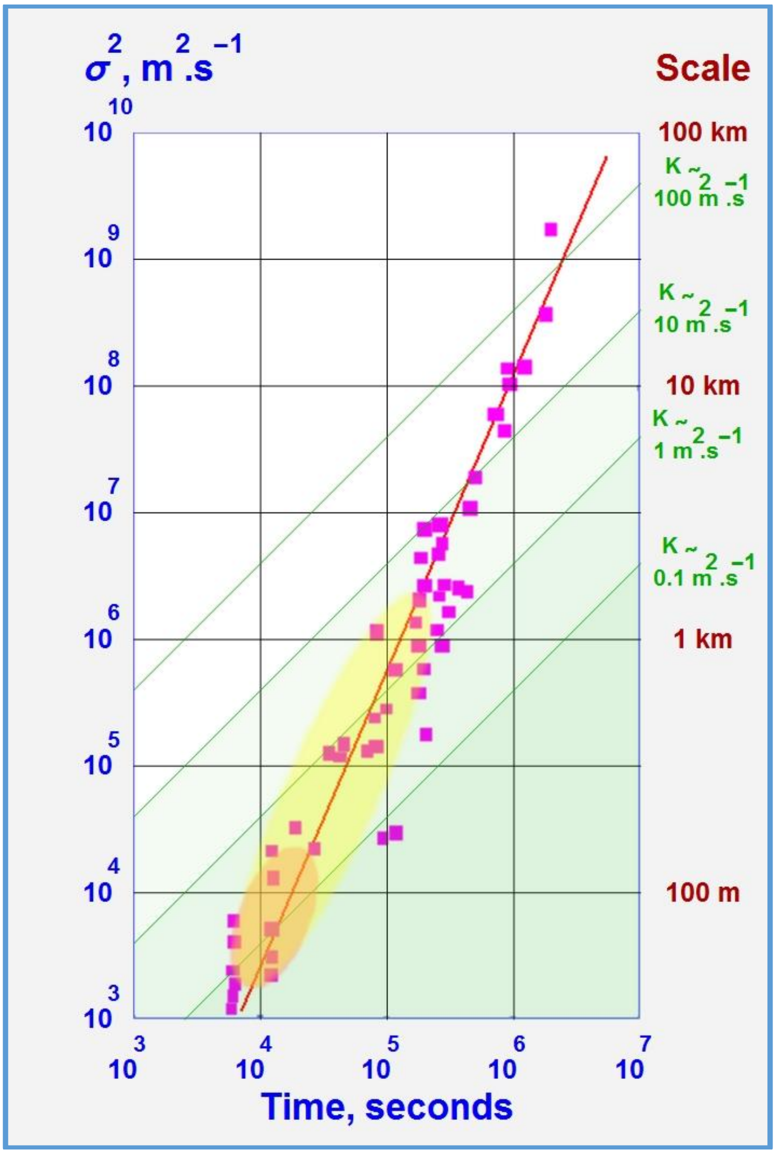
$$K(t) = \sigma^2(t)/4t \qquad \ldots \{1\}$$

where $K(t)$ is considered as an increasing function of time t rather than constant.

The scale on the right of Figure 13 is the typical dimension of the patch, ***σ***.

At larger time and space scales, ***K*** is larger. The red regression line is a linear fit to the measurements. Its slope significantly exceeds unity, revealing that the dispersion increases with time and spatial scale.

Figure 13: A diffusion diagram for variance versus diffusion time (recast from Okubo, 1971)



The regression shows the corresponding apparent dispersion coefficient:

$K(t) = a.t^{1.33}$ … {2}

Where ***a*** is a constant (~3x10^{-7} $m^2.sec^{-2.33}$).

In Scapa Flow, the relevant space scale is a few km, the semidiurnal tide scale is a few hours, and the indicative value of ***K*** (yellow zone) is therefore around 1 $m^2.s^{-1}$.

5.2.2 Irish Sea Studies

Elliott et al. (1997) examined the dependence of the diffusion coefficients on the ambient tidal currents and winds around the coastline of Ireland. Elliott's experiments were done over two to five hours; they were therefore relevant to regulatory time scales. Most of the sites were characterized by strong currents and the dye used to quantify the dispersion was vertically well mixed.

In these coastal sites, similar to many fish farm locations, the measured dispersion coefficient approached values of 1 $m^2.s^{-1}$, with mean 0.6 $m^2.s^{-1}$.

5.2.3 Other Studies

Many other studies have been reported (Cromey et al, 2001; Riddle & Lewis, 2000; Talbot and Talbot, 1974; Turrell & Gillibrand (1999); Turrell, 1990).

5.2.4 Typical Dispersion Coefficient in Literature

The above sources point to a large range of values of the dispersion coefficient in coastal waters. The results of Elliott are the most instructive, because they were obtained over periods similar to regulatory time scales, were in a variety of similar coastal regions, explicitly included wind, and were reported most competently, well after the SEPA default value had been set.

Elliott's results are particularly useful in demonstrating the empirical relationship between dispersion coefficient and wind. They point to representative values of dispersion coefficient above 0.1 $m^2.s^{-1}$ and up to about 1 $m^2.s^{-1}$. Other sources mentioned here (such as Cromey at al, 2001), when adjusted to periods of three or more hours by using Okubo's dependence of equation {2}, also support a typical coefficient somewhat higher than 0.1 $m^2.s^{-1}$.

5.2.5 Shear Dispersion

Horizontal advective currents (or large eddies) distort and stretch patches or plumes of released material from sources such as fish farms. Differences in current from place to place, either horizontally or vertically, are responsible for a phenomenon known as shear dispersion.

Figure 14 is a cartoon of shear dispersion in the cycle of an oscillatory current which varies with depth. From left to right: an expanding patch is stretched horizontally by the shear of the current; mixing spreads the sheared patch vertically; the patch is then sheared horizontally in the opposite direction; it then mixes vertically; in reality, the shearing and diffusion occur simultaneously but the end result is, as in the cartoon, a much-enhanced dispersion along the axis of the current, much greater than if the patch had not been vertically sheared.

Figure 14: Shear-induced dispersion in an oscillating tide

In coastal flows, this process spreads material faster along the direction of flows than laterally. There is never a radial symmetry to expanding patches in such conditions; the spread is always anisotropic. This points to modelling approaches in which lateral dispersion may be distinguished from axial dispersion both in nature and in magnitude.

According to Simpson and Sharples (2012), the problem of determining shear dispersivity in oscillatory flow with period T for an arbitrary vertical mixing time over some depth has been solved (Fischer *et al* 1979). The maximum dispersion occurs when the vertical mixing time is equal to T. With this optimal matching of the vertical mixing time to the tidal period, the shear diffusion coefficient becomes:

$$K \sim 0.0067\, U_h^2 T \qquad \ldots \{3\}$$

where the velocity U_h is the difference in velocities between the top and bottom of the mixing zone. This is about the upper limit of K for shear dispersion.

Estimation of shear dispersion at Toyness and Bring Head

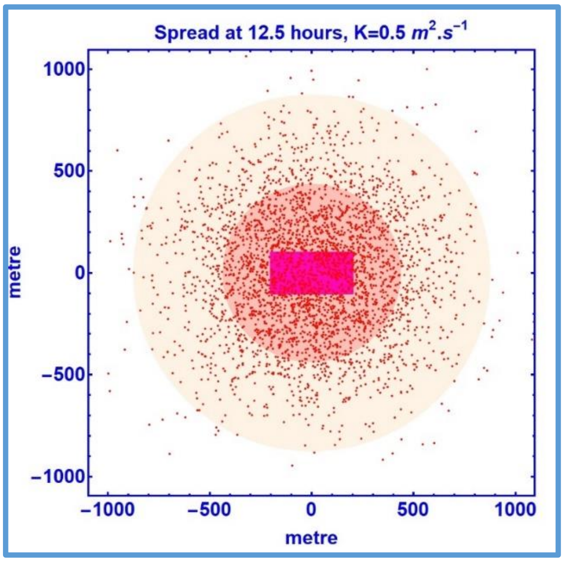
The mean difference between near surface and middle depth speeds in the 2018 Toyness record is about 0.04 $m.s^{-1}$ over a depth range of about 10 metres in a semi-diurnal tidal cycle of about twelve hours. This would lead to a shear dispersion coefficient K ~ 0.4 $m^2.s^{-1}$.

At Bring Head, the mean difference between near surface and middle depth speeds in the 2018 record is about 0.05 $m.s^{-1}$ over a depth range of about 10 metres in a semi-diurnal tidal cycle of about 12 hours. This would lead to a shear dispersion coefficient of K ~ 0.7 $m^2.s^{-1}$.

5.2.6 Spread Size

Typical rectangular dimensions of a 2500 tonne farm are 200 m x 400 m. A suitable approximation is to describe nutrients as being released uniformly over this area and over the cage depth of about 15 m. As effluent water moves away from the farm it disperses. Initial rectangular patch structure is soon destroyed by the dispersion. Figure 15 superimposes the original rectangular distribution and the predicted shape of the spread patch after a tidal cycle of 12.5 hours, modelled with a dispersion coefficient of 0.5 $m^2.s^{-1}$.

Figure 15: Spread from a rectangular source at 12.5 h, K = 0.5 $m^2.s^{-1}$, with circles of 1 & 2 standard deviations σ.



Similar calculations have been done for various dispersion coefficients and the implications of these for the spread from a 2500 tonne farm over a semidiurnal 12.5 hour tidal cycle are:

Table 16: Spread radius, 12.5 hours, various dispersion coefficients K

K, $m^2.s^{-1}$	**0.1**	**0.2**	**0.5**	**1**	**2**
Patch radius σ, m	230	300	440	620	850

5.2.7 Regulatory models and the choice of dispersion coefficient

The regulatory sub-models describing dispersion from cage sites are described in Annex G of the SEPA Fish Farm manual (SEPA, 2008). In the regulatory modelling, the horizontal dispersion coefficient (*K*) appropriate to the time and length scales pertaining in 1997 was originally given a default value of 0.1 $m^2.s^{-1}$. *K* is a measure of the rate of increase in area affected by discharged material.

The value of 0.1 $m^2.s^{-1}$ was adopted as a precautionary parameter based on the limited information available at that time. It was predicated on the notion of discharge into a uniform flow; it took no account of scale effects; it took no account of spatial variability in current, either in depth (vertical shear) or plan (horizontal shear); and it took no account of wind.

From the literature (sections 5.2.1 to 5.2.5) and from the example shear calculations (section 5.2.5) at Toyness and Bring Head, it is therefore reasonable and expected that the dispersion coefficient in farm sites in Scapa Flow – as in other sites reviewed above – has values significantly higher than the regulatory default value, by a significant factor as much as ten, and is thus of the order of 1 $m^2.s^{-1}$. A prudent and conservative estimate may be 0.2 $m^2.s^{-1}$.

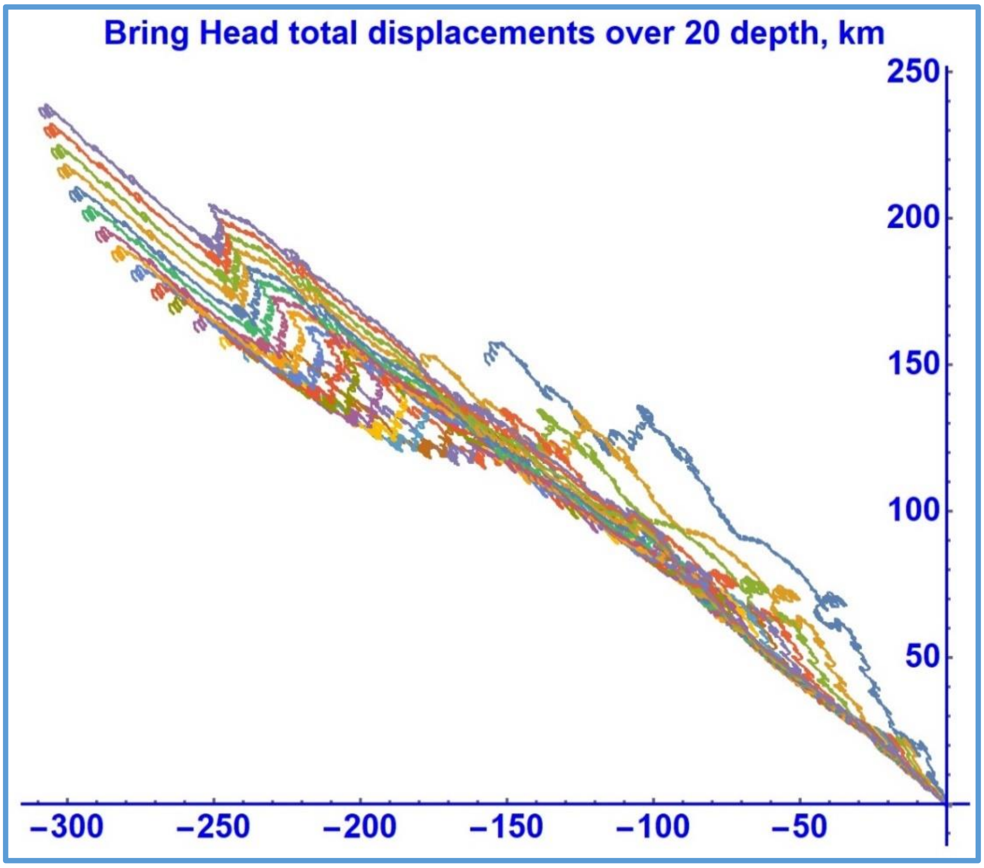
5.2.8 The Importance of current shear

A complementary approach to shear is to consider the release (of nutrient) from cages typically 15 m deep. The release is distributed over the depth. At each depth, the release moves with the appropriate velocity.

Some past measurements were made at a few specific depths with recording meters. Contemporary current measurements are made with ADCP meters that produce records at depth intervals of one metre. This allows deeper analysis of the hydrography at sites. In particular, shear may be quantified in greater detail.

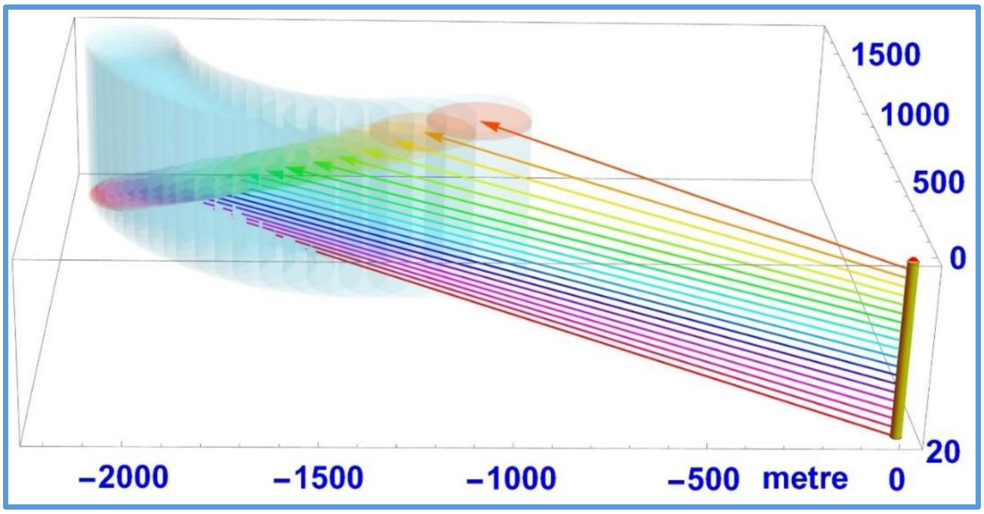
As an example, Figure 16 shows the total displacements in a depth range of 20 m from the near-surface series at each metre of depth at Bring Head over the 76 days of record. Farm depth is about 15 metres and vertical mixing within the tidal period (12.5 hours) may be expected to deepen the dispersion; a nominal depth range of 20 metres is appropriate and echoes other published work.

Figure 16: Total displacement in 20 depth layers, 76 days record at Bring Head



The mean tidal (12.5 hour) displacements of patches created by such a point (hypothetical, with no plan area to the farm, K~0.1 $m^2.s^{-1}$) source are shown from Bring Head in Figure 17. Because of vertical mixing in non-stratified coastal waters, the patch at each depth is shown mixed throughout all depths.

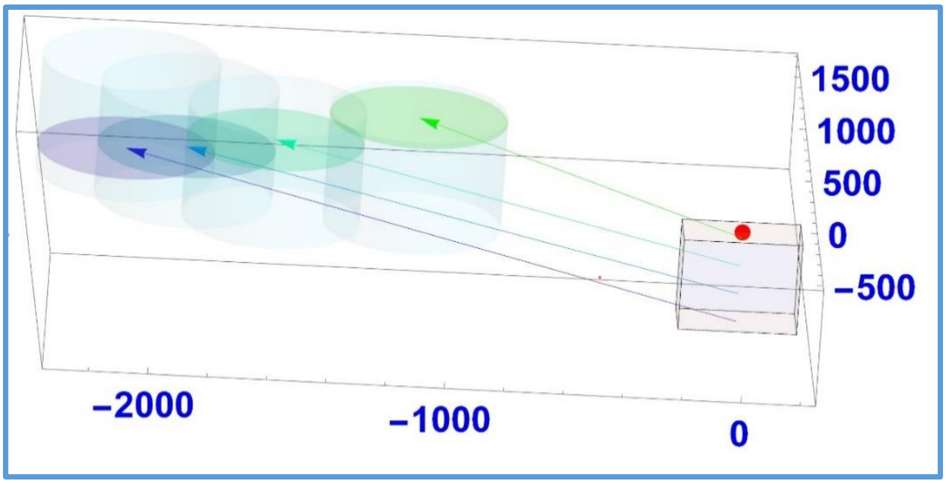
Figure 17: Tidal displacement (m) over 20 m depth from a point source, with vertical mixing



5.2.9 Bring Head Shear

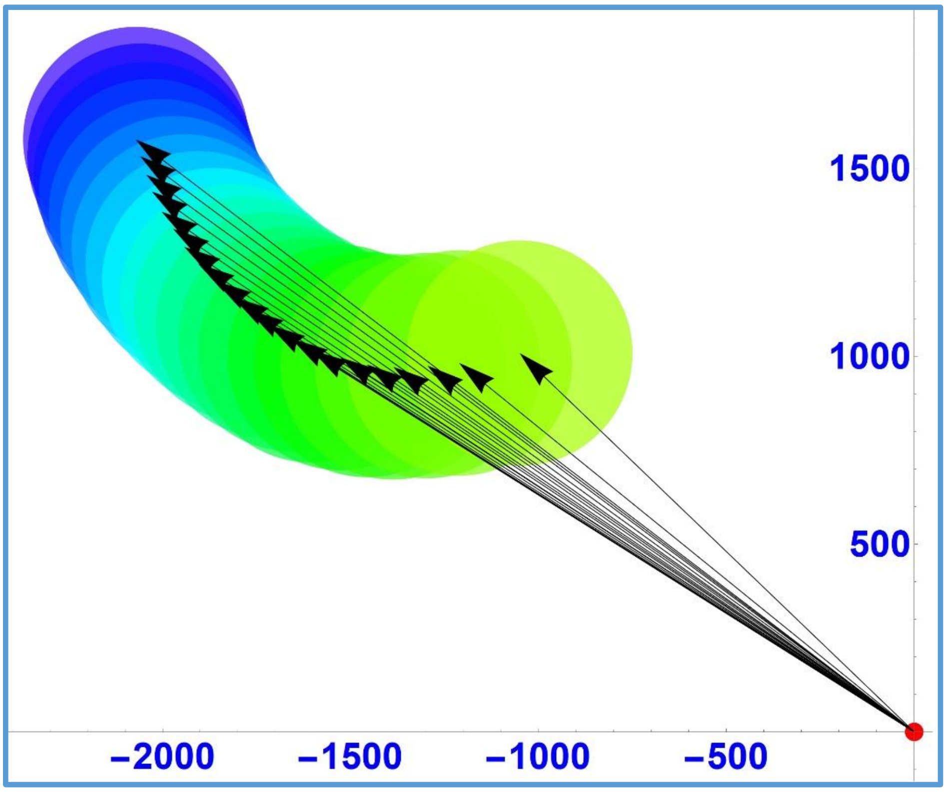
An alternative and simplified presentation of the previous data is made in Figure 18, which shows the displaced spread (radius 300 m, with a conservative value of K ~ 0.2 $m^2.s^{-1}$, from Table 16) from a farm every five (*for clarity, rather than showing all twenty*) metres of depth after 12.5 hours of the semidiurnal tide.

Figure 18: Bring Head, tidal displacement (m), spread and vertical mixing over 12.5 hours



The total affected volume of water in this sheared flow is about three times that which would be modelled by simple patch dispersion in uniform flow. In plan view, Figure 19 shows the increase in affected area from a single patch of diameter 600 metres.

Figure 19: Bring Head, tidal displacement (m) and spread over 20 m depth, over 12.5 hours

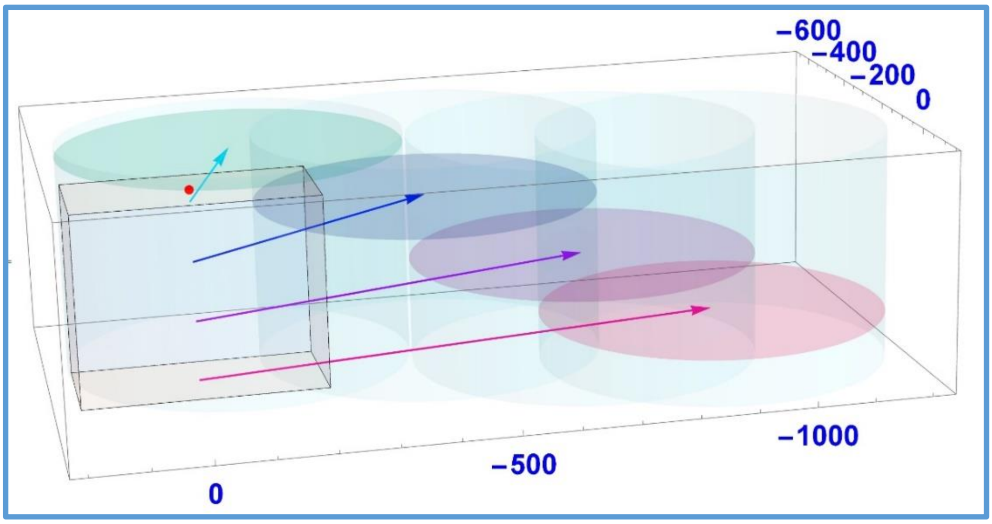


In the direction of the residual flow, shear has increased the patch size significantly. Rather than being spread over a width of 600 m, effluent is spread over a typical width of about 1 km or more.

5.2.10 Toyness Shear

Similar modelling has been done with the Toyness results. Figure 20 (viewed from the North, the farm shown as a rectangular area, $K = 0.2\ m^2.s^{-1}$) shows how material from each depth displaces, spreads horizontally and mixes vertically over a tidal cycle of 12.5 hours. Near the surface there is a marked southward residual away from the coast, suggesting that divergence from the coast may be a normal feature of this region of Scapa Flow.

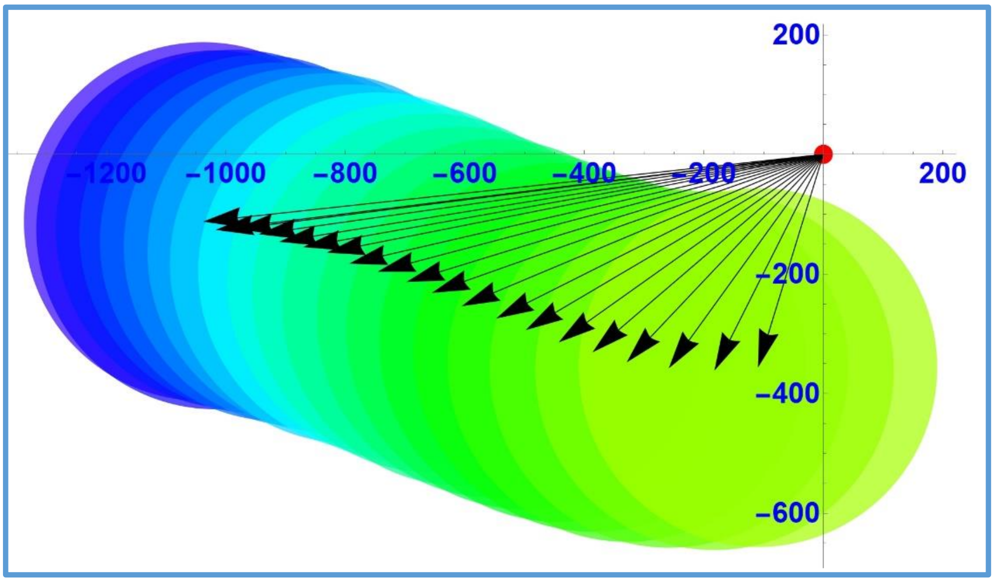
Figure 20: Toyness, displacement (m), spread & mixing over 12.5 h, $K = 0.2\ m^2.s^{-1}$



The total affected volume of water in this sheared flow is about three times that which would be modelled by simple patch dispersion in uniform flow.

The plan view is shown in Figure 21.

Figure 21: Toyness, displacement (m) and spread over 12.5 h, $K = 0.2\ m^2.s^{-1}$



In the direction of the overall residual flow, shear has increased the patch size significantly. Rather than being spread over a width of 600 m, effluent is spread over a typical width of about 1 km or more.

5.2.11 Summary

There is always shear in the vertical, and its effect is to increase dispersion. These examples from Bring Head and Toyness show the scale of effect over a tidal cycle, although they do not take account of the details of shear within the 12.5 hours of tidal cycle, which may be expected to add further to the dispersion.

6 SCAPA FLOW NUTRIENT INCREASE

6.1 ESTIMATION OF LOCAL CONCENTRATION WITH PROPOSED BIOMASS

It is useful to estimate the local increases (CE) in nutrient concentration at the farm and after 12.5 hours of spread. At Bring Head and Toyness after 12.5 hours the effluent is spread over a width of about one km (section 5.2.11) and is moving with the residual speed away from the farm. Table 17 summarises the calculations.

Table 17: Local concentration increase at farm and within 12.5 hours

	Section area, m^2	Residual $m.s^{-1}$	Flow $m^3.s^{-1}$	Biomass tonne	Nitrogen $gm.s^{-1}$	CE $\mu gN.litre^{-1}$
Toyness						
At Farm	20 x 200	0.02	80	2500	4.75	**60**
After 12.5 h	20 x 1000	0.02	400	2500	4.75	**12**
Bring Head						
At Farm	20 x 200	0.04	160	2500	4.75	**30**
After 12.5 h	20 x 1000	0.04	800	2500	4.75	**6**

It follows that significant local increases are restricted to small areas even close to the farms and that after the passage of a few hours the predicted concentrations are well below those expressed by an Environmental Quality Standard for available nitrogen of 168 $\mu gN.litre^{-1}$. They are also low in comparison with winter nutrient levels of around 160 $\mu gN.l^{-1}$ (10 or 11 µM quoted by Hydes *et al.* 2004; also see Annual mean total nitrogen (NO2+NO3) concentrations observed in European seas, 2013-2017 — European Environment Agency (europa.eu).

These predicted increases in the average nitrogen concentration of Scapa Flow are therefore insignificant in their likely local effects.

6.2 ECE FOR THE SCAPA FLOW WATER BODY

6.2.1 Nutrient Inputs

Proposed and existing SSF sites in Scapa Flow are listed in Table 18 together with other proposed and existing consents.

Table 18: Proposed and existing consents in Scapa Flow

Site	CAR Licence	Position	Biomass	Biomass
	Or MSS Reference	Lat Long or OSGrid	Existing	Proposed
Bring Head	CAR/L/1015854/V5	58 54.04N 3 15.85E	968	2500 *[2750]***
Toyness	CAR/L/1015855/C1/V1	58 54.99N 3 07.41E	1343	2500
Westerbister	CAR/L/1143253/V1	58 54.38N 2 57.11E	1791	1791
Ore Bay	CAR/L/1003962	ND 3120 9440	0	(450)
West Fara	CAR/L/1004229/V3	ND 3210 9530	800	(800)
Chalmers Hope	CAR/L/1003062/V6	HY 2880 0070	1000	(2500)
South Cava	CAR/L/1082725/V3	ND 3333 9989	2500	(2500)
Lyrawa Bay	CAR/L/1003960/V1	ND 3299 9989	400	(400)
Pegal Bay	CAR/L/1003961/V1	ND 3302 9976	400	(400)

Site	CAR Licence	Position	Biomass	Biomass
	Or MSS Reference	Lat Long or OSGrid	Existing	Proposed
Hunda North	CAR/L/1157278	ND44319757	1680	1680
Glimps Holm	CAR/L/1122569/V2	ND 4650 9910	0	(1247)
St Margaret's Hope	CAR/L/1157275	ND43369463	1247	1247
Total	**All sites**		**12129**	**18015 *[18265]*****
** A possible biomass of 2750 tonne has also been included in following calculations, for completeness				

Nitrogen input from biomass may be estimated from the source rate. An assumed source rate of 60 kgN.tonne^{-1}.year^{-1} represents the direct input from excretion and the indirect inputs from decomposition of faeces and seabed inputs. For example:

- the total input rate ***I*** from the existing consents at full biomass (12129 tonne) is about 7.3x10^5 kgN.year^{-1}, or about 23.1 gmN.s^{-1};
- the total input rate ***I*** from all existing and proposed consents at full biomass of 18015 *[18265]* tonnes is about 10.8x10^5 *[11x10^5]* kgN.year^{-1}, corresponding to about 34.3 *[34.5]* gmN.s^{-1}.

6.2.2 Concentration enhancement

The tidal and residual flows both flush Scapa Flow. In relation to the nitrogen input rate, their combined flow determines the overall increase in nitrogen concentration, the ECE. These flows are considered together in the following section.

Assuming that Scapa Flow mixes well internally by tidal and wind action, the effect of the nutrient inputs on the whole of the area may be considered and converted to an estimated increase in nutrient concentration over background levels.

6.2.3 Tidal flows and recirculation

Some of the tidal flows (sections 2.3.4 and 2.3.5) may re-enter Scapa Flow because of the oscillatory nature of tidal flow in the entrance sounds. Section 2.1 suggests that flows outside Scapa Flow are such as to remove much of the outflows but, taking a very conservative view and allowing as much as 90% recirculation, the effective tidal flow through Scapa Flow might be decreased by as much as a factor of ten.

6.2.4 Residual flows

The measured residual speeds (sections 3.1.1 and 3.1.3) at the side of Hoy Sound are about 0.04 m.s^{-1} to the North of West at Bring Head and to South of West at Toyness. Residual flow may be different in mid-channel in Hoy Sound but, from section 2.3.5, residual speeds elsewhere (other than in the narrows near Fara West, section 3.1.13) are unlikely to exceed this; indeed, in the eastern area around Westerbister the measured residuals are similarly low and are wind-affected.

Through the cross section of the Sound of Hoy such a flow might therefore represent a residual flow through Scapa Flow of about 4x10^3 m^3.s^{-1}.

The fast, albeit in a narrow sound, residual flows near Fara West, may amount to a flow of about 10^3 m^3.s^{-1} (section 3.1.13).

Conservatively ignoring any unknown residuals in north Hoy Sound or Hoxa Sound, the combined measured Hoy and Fara West residuals are therefore estimated as about 4x10^3 m^3.s^{-1}. These flows augment the rather greater tidal exchanges of around 3x10^4

$m^3.s^{-1}$ discussed in sections 2.3.4 and 2.3.5, adding to the dilution within Scapa Flow taken as a whole.

6.2.5 Total Flushing flows

From the foregoing, typical tidal and residual flows of new water are shown in Table 19. These values will be less at neaps, more at springs.

Table 19: Flushing flows from tidal and residual flows, various recirculations

Recirculation	10%	50%	90%
Tidal flow, $m^3.s^{-1}$	3×10^4	1.5×10^4	3×10^3
Residual flow, $m^3.s^{-1}$	4×10^3	4×10^3	4×10^3
Total Flushing flow $m^3.s^{-1}$	3.4×10^4	1.9×10^4	7×10^3

6.2.6 ECE Estimates

If the nitrogen input rate is ***I*** (section 6.2) and the flow is ***T*** (section 2.3.5 and Table 4), the increase in concentration is:

ECE = ***F*.*I*/*T***

where the factor ***F*** is a tidal flow recirculation factor (1 for no recirculation; 2 for 50% recirculation; 10 for 90% recirculation). Estimates of ***ECE*** are shown in Table 20**:**

Table 20: ECE estimates – tidal and residual flows for various % recirculation

ECE, µgN.litre^{-1}		**T, $m^3.s^{-1}$**		
		F=1*: 10%	**F=2: 50%**	**F=10*: 90%**
Biomass tonnes	***I*, gmN.s^{-1}**	**3.4×10^4**	**1.9×10^4**	**7×10^3**
12129	**23.1**	**0.68**	**1.21**	**3.3**
18015 [18265]	**34.3 *[34.5]***	**1.01 *[1.02]***	**1.80 *[1.83]***	**4.90 *[4.96]***
** F= 1 represents no recirculation, and F=10 is a very conservative value of 90% recirculation*				

The residual flow has only trivial reductive effect (~10%) on ECE when there is no tidal recirculation. In the case of 90% tidal recirculation, the residual flow decreases the tidally estimated ECE by about 50%.

Because ECE is proportional to biomass, the increase associated with *[2750]* tonne at Bring Head rather than 2500 tonne is trivial, less than 2% of the total.

6.3 SUMMARY OF ECE VALUES

6.3.1 Worst case ECE

The maximum value of ECE in Table 20 is almost 5 µgN.litre^{-1}. With the nitrogen inputs from existing real or consented sites of Table 18 applied to the typical measured tidal and residual flows to and from Scapa Flow, the ECE of the average nitrogen concentration of Scapa Flow is therefore likely to be 5 µgN.litre^{-1} or less.

Higher values of ECE would require more recirculation than 90% or lower residual flows or both. Such conditions are pessimistic and overly-conservative when considered from the perspective of the known residual and tidal flows.

6.3.2 Residual flows

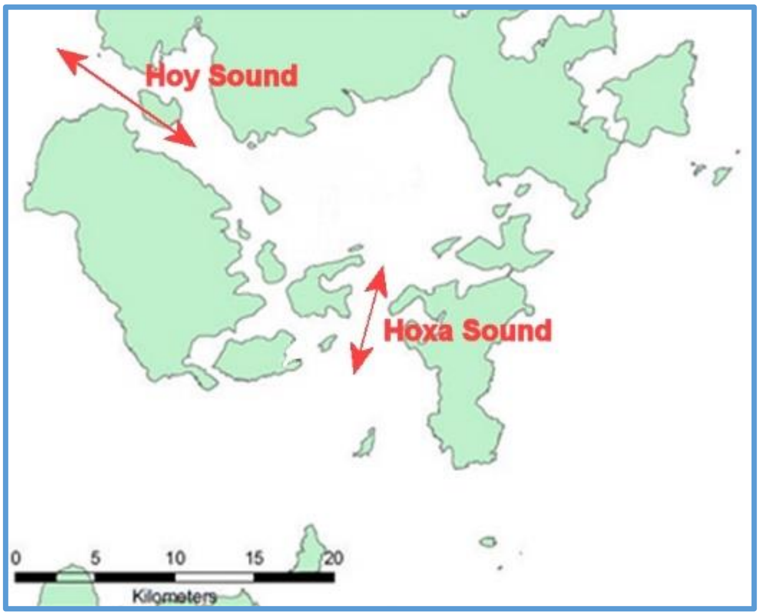
Residual flows in the Orkney Islands are widespread and pervasive (section 2.1) and in the light of the large suite of measurements reported in section 2.3 are very unlikely to be zero over time scales of 12 hours or more.

6.3.3 Recirculation

Some recirculation of ejected water seems inevitable. Nevertheless, 90% is a very conservative estimate, for the following reasons.

The speeds of tidal outflows from Scapa Flow in Hoxa and Hoy Sounds reach about 0.5 $m.s^{-1}$ and 1 $m.s^{-1}$ respectively (Table 3). These correspond to semi-diurnal tidal excursions of about five km (Hoxa) and up to ten km (narrow parts of Hoy). Such excursions are shown in Figure 22. They extend from the Sounds into external adjacent waters flushed by the external tidal flows of section 2.3.2 and the flows of section 2.1.

Figure 22: Typical tidal excursions in the Sounds of Hoxa and Hoy



The measurements made at Bring Head show that the tidal ellipses in this area (Figure 10) extend a significant fraction of Hoy Sound, as do those at Fara West in the south. The long ellipses, extending well into coastal circulation outside Scapa Flow, ensure that a significant fraction of water leaving will enter the external circulation.

From this perspective, tidal recirculation into Scapa Flow of previously ejected water is unlikely to be as much as 90%. A value in a range around 50% is more reasonable.

6.3.4 Other estimates of ECE

Greenwood (2020)

An alternative approach was made by Greenwood (2020, Tables 9 & 15), who arrived at ECE estimates in the neighbourhood of Chalmers Hope of about 4.2 $\mu gN.litre^{-1}$. The overall ECE for Scapa Flow was estimated as about 12 $\mu gN.litre^{-1}$. This estimate was based on an area limited to zones around sites and contained a conservative factor of 2; greater area relevant to the whole water body and no arbitrary factor would reduce this estimated ECE considerably (to 6 µgN.litre^{-1} or less). Greenwood's work is therefore consistent with the estimates presented here, particularly in the light of section 6.1.

Xodus (2013)

In eastern Scapa Flow, Xodus (2013) estimated an ECE of about 6 µgN.litre^{-1}. The estimate was based on the residual flow through a cross sectional area 20 m deep (roughly, cage depth) and width (similar to Table 16) determined by dispersive spread with a dispersion coefficient of 0.1 m^2.s^{-1}. For the reasons outlined in section 5.2, this may be too conservative an account of dispersion, especially when longer time scales are considered, meaning the consequent ECE would be less than the estimate.

Intertek (2018)

Intertek (2018) describes the results of a briefly described standard coastal hydrodynamic model constructed for Scapa Flow. It is driven by the changing sea surface elevations on the boundary of an area, centred on Orkney, whose western limit runs north of Cape Wrath and whose eastern limit runs north of Fraserburgh.

The report does not use an explicit dispersion coefficient, makes no mention of residual flows, takes no account of wind, assumes calm conditions, gives no account of how model predictions within Scapa Flow have been validated, and makes no comparison with any of the relevant and quoted fish farm current measurements within Scapa Flow. The source rate used is lower than others at 35.6 kgN.tonne^{-1} year^{-1}. ECE values would be about 33% higher were a source rate of 48.2 kgN.tonne^{-1} year^{-1} used. There is reference to local maxima in nutrient concentration without quantifying the area or volume around each site to which they apply.

Because of these features, it is not possible to make reliable comparison of the predictions with other studies (Xodus, 2013; Greenwood, 2020) or with the overall water body analysis of section 6.2.

There is a suggestion in the report of "accumulation" of nitrogen in small bay areas; this may be interpreted as local maxima. Some may be explained by proximity of nutrient sources such as farms. For others such as Scapa Bay in the north there is no shown local source and the mechanism by which a dissolved constituent might develop a local maximum is not clear. Indeed, in view of the way that shear has now been seen (section 5.2.10) to transport near-surface coastal water offshore at Toyness on the north shore, significant accumulation in northern bays seems less likely.

The quoted Mean Winter Predicted DIN for each site (Intertek Table 3.2) is typically from 10 to 100 µgN.litre^{-1}, with most sites in the lower part of this range. The quoted values represent significant fractions of a regulatory standard of 168 µgN.litre^{-1}. Highest value near farms occurs around Westerbister, where a value of over 100 µgN.litre^{-1} is quoted, contrasting markedly with the lower values of other work (Greenwood, 2020; Xodus, 2013; this report section 6.2).This mismatch deserves further analysis.

Most crudely, imagine the farm at Westerbister to be 20 m deep and to present its narrowest dimension (say 200 m) to the north-south flows of section 3.1.12, whose residual flow through and immediately past the cages is about 0.025 m.s^{-1} through the section of 4000 m^2, corresponding to a volume flow of 100 m^3.s^{-1}. With a biomass of 1800 tonne at 60 kgN.kg^{-1}.y^{-1}, this would produce an immediate ECE of 34 µgN.litre^{-1}, about a third of the quoted Intertek value. Using the Intertek source rate would produce about 20 µgN.litre^{-1}, about a fifth of the quoted Intertek value.

Perhaps the Intertek higher quoted values arise because the farms are modelled as point sources rather than areas; the report does not deal with this issue. This comparison throws doubt on the significance of the site values quoted in the Intertek report for ECE on practical site scales; from the perspectives considered here they are too high.

The final recommendations of the Intertek report are largely focussed on advocacy of more modelling studies and include the conclusion that "*dispersion and transport of DIN does not cause a risk of breaching the High WFD standard across the majority of Scapa Flow*". In this respect the report is consistent with Greenwood (2020), Xodus (2013) and the present analysis (section 6.2).

6.4 IMPLICATIONS OF THE ECE CALCULATIONS

This analysis conservatively uses a source rate ***S*** of 60 kgN.tonne^{-1}.year^{-1}. Lower source rates, (48.2 kgN.tonne^{-1}.year^{-1}: Greenwood, 2020; Davies, 2000; Xodus, 2103) would reduce all ECE estimates in direct proportion, typically by 20%..

Very local increases (section 6.1) are limited by local flows to values that give no cause for concern. Within a tidal cycle, residual flow combined with dispersion dilutes concentrations to insignificant levels.

Considering the whole water body, the worst case in section 6.2 of about 5 µgN.litre^{-1} is conservative. Recirculation of tidal flows to Scapa Flow is likely to be in a range around 50% rather than 90%. This, when combined with conservative estimates of residual flows, reduces the maximum estimate of ECE to about 1.8 µgN.litre^{-1}.

Likely ECE increases for the whole of Scapa Flow are therefore in the rough range 1.8 to 5 µgN.litre^{-1}. These predicted increases are small in relation to an Environmental Quality Standard for available nitrogen of 168 µgN.litre^{-1}. They are also low in comparison with winter nutrient levels of around 160 µgN.l^{-1} (10 or 11 µM quoted by Hydes *et al.* 2004; also see Annual mean total nitrogen (NO2+NO3) concentrations observed in European seas, 2013-2017 — European Environment Agency (europa.eu).

These predicted local or whole water body increases in the average nitrogen concentration of Scapa Flow are therefore insignificant in their likely effects on this water body.

7 CONCLUSION

7.1.1 General applicability of the measurements

New long series (>2 months) measurements at Bring Head and Toyness have similar statistics and characteristics to previous 15-day records. This agreement suggests that measurement series are reasonably representative of longer term conditions.

7.1.2 Scapa Flow Circulation

In the West, highest tidal currents and measured residuals create well-flushed and mixed conditions around Bring Head and to a lesser extent near Toyness. These flows contribute significantly to local dilution and to exchange with outer waters.

In the East, wind measurements at Westerbister that were made to support a previous licence application have been compared with long term conditions and from this perspective, the licence application measurements there are believed to be typical of long-term conditions. The Westerbister results suggested the presence of an anticlockwise gyre filling Scapa Flow. This hypothesis is supported by all other previous measurements and by the new record from Toyness. The gyre is therefore suggested as a permanent feature of the system. Waters from Bring Head and Toyness will be transported in the relatively vigorous circulation and mixing of the west away from the east of Scapa Flow.

The circulation time based on the inferred anticlockwise circulation in Scapa Flow is comparable with the flushing time of Scapa Flow estimated from a tidal flow budget and with that implicit in other modelling (Intertek, 2018). This agreement suggests that eastern waters near Westerbister are reasonably well connected and mixed into the general circulation of Scapa Flow within a time scale of days.

7.1.3 ECE

Tidal and residual flows to Scapa Flow have been estimated by various methods (tide tables, direct observation and water budgets) to be sufficient to dilute the nitrogen released from existing consented sites and proposed sites such that the likely ECE of nitrogen concentration is about 5 µgN.litre^{-1} or less.

This analysis is based on a conservative assumption of 90% recirculation and a conservative estimate of residual flow. The recirculation is expected to be less than 90%, increasing the flushing of Scapa Flow, reducing predicted overall ECE further to the lower part of the range 1.8 to 5 µgN.litre^{-1}.

The estimates are based on a source rate of 60 kgN.tonne^{-1}.year^{-1} but would be 20% less with a more contemporary rate of 48.2 kgN.tonne^{-1}.year^{-1}.

Increases of tonnage at Bring Head from 2500 to 2750 tonnes have less than 2% influence on the overall estimates for Scapa Flow.

Local concentration enhancement other than near cages within a short time of release less than a tidal period similarly gives no cause for concern.

An ECE of up to 5 µgN.litre^{-1} may be compared with various relevant or regulatory standards:

- typical background concentrations
- 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 above 34), the DIN (Dissolved Inorganic Nitrogen) reference value is 10µM and the threshold 15µM. Increases are therefore limited to 5 µM (70 µgN.l^{-1}).

In the cases and circumstances examined here, predicted ECE increases are therefore insignificant on the scale of the Scapa Flow water body.

The large precautionary margin between these conservative estimates and the regulatory standards means that more detailed modelling is not needed.

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