

Evidence of potential synergy between aquaculture and offshore renewable energy

J. Demmer, M. Lewis, P. Robins and S. Neill

Abstract—Worldwide increased demand for offshore renewable energy (ORE) industries and aquaculture requires developing efficient tools to optimize the use of the offshore space, reducing anthropic pressure. The synergetic development of marine renewable energy infrastructure with mariculture has been hypothesized as a way to reduce costs through shared infrastructure. In the Irish Sea, blue mussels (*Mytilus edulis* L.) represent 40 - 50 % of the total gross turnover of Welsh shellfish industries and the industry has been operating sustainably for over 50 years in North Wales. However, the region is also attractive for tidal energy projects, with strong tidal currents (> 2m/s) occurring, and offshore wind farms, with shallow waters (approx. 50 m) and consistent winds. In this context, it is of scientific and economic interest to study the potential impact of ORE on shellfish larvae recruitment. A numerical approach has been developed using an Eulerian hydrodynamic model coupled with a Lagrangian particle tracking model, which allowed the simulation of tidal currents, wind-driven currents and larval dispersal. Results show: 1) interannual variability of density distribution of larvae; and 2) strong connectivity between commercial shellfish beds and ORE sites. This study shows the importance of ORE site selection in order to: 1) reduce biofouling on ORE infrastructures and 2) develop multi-use platforms at sea to combine needs for ORE and for mariculture.

Keywords—Aquaculture, Connectivity, Larvae, Numerical model, Offshore renewable energy,.

I. INTRODUCTION

The Irish Sea is host to numerous activities such as renewable energy, tourism, aquaculture and maritime transport, resulting in an increase of offshore human infrastructures and pressure on marine sea space with implications for wildlife [1]. One option, to ease the demand for space, is the development of multi-use

platforms at sea, where co-location of industries such as aquaculture and offshore renewable energy projects can exist without detrimental feedbacks – or even benefit from one another [2].

Offshore renewable energy (ORE) in the Irish Sea is predicted to occupy approximately 14% (6,564 km²) of the sea space in the future, assisting the UK government ambition of Net Zero carbon emission (Fig. 1). The highest concentration of ORE is located in the eastern Irish Sea, which is also an important region for shellfish aquaculture (Fig. 1). In the UK, blue mussel cultivation represents 95% of production and 82% of imputed value [3]. The mussel industry in North Wales represents one third of the UK production (valued at ~ £15M), which makes shellfisheries aquaculture economically significant to the area, hence the concern that it could be impacted by the development of other industries [3].

The connectivity between distinct shellfish populations within the Irish Sea has been studied by Robins et al. [4], who showed variable connectivity according to the site of release and larvae behaviour (e.g. larvae that are passively transported by currents or which vertically migrate at diurnal timescales). However, that study did not include the connectivity with ORE sites. It has been calculated that each turbine within the North Hoyle wind farm contains 1,000 - 1,300kg of attached marine life, with *Mytilus edulis* the dominant species [5] and [6]. Furthermore, Inger et al. [7] showed that offshore marine renewable energy infrastructures can be both detrimental (e.g. habitat loss and/or spread of invasive species) and beneficial (e.g. acting as an artificial reef and/or fish aggregation devices) on biodiversity. In this context, we seek to understand the potential impacts of ORE developments in the Irish Sea on larval connectivity amongst aquaculture sites.

A key aim of this study is to use modelling to: 1) study the interannual (2014 and 2018) dispersal of mussel larvae from 6 commercial mussel beds according to two plausible

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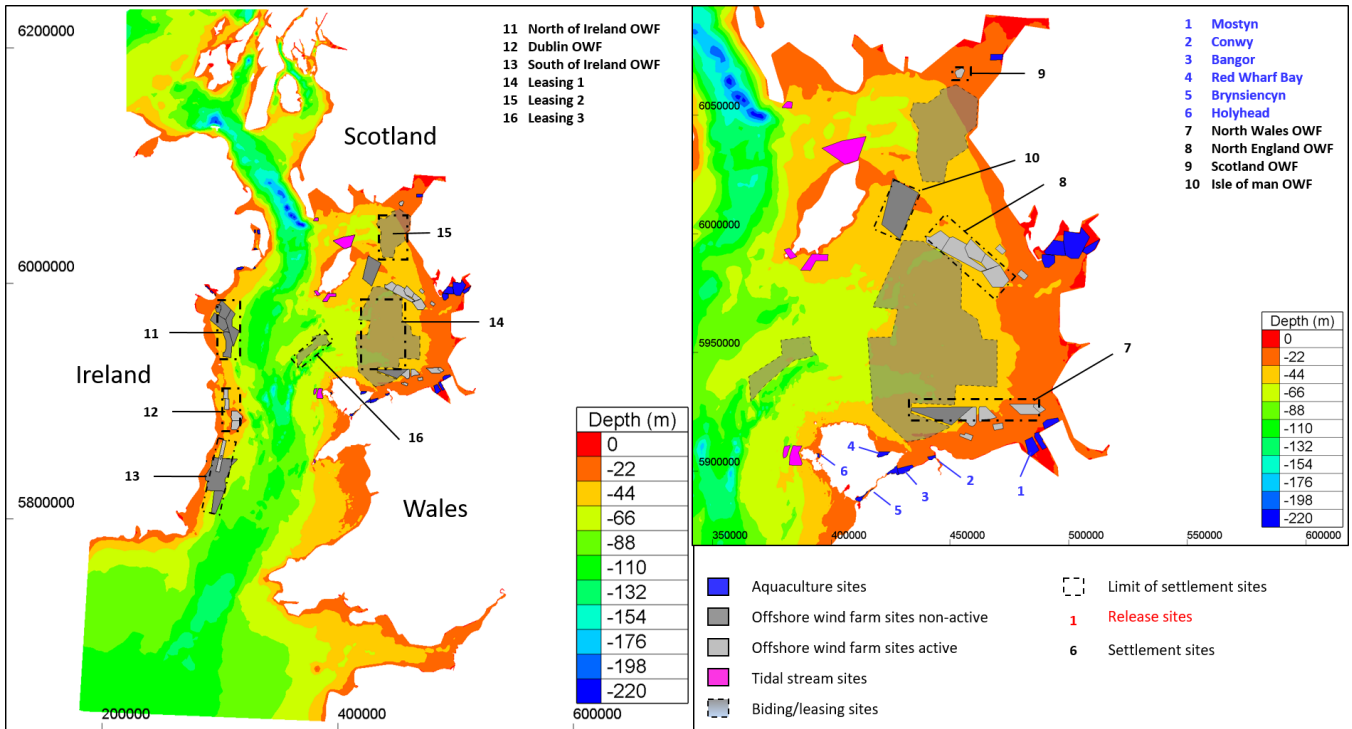


Fig. 1. Domain of study showing the Irish Sea hydrodynamic model domain (WGS84 coordinates in m) and bathymetry (m relative to MSL), the larval release and sink sites (1-6 in blue), plus additional sink sites only (black dashed-dotted area 7-16).

larval behaviours (i.e. larvae remain at the surface or larvae travel in the mid-water column); 2) qualify the density distribution; and 3) qualify and quantify the connectivity between ORE (10 Sites) and aquaculture (6 Sites).

II. MATERIAL AND METHODS

A. Study area

The Irish Sea connects Ireland and Great Britain, coverings approximately 47,000 km² with a volume of 2,430 km³, connecting to the Atlantic Ocean via the Celtic Sea in the southwest by St George's Channel and via the North Channel in the north [8] and [9] (Fig. 2). The Irish Sea is approximately 300 km in the northwards direction and varies from 75 km to 200 km in the eastwards direction reducing to 30 km in the North Channel [8]. The topography consists of a deeper channel in the west (30-50 km wide, 300 km long and up to 175 m deep) but depths remain generally shallow, especially in the eastern Irish Sea, with a mean depth of 60 m [10] (Fig. 1).

The Irish Sea circulation is primarily controlled by an energetic tidal regime, which creates an annual average net flux northward of 2.5 Sverdrups [11]. Tidal velocities are governed by local bathymetry and tidal range, which varies from over 10 m in Liverpool Bay and the Bristol Channel, to amphidromic points (near zero tidal amplitude) southeast of Ireland and northeast of Northern Ireland [8]. Tidal currents exceed 1 m/s at spring tides throughout St Georges Channel and the North Channel, and can locally exceed 2 m/s in regions such as around headlands (e.g. Pembrokeshire, Llyn Peninsula and northwest Anglesey), and through tidal channels (e.g. the

Menai Strait). Areas of weaker tidal currents (less than 0.5 m/s) can be found in shallower and sheltered bays (e.g. Cardigan Bay, Liverpool Bay and along the Cumbrian coast).

Significant residual flows are observed: 1) directed southward along the east coast of Ireland; 2) westward from South Wales towards Ireland along St. George's Channel: the Celtic Sea front; 3) directed southward from Llyn peninsula to Cardigan Bay; and 4) directed westward along the north Wales coast: Liverpool bay front [12] (Fig. 2). Due to high energy, most of the Irish Sea remains well mixed throughout the year. However, stratification over the summer months occurs in the east and west of the Isle of Man and in Cardigan Bay due to weaker tidal currents in these areas.

All these observations show that both barotropic (gravity-driven; e.g., tides or wind) and baroclinic (density-driven; e.g., tidal mixing fronts) components have a fundamental roles in the water circulation in the Irish Sea and consequently may influence larval dispersal [4].

B. Irish Sea hydrodynamic model and validation

Telemac-2D depth averaged model (V7p2, www.opentelemac.org) has been applied as the unstructured finite-element method is well suited to resolve complex tidal flow in coastal areas [13] and [14]. The mesh density varied from 30 m in the coastal regions to 5,000 m in deeper offshore regions. The domain covered an area of 165,000 km², and contains 206,413 nodes, which correspond to the whole Irish Sea as previous studies show that larvae can potentially travel up to 300 km [15].

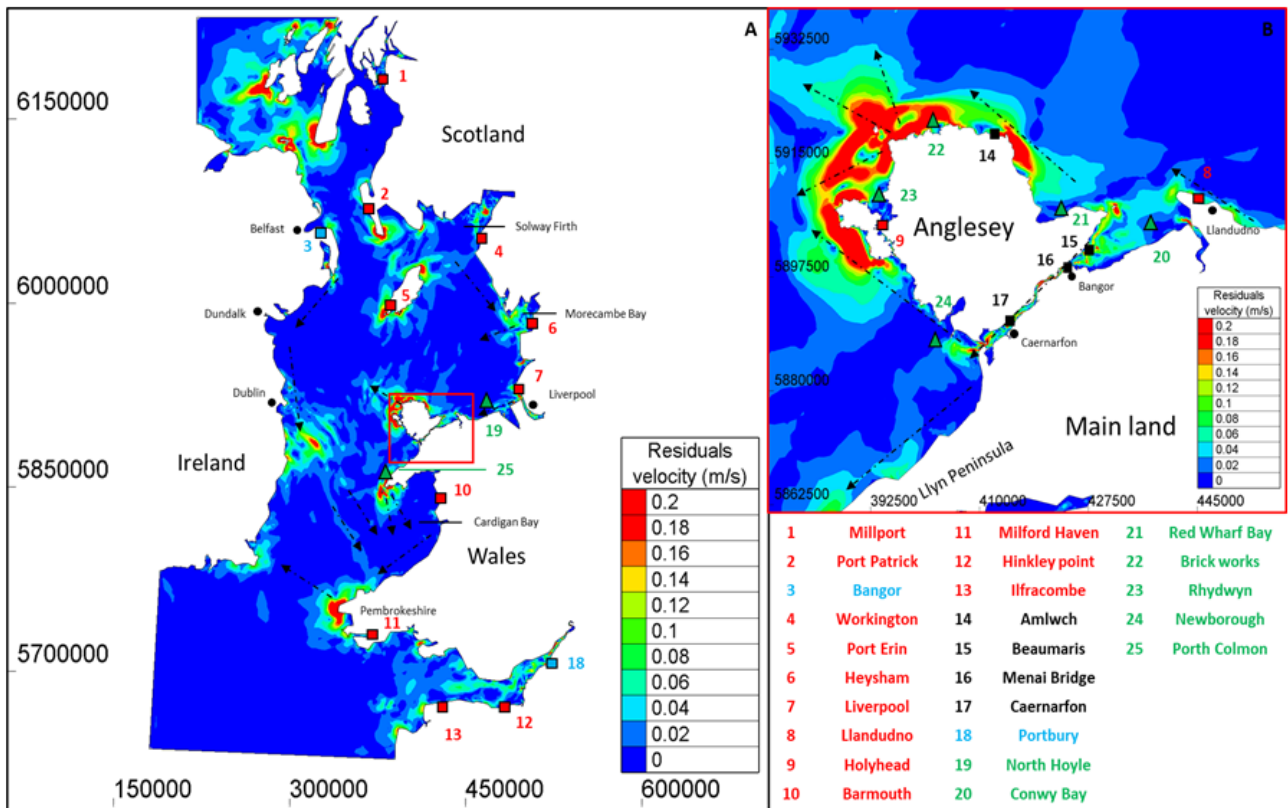


Fig. 2. Contour map showing the simulated residuals (m/s) in the Irish Sea, using the model described here, with direction of the main residuals plotted (black arrows). Tide gauge sites (red, black and blue squares) and ADCP velocity sites (green triangles) used for model validation are shown.

The computational grid was mapped onto bathymetric data comprising an assemblage of: 1) multi-beam data collected during 2012 (high resolution: ~ 5 m); 2) LiDAR data collected during 2013 (high resolution: ~ 2 m); and 3) Admiralty bathymetric data of the offshore regions at both end of the Strait (interpolated onto a 200 m horizontal resolution grid) [16]. To ensure stability, models ran with a 2 seconds time-step and models outputs (velocity and water elevation) were stored every 30 minutes. A constant coefficient friction of 0.1 was implemented in Nikuradse's law of bottom friction, which correspond to a bottom composed mostly by sand, i.e. the composition of the majority of the sea bed of the Irish Sea [17].

Validation was based on the Root Mean Square Error (RMSE) and the Normalized Root Mean Square Error (NRMSE), between the observations and model outputs: (1) for water elevation (14 tide gauge sites); (2) for velocity (7 sites for velocity magnitude and direction); and (3) for tidal analysis was (16 sites on the primary semi-diurnal lunar tidal constituent (M_2)); as shown on Fig. 2.

C. Particle tracking model simulations

A Lagrangian particle tracking model (PTM) was developed for this study to predict the likely dispersal of *M. edulis* larvae from six released sites (Fig. 1). Parameters and assumptions used for this study of larvae dispersal in the Irish Sea were as follows:

- Simulate dispersal using both advective and diffusive processes [18]; [19] and [4].

- 7,000 particles per site scattered in an area of 0.2 km² during 45 days.
- No larval swimming behaviour was simulated as the strong tidal currents in the region (up to 3 m/s) are vertically homogenous, and so any vertical migration behaviour of the larvae would have minimal impact on their horizontal dispersal [20].
- The Irish Sea is considered well mixed during the period of study [8].
- No mortality was considered as this would reduce the data size for the statistical analysis [21].
- Linear interpolation of velocity data: 1) temporally from 30 min (Telemac output) to 5 min (PTM output); and 2) spatially to individual particle positions in order to represent the continuity of the velocity field.
- Particles advected onto land are reflected back to their previous position, maintaining the maximum number of particles throughout the simulated period [22] and [23].
- Simulations were performed using wind data from 3 local meteorological stations downloaded from the Centre for Environmental Data Analysis (CEDA). The simulated trajectories from each wind scenario every year were combined. The approximation of the surface current and wind impact was made based on Proctor *et al.* [14].

D. Analysis methods

Spatial density distribution of dispersed particles (or ‘heat maps’) were calculated every week (i.e. weekly cumulative dispersal) as the percentage of all released particles per 25 km² grid cell. This procedure was repeated for both larval behaviours (i.e. transported at mid water depth or at the surface) and for both years studied (i.e. 2014 and 2018).

Connectivity and self-recruitment were calculated every week (i.e. 6 weeks in total) for all simulations. In this study, 16 sites were studied: 1) six sites will be used as source and sink and are located in North Wales; and 2) 10 settlement sites representing ORE sites (Fig. 1). Connectivity has been adapted from the method used in [4] to obtain results in percentage (%). The calculation gave the proportion of larvae that successfully settle after the PLD. Particles were assumed to have settled when they were present within the boundary of one of the 16 sites of interest. Every particle that reached one of the sites of interest during the whole week was counted as a settler. The surface of settlement area was defined according to the site of interest to create deterministic results (Fig. 1).

Surface elevation		
RMSE (m)	NRMSE (%)	R ²
0.45	~6	0.92
Velocity direction		
RMSE (degree)	NRMSE (%)	R ²
36.27	~11	0.84
Velocity magnitude		
RMSE (m/s)	NRMSE (%)	R ²
0.07	~10	0.88
Tidal analysis		
Difference (%)		
-4		

III. RESULTS

E. Validation

Results showed the NRMSE for water elevation was 5.7%, on average for the 14 sites, and for velocity magnitude and direction were 9.8% and 11.2% respectively, on average for seven sites (Table 1). Tidal

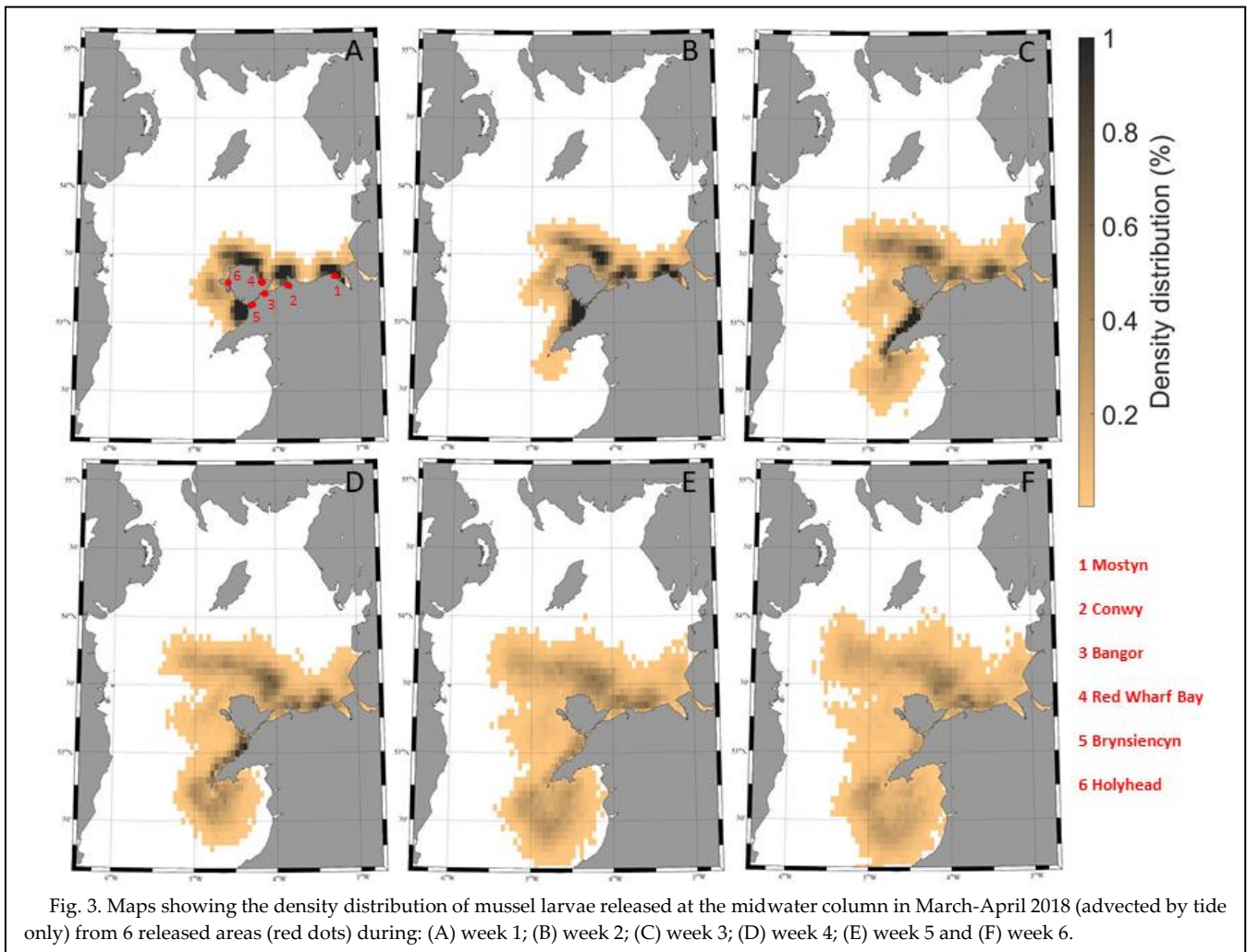


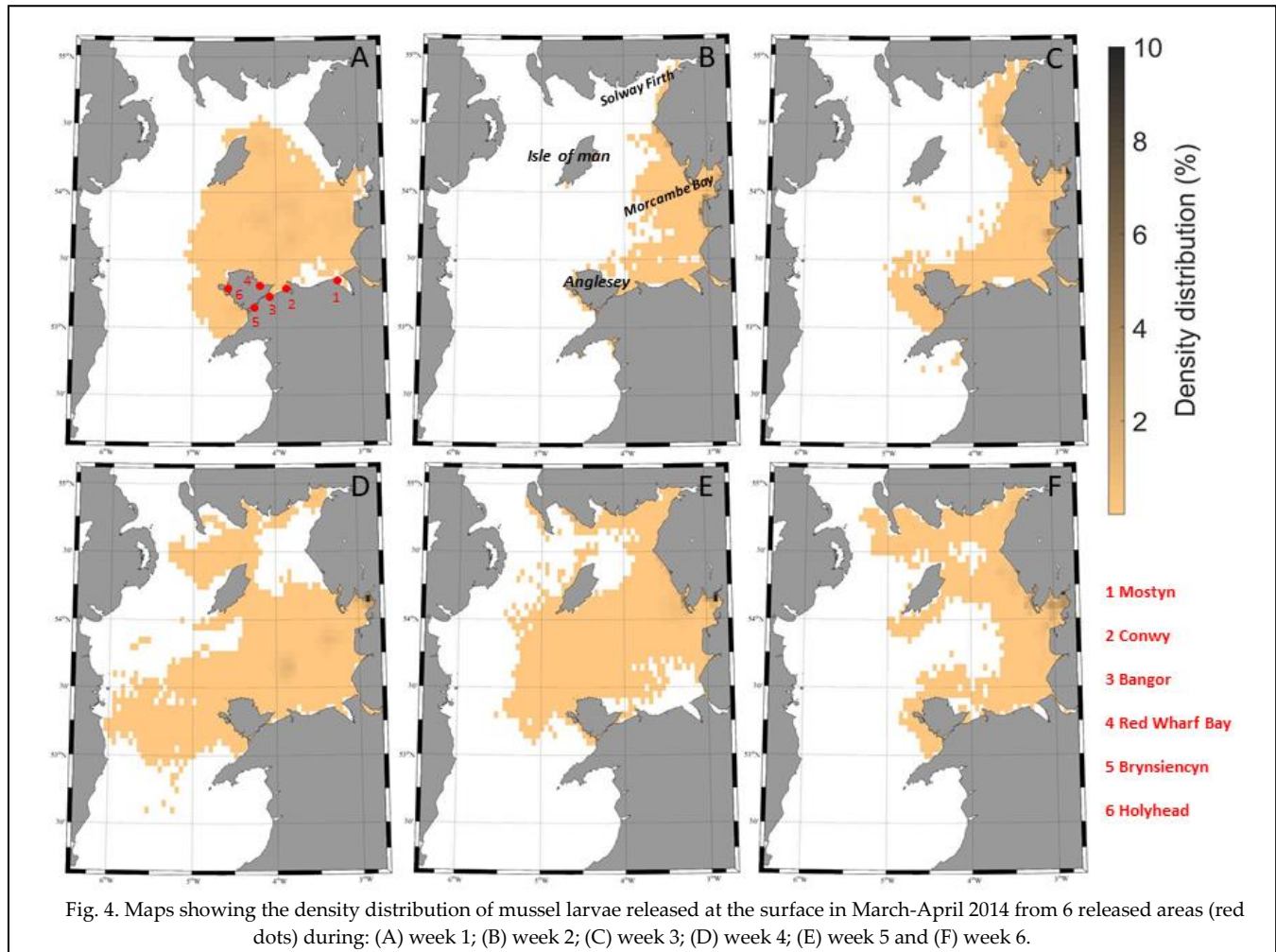
Fig. 3. Maps showing the density distribution of mussel larvae released at the midwater column in March-April 2018 (advected by tide only) from 6 released areas (red dots) during: (A) week 1; (B) week 2; (C) week 3; (D) week 4; (E) week 5 and (F) week 6.

analysis showed that the model underestimate the M2 tidal constituent by 4.3% on average for 16 sites (Table 1).

F. Density distribution

1) Mid-water depth dispersal

Larvae originated from the Menai Strait (Brynsiencyn and Bangor, Wales) are mostly found along the Llyn Peninsula and south of the Llyn Peninsula. Finally, mussel larvae from Holyhead are mostly observed in the middle of the Irish Sea.



Very similar results were obtained for particles released at mid-water depth during spring 2014 and 2018. Consequently, only the results of density distribution during spring 2018 are shown.

Density distribution of larvae varied temporally and spatially. The highest density distribution of larvae is found at the southwestern approach to the Menai Strait at week 1 and week 2 on average for all sites (5% and 3% respectively; Fig. 3A and 3B). After, 3 and 4 weeks of simulation 2% of larvae are found along the Llyn peninsula on average for all release sites (Figure 3C and 3D). The last two weeks simulated (week 5 and week 6) showed that the larvae are more likely to be found (1%) between Anglesey and the Isle of Man on average for all sites (Fig. 3E and 3F).

Larvae released from Mostyn are mainly found between Llandudno and Mostyn along the coast after 6 weeks of simulation (2%). Mussel beds located in Conwy and Red Wharf Bay contribute mostly to the larval density between Anglesey and Isle of Man (1.8% and 2.5%, respectively).

2) Surface dispersal in spring 2014

For all sites together, the highest density of larvae is located at the southwestern approach to the Menai Strait after one week (3%; Fig. 4A). From week two to six, the highest density of mussel larvae is found in Morecambe Bay, with values reducing from 19.5% to 8.7% between the second and the sixth week for all released sites (Fig. 4B, 4C, 4D, 4E and 4F). However, results showed that larvae dispersed in most of the eastern Irish Sea after one week, four week and five week during spring 2014 (Fig. 4A, 4D and 4E).

3) Surface dispersal in spring 2018

As previously observed for the year 2014, the highest density of larvae is located at the southwestern approach to the Menai Strait after one week during spring 2018 (3.5%; Fig. 5A). After two weeks, mussel larvae are mostly present in the western Irish Sea (Irish coast 2.5%; Fig. 5B). From week three to five, results showed that larvae are mainly located offshore on average for all sites, varying from 1.5% to 0.6% (Fig. 5C, 5D and 5E). At the end of the

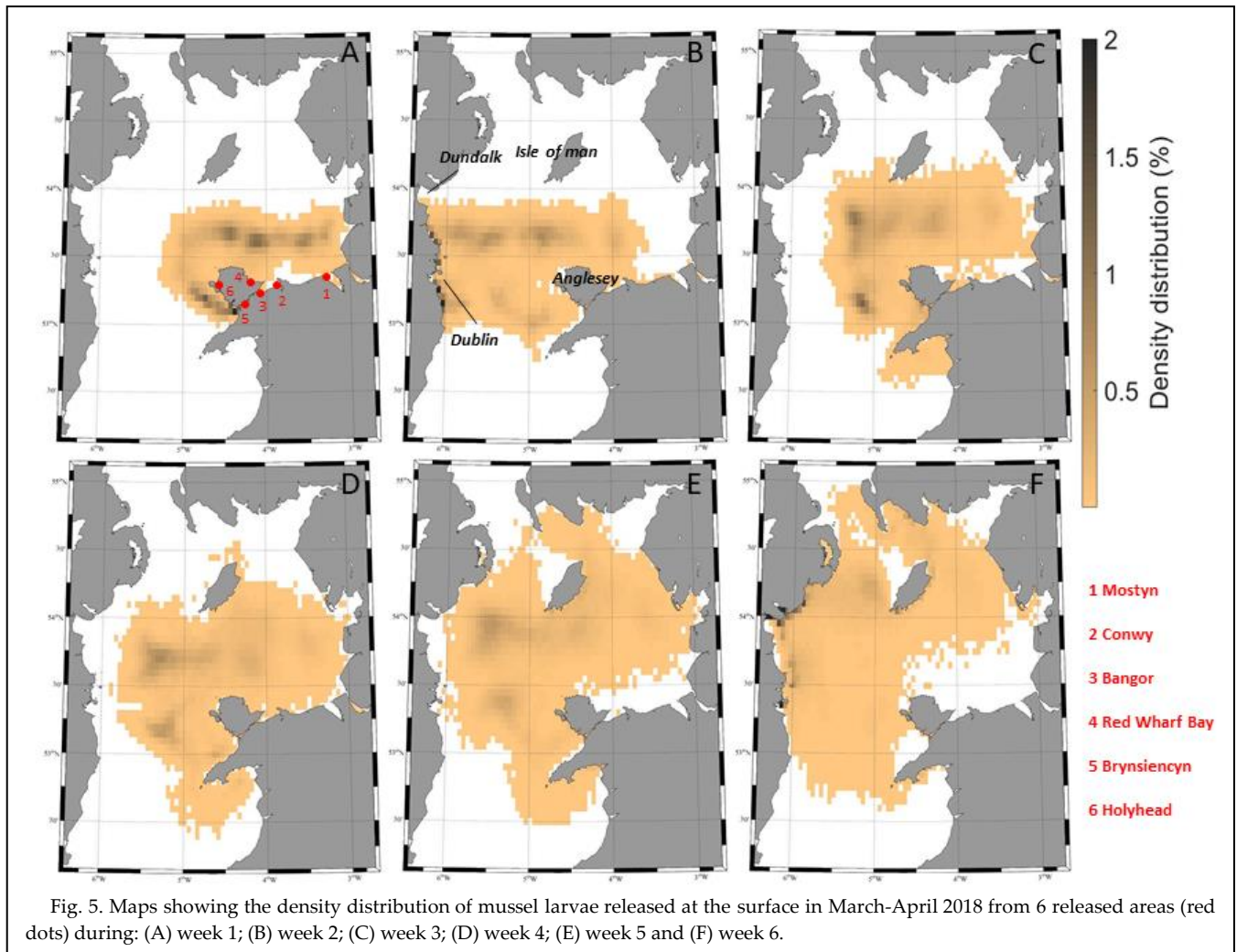


Fig. 5. Maps showing the density distribution of mussel larvae released at the surface in March-April 2018 from 6 released areas (red dots) during: (A) week 1; (B) week 2; (C) week 3; (D) week 4; (E) week 5 and (F) week 6.

simulation (week 6), 3.5% of the larvae are located on the Irish coast again (3.5%) (Fig. 5F).

G. Connectivity

4) Midwater depth dispersal

Leasing 1 (sink site 14) was connected with Conwy (46% on average for all the weeks), Red Wharf Bay (41% on average for all the weeks) and Holyhead (6% on average for all the weeks) (Figure 6.1). The connectivity between Mostyn and Leasing 1 increased from 3% (week 2) to 36% (week 6) (Fig. 6.1.b and 6.1.f). In addition, Conwy showed an increase of connectivity with North Wales offshore windfarms (OWF) from week 1 (3% on average for both sites) to week 6 (19% on average for both site). Bangor (Wales) and Brynsiencyn showed no connectivity with ORE sink sites selected (Fig. 6.1). From week 3, Red wharf bay and Holyhead showed connectivity (2% on average for both sites and all weeks) with Leasing 3 (sink site 16). No significant connectivity is observed between the source sites and the sink sites located on the Irish coast (north of Ireland, Dublin and south of Ireland), Isle of Man OWF, north England OWF and Scotland OWF.

5) Surface dispersal in spring 2014

Leasing 1 is connected with all source sites with weekly variability. On average for all weeks, the highest

connectivity is observed with Conwy and Bangor, Wales (23%) followed by Red Wharf Bay (18%); Brynsiencyn and Hoyhead (13%) and Mostyn (6.5%) (Fig. 6.2). No connectivity was observed between source sites and sink sites located on the Irish coast (north of Ireland OWF, Dublin OWF and south of Ireland OWF); Leasing 3 and Scotland OWF. North Wales OWF is mostly connected with Bangor and Brynsiencyn (1.8% on average for all weeks and both sites). On average for all weeks, North England OWF is connected mainly with Mostyn (3%).

6) Surface dispersal in spring 2018

North Wales OWF showed connectivity with Mostyn (15%) and Conwy (19%) at week 1, and then no connectivity was observed during the rest of the simulation (Figure 6.3). In addition, North England OWF, Scotland OWF, Leasing 2 and South of Ireland OWF showed no connectivity during spring 2018 with the source sites (Fig. 6.3). Mostyn and Conwy are highly connected with Leasing 1 (33% for both on average for all weeks), with the highest connectivity at week 1 and week

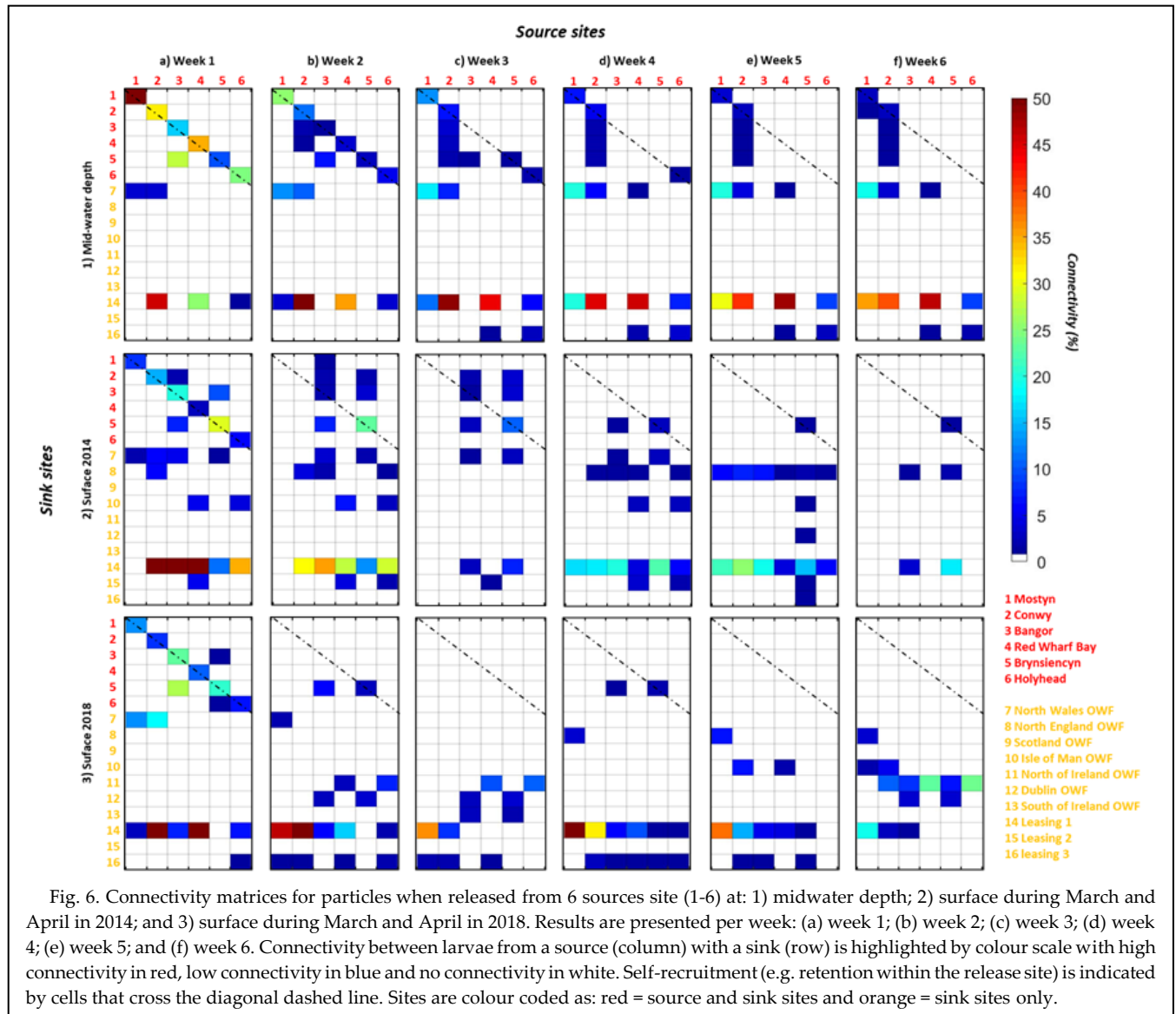


Fig. 6. Connectivity matrices for particles when released from 6 sources site (1-6) at: 1) midwater depth; 2) surface during March and April in 2014; and 3) surface during March and April in 2018. Results are presented per week: (a) week 1; (b) week 2; (c) week 3; (d) week 4; (e) week 5; and (f) week 6. Connectivity between larvae from a source (column) with a sink (row) is highlighted by colour scale with high connectivity in red, low connectivity in blue and no connectivity in white. Self-recruitment (e.g. retention within the release site) is indicated by cells that cross the diagonal dashed line. Sites are colour coded as: red = source and sink sites and orange = sink sites only.

2 for Conwy (68%) and highest connectivity at week 4 for Mostyn (62%) (Fig. 6.3.a and 6.3.d). The Isle of Man showed a low connectivity at week 6 with Mostyn and Conwy (< 5% for both) (Fig. 6.3.f). Dublin showed connectivity with Bangor, Wales (3.4%) and Brynsiencyn (3.7 %) at week 3 and week 6 (Fig. 6.3.c). After six weeks of simulation, north Ireland OWF showed connectivity with: (1) Holyhead and Red Wharf Bay (23% for both); (2) Bangor, Wales and Brynsiencyn (7.3% for both); and (3) Conwy (10%) (Fig. 6.3).

IV. DISCUSSION

The simulated dispersal scenarios were chosen to represent two extreme cases of larvae behaviour (e.g. larvae travelled at the surface and larvae travelled in midwaters with no vertical swimming) and, hence, capture a wide range of potential dispersal distributions, in order to define the best area for co-location between mussel aquaculture and offshore wind farms. Indeed, if particles stay at mid-water depth, they are only submitted to tidal advection, whereas when larvae are at the surface, they encountered stronger currents (e.g. wind driven currents)

which increase their dispersal [24] and [25]. In addition, previous studies showed the importance of circulation patterns on interannual variability of larvae recruitment and eggs/larvae dispersal [26] and [27]. In order to resolve interannual variability in mussel larvae dispersal, simulations occurred during two contrasting years (e.g. 2014 and 2018). Indeed, the wind during March and April 2014 and 2018 were different in strength and direction and consequently have a different impact on surface currents (data not shown). These years were also chosen according to mussel farms harvest data, which showed that in 2014, 1,100 tonnes of seed were harvested in Morecambe Bay, whereas recruitment in 2018 was too small to be harvested.

Assuming mussel larvae are distributed throughout the water column, e.g. developing weak vertical migration, then their dispersal will be controlled by tidal currents and in particular tidal residuals [28]. These tidal residuals can be represented by the monthly-averaged velocities output from the model (Fig. 2). The same pattern of results are observed when the strength and the residual currents are compared between simulation in 2014 and 2018 (data not shown), which explains why the mussel larvae distribution is the same when released at mid-water depth.

These patterns can be used to explain the variability in the larvae dispersal simulated from the mid-water scenarios (Fig. 3). Particles released from Bangor (Wales) and Brynsiencyn dispersed south-westwards through the Menai Strait, along the Llyn Peninsula and into Cardigan Bay – in accordance with the residual tidal currents shown in Fig. 2 [29]. Consequently, the mussel larvae released in the middle of the water column from these two sites showed no connectivity with offshore renewable structures located in the eastern Irish Sea or along the Irish coast (Fig. 6). The dispersal of particles from Conwy was westwards due to westwards residual currents along the north Wales and Anglesey coasts, and south-westwards towards the Menai Strait (Fig. 2). Particles from Red Wharf Bay and Holyhead dispersed westwards then offshore and northwards in accordance with the residual currents, which explain the increase in connectivity through time with Leasing 1 (Fig. 2 and 6). The same residual currents were observed by Ward *et al.* [30] around Anglesey, especially near Holyhead where strong tidal currents occur. Mostyn showed a different pattern compared to the other release sites as particles travelled both westwards along the coast of North Wales and northwards along the English coast to Southport [31] (Fig. 2). The larvae dispersal varied in direction and distance travelled between the 6 released sites, which is the consequence of large variability of tidal current velocities which can reach 2 m/s in certain localised regions such as headlands (e.g. Llyn Peninsula and northwest Anglesey) and tidal channel (e.g. the Menai Strait) [29]. The site of larval release is of major importance as previously demonstrated for other area and other species [32] and [33].

For the 2014 simulations, results showed that particles from all sites mostly concentrate near Morecambe Bay. This is the consequence of a persistent westerly wind during March and April which reduced the influence of residual tidal currents shown in Fig. 2. These results are correlated with previous studies [29] and [34], which showed that southwards residual currents in the Menai Strait can be reversed to northwards flow at the surface during strong and consistent wind events. For the 2018 simulations, the wind in March and April was generally weaker than March-April 2014 and the wind direction varied (data not shown). Consequently, particles were influenced by both wind-driven and tidal residuals, and the local release locations remained an important factor for dispersal. For the first time, this study showed that site's effect on dispersal could be removed if PLD occurs during strong and persistent wind events like that occurred in March-April 2014. In addition, the results support the observations made by mussel farmers in Morecambe Bay during spring/summer 2014 and 2018, suggesting that mussel larvae are mostly influenced by surface current (Fig. 4 and 5).

The results highlight the importance of the vertical position of larvae in the water column to study potential areas for multi-use platforms at sea (MUPS). Indeed, the

results indicate that Leasing 1 is connected with released sites for all scenarios tested. Consequently, the chance of bio-fouling if offshore renewable energy is installed in this area is high, which could increase the cost of maintenance and the erosion of the structure. The development of MUPS on Leasing 1 will benefit: 1) for both industry by collect mussel larvae before they settle on offshore structures; and 2) for coastal biodiversity by reducing dredging on coastal area. As leasing 1 is a large area (748 km²), the result could be refined and adding sustainability index (e.g. Sea surface temperature, Chlorophyll-a concentration) to define the best area for co-location of offshore wind farm and aquaculture [35] and [36]. In addition, further studies are required to understand the contribution of new mussel beds installed on ORE infrastructure: 1) qualify and quantify the contribution to coastal biodiversity; and 2) study the potential impact of stepping stone effect, which could help to spread invasive species.

V. CONCLUSION

The overall results suggest that mussel larvae dispersal is mostly influenced by near-surface currents in the Irish Sea. In addition, the possibility of multi-use platforms at sea in the Irish Sea, co-locating mussel farms with offshore renewable energy, has been proven using numerical studies, especially in the eastern Irish Sea.

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