ORKNEY ISLANDS COUNCIL

Aquaculture Water Quality Impact Modelling

Dissolved Nutrient Modelling Results

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Modelling Results

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Rev 4	31/08/2018	Fifth draft addressing OIC comments	JFA	RPD	RPD

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GLOSSARY

BOD
Biochemical Oxygen Demand

CAR
Controlled Activities Regulations

CEH
Centre for Ecology and Hydrology

DIN
Dissolved Inorganic Nitrogen

DO
Dissolved Oxygen

ECE
Equilibrium Concentration Enhancement

ITI
Infaunal Trophic Index

JNCC
Joint Nature Conservation Committee

MCFF
Marine Cage Fish Farm

PE
Population Equivalent

PMF
Priority Marine Feature

SNH
Scottish Natural Heritage

STW
Sewage Treatment Works

WFD
Water Framework Directive

WWTP
Waste Water Treatment Plant

1. INTRODUCTION

1.1 Project Outline

Orkney Islands Council (OIC) commissioned Intertek Energy and Water Consultancy Services (Intertek) to provide a predictive far-field modelling assessment of current and proposed fish farms in Scapa Flow, Orkney. This is to assess whether there are any possible detrimental effects to water quality due to nutrient loading and enrichment, including an assessment of dissolved nutrient cumulative impacts, and maximum fish farm capacity.

In agreement with OIC, this appraisal considers the nutrients to be dissolved pollutants (defined here in modelling terms as dissolved inorganic nitrogen, DIN) and therefore does not consider other chemical discharges or the settling and re-suspension of particulate matter.

This document details the modelling approach taken and preliminary findings.

Recommendations are given for potential future scenarios and applications relating to aquaculture that could be tested with this model by carrying out further model runs.

Figure A-1 provides an overview of the study area and highlights key locations referred to throughout this assessment. The extent of the study area is the entire water body of Scapa Flow within the Orkney statutory Harbour limit.

1.2 Rationale

Why is there a requirement for aquaculture water quality modelling in Scapa Flow?

Under statutory legislation, all new fish farm developments in Scotland are required to consider, amongst others:

- Potential effects, including cumulative, on the environment
- Potential impacts to nature conservation interests, including priority habitats and wild fish populations
- Existing aquaculture in the locality
- Potential for nutrient enhancement and benthic impacts
- Carrying capacity of the area of water.

The ongoing release of dissolved nutrients and solid organic material in the form of waste feed pellets and fish faecal matter during fish farm operation has the potential to have a detrimental impact to water quality and the seabed, in the form of nutrient enrichment and deposition of organic matter. This may alter existing biodiversity and water quality, from nutrient dispersal in the water column and waste accumulation beneath fish pens. Nitrogen is the key nutrient limiting planktonic growth in marine waters.

These potential effects highlight the importance of characterising the nature and dispersal of dissolved and particulate fish farm waste products responsible for organic enrichment.

Fish farm impact modelling has been undertaken using DEPOMOD, a fish farm specific version of the deposition model BenOss, which was developed for Comprehensive Studies under the Urban Wastewater Treatment Directive. DEPOMOD uses a flow field model coupled with a particle tracking and deposition model to predict the impact of organic particulates, using an empirically-derived relationship between deposition and the Infaunal Trophic Index (ITI, an index of impact on benthic fauna residing in the sediment). AutoDEPOMOD is a software package providing additional functionality to the DEPOMOD aquaculture impact model. It is used for consenting site biomass limits from modelled benthic impact due to organic wastes and can account for specific fish farm configurations and load scenarios.

Despite its predictive abilities, DEPOMOD may have some practical limitations as a regulatory tool, since it is unable to dynamically represent localities and may not adequately represent far-field (regional/dispersed) effects. Transport and re-suspension processes in DEPOMOD are based on the dispersion of small, slow-settling particles in a low-energy in-shore environment (Fisheries and Oceans Canada, 2011). As such, soluble nutrient dispersion may be represented ineffectively, particularly at more exposed sites, therefore underestimating the 'zone of influence' surrounding fish farms.

SEPA apply a technique of Equilibrium Concentration Enhancement (ECE) for Fish Farm Locational Guidance (Gillibrand et al., 2002). This is a simple box model used to predict the level of soluble nitrogen enhancement from fish farms. Areas with higher ECE values are predicted to be more sensitive to fish farming due to higher predicted levels of nutrient enhancement. Nitrogen is treated as a conservative substance in the model and the model is a function of the flushing rate of a sea loch, nitrogen source rate and total consented biomass. However, this model is not appropriate for open-water fish farm sites.

1.3 Project Aims

The aim of this modelling study is to provide a predictive far-field modelling assessment of water quality for existing and proposed fish farms in Scapa Flow, with particular focus on nutrient enrichment. The method applied here is intended to serve as a basis for further dynamic, predictive modelling for future fish farm development. It also aims to inform planning policy for aquaculture and support the development of a decision support tool for future development. In agreement with OIC, this appraisal considers the nutrients to be dissolved pollutants (defined here in modelling terms as dissolved inorganic nitrogen, DIN) and therefore not subject to settling and re-suspension.

As agreed with OIC, there was a requirement to:

- Utilise the existing Intertek/OIC Marine Services hydrodynamic model to look at the whole water body of Scapa Flow, considering dissolved nutrient inputs from existing/planned fish farming and assess potential for further development. This aims to consider how multiple fish farms interact and provide a high-level assessment of cumulative impacts.
- Undertake a numerical modelling assessment to determine maximum biomass (defined as weight of farmed fish) for fish farms in Scapa Flow, i.e. the maximum DIN discharge for existing and proposed fish farms.
- Identify areas that are more suitable and less suitable for fish farm development in terms of nutrient enrichment/pollution effects, having considered cumulative dissolved nutrient impacts.

2. METHOD STATEMENT

2.1 Approach

Intertek prepared a Method Statement (P2218_R4425) which has been agreed with OIC and SEPA.

The following section provides an overview:

The assessment made use of Intertek's existing Scapa Flow hydrodynamic and water quality model. This model was originally developed for impact assessment of Scottish Water wastewater discharges to the coastal environment. The Scottish Environment Protection Agency (SEPA) was closely involved in the development and application of the model for wastewater assessment and were satisfied with the performance of the model and the assessments undertaken.

The model was then used as the basis for the development of a detailed model of the Orkney coastline, particularly in Scapa Flow, which was then applied to a study of the potential risk of non-native species arising from the management of ballast water from shipping. The study was therefore principally concerned with understanding hydrodynamics and the dispersion of ballast water, and the organisms that may potentially be released. The studies were essentially water quality studies and again were therefore similar to the proposed studies for fish farm impacts. As for previous studies, SEPA were able to review and comment on the modelling undertaken for these studies and assessed the performance of the model. The model was also judged to be fit for purpose by Marine Scotland who reviewed the model on behalf of Scottish Natural Heritage.

On the basis that this latest iteration of the model is fit for purpose for the assessment of nutrient dispersion and impacts (as measured against agreed thresholds), the model was deemed appropriate for this study which seeks to understand the long-term impact of existing fish farms, and the impact of the proposed fish farms.

The model was run in advection-dispersion mode for one year (January to December), which is appropriate for a relatively long-term (or ‘far-field’) model run. This allows nutrient build-up and dispersion across Scapa Flow to establish a dynamic equilibrium of concentration (assuming a relatively steady input regime). The run length was deemed sufficiently representative of feeding and growth regimes and nutrient production over the complete growth cycle. The model assumes that the released nitrogen is conserved and modelled concentrations are only reduced through advection and dispersion. It does not account for the nitrogen cycle.

The nutrients were modelled as dissolved pollutants (i.e. in the water column) which provides an effective representation of dispersal. It is accepted that a component of the nutrients will be held in the short term as settled or suspended particles, although this has not been represented in the model at this stage.

Pollutant load was calculated for each fish farm being represented in conjunction with estimates of nutrients inputs from wastewater treatment works and diffuse land-based sources (including run-off associated with farmland, livestock and treated wastewater). Specific model input data, estimation methods and model runs are detailed in Section 2.2 and 2.3.

Based upon available data and discussion with SEPA and Orkney Islands Council, there is no evidence that bacterial impacts currently pose a significant issue to nutrient enrichment and water quality in Scapa Flow. Prosafe Offshore Ltd own the accommodation rigs that abstract water from Scapa Flow and undertake risk assessments for potable water production. To comply with these assessments, monthly seawater samples from Scapa Flow have been collected by the Orkney Harbour Authority since December 2015 and are tested for Coliforms, *Escherichia Coli* and intestinal Enterococci. These bacterial levels are assessed against the Bathing Water Directive 2006 thresholds for coastal and transitional waters. Sampled bacterial levels have always been minimal. Therefore, bacterial discharges from fish farms in Scapa Flow have not been included in this assessment.

2.2 Input Data

2.2.1 Fish Farms

2.2.1.1 Locations

There are nine existing aquaculture licences within Scapa Flow, of which eight are currently operational. These are predominantly located in the western bays (Figure A-1). In addition, there are three fish farms currently under proposal, located along the east coast. The fish farms considered in this assessment are detailed in Table 2-1 and are listed in order moving anti-clockwise around Scapa Flow. Our justification for the exclusion of Weddell Sound fish farm is provided in Section 2.2.1.

Table 2-1 Existing and Proposed Fish Farms in Scapa Flow considered in this study

Fish Farm	Number of Cages (* = Proposed)	Maximum Licensed Biomass (t) (CAR Application)
St Margaret's Hope	*12	1247
Hunda North	*12	1697
West Glimps Holm	*12	1247
Westerbister	16	1791
Toy Ness	10	1342
Bring Head	10	968
Chalmers Hope	8	1000
Lyrawa Bay	4	400
South Cava	16	2500
Pegal Bay	6	400
West Fara	16	800
Ore Bay	7	450

Fish farm cage coordinates provided by SEPA were plotted in GIS and their centre point extracted. These were extracted from GIS using the cage arrangement coordinates provided by OIC. Google Earth imagery was used to identify the number of cages at Ore Bay. For each farm, the discharge point was treated in the model as the centre of the agglomeration of cages. It is considered that for a far-field assessment this is a reasonable approximation of discharge location.

Weddell Sound was excluded from this assessment as it discharges outside of Scapa Flow. Another fish farm, Ore Bay, is not currently in operation but was included as a discharge input in model runs as a conservative approach, given that it could resume operation in the future.

2.2.1.2 DIN estimates

For each fish farm, dissolved pollutant load was estimated based on operational data provided by SEPA (Table 2-2). Each farm was modelled as an independent source, to calculate cumulative impacts and the proportion of overall impact from each farm.

Using the fish farm biomass values provided by SEPA, the following SEPA-derived relationship for estimating daily DIN rate was applied:

Biomass (t) x 2 (production factor) x 35.6 (kg/t) / (2 (years) x 365 (d/y)),

where: t= tonnes, kg = kilograms, d = days, and y = years.

This relationship is derived from a mass balance model approach (Davies, 2000) and applies a feed wastage value of 5%, assuming the diet is 90% digestible and a 10% mortality rate over the 20-month production cycle. Dissolved nitrogen was calculated as the difference between the input amount in the feed and the sum of the amounts in particulate waste (excess pellets and undigested material) and fish growth.

Maximum biomass values from the corresponding fish farm CAR applications were used.

Table 2-2 DIN estimates for Assessed Fish Farms

Licence Number	MCFF Site Name (*Proposed)	Biomass (t)	Estimated DIN Rate (t/day)
CAR/L/1003962	Ore Bay	450	0.0439
CAR/L/1003961	Pegal Bay	400	0.03901
CAR/L/1003062	Chalmers Hope	1000	0.09753
CAR/L/1004229	West Fara	800	0.07802
CAR/L/1003960	Lyrawa Bay	400	0.03901
CAR/L/1143253	Westerbister	1791	0.1747
CAR/L/1015855	Toy Ness	1342	0.13097
CAR/L/1015854	Bring Head	968	0.09491
CAR/L/1082725/V3	South Cava	2500	0.24384
CAR/L/1122569	*West Glimps Holm	1247	0.12162
CAR/L/1157278	*Hunda North	1697	0.1655
CAR/L/1157275	*St Margaret's Hope	1247	0.1216

2.2.2 Sewage Treatment Works

DIN was estimated using the Population Equivalent (PE) Post-Treatment values from CAR Licences provided by SEPA (Table 2-3). Population Equivalent is the organic biodegradable load of a waste water expressed in terms of an equivalent population, with one unit having a five-day biochemical oxygen demand (BOD) of 60 g of oxygen per day. In terms in nitrogen, 1 P.E corresponds to 12 g N/day (OSPAR, 2004). Post Treatment is defined as the application of a treatment system to a discharge, either as a single component (such as a septic tank) or a combination (such as septic tank plus reed bed). Estimated DIN rates for sewage treatment works are provided in Table 2-3 below.

Table 2-3 DIN estimates for Sewage Treatment Works

Licence Number	Site Name	PE Post Treatment	Estimated DIN Rate (t/day)
CAR/L/1003942	Lyness STW	40	0.00038
CAR/L/1005016	East Septic Tanks, Leaburn, Burray	60	0.00057
CAR/L/1002972	St Colms Housing, Longhope, Hoy	70	0.00067

Licence Number	Site Name	PE Post Treatment	Estimated DIN Rate (t/day)
CAR/L/1005003	St Marys Waste Water Treatment Works	308	0.00295
CAR/L/1005018	West Septic Tank, Sunfield, Burray	40	0.00038
CAR/L/1005017	Burray Village STW	50	0.00048
CAR/L/1016489	Stromness WWTP	3765	0.03163
CAR/L/1002984	St Margaret's Hope Main Outfall	303	0.00254
PPC/A/1012610	Repsol Sinopec Resources UK Limited	251	0.00211

N.B. STW: Sewage Treatment Works, WWTP: Wastewater Treatment Plant.

2.2.3 Watercourses

Diffuse, land-based runoff from agriculture and other anthropogenic activity was characterised by identifying all watercourses (from small burns to larger streams and rivers) discharging into Scapa Flow. 41 watercourses were grouped geographically for inclusion in the model into 7 components. The approach was discussed and agreed with SEPA.

Catchment land use was characterised using the CEH Land Cover Map 2007 raster product. The islands surrounding Scapa Flow are predominantly characterised by low lying, flat topography occupied by simple agricultural improved grassland or arable pasture with scattered farmsteads, and some areas of heather moorland and rough grassland (Figure A-2).

Two waterbodies in the Upper Clyde catchment were used as a proxy for estimating winter DIN, given they are both mostly improved grassland. The Upper Clyde was selected because Intertek have undertaken significant amounts of modelling work in this region and possess water quality sampling data for this catchment. Sampled winter mean DIN for two waterbodies (Duneaton Water = 130 µg/l, Medwin Water = 590 µg/l) was used. Medwin Water was selected as the higher mean. DIN for heather catchments was assumed to be 0.5 of grassland catchments.

Mean flow from the Durkadale flow gauge on Orkney (ID 107001, 0.489 m^3/s) was used to estimate mean flows (Table 2-4), scaled to catchment areas derived from the CEH Flood Estimation Handbook web tool.

Table 2-4 Flow and DIN Estimates for Grouped Watercourse Discharges into Scapa Flow

Group	Total Catchment Area (km^2)	Mean Flow (m^3/day)	Estimated Mean DIN Flux (t/day)	Dominant Land Cover
1	47.59	1.22	6.2E-02	Grassland
2	7.29	0.19	9.6E-03	Grassland
3	158.33	4.07	2.1E-01	Grassland
4	7.70	0.20	5.1E-03	Heather
5	33.24	0.86	2.2E-02	Heather
6	8.59	0.22	1.1E-02	Grassland
7	2.33	0.06	3.1E-03	Grassland

2.3 Model Set-up

2.3.1 Model Boundaries

The model boundary data are re-predictions from 20 hourly level data points for 1999 from the Proudman Oceanographic Laboratory (POL) Continental Shelf Model (CS3-30HC). This model is recognised as a source of high quality boundary data and accounts for the continental shelf to the west, which has a significant impact on currents. The boundary extents are outlined in Table 2-5.

Table 2-5 Model Boundaries

Boundary	Start		End	
	Easting	Northing	Easting	Northing
Western Boundary	396630	867900	396630	1088070
Northern Boundary	396630	1088070	232200	1088070
Eastern Boundary	232200	1088070	232200	973400

N.B All Eastings and Northings are provided in OSGB36.

The hydrodynamic model was run for a specified set of boundary conditions (which take the form of time series of water elevations along the model boundaries). The model is driven at its seaward boundaries by water level data. The hydrodynamic flow field was generated at each time step for each model grid cell. The boundary conditions generate a tidal wave within the model that propagates from one grid cell to the next. The information in each grid cell is updated at every timestep as the boundary condition changes. This means that water levels and currents are predicted dynamically (i.e. change with every time step) according to the prevailing tidal conditions. Calm conditions are assumed.

Figures 2-1 to 2-4 below show the dynamic nature of the flow throughout a tidal cycle. This clearly demonstrates the need for well-resolved hydrodynamics as the flow field changes significantly throughout the tide. Note the minimal circulation and flushing along the north-eastern boundary of Scapa Flow.

Figure 2-1 Flow Field at High Water

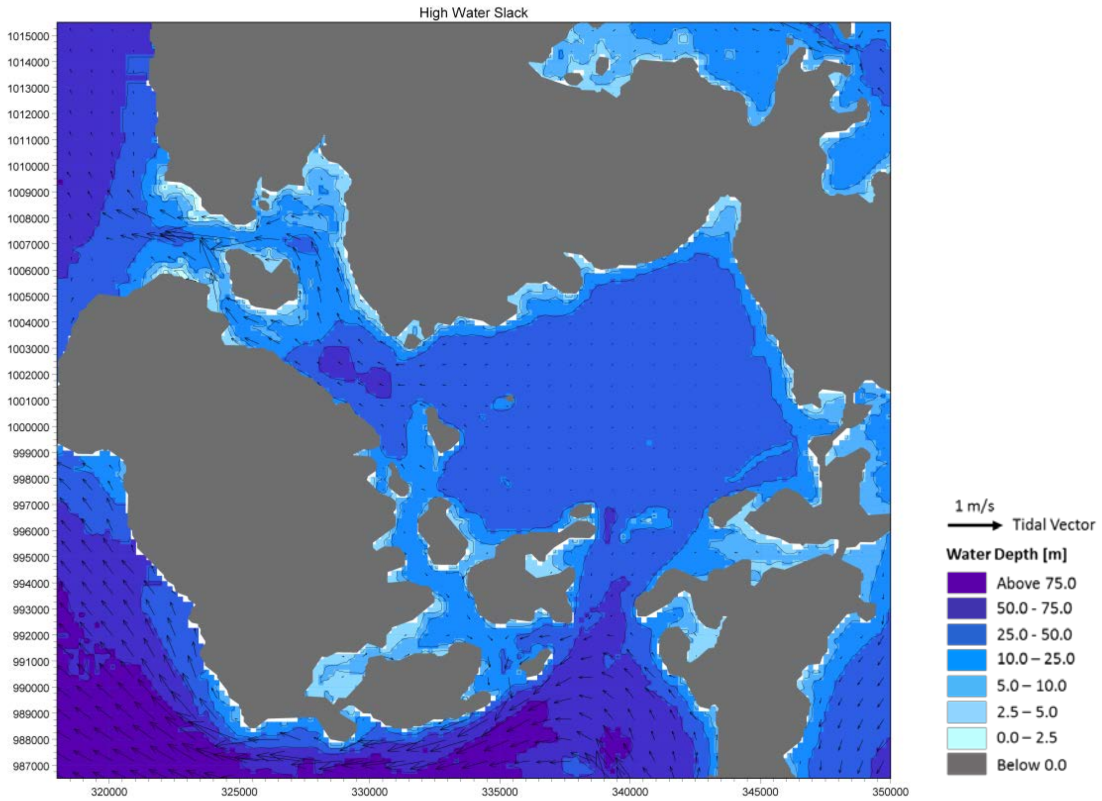


Figure 2-2 Flow Field at Mid Ebb

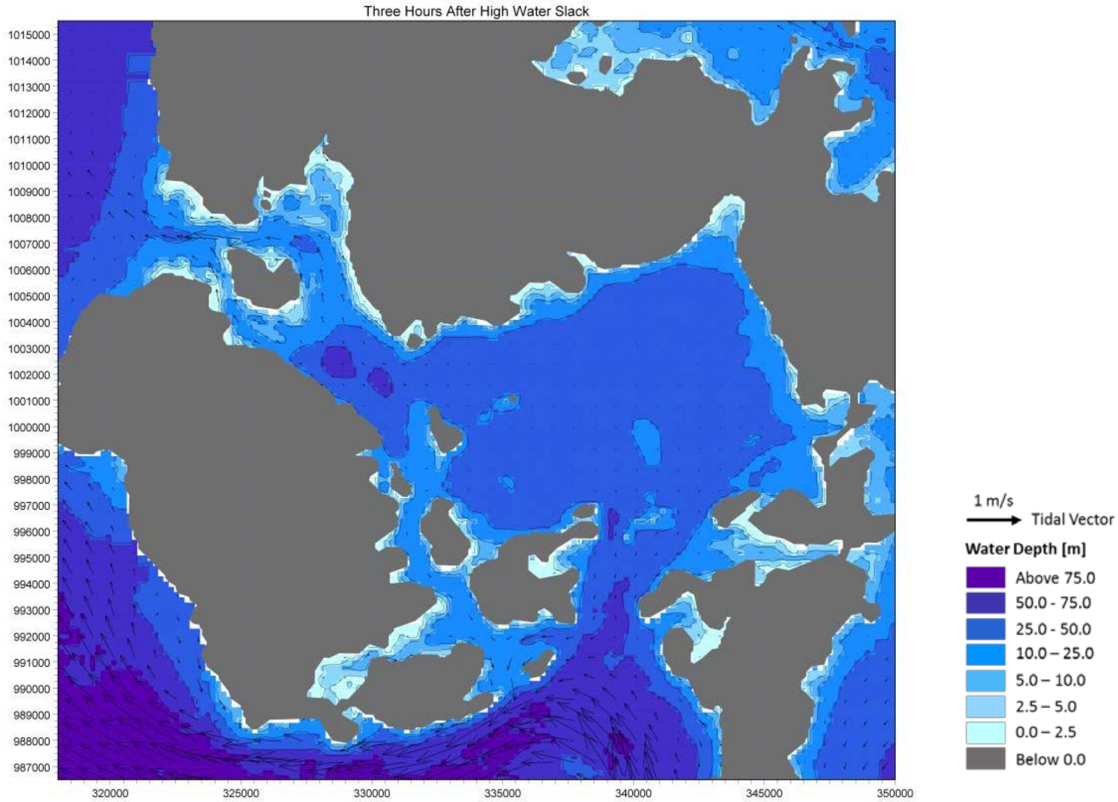


Figure 2-3 Flow Field at Low Water

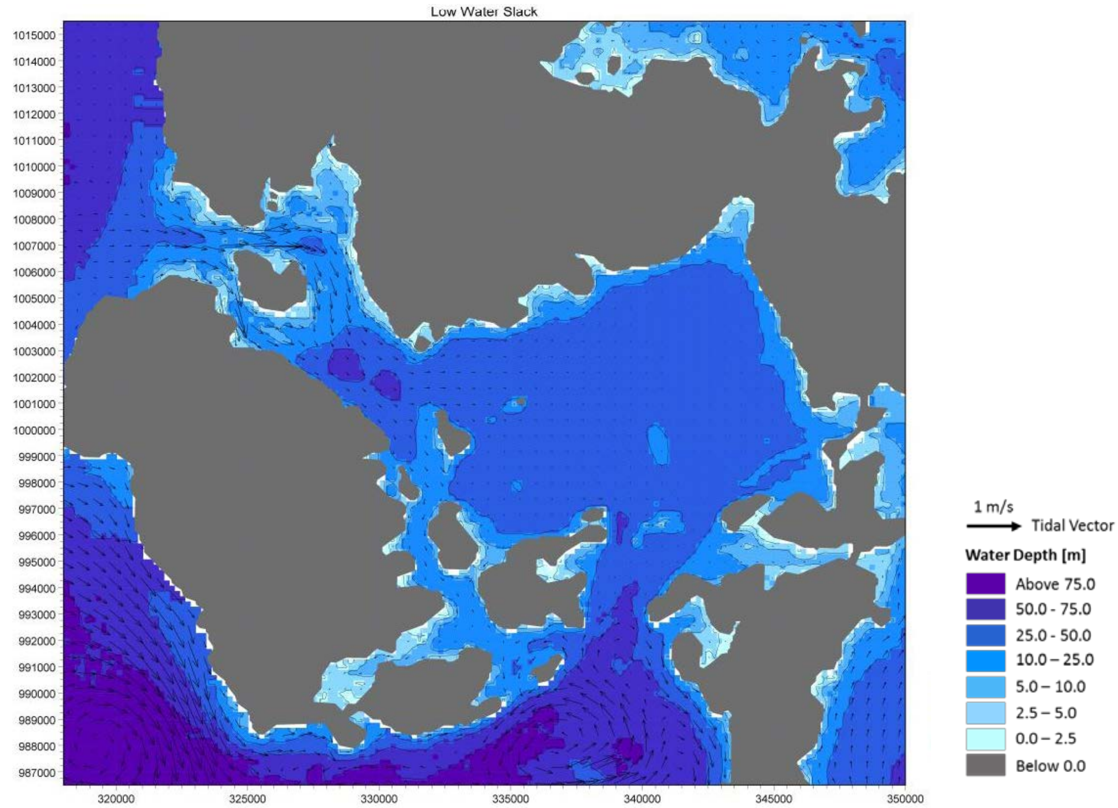
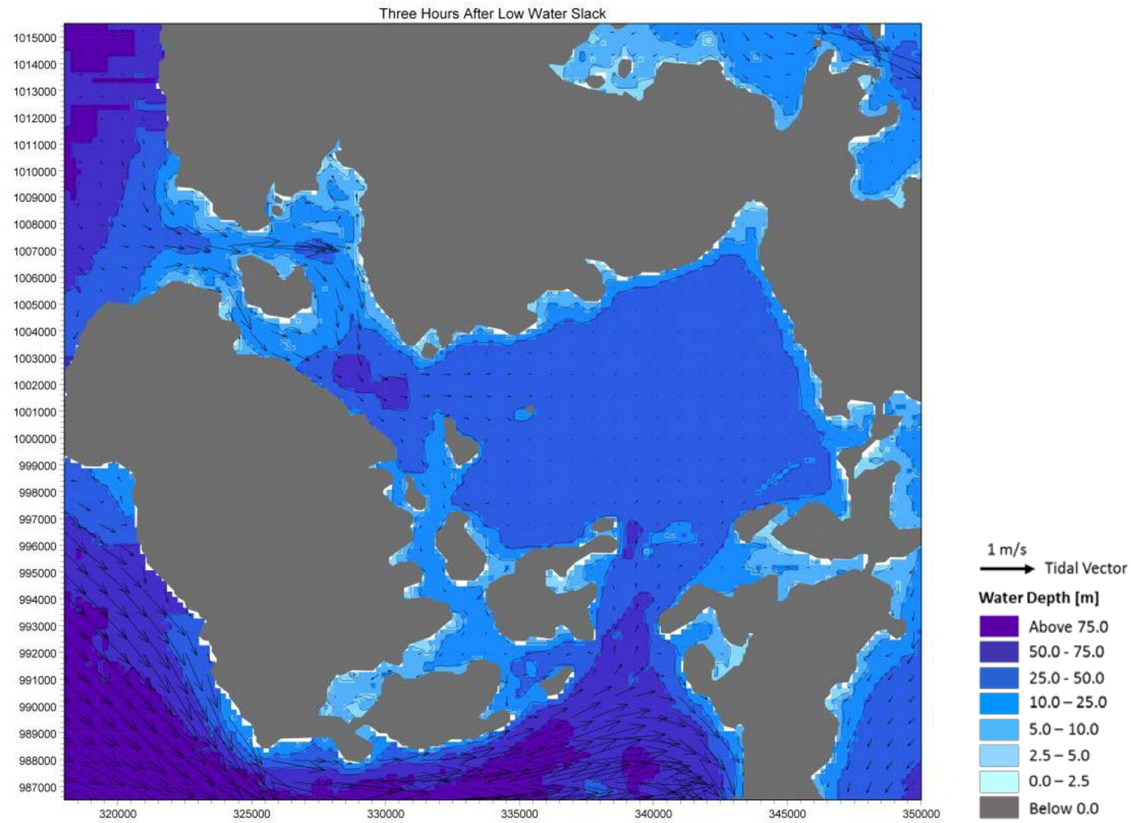


Figure 2-4 Flow Field at Mid Flood



2.3.2 Model Resolution

The hydrodynamic model grid and output domain are shown in Figure A-3. The grid has a resolution of 200m which contains 1,205,695 grid cells in total. Within Scapa Flow, there are approximately 8000 grid cells, meaning current flows are well resolved.

2.3.3 Model Time Step

The model was run with a maximum time step 20 seconds.

2.3.4 Bed Roughness

Bed friction influences the hydrodynamics of a water body. A bed roughness map was applied to the 200m grid across the whole model domain with a Manning Number ranging from 25-30$m^{1/3}s^{-1}$. The Manning Number is an empirically-derived coefficient which is commonly used to approximate bed roughness and therefore bed resistance to flow. An input value is required during the hydrodynamic model setup. A value of 25 $m^{1/3}s^{-1}$ was applied across Scapa Flow, the area from which results were extracted. This value is within the typical range for this type of environment. It should be noted that bed roughness as referred to here does not relate to physical bed roughness, but it is a calibration parameter for the model used to refine other parameters in the model, such as current velocity.

3. MODEL OUTPUTS

Model outputs have been presented in the following ways: as contour plots of average winter Dissolved Inorganic Nitrogen concentration, and as concentration against Water Framework Directive (WFD) Coastal Water Standard thresholds (Table 3-1).

Table 3-1 WFD DIN Standards for Coastal Waters

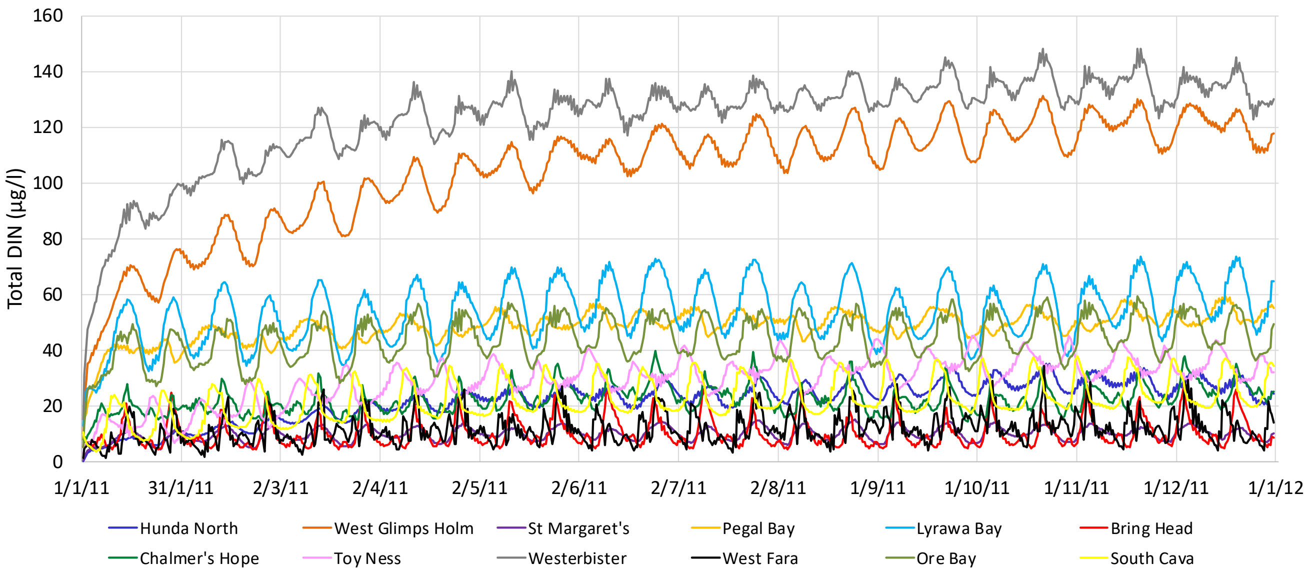
		Dissolved Inorganic Nitrogen (Winter mean as µg/l) WFD Standard			
Area	**Salinity**	High	Good	Moderate	Poor
Coastal	30 – 34.5	168	252	378	567

Plots are displayed showing discharge components separately and the overall combined contribution, so that contributions from existing and proposed fish farms, and other discharge sources, can be separated. For each of the time series graphs presented below, each individual line represents the total modelled DIN extracted from the model at that particular fish farm location. The figures show the following, at each modelled fish farm location:

- Figure 3-1 shows the combined total impact of all modelled discharges (fish farms, treatment works and watercourses)
- Figure 3-2 shows the impact of existing fish farms
- Figure 3-3 shows the impact of proposed fish farms
- Figure 3-4 shows the impact of treatment works
- Figure 3-5 shows the impact of watercourses.

Figure 3-1 clearly shows the initial build-up of DIN during the first 3 months after which conditions in the model reach dynamic equilibrium. For this reason, mean Winter DIN was calculated as mean DIN across November and December.

Figure 3-1 Contribution of all Modelled Discharges to DIN Variation



3.2 Predicted Water Quality in Scapa Flow

3.1.1 Contributions from All Modelled Discharges

The combined contribution of Mean Winter DIN from all modelled discharges complies with the 'High' WFD Classification for coastal waters across the majority of Scapa Flow (Figure A-4). This is in accordance with current WFD classification of Scapa Flow for DIN (SEPA, 2016). Mean Winter DIN is spatially variable across Scapa Flow, reaching an estimated maximum of 509.61 µg/l in Water Sound (Figure A-5). Table 3-2 shows the total impact from all modelled discharges at each fish farm location. The fish farm where predicted DIN reaches its highest concentration is Westerbister (134.4 µg/l), followed by West Glimps Holm (120.9 µg/l) (Table 3-2). A plume accumulates along Scapa Flow's north-eastern boundary, reaching the highest concentrations around Water Sound, St Margaret's Bay, Scapa, and the Westerbister and West Glimps Holm fish farms. These sites are largely removed from the main flows that circulate through Hoy Sound and Hoxa Sound. This plume is predominantly created in the model by the combined contributions of the existing and proposed fish farms (see Sections 3.2.2. and 3.2.3). The model also predicts some DIN accumulation in western cul-de-sac bays, particularly Lyrawa Bay, Pegal Bay and Ore Bay, as well as a low amount of DIN accumulation adjacent to South Cava.

Mean winter DIN contributions of individual modelled discharge components extracted at modelled fish farm locations strongly reflect the most proximal fish farms (Figure A-6). Some modelled stream discharge contributions are also reflected at these locations. It is worth noting that Westerbister fish farm has a predicted zone of influence that extends across to the western edge of Scapa Flow. This is also the case for modelled stream group 7 (the two stream discharges on South Ronaldsay closest to St Margaret's proposed fish farm). Otherwise, zones of influence are largely restricted to their immediate locality. Contributions to mean winter DIN from the fish farm with the largest consented biomass (South Cava) are seen at all nearby fish farms along the western boundary of Scapa Flow.

Table 3-2 Mean Winter Predicted DIN at Modelled Fish Farm Sites

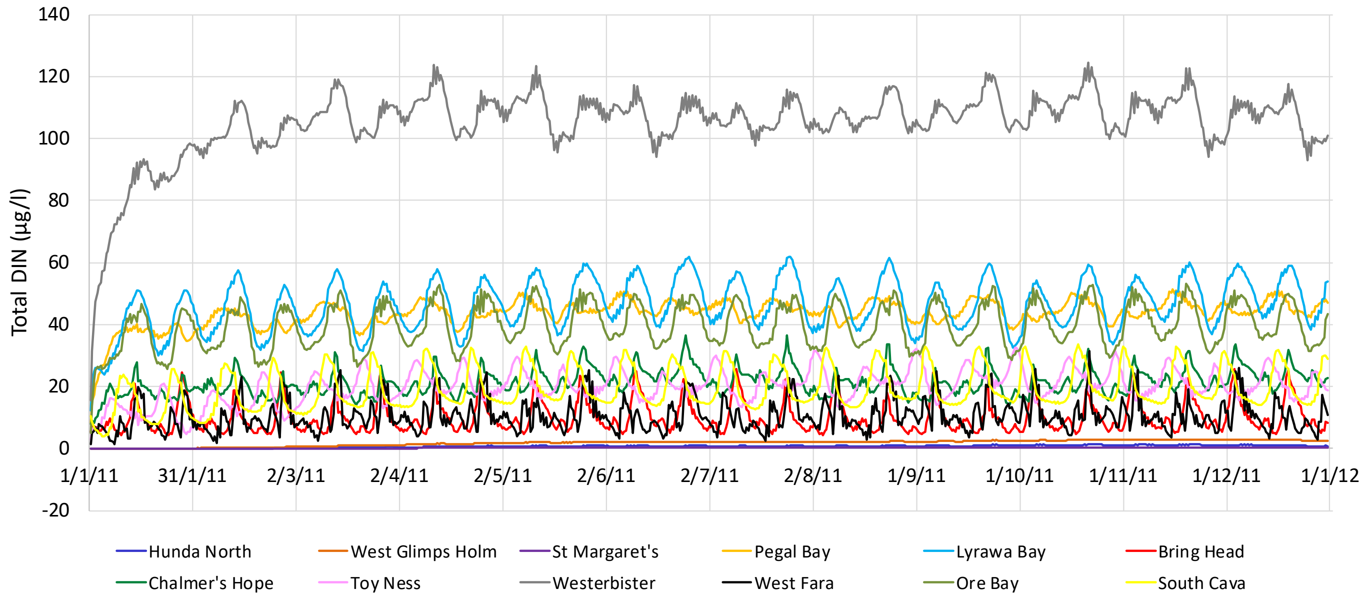
Fish Farm	Winter (November/December) Mean DIN (µg/l)
Hunda North	27.93
West Glimps Holm	120.97
St Margaret's	10.46
Pegal Bay	52.30
Lyrawa Bay	59.00
Bring Head	11.59
Chalmers Hope	25.32
Toy Ness	34.50
Westerbister	134.48
West Fara	13.01
Ore Bay	47.11
South Cava	26.11

3.2.2 Contributions from Existing Fish Farms

When isolating the contributions from existing fish farms only, predicted DIN is highest around the Westerbister fish farm, where a plume develops along the northern boundary of Scapa Flow (Figure A-7). Estimated mean winter DIN reaches 107.49 µg/l at this location. On the western side of Scapa Flow, estimated DIN reaches a maximum of 49.4 µg/l at Lyrawa Bay. Predicted water quality maintains a 'High' WFD Compliance when contributions from treatment works, watercourses and proposed fish farms are excluded (Figure A-8).

The time series below shows the impact from existing fish farms over the model run duration at each fish farm location.

Figure 3-2 Contribution of Existing Fish Farms to Modelled DIN Variation

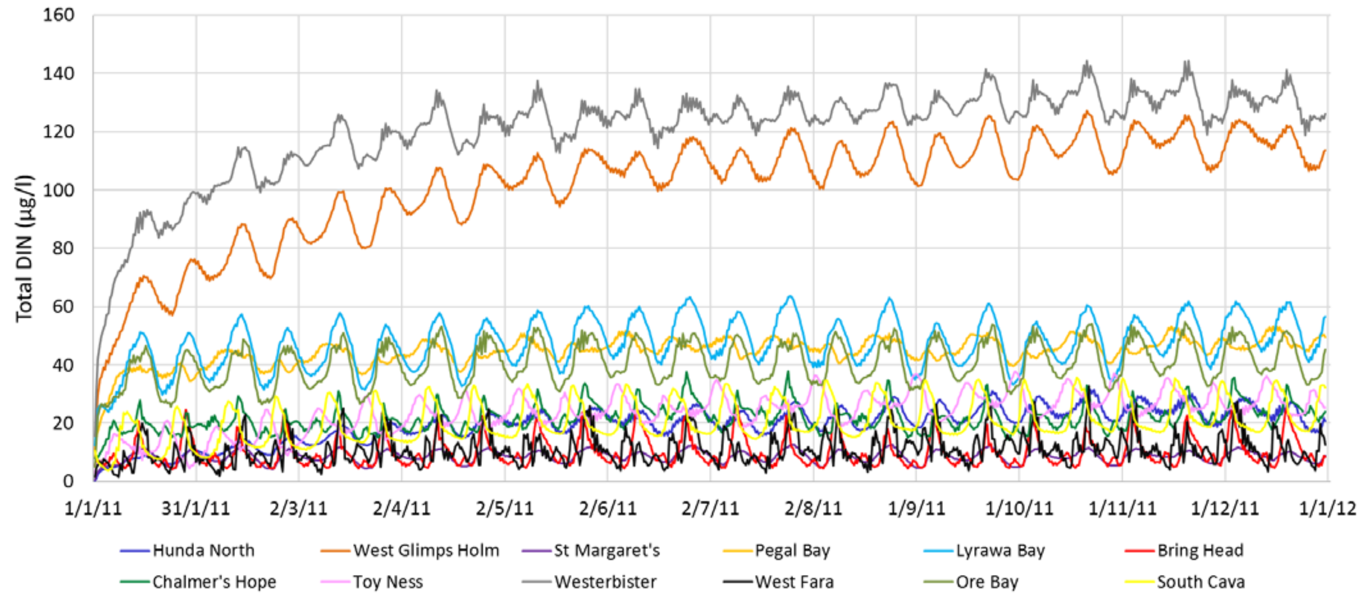


3.2.3 Contributions from Proposed Fish Farms

Predicted water quality maintains a 'High' WFD Compliance when isolating the contributions from proposed fish farms only and all other contributions from existing farms, treatment works and watercourses are excluded (Figure A-9). West Glimps Holm is the biggest contributor to DIN, followed by Hunda North. Given their close proximity, there is the possibility of interaction between discharges at these two sites. However, this appears to be limited and does not reach St Margaret's Hope (Figure A-10).

The time series below shows the impact from proposed fish farms over the model run duration at each fish farm location.

Figure 3-3 Contribution of Proposed Fish Farms to Modelled DIN variation



3.2.4 Contribution from Other Nutrient Sources

The model predicts a low contribution in general from diffuse land-based discharges (represented as point sources where watercourses drain into Scapa Flow), and from treatment works. Predicted water quality maintains a 'High' WFD Compliance when isolating the contributions from watercourses only and all other contributions are excluded (Figure A-11). Predicted water quality maintains a 'High' WFD Compliance across the majority of Scapa Flow when isolating the contributions from treatment works only and all other contributions are excluded (Figure A-12).

There is an area of predicted DIN accumulation in Water Sound, (adjacent to Churchill Barrier Number 4) classified as poor under WFD Standards.

A model extraction at the location of highest predicted DIN concentration in Water Sound shows that the modelled watercourses discharging into Water Sound and St Margaret's Bay are the primary contributors to this area of 'Poor' WFD Compliance (Figure A-13). Two sewage treatment works (East Septic Tanks, Leaburn, and Burray Village) and the proposed St Margaret's fish farm represent minor contributions to predicted DIN at this location.

However, the predicted DIN in this area is considered to be conservatively high. Model runs did not simulate wind conditions, which may also increase mixing and flushing of the inlet, resulting in a reduction of DIN concentrations. The model resolution (200m) is adequate for modelling Scapa Flow in general, but localised effects in this small inlet may not have been represented at a fine enough resolution in the model. Finally, the estimate of nitrogen loadings in the rivers is assumed to be conservative and not based on local sampling. The results do however suggest an overall tendency for accumulation to occur in this area, which should be considered when assessing the impact of present or planned fish farms. The time series below shows the impact from treatment works (Figure 3-4) and the impact from watercourses (Figure 3-5) over the model run duration at each fish farm location.

Sampled background seawater nutrient DIN levels extracted from continental shelf waters around Orkney vary between the Moderate and Poor standards in winter (SARF, 2012). Given that the modelling results currently agree with the 'High' WFD Classification from sampled water quality data in north Scapa, the inclusion of these background DIN levels would lead to over-prediction of impacts by the model. Whilst the model may over-represent some local sources and under-represent more distant sources, the relatively high continental shelf concentrations are not deemed to be representative of conditions within Scapa Flow. Therefore, these data have not been included in the modelling assessment at present.

Figure 3-4 Contribution of Treatment Works to Modelled DIN variation

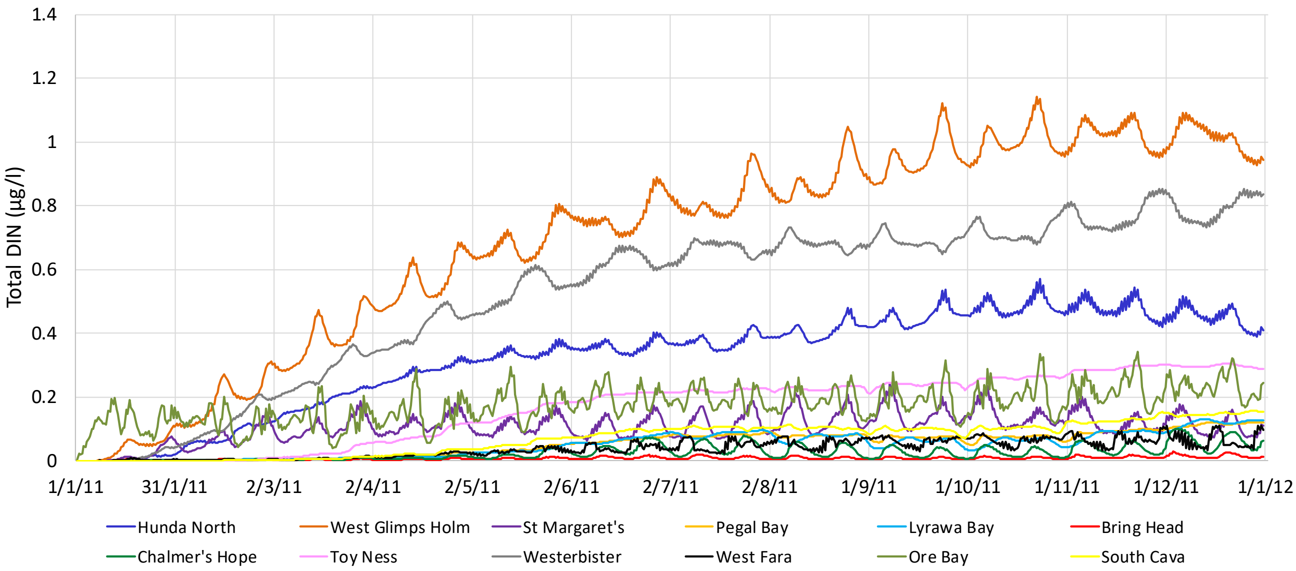
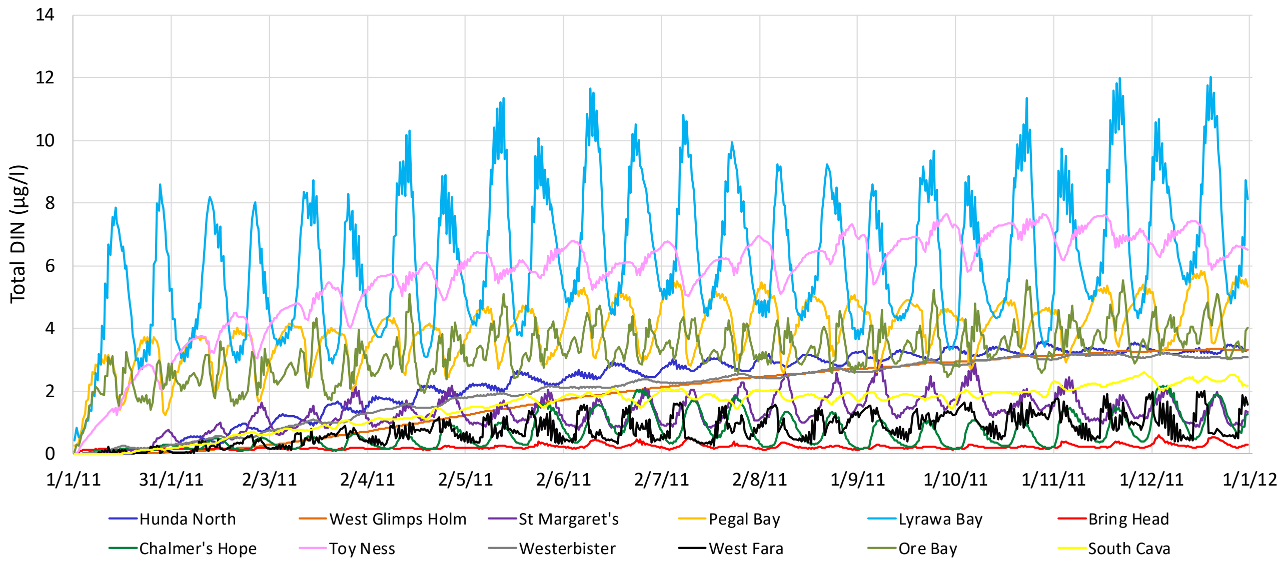


Figure 3-5 Contribution of Watercourses to Modelled DIN Variation



3.3 Fish Farming Carrying Capacity in Scapa Flow

The individual and combined estimated DIN release from the eight existing and three proposed fish farms in Scapa Flow is sufficient to maintain current compliance with High WFD Coastal Water DIN standards. The conservative dissolved nutrient modelling undertaken here therefore implies that water in Scapa Flow is at very low risk of regulatory non-compliance, even when considering cumulative impacts.

3.3.2 Maximum Biomass Estimates

The implications of these preliminary model runs are that the current fish farms are not predicted to represent a significant threat to compliance with the WFD DIN standards. Simple analysis of the data predicts that modelled pollutant loads could be increased before the High WFD Standard (168 µg/l) is breached (Table 3-4).

Table 3-4 Maximum Estimated Fish Farm Biomass

Site Name	Maximum Licensed Biomass (t)	Total Mean Winter DIN (µg/l)	Maximum Estimated Biomass (t)
Pegal Bay	400	52.30	1284.70
Chalmer's Hope	1000	25.32	6633.73
West Fara	800	13.01	10328.26
Lyrawa Bay	400	59.00	1138.88
West Glimps Holm	1247	120.97	1731.76
Westerbister	1791	134.48	2237.53
Toy Ness	1342	34.50	6538.07
Bring Head	968	11.59	14022.65
Hunda North	1697	27.93	10204.86
St Margaret's Hope	1247	10.46	20015.71
Ore Bay	450	47.11	1604.50
South Cava	2500	26.11	16081.77

It should be noted that biomass for each of these fish farms could be increased individually before the WFD High Standard (168 µg/l) is breached, rather than in combination.

Although the current representation simplifies the situation, the results would suggest that both the current and proposed operations do not present a threat to nutrient status over Scapa Flow. Local impacts, arising through deposition, have not been assessed during this study.

3.4 Predicted Benthic Impacts

3.4.2 Priority Marine Features

13 Priority Marine Features (PMF) within Scapa Flow were identified and their coordinates extracted using the Marine Scotland NMPi tool. These are detailed in Table 3-5. Although some features intersect areas of highest predicted DIN (Figure A-14), these have been identified using the Feature Activity Sensitivity Tool (developed by SNH, JNCC and Marine Scotland) having low sensitivity to nitrogen and phosphorus enrichment.

Table 3-5 Priority Marine Features within Scapa Flow

PMF	Component Biotope Species	Type	Sensitivity to Nitrogen and Phosphorus enrichment
Flame Shell Bed	*Limaria hians* beds in tide swept sublittoral muddy mixed sediment	Seabed habitat	Low

PMF	Component Biotope Species	Type	Sensitivity to Nitrogen and Phosphorus enrichment
Low or variable salinity habitats	Submerged fucoids, green or red seaweeds (low salinity infralittoral rock)	Seabed habitat	Low
Low or variable salinity habitats	Kelp in variable or reduced salinity	Seabed habitat	Low
Kelp Beds	*Laminaria hyperborea* and foliose red seaweeds on moderately exposed infralittoral rock	Seabed habitat	Low
Horse Mussel beds	*Modiolus* beds *with Chlamys varia*, sponges, hydroids and bryozoans on slightly tide swept very sheltered circalittoral mixed substrata	Seabed habitat	Low
Horse Mussel beds	*Modiolus* beds with fine hydroids and large solitary ascidians on very sheltered circalittoral mixed substrata	Seabed habitat	Low
Horse Mussel beds	*Modiolus* beds with hydroids and red seaweeds on tide swept circalitoral mixed substrata	Seabed habitat	Low
Horse Mussel beds	*Modiolus* beds on open coast circalittoral mixed substrata	Seabed habitat	Low
Tidal-swept algal communities	Fucoids in tide-swept conditions	Seabed habitat	Low
Kelp and seaweed on sublittoral sediment	Kelp and seaweed on sublittoral sediment	Seabed habitat	Low
Maerl Beds	Maerl Beds	Seabed habitat	Low
Maerl or coarse shell gravel with burrowing sea cucumbers	*Neopentadactyla mixta* in circalittoral shell gravel or coarse sand	Seabed habitat	Low
Seagrass beds	*Zostera* Marine beds on lower shore or infralittoral clean or muddy sand	Seabed habitat	Low
Burrowed Mud	Seapens and burrowing megafauna in circalittoral fine mud	Seabed habitat	Low
Ocean Quahog	Ocean Quahog	Low or limited mobility species	Low
Northern feather star	Northern feather star	Low or limited mobility species	Low

PMF	Component Biotope Species	Type	Sensitivity to Nitrogen and Phosphorus enrichment
Fan mussel	Fan mussel	Low or limited mobility species	Low

4. CONCLUSIONS

The conservative modelling supporting this report of dissolved nutrient release from the nine existing and three proposed fish farms in Scapa Flow examined in this study is sufficient to maintain current compliance with High WFD Coastal Water DIN standards. This implies that water in Scapa Flow is at very low risk of regulatory non-compliance, even when considering cumulative impacts of dissolved nutrient release to water quality. The model predicts in general a low impact of dissolved nutrient release from sewage treatment works and watercourse discharges, sufficient to maintain compliance with High WFD Coastal Water DIN standards with the exception of Water Sound where concentrations exceed this limit.

We recommend that the model is run with the inclusion of dissolved nutrient breakdown processes and suspended solid dispersion to investigate fish farm depositional footprints. This will enable more accurate water quality predictions for a greater range of scenarios and potential pollutants.

5. RECOMMENDATIONS

The described far-field modelling approach provides a better understanding of the water quality impacts of nutrient dispersion arising from existing and planned fish farms (including cumulative impacts) than current steady-state approaches could provide.

Modelling suggests that the dispersion and transport of DIN does not cause a risk of breaching the High WFD standard across the majority of Scapa Flow. It is noted that this result refers to dissolved pollutant and does not consider the impact of settled solids on local areas at this stage. The model can be run with a Particle Tracking module which has the capability to model these processes.

There are a number of considerations which have not been included at this stage, but which our model is fully capable of including. While these fall outside of the agreed scope of this assessment, further model runs could be undertaken under a variation, in agreement with OIC.

The model lends itself to further indicative development scenarios that could be used as a predictive tool for OIC, the aquaculture industry and regulators. The dynamic model is able to accurately recreate hydrodynamic conditions and represent water quality and potential pollutant scenarios, at a higher resolution in some parts of Scapa Flow than the Marine Scotland Scottish Shelf Model in this area (Wolf et al., 2016).

We recommend that the model is run for a sufficient period (e.g. 2.5 – 3 years) to cover the full 2-year fish farm production cycle and is run with time-varying inputs using feed input data to account for varying feed composition over the fish growth cycle (and therefore varying nutrient content). This would provide the baseline data for a whole growth cycle.

The nature of the dynamic model, with its ability to accurately recreate hydrodynamic conditions, and to represent numerous water quality scenarios and potential pollutants, means that the model can be used for a number of other functions. These include:

Ongoing appraisals of future applications for fish farms

- Once the 'baseline' of impacts (i.e. the position in early 2018) is established, the approach can be used to test the impact of additional sites, or changes in production at established sites.

Optimised location and biomass limits

- The model outputs can be used to easily visualise and understand optimal locations for siting proposed fish farms. In addition, these outputs can be used to provide maximum biomass predictions, ie. maximum farmed fish volumes for fish farms under different scenarios.

Impacts of any pharmacological impacts to the environment (for example for multiple site applications of sea lice treatments)

- Chemical discharges are dissolved pollutants, and thus can be appraised in the same way as the initial nutrient study which has examined the impact of Dissolved Inorganic Nitrogen. Information regarding loads, decay and any interactions with other substances may be required. Synergies, antagonisms, etc can all be appraised, but note that any decay or interaction processes may require additional runs.

Basis for a general modelling approach for environmental impact assessments for other sites.

- Existing data produced by the model runs from this assessment can be used to test particular environmental issues or scenarios. For example, newly designated sensitive areas or specific priority marine features can be overlaid onto contour plots of nutrient dispersion to facilitate assessment of environmental impact at these locations. This will save time and resources in not having to re-run the model. The model can also be applied for additional environmental impact scenarios, although note that additional runs may be required.

Deposition modelling and associated impacts (as a dynamic substitute for DEPOMOD, which could assess other pollutants and impacts, and provide cumulative impacts of deposition)

- The model of Scapa Flow can be used to model the fate of suspended solids in the water column, which is essentially the process modelled in DEPOMOD. A particle tracking approach would be appropriate, together with particle size data and mass of the solids to be modelled. Re-suspension could also be modelled. Transport and deposition could be modelled over a wider area, and with greater accuracy, than the flow-field approach in DEPOMOD, enabling a better understanding of zones of influence around fish farms.

Interactions with wild fish populations

- There may be possibilities to understand more about the potential for farmed fish to interact or affect wild fish populations. In Scapa Flow sea trout feed in the inter-tidal coastal zone, with easy access to spawning burns. A number of other species also spawn and/or nurse within Scapa Flow, including Sprat, Sandeel, Saithe, Lemon Sole and Herring (Coull et al., 1998). This could be undertaken using maps of potential impact and plotting these over wild fish distributions, or even the application of agent-based modelling techniques to represent the movement and reaction of wild fish. Similarly, bird survey or observational data could be overlaid onto maps of modelled potential impact to help understand potential hot spots of disturbance.

Interactive Prediction Tool

- Use of the model can either be as direct runs, undertaken discretely for individual tasks or schemes, or as a basis for generating data to populate the development of a tool, which can be interrogated for a local area and will use data already generated by the model to provide predictions of impact and transport.
- For each pollutant to be assessed, a requirement would be a knowledge of load and decay characteristics. For conservative pollutants, these all could be represented with one set of runs. For pollutants with specific decay or interaction characteristics, then discrete runs for each would be required. There are a number of options which could be developed. The interactive tool could be web-based and users provided with a secure log-in. This would remove the requirement for users to have any proprietary GIS software licences, or GIS expertise. The ability to interrogate impacts at particular areas would prove a useful basis for customised local management strategies, which could account for local conditions and optimise farm number and placement.

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APPENDIX A

Figures

AQUACULTURE WATER QUALITY IMPACT MODELLING

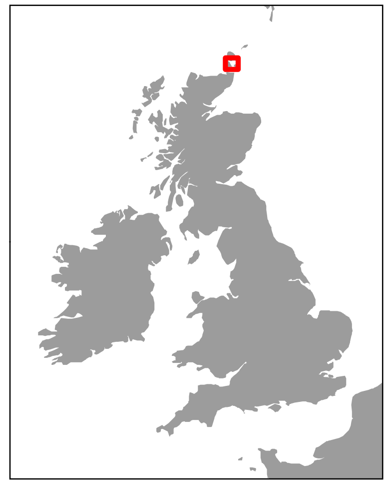
Figure A-1: Geographical Overview

Legend

- Sewage Treatment Works
- River
- Orkney Harbour Limit

Fish Farms

- Existing
- Proposed
- Not modelled in this study



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Created By	Jennifer Arthur
Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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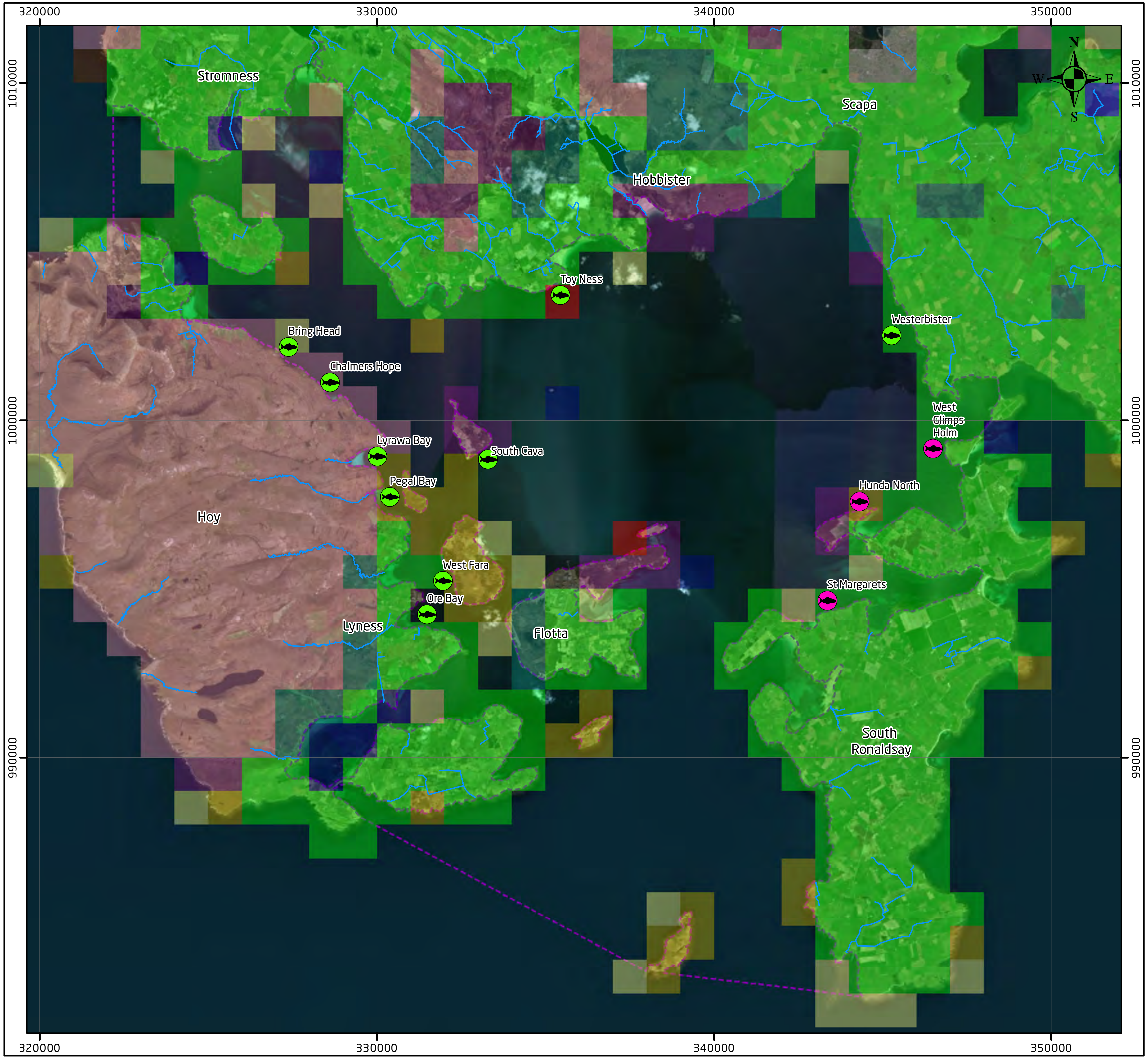

AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-2: Dominant Land Cover Surrounding Scapa Flow

Legend

- Orkney Harbour Limit
- River

Fish Farms

- Existing
- Proposed

Dominant Land Cover Classes

- Broadleaved Woodland
- Arable and Horticulture
- Improved Grassland
- Heather
- Heather Grassland
- Bog
- Saltwater
- Freshwater
- Supralittoral Rock/Sediment
- Littoral Rock/Sediment

NOTE: Not to be used for Navigation

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Created By	Jennifer Arthur
Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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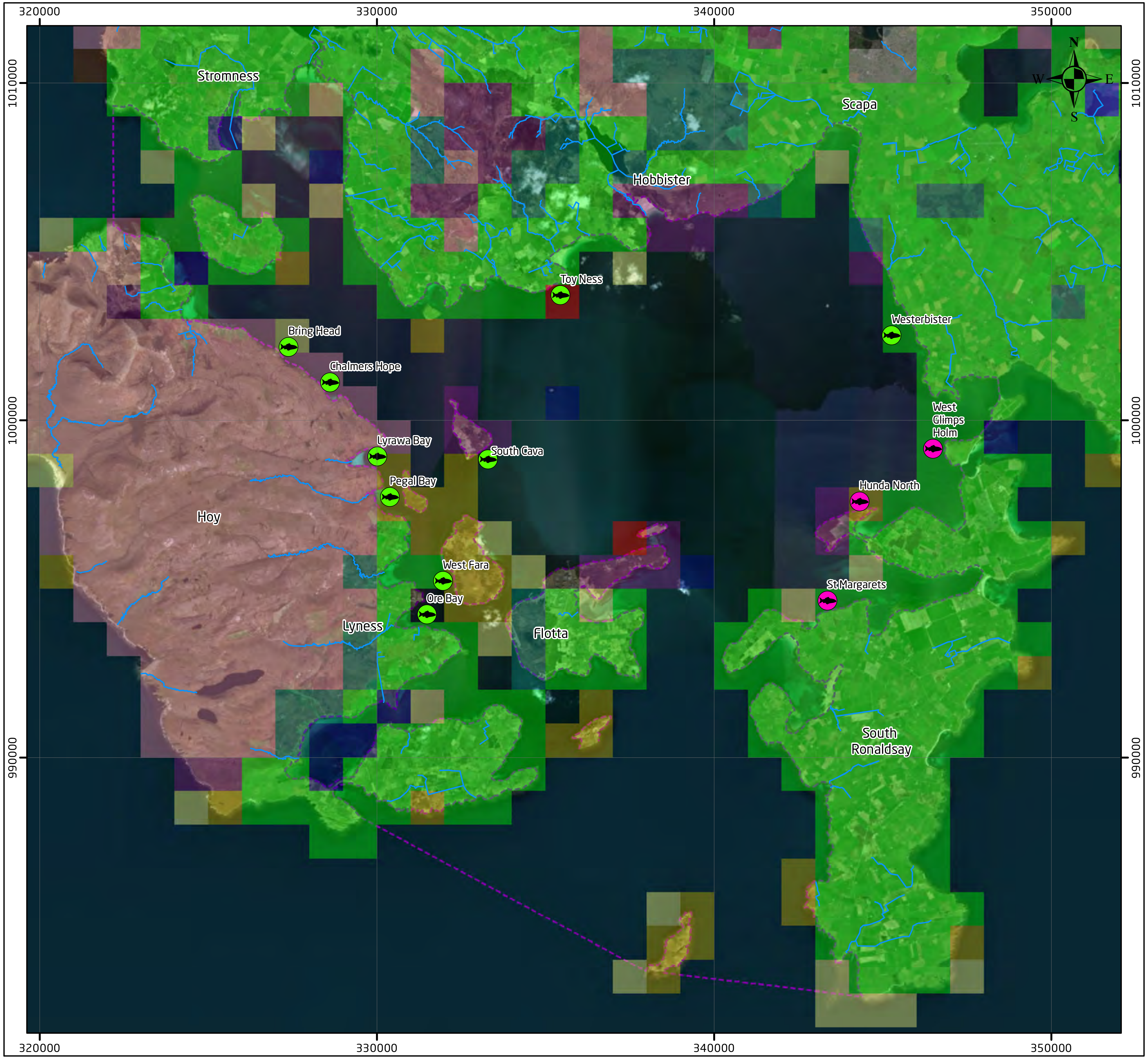
AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-2: Dominant Land Cover Surrounding Scapa Flow



Legend

- Orkney Harbour Limit
- River

Fish Farms

- Existing
- Proposed

Dominant Land Cover Classes

- Broadleaved Woodland
- Arable and Horticulture
- Improved Grassland
- Heather
- Heather Grassland
- Bog
- Saltwater
- Freshwater
- Supralittoral Rock/Sediment
- Littoral Rock/Sediment

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Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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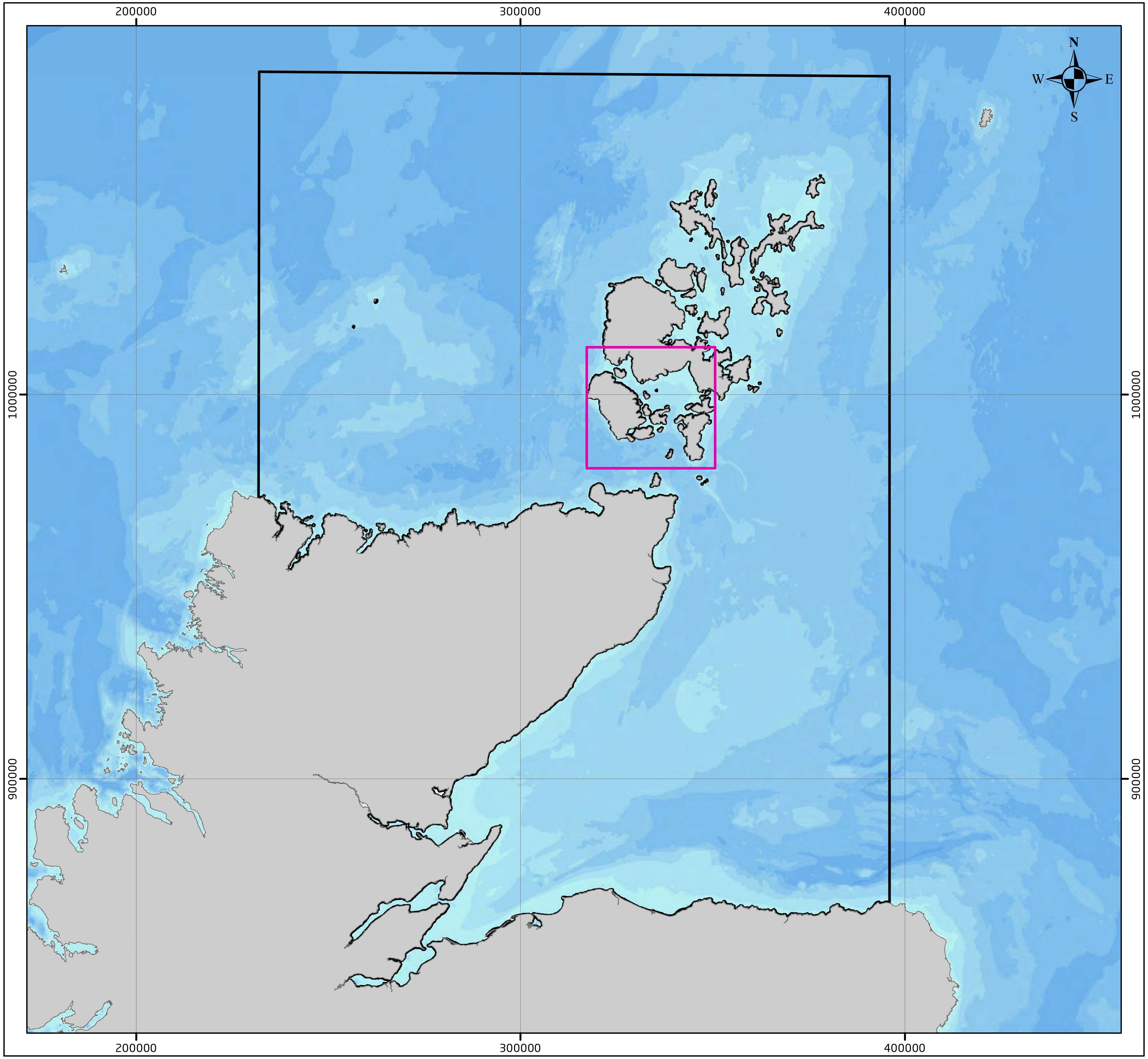

AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-3: Model Grid and Output Domain

Legend

Model Output Domain

Model Grid Extent

Bathymetry

Depth (m)

-500 - -250
-250 - -200
-200 - -100
-100 - -80
-80 - -60
-60 - -40
-40 - -20
-20 - 0

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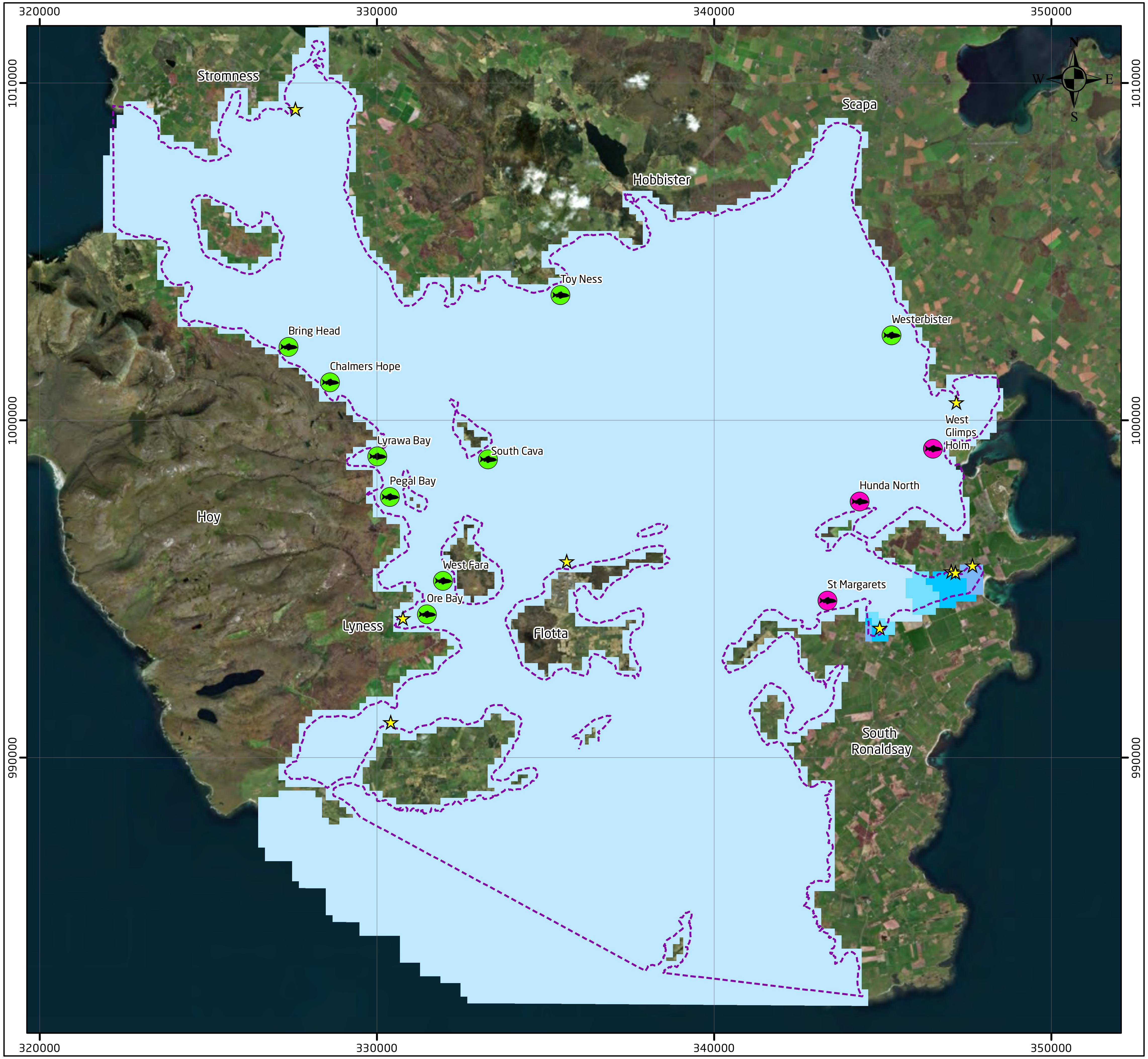

AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-4: Mean Winter DIN WFD Compliance - Combined Contribution from All Modelled Discharges

Legend

- STW
- Orkney Harbour Limit

Fish Farms

- Existing
- Proposed

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 168 (High)
- 168 - 252 (Good)
- 252 - 378 (Moderate)
- > 378 (Poor)

Note: Mean Winter DIN is calculated for the months November through to December.

NOTE: Not to be used for Navigation

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Created By	Jennifer Arthur
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Approved By	Richard Dannatt

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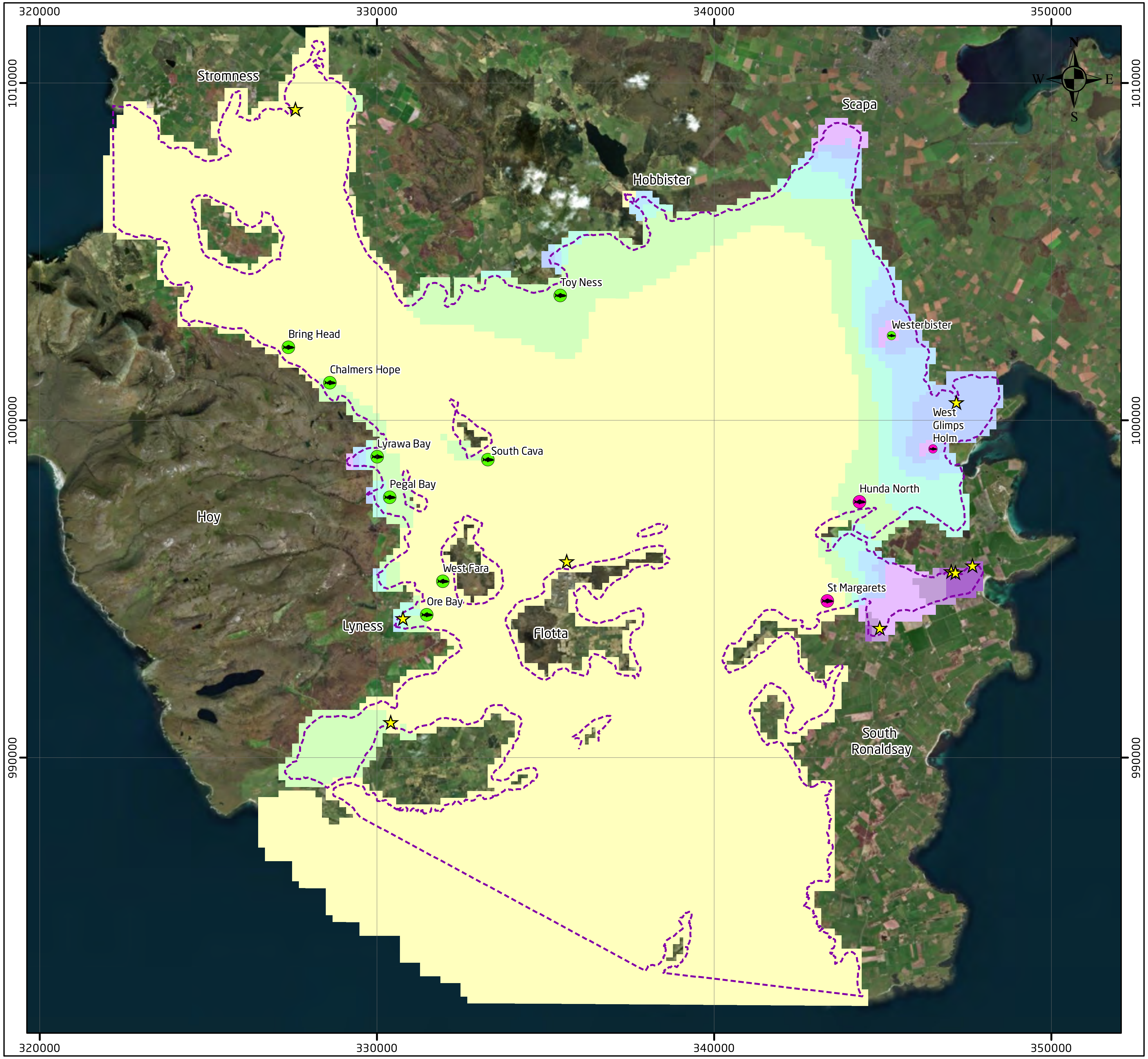
AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-5: Mean Winter DIN - Combined Contribution from All Modelled Discharges



Legend

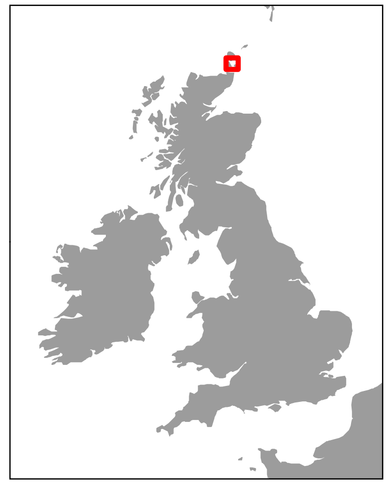
Fish Farms

- Existing
- Proposed
- STW
- Orkney Harbour Limit

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 20
- 20 - 40
- 40 - 60
- 60 - 80
- 80 - 100
- 100 - 200
- 200 - 300
- 300 - 500

Note: Mean Winter DIN is calculated for the months November through to December.



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Approved By	Richard Dannatt

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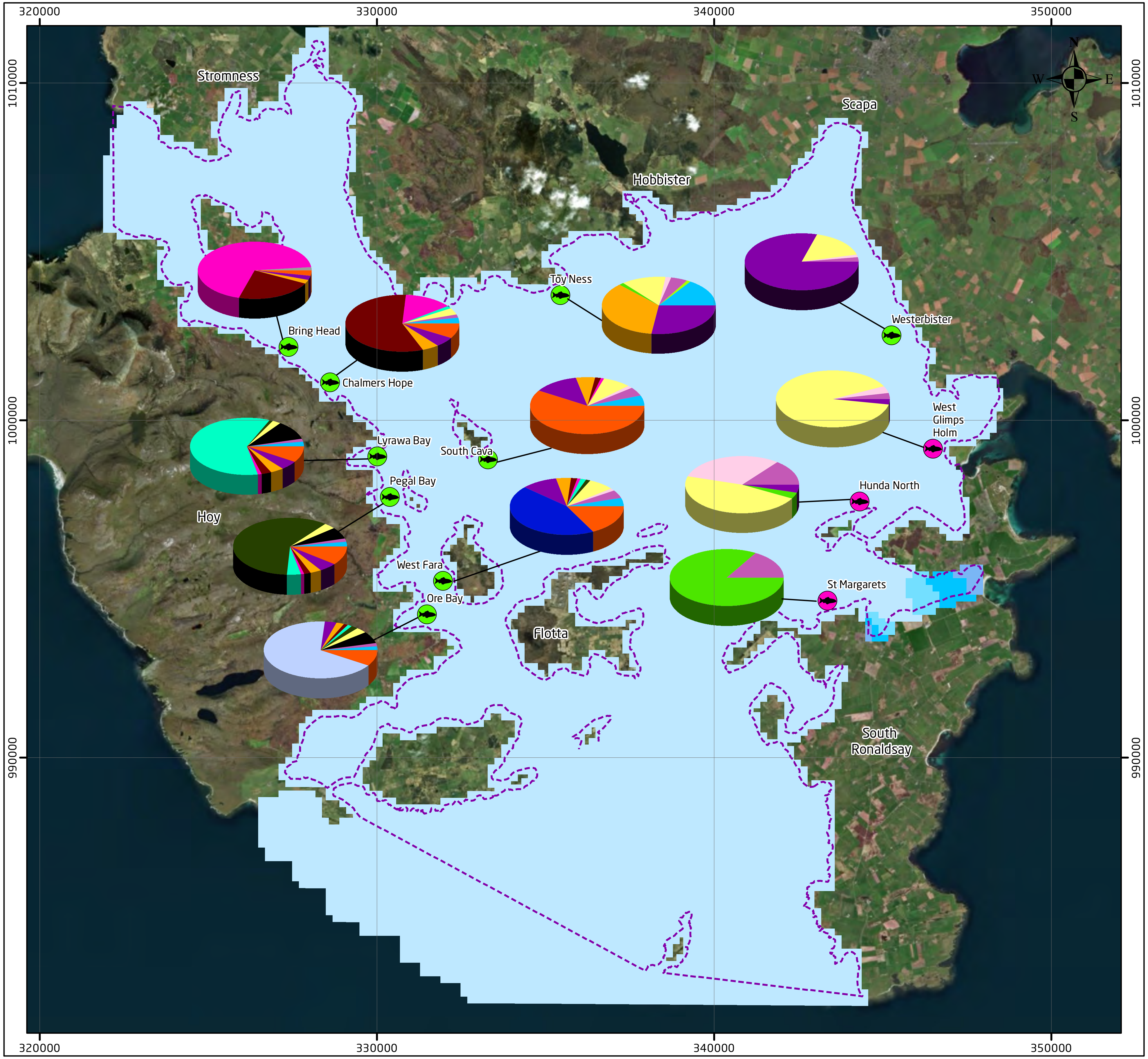

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AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-6: Modelled Fish Farm Contributions to Mean Winter DIN WFD Compliance

Legend

Orkney Harbour Limit

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 168 (High)
- 168 - 252 (Good)
- 252 - 378 (Moderate)
- > 378 (Poor)

Mean Fish Farm Contribution (%)

- Hunda North
- West Glimps Holm
- St Margaret's
- Pegal Bay
- Lyrawa Bay
- Bring Head
- Chalmers Hope
- Toyness
- Westerbister
- West Fara
- Ore Bay
- South Cava
- Stream Group 1
- Stream Group 2
- Stream Group 7
- Stream Group 5
- Stream Group 4

Note: Mean Winter DIN is calculated for the months November through to December.

NOTE: Not to be used for Navigation

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Created By	Jennifer Arthur
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Approved By	Richard Dannatt

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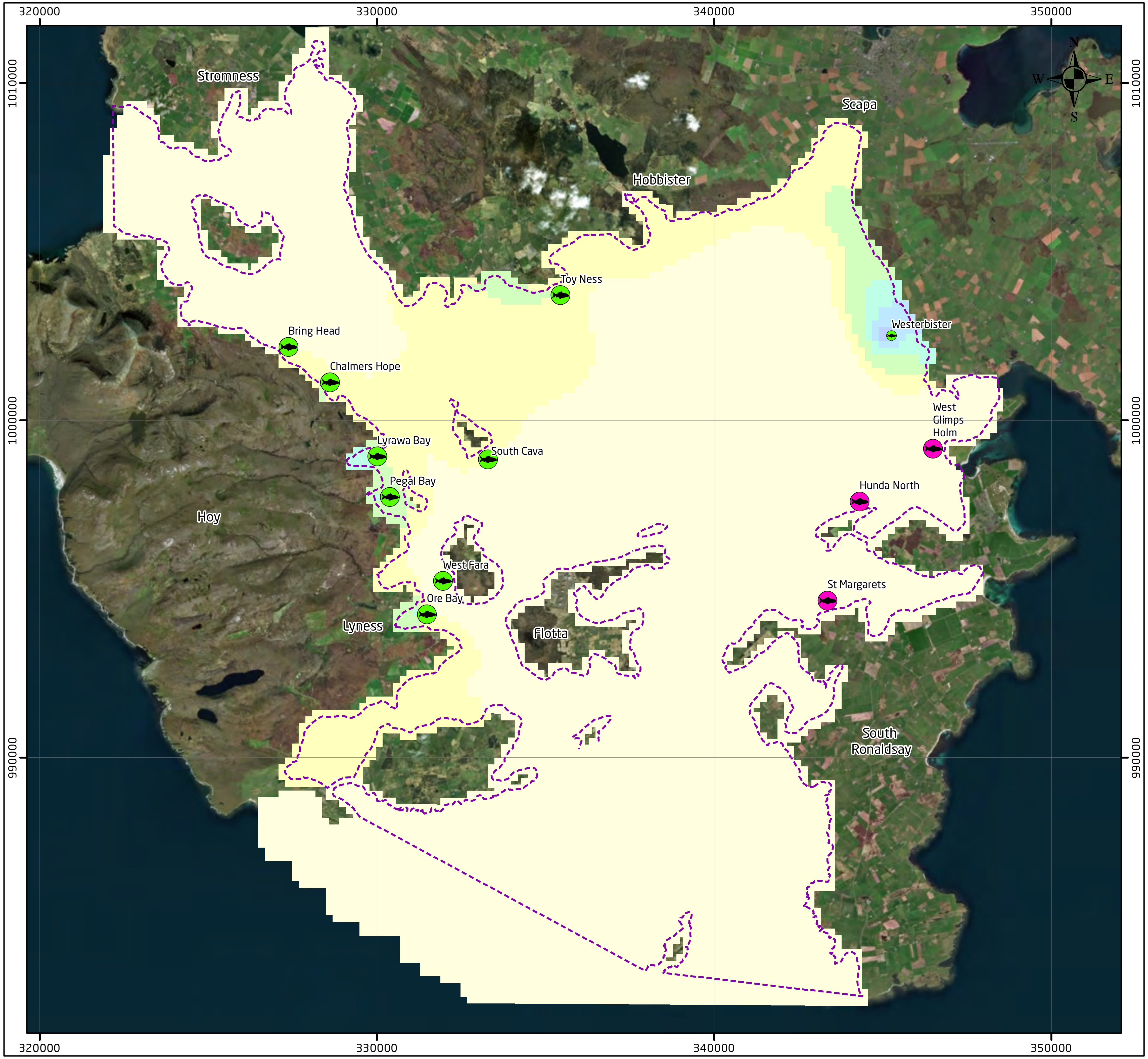
0 1 2 3 4 km



AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-7: Mean Winter DIN - Combined Contribution from Existing Fishfarms

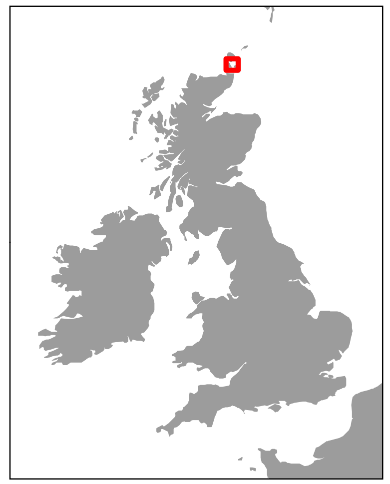
Legend

Fish Farms

- Existing
- Proposed
- Orkney Harbour Limit

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- 50 - 60
- 60 - 70
- 70 - 80
- 80 - 90
- 90 - 100
- 100 - 108



Note: Mean Winter DIN is calculated for the months November through to December.

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Created By	Jennifer Arthur
Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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0 1 2 3 4 km

AQUACULTURE WATER QUALITY IMPACT MODELLING

FIgure A-8: Mean Winter DIN WFD Compliance - Combined Contribution from Existing Fishfarms

Legend

Orkney Harbour Limit

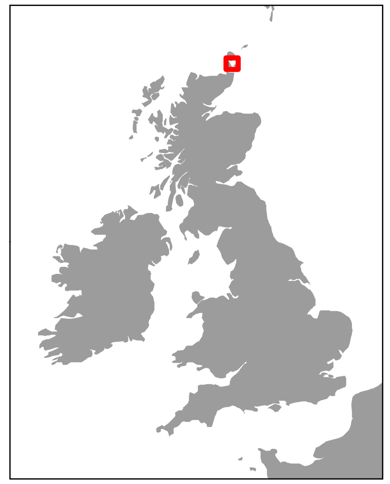
Fish Farms

- Existing
- Proposed

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 168 (High)
- 168 - 252 (Good)
- 252 - 378 (Moderate)
- > 378 (Poor)

Note: Mean Winter DIN is calculated for the months November through to December.



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Created By	Jennifer Arthur
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Approved By	Richard Dannatt

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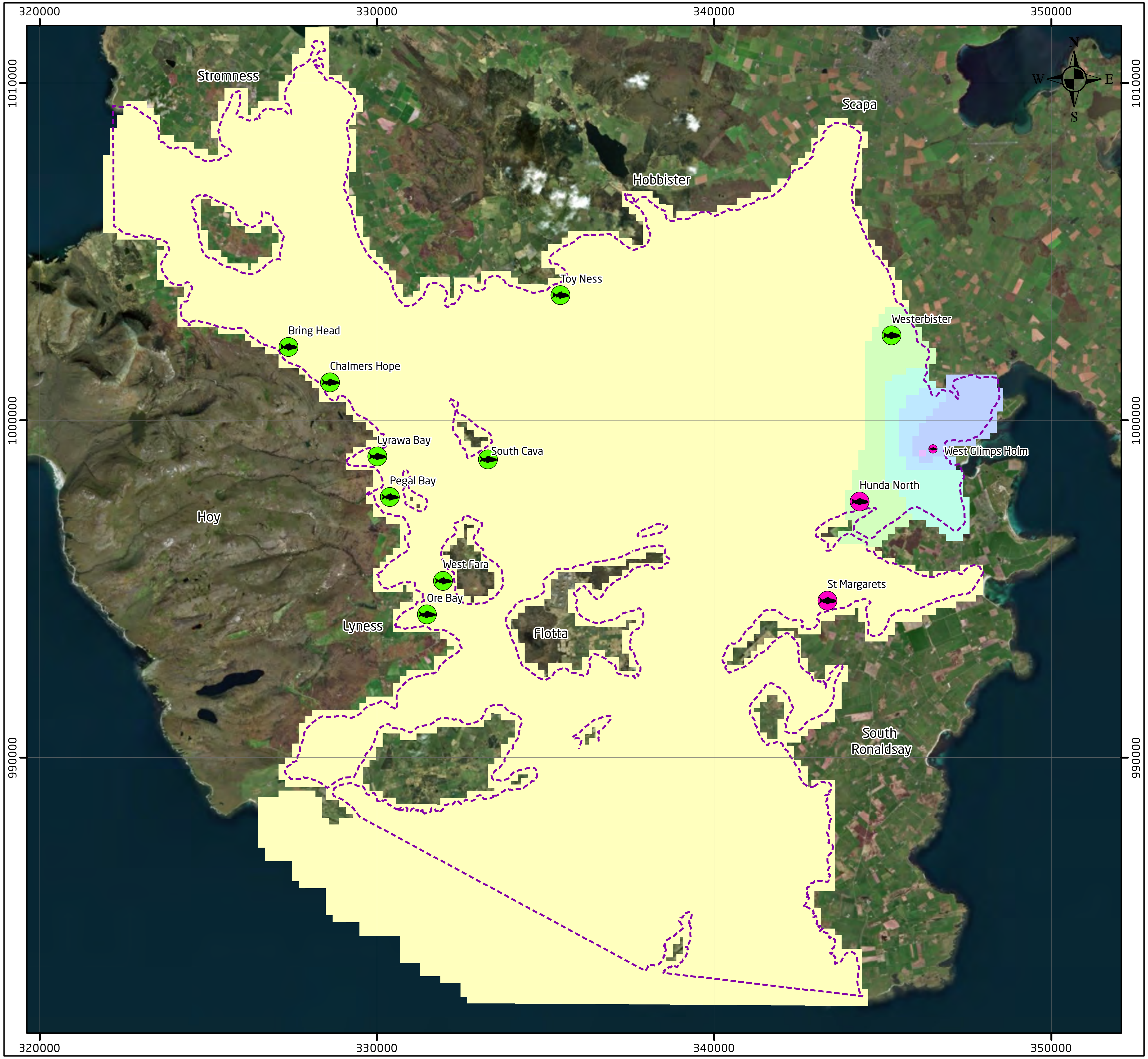

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AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-10: Mean Winter DIN - Combined Contribution from Proposed Fishfarms

Legend

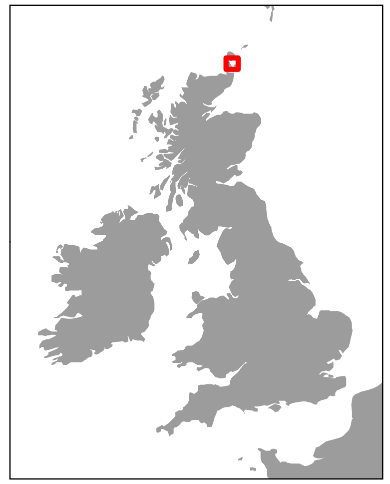
Fish Farms

- Existing
- Proposed
- Orkney Harbour Limit

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 20
- 20 - 40
- 40 - 60
- 60 - 80
- 80 - 100
- 100 - 200

Note: Mean Winter DIN is calculated for the months November through to December.



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Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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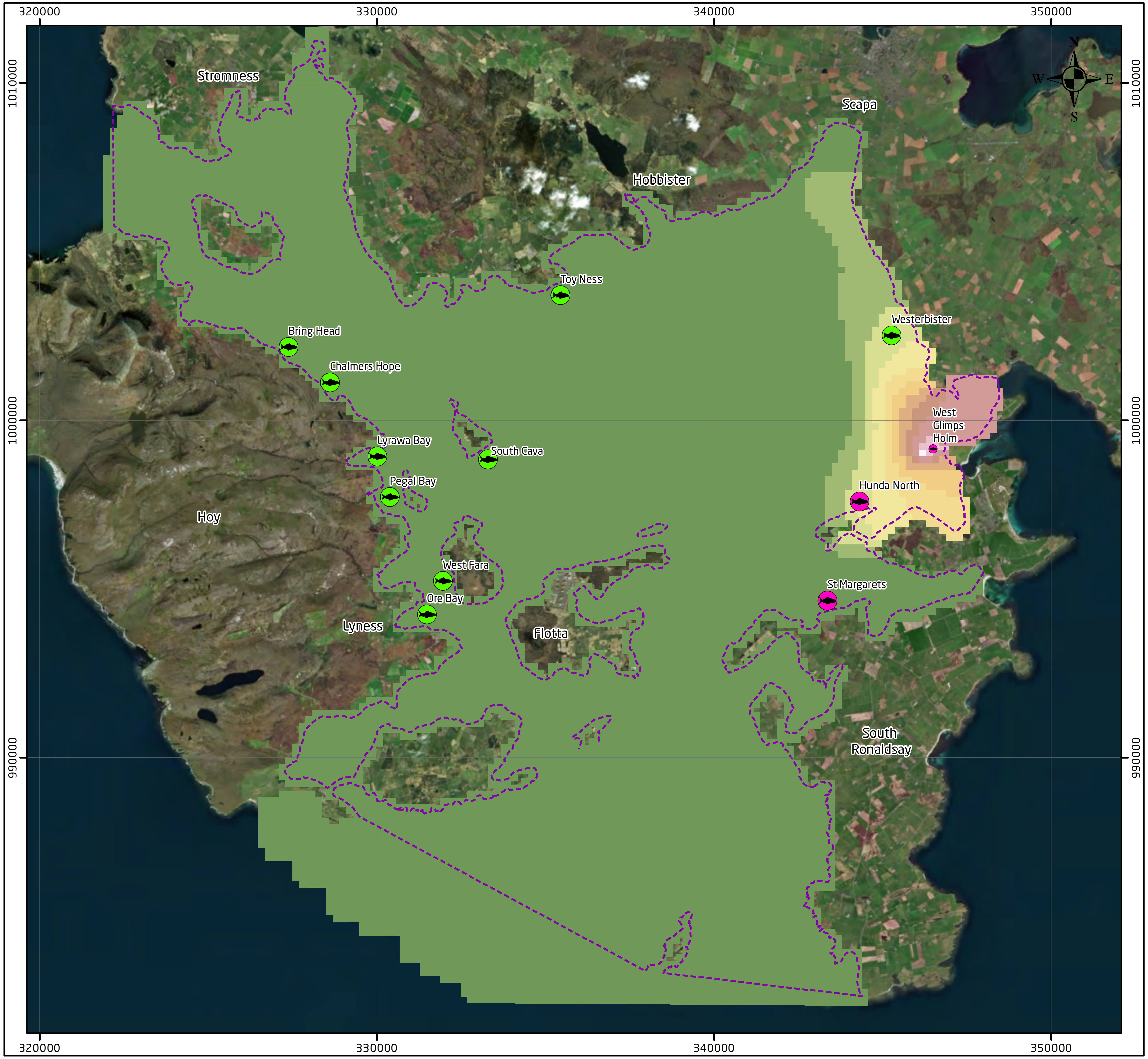
0 1 2 3 4 km



AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-10: Mean Winter DIN - Combined Contribution from Proposed Fishfarms

Legend

Orkney Harbour Limit

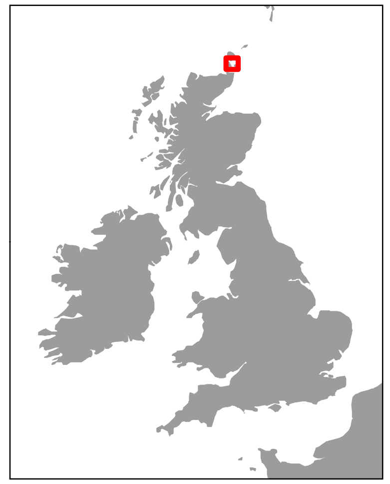
Fish Farms

- Existing
- Proposed

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 10
- 10 - 20
- 20 - 30
- 30 - 40
- 40 - 50
- 50 - 60
- 60 - 70
- 70 - 80
- 80 - 90
- 90 - 100
- 100 - 114

Note: Mean Winter DIN is calculated for the months November through to December.



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Created By	Jennifer Arthur
Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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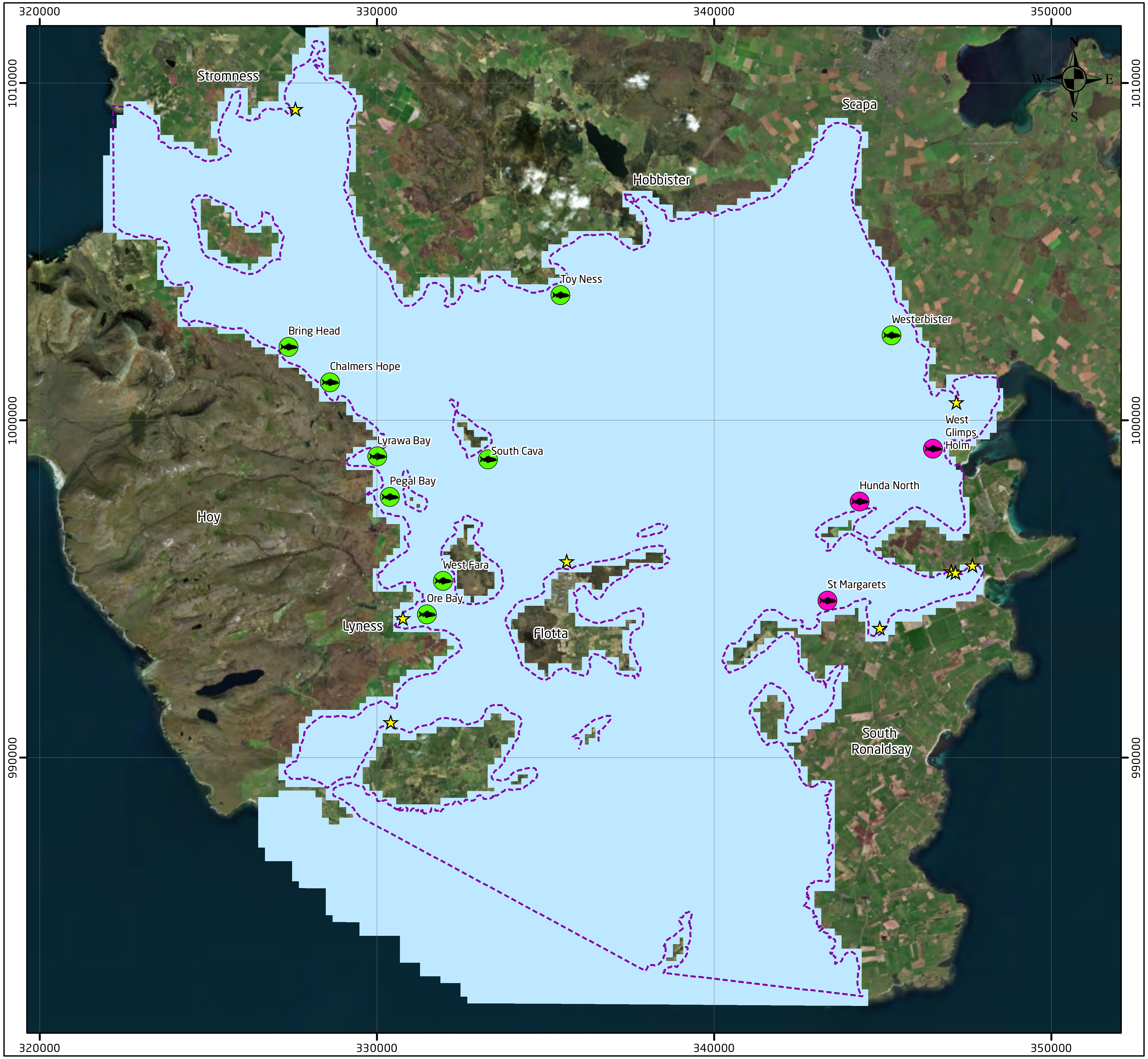
0 1 2 3 4 km



AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-11: Mean Winter DIN WFD Compliance - Combined Contribution from Treatment Works

Legend

- STW
- Orkney Harbour Limit

Fish Farms

- Existing
- Proposed

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 168 (High)
- 168 - 252 (Good)
- 252 - 378 (Moderate)
- > 378 (Poor)

Note: Mean Winter DIN is calculated for the months November through to December.

NOTE: Not to be used for Navigation

Date	Thursday, April 26, 2018 16:16:18
Projection	British_National_Grid
Spheroid	Airy_1830
Datum	D_OSGB_1936
Data Source	OSOD, ESRI, MS
File Reference	J:\P2218\Mxd\Modelling_Report\ Mean_Winter_DIN_STW.mxd
Created By	Jennifer Arthur
Reviewed By	Richard Marlow
Approved By	Richard Dannatt

Orkney Islands Council

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0 1 2 3 4 km

AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-12: Mean Winter DIN WFD Compliance - Combined Contribution from Watercourses

Legend

Orkney Harbour Limit

Fish Farms

- Existing
- Proposed

Modelled Watercourse Discharges

- Group 1
- Group 2
- Group 3
- Group 4
- Group 5
- Group 6
- Group 7

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 168 (High)
- 168 - 252 (Good)
- 252 - 378 (Moderate)
- > 378 (Poor)

Note: Mean Winter DIN is calculated for the months November through to December.

Date	Thursday, April 26, 2018 16:18:11
Projection	British_National_Grid
Spheroid	Airy_1830
Datum	D_OSGB_1936
Data Source	OSOD, ESRI, MS
File Reference	J:\P2218\Mxd\Modelling_Report\ Mean_Winter_DIN_Watercourses.mxd
Created By	Jennifer Arthur
Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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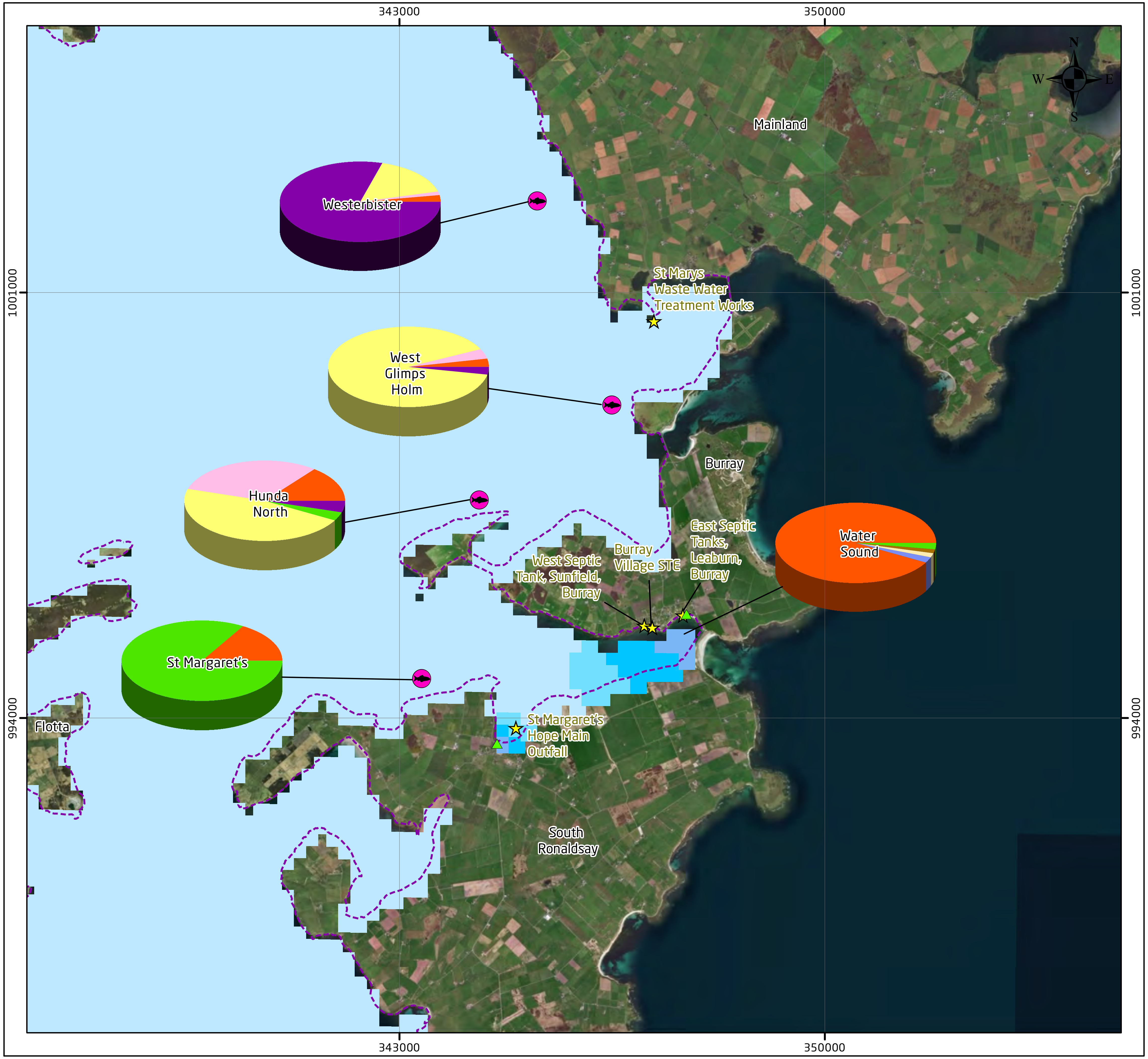
0 1 2 3 4 km



AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-13: Modelled Contributions to Mean Winter DIN WFD Compliance Around the Area of Highest Predicted Dissolved Inorganic Nitrogen

Legend

- Modelled Watercourse Discharge
- Orkney Harbour Limit

Mean Winter Dissolved Inorganic Nitrogen Concentration (µg/l)

- 0 - 168 (High)
- 168 - 252 (Good)
- 252 - 378 (Moderate)
- > 378 (Poor)

Mean Contribution to Dissolved Inorganic Nitrogen (%)

Fish Farms

- Hunda North
- West Glimps Holm
- St Margaret's
- Pegal Bay
- Bring Head
- Westerbister

Modelled Watercourse Discharges

- Group 7

Sewage Treatment Works

- St Margaret's Hope Main Outfall STW
- East Septic Tanks, Leaburn, Burray
- Burray Village STW

Note: Mean Winter DIN is calculated for the months November through to December.

NOTE: Not to be used for Navigation

Date	Tuesday, May 15, 2018 10:17:08
Projection	British_National_Grid
Spheroid	Airy_1830
Datum	D_OSGB_1936
Data Source	OSOD, ESRI, MS
File Reference	J:\P2218\Mxd\Modelling_Report_Rev1\Mean_Winter_DIN_Contributions_Water_Sound.mxd
Created By	Jennifer Arthur
Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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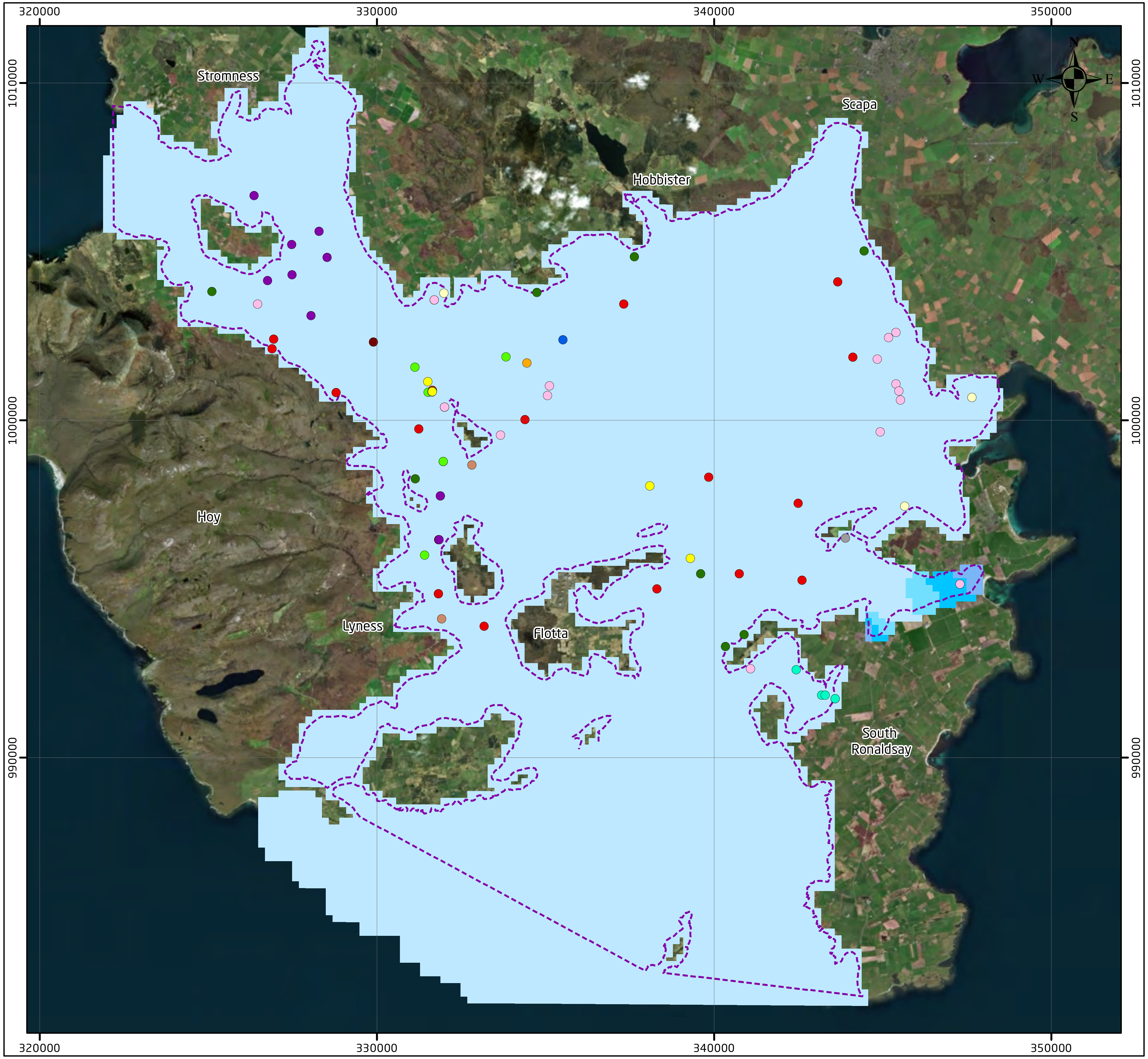
0 1 2 3 4 km



AQUACULTURE WATER QUALITY IMPACT MODELLING

Figure A-14: Locations of Priority Marine Features in Scapa Flow

Legend

- - - Orkney Harbour

Priority Marine Features

- Burrowed Mud
- Fan Mussel
- Flame Shell Bed
- Horse Mussel Bed
- Kelp and Seaweed on Sublittoral Sediment
- Kelp Bed
- Low or Variable Salinity Habitat
- Maerl Bed
- Maerl or Coarse Shell Gravel with Burrowing Sea Cucumbers
- Northern Feather Star
- Ocean Quahog
- Seagrass Bed
- Tidal-swept Algal Community

Mean Winter Dissolved Inorganic Nitrogen Concentration (μg/l)

- 0 - 168 (High)
- 168 - 252 (Good)
- 252 - 378 (Moderate)
- > 378 (Poor)

Note: Mean Winter DIN is calculated for the months November through to December.

Date	Thursday, April 26, 2018 16:13:33
Projection	British_National_Grid
Spheroid	Airy_1830
Datum	D_OSGB_1936
Data Source	OSOD, ESRI, MS
File Reference	J:\P2218\Mxd\Modelling_Report\Mean_Winter_DIN_PMF.mxd
Created By	Jennifer Arthur
Reviewed By	Richard Marlow
Approved By	Richard Dannatt

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0 1 2 3 4 km