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Scallop larval dispersal, Northern Ireland

Contents

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Executive Summary

With scallop stocks declining around the Northern Irish coast, the Northern Ireland Scallop Fisherman's Association (NISFA) have become proactive in working with Seafish, the Department of Agriculture, Environment and Rural Affairs (DAERA) and the Agri-Food and Biosciences Institute (AFBI) to improve the long-term sustainability of stocks.

In 2017, four sites were highlighted as having potential for any future scallop enhancement. In 2020, a desktop study was prepared by AFBI to assess the options available for scallop enhancement. In 2022, legislation was introduced which prohibits the use of mobile gear and the taking of any scallops, from these sites. At the time of site selection there was no model available to determine the potential location of settlement of the larvae produced from the scallops within the enhancement sites. With scallop larvae drifting in the water column for 3-4 weeks before becoming actively able to swim, larvae can potentially move great distances from the location where they were spawned. The aim of this current project was to develop a larval dispersal model for scallops which could be used to determine potential larval dispersal routes from the four enhancement sites.

MerMADE is a coupled biophysical, eco-evolutionary modelling software for predicting population dynamics, movement, and dispersal evolution in aquatic environments. Following developments to the model functionality to account for the life history of scallops, the model was initially run for the entire species distribution to get a visual representation of general movement patterns in the study area.

Following this proof-of-concept run, the model was applied to the four scallop enhancement sites using dates chosen to cover both the spring and autumn spawning periods. Of the four enhancement sites, larvae spawned from Whitehead had the highest incidence of settlement within Northern Ireland waters. Larvae from the other three enhancement sites was shown to have lesser or no settlement within Northern Ireland waters.

Based on these model outputs, the NISFA requested other sites be examined as potential enhancement sites that would show settlement within NI waters. It was decided that current Marine Protected Areas (MPA's), which are already closed to scallop fishing, be examined. The suggested sites were:

1. Skerries and Causeway MPA
2. Rathlin Island MPA
3. The Maidens MPA
4. Outer Belfast Lough MPA

The additional sites, which were modelled only for the spring dispersal, showed a higher success in terms of scallop larval settlement within NI waters. The Maidens showed settlement aggregations throughout NI waters on each of the dates modelled. The area of Muck Island/Moyle Interconnector, close to the Maidens MPA, was investigated during the 2017 site selection scoping exercise. This area was shown to be suitable for scallop settlement and survival scoring

favourably across all site characteristics. However, discussions with the industry led to the current four sites being selected above this area at that time. Based on these model outputs, it is recommended that the Maidens MPA is the most suitable site, of those investigated during this study, for survival of scallops (juvenile and adult) and with dispersal of the scallop larvae from this site showing successful settlement within NI waters.

While the other three additional sites showed success in terms of larvae from these areas settling in NI waters, the characteristics of these sites was not analysed in the 2017 site selection report and therefore the suitability is unknown. However, since adult scallops are found in each of these areas, this would indicate that they are suitable sites for juvenile and adult scallop survival.

1.0 Project Background

Fishing for the king scallop, *Pecten maximus*, has been established in Northern Ireland since 1935 (Briggs, 1992). Scallop landings from Northern Ireland waters (considered as ICES rectangles 37E3, 37E4, 38E4, 39E3, 39E4) were relatively steady from 2000 to 2011. In 2012 they saw an increase, going from an average of 357 tonnes, to a peak of 1,634 tonnes in 2014. Since 2014, annual scallop landings have steadily declined and in 2022, 393 tonnes of scallops were landed by vessels fishing within NI waters (Figure 1). Whilst the effort of the fishery, provided as the vessel power (in kilowatts) by the number of days active per trip, has decreased since 2015, the Landings Per Unit Effort (LPUE) indicates that the stock is still in a poor condition.

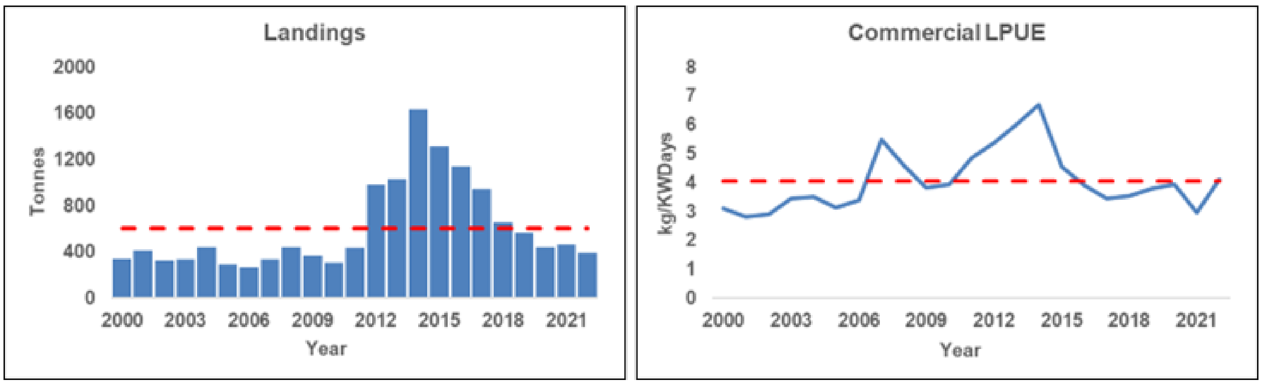

Figure 1: King scallops in ICES rectangles 37E3, 37E4, 38E4, 39E3 and 39E4 (excluding Clyde fishery). Landings and LPUE. Red dashed line indicates time series average.

With scallop stocks declining around the Northern Irish coast, the Northern Ireland Scallop Fisherman's Association (NISFA) have become proactive in working with Seafish, the Department of Agriculture, Environment and Rural Affairs (DAERA) and the Agri-Food and Biosciences Institute (AFBI) to improve the long-term sustainability of stocks. AFBI, with support from Seafish, have carried out desktop studies for the NISFA, to identify potential sites for scallop stock enhancement around the Northern Ireland Coast (AFBI, 2017), as well as examining the best ways to use these sites for scallop enhancement (McMinn, 2020).

The aim of this current project was to develop a larval dispersal model which can then be applied to the designated scallop enhancement sites. This model will then be available to address the question of where scallops spawned from the enhancement sites are most likely to settle. This is an important question for both the scallop industry who have driven this work, as well as for Government and science, to monitor the success of the enhancement sites.

2.0 Selection of sites, 2017

In 1999 the NISFA carried out a reseeding project with the Centre for Marine Resources and Mariculture (C-Mar) (Centre for Marine Resource and Mariculture, 2000). Whilst the outcome of the reseeding was highly variable between sites, the reseeding was regarded as having partial success in some of the areas in terms of survival of re-laid scallops. For example, in Strangford Lough reseeded scallops had a high survival rate but with below average growth.

Issues identified for further work during the initial project were; the survival of scallop seed during transport to the reseeding site, lack of predator control, continued fishing of the reseeded sites and lack of suitable post reseeding monitoring. Furthermore, it was observed that a significant proportion of the scallop seed which was re-laid onto the reseeding sites could not be detected. This was thought to be due to seed being washed away by strong currents in the area.

With this C-Mar study in mind, the NISFA asked AFBI to investigate the suitability of sites for a potential new scallop reseeding scheme. Twelve sites were selected by the Scallop Association and one site selected by DAERA (Figure 2) for investigation.

Suitable habitat for scallops in NI waters was identified using scallop catch information taken from the annual AFBI scallop survey. The habitat type where scallops are found was then highlighted on combined seabed habitat maps to create a map which showed the suitable habitat for adult scallops within NI waters. All the proposed reseeding sites fell within areas of suitable habitat.

To examine further characteristics of the proposed sites, a combination of measured and modelled data was used. Much of the measured data used was collected as part of the 2016 winter and summer Water Framework Directive sampling schedule, either using set stations where profiles are recorded, or via the flow-through system onboard the RV *Corystes* which collects continuous georeferenced data. A summary of findings is provided in Table 1. Details behind this summary can be found in AFBI (2017).

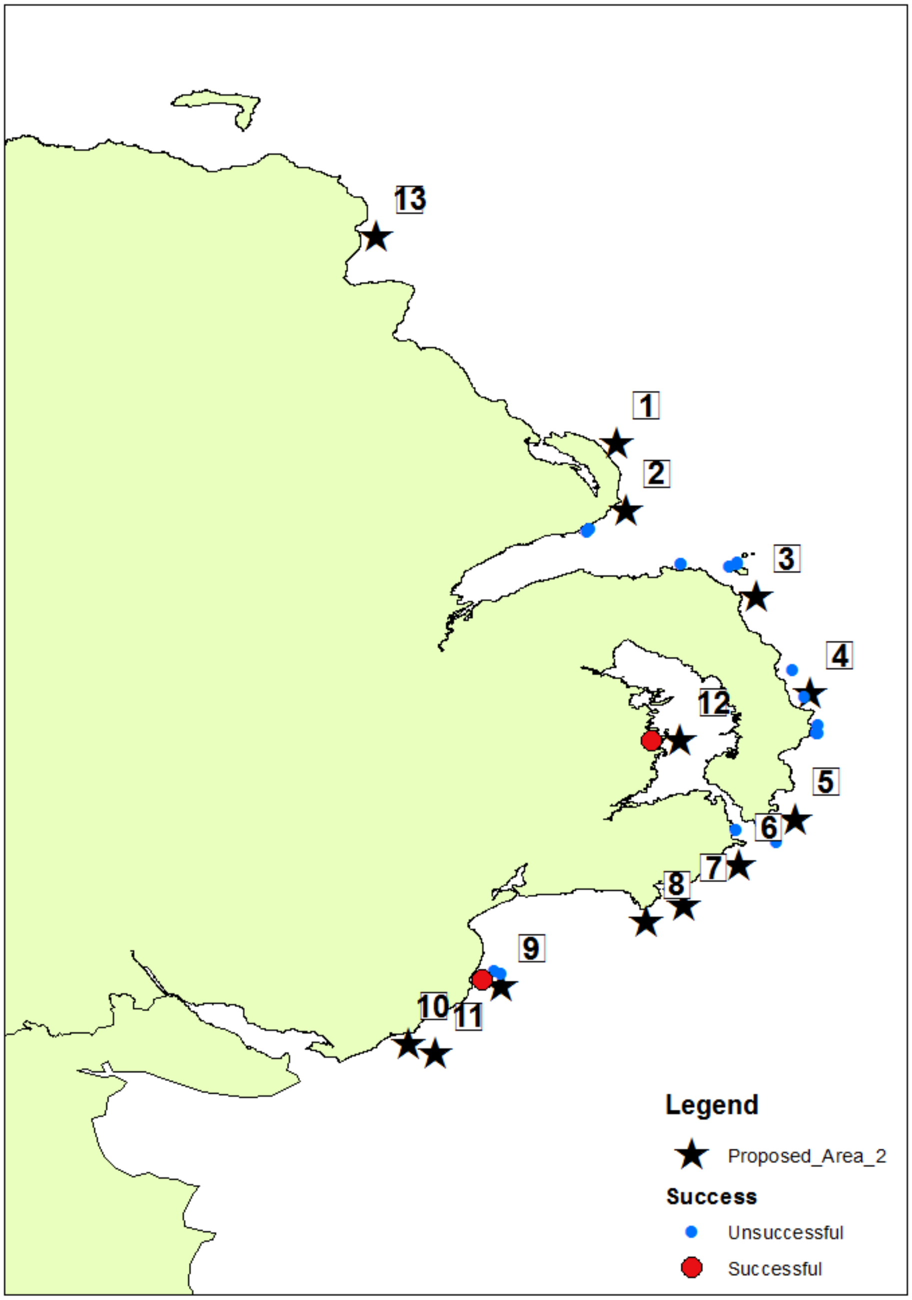

Figure 2: Location of potential sites for reseeding (black stars). The coloured circles represent sites which were surveyed during the 1999 C-Mar trial (blue areas which were surveyed but not reseeded due to unsuitability or reseeding was unsuccessful; red areas were deemed as having been reseeded successfully).

Table 1: Summary of the 13 proposed reseeding sites, providing scores for each of the site characteristics that were examined. Green means the site scored favourably (score 1); amber, no data available; red, site was least favourable (score 0); grey means that the larvae would potentially leave NI waters (sites 10 and 11) or be caught in Strangford Lough (site 12) and therefore could not be fished (score -1).

Site / Characteristic	1: Muck Isl./ Moyle Interconnector	2: Black Head/ Cloghan Point/Whitehead	3: Donaghadee Sound/Drumfad Bay	4: Ballyhalbert Bay	5: Ballyquintin Point	6: Killard Point/ Gun Island	7: St. Johns Point, Ardglass	8: Killough	9: Roaring Rock/ Russell' s Point, Annalong	10: Cranfield Point inshore	11: Cranfield Point offshore	12: Scott' s Hole Strangford Lough	13: Red Bay
Salinity													
Thermal stratification													
Food availability													
Bed stress													
SPIM													
Predation													
Toxic algal blooms													
Dispersal distance													
Dispersal direction	North	North	South	South	South	South	South; may be affected by Irish Sea gyre	South; may be affected by Irish Sea gyre	South	South	South	Within Strangford Lough	North, unless extreme wind forcing drives south
Total score	8	7	6	6	8	6	5	4	5	4	4	4	5

Unfortunately, at the stage of site selection, the project was limited to using resources which were already available. To determine the potential movement of larvae produced by scallops at the proposed reseeding sites, published relevant larval dispersal and hydrodynamic models were used and POLPRED tidal prediction software was accessed to determine tidal currents in the areas of the proposed reseeding sites. These showed a notable split between current directions north of Belfast Lough and that south of the Lough, with a net movement north inshore along the County Antrim coast whilst there is a net movement south along the County Down coast. It was also shown that dispersal distances are affected by the timing of spawning events; where spawning coincides with the establishment of the western Irish Sea gyre and sites are proximal to the gyre, dispersal distances increase.

Based on this study, with input from the NISFA on fishing preferences, it was decided that initially three reseeding sites would be put forward with a fourth, Roaring Rock, having potential for any future reseeding plans. The three selected sites were;

1. Whitehead (3.26km^2)
2. Drumfad Bay (1.46km^2)
3. Ballyquintin Point (3.22km^2)

The sites which were highlighted as the most suited for scallop enhancement are shown in Figure 3. It was recommended that enhancement of these sites would only be successful if they were closed to mobile fishing gear, allowing each site to act as a source of larval production. In 2022, legislation was introduced which prohibits the use of mobile gear and the taking of any scallops, from these sites.

It was also recommended that, if possible, a full larval dispersal model should be produced to determine a more accurate location of settlement of the larvae produced by the reseeded scallops.

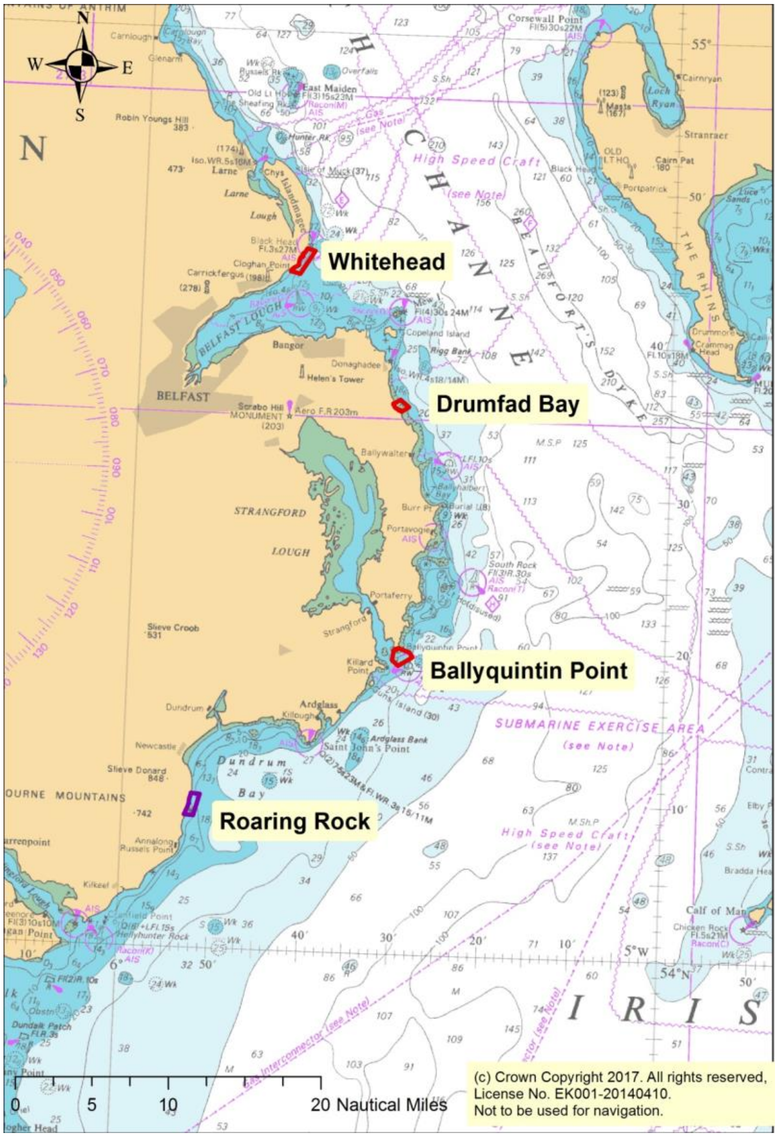

Figure 3: Sites selected for scallop enhancement. Sites in red were identified as most suitable during the reseeding study (AFBI, 2017) and engagement with the NISFA. Roaring rock was added following engagement with NISFA as a site with reseeding potential.

3.0 Scallop life history

The king scallop is a long-lived bivalve that can live twenty years or more. Scallops are hermaphrodite having both male (creamy testis) and female (orange red ovary) structures forming the “roe”. Scallops tend to mature at 2-3 years of age when they reproduce by spawning. Scallops in British waters tend to have two spawning peaks, one in spring and one in autumn (Briggs, 2000).

During spawning, the male gonad tends to release sperm into the water column first, with one emission continuing for about one hour (Pennec et al, 2003). The ovary releases eggs several hours later (Franklin et al 1980), with emission lasting for about 30 minutes (Pennec et al 2003). When one individual spawns, some of the eggs which are released may be filter fed out by its neighbour. The pheromones contained in the eggs then cause the neighbour to release its eggs and so on. Fertilization occurs in the water column when an egg and sperm come into contact. In low density populations it is possible that there is a spawning stock but no reproduction due to a phenomenon known as the Allee effect (i.e. when there are too few individuals around to come in to contact for fertilisation). As they are hermaphrodite, scallops have the potential to self-fertilise. However, if this occurs the progeny may be less viable than if the eggs had been fertilised by a different scallop.

Fertilisation produces veliger larvae (Figure 4). Initially these larvae rise through the water column to the surface where they are carried, with other plankton, by water currents, before undergoing diel vertical migration, moving between 10-150m on day-night cycles. After 3-4 weeks the larvae, now at the pediveliger stage, develop active swimming abilities and move down to the seabed where it will settle onto other sessile organisms such as bryozoans using byssus threads, before developing in to a small, more robust, scallop. After a while the byssus threads break down and the scallop can join the adult population (Briggs, 2000). In colder years, the growth of the larvae is much slower and so they remain in the plankton for longer. The longer the larvae remain in the plankton the further they are carried away from the broodstock and suitable attachment substrates. This may mean that after colder periods recruitment is reduced as the larvae are lost from the system.

The pelagic phase of scallops can range from 18-42 days (Le Pennec *et al*, 2003). With the scallop larvae being passive for the early stages of their pelagic phase, their distribution is driven by abiotic (hydrodynamics, sediment type etc.) and biotic (individual physiology characteristics, ecological interactions) factors (Le Goff et al., 2017). It is estimated that the survival rate of scallops during the larval stage is only 0.1%.

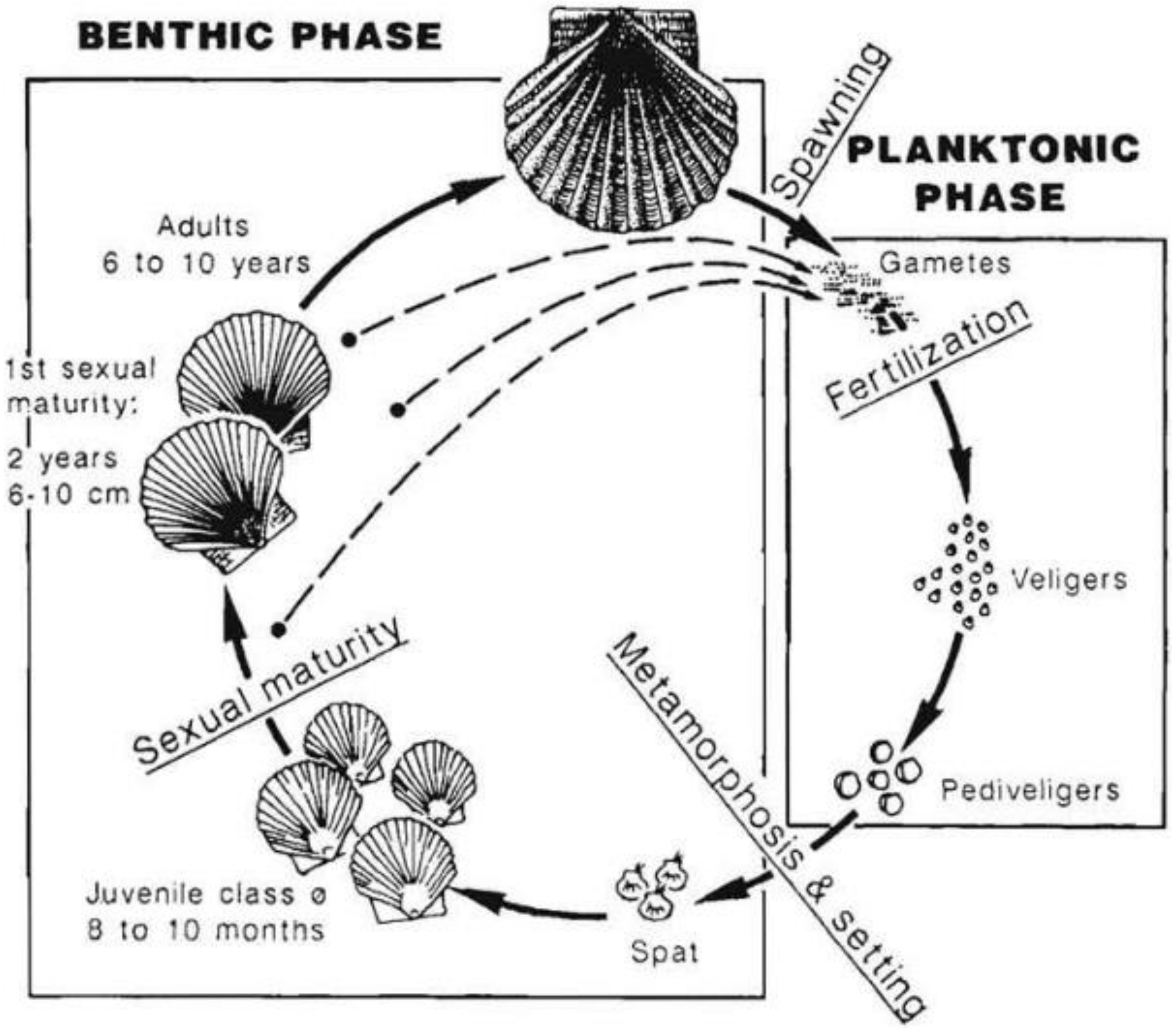

Figure 4: Life cycle of the scallop Pecten maximus (Source: Devauchelle and Mingant, 1991)

4.0 Introduction to the model

MerMADE is a coupled biophysical, eco-evolutionary modelling software for predicting population dynamics, movement, and dispersal evolution in aquatic environments (Allgayer *et al*. 2022). It is spatially explicit, individual based and incorporates external forces like hydrodynamics with biological, physiological processes like growth, development, dispersal (Figure 5). It bookends the pelagic dispersal phase of focal species with population dynamics and evolutionary capabilities over long periods of time. It includes functionality such as implementing patch-extinction scenarios, harvest pressure and habitat fragmentation (Allgayer *et al*. 2023).

MerMADE is well-suited for application to *P. maximus* as it is flexible in its inputs and can accommodate a range of behavioural and life history traits. The complex dispersal strategy (initial passive movement, followed by diel vertical migration and active habitat selection) of *P. maximus* can be considered, as well as the stage-structured nature of the population. Flexibility in initialisation rules allows us to compare the different release sites, as each can be focused on independently.

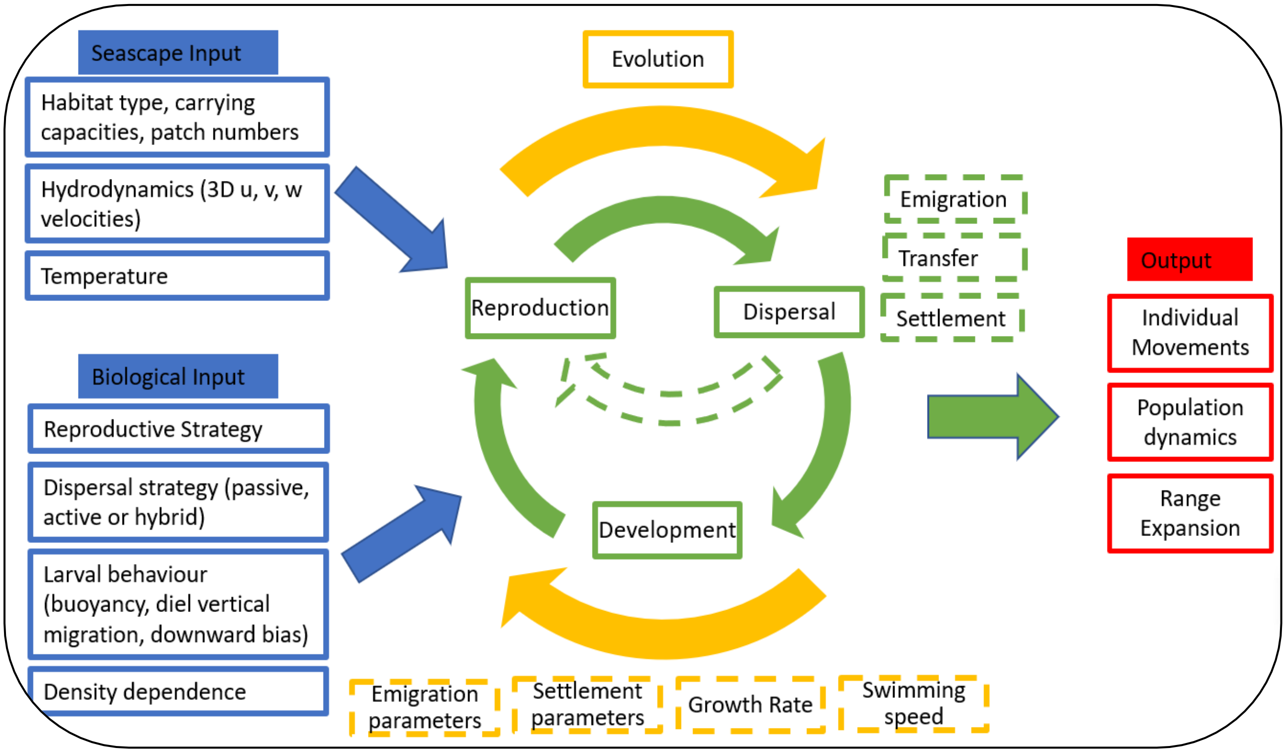

Figure 5: A schematic of the MerMADE model inputs and outputs. (Source: Allgayer et al. 2022).

5.0 Bespoke model development

Initial scoping between AFBI staff and the model developer at Aberdeen indicated that developments in model functionality would be required for the needs of AFBI and industry stakeholders for this project. Specifically, the software model needed to be extended to incorporate functionality to:

a) start model simulations in single or multiple non-random locations (representing specific sites for reseeding).

b) incorporate spatially varying fishing pressure information.

c) account for differences in the suitability of individual cells (i.e. cell-based heterogenous carrying capacity).

In addition to these software changes, it was necessary to collate bespoke input datasets on *P. maximus* biology, habitat suitability and hydrodynamics relevant to the region (described below).

5.1 Parameterisation of the model

Species-specific dispersal and population dynamic parameters for *P. maximus* were collated based on AFBI (2017). This species is a broadcast spawner with a high fecundity rate. On average, <1% of dispersers will survive the dispersal phase (the high volume of dispersers counteracts this significantly high mortality rate). Successful dispersers become immature adults but do not become sexually mature and breed until they are 3 years of age. Once settled, annual survival is quite high (0.7 for immature adults and 0.9 for mature adults).

Table 2: Population 'Leslie matrix' for *P. maximus* showing survival rates, transition rates and fecundities used in the model. Top row shows the number of larval offspring produced at each of the three stages. The lower two rows, show the probability of an individual staying in the same stage or transitioning to another stage in a given year.

	Larvae	Settled immature	Settled mature
Larvae	0	0	15,000
Settled Immature	*1	0.14	0
Settled mature	0	0.56	0.9

*Larval mortality during dispersal, is computed separately in the MerMADE model, and not included in the transition value shown here.

5.2 Habitat suitability and species distribution

Habitat suitability was based on the presence of suitable bathymetry (depths between 10-150m) and seabed habitat type for settlement. Seabed habitat types were based on EUNIS category 3 definitions, and included sand, coarse sediment, sublittoral sands and muddy sands, mixed sediment areas and a small amount of rock habitats (cobbles or small bedrock outcrops interspersed/adjacent to sediment substrata) shallower regions (see AFBI, 2017, for details). The 2D habitat map created by AFBI (2017), was converted to the 3D model formats required by MerMADE using R 4.0.3. Specifically, this habitat map was converted into a set of 17 raster suitability maps each representing a depth range of 10m within the water column (e.g. 0-10m, 10-20m, 20-30m etc.). Each cell was assigned a value of 0 = open water, 1 = suitable habitat or 2 = unsuitable, cell size was 500m. Depths were based on EMODnet bathymetry DTM tiles downloaded 08/09/2023 from: EMODnet Map Viewer (europa.eu).

Species distribution rasters representing the known distribution of scallops in Northern Irish waters were developed based on a combination of landings data, VMS, and AFBI survey data.

VMS data from 2018-2021 were filtered based on vessel speeds to identify fishing locations, and these fishing locations were then matched to landings data based on times, dates, and vessel identity, to identify likely commercial catch locations of scallops within the study area in the recent time period. To these data, locations with observed scallop catches from the AFBI scallop survey (2018-2022) were added. The data was then converted to 0's and 1's representing the absence or presence of scallop catches within a 500m area. Processing of confidential VMS and landings data was conducted within AFBI, under a Data Sharing Agreement with the data owner (DAERA). All potentially confidential information (e.g. relating to individual vessels and landings) was removed prior to transfer of raster maps to the external contractor for model development.

5.3 Hydrodynamics

Simulations were run for the spring as well as autumn spawning dates, by extracting average daily residual hydrodynamic values from the West Scotland Coastal Ocean Modelling System (WeStComs v.2). Hydrodynamics are represented as 3D vectors: *u* (eastward), *v* (northward), and *w* (upward) velocities. These together give MerMADE enough information to calculate direction and speed of the current in each of the seascape's cells. These data are interpolated onto a structured grid of 500m x 500m cells. The residuals across a 24-hour period were calculated to use the net movement as input, thereby taking tides into account.

6.0 Results

6.1 Phase 1 - Proof of Concept

Initial simulations were conducted using hydrodynamics from 30th April and 30th of September 2020, taken to broadly represent spring and autumn spawning times. Simulations were initialised from the entire species distribution to get a visual representation of general movement patterns in the study area (Figure 6). Though the tracks show circular movement patterns, it does not appear as though many of them lead back to the Northern Ireland waters. Simulations were then run for each of the four release sites individually (Figures 7 and 8).

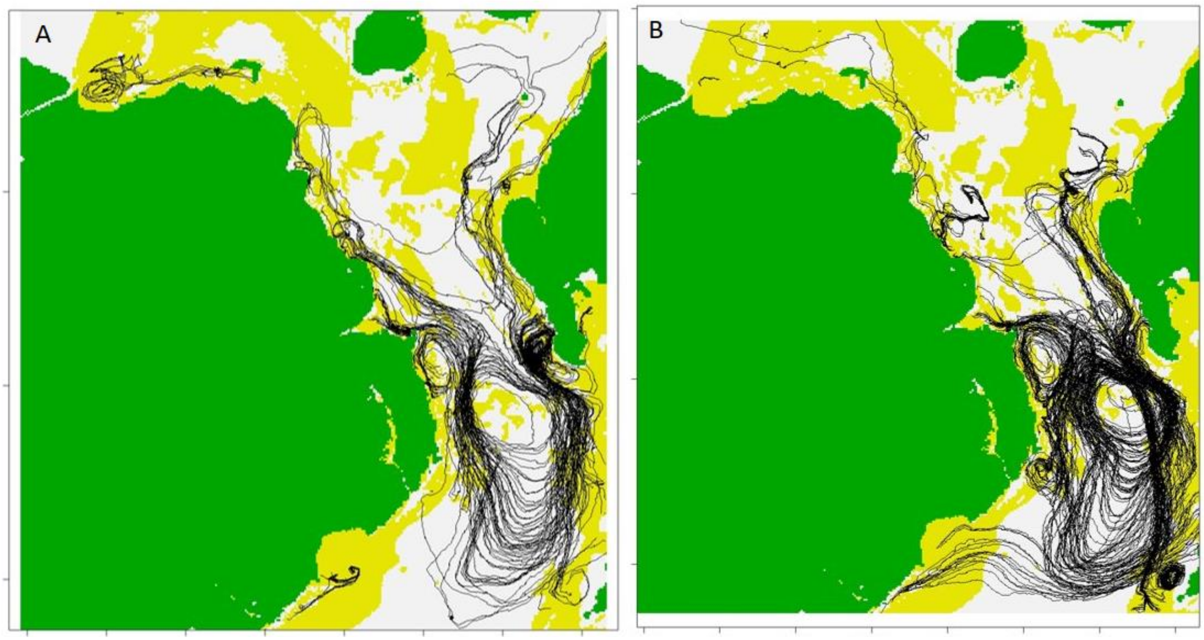

Figure 6: Movement trajectories when dispersers are released from entire species distribution during the spring (A) and autumn (B) spawns.

Whitehead and Drumfad Bay had a circular movement pattern and stayed within the study site but settled on the west coast of Scotland instead of the Northern Irish coast, though in the autumn spawn there were more eddy patterns that may lead to retention in some cases.

Roaring Rock and Ballyquintin had the strongest seasonal differences in movement tracks. From Roaring Rock, individuals were all transported south and out of the study area in April while they were transported east and out of the study area in September. From Ballyquintin, the April dispersers got stuck on the southern edge of the map. We theorised that they hit the gyre present there and were likewise transported east and out of the area in September.

These initial runs were reported to the NISFA for discussion. it was suggested by the scallop fishers that these dates may be slightly unaligned with actual spawning of scallops, with recommendations that the dates used were slightly too early to capture the spring and autumn spawning event.

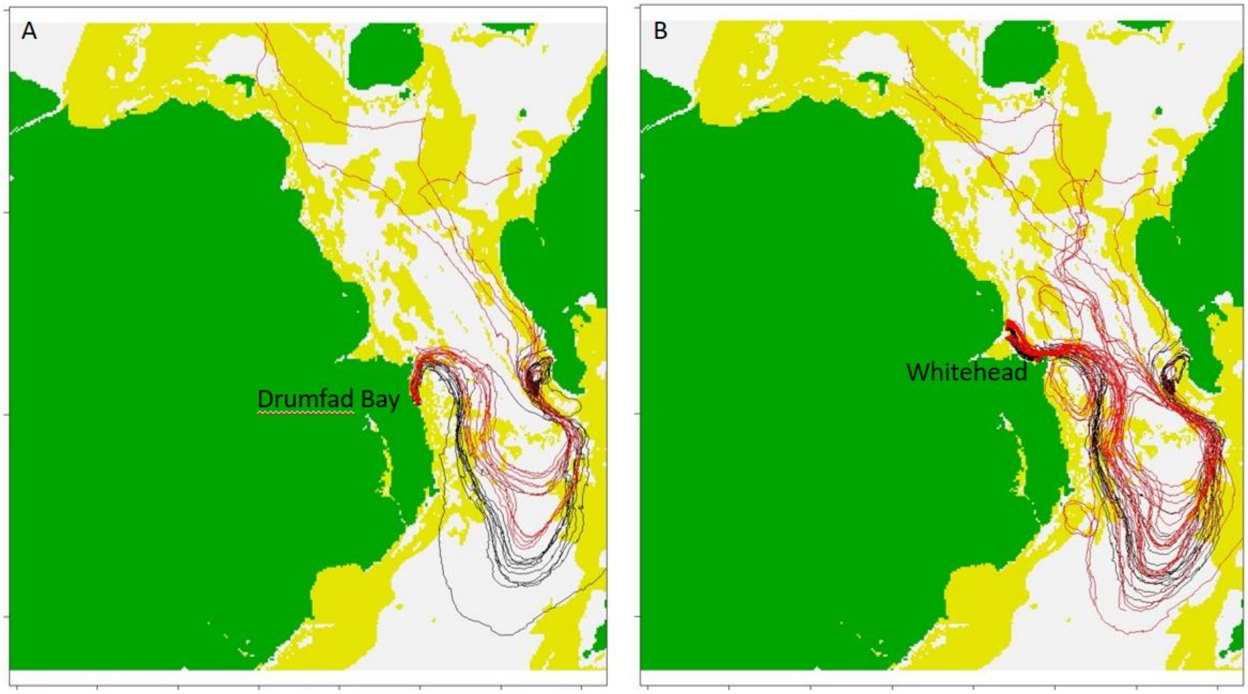

Figure 7: Movement tracks from Drumfad Bay (A) and Whitehead (B) during April (black) and September (red) spawning times.

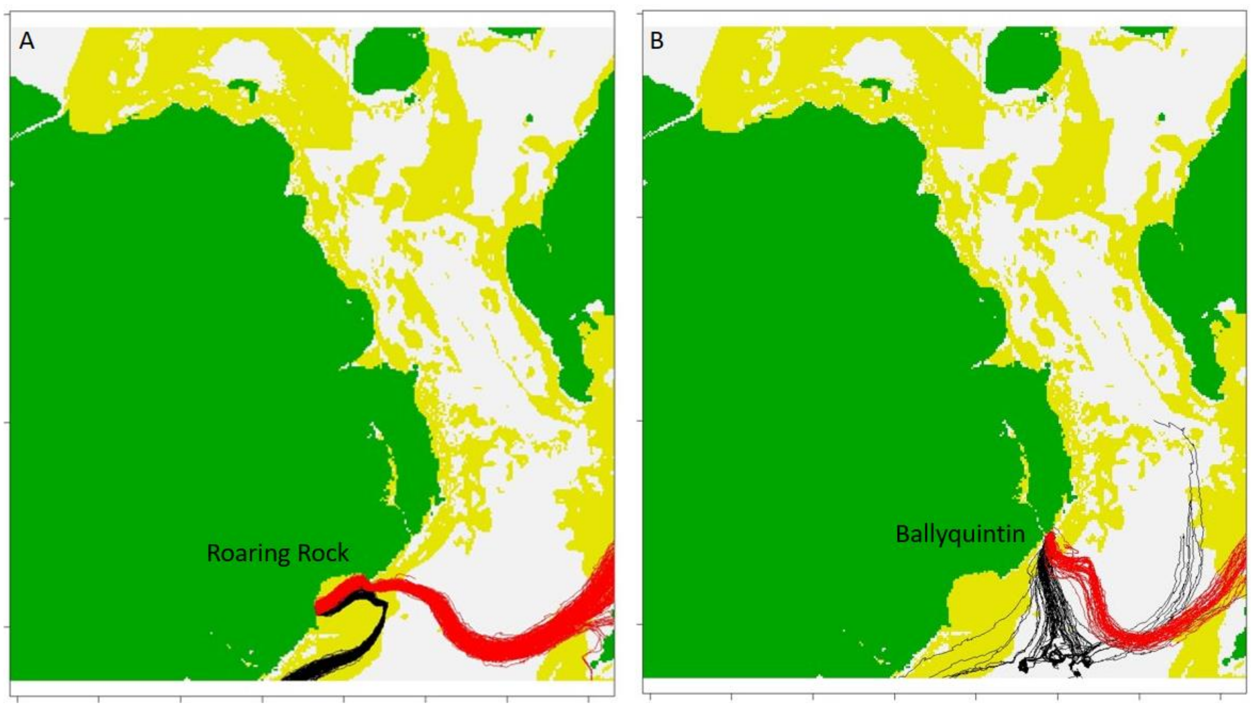

Figure 8: Movement tracks from Roaring Rock (A) and Ballyquintin (B) release sites during April (black) and September (red) spawning times.

6.2 Phase 2 - Larval Dispersal routes, enhancement sites.

Following these discussions with the NISFA, the dates used in the simulations were broadened to take onboard this feedback. To cover the spring spawning period, the model was run between 7 April and 26 May, every 7 days, using 2022 hydrodynamics. To cover the autumn spawning period the model was run weekly from 4th-25th September, again using 2022 hydrodynamics. Over this timeframe, dispersal was extremely variable, depending on changes in the currents.

6.2.1 Ballyquintin

Spring Dispersal

Larvae released from Ballyquintin showed variable dispersal routes (Figure 9a). On 7th April the larvae initially moved south before moving north towards the west coast of Scotland, potentially redirected by the Irish Sea gyre. On 14th April the larvae were swept east before travelling further north, again finishing on the Scottish coast. On this date, the currents moving south along the coast are weaker allowing for this movement northwards (Figure 20a). For the next four-week period, all larvae moved south and out of the study area, with all larvae following a similar path. The 19th May showed massive variation in the pathways travelled by the larvae with transport throughout the study area. On the 26th May, larvae from Ballyquintin were again predominantly moving south out of the study area.

Autumn Dispersal

Larvae released on the 4th September showed an initial south and then east movement onto the coast of Scotland (Figure 9b). The tracks then started to diverge more with variable tracks along the Scottish and NI coast. Larvae released in the three weeks following this date all showed movement south and out of the study area.

Settlement

Larvae tracks which ended within the domain of the study area, within 500m of an area considered to be a suitable settlement habitat for scallops and within a depth range of 10-150m, were considered to lead to successful settlement. Tracks that ended more than 500m from a suitable settlement site were considered to lead to larval mortality.

For larvae that were released from Ballyquintin during the spring spawning, three dates showed successful settlement within the study area (Figure 9c), with 2 of these dates showing some settlement in NI waters. On the 14th May a small amount of settlement was located along the east Antrim coast. There was greater settlement in this area, as well as around Rathlin Island and Outer Ards peninsula when larvae were released a week later, on the 19th May.

For larvae that were released from Ballyquintin during the autumn spawning, two dates showed successful settlement within the study area (Figure 9d). On the 4th September, settlement was predicted to the east of Rathlin Island, along the east Antrim coast and on the County Down offshore region. On the 11th September a small settlement patch was modelled within Dundrum Bay.

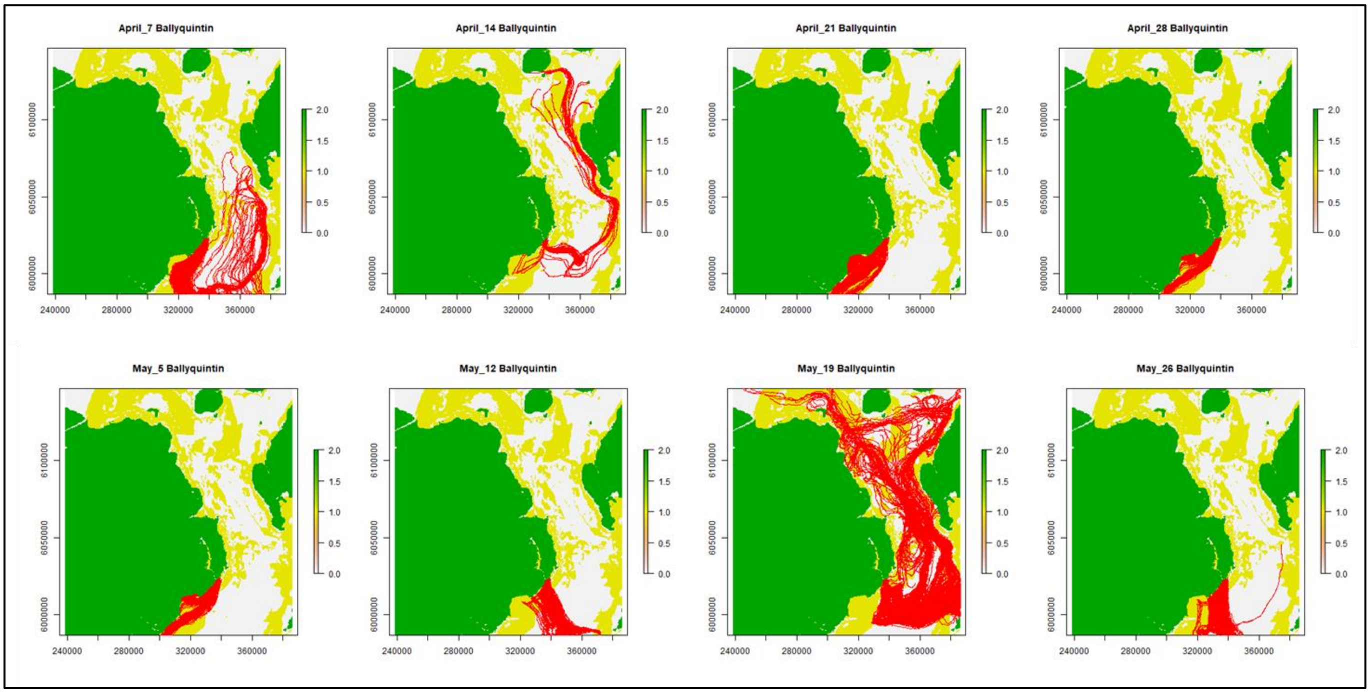

Figure 9a: Modelled movement of larvae released from Ballyquintin between 7th April and 26 May 2022.

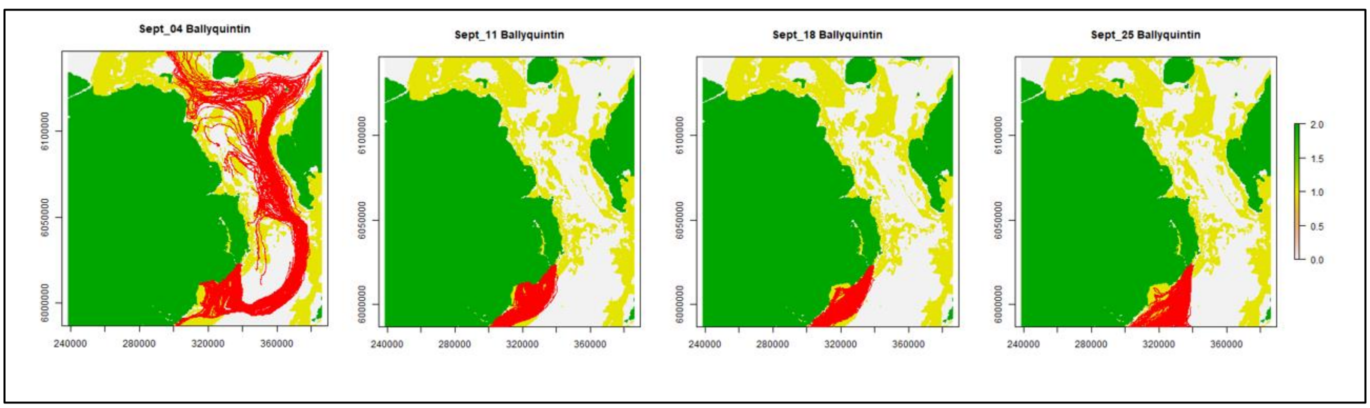

Figure 9b: Modelled movement of larvae released from Ballyquintin between 4th and 25th September 2022.

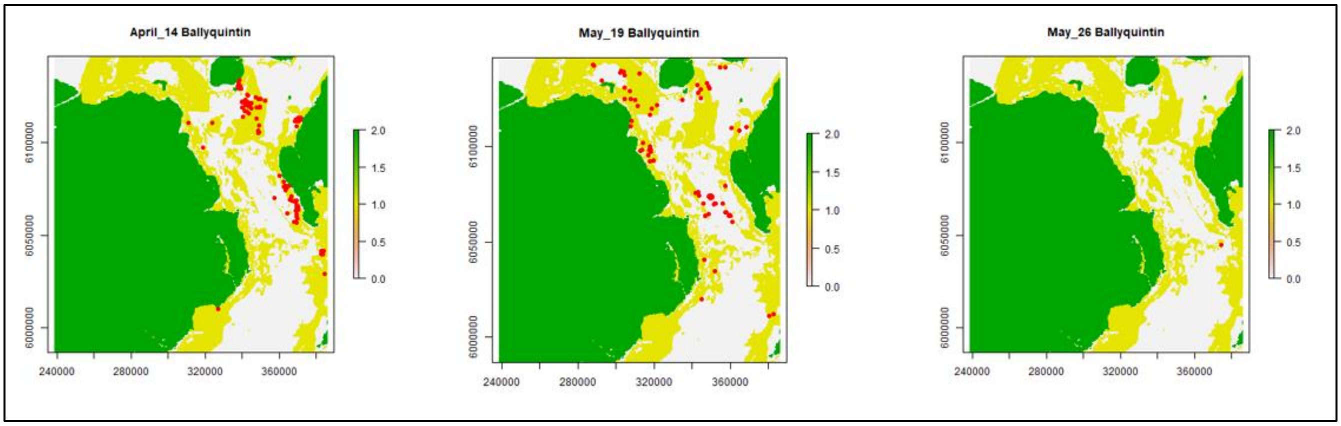

Figure 9c: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from Ballyquintin during the spring model runs (April and May).

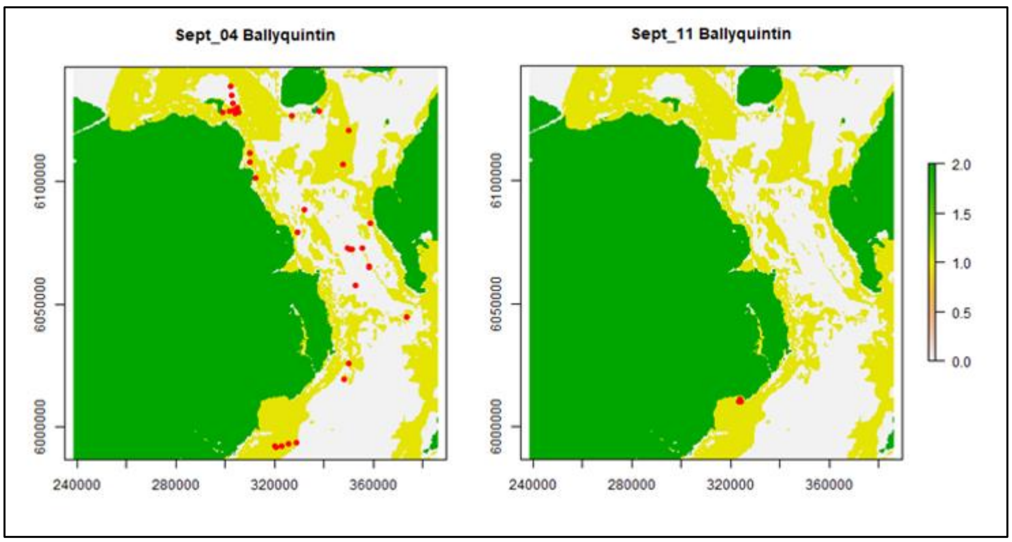

Figure 9d: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from Ballyquintin during the autumn model runs (September).

6.2.2 Drumfad Bay

Spring Dispersal

Larvae released from Drumfad Bay showed variable dispersal routes (Figure 10a). On 7th April the model showed that the larvae were pushed onto the land and therefore there was no further dispersal modelled. On 14th April the larvae were swept west before travelling north, finishing on the Scottish coast. On the 21st April larvae were carried south out of the study area. For the next two-week period there was again no movement of larvae with it expected to have been carried onto land. On the 12th May larvae moved southeast towards the Isle of Man. As with Ballyquintin, release of larvae from Drumfad Bay on the 19th May showed massive variation in the pathways travelled, with transport throughout the study area. On the 26th May, larvae from Drumfad Bay moved south out of the study area.

Autumn dispersal

Larvae released on the 4th September from Drumfad Bay followed a northeasterly track before moving back towards the NI coast, with some tracks ending around Rathlin and the north Antrim area, and other tracks moving north out of the study area (Figure 10b). On the 11th September, the model showed larvae moving south as far as Portavogie, before changing direction and moving along the west coast of Scotland. On both the 18th and 25th September, larvae released from Drumfad Bay were shown to move south and out of the study area.

Settlement

For larvae that were released from Drumfad Bay during the spring dates, two dates showed successful settlement within the study area (Figure 10c), with one of these dates showing some settlement in NI waters. On May 19th settlement was shown along the east Antrim coast.

For larvae that were released from Drumfad Bay during the autumn spawning, two of the September dates showed successful settlement within the study area - 11th and 25th September, with settlement in NI waters being predicted from the 11th September release date (Figure 10d). On this date a small amount of settlement was predicted east of Rathlin, south of Glenarm, and offshore from Dundrum Bay.

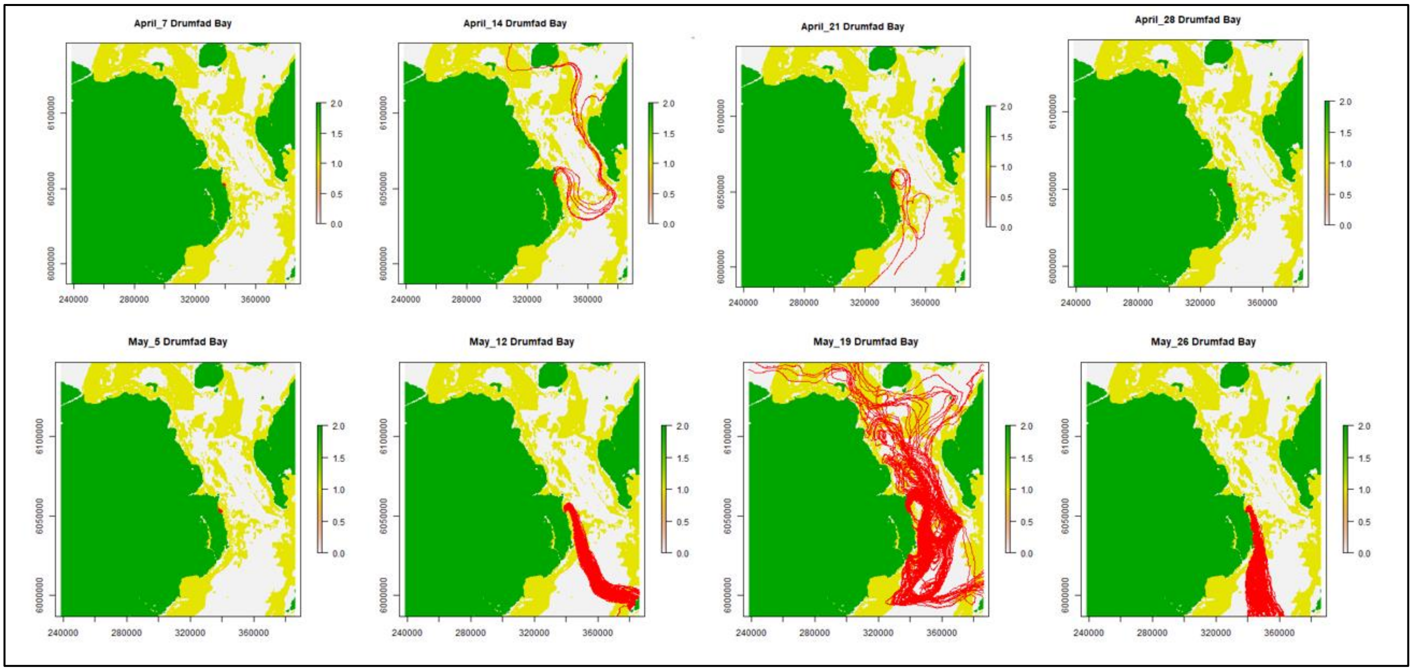

Figure 10a: Modelled movement of larvae released from Drumfad Bay between 7th April and 26 May 2022.

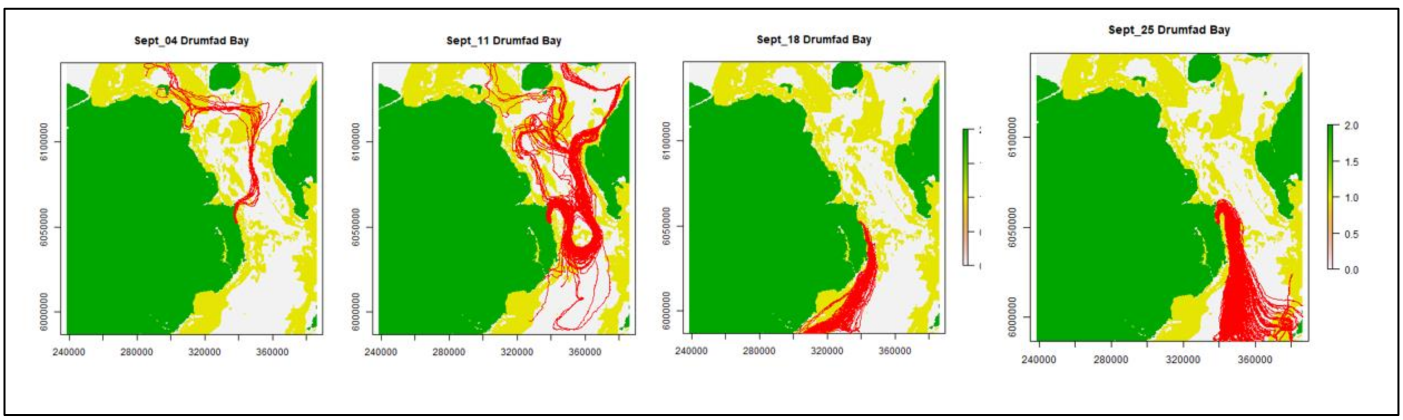

Figure 10b: Modelled movement of larvae released from Drumfad Bay between 4th and 25th September 2022.

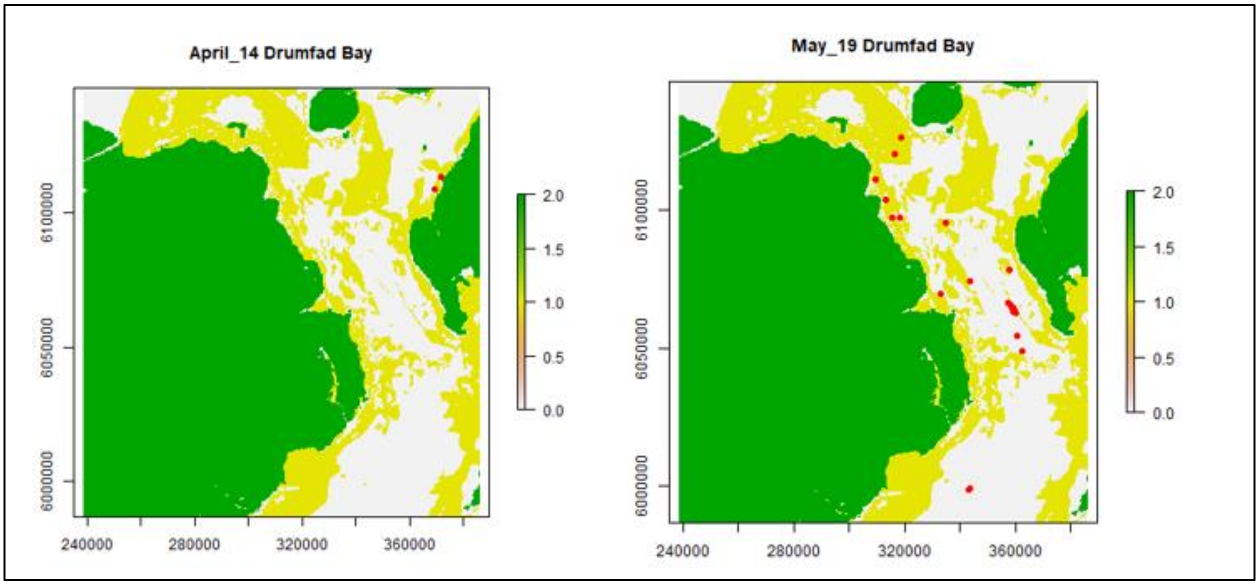

Figure 10c: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from Drumfad Bay during the spring model runs (April and May).

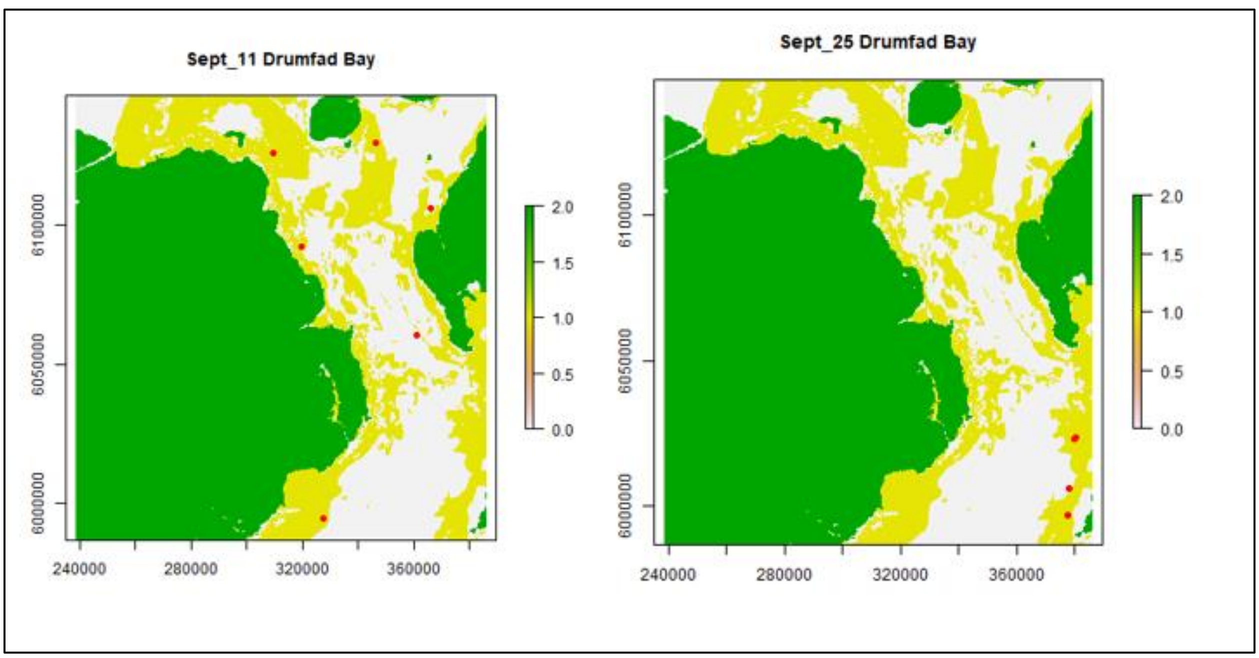

Figure 10d: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from Drumfad Bay during the autumn model runs (September).

6.2.3 Whitehead

Spring Dispersal

Larvae released from Whitehead showed variable dispersal routes (Figure 11a). On 7th April the model showed that there was minimal movement of the larvae, with movement only occurring from the enhancement site to the southern shore of Belfast Lough. On 14th April the larvae were generally swept southeast before moving north, finishing on the Scottish coast. On the 21st April there was a lot of variation in the tracks taken by the larvae, with movement north and south within NI waters, and little transport of larvae outside of NI waters. Larvae released from Whitehead on the 28th April and 5th May showed similar southerly patterns, with some larvae moving into Dundrum Bay whilst the remaining larvae moved south out of the study area. On the 12th May all larvae moved southeast towards the Isle of Man and out of the study area. As with Ballyquintin and Drumfad Bay, release of larvae from Whitehead on the 19th May showed massive variation in the pathways travelled, with transport throughout the study area. On the 26th May, larvae from Whitehead moved south out of the study area.

Autumn Dispersal

Larvae released on the 4th September from Whitehead followed a northeasterly track before moving back towards the NI coast, similar to the pattern observed in the model run from Drumfad Bay on this date (Figure 11b). On the 11th September, the model showed large variations in the tracks of the larvae, with larvae moving across the extend of the study area.
On both the 18th and 25th September, larvae released from Drumfad Bay were shown to move south, and while some of these then changed direction and circled north again, the majority of the larvae moved out of the study area.

Settlement

For larvae that were released from Whitehead during the spring dates, four dates showed successful settlement within the study area (Figure 11c), with three of these dates showing some settlement in NI waters. Of these dates, 19th May had the highest settlement within NI waters, with settlement predicted along the NI coastline between Rathlin Island and Dundrum Bay. On the 7th May a small settlement was predicted back at the reseeding site. On the 21st April, settlement was modelled from Rathlin Island to the outer Ards peninsula.

For larvae that were released from Whitehead during the autumn model runs, whilst all four dates showed settlement within the study area, two dates (4th September and 1 September) showed settlement in NI waters (Figure 11d).

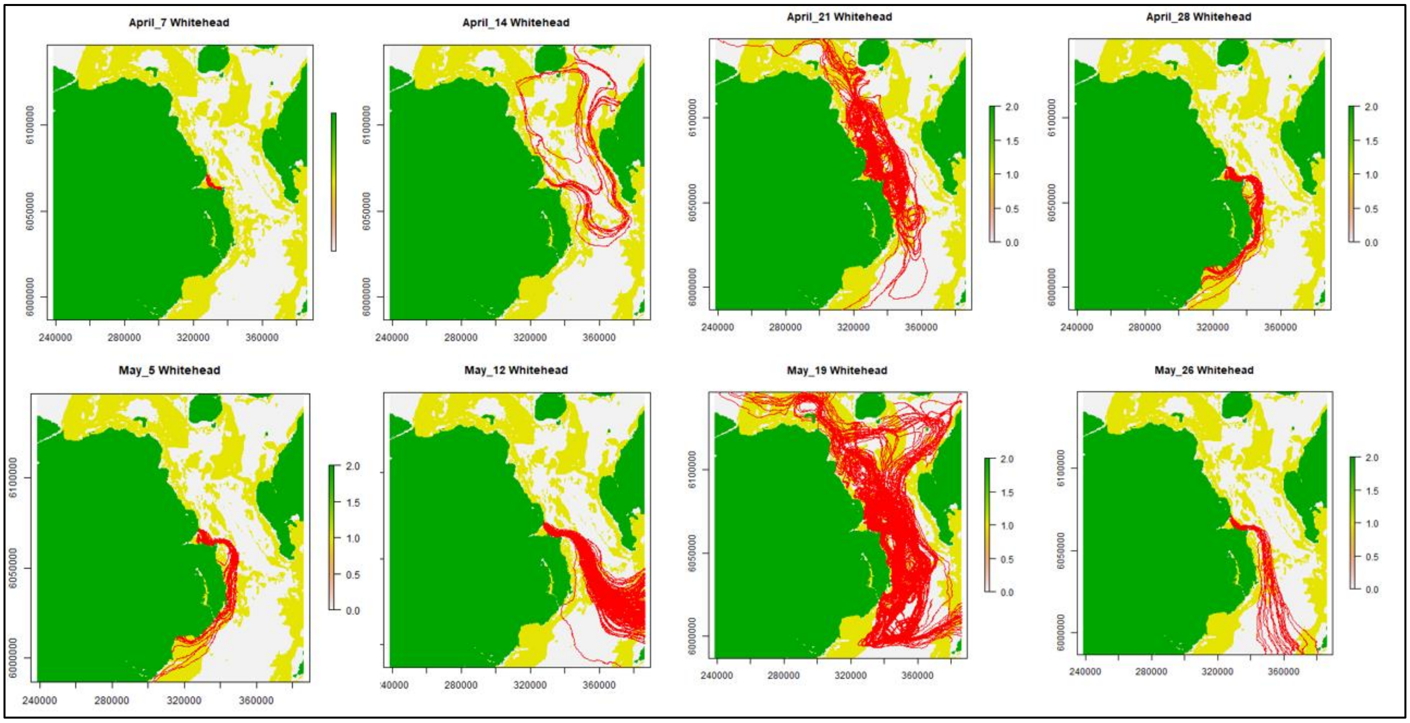

Figure 11a: Modelled movement of larvae released from Whitehead between 7th April and 26 May 2022.

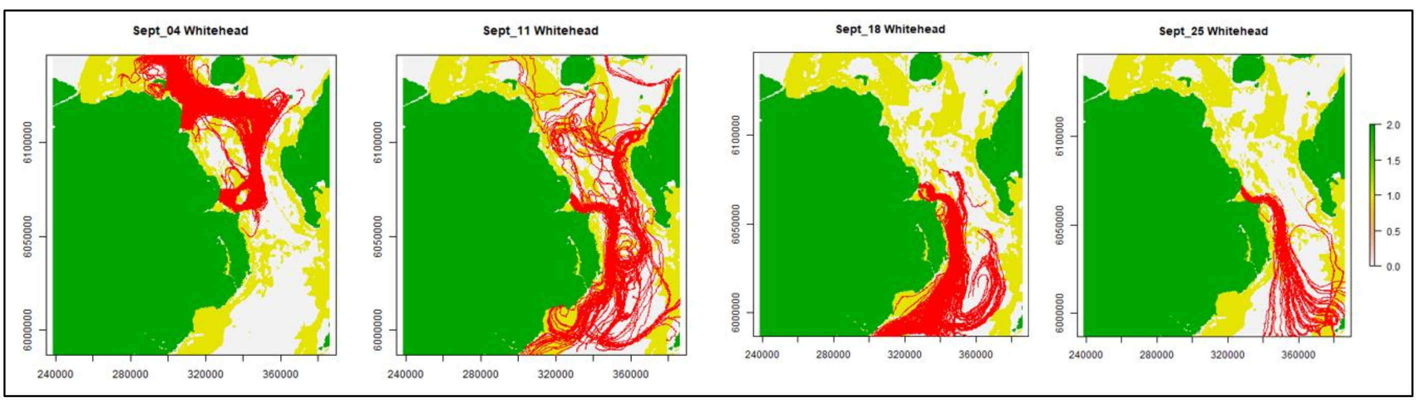

Figure 11b: Modelled movement of larvae released from Whitehead between 4th and 25th September 2022.

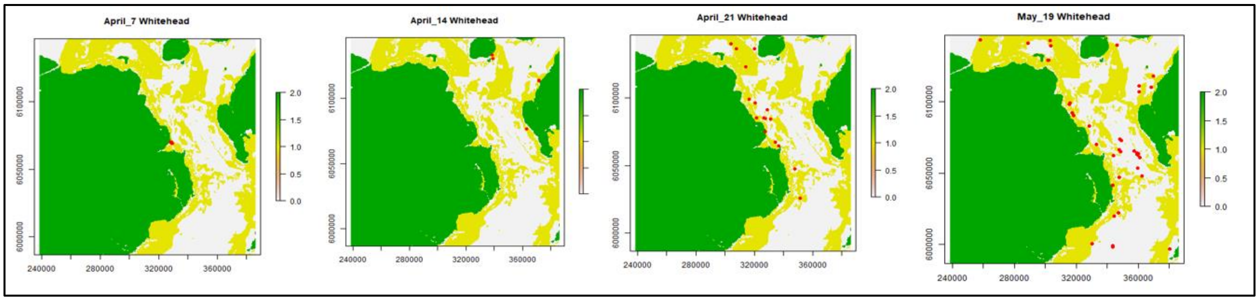

Figure 11c: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from Whitehead during the spring model runs (April and May).

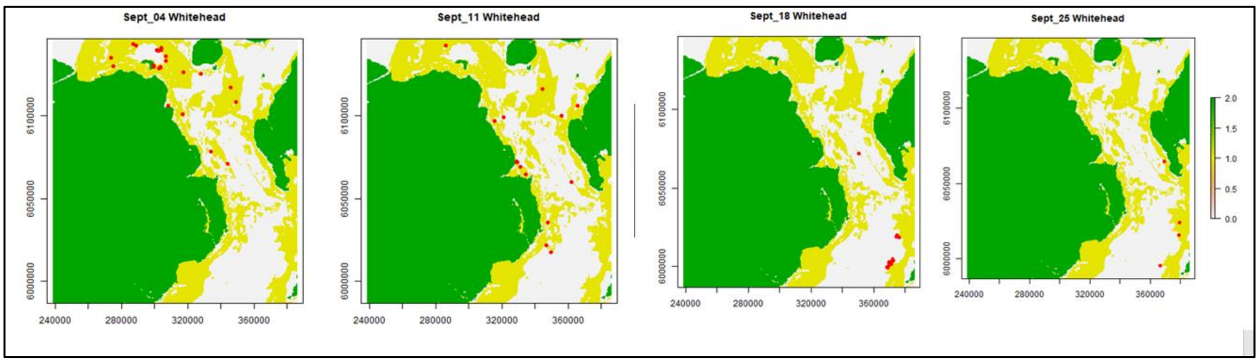

Figure 11d: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from Whitehead during the autumn model runs (September).

6.2.4 Roaring Rock

Spring Dispersal

Larvae released from the Roaring Rock enhancement site showed less variable dispersal routes than the other sites (Figure 12a). On 7th April the model showed that the larvae moved south out of the study area. Larvae released from the site between 14th April and 5th May showed very little movement, with larvae all staying within Dundrum Bay. On the 12th May larvae moved south out of the study area. Whilst on the 19th May larvae released from the three other enhancement sites showed movement across the greatest extent of the study area, larvae released on this date from Roaring Rock remained in Dundrum Bay. On the 26th May, larvae from Roaring Rock moved south out of the study area.

Autumn Dispersal

As was observed during some of the spring model runs for the area, larvae released from the Roaring Rock site stayed completely within Dundrum Bay on three of the modelled autumn dates (Figure 12b). On the 25th September, larvae released from the site moved out of the Bay and south out of the study site.

Settlement

For larvae that were released from Roaring Rock during the spring dates, there was no successful settlement within the study area. However, it is possible that the larvae caught within Dundrum Bay may eventually settle onto the suitable habitat in the Bay. This is true also for the autumn dates, with larvae remaining within Dundrum Bay in three of the four modelled dates.

The set-up of the MerMADE model means that once larvae reach land that is the end of the pathway. However, in reality, the larvae may be carried back out into the Bay or further. Therefore, the larvae within Dundrum Bay may move more than suggested by the model.

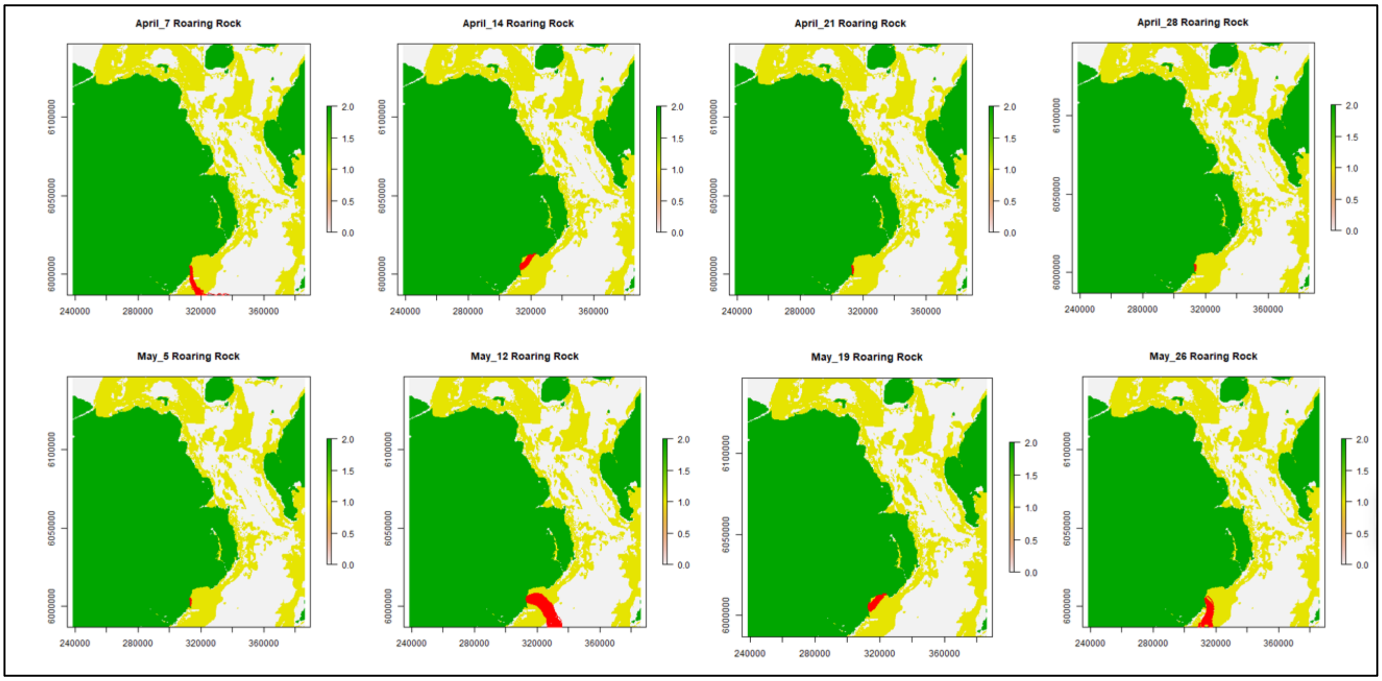

Figure 12a: Modelled movement of larvae released from Roaring Rock between 7th April and 26 May 2022.

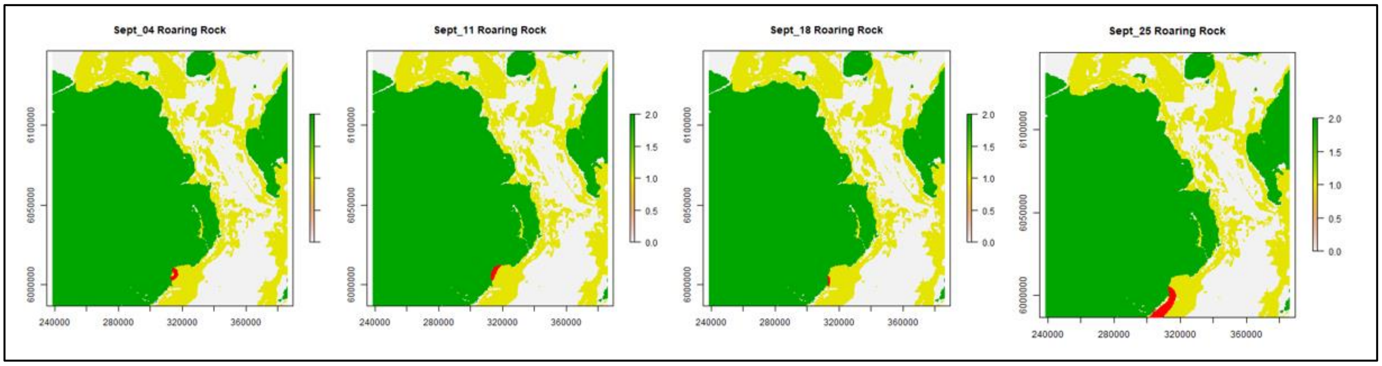

Figure 12b: Modelled movement of larvae released from Roaring Rock between 4th and 25th September 2022.

6.3 Phase 3 - Larval Dispersal routes, additional sites (MPAs)

Following presentation of the Phase 2 results to NISFA, they asked that other sites be examined as potential enhancement sites that would show settlement within NI waters. For ease, it was suggested that current Marine Protected Areas (MPA's), which are already closed to scallop fishing, be examined[1]. The suggested sites were:

5. Skerries and Causeway MPA
6. Rathlin Island MPA
7. The Maidens MPA
8. Outer Belfast Lough MPA

The model was run for these sites, using conditions based on 7th April 2022 to 19th May 2022, to cover the period thought to be the most common time of spawning for scallops in NI waters.

6.3.1 Skerries and Causeway MPA

The model showed that larvae released from the Skerries and Causeway predominately moved north or west, out of the study area, and east, around Rathlin Island (Figure 13a). However, on the 7th April and the 5th May, some larvae did move south with many of these tracks staying within Northern Ireland waters. On these two dates there was settlement of larvae within NI waters as far south as Dundrum Bay (Figure 13b). Larvae on these dates also settled along the Scottish coast. On the 21st April, larvae released from the Skerries settled in a "hotspot" to the north-west of the release zone. On the 19th May all larvae moved out of the study area, with no settlement in NI waters.

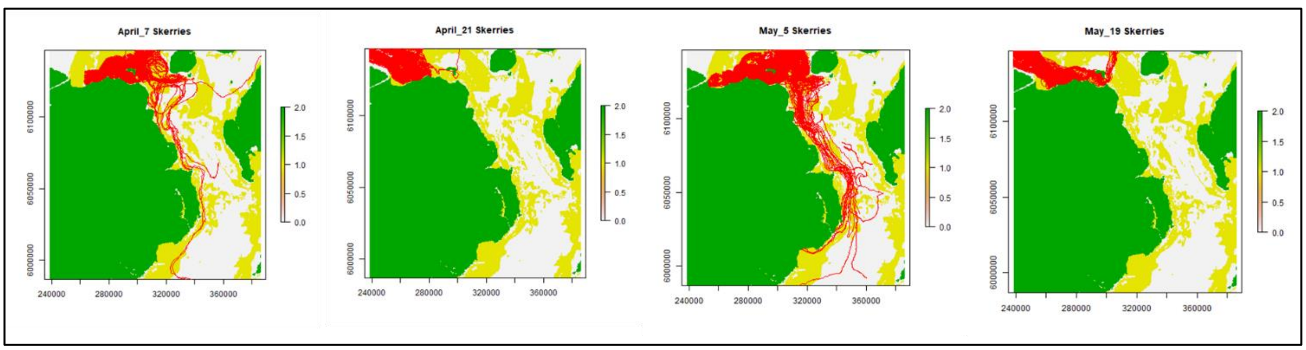

Figure 13a: Modelled movement of larvae released from Skerries and Causeway MPA between 7th April and 19th May 2022, on a fortnightly basis.

[1] More details on the MPA's can be found on the DAERA website: [Marine Protected Areas | Department of Agriculture, Environment and Rural Affairs (daera-ni.gov.uk)].

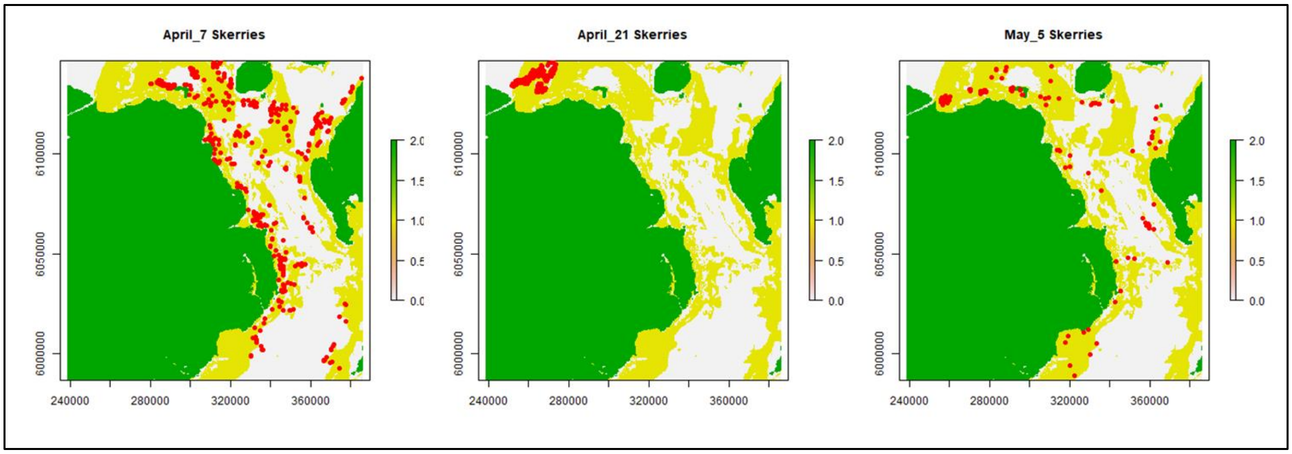

Figure 13b: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from Skerries and Causeway MPA during the spring model runs (April and May).

6.3.2 Rathlin MPA

While most of the larvae released from the Rathlin MPA tends to remain around Rathlin Island or move north out of the study area, on the 7th April and the 5th May, some larvae do move south with many of these tracks staying within Northern Ireland waters (Figure 14a). On these two dates there was settlement of larvae within NI waters as far south as Dundrum Bay (Figure 14b). Larvae on these dates also settled along the Scottish coast. On the 21st April and 19th May there was a small amount of settlement within NI waters along the North Coast.

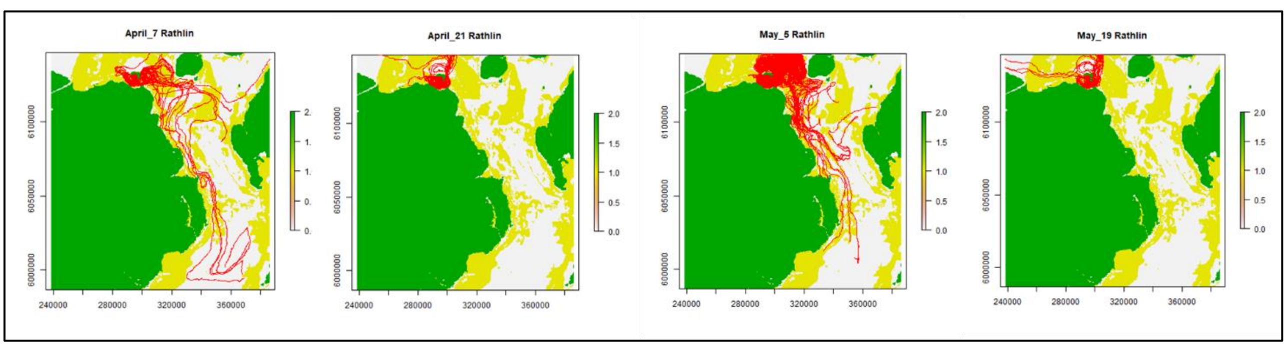

Figure 14a: Modelled movement of larvae released from Rathlin MPA between 7th April and 19th May, on a fortnightly basis.

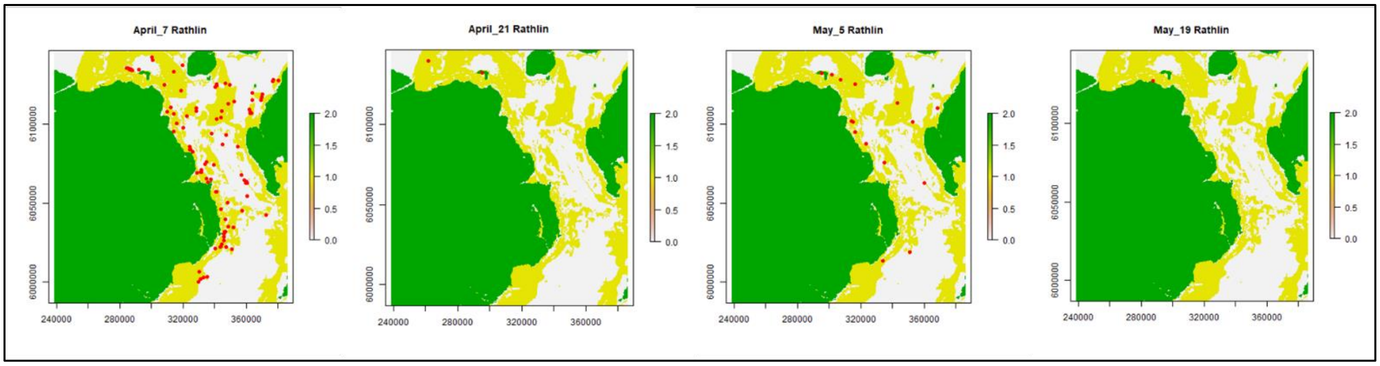

Figure 14b: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from Rathlin MPA during the spring model runs (April and May).

6.3.3 Maidens MPA

Dispersal of larvae from the Maidens MPA shows distribution throughout the study area on all four dates modelled (Figure 15a). These tracks, which mainly stay along the North Channel, show some loss of larvae both north and south of the study area. Release of larvae from the Maidens MPA resulted in settlement within NI waters on all four dates modelled (Figure 15b). This is the most extensive settlement within NI waters for all sites modelled, both in Phase 2 and Phase 3. Dispersal from the Maidens also results in settlement on the west coasts of Scotland and the Isle of Man.

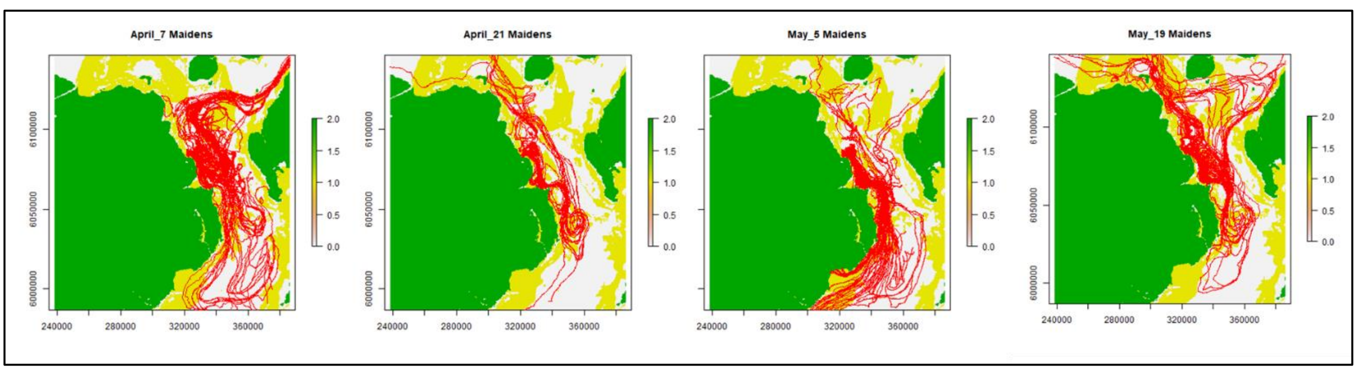

Figure 15a: Modelled movement of larvae released from Maidens MPA between 7th April and 19th May, on a fortnightly basis.

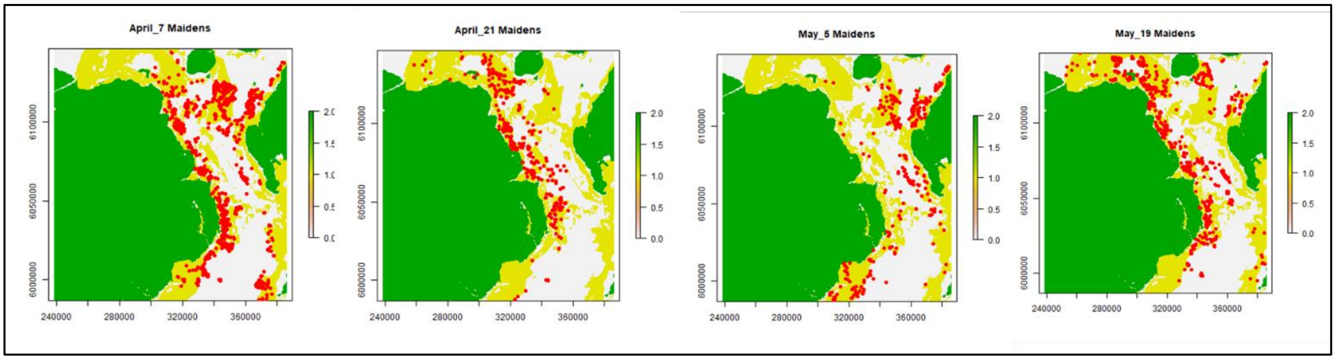

Figure 15b: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from the Maidens MPA during the spring model runs (April and May).

6.3.4 Outer Belfast Lough MPA

Larvae released from the Outer Belfast Lough MPA show similar dispersal tracks to those released from the Whitehead scallop enhancement site. The main difference between the two sites is for larvae released on the 7th April. On this date, larvae from Whitehead showed minimal movement only occurring from the enhancement site to the southern shore of Belfast Lough. The larvae released from the Outer Belfast Lough MPA all moves south and out of the study area (Figure 16a). As with Whitehead, on the 21st April there was a lot of variation in the tracks taken by the larvae, with movement north and south within NI waters, and little transport of larvae outside of NI waters. Larvae released from the Outer Belfast Lough MPA on 5th May showed southerly patterns, with some larvae moving into Dundrum Bay whilst the remaining larvae moved south out of the study area. A very small proportion of the larvae released on this date moved east to the Scottish coast. Release on the 19th May showed massive variation in the pathways travelled, with transport throughout the study area.

Of the four dates modelled for release from Outer Belfast Lough MPA, all four dates showed successful settlement within NI waters but at different levels. (Figure 16b). The greatest settlement in NI waters was on the 21st April and 19th May. Settlement patterns were similar as for Whitehead dispersal, with settlement predicted along the NI coastline between Rathlin Island and just South of Dundrum Bay. There was also some settlement on the west coast of Scotland.

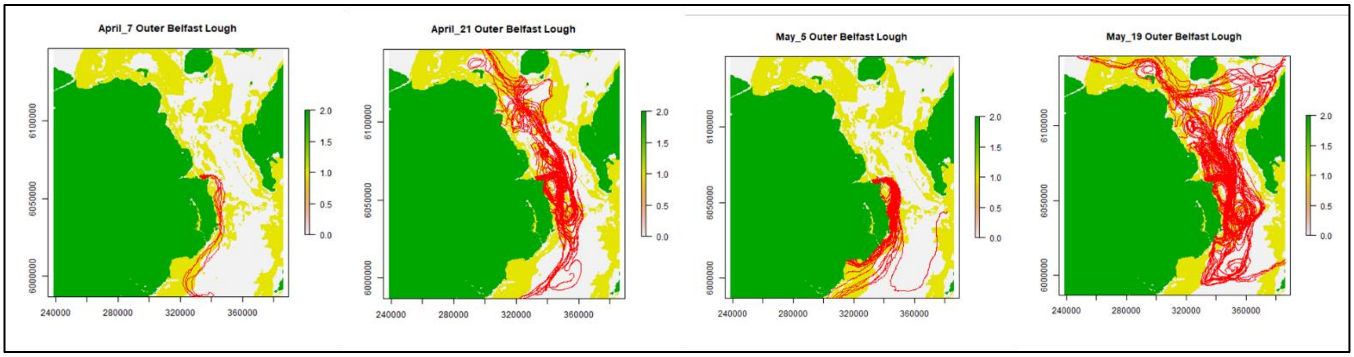

Figure 16a: Modelled movement of larvae released from Outer Belfast Lough MPA between 7th April and 19th May, on a fortnightly basis.

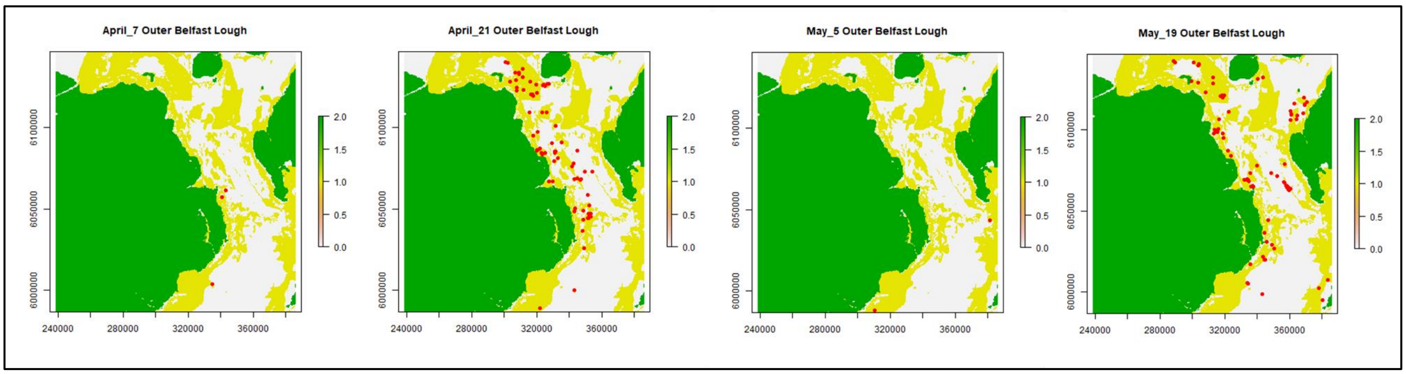

Figure 16b: Predicted sites of successful settlement (red dots) occurring within the model study area, following release of larvae from the Outer Belfast Lough MPA during the spring model runs (April and May).

7.0 Environmental conditions

The model simulations (after 'Phase 1 – proof of concept), were run using 2022 environmental conditions. Environmental conditions shown below are intended to give further context to the model results and were obtained from several sources to cover the periods modelled.

7.1 Wind

Wind data was taken from the Met Eireann Harmonie-Arome system. The system has a configuration of 1000 x 900 grid points at a resolution of 2.5km. The model predicts the hourly forecast, 54 hours at a time (Operational NWP In Met Éireann - Met Éireann - The Irish Meteorological Service).

As part of a separate AFBI project, data for specific locations, had been downloaded from this system daily from 2019. Wind data for 2022 was isolated and data closest to the sites modelled in this current project were processed to cover the model. Figure 17 shows the positions for which wind data has been processed in relation to the modelled sites. Wind roses were prepared to cover both the spring and autumn model runs plus a period following to allow for settlement of larvae from the model's run at the end of each season. Wind direction and speed is most likely to influence the direction of travel of larvae during the veliger stage, when they are closer to the sea surface.

The wind roses (Figure 18) show wind direction and speed from 1st April to 30th June 2022. In spring, whilst there was variation in the wind direction for most areas, the direction was principally southern, ranging from SSE to SW. Ballycastle had the highest average wind speed at 5.72m/s, with Ballyholme having the lowest at 4.69m/s.

The autumn wind roses (Figure 19) show wind direction and speed from 1st September to 31st October 2022. In autumn 2022, wind direction for each area is similar to that in spring, with the prevailing winds for those months ranging from SSE to SW. As would be expected, average wind speed is higher in the autumn than in spring, with Ballycastle again having the highest average wind speed at 7.2 m/s and Ballyholme the lowest at 5.48m/s.

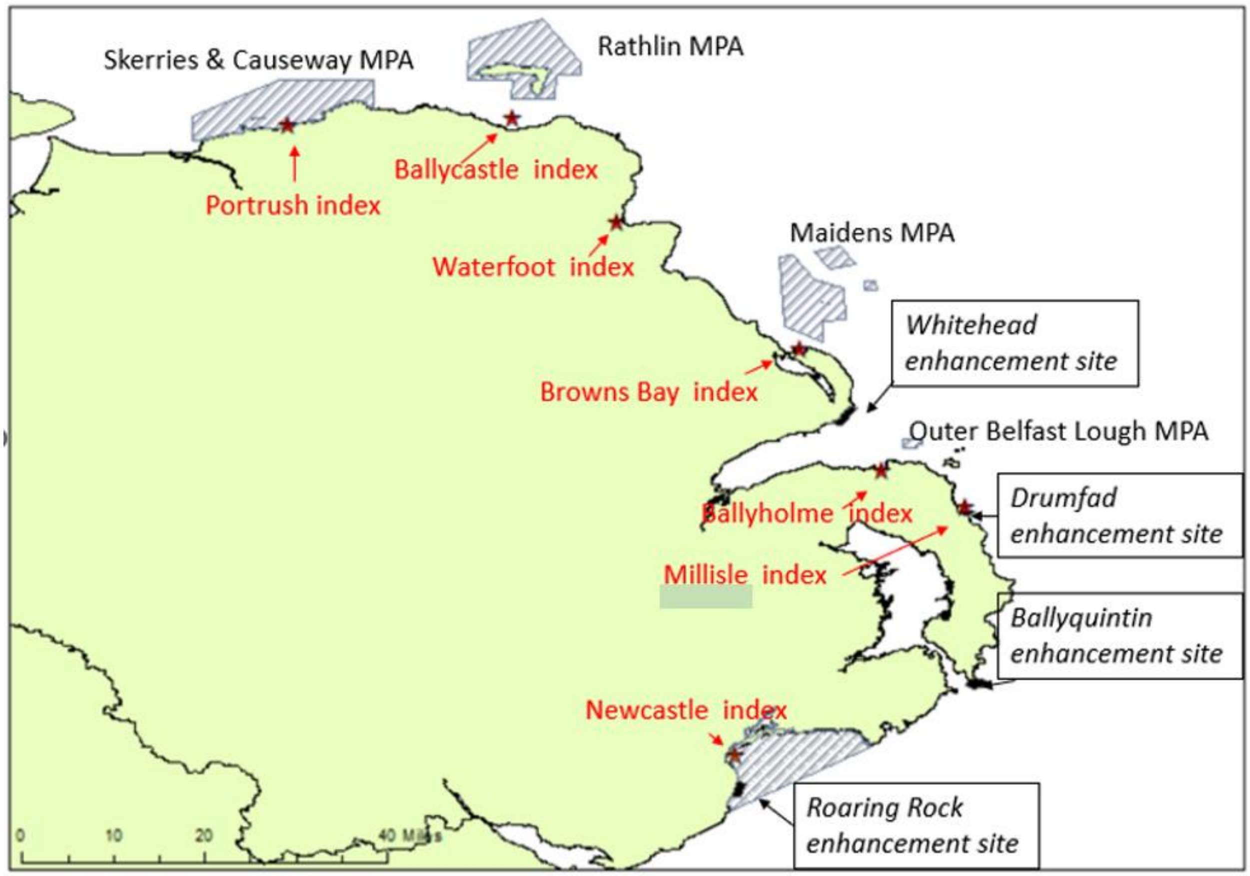

Figure 17: Location of sites for which wind data has been analysed (red stars and text) in relation to the modelled sites (MPA's, dashed areas; scallop enhancement sites, black polygons).

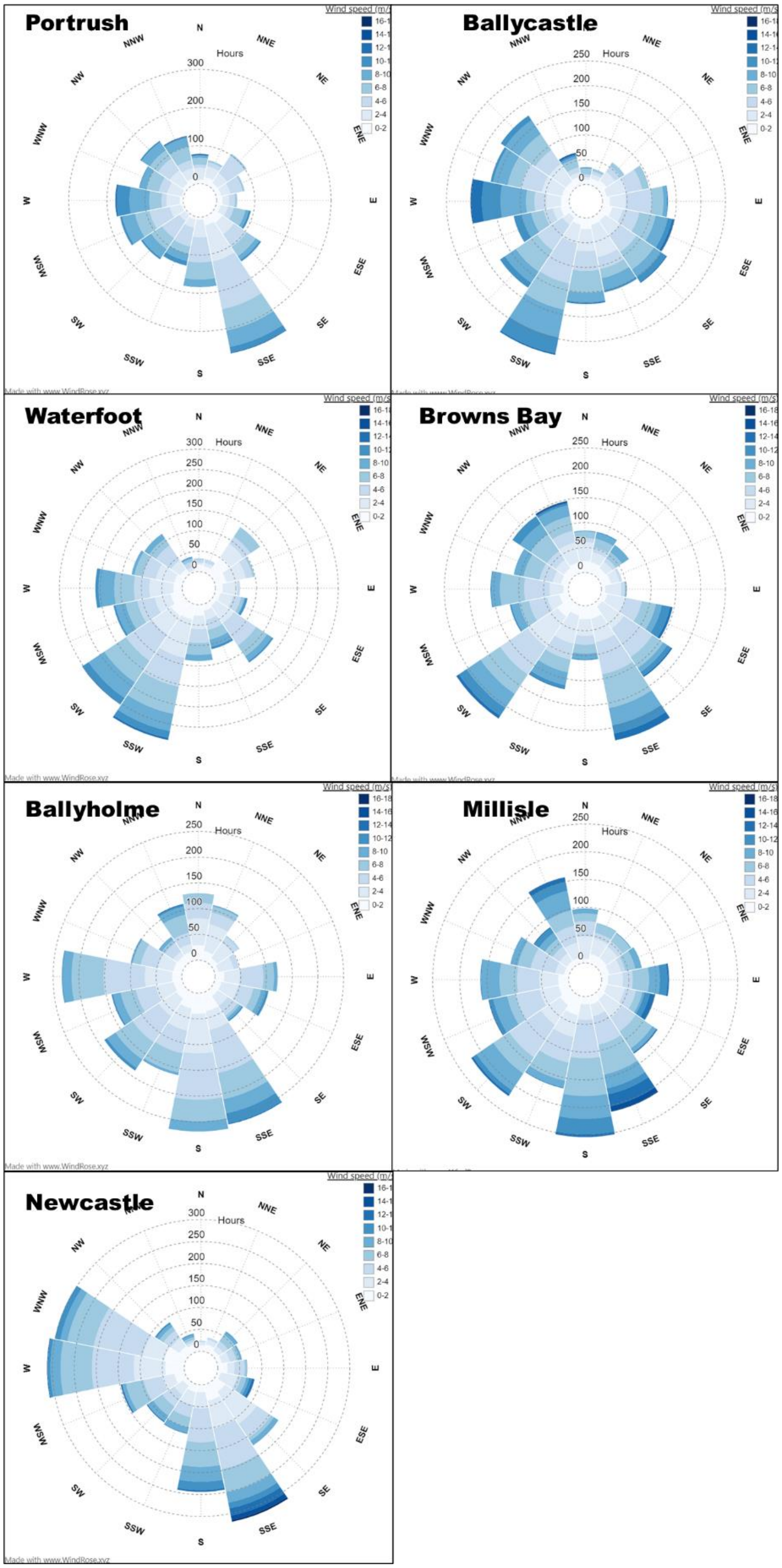

Figure 18: Wind roses for locations around NI between 1st April and 30th June 2022, covering the period of the spring model runs. Wind was reported every hour and is recorded as metres per second. Wind roses were created using http://windrose.xyz.

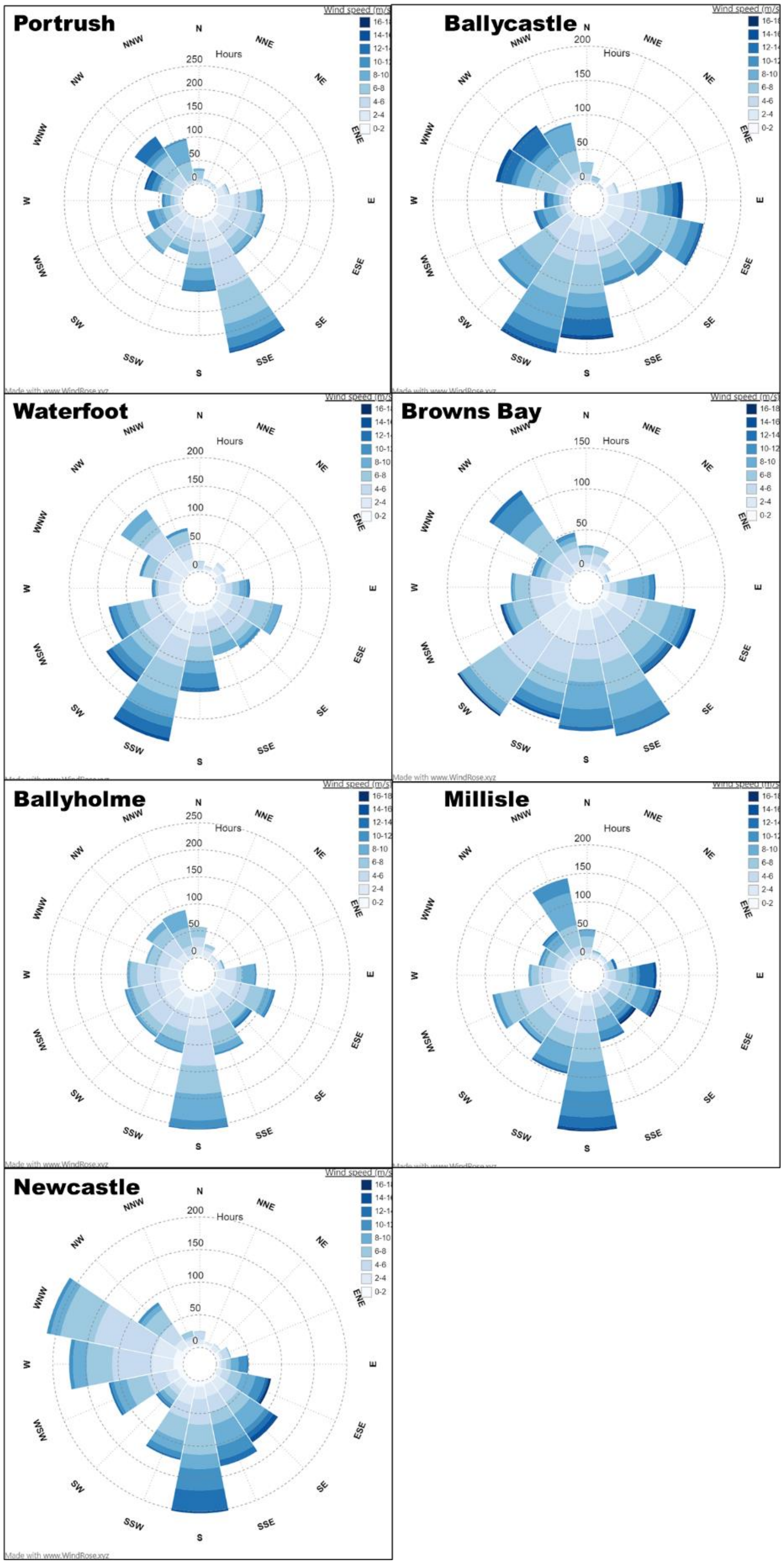

Figure 19: Wind roses for locations around NI between 1st September and 31st October 2022, covering the period of the autumn model runs. Wind was reported every hour and is recorded as metres per second. Wind roses were created using http://windrose.xyz.

7.2 Currents

Surface current speed and direction for the dates used for larval release were extracted from the model[2]. These are shown in Figure 20. The currents in the study area, while showing some variations, tend to follow similar patterns for the dates examined. West of the North Channel, along the NI east coast, currents close to the shore tend to move south. At Cushendun there is a shift in current direction, changing from south to north. Around Rathlin Island currents are more variable. There is also variation in the currents running along the north coast of NI.

Many of the dates show that the currents further offshore change direction. Offshore from the Ards Peninsula currents change from moving south and go east towards the Scottish coast. At the Scottish side of the North Channel, the currents tend to flow north.

Off the Bangor coast the current runs differently to the rest of the County Down coast, as it moves east into the North Channel, rather than south down the coast.

The currents displayed here are supported by the findings of Knight and Howarth (1999) who described the dominant currents in the North Channel (Figure 21).

[2] The hydrodynamic model used incorporates a range of factors, including temperature, salinity, tides, currents and local weather patterns (i.e. wind conditions). The current maps are the outcome of a complex interaction of all of these factors. Further information on the WeSTCOMS hydrodynamic model can be found here: A high resolution hydrodynamic model system suitable for novel harmful algal bloom modelling in areas of complex coastline and topography - ScienceDirect

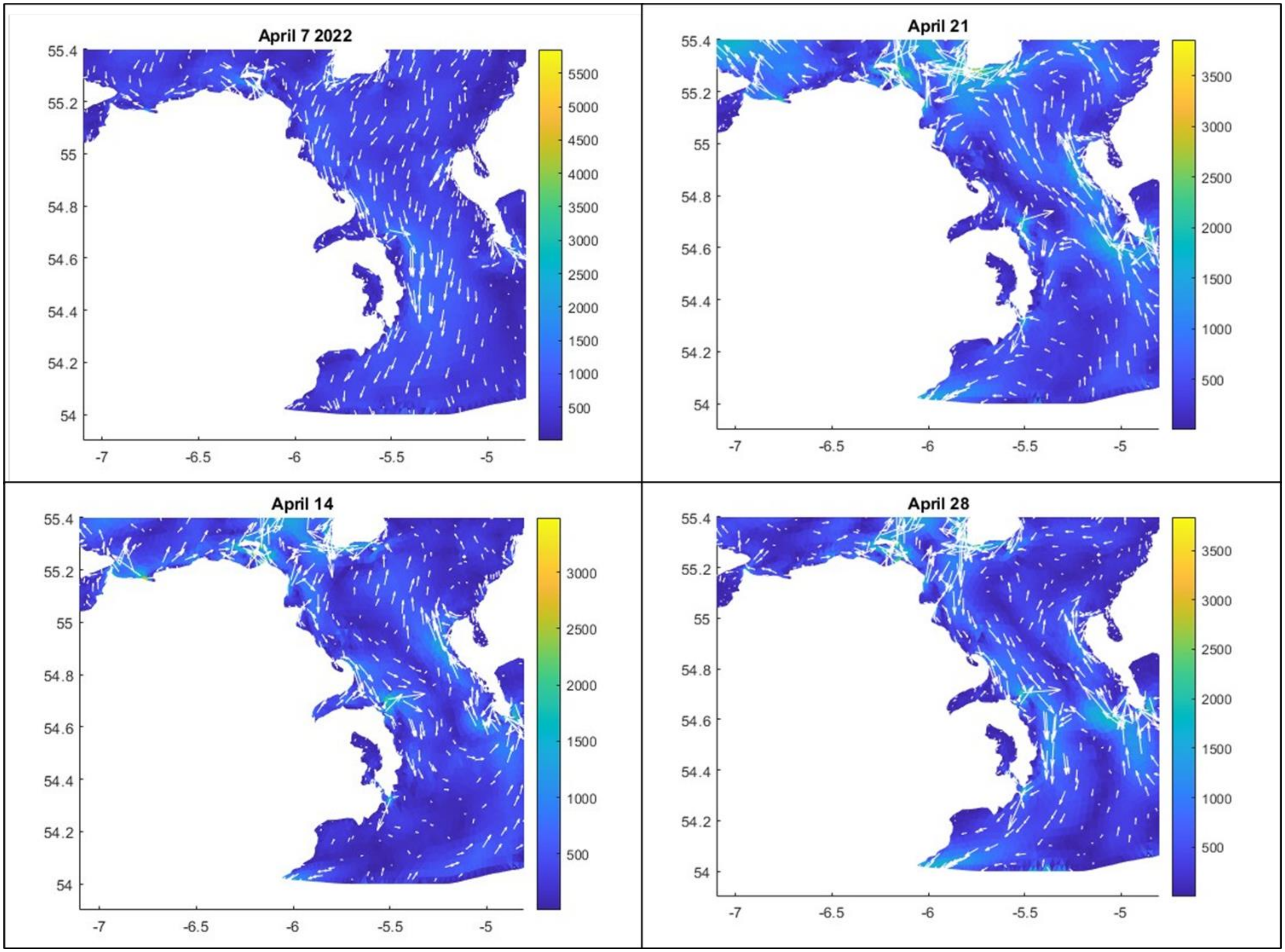

Figure 20a: Surface current direction and speed (m/hr) between 0-10m depth within the study area in April 2022.

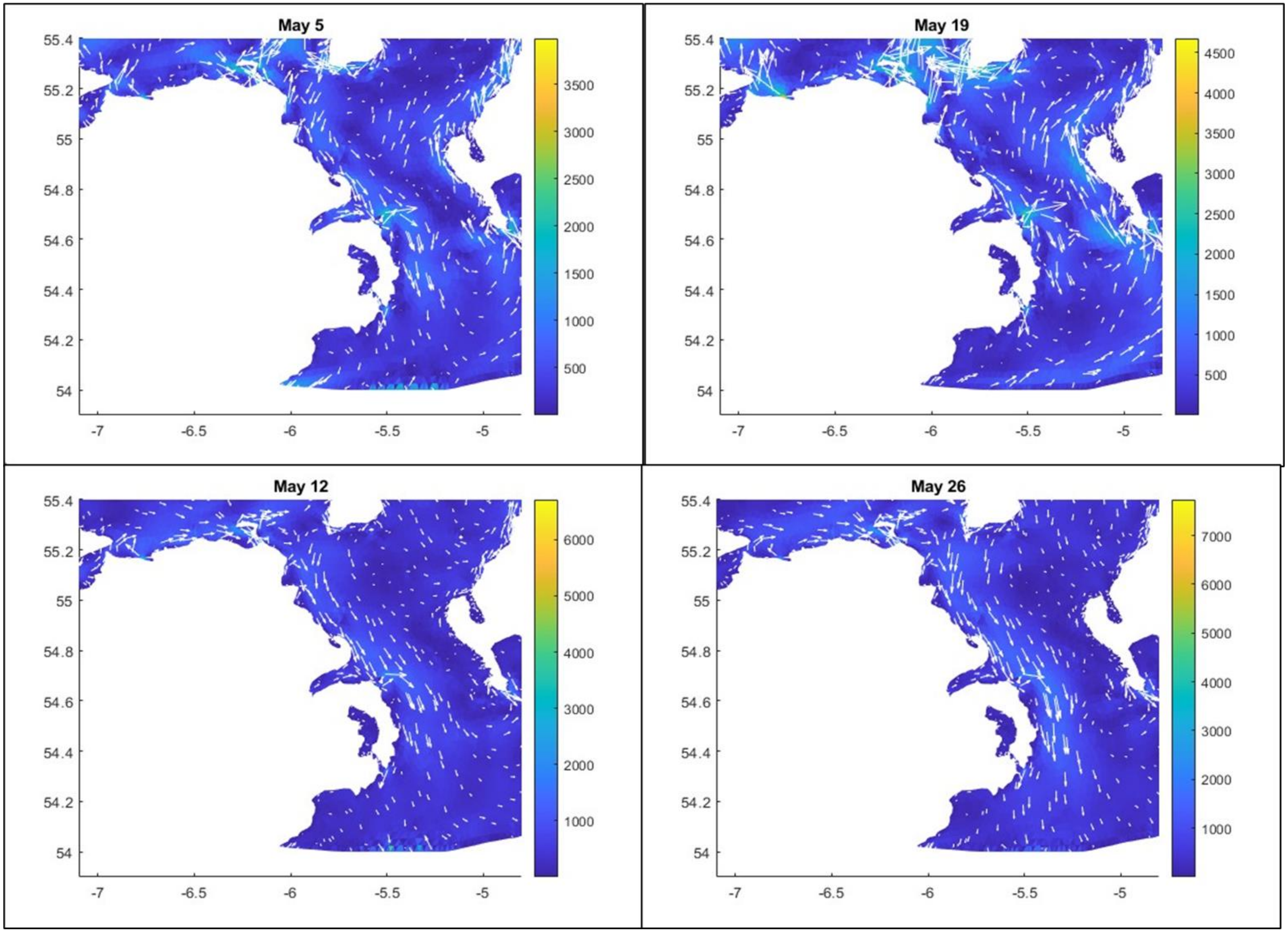

Figure 20b: Surface current direction and speed (m/hr, 0-10m depth) within the study area in May 2022.

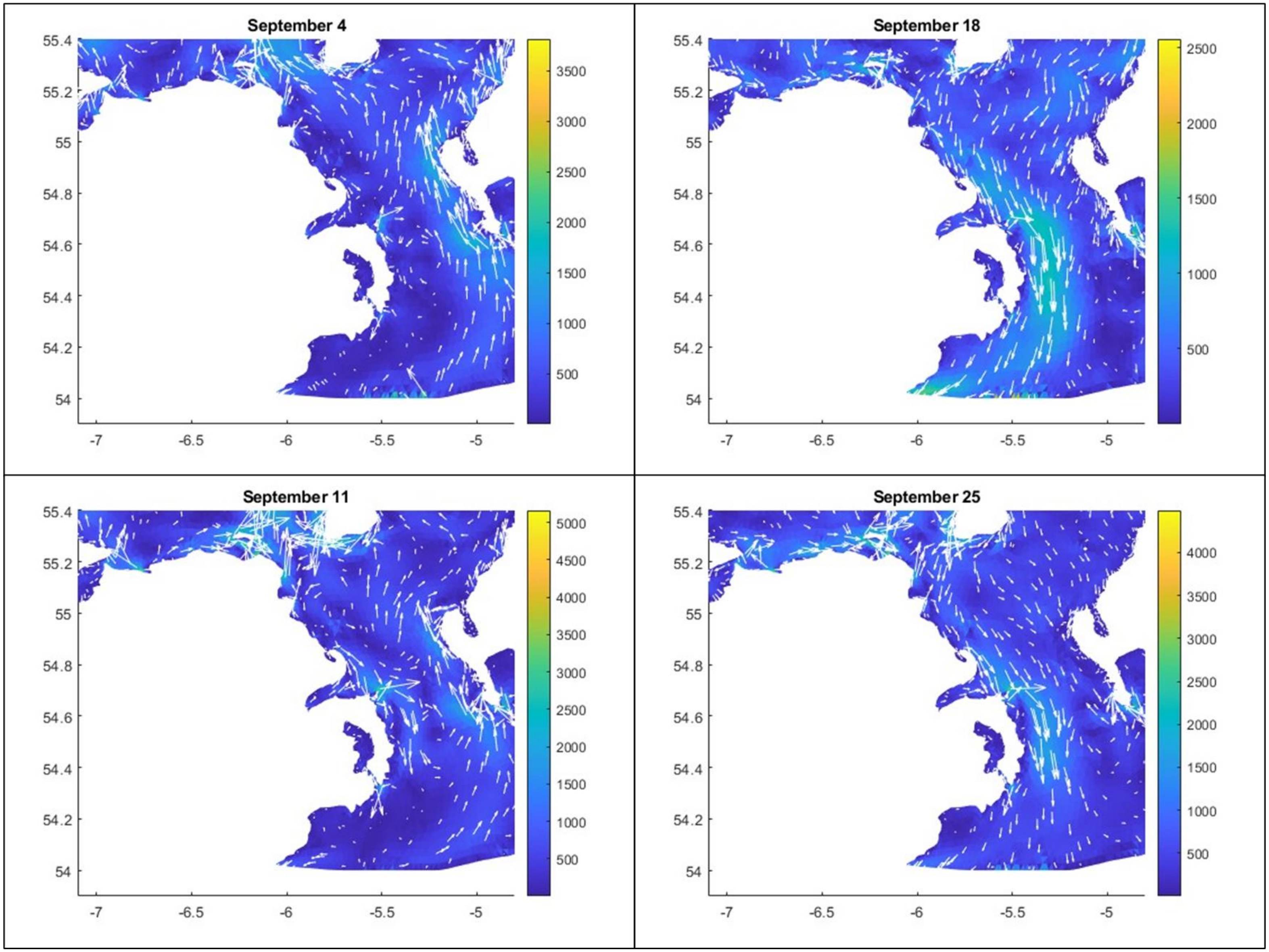

Figure 20c: Surface current direction and speed (m/hr, 0-10m depth) within the study area in September 2022.

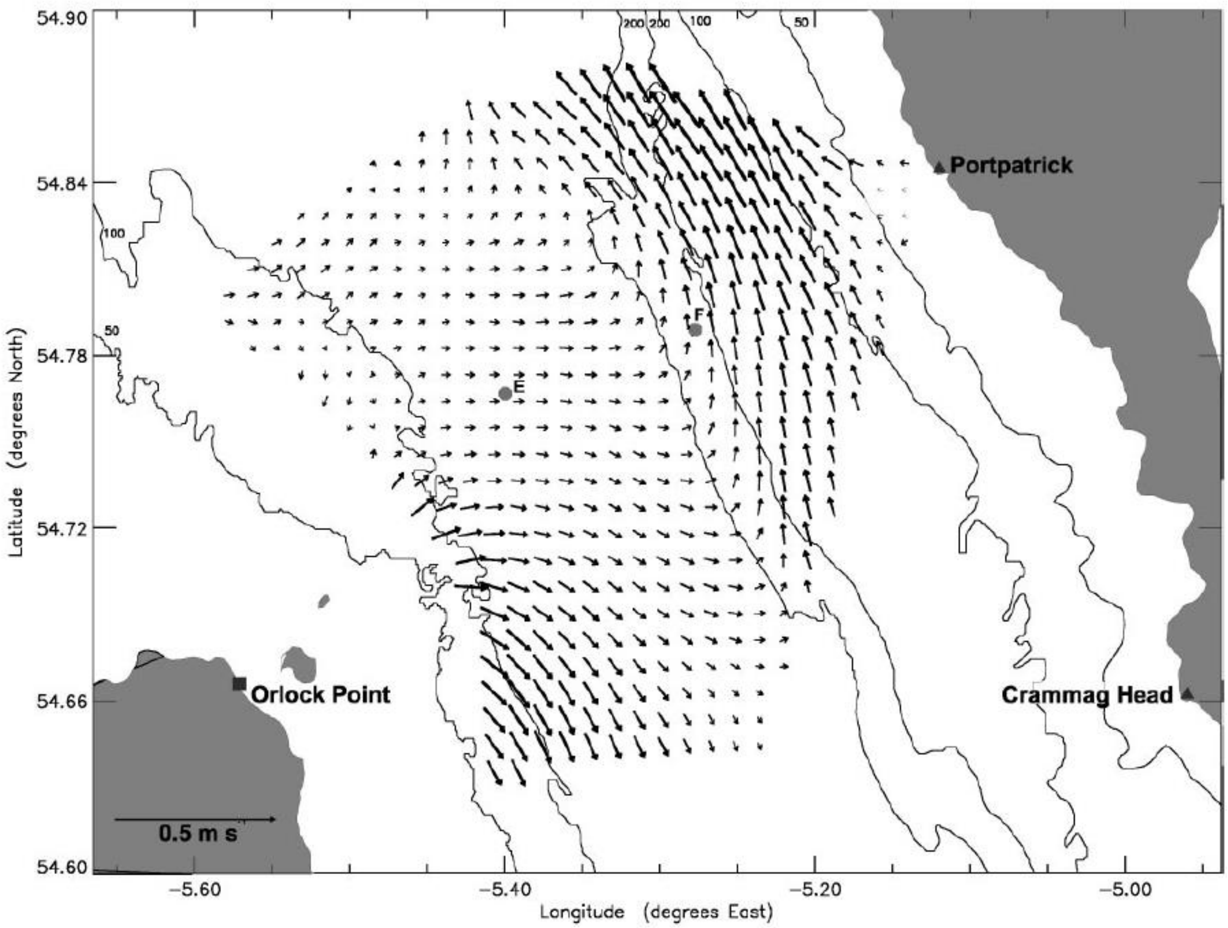

Figure 21: Surface mean flows in a section of the North Channel as described by Knight and Howarth (1999)

7.3 Tides

Tide information was taken from Total Tide, for the same locations which were used for the wind data. Tide information is shown in figure 21.

The dates the models were run cover all stages of the tides (low to high) for both the spring and autumn. For both seasons, the highest tides were in Newcastle, with the lowest tides in Ballycastle. In general, the smallest tides were along the north coast, with tides increasing the further south along the east coast of NI.

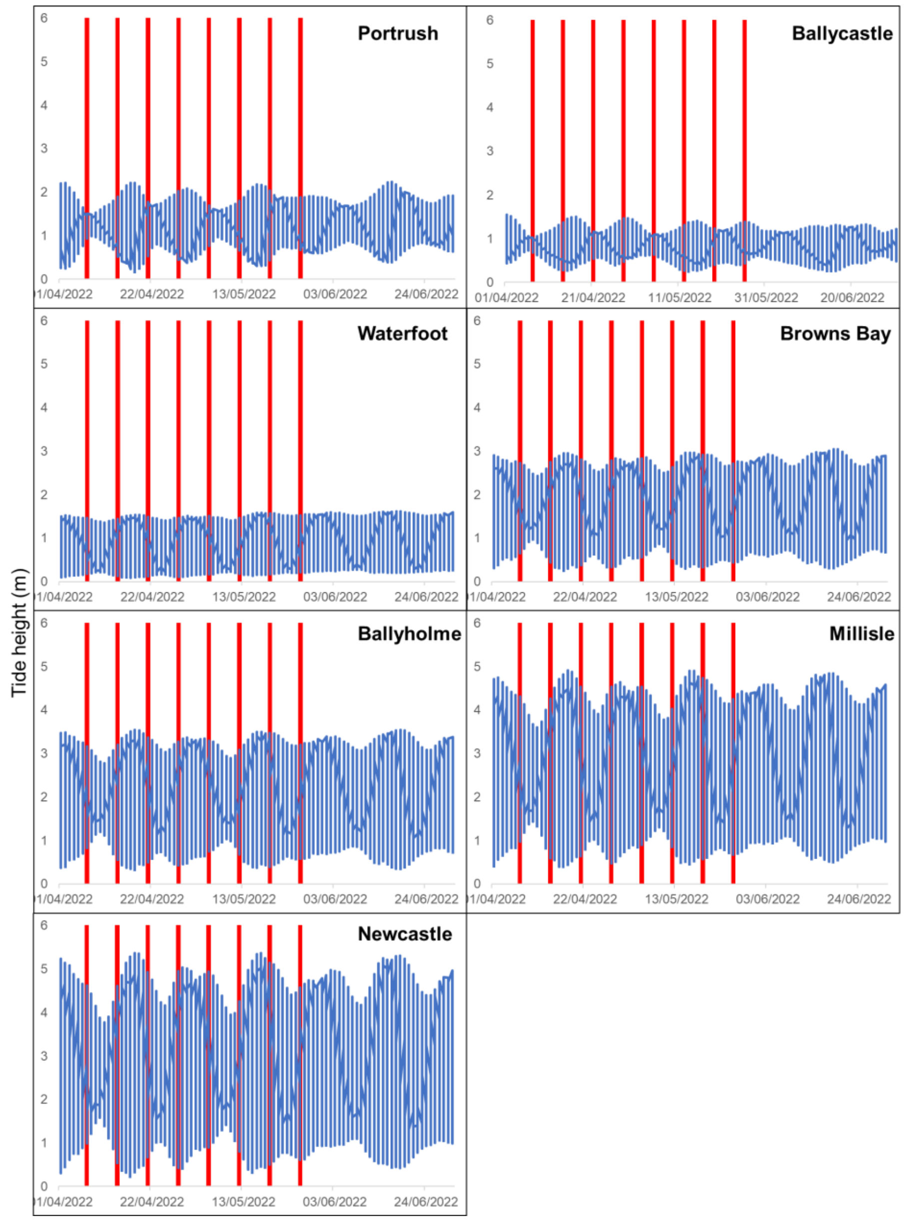

Figure 21a: Tides for 1st April to 30th June 2022. The red line indicates the dates the models were run. Tide information taken from Total Tide.

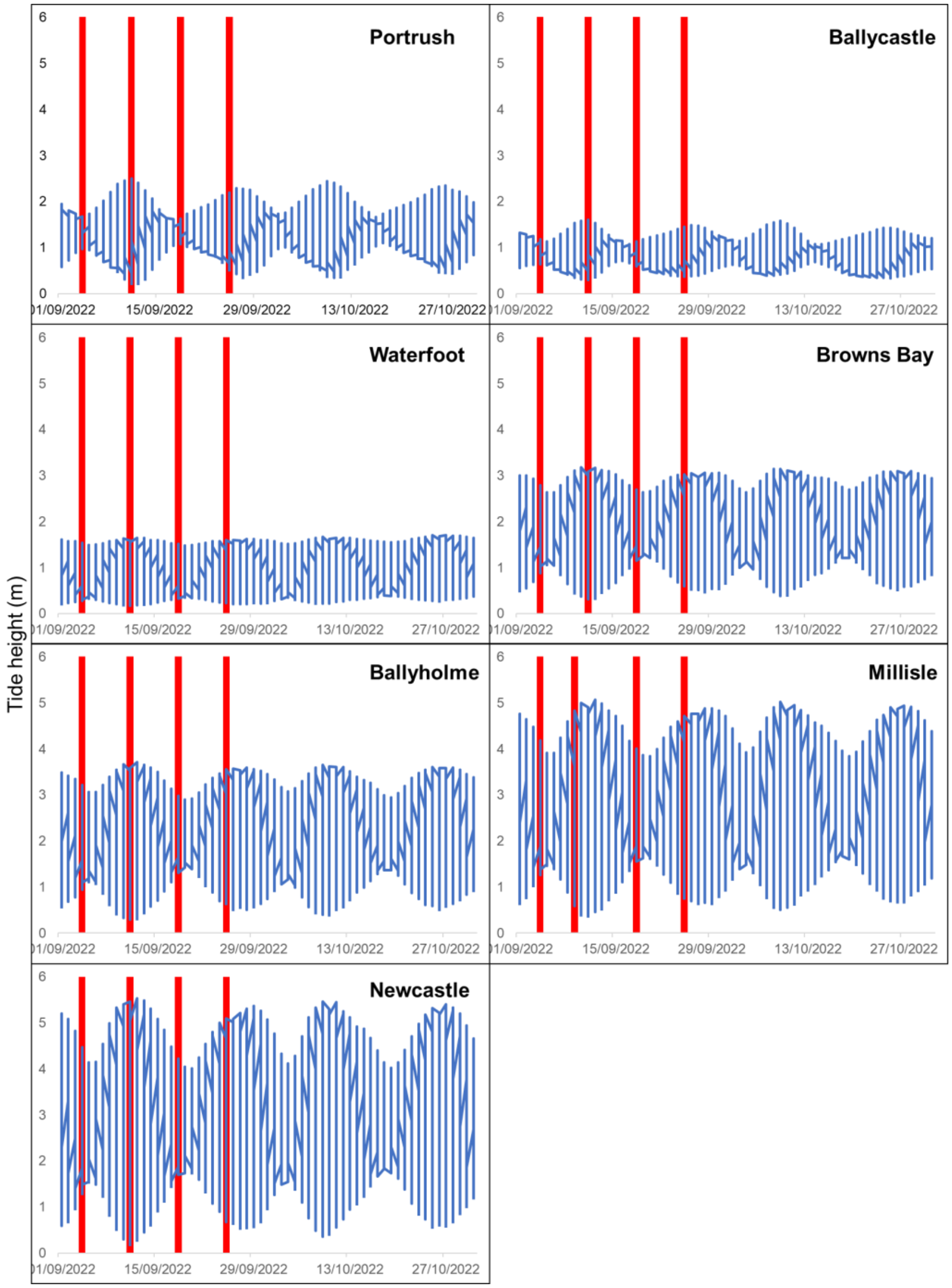

Figure 21b: Tides for 1st September to 31st October 2022. The red line indicates the dates the models were run. Tide information taken from Total Tide.

8.0 Discussion

The movement of larvae is primarily driven by the current. The hydrodynamic model used to describe currents (WeStCOMS v.2) incorporates a range of factors, including local weather conditions (e.g. winds), temperature, salinity and tides (Aleynik et al. 2016). Surface currents (shown in Figure 20 above), are likely to be particularly important in the dispersal of scallop larvae, as initially scallop larvae rise through the water column to the surface. Furthermore, during dispersal, apart from moving up or down in the water column, scallop larvae cannot actively move against the direction of strong currents. For example, in Ballyquintin, for five of the eight spring model runs, the larvae move south out of the study area. In the remaining three runs of the model the larvae move east to the Scottish coast. On these three dates the currents change direction around Dundrum Bay and head east towards Scotland. This change in direction is not evident on the dates when the larvae move south out of the study area. Figure 22 shows an example of how the dispersal is linked to currents, showing examples of when the change in current direction off Dundrum is present and when it is absent. The dispersal tracks also show that the stronger the currents the tighter together the pathways of dispersal.

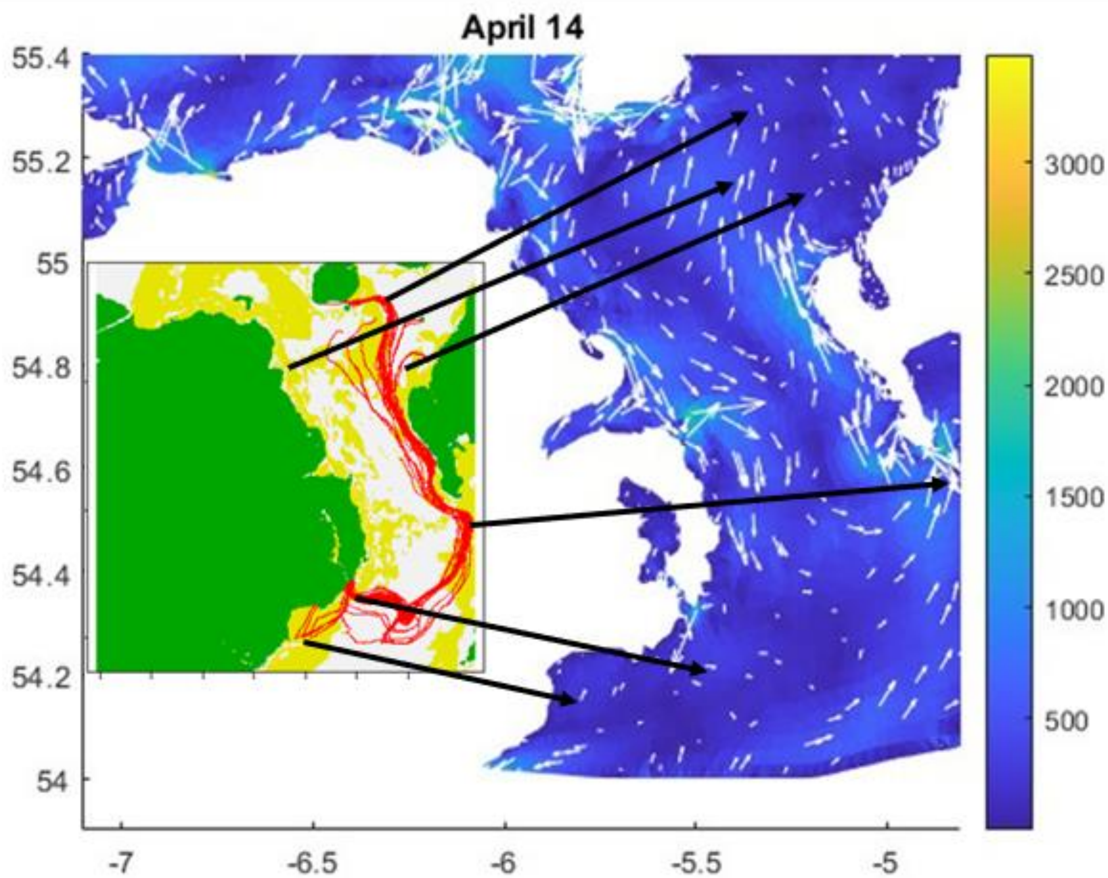

Figure 22a: example of dispersal from Ballyquintin when there is a change in direction of the current offshore from Dundrum Bay.

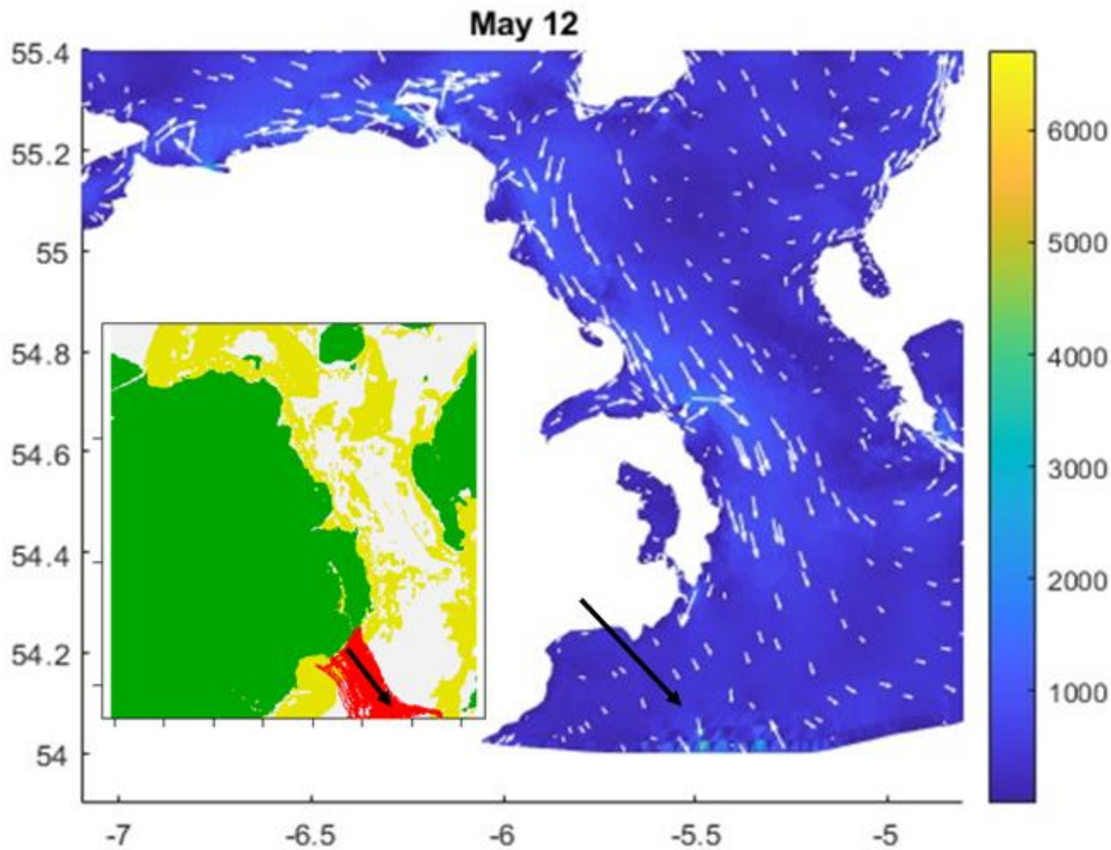

Figure 22b: Examples off dispersal from Ballyquintin Bay when there is no change in direction of the current offshore from Dundrum Bay.

The most variable dispersal pathways from release at the original enhancement sites was noted for the 19th May. On this date, and the 6 days previous and after, for the wind speed and direction are similar to the rest of the month, as are the temperature and pressure. Therefore, local weather conditions cannot account for the divergence in dispersal pathways.

The 19th May is just following a spring tide for the enhancement areas. However, the larval dispersal on the 21st April, also just after a spring tide, does not show this large variation in dispersal pathways, apart from Whitehead, which shows some differences in tracks, but to a lesser degree than on the 19th May. Therefore, currents must account for the movements on the 19th May. Dispersal from the additional modelled sites along the east coast (Maidens MPA and Outer Belfast Lough MPA) show the same divergence in pathways on the 19th May. The north coast sites (Skerries and Causeway MPA and Rathlin MPA) do not show a similar variance in tracks.

The additional sites, which were modelled only for the spring dispersal, showed a higher success in terms of larval settlement within NI waters. The Maidens showed settlement aggregations throughout NI waters on each of the dates modelled. The area of Muck Island/Moyle Interconnector, which is inshore of the Maidens MPA, was investigated during the 2017 site selection scoping exercise. This area was shown to be suitable for scallop settlement and survival scoring favourably across all site characteristics (salinity, thermal stratification, food availability, bed stress, suspended particulate inorganic matter, predation, toxic algal blooms). However, discussions with the industry led to the current four sites being selected above this area. Based on the model outputs shown in this study, it is recommended that the Maidens MPA is the most suitable site of those investigated here for survival of scallops (juvenile and adult) and dispersal of the scallop larvae from this site shows successful settlement within NI waters.

While the other three additional sites showed success in terms of larvae from these areas settling in NI waters, the characteristics of these sites was not analysed in the 2017 site selection report and therefore the suitability is unknown. However, since adult scallops are found in each of these areas, this would indicate that they are suitable sites for juvenile and adult scallop survival.

9.0 Conclusion and next steps

The results presented here suggests that scallops in NI waters have strong linkages with stocks in adjacent waters. Specifically, dependent on the timing of spawning, it is likely that a large proportion of the scallop larvae from the enhancement sites could follow hydrodynamic currents to settle on the west coast of Scotland. Long distance dispersal of scallop larvae is also suggested by results of recent genetic work conducted at AFBI which shows little evidence of genetic differentiation of populations along the Northern Irish coast (currently unpublished). In addition, to further investigation into the influence of timing on the dispersal of scallop larvae, this modelling has given rise to the question of where Northern Irish scallop populations are coming from. Therefore, it is suggested that hindcasting, to see where the population that has settled in the Northern Irish fishery have come from, is suggested for future modelling work.

10.0 References

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Annex 1a

Summary table describing the general dispersal route of larvae from each site, over the spring spawning period. As the figure for settlement is not exact, it has been graded as 0, 1+, 10+, 20+, 30+. Settlement in Northern Ireland waters has been colour coded; red means there is no settlement modelled for NI waters, green means settlement was shown in the model, with the shade of green intensifying with greater settlement.

Site		7th April	14th April	21st April	28th April	5th May	12th May	19th May	26th May
Ballyquintin	General dispersal	South then North to Scotland	East to Scotland	South	South	South	Southeast	Throughout study area	-
	Settlement sites	0	30+	0	0	0	0	30+	1+
	Settlement sites in NI	0	1+	0	0	0	0	30+	0
	Settlement sites in Scotland	0	30+	0	0	0	0	10+	1+
	Settlement sites Isle of Man	0	0	0	0	0	0	1+	0
Drumfad Bay	General dispersal	Onto shore	to Scottish coast	south	Onto shore	Onto shore	southeast to Isle of Man	throughout the study area	south out of study area
	Settlement sites	0	1+	0	0	0	0	10+	0
	Settlement sites in NI	0	0	0	0	0	0	10+	0
	Settlement sites in Scotland	0	1+	0	0	0	0	1+	0
	Settlement sites Isle of Man	0	0	0	0	0	0	0	0
Roaring Rock	General dispersal	south out of study area	retained in Dundrum Bay	retained in Dundrum Bay	retained in Dundrum Bay	retained in Dundrum Bay	south out of study area	retained in Dundrum Bay	south out of study area
	Settlement sites	0	0	0	0	0	0	0	0
	Settlement sites in NI	0	0	0	0	0	0	0	0
	Settlement sites in Scotland	0	0	0	0	0	0	0	0
	Settlement sites Isle of Man	0	0	0	0	0	0	0	0
Whitehead	General dispersal	To southern bank of Belfast Lough	Mainly to Scottish coast	Lenth of east coast of NI	South	South	Southeast	Throughout study area	south
	Settlement sites	1+	1+	10+	0	0	0	30+	0
	Settlement sites in NI	1+	0	10+	0	0	0	10+	0
	Settlement sites in Scotland	0	1+	1+	0	0	0	1+	0
	Settlement sites Isle of Man	0	0	0	0	0	0	1+	0

Maidens MPA	General dispersal	Throughout study area	-	Throughout study area; mainly north	-	Throughout study area; mainly south	-	Throughout study area; mainly north	
	Settlement sites	30+	-	30+	-	30+	-	30+	-
	Settlement sites in NI	30+	-	30+	-	30+	-	30+	-
	Settlement sites in Scotland	30+	-	1+	-	30+	-	30+	-
	Settlement sites Isle of Man	20+	-	0	-	1+	-	1+	-
Skerries and Causeway MPA	General dispersal	primarily North Coast	-	West	-	primarily North Coast; some South	-	All north Coast	-
	Settlement sites	30+	-	30+	-	30+	-	0	-
	Settlement sites in NI	30+	-	10+	-	30+	-	0	-
	Settlement sites in Scotland	30+	-	0	-	10+	-	0	-
	Settlement sites Isle of Man	1+	-	0	-	0	-	0	-
Outer Belfast Lough MPA	General dispersal	All south	-	Length of NI	-	All south	-	Throughout study area	-
	Settlement sites	1+	-	30+	-	1+	-	30+	-
	Settlement sites in NI	1+	-	30+	-	1+	-	30+	-
	Settlement sites in Scotland	0	-	0	-	1+	-	10+	-
	Settlement sites Isle of Man	0	-	0	-	0	-	1+	-
Rathlin MPA	General dispersal	primarily North Coast; some east and south movement	-	primarily around Rathlin Island	-	primarily around Rathlin Island; some south	-	primarily around Rathlin Island, some west	-
	Settlement sites	30+	-	1+	-	10+	-	1+	-
	Settlement sites in NI	30+	-	1+	-	10+	-	1+	-
	Settlement sites in Scotland	20+	-	0	-	1+	-	0	-
	Settlement sites Isle of Man	0	-	0	-	0	-	0	-

Annex 1b

Summary table describing the general dispersal route of larvae from each site, over the autumn spawning period. As the figure for settlement is not exact, it has been graded as 0, 1+, 10+, 20+, 30+. Settlement in Northern Ireland waters has been colour coded; red means there is no settlement modelled for NI waters, green means settlement was shown in the model, with the shade of green intensifying with greater settlement.

Site		4th Sept	11-Sep	18-Sep	25-Sep
Ballyquintin	General dispersal	Throughout study area	south	south	south
	Settlement sites	30+	1+	0	0
	Settlement sites in NI	20+	1+	0	0
	Settlement sites in Scotland	1+	0	0	0
	Settlement sites Isle of Man	0	0	0	0
Drumfad Bay	General dispersal	North	Throughout survey area	South	South
	Settlement sites	0	1+	0	1+
	Settlement sites in NI	0	1+	0	0
	Settlement sites in Scotland	0	1+	0	0
	Settlement sites Isle of Man	0	0	0	1+
Whitehead	General dispersal	North	Throughout survey area	south	south
	Settlement sites	20+	10+	1+	1+
	Settlement sites in NI	10+	10+	0	1
	Settlement sites in Scotland	1+	1+	0	1+
	Settlement sites Isle of Man	0	0	0	0
Whitehead	General dispersal	retained in Dundrum Bay	retained in Dundrum Bay	retained in Dundrum Bay	South
	Settlement sites	0	0	0	0
	Settlement sites in NI	0	0	0	0
	Settlement sites in Scotland	0	0	0	0
	Settlement sites Isle of Man	0	0	0	0