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Cefas

Modelling the optimal position of a fish recovery and return outfall for Sizewell C

Modelling the optimal position of a fish recovery and return outfall for Sizewell C

Luz Garcia, Liam Fernand and Dave Sheahan

Version and Quality Control

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Executive summary

The proposed Sizewell C (SZC) would be fitted with two embedded mitigation measures to reduce the impingement mortality of fish and crustacea; Low Velocity Side Entry (LVSE) intakes and a fish recovery and return (FRR) system. This report presents the analysis undertaken in August 2016 to determine the optimal placement of the SZC FRR system outfall. At that time, the chlorination strategy for SZC had not yet been finalised and it was not possible to rule out chlorination of the FRR system. However, EDF Energy has subsequently determined that the SZC FRR system will not be chlorinated and therefore some of the analyses in this report are no longer relevant but are preserved as a record of the design evolution.

In principle the FRR outfall should be as short as reasonably practical in order to return impinged fish as quickly as possible to the marine environment. However, there are several constraints to be considered:

a. Water depth. This must be sufficient to ensure that fish are returned to a minimum water depth under all tidal conditions in order to reduce predation by surface feeding birds.
b. Avoidance of mobile geomorphic features. There are 2 inshore bars at Sizewell which are important to sediment transport at the coast and which move naturally in response to the prevailing wave climate.
c. Fish exposure to TROs in the FRR tunnel, if the FRR system was chlorinated. (In August 2016 the chlorination strategy for SZC had not been decided)
d. Proximity of the Sizewell B (SZB) discharge plume. The SZB outfall is at 150m offshore (from mean water level) and a short FRR tunnel would, therefore, release fish into the SZB TRO plume on the ebb tide. The SZB cooling water discharge is chlorinated throughout the year.
e. Risk of fish re-impingement into SZB. The SZB intake is 600m offshore and there is a risk that on the flood tide that some fish discharged from the FRR outfall could be re-abstracted at the SZB intake.

Five potential FRR outfall locations were considered at locations FRR1 – FRR5 in Figures 1 and 2 and Table 1 with FRR1 being at the most inshore location. In Figure 1 the SZB intake is at location ‘B in’. In Figure 2 the SZB intake is labelled as ‘IB’.

The first two constraints (a. and b.) above can be satisfied by locating the FRR discharge in water depths greater than 4m. The FRR1 position is Eastward (seaward) of the current outer bar position, however the bar position regularly changes in response to the prevailing wave climate. The extent of the movement is estimated to be within ± 100m (east or west) of the present position and thus FRR2 would be far enough east to be free from the risk of burial by the bar movement.

The purpose of this report is to consider the risks associated with the possible SZC FRR discharge locations, to recommend which provides the lowest risk of fish mortality and to quantify the expected mortality for fish species of interest at Sizewell.

Table 1 Potential SZC FRR outfall locations and water depths, tunnel lengths (from the forebay) and fish travel times in the tunnel to the outfall

Location	Depth of discharge ODN	OSGB_E	OSGB_N	Tunnel length (m)	Travelling time (min)
FRR1	4.2m	647817	264109	325	9.0
FRR2	5.0m	647977	264109	475	13.2
FRR3	6.7m	648127	264109	625	17.4
FRR4	8.4m	648277	264109	775	21.5
FRR5	8.9m	648427	264109	925	25.7

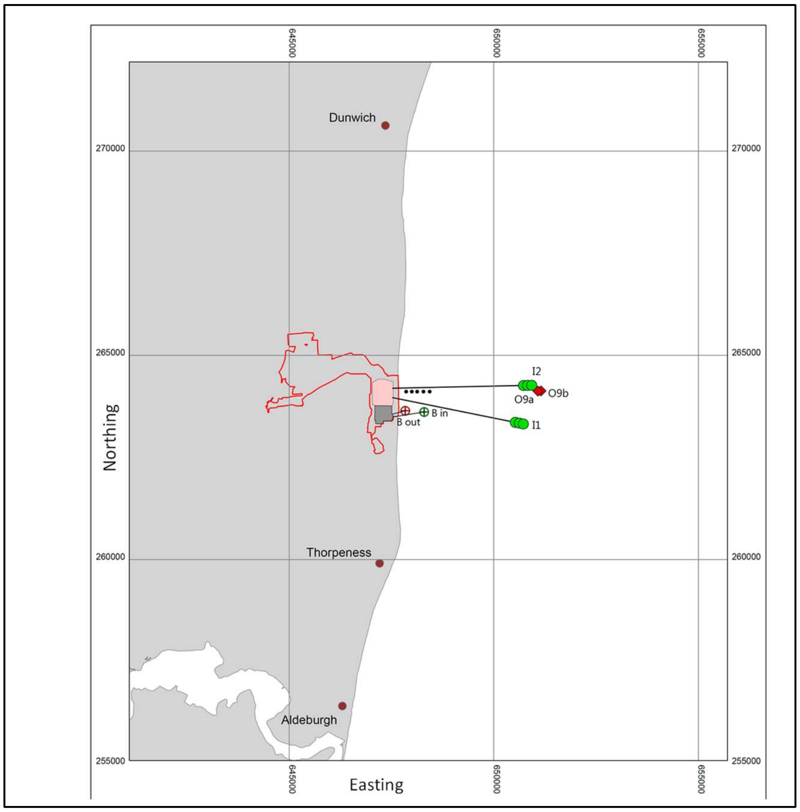

Figure 1 Overview of the SZC and SZB cooling water infrastructure. Black dots mark the modelled SZC FRR outfall positions, FRR1-FRR5, with FRR1 being the closest inshore.

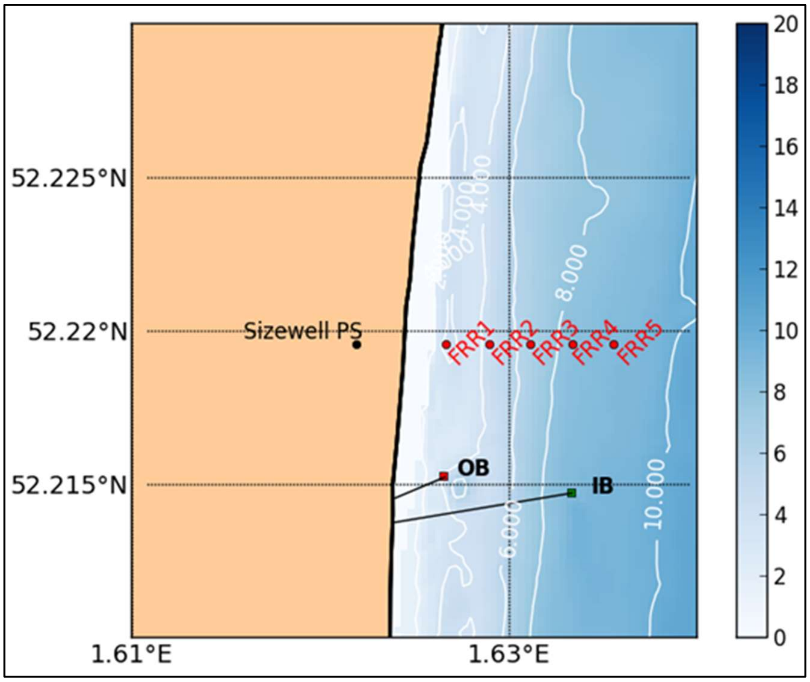

Figure 2 Expanded view of the modelled FRR locations including bathymetry (m ODN)

It was concluded that:

a. Subject to other considerations, shorter FRR tunnels are preferred in order to return fish as quickly as possible to sea.
b. Locations FRR1 and FRR2 would produce a negligible risk of re-impingement into SZB due to their inshore location with respect to SZB intake.
c. BEEMS TRO toxicity data derived using what would have been a SZC FRR dosing profile (BEEMS Technical Report TR362), showed that whilst flatfish, eels and lampreys would be expected to survive all of the TRO profiles from FRR1-5, juvenile bass would be expected to suffer high mortality. The toxicity experiments indicated that it was the exposure to the simulated high doses in the FRR tunnel and shortly after discharge that was the probable cause of the measured toxicity. The shortest total exposure to TRO doses> 0.1 mg l^{-1} in locations FRR1-5 was at location FRR2. FRR2 was preferable to FRR1 because of the high dose predicted in the Sizewell B plume after fish discharge from FRR1.
d. Using a more accurate real-time tracking model to determine fish exposure to TROs it was demonstrated that FRR2 would produce no excess mortality for flatfish, eel and lampreys if the SZC FRR system was chlorinated and would also produce no additional mortality for juvenile bass in winter when the system would not be chlorinated (bass are mostly present in winter at Sizewell).
e. The excess mortality at the FRR2 location due to re-impingement at SZB would be a worst case of 0.7%.

Table 2 shows the predicted fish mortality rates with FRR outfall location FRR2. The right-hand column combines the predictions of FRR mortality from Turnpenny and O' Keefe 2005 with the predicted excess mortality for the SZC FRR system.

Table 2. Predicted mortalities for fish in the SZC FRR system when a. chlorinated and b. unchlorinated.

Option: FRR2	Re-impingement mortality at SZB	Mortality due to TRO exposure	Total excess mortality due to FRR location	Total FRR mortality (incorporating FRR survival data from Table 12)
a. FRR2 chlorinated				
Flatfish, eels & lamprey	0.7%	0%	0.7%	20.56%
2y old bass	0.7%	90%	90.07%	95.04%
3y old bass	0.7%	40%	40.42%	70.21%
b. FRR2 unchlorinated (winter regime)				
Flatfish, eels & lamprey	0.7%	0%	0.7%	20.56%
2y old bass	0.7%	0%	0.7%	50.35%
3y old bass	0.7%	0%	0.7%	50.35%

Note: the mortality due to TRO exposure for juvenile demersal species (e.g. cod) would be expected to be similar to that for bass.

The predicted re-impingement losses shown above are precautionary as the modelling undertaken for this report makes several assumptions that will overestimate re-impingement e.g. the model does not take into account that the SZB intakes do not abstract fish from the whole water column, it is assumed that as a worst-case that live fish discharged from the SZC FRR system will just drift with the tide for 4 hours after discharge, whereas any that need to recover would be more likely to settle on the seabed whilst their swimming abilities were impaired and thereby reduce their risk of re-impingement into SZB and no benefit is assumed from the SZB fish recovery and return system.

The exact location for the FRR outfall will depend upon constructability, but this assessment suggests that between BNG Easting 647977 and 648127 along Northing 264109 (i.e. locations FRR2 – FRR3) would be optimal, with a preference for the Western end of this line (i.e. near to FRR2). The exact Northing does not really matter as the tidal excursion at the site is large, but the position should be chosen to keep the FRR tunnel length as short as possible. It is considered that the conclusions presented in this report will be valid for positions up to 100m to the North and South of those tested here. The Northing location used in this report is between the 2 SZC forebays; the actual onshore start position is likely to change slightly once the design of the FRR system is finalised.

Due to space constraints on the Sizewell C plot plan it was considered possible that there could be two FRR tunnels; one from each unit. This option was not expected to change the predictions in this report.

Changes in Revision 3 of this report

Revision 2 of this report dated August 2016 was produced before EDF Energy had decided on the final chlorination strategy for SZC. The report therefore considered a worst-case option whereby the FRR system would be chlorinated in the growth season when seawater temperatures exceeded 10°C. The assessment concluded that FRR2 would be the optimal position for the FRR outfall. The contents of this report were subsequently discussed with stakeholders at a Sizewell Marine Technical Forum meeting on 12th September 2016.

Between the release of revision 2 and the production of the SZC DCO application in 2020, EDF Energy decided that the FRR system would not be chlorinated but the recommendation of the location of the FRR outfall at FRR2 was not changed by this decision. EDF Energy has also confirmed that elevation levels of the associated buildings allow the FRR tunnel to exit from the debris recovery building to sea so that each EPR unit will have its own dedicated FRR system with a separate tunnel and outfall head (as opposed to a single outfall being shared at HPC). This design improves FRR performance by limiting transit time and would not alter the results of this study which are not sensitive to latitudinal variation.

The purpose of this Revision 4 report was to clarify that the chlorination strategy had not been decided in 2016 and, therefore, that some of the design options for the FRR system assessed in Revision 2 were just that; options that had not been fully evaluated until later in the SZC design process.

A minor correction was made to Table 2~~Table 2~~ and Table 14~~Table 14~~ where the total FRR mortality for FRR2 unchlorinated for the 2 and 3 year old bass was incorrectly stated as 50.6% in Revision 2. This was corrected to 50.35% in both tables

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The data of relevance to the SZC WDA and DCO submissions (as made May 2020), given the updated/confirmed chlorination strategy, from Table 2 are:

Option: FRR2	**Re-impingement mortality at SZB**	**Total FRR mortality (incorporating FRR survival data from Table 12)**
b) FRR2 unchlorinated		
Flatfish, eels & lamprey	0.7%	20.56%
2y old bass (demersal fish)	0.7%	50.35%
3y old bass (demersal fish)	0.7%	50.35%

Changes in Revision 4 of this report

The only changes in Revision 4 were minor clarifications in response to client comments.

1 Background

To minimise fish mortality due to impingement in SZC, EDF Energy propose to install two embedded mitigation measures; Low Velocity Side Entry (LVSE) intakes and a Fish Recovery and Return (FRR) system.

In ideal circumstances impinged fish would not be exposed to TROs created by chlorination of the cooling water system. However, in practice, due to the risk of biofouling at Sizewell it was considered possible that there was a risk that fish recovered in the FRR would be exposed to TROs for variable amounts of time before discharge at the FRR outfall. The potential effects of such exposure are dependent upon the cumulative exposure i.e. the integral of dose and exposure time and particularly on the peak TRO level experienced in the system. EDF Energy's chlorination policy options for SZC in 2016 were described in BEEMS Technical Report TR316 Ed 6 (Rev 8) and, at that time, it was considered that:

a. the cooling water intake heads, the intake tunnels and the forebay would not be chlorinated;

b. chlorination would be applied at the input to the condensers to produce an initial TRO concentration of 0.2mg l^{-1}. Chlorination would be applied all year round to protect the essential cooling water systems.

c. Chlorination would be applied in front of the drum screens to produce an initial TRO dose level of 0.2mg l^{-1} when seawater temperatures exceed 10°C (i.e. not in winter);

On that basis, outside of the winter period, fish in the SZC FRR system would be exposed to TROs from the drum screens to the FRR outfall.

Once the fish are discharged from the SZC FRR outfall, dependent upon the location of that outfall, there is a risk that on the ebb tide they will enter the SZB TRO plume and experience an additional TRO dose. In addition, on the flood tide there is a risk that fish discharged from the SZC FRR system will be re-abstracted at the SZB intake.

The purpose of this report is to consider the risks associated with the possible SZC FRR discharge locations, to recommend which provides the lowest risk of fish mortality and to quantify the expected mortality for fish species of interest at Sizewell.

1.1 Assumed FRR discharge characteristics in August 2016

Based upon design studies undertaken for Hinkley Point C the following assumptions were made about the SZC FRR system:

a. A single outfall with a mean flow rate of 1,050m^3 h^{-1} or 0.29 m^3 s^{-1} (under normal operating conditions; the flow rate could be increased under clogging conditions to 1,500m^3 h^{-1})

b. FRR tunnel internal diameter of 0.8 m

c. Flow velocity in the FRR tunnel of approximately 0.6m s^{-1}.

1.2 Modelling Approach

To derive the likely exposure to chlorine of fish released from the SZC FRR and the potential re-impingement loss to SZB, a particle tracking model has been used. This model uses the current fields from the validated Sizewell GETM curvilinear grid model. The description and validation of the GETM configuration for the Sizewell area are presented in BEEMS Technical Report TR229. The validation of this model was performed against different observations, such as temperature and currents. The particle tracking module was also validated by comparing observed drogue trajectories against model results. One issue identified in TR229 was that, despite the high model resolution close to Sizewell, the coastline was offset from its real position and didn't cover the shallowest area. This led to issues in the drogue validation around the Sizewell B outfall.

Since then, the model domain has been improved to extend closer to the coastline and this has been used in investigations of the thermal and chemical plume (BEEMS Technical Reports TR302 and TR303, respectively). Since the particle tracking model is important to this study on the location of the FRR outfall, a model revalidation in comparison to deployed drifters for the new domain, named V2, is presented in Appendix A. This revalidation showed that the revised model produced an improvement in the representation of coastal currents with a consequential improvement in the accuracy of predicted particle trajectories.

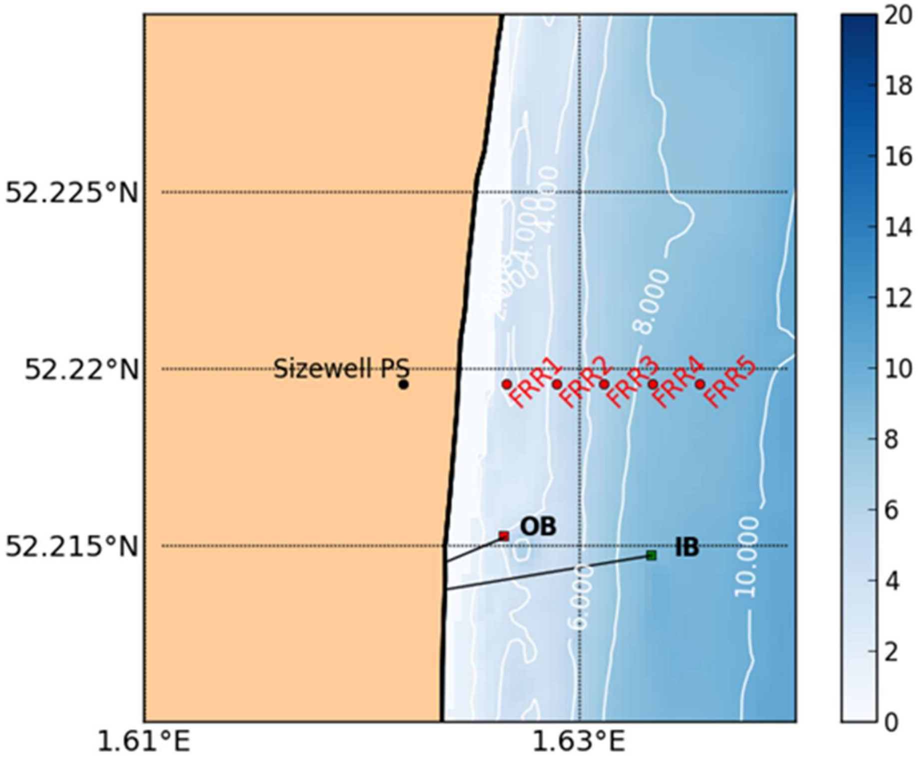

Figure 3: Potential locations of the proposed outfalls for the SZC fish return and recovery system. The Sizewell B intake is also shown on the map (IB).

2 Methodology

2.1 Introduction

The validated BEEMS General Estuarine Transport Model (GETM) model of Sizewell was used for this study to generate the forcing fields that drive the particle tracking. A Lagrangian particle tracking model developed at Cefas and based on the algorithm of Wolk (2003) was then used to generate particle tracks. The equation of motion was solved with a time step of 1 or 2 seconds, depending on the simulation, and has two components: the advection is calculated from the 3D velocity fields using the Runge-Kutta method, while the turbulent diffusion is modelled using a stochastic differential equation for a random walk, where the length and direction of each step depends on the eddy diffusivity from GETM's turbulence closure.

The GETM model output used was ReferenceV2 which corresponds with the present-day situation with the Sizewell B cooling water discharge. The model results are saved at 1-hour resolution to allow for a correct representation of the tides. ReferenceV2 configuration is an update of the model runs used in the GETM Stage 3 report (BEEMS Technical Report TR302). The changes consisted of:

- Extension of the model domain to include shallower water closer to the coastline in order to improve plume mapping and area calculations
- A slight reduction in the model internal time step to ensure numerical stability in the shallow water areas.

These changes in the hydrodynamic model setup required an update of the validation of the Lagrangian model with respect to BEEMS Technical Report TR229, which is included in Appendix A.

The hydrodynamic model uses a curvilinear grid, whereas the Lagrangian model requires an equidistant lat/long grid to do the calculations. Therefore, the model results must be interpolated to a regular grid sufficiently fine to be able to simulate the highly variable near-shore region where the drifters were released. For these simulations, a horizontal resolution of 25 m was used.

The Sizewell B intake is to the south of the considered SZC FRR outfall positions. Therefore, we expect that fish (modelled as passive tracers) are likely to be transported to the SZB intake only during the flood tide. This was checked by model simulations that confirmed that no fish released from any SZC FRR location would be transported to SZB intake during the ebb phase. All the impingement simulations were, therefore, carried out only during the flood phase of the neap and spring tides. The simulations lasted 4h because it was considered that animals that survive longer than this time would have recovered and no longer behave as passive tracers. For each simulation, a neutrally buoyant passive tracer was released at the seabed every minute during flood tide (6h), meaning that a total number of 360 particles were released.

Another issue that may affect fish survival is the chlorination system of the power stations. Two different sources of hazard were identified:

- The potential chlorination of the SZC FRR system and tunnel.
- The chlorination of the existing SZB cooling water system and the subsequent TRO plume discharge. (Fish discharged from the SZC FRR outfall would not interact with the SZC TRO discharge plume which would be approximately 3km offshore).

For this study it was assumed that chlorination could be required to avoid bio-fouling of the SZC FRR system.

When chlorination is applied to the SZC FRR system, the initial concentration of TROs in the FRR tunnels would be 0.2 mg l^{-1}. Therefore, although TRO concentration decays with time, a shorter tunnel would be more desirable to reduce the exposure of fish to TROs. In this report we will examine the different tunnel lengths, together with the flow velocities to obtain the travelling time and the TRO concentration inside the tunnel.

In the case of SZB, chlorinated cooling water is released from the outfall structure throughout the year. When chlorine and organic matter in the water combine, total residual oxidants (TROs) are produced. This process has been studied for Sizewell seawater and an empirical equation for TRO decay has been coupled into the GETM Sizewell model (BEEMS Technical Report TR143). In this report, the model configuration used was TRO_2outf-MayTROB (see BEEMS Technical Report TR303), for which TRO is discharged only from SZB. The concentration of TRO at the outfall is 300µg l^{-1} (i.e. the SZB discharge permit value) with the discharge being at $51.5m^3s^{-1}$.

The total exposure to TROs of impinged fish from SZC would be the sum of the exposure in the FRR system and any subsequent exposure in the SZB chemical plume.

The Environmental Quality Standard (EQS) for TRO is 10µg l^{-1}. Hence, the exposure of the particle trajectories to concentrations of TRO higher than the EQS was analysed as a proxy of the possible hazard. In addition, an estimation of fish mortality was undertaken using toxicity information from BEEMS Technical Report TR316, where empirical data on different fish species mortality is compiled depending on the concentration of chlorine and the exposure time.

2.2 Selection of the modelling simulation dates

According to BEEMS Technical Report TR302, the year 2009 is representative of the mean conditions at Sizewell. From a biological point of view, the month of May is relevant, since it corresponds to the spring phytoplankton bloom, with all the implications of this fact for the marine ecosystem. Consequently, we focused on May 2009 to carry out this study. In particular, two dates were chosen, both satisfying the following conditions simultaneously:

- Each date should correspond to a neap and spring tide, respectively.
- Each date should be representative of the month of May in terms of wind conditions, thus allowing for a “mean transport study”.

To determine the most representative wind conditions for the month of May, a wind rose for this month in the period 1958-2014 was calculated. The ECMWF winds obtained from the reanalysis products ERA-40 and ERA-operational (the same products that are used to force GETM) were considered to carry out this task. Figure 4 left shows the wind rose for May in the period 1958-2014. The SW component is the most frequent (approximately 27% if we sum the SW, WSW and SSW components), followed by the NE component (approximately 24% summing the NE, NNE and ENE components). The average wind speed for this period is 5.74 ± 2.5ms^{-1}, although the most frequent winds are in the range of 3.1-9 ms^{-1}. In the case of May 2009 (Figure 4 right), the SW component is the most frequent, with wind velocities slightly higher than the mean (average velocities 5.9 ± 2.4 ms^{-1}).

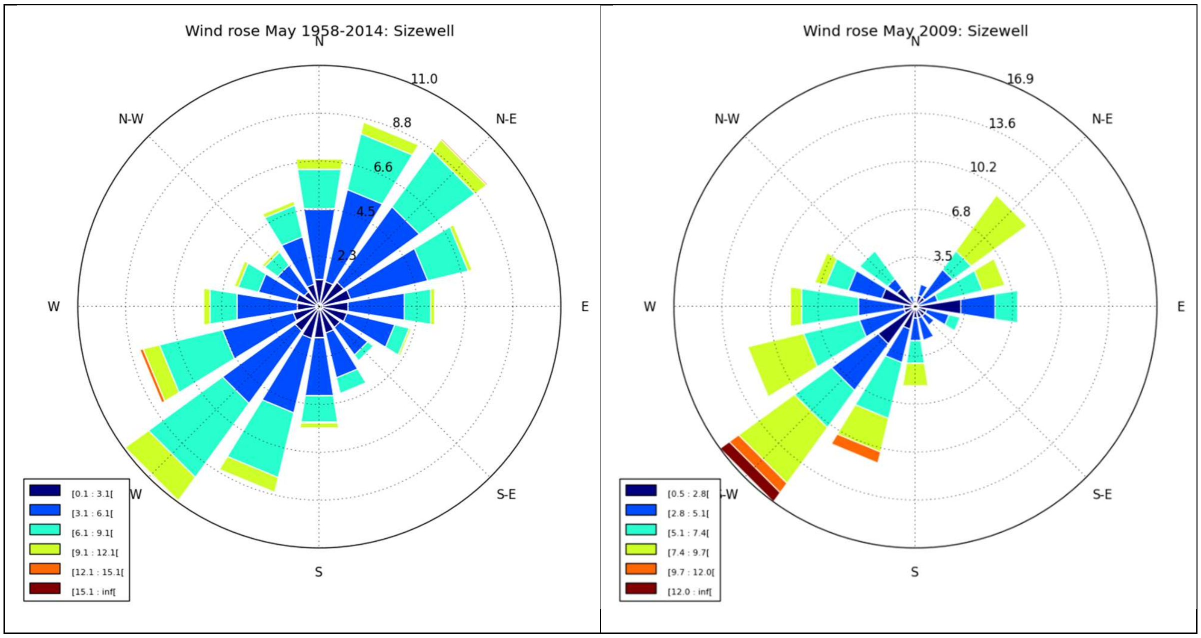

Figure 4: Left: Wind rose for the month of May in 1958-2014. Right: Wind rose for the month of May 2009

On this basis, the wind direction of the selected days should be in the third quadrant (SW), and the wind velocity should be around 5-6 ms^{-1}. The days that accomplish all the conditions (at least most of the time) are the 19th of May 2009 (neap tide) and the 26th of May 2009 (spring tide, see Figure 5 corresponding to a reconstruction of the tides in the area considering the two main semidiurnal constituents M2 and S2). The wind velocities and directions are depicted in Figure 6.

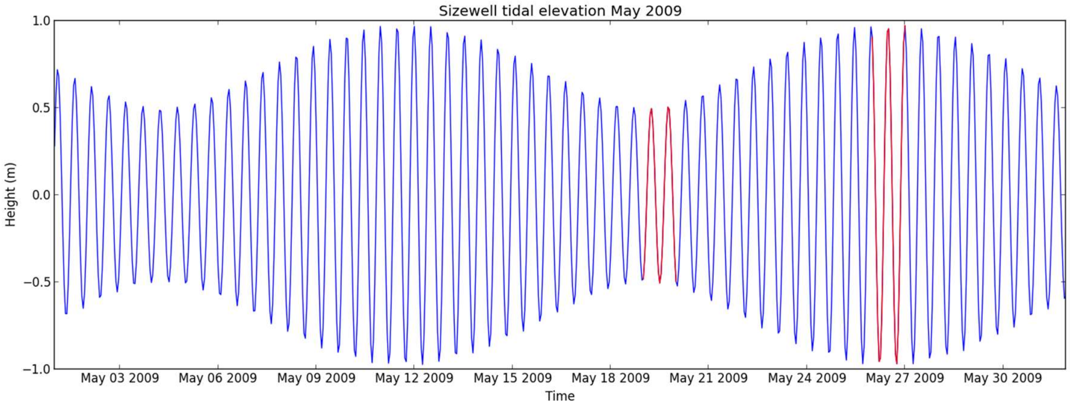

Figure 5: Tidal elevation for May 2009 at Sizewell. The selected days for the FRR simulations are shown in red.

Figure 7~~Figure 7~~ summarizes the relevant time periods in the particle tracking simulations. For each of the selected dates particles are released during the 6-hour duration of the flood tide. The simulation period lasts 10 hours to guarantee that all the particles are followed for 4 hours. In order to keep this study statistically consistent, only the trajectories corresponding to the first four hours are considered for the particles that experience longer transports.

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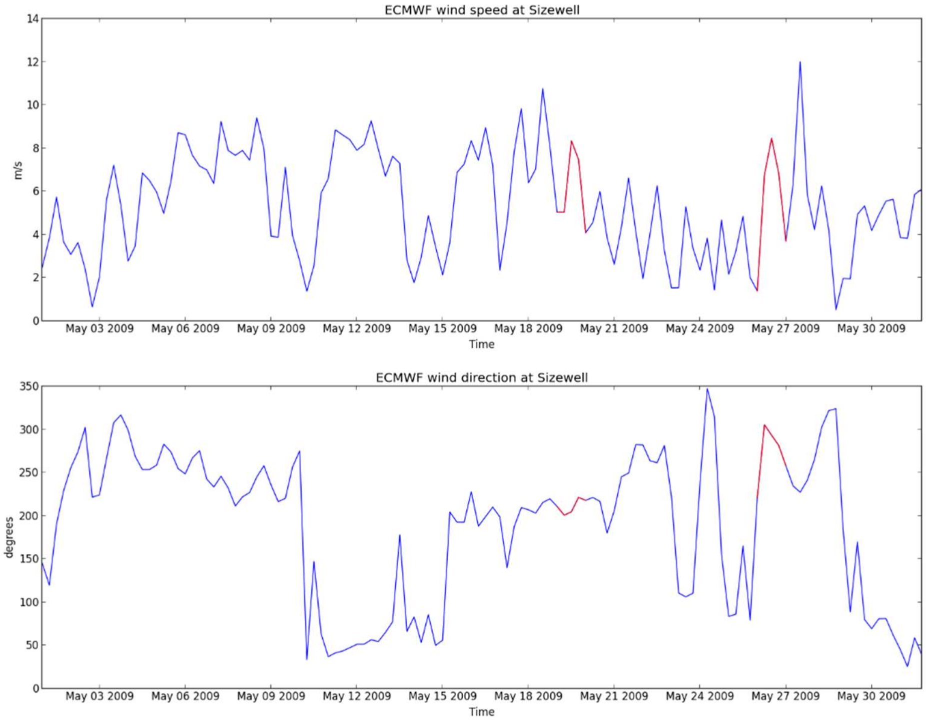


Figure 6: Wind speed and direction for May 2009 at Sizewell. The selected days for the FRR simulations are shown in red.

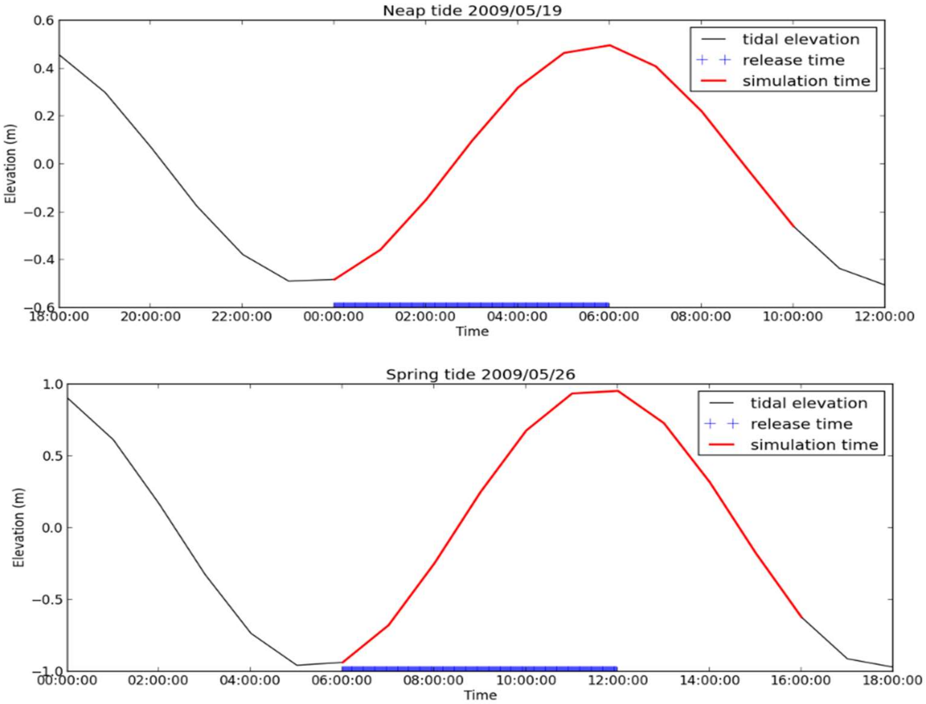


Figure 7: Tidal elevation, discharge and simulation periods

2.3 Approximations and assumptions

The assumptions made for modelling the Sizewell C FRR system are summarized below:

1. The GETM model includes vertical movements through advection or dispersion processes. However, for this report, all the particles that are within a horizontal radial distance of 25m (size of the Sizewell intake structure) of the SZB intake are considered to have been impinged, regardless of the vertical position. The water depth at the SZB intake structure is around 8.8m. The maximum tidal range (during spring tide) is less than two metres, meaning that the water column would be greater than 7m at the lowest low tides. The intake structure has a capped head and only extracts water from water from the bottom half of the water column, meaning that the assessment would overestimate the percentage of re-impingement by neglecting the vertical component of the particle positions.

2. As mentioned at the beginning of Section 2.1, the model results are only shown for the flood tide, because during the ebb tide the currents transport the particles away from the SZB intake. It is assumed that the selected simulation days (see Section 2.2) are representative of the most frequent conditions in the area. Longer simulations could reproduce a more accurate representation of existing variability in the area of interest but we would not expect that such extended model runs would lead to a modification of the conclusions of this report.

It was assumed that the SZC FRR system would be chlorinated outside of the winter period with an initial TRO concentration of 200 µg l^{-1}. The derived assumptions are summarized in the following points:

1. Fish would be exposed to high concentrations of TRO before being released back to the sea. The amount of time they would be exposed depends on the length of the FRR tunnel and the flow velocity, which is expected to be 0.6 ms^{-1} on average. Based upon experiments on the decay of TROs in Sizewell seawater a mathematical model of decay was developed (BEEMS Technical Report TR143 Ed. 2). The model approach assumes an initial fast ‘demand’ reaction involving an unspecified reactant that continues until that unknown reactant is exhausted. Simultaneously a

slower decrease in TRO concentrations is assumed to occur by a decay reaction dependent only on TRO concentrations. The concentration of TRO decays with time according to equation:

$$\frac{dC}{dt} = -k_2 C^2 S - k_1 C,$$
$$\frac{dS}{dt} = -k_2 C^2 S,$$

with C=TRO, S =0.6 mg l^{-1} and the kinetic constants are $k_1 = 0.000041$ and $k_2 = 0.0078$, respectively. (see BEEMS Technical Report TR143 Ed. 2).

Table 3 compiles for each potential FRR tunnel length, the travelling time for fish (flow velocity 0.6ms^{-1}) and the concentration of chlorine after this time obtained by solving the system of ordinary differential equations above.

Table 3: FRR tunnel lengths (from forebay), travelling time and concentration of TRO at the end of the tunnel

Location	Depth of discharge ODN	OSGB_E	OSGB_N	Tunnel length (m)	Travelling time (min)	TRO at the end of the tunnel (mg l^{-1})	Effective volume flux (EVF).
FRR1	4.2m	647817	264109	325	9.03	0.133	3.99
FRR2	5.0m	647977	264109	475	13.19	0.116	3.48
FRR3	6.7m	648127	264109	625	17.36	0.103	3.1
FRR4	8.4m	648277	264109	775	21.53	0.092	2.76
FRR5	8.9m	648427	264109	925	25.69	0.084	2.52

2. After impingement and exposure to TRO, fish returned to sea via the FRR may be disoriented and their short-term swimming behaviour is difficult to predict. Therefore, it is assumed that fish behaviour at this stage should be considered as random. For this reason, a particle tracking model that includes a random walk has been selected to carry out this study.

3. As the FRR discharge rate is very small (0.3 m^{3}s^{-1}) the chemical plume model setup described in BEEMS Technical Report TR303 does not include the FRR chlorinated discharges.

   The SZC H1 discharge assessment is presented in BEEMS Technical Report TR193. The Effective Volume Flux (EVF) for the FRR discharge is given by $EVF = \frac{Dishcarge\ volume * concentration}{EQS}$. In this case the EQS is 0.01 mg l^{-1} and the volume 0.3 m^{3}s^{-1}. According to Environment Agency guidance EVF values above 3.5 (i.e. only for FRR1 here) require a more extensive assessment. However, the FRR dosing will be seasonal so that average EVFs will be less than those shown in Table 3 and none of the FRR discharges would fail the EVF test.

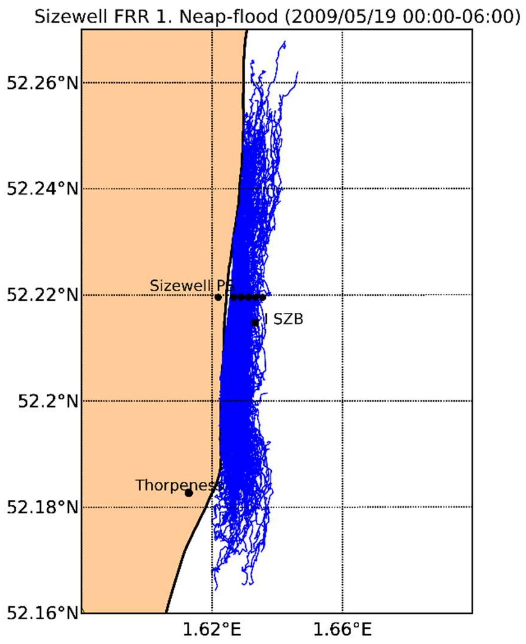
3 Modelling Results

3.1 Particle trajectories and re-impingement in the Sizewell B intake structure

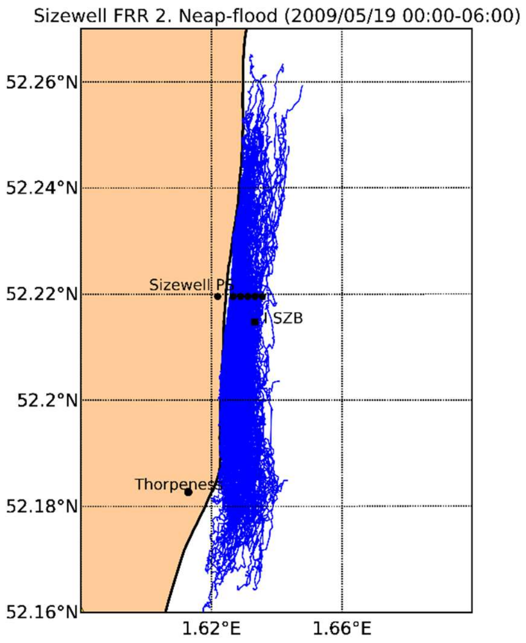
3.1.1 Neap tide, flood phase

Figure 8 shows the trajectories of the particles released at FRR1 to FRR5 during the flood phase of the Neap tide occurring on the 19th of May 2009. Since the particles are released every minute during the 6 hours of the flood tide and followed for 4 hours, some of them experience only southward transport (flood tide) while others (the particles released at the end of the six-hour period) experience a combination of southward transport followed by northward transport (neap tide). Particles released at FRR1 and FRR2 (the closest outfalls to the coast) remain close to the coast. As we move from FRR3 to FRR5 the west-east spread increases and the north-south transport decreases. To determine the probability of re-impingement at the Sizewell B intake, the density of particle position points at each model grid cell (25m x 25m) during the 4h transport period was calculated (see Figure 9). The probability of re-impingement is higher if the particles are released from FRR4 or FRR5.

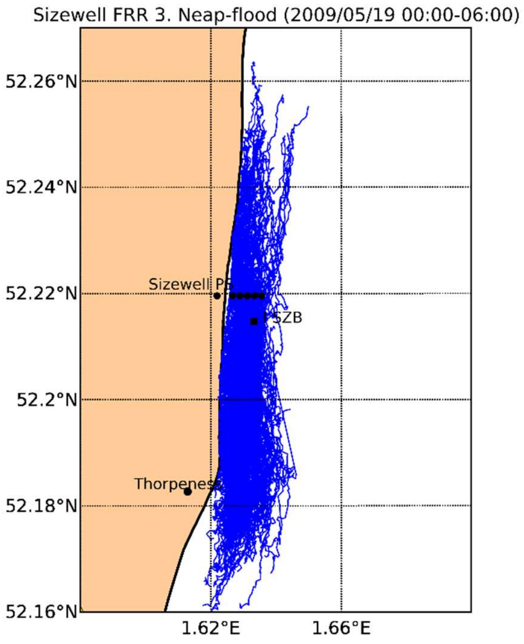
Table 4 compiles the results of calculating the percentage of particles released from each of the five FRR positions that are re-impinged in the Sizewell B intake structure on the Neap tide, flood phase. The FRR4 and FRR5 releases result in the highest percentages of re-impingement, (9.7% and 9.4%, respectively). FRR3 also leads to high re-impingement (8.3%), whereas FRR1 and FRR2 produce much lower values (less than 3%).



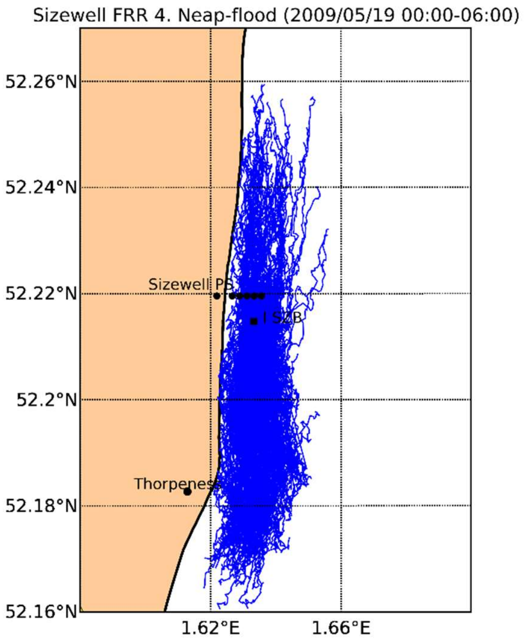
Sizewell FRR 1. Neap-flood (2009/05/19 00:00-06:00)



Sizewell FRR 2. Neap-flood (2009/05/19 00:00-06:00)



Sizewell FRR 3. Neap-flood (2009/05/19 00:00-06:00)



Sizewell FRR 4. Neap-flood (2009/05/19 00:00-06:00)

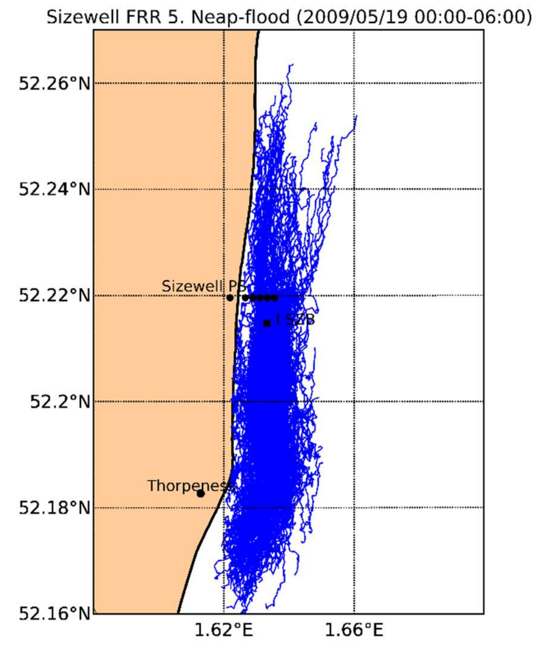
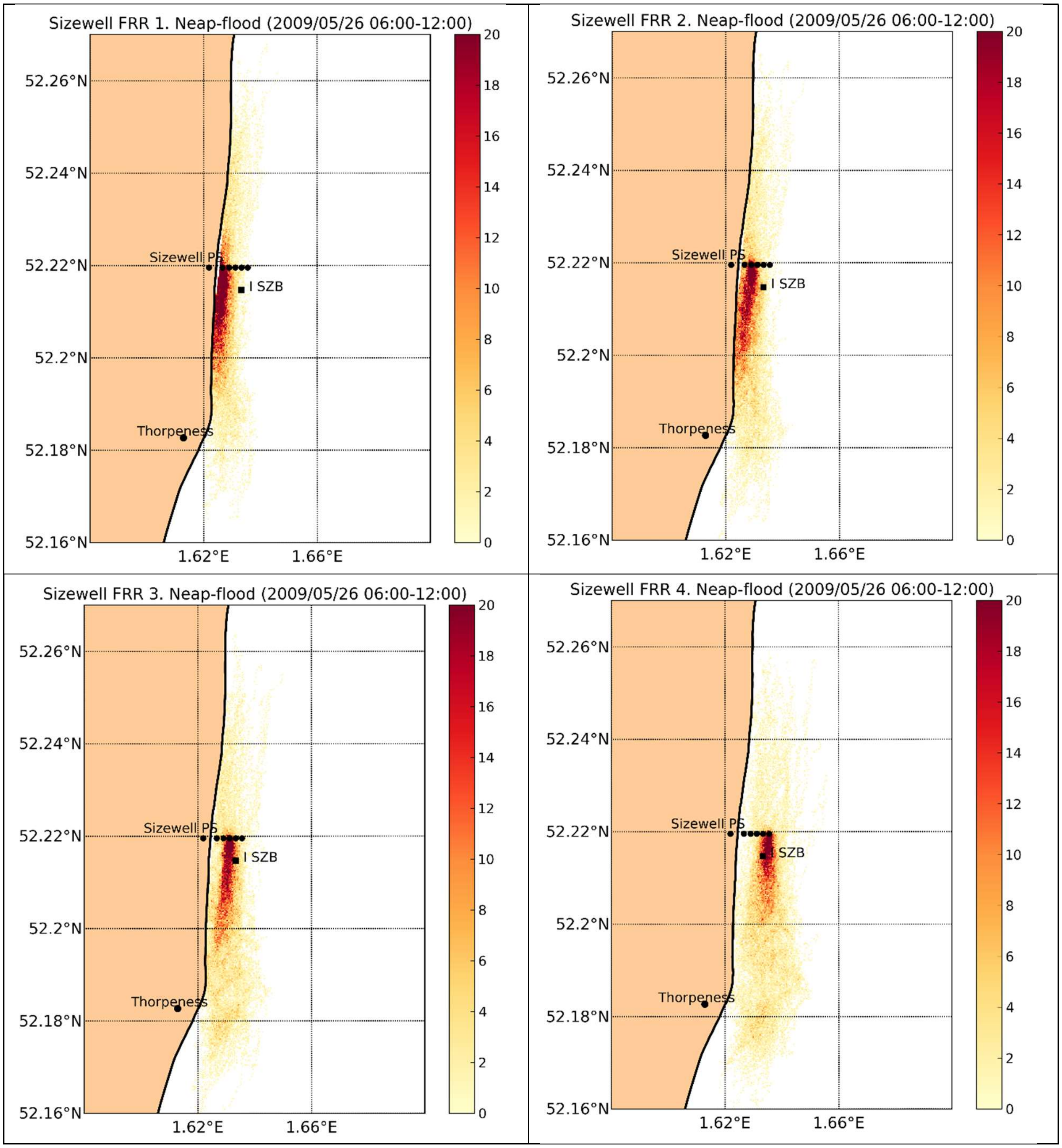

Sizewell FRR 5. Neap-flood (2009/05/19 00:00-06:00)

Figure 8: Trajectories of particles released from FRR1-5 (A-E, respectively) during the flood phase of Neap tide


Sizewell FRR 1. Neap-flood (2009/05/26 06:00-12:00)
Sizewell FRR 2. Neap-flood (2009/05/26 06:00-12:00)
Sizewell FRR 3. Neap-flood (2009/05/26 06:00-12:00)
Sizewell FRR 4. Neap-flood (2009/05/26 06:00-12:00)
52.26°N
52.24°N
52.22°N
52.2°N
52.18°N
52.16°N
1.62°E
1.66°E
Sizewell PS
I SZB
Thorpeness
20
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6
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2
0

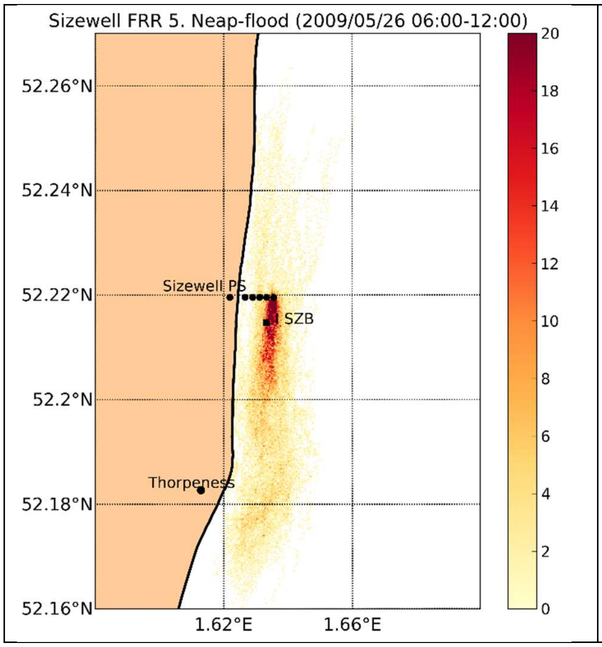


Figure 9: Density of particle positions in each 25m x 25 m model grid cell for all the transport period. Particles were released at FRR1-5 (Panels A-E, respectively) during the flood phase of Neap tide

Table 4: Re-impingement of passive tracers into the Sizewell B intake for release sites FRR1 to FRR5 during Neap tide (flood phase only)

Location	Depth of discharge ODN	Proportion re-impinged %	OSGB_E	OSGB_N	Tunnel length (m)
FRR1	4.2m	0.55%	647817	264109	325
FRR2	5.0m	2.8%	647977	264109	475
FRR3	6.7m	8.3%	648127	264109	625
FRR4	8.4m	9.7%	648277	264109	775
FRR5	8.9m	9.4%	648427	264109	925

3.1.2 Spring tide, flood phase

Figure 10 shows the trajectories of the particles released at FRR1 to FRR5 during the flood phase of the Spring tide occurring on the 26th of May 2009. If we compare this figure with Figure 8, we see that the particle trajectories extend further north and south dependent upon the location of the FRR outfall.

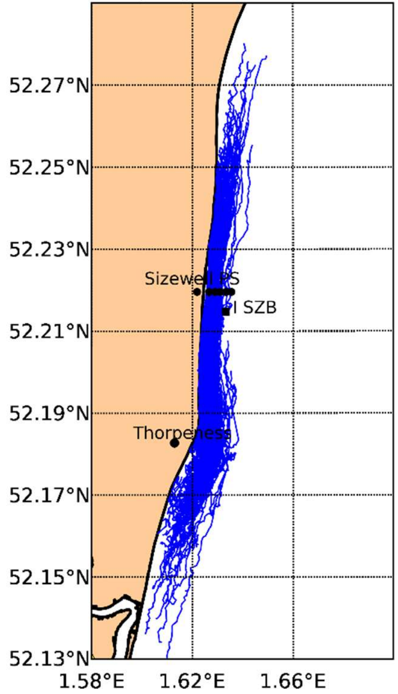
Comparing the five different FRR outfall locations, the particles remain closer to the coast if they are released at FRR1 or FRR2 and present a longer east-west distribution if they are released at FRR4 or FRR5. Figure 11 shows the density of particle position points at each model grid cell (25m x 25m) during the 4 h transport period. As for the Neap tide (see Figure 9), the probability of re-impingement is higher for the particles released at FRR4 or FRR5. Again, remaining close to the coast is not a guarantee of survival (as is the case of the particles released at FRR1) due to the higher probability of being predated or exposed to the Sizewell B chemical plume (see Section 3.2).

The percentage of particles released at each of the five FRR outfalls that are re-impinged in the Sizewell B intake structure on Spring tides, flood phase is shown in Table 5. The highest percentage corresponds to FRR4, as for the Neap tide (see Table 4), although in this case the value is a little higher (11% vs. 9.7%). During spring tide, there is a clear difference between FRR4 and FRR5, since less than 7% of the particles released at FRR5 are re-impinged. No re-impingement is observed for FRR1 and FRR2 outfalls within the four hours, and FRR3 shows low values (3%).

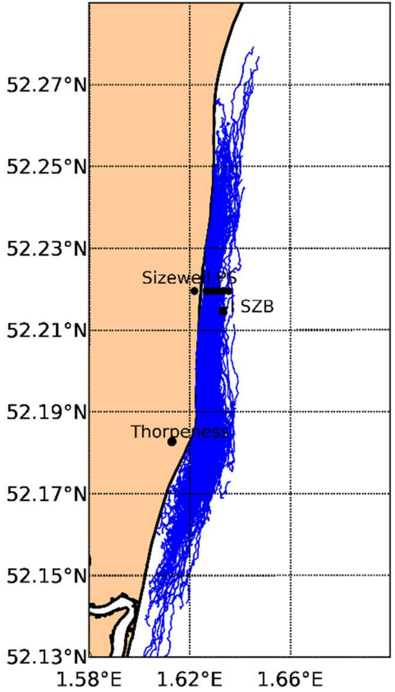
Table 5 Re-impingement of passive tracers into the Sizewell B intake for release sites FRR1 to FRR5 during Spring tide (flood phase)

Location	Depth of discharge ODN	Proportion Re-impinged (%)	OSGB_E	OSGB_N	Tunnel length (m)
FRR1	4.2m	0%	647817	264109	325
FRR2	5.0m	0%	647977	264109	475
FRR3	6.7m	3.3%	648127	264109	625
FRR4	8.4m	11.1%	648277	264109	775
FRR5	8.9m	6.4%	648427	264109	925

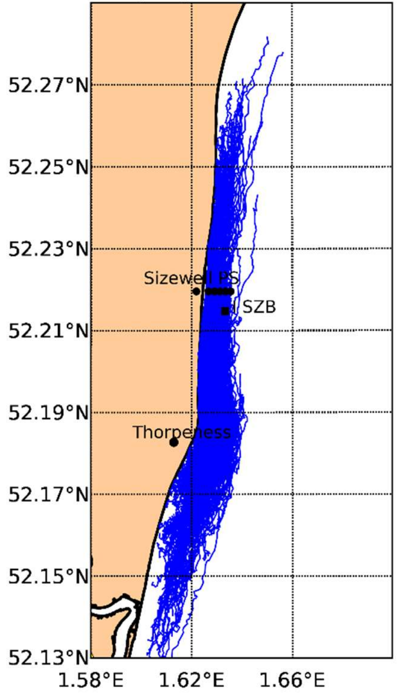
Sizewell FRR 1. Spring-flood (2009/05/26 06:00-12:00)



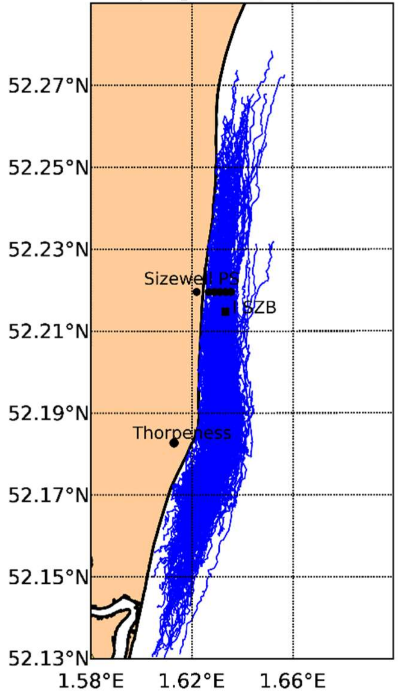
Sizewell FRR 2. Spring-flood (2009/05/26 06:00-12:00)



Sizewell FRR 3. Spring-flood (2009/05/26 06:00-12:00)



Sizewell FRR 4. Spring-flood (2009/05/26 06:00-12:00)



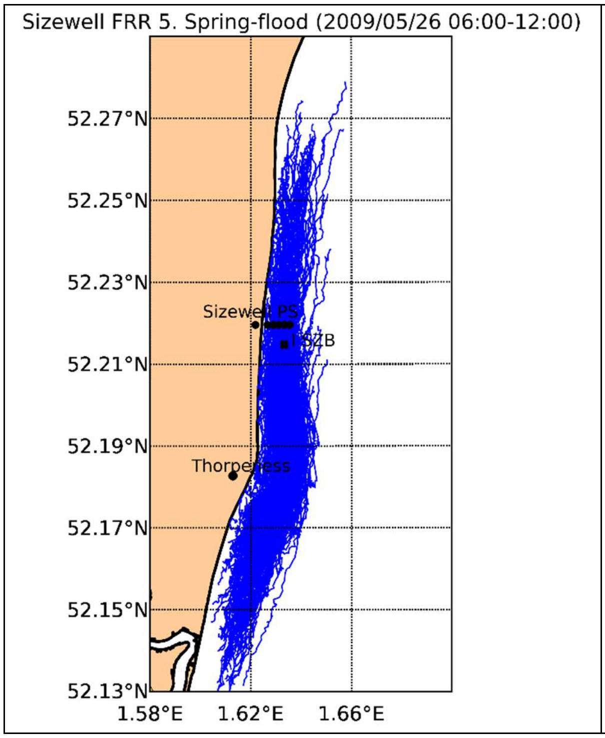
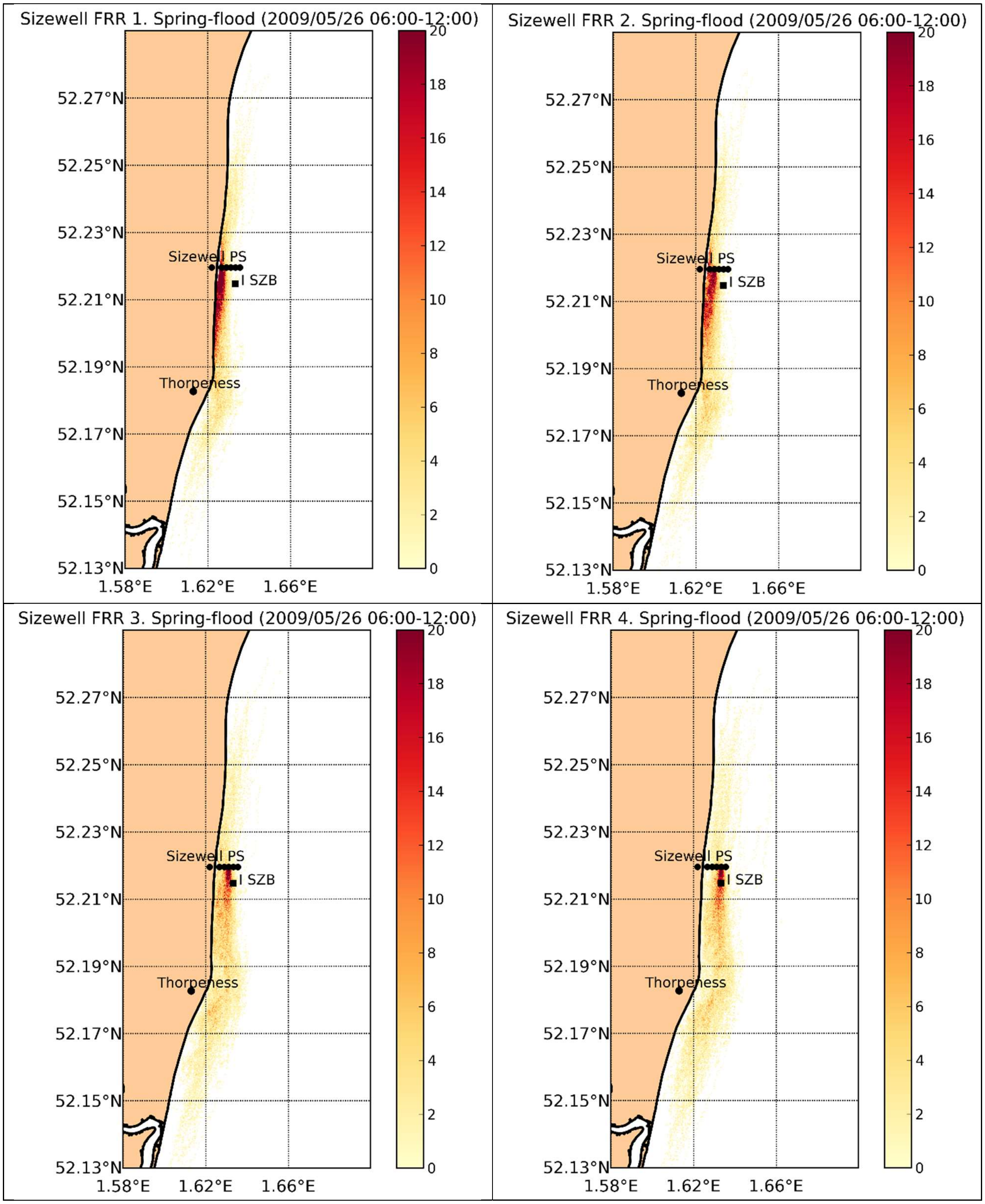


Figure 10 Trajectories of particles released from FRR1-5 (panels A-E, respectively) during the flood phase of Spring tide


Sizewell FRR 1. Spring-flood (2009/05/26 06:00-12:00)
Sizewell FRR 2. Spring-flood (2009/05/26 06:00-12:00)
Sizewell FRR 3. Spring-flood (2009/05/26 06:00-12:00)
Sizewell FRR 4. Spring-flood (2009/05/26 06:00-12:00)
52.27°N
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52.23°N
52.21°N
52.19°N
52.17°N
52.15°N
52.13°N
1.58°E
1.62°E
1.66°E
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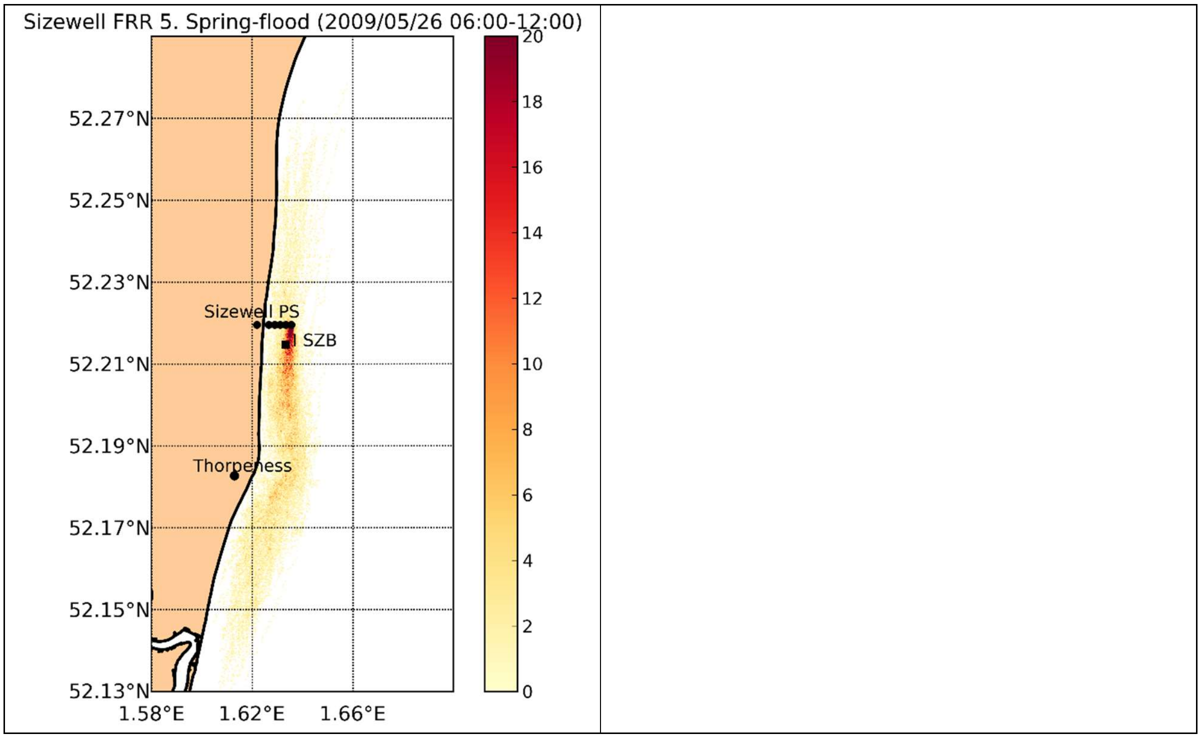

Figure 11 Density of particle positions in each 25m x 25 m model grid cell for all the transport period. Particles were released at FRR1-5 (Panels A-E, respectively) during the flood phase of Spring tide

3.1.3 Mean impingement rates over a Spring-Neap cycle

The total mean re-impingement (i.e. integrated flood + ebb tide impingement) has been calculated over a spring-neap cycle in Table 6. These data show that although FRR4 and FRR5 produce the highest re-impingement rates even these locations only result in a worst case 5.2% rate. The re-impingement rates produced at FRR locations 1 and 2 are negligible.

Table 6 Estimated mean re-impingement at SZB over a Spring-Neap cycle

Location	Depth of FRR discharge ODN	Proportion of fish re-impinged (%)	OSGB_E	OSGB_N	FRR Tunnel length (m)
FRR1	4.2m	0.14%	647817	264109	325
FRR2	5.0m	0.70%	647977	264109	475
FRR3	6.7m	2.90%	648127	264109	625
FRR4	8.4m	5.20%	648277	264109	775
FRR5	8.9m	3.95%	648427	264109	925

3.2 Interaction of fish discharged from the SZC FRR outfalls with the SZB chemical plume

3.2.1 Interaction with the SZB chemical plume: Neap-flood

Figure 12~~Figure 12~~ shows the 95 percentile of bottom TRO concentration for the month of May 2009 at the position of the particle trajectories released at each of the five potential FRR locations. Fish released at the FRR systems that are closer to the coast (FRR1 and FRR2) are more likely to experience concentrations of TRO above the EQS (10µg l^{-1} or 0.01mg l^{-1}) than those released at FRR outfalls 4 and 5.

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This is most clearly seen in Figure 13~~Figure 13~~, where most particles released from FRR3-5 are exposed to low TRO concentrations, whereas those released at FRR1-2 show larger numbers of particles exposed to higher concentrations of TRO.

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Table 7~~Table 7~~ shows that particles released at FRR1 are subjected to TRO concentrations higher than the EQS (at a mean exposure of 0.037mg l^{-1}) for approximately 60% of their transport time after being released (this is 2.4 hours out of 4). If a fish is released from FRR2, it will experience concentrations of around 0.027mg l^{-1} on average for 38% of the transport time. Mean TRO concentrations of approximately 0.02mg l^{-1} are experienced by particles released from FRR3 during 15% of the transport time. The lowest exposure to TRO concentrations exceeding EQS correspond to FRR4 and FRR5, with less than 4% of the transport time subjected to concentrations of around 0.02mg l^{-1}.

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Focusing on the full transport time that each particle experiences (4h), only particles released at FRR1 and 2 are exposed on average to concentrations above the EQS (at 0.02 and 0.01 mg l^{-1}, respectively). (See Table 7~~Table 7~~).

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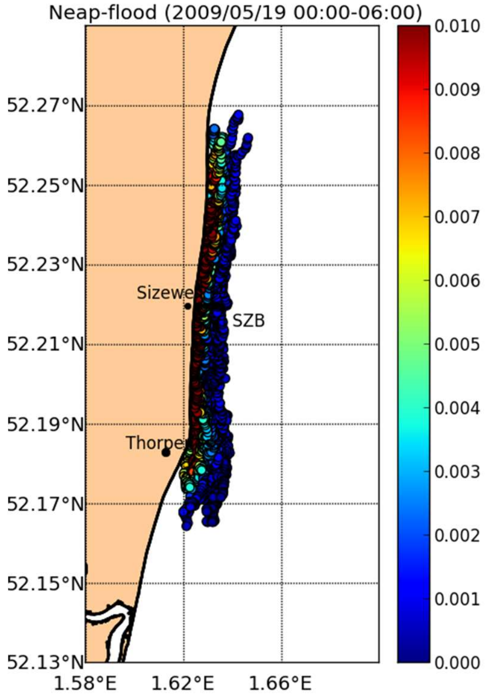
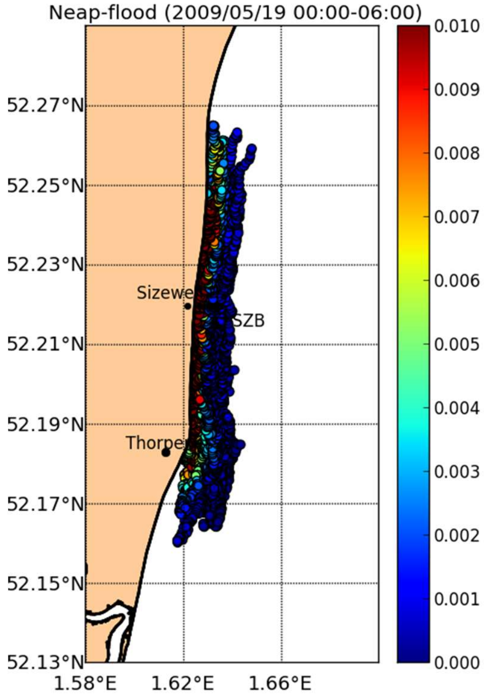
Sizewell FRR1. Bott. Chlorine.
Neap-flood (2009/05/19 00:00-06:00)



Sizewell FRR2. Bott. Chlorine.
Neap-flood (2009/05/19 00:00-06:00)



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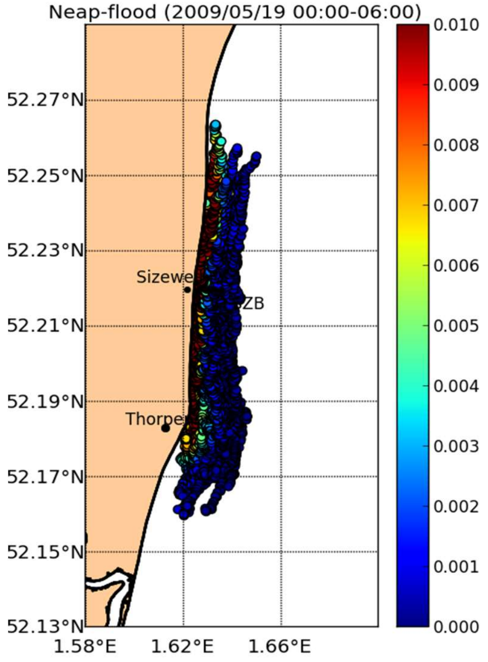
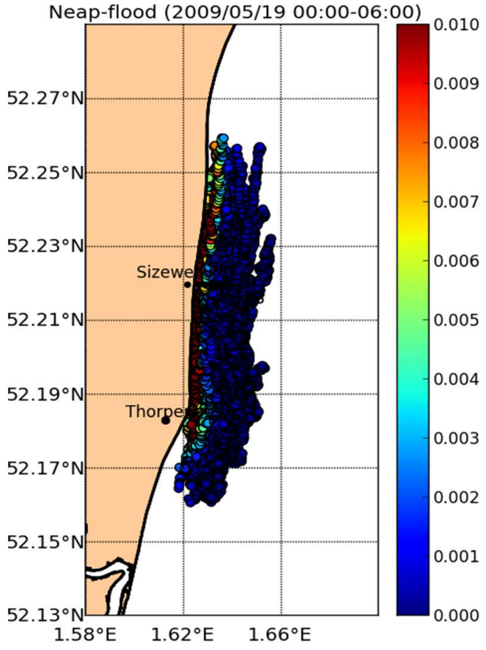


Sizewell FRR4. Bott. Chlorine.
Neap-flood (2009/05/19 00:00-06:00)



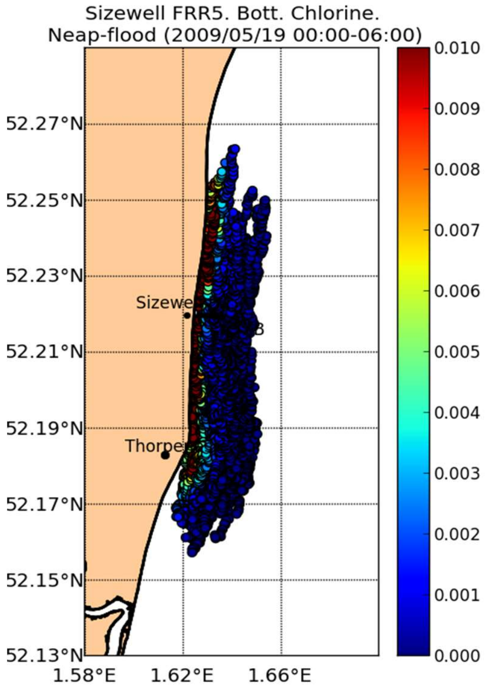


Figure 12: Bottom 95 percentile TRO concentration (mgl^{-1}) along the particle trajectories released from FRR1-5 (panels A-E, respectively) during the flood phase of Neap tide.

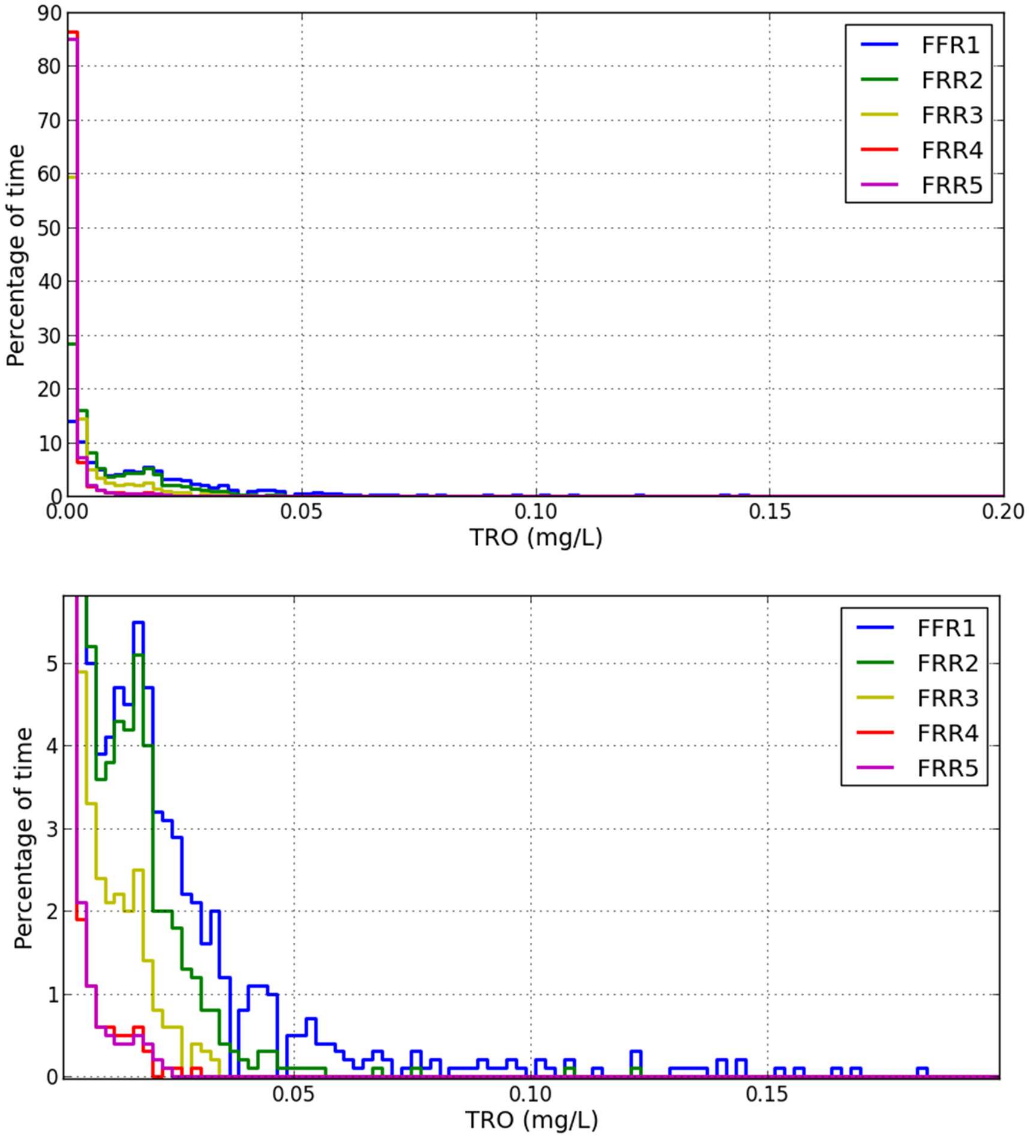


Figure 13: Top: Histogram showing the percentage of time that the particles are exposed to a certain TRO concentration. Bottom: A zoom for percentages <6%

Table 7: Exposure of particles to TRO in the SZB plume for release sites FRR1 to FRR5 (Neap tide)

Location	Depth of discharge ODN	Percentage of time along trajectory with TRO> EQS (0.01 mgl^{-1})	Average TRO (mgl^{-1}) for positions of TRO>0.01	Average TRO along the trajectories (mgl^{-1})
FRR1	4.2m	59.9%	0.037	0.024
FRR2	5.0m	38.12%	0.027	0.012
FRR3	6.7m	15.48%	0.021	0.005
FRR4	8.4m	3.61%	0.019	0.0017
FRR5	8.9m	3.26%	0.021	0.0018

3.2.2 Interaction with the SZB chemical plume – Spring Flood

Figure 14~~Figure 14~~ shows the 95th percentile (the EQS standard) of bottom TRO concentration for the month of May 2009 at the position of the particle trajectories released at each of the five FRR locations. The results for spring tide are very similar to those for Neap tide (see Section 3.2.1) in the sense that the particles released at the FRR systems that are closer to the coast (FRR1 and FRR2) are more likely to experience concentrations of TRO above the EQS (10µg l^{-1} = 0.01mg l^{-1}) than those released at FRR outfalls 4 and 5.

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The histogram shown in Figure 15~~Figure 15~~ clearly reflects the comments above. As can be seen, the particles released from FRR3-5 accumulate at lower concentrations, whereas those released at FRR1-2 experience higher concentrations of TRO.

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The results are summarised in Table 8~~Table 8~~. In general, during spring tide particles are subjected to TRO concentrations higher than the EQS during slightly longer periods of time than in the case of the neap tide (between 4 and 7% more time, see Table 7~~Table 7~~), except for FRR5, which is very similar. This is related to the fact that the particles are more confined to the coast where the concentration of TRO is higher. The mean concentration above the EQS (column 3 in Table 8~~Table 8~~) and for all the trajectories (column 4) is very similar to neap tide, with FRR1 and FRR2 providing the worst results and FRR4 and FRR5 the best ones.

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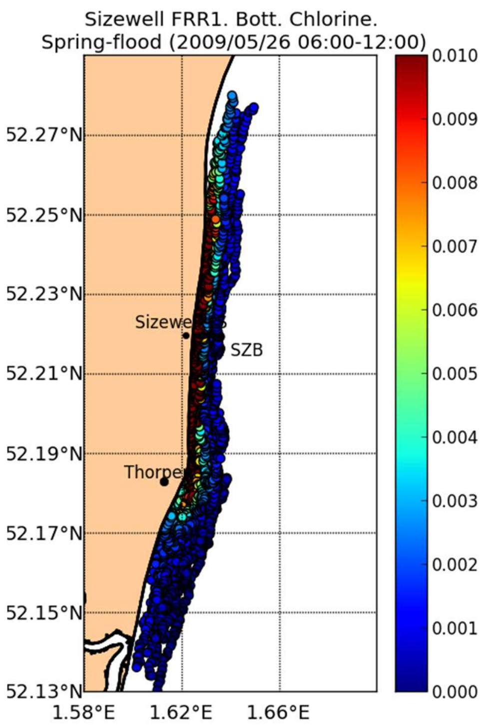
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52.23°N
52.21°N
52.19°N
52.17°N
52.15°N
52.13°N
1.58°E
1.62°E
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0.001
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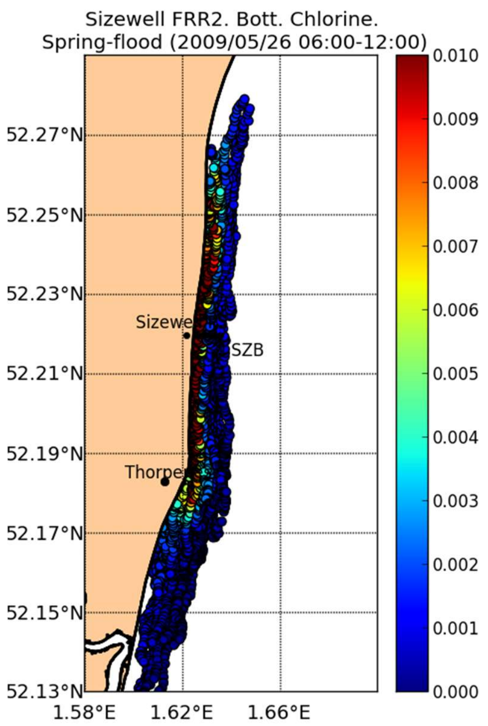
Sizewell FRR2. Bott. Chlorine.
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52.21°N
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52.17°N
52.15°N
52.13°N
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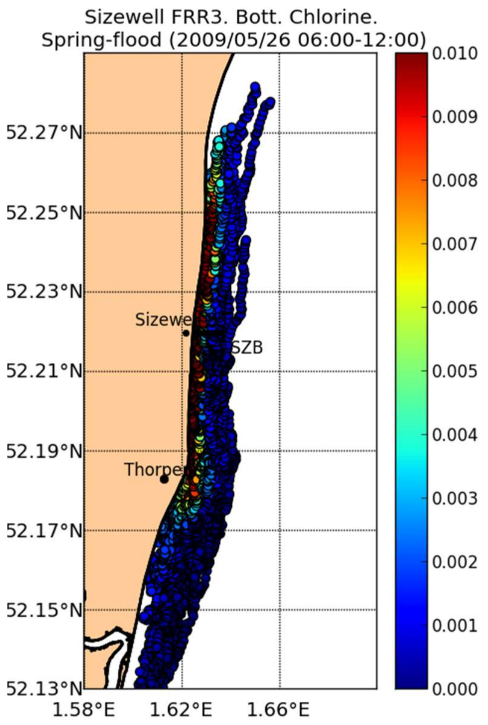
Sizewell FRR3. Bott. Chlorine.
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52.19°N
52.17°N
52.15°N
52.13°N
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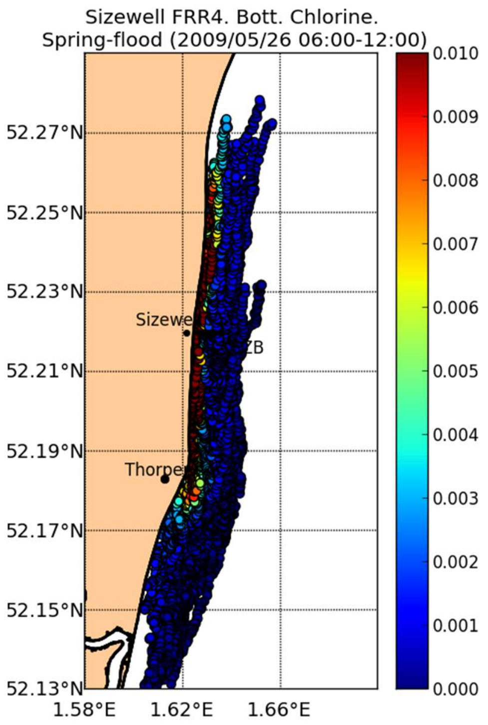
Sizewell FRR4. Bott. Chlorine.
Spring-flood (2009/05/26 06:00-12:00)
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52.17°N
52.15°N
52.13°N
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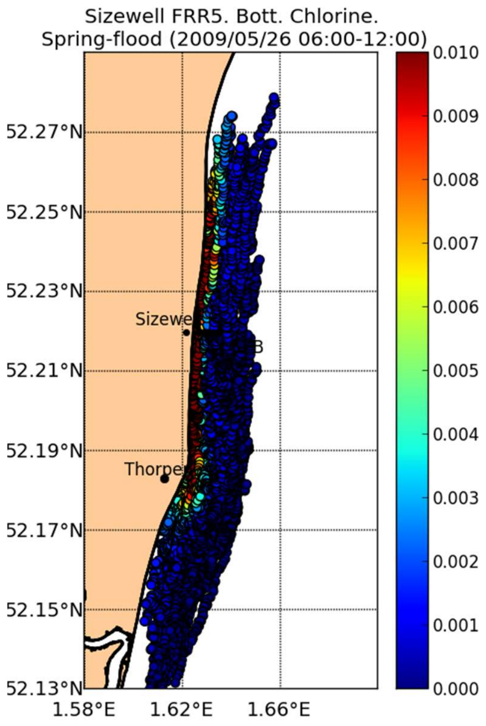
Sizewell FRR5. Bott. Chlorine.
Spring-flood (2009/05/26 06:00-12:00)

Figure 14: Bottom 95 percentile TRO concentration (mg l^{-1}) along the particle trajectories released from FRR1-5 (Panels A-E, respectively) during the flood phase of Spring tide.

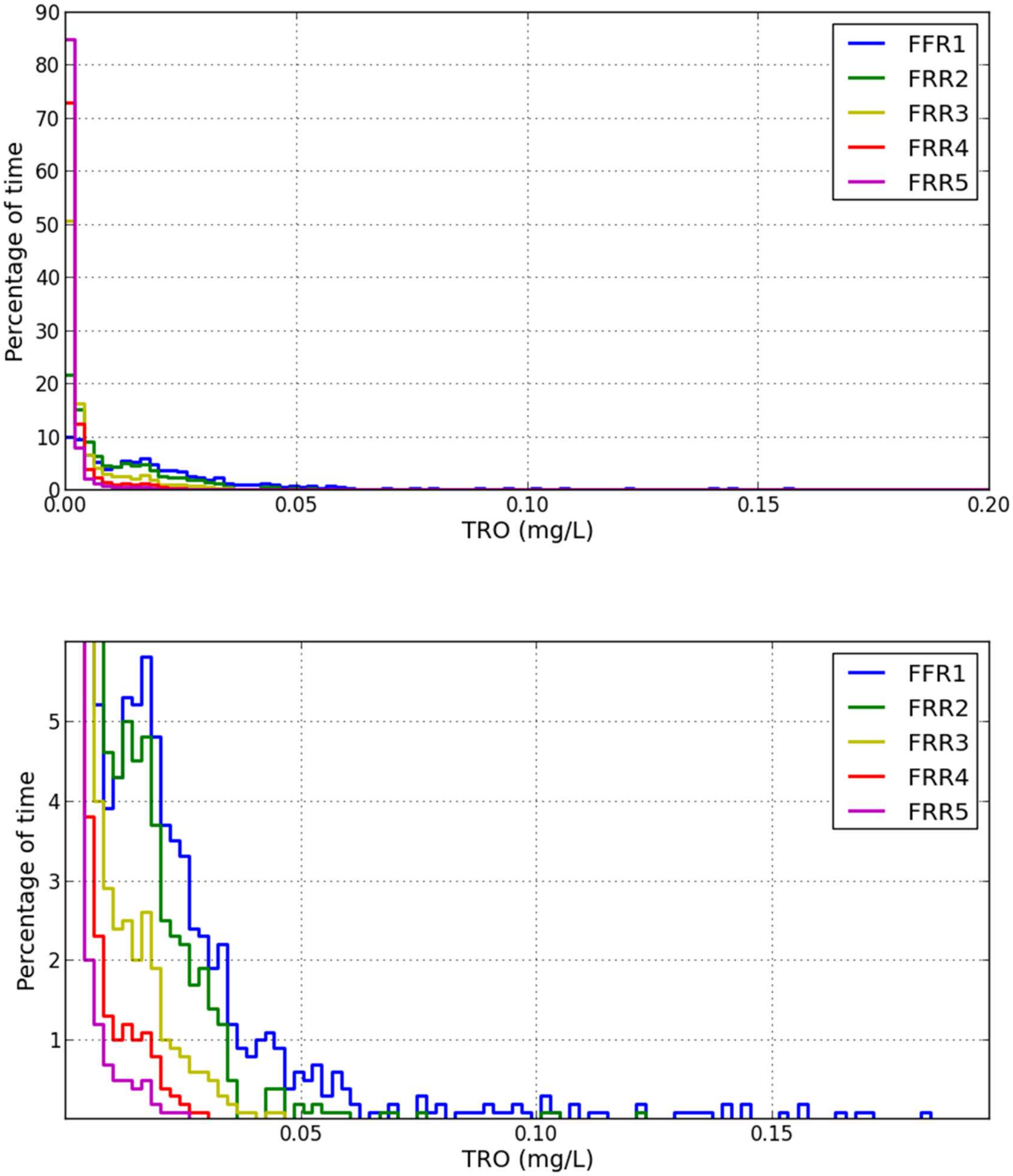

Figure 15: Top: Histogram showing the percentage of time that the particles are exposed to a certain TRO concentration (spring tide). Bottom: A zoom for percentages <6%

Location	Depth of discharge ODN	Percentage of time along trajectory with TRO>0.01 (mgl^{-1})	Average TRO (mgl^{-1}) for positions of TRO>0.01 (mgl^{-1})	Average TRO along the trajectories (mgl^{-1})
FRR1	4.2m	63.7%	0.036	0.024
FRR2	5.0m	43.44%	0.0285	0.014
FRR3	6.7m	19.32%	0.025	0.007
FRR4	8.4m	7.19%	0.021	0.003
FRR5	8.9m	3.24%	0.022	0.0018

Table 8: Exposure of particles to TRO for release sites FRR1 to FRR5 (Spring tide)

4 Estimates of fish mortality from different SZC FRR outfall locations

4.1 Comparative mortality estimates based upon particle tracking in the 95th percentile TRO plume

If the FRR was chlorinated, fish would experience high concentrations of chlorine inside the FRR tunnels for shorter times if they are released from FRR1 or FRR2 and the percentage of re-impingement is lower when particles are released from FRR1 or FRR2 than in any of the other cases (see Table 6). However, when particles are released to the sea on the ebb tide, they could be in contact with concentrations of TRO from the SZB plume as high as the ones inside the FRR tunnel (if chlorinated). A longer FRR tunnel, such as FRR3, is advantageous in the sense that the particles released to the sea will experience the chemical plume of SZB to a much lesser extent. The downside would be a longer exposure to TRO inside the tunnel and a higher percentage of re-impingement than at FRR1 or FRR2.

Figure 16 and Figure 17 show the cumulative percentage of time at which the particles are subjected to different TRO concentrations inside the chemical plume during neap tide and spring tide, respectively. In particular, the EQS (0.01 mgl^{-1}) and the concentrations at the end of FRR1-3 (see Table 3) are indicated in each plot.

Focusing on FRR1, the concentration of TRO at the end of the FRR tunnel will be approximately 0.13 mgl^{-1} (see Table 3). According to Figure 16, the particles will be exposed to concentrations less than 0.13 mgl^{-1} inside the chemical plume 97.21% of the time (during neap tide), meaning that the concentration will be higher 2.8% of the time (this is 6.34 minutes of the 4h trajectories). If we sum this time with the time at which they have already been exposed to TRO concentrations higher than 0.13 mgl^{-1} inside the tunnel, this results in 15.73 min (9.03 min inside FRR1 +6.7 min in the chemical plume).

In the case of FRR2, the concentration at the end of the tunnel is 0.11 mgl^{-1}. Figure 16 shows that only 1.36% of the time (3.26 minutes) they will be subjected to concentrations higher than 0.11 mgl^{-1} in the interior of the chemical plume, meaning that the total exposure to concentrations higher than 0.11 mgl^{-1} is 16.26min (13 min inside FRR2 + 3.26 min in the chemical plume).

Finally, for FRR3 the concentration at the end of the tunnel is 0.103 mgl^{-1}. According to Figure 16, the concentration of TRO inside the chemical plume would be above the concentration at the end of the tunnel only 0.95% of the time, this is 2.28 minutes. This means that the total time at which fish will be exposed to concentrations higher than 0.010 mgl^{-1} is 19.64 min (17.36 min inside FRR3 + 2.28 min in the chemical plume). For FRR4 and 5 the exposure to the SZB plume becomes progressively smaller and the time in the FRR tunnel dominates the exposure time e.g. the time in the tunnel for FRR4 is 21.5 min which is greater than the entire predicted FRR3 exposure. FRR4 and 5 are, therefore, not considered further in this report.

Table 9 compiles the modelled TRO exposure times for FRR1 – FRR3. When the FRR is chlorinated fish released from FRR1 are exposed to TROs above the EQS for longer total times (175min) than from FRR3 (50mins). However, when exposures to high TRO doses above 0.1 mg l^{-1} are considered, FRR2 produces the lowest exposure time (16.5 min) with FRR3 producing an increased exposure time (19 min).

To estimate the hazard to which fish species entering the FRR system will be exposed, we combined Figure 1 from BEEMS Technical Report TR316, which depicts the TRO concentration and exposure time resulting in approximately 40-60% mortality of exposed fish species with the decay curves for chlorine inside FRR1, FRR2 and FRR3 obtained by solving the TRO decay equation in Section 2.3 for the respective transport duration inside each tunnel and the TRO exposure curves inside the SZB chemical plume (see Figure 16). The resulting Figure 18~~Figure 18~~ shows that for both FRR1 and FRR2 the concentration of TRO inside the chemical plume will be higher than the concentration at the end of the FRR tunnel. In the case of FRR3, fish would experience considerably lower concentrations in the chemical plume than inside the tunnel, although the transport time inside the tunnel is higher than for FRR1 and FRR2.

According to Figure 18, for the fish species shown, when the system is chlorinated all of the 3 FRR locations (FRR1-3) would be expected to expose fish to dose profiles lower than those required to cause 40-60% mortality.

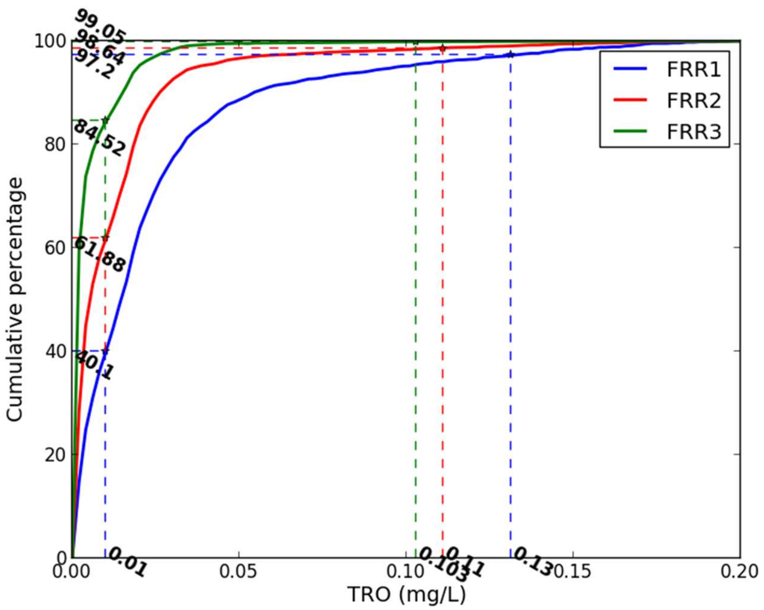

Figure 16: Cumulative histogram of the percentage of time at which the particles released during Neap tide (flood phase) are exposed to TRO. Dotted lines mark the concentration at the discharge point.

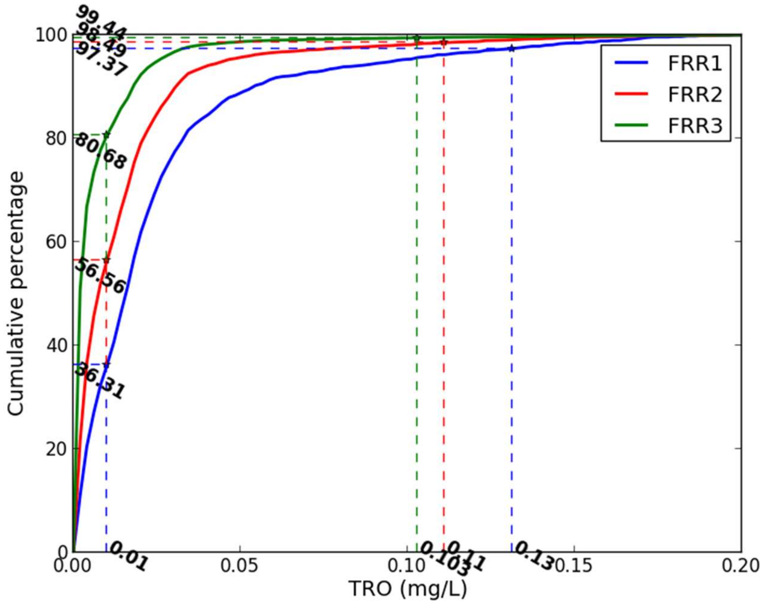

Figure 17: Cumulative histogram of the percentage of time at which the particles released during Spring tide (flood phase) are exposed to TRO. Dotted lines mark the concentrations at release from the discharge.

Table 9 Total exposure time of fish to TRO concentrations with different FRR outfall locations

	Time inside the tunnel (mins)	**TRO concentration at FRR discharge mg l^{-1}**	**Total time exposed to TRO>0.1mgl^{-1} (mins)**	**Total time above EQS Summer regime (mins)**	**Cumulative exposure time mg mins (in 1st 4 hours)**	
			Summer regime		Summer regime	Winter regime
FRR1	9.03	0.133	20.0	175	8.86	7.40
FRR2	13.19	0.116	16.5	100	5.77	3.79
FRR3	17.36	0.103	19.0	50	4.25	1.82

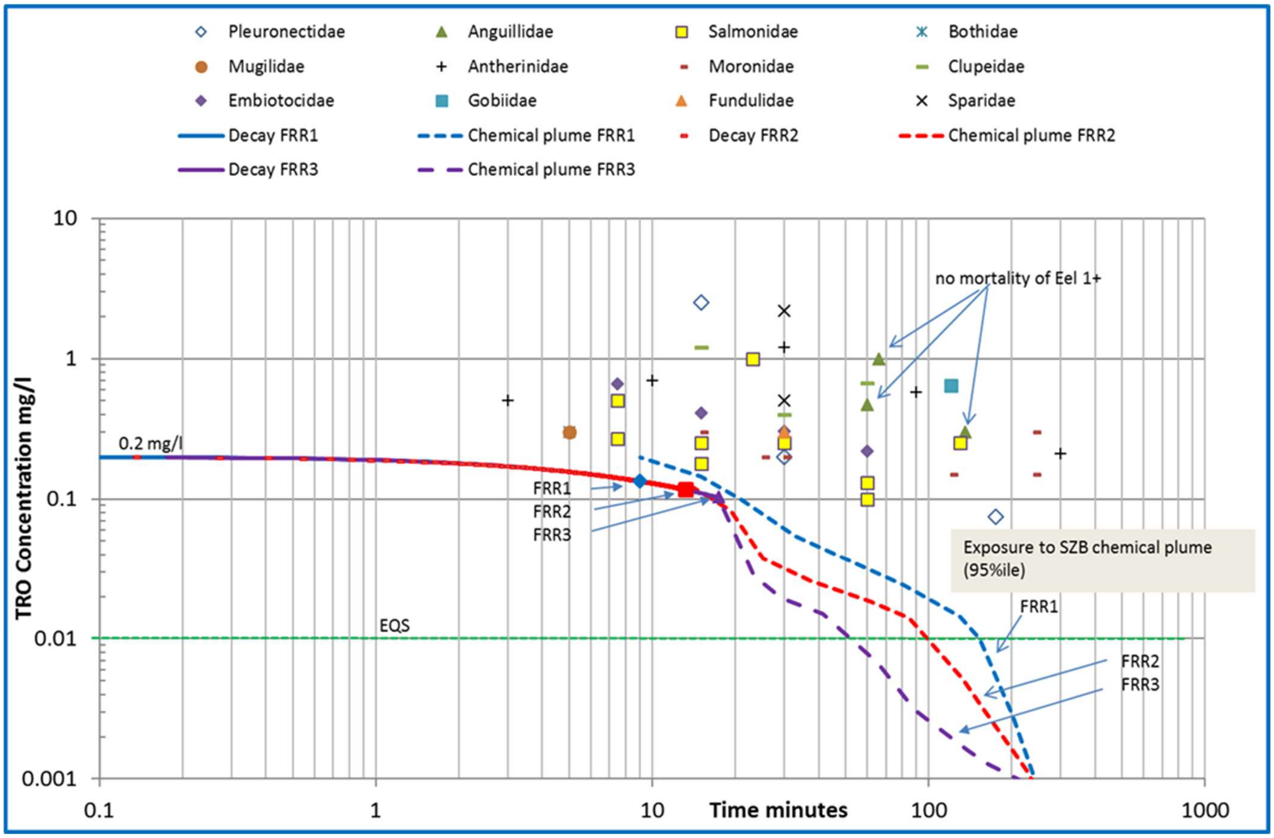

Figure 18: Profiles of potential fish exposure to TROs with different SZC FRR outfall locations shown against published fish toxicity data. Timeline is from entering the FRR system to subsequent exposure in the SZB plume under a regime when the FRR system is chlorinated (referred to in this report as the ‘summer regime’).

In should be noted from Figure 18 that after discharge from location FRR1 fish would be exposed to higher TRO doses in the SZB TRO plume than they would experience in the SZC FRR tunnel (the solid red line from time =0.1 minutes to approximately 9 minutes). This is because the modelled SZB TRO discharge concentration is the permit value of 300µg l^{-1} (or 0.3mg l^{-1}. See section 2.1).

Figure 19 shows the predicted TRO exposure during the ‘winter’ regime when the FRR system would not be chlorinated. As would be expected in the winter regime there is a reduction in the total cumulative exposure, with the reduction being greater for the longer FRR tunnels.

From a total TRO exposure time above the EQS perspective, both Figures 18 and 19 show that FRR3 would produce the lowest total TRO exposure for fish.

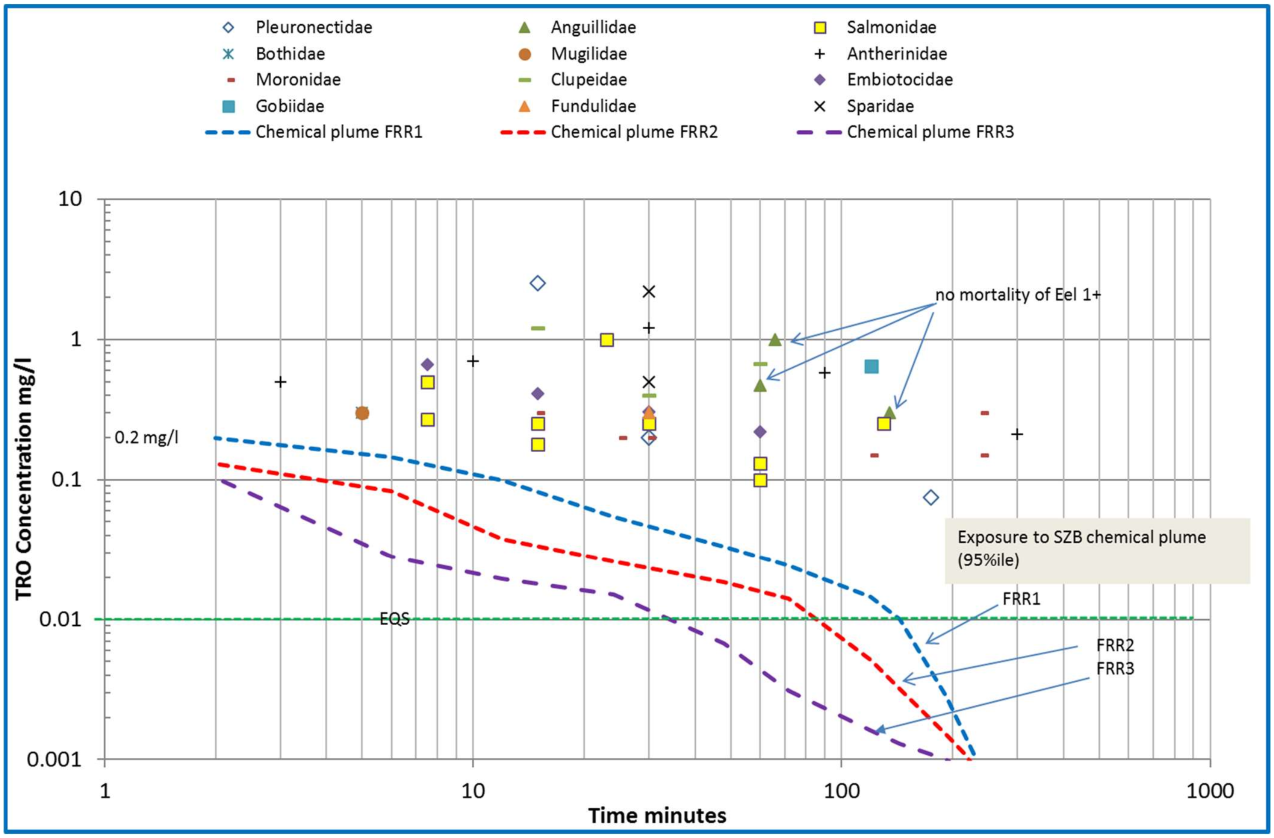

Figure 19 Profiles of potential fish exposure to TROs with different SZC FRR outfall locations shown against published fish toxicity data. Timeline is from the discharge from the FRR system outfall (there being no exposure in the FRR tunnel) and shows the exposure in the SZB plume under a regime when the FRR system is not chlorinated (referred to in this report as the ‘winter regime’).

This modelling is useful for ranking the different FRR outfall locations in terms of potential effects but to determine effects on fish populations it is necessary to determine the expected absolute levels of mortality in the FRR system. The toxicity data in Figures 18 and 19 are at best indicative because:

- The species for which data are available are either mostly US species or not those found at Sizewell
- The TRO concentrations (with a few exceptions e.g. for eel) are predominantly those found to produce 40-60% mortality but the published sources do not provide data for the no effects concentrations.

In the absence of data, it is reasonable to assume, based upon Cefas ecotoxicology experience, that TRO concentrations that are approximately an order of magnitude below those producing 50% mortality (or below the EQS) would have negligible effect. That concentration is shown on Figure 20 with the upper blue line being the worst-case doses shown to produce 40-60% toxicity and the lower blue line being doses an order of magnitude lower. From Figure 20 it is evident that yellow eels would be expected to survive chlorination of the SZC FRR system no matter which of the potential discharge locations was selected. However, for other species mortality is expected to be below 40-60% but not negligible. From the figure FRR3 would be expected to have the least effects but the high TRO exposures in the FRR tunnel and for 10 minutes after discharge would be expected to cause some fish mortality

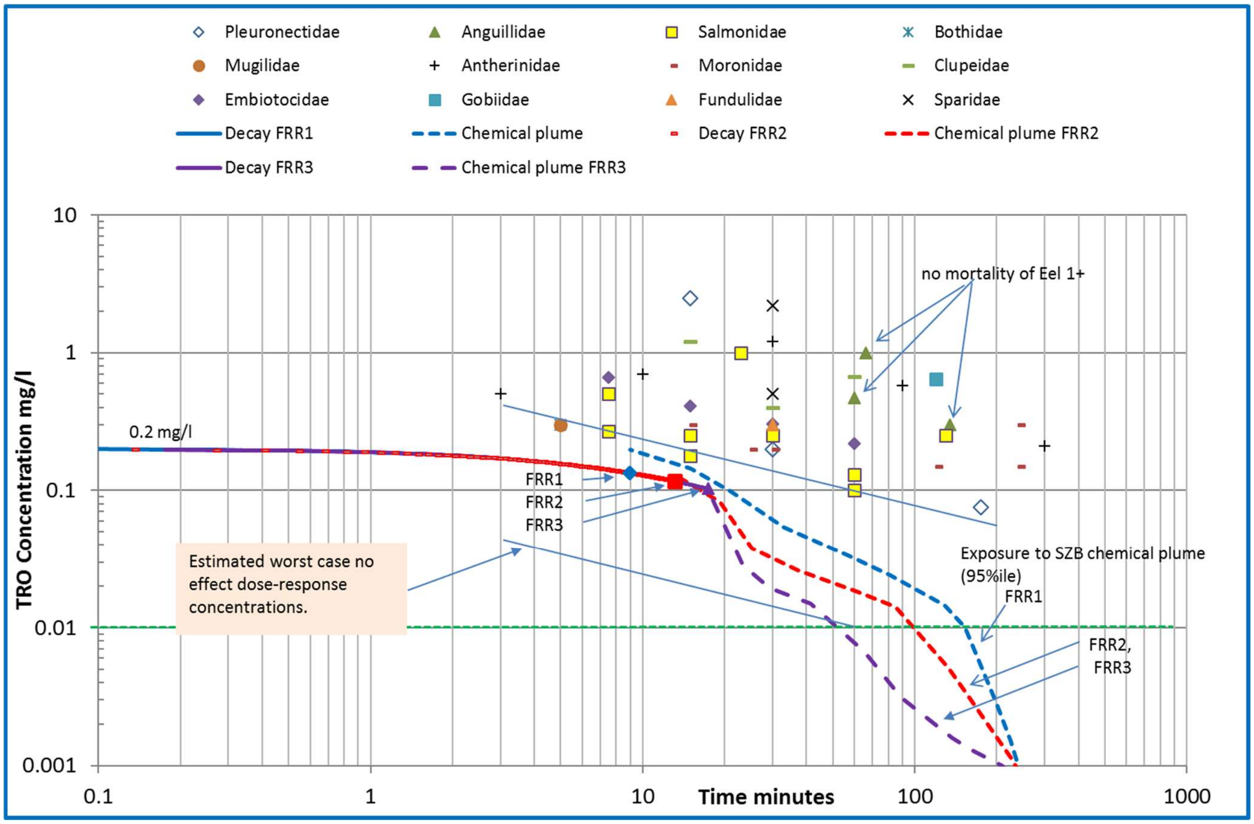

Figure 20 Modelled TRO exposure for different FRR locations against estimated no effect concentrations. Timeline is from entering the FRR system to subsequent exposure in the SZB plume under a regime when the FRR system is chlorinated (referred to in this report as the ‘summer regime’).

Figure 21 shows the TRO exposure for fish that have been returned to sea when the FRR system is not chlorinated i.e. the dose in the FRR tunnel is zero. This figure shows that FRR3 is again the preferred option but even so it is likely that some excess mortality would occur due to the high exposure concentration in the first 5 minutes after discharge from the FRR outfall.

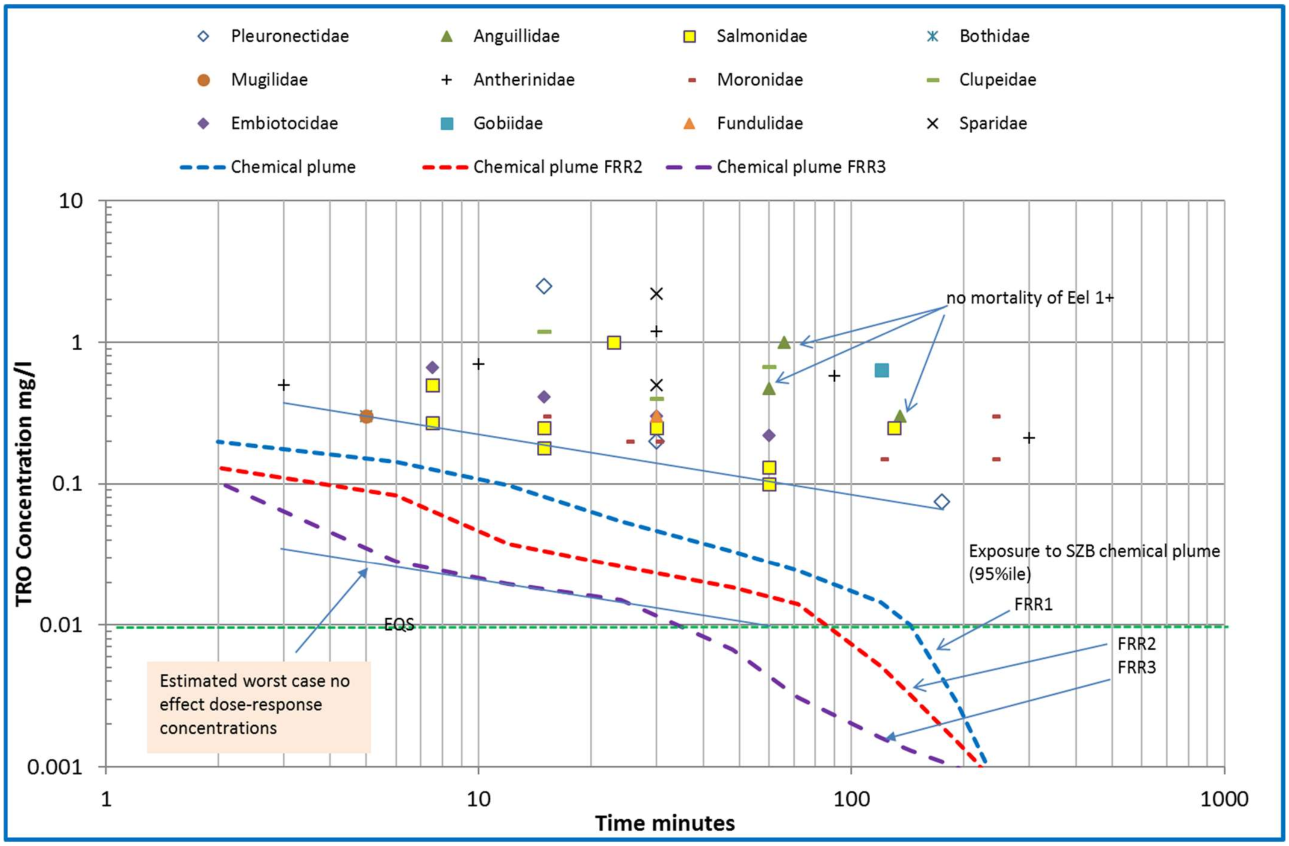

Figure 21 Profiles of potential fish exposure to TROs with different SZC FRR outfall locations shown against the estimated no effect TRO concentrations. Timeline is from the discharge from the FRR system outfall (there being no exposure in the FRR tunnel) and shows the exposure in the SZB plume under a regime when the FRR system is not chlorinated (referred to in this report as the ‘winter regime’).

4.2 Improved estimates of fish mortality using real-time fish tracking in the SZB TRO plume

The results presented in section 4.1 indicate that FRR3 would be the preferred Sizewell C FRR outfall location in terms of minimising fish exposure to TROs above the EQS. However, the reliability of this analysis is questionable because:

a. The species shown in Figures 20 and 21 are generally not those found at Sizewell and the mortalities may, therefore, not be representative. Indeed, the worst-case predictions in section 4.1 are largely based upon TRO toxicity to salmonids which are known to be particularly sensitive species, but which are not found at Sizewell.

b. The toxicity data have been interpreted to imply that it is the total dose exposure profile that causes the measured experimental mortalities but there are very few data available for short exposure (<10mins) and high doses (of >0.2 mg l^{-1}.) to construct that part of the dose-response curve and for some species it is possible that even very short exposures to high doses could prove fatal.

c. The area of the 95%ile TRO plume is not an accurate representation of the dose that individual fish would experience after discharge from the FRR outfall.

4.2.1 Toxicity of TROs to representative Sizewell fish species

The SZC FRR is designed to substantially reduce mortality for flatfish and other robust species such as eel, lamprey, and crustaceans. It is also expected to have a beneficial effect for more robust demersal species such as bass and cod but no benefit for pelagic species such as sprat, herring, anchovy, and shad which are not expected to survive recovery from the drum screens. In order to determine the effects of short term exposure to TROs for the FRR target species at Sizewell a series of laboratory experiments have been conducted to approximate the TRO exposure profile that fish in the SZC FRR system would experience when chlorination is applied (BEEMS Technical Report TR362). This work found the following results:

Table 10 Measured mortality of fish exposed to the approximate TRO profile resulting from a chlorinated SZC FRR system (From BEEMS Technical report TR362)

Species (and age where known)	**Measured 24h mortality (control = 0%)**	**Measured time taken (minutes) for the TRO level to decay from the initial dose level of 0.2 mg l^{-1} to the EQS (10µg l^{-1})**
Sole (adults – mixed age)	0%	90
Plaice (1.5y)	0%	120
Turbot (3y)	0%	180
Eel (yellow)	0%	120
European bass (2y)	90%	60
European bass (3y)	40%	180

These toxicity experiments indicated that the bass toxicity was probably due to the high TRO exposure in the initial 15 minutes of the experiments when TRO concentrations were in the range 0.2 to 0.1 mg l^{-1}. i.e. the predicted exposure in the FRR2 tunnel for approximately 13 minutes could be sufficient to cause the observed mortality for bass. Whilst the flatfish and eels showed a behavioural reaction to this dose level they did not suffer any mortality and recovered from the exposure.

4.2.2 Realistic dose assessment for fish discharged from the SZC FRR.

The modelling of fish exposure to the SZB discharge plume described in Section 4.1 used particle tracking within the derived 95%ile TRO field. This method is computationally efficient and is, therefore, useful for comparative estimates of the effects of the different FRR locations but it does overestimate fish exposure to TROs. The 95%ile plume area is the area of the plume where TRO concentrations are at or exceed a given concentration for 5% of the modelled time i.e. 37h in 31days, it does not represent the instantaneous fish exposure. For example, only fish released from the SZC FRR outfall on the ebb tide will be released into the SZB plume but the 95%ile plume area covers both tides. A more accurate method, but which is considerably more computationally expensive, is to run the hydrodynamic chemical modelling and particle tracking at the same time, so that a field of the likely TRO exposure can be derived i.e. a real-time tracking model.

Using the Sizewell GETM model setup in this manner, the particles were released near the bed, every minute for 12 hours. 720 particles were released over 12 hours, with each particle tracked for four hours, so that the decay of TRO could be accurately modelled (Table 11). Figure 22 shows the calculated fish exposure to TROs from the drum screens to the marine environment, assuming FRR location FRR2, from the real-time tracking model on Spring and Neap tides compared with the results obtained from computations with the 95%ile TRO field. As expected, the calculated exposure is substantially lower with the real-time tracking model. Figure 22 also shows the modelled exposure against the results of the short-term toxicity experiments described in Section 4.2.1.

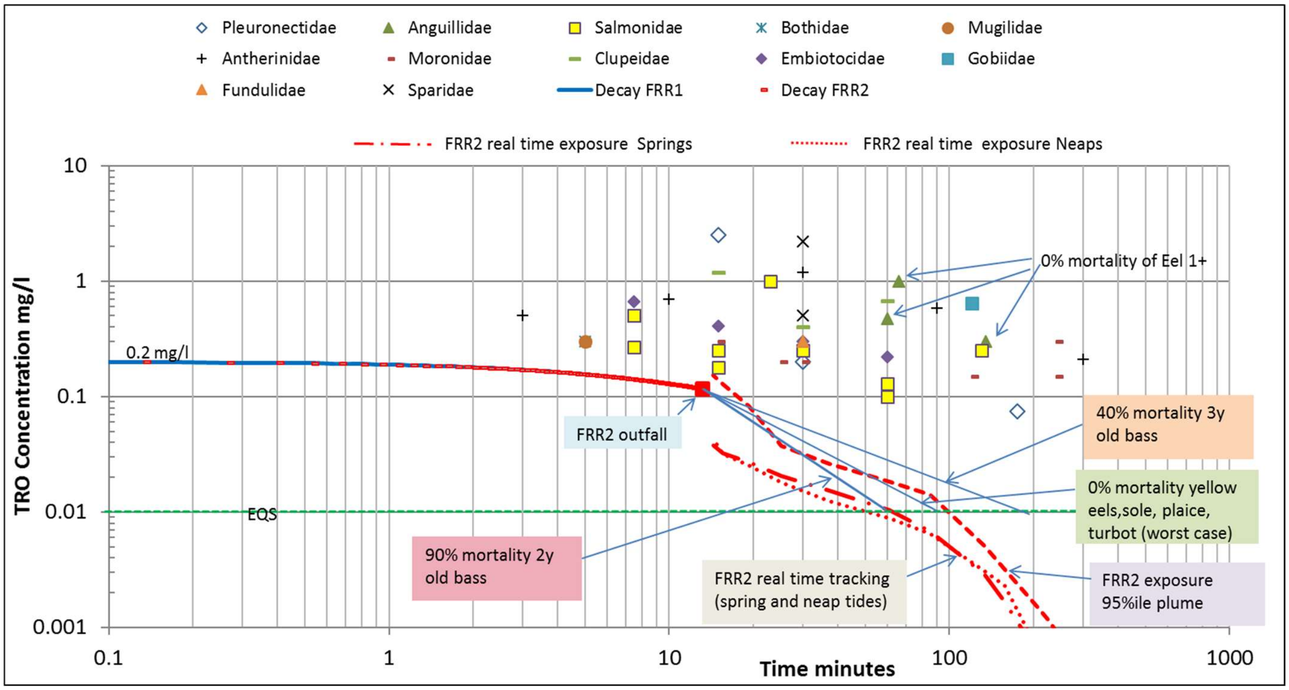

Figure 22 The most likely TRO exposure levels from real time tracking compared with the calculated exposure to the 95%ile plume with the FRR2 position. The blue lines show measured fish toxicity profiles for selected species.

Whereas previously Section 4.1 indicated that FRR2 would produce high fish mortalities, the more accurate dose modelling shown in Figure 22 set against the recent BEEMS toxicity data clearly demonstrates that the FRR2 location would expose flatfish, eels and lamprey to TRO doses that would be not expected to produce any additional mortality (over that expected from an unchlorinated SZC FRR system). These results demonstrate that the main target species (flatfish, eels and by physiological analogy lamprey) would be expected to survive the expected worst-case chlorination regime at SZC. However, if as expected the toxicity to juvenile bass is predominantly due the predicted exposure in the FRR tunnel, then especially 2y old bass would still be expected to suffer considerable mortality.

Figure 23 shows the modelled TRO exposure in winter when the SZC FRR system would not be chlorinated.

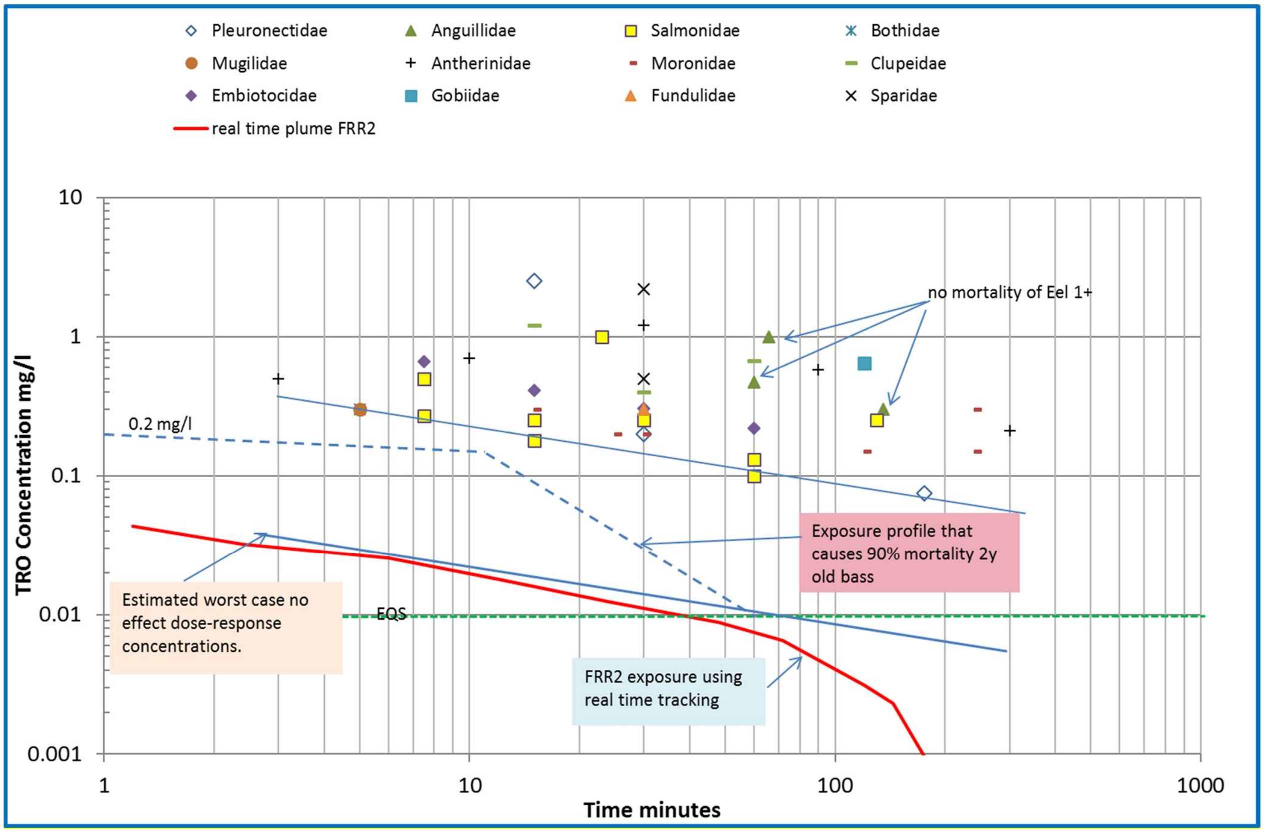

Figure 23. Profile of potential fish exposure to TROs with SZC FRR outfall location FRR2 from real time tracking (red line) shown against the estimated no effect TRO concentrations and the exposure profile which caused 90% mortality for 3y old bass. Timeline is from the discharge from the FRR system outfall (there being no exposure in the FRR tunnel) and shows the exposure in the SZB plume under a regime when the FRR system is not chlorinated (referred to in this report as the ‘winter regime’).

When the SZC FRR system is not chlorinated the TRO exposure to juvenile bass in the SZB plume is predicted to be below that expected to produce no effect (lower, dark blue solid line in Figure 23) and, in particular, the dose levels are expected to be approximately 4.5 to 6 times lower than when the SZC FRR is chlorinated. For example, by comparing Figures 23 and 22 it can be seen that 1.2 minutes after discharge from the SZC FRR fish are predicted to be exposed to TRO doses of 0.04mg l^{-1} with an unchlorinated SZC FRR but 0.2 mg l^{-1} with a chlorinated FRR or, after 6 minutes, 0.025 mg l^{-1} compared with 0.15 mg l^{-1}. Based upon these predictions, it is not expected that juvenile bass will be subject to any additional mortality by being discharged into the SZB plume during periods when the SZC FRR system is not chlorinated.

Table 11 Estimate of actual TRO exposure on release from FRR2 for Spring and Neap tides from the real-time tracking model

Percentile	Time represented (min)	Concentration of TRO (mg/l)	
		Neap tide (19/05/09)	Spring tide (26/05/09)
5	12	0.0003	0.0002
10	24	0.0005	0.0004
20	48	0.0007	0.0006
40	96	0.0023	0.0017
50	120	0.0031	0.0029
70	168	0.0065	0.0069
80	192	0.0088	0.0103
90	216	0.0124	0.0154
95	228	0.0180	0.0206
98	235.2	0.0254	0.0269
99	237.6	0.0319	0.0322
99.5	238.8	0.0433	0.0380
100	240	0.1412	0.1419

Table 11 shows that there is very little difference between the Neap tide and Spring tide simulations. With particles, once released from the FRR tunnel, being exposed to values above the EQS for approximately 24 mins. The time in the tunnel being about 13 minutes (for FRR2).

5 Discussion

The SZC FRR is designed to substantially reduce mortality for flatfish and other robust species such as eel, lamprey, and crustaceans. It is also expected to have a beneficial effect for more robust demersal species such as bass and cod but no benefit for pelagic species such as sprat, herring, anchovy, and shad which are not expected to survive recovery from the drum screens The FRR recovery rates shown in Table 12 have been derived from experiments conducted at operational power stations (Turnpenny and O’Keefe 2005).

However, it is possible that SZC would have to chlorinate its FRR system in the biological growth season i.e. when seawater temperatures exceed 10°C.

Table 12. Estimates of fish survival achieved using a fish recovery and return system (Turnpenny and O'Keefe 2005)

Group	Survival rate
Pelagic (e.g. herring, sprat, shad),	0%
Demersal (e.g. cod, whiting, gurnard)	50%
Epibenthic (e.g. flatfish, eels, gobies, rocklings and crustaceans)	80%

Fish recovered into the SZC FRR system will be exposed to several hazards:

i. TRO exposure in the SZC FRR system prior to the outfall (only when the FRR system is chlorinated)
ii. TRO exposure in the SZB plume on the ebb tide – sometimes referred to as secondary entrainment.
iii. Re-impingement into SZB on the flood tide.

Modelling has shown that the risk of re-impingement is a negligible to minor issue, with FRR1 and FRR2 producing the lowest mean rates over a tidal cycle at 0.14% and 0.7% respectively and FRR4 the largest mean rate at 5.2% (Table 6).

Comparative ranking of the locations showed that FRR1 produced the highest exposure to TROs above the EQS, with decreasing exposure profiles at FRR2 and FRR3 (Figures 20 and 21). However, whilst the total TRO exposure in the SZB plume decreases with FRR tunnel length, the exposure to high doses in the tunnel itself increases. Table 9 shows that FRR2 produces the shortest exposure time to TRO doses > 0.1 mg l^{-1}. Recent BEEMS TRO toxicity data assuming an approximate FRR location at FRR2 showed that whilst flatfish and eels would be expected to survive all of the TRO profiles from FRR1-3, juvenile bass would suffer high mortality, even in FRR3. The toxicity experiments indicated that the exposure to the high doses in the FRR tunnel and shortly after discharge were the probable causes of the measured bass toxicity (BEEMS Technical Report TR362). FRR locations FRR4 and 5 were discounted for this reason as the exposure to doses > 0.1 mg l^{-1} becomes dominated by the time in the tunnel after location FRR3 e.g. the time in the tunnel alone for FRR4 is 21.5 min which is greater than the total predicted FRR3 exposure to the same dose levels (Section 4.1).

Using a real-time tracking model, it was demonstrated that the TRO exposure profile and consequential fish mortality predicted with FRR2 in Figures 20 and 21 were overestimated and that FRR2 would ensure no additional TRO related mortality for flatfish, eels and lamprey when the system was chlorinated (Figure 22) and would also produce no additional mortality for juvenile bass in winter when the system was not chlorinated (Figure 23).

Table 13 summarises the modelling results for FRR locations FRR2 and FRR3 when the system is chlorinated and demonstrates that FRR2 is the preferred option. As the mortality to demersal species such as bass is considered to be due to exposure to TRO dose levels between 0.2 and 0.1mg l^{-1}, it is expected that the shorter FRR2 tunnel length would be preferable for those species. However, in the absence of sufficient data, a worst-case assumption has been made that toxicity is 90% for 2y old bass and 40% for 3y old bass when the FRR system is chlorinated.

When the FRR system is not chlorinated bass would be exposed to a much lower TRO dose profile of approximately 4.5 to 6 times lower doses that when the FRR is chlorinated. For example, by comparing Figures 23 and 22 it can be seen that 1.2 minutes after discharge from the SZC FRR fish are predicted to be exposed to TRO doses of 0.04mg l^{-1} with an unchlorinated SZC FRR but 0.2 mg l^{-1} with a chlorinated FRR or, after 6 minutes, 0.025 mg l^{-1} compared with 0.15 mg l^{-1}. This much lower dose profile is not expected to result in excess bass mortality (Table 14).

Table 13. Predicted excess mortality in a chlorinated SZC FRR system for flatfish, eel and lampreys and 2 and 3y old bass (summer regime)

Option	Re-impingement mortality at SZB	Mortality due to TRO exposure	Total excess mortality due to FRR location	Total FRR mortality (incorporating FRR survival data from Table 12)
FRR2				
Flatfish, eels & lamprey	0.7%	0%	0.7%	20.56%
2y old bass	0.7%	90%	90.07%	95.04%
3y old bass	0.7%	40%	40.42%	70.21%
FRR3				
Flatfish, eels & lamprey	2.9%	0%	2.9%	22.32%
2y old bass	2.9%	90%	90.29%	95.15%
3y old bass	2.9%	40%	41.74%	70.87%

Note. A conservative assumption has been made that no fish would survive re-impingement into SZB.

Table 14 Predicted excess mortality in an unchlorinated SZC FRR system for flatfish, eel and lampreys and 2 and 3y old bass (winter regime)

Option	Re-impingement mortality	Mortality due to TRO exposure	Total excess mortality due to FRR location	Total FRR mortality (incorporating FRR survival data from Table 12)
FRR2				
Flatfish, eels & lamprey	0.7%	0%	0.7%	20.56%
2y old bass	0.7%	0%	0.7%	50.35%
3y old bass	0.7%	0%	0.7%	50.35%
FRR3				
Flatfish, eels & lamprey	2.9%	0%	2.9%	22.32%
2y old bass	2.9%	0%	2.9%	51.45%
3y old bass	2.9%	0%	2.9%	51.45%

Note. A conservative assumption has been made that no fish would survive re-impingement into SZB.

6 Conclusions

Five potential FRR outfall locations were considered at locations FRR1 – FRR5 where FRR1 was the most inshore (Figure 2). It was concluded that:

a. Subject to other considerations, shorter FRR tunnels are preferred in order to return fish as quickly as possible to sea.
b. Locations FRR1 and FRR2 would produce a negligible risk of re-impingement into SZB due to their inshore location with respect to SZB Intake.
c. Recent BEEMS TRO toxicity data derived using what would have been a SZC FRR dosing profile showed that whilst flatfish, eels and lampreys would be expected to survive all of the TRO profiles from FRR1-5, juvenile bass would be expected to suffer high mortality. The toxicity experiments indicated that it was the exposure to the simulated high doses in the FRR tunnel and shortly after discharge that was the probable cause of the measured toxicity. The shortest exposure to TRO doses> 0.1 mg l^{-1} in locations FRR1-5 was at location FRR2.
d. Using a more accurate real-time tracking model to determine fish exposure to TROs it was demonstrated that FRR2 would produce no excess mortality for flatfish, eel and lampreys when the

system was chlorinated and would also produce no additional mortality for juvenile bass in winter when the system was not chlorinated.

e. The excess mortality at the FRR2 location due to re-impingement at SZB would be a worst case of 0.7%.

The exact location for the outfall will depend upon constructability, but this assessment suggests that between BNG Easting 647977 and 648127 along Northing 264109 would be optimal, with a preference for the Western end of this line. The exact Northing does not really matter as the tidal excursion at the site is large, but the position should be chosen to keep the FRR tunnel length as short as possible. It is considered that the conclusions presented in this report will be valid for positions up to 100m both to the North and South of those tested here. The Northing location used in this report is approximately between the 2 SZC forebays; the actual onshore start position is likely to move once the design of the FRR is finalised.

Due to space constraints on the Sizewell C plot plan it was considered possible that there could be two FRR tunnels; 1 from each forebay. This option was not expected to change the predictions in this report. (EDF Energy subsequently decided that two FRR tunnels would be installed at SZC).

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Appendix A Re-Validation of the particle tracking model

A number of drogues were released at Sizewell during the spring and summer 2009 covering spring and neap tides, both in the ebb and flood phases. In particular, observations were obtained along 4 days: 2nd of May 2009 (neap tide), 22nd of June 2009 (Spring tide), 28th of June 2009 (Spring tide) and 1st of July 2009 (Spring tide).

A.1 GPS drifter measurements

Figure 24, extracted from the BEEMS Technical Report TR047, shows the drifters that were employed to track the currents during the spring and ebb tides. The drifters have a parachute drogue at around 1-1.5m depth. As mentioned in the BEEMS Technical Report TR229, this is beneath the heavily stratified layer, meaning that the measured tracks would not be representative of the surface layer circulation, but of the subsurface layer, mainly reproducing the bulk tidal flow.

However, the presence of a flag above the sea surface makes the employed drifters prone to be subjected to leeway, which is defined as the motion of the object induced by wind and waves relative to the ambient current (Allen and Plourde, 1999).

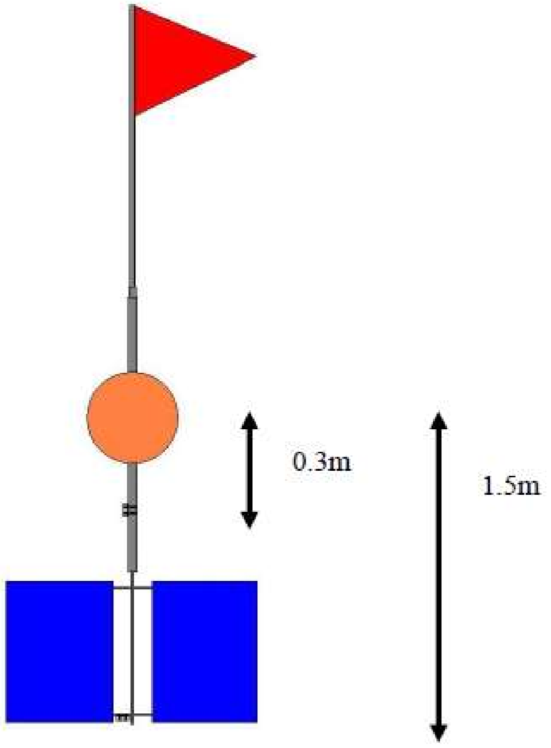

Figure 24: GPS drifters

BEEMS Technical Report TR047 includes the dates and the sites of all the drifter releases. In line with BEEMS Technical Report TR229, not all of them were considered for the model validation, but only some comprising the most relevant periods. Table 15 summarizes the position and date of all the drifters considered in the present model validation. They mostly comprise the same drifters as the ones used in BEEMS Technical Report TR229 in order to allow for a direct comparison of the model results.

Table 15: Initial position and dates of the drifters considered in the present validation

Tidal phase	Code	Latitude	Longitude	Date	Time
Neap ebb	NE 1	52.2162	1.6259	2009/05/02	7:51
	NE 2	52.2162	1.6268	2009/05/02	7:52
	NE 3	52.2162	1.6257	2009/05/02	7:54
	NE 4	52.1643	1.6271	2009/05/02	7:56
Neap flood	NF 1	52.2143	1.6264	2009/05/02	09:54
	NF 2	52.2137	1.6267	2009/05/02	09:50
	NF 3	52.2143	1.6265	2009/05/02	09:51
	NF 4	52.4142	1.6268	2009/05/02	09:49
Spring ebb	SE 1	52.2163	1.6261	2009/06/22	10:38
	SE2	52.27	1.6341	2009/06/22	13:48
Spring flood	SF 1	52.1899	1.6253	2009/06/28	10:36
	SF 2	52.2001	1.6242	2009/06/28	10:09
	SF 3	52.1884	1.6249	2009/06/28	10:39

A.2 Model setup

The drifters were simulated as passive particles using a Lagrangian particle tracking model developed at Cefas and based on the algorithm by Wolk (2003). Particle advection is calculated from the 3D velocity fields of the GETM model run ReferenceV2 which corresponds with the present day situation of Sizewell B cooling water discharge. The model results are saved at 1 hour resolution to allow for a correct representation of the tides. ReferenceV2 configuration is an update of the model runs used in the GETM Stage 3 report (BEEMS Technical Report TR302). The changes consisted of:

- Extension of the model domain to include shallower water closer to the coastline in order to improve plume mapping and area calculations
- Associated changes to the model internal time step from to ensure numerical stability in the shallow water areas.

These changes in the hydrodynamic model setup require an updating on the validation of the Lagrangian model with respect to BEEMS Technical Report TR229, which is the purpose of the present section.

The hydrodynamic model uses a curvilinear grid, whereas the Lagrangian model requires an equidistant lat/long grid to do the calculations. Therefore, the model results must be interpolated to a regular grid sufficiently fine to be able to simulate the highly variable near-shore region where the drifters were released. For these simulations a horizontal resolution of 25 m was considered.

Another consequence of the high variability of the near-shore environment is related to the fact that particles that are released at very short distances may experiment very different trajectories due to the rapidly varying bathymetry and tidal currents. To account for this effect, we released for each validation experiment 100 particles randomly distributed in a circle centred at the position of the drogue release (see Table 15~~Table 15~~) and 70 m radius. Different conditions and hence, different trajectories, are also expected for particles that are released at the same position but at slightly different times.

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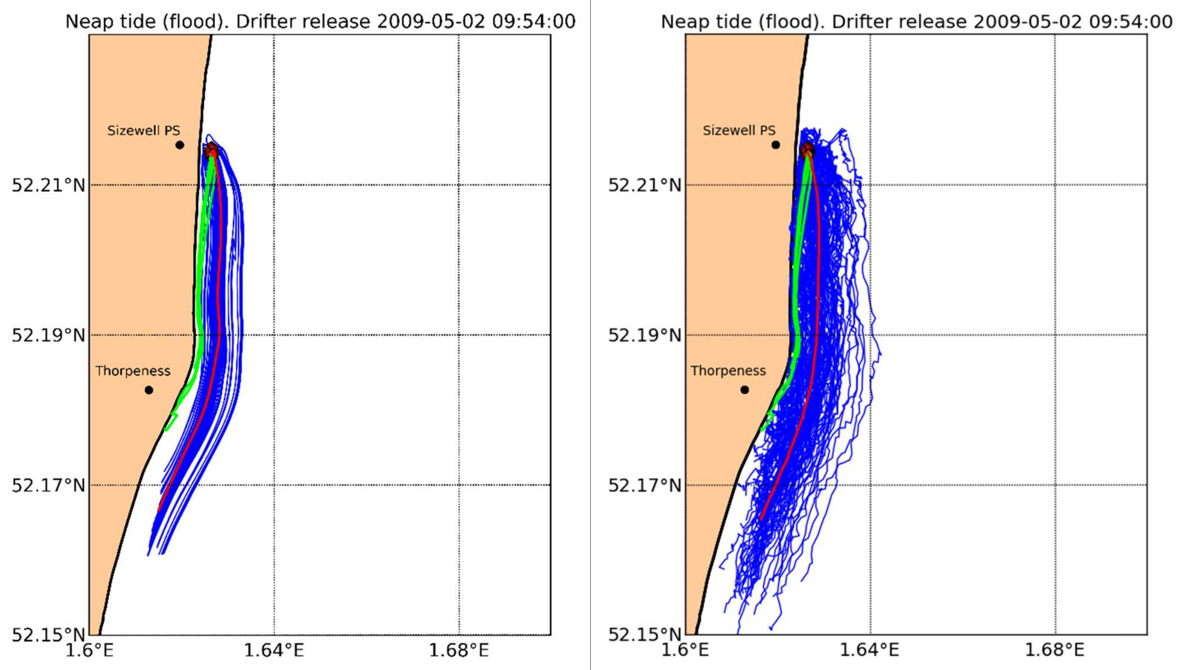
Additional issues in the model set up involve whether to consider or not horizontal and vertical dispersion in the model and the determination of the particle depths. For this purpose, a couple of sensitivity test were carried out.

A.2.1 Sensitivity to horizontal and vertical dispersion

Figure 25 shows the observed (green lines) and modelled (blue lines) trajectories of the 100 particles randomly released around position NF1 (see Table 15) without diffusion (left panel) and with diffusion (right panel). Particles are released at the surface and are forced to remain at approximately the same depth all along the simulation.

Figure 25 right shows that diffusion results in wiggling particle trajectories that do not correspond with the observations. Moreover, the modelled particles are transported much further to the south than the observations, as the red line that represents the centre of mass of all the particle trajectories shows. By contrast, the simulation without dispersion shows a better agreement with the measurements, both in the shape of the trajectories and the average extent.

Indeed, the size of the submerged drogue of the drifters (around 1.5m) would increase the object inertia in such a way that it would make it less prone to be affected by small scale diffusion. Consequently, no dispersion was considered in the rest of the simulations.



WITHOUT DISPERSION

WITH DISPERSION

Figure 25: Observed and modelled particle tracks for a surface release of NF1 (see Table 15). Left: No horizontal and vertical dispersion. Right: with horizontal and vertical dispersion. The blue lines represent

modelled trajectories, the red line represents the centre of mass of the modelled trajectories and the green line are the observations for releases NF1-4.

A.2.2 Sensitivity to particle depth

As stated in Section A.1, the presence of a 1-1.5m depth drogue means that the drifters would not exactly be representing the surface, but the sub-surface circulation.

A sensitivity test was carried out to determine the influence of the depth on the model results. For this purpose, three simulations were run considering that the particles were released at the time and horizontal position NF1 (see Table 15), and three different depths: 0m, 1m and 1.5m. Note that the particles are forced to remain at approximately the release depth all along the simulation.

Figure 26 shows the results for each of the selected depths. As can be seen, if the particles are forced to remain at the surface (Figure 26 A) they are more dispersed offshore and the net transport to the south is larger than observed. The opposite occurs when particles are kept at 1.5m depth (see Figure 26 C). Therefore, a depth of 1m is considered to be the one that better fits the observations (see Figure 26 B).

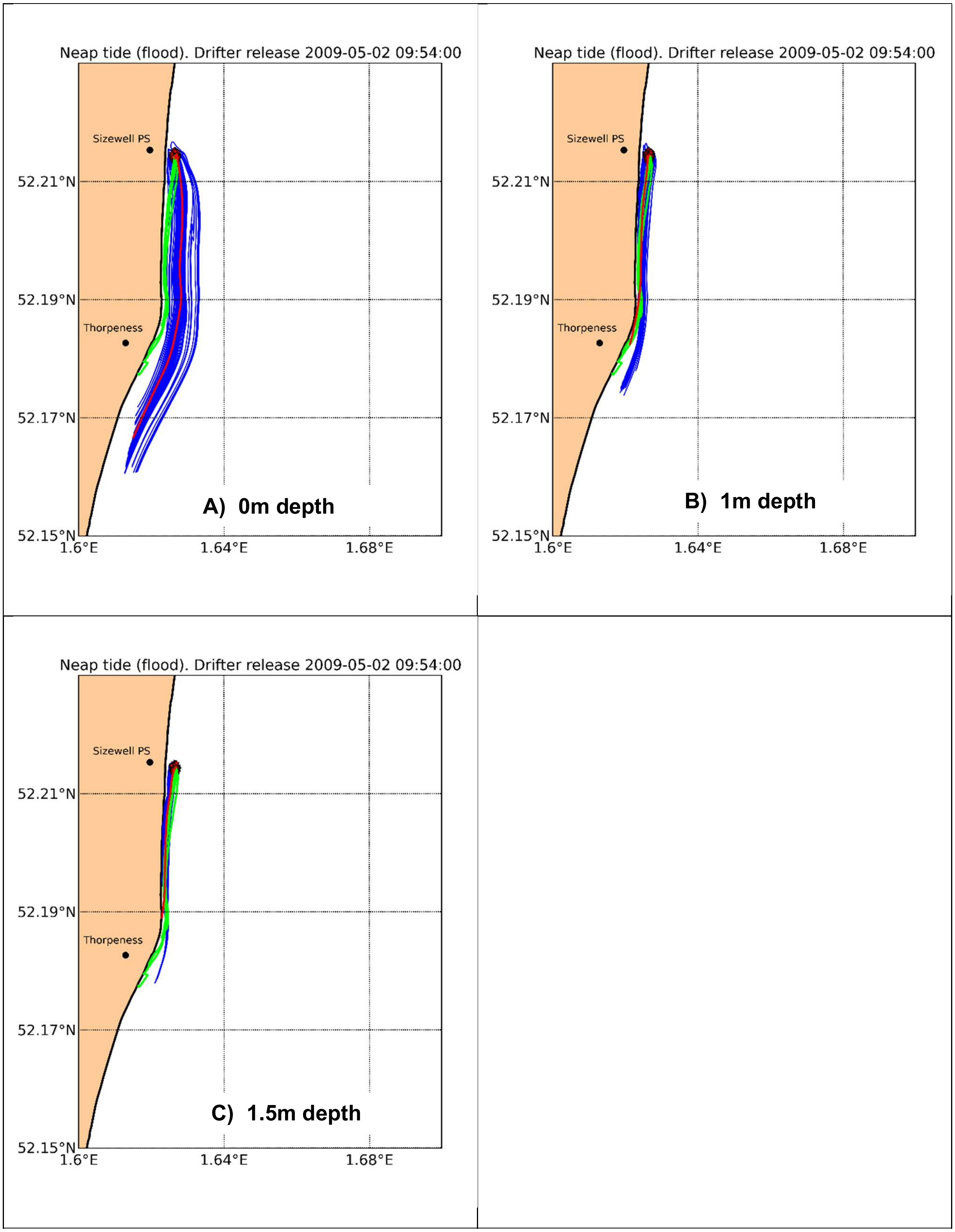


Figure 26: Sensitivity of the particle trajectories to simulation depth. Simulated trajectories in blue, centre of mass in red and observations from releases NF1-4.

A.3 Model results

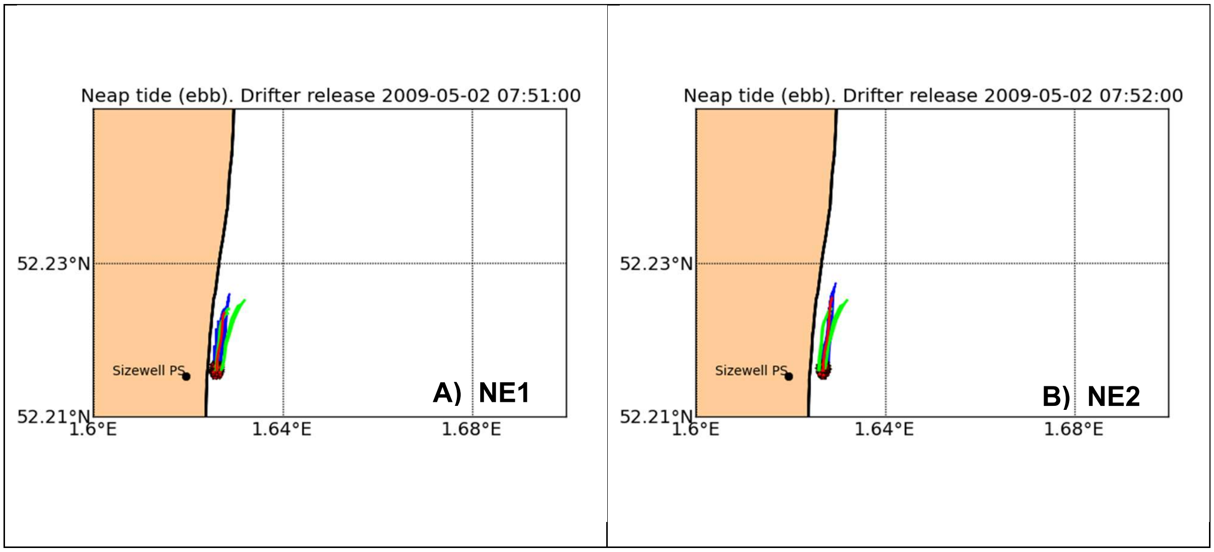
The results of the simulated trajectories are presented according to the phase of the tide:

- Neap tide ebb phase
- Neap tide flood phase
- Spring tide ebb phase
- Spring tide flood phase

A.3.1 Neap tide ebb phase

Particles were released at the positions and times indicated in Table 15 (NE1-4) and were followed for approximately 2h. Figure 27 shows the model results for each of the releases. As can be seen, only slight differences are observed among the plots. In any case, all of them seem to reproduce quite reasonably the observed trajectories. Figure 28 is included to show the wind conditions during the drifting experiment. As can be seen, weak easterly/south-easterly winds prevailed this day. The offshore component of the wind might be responsible to a certain extent for the offshore turning trajectories of the drifters at the end of the drifting experiment. In any case, the leeway drift due to wind must have been very low due to the weak wind conditions (less than 4m/s, being the average for this month above 5m/s, see Section A.2) and the inertia of the drifters.

If we compare these results with the previous model validation (see BEEMS Technical Report TR229) we observe a clear improvement, especially with respect to the extension of the trajectories, which were underestimated in the previous version of the ReferenceV2 run.



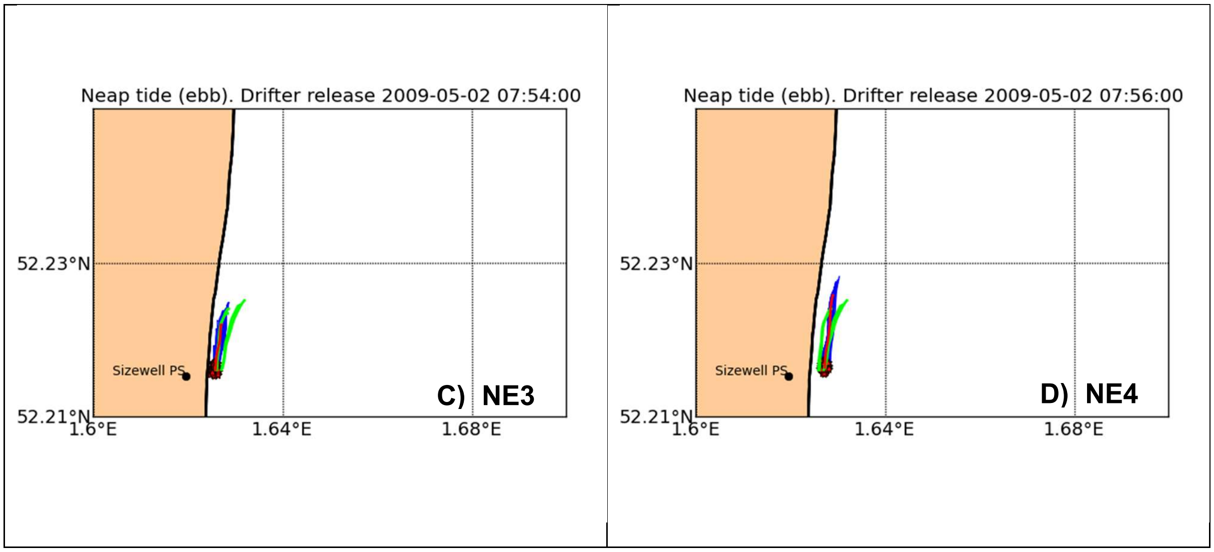


Figure 27: Modelled and observed particle trajectories released at Neap tide (ebb phase). The different plots correspond to the releases NE1-4 in Table 15. Simulated trajectories in blue, centre of mass in red and observations from releases NE1-4 in green.

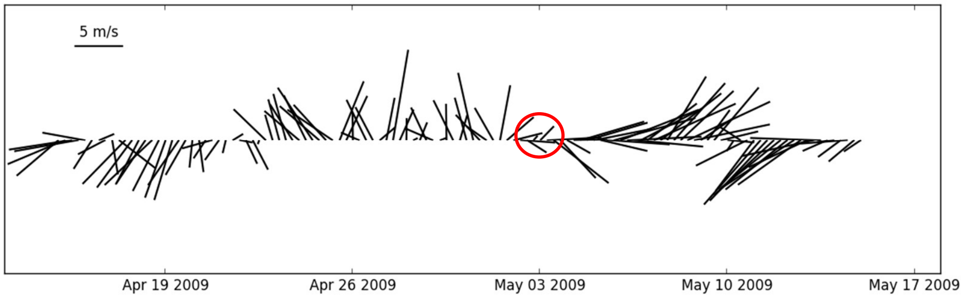


Figure 28: Wind conditions (ECMWF-operational product) before and after the simulated period. We highlight in red the wind conditions for the 02/05/2009

A.3.2 Neap tide flood phase

Particles were released at the positions and dates indicated in Table 15 (NF1-4) and kept at 1 m depth. As in the previous section, all the particles are released from very close positions within a time frame of 5 minutes. They are followed for 3 to 5 hours (depending on the release experiment). NF1, NF2 and NF4 trajectories are very similar (see Figure 29). Only NF3 shows some differences, mainly with respect to the extension of the trajectories to the south (more particles are able to go round Thorpeness and continue southwards).

Again, these results constitute an improvement with respect to the previous model validation (BEEMS Technical Report TR229), since the particles remain closer to the shore and present trajectories more extended to the south.

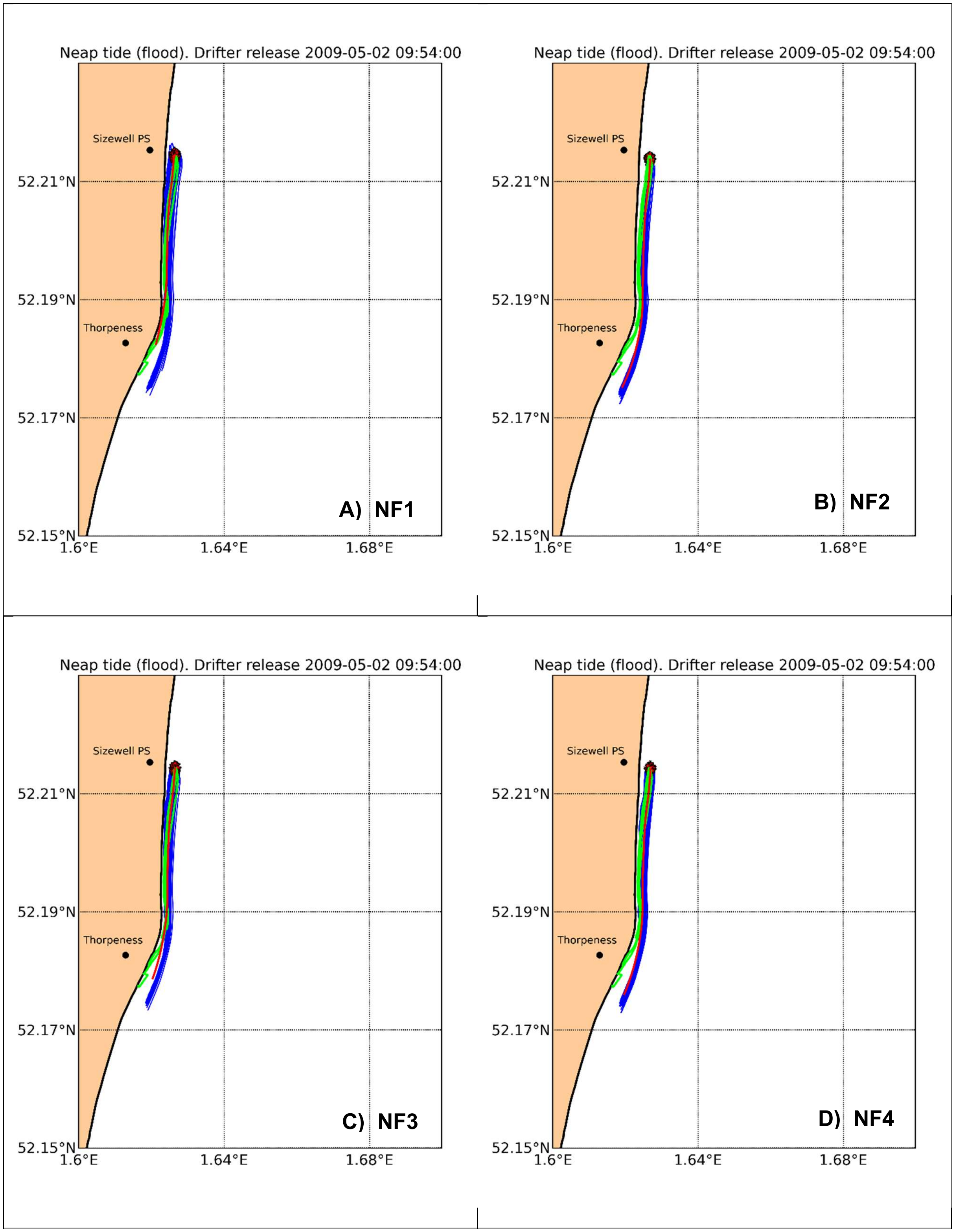


Figure 29: Modelled and observed particle trajectories released at Neap tide (flood phase). The different plots correspond to the releases NF1-4 in Table 15. Simulated trajectories in blue, centre of mass in red and observations from releases NF1-4 in green.

A.3.3 Spring tide ebb phase

In this case, the results of the run corresponding to the initial positions and dates referred to as SE1 and SE2 in Table 15 are shown. The drifters released at SE1 are followed for more than 4 hours, whereas the ones corresponding to SE2 are only tracked for 2 hours, thus presenting much shorter trajectories. Figure 30 shows the model results versus the observations. In the case of the SE1 run (Figure 30 A) the model overestimates the observed trajectories, being the particles displaced further north. On the other hand, SE2 trajectories (Figure 30 B) present a good fitting with the observations.

The prevailing wind conditions for the 22nd of June 2009 are depicted in Figure 31 left red circle. Weak South-easterly winds dominate the whole day (average wind speed below 4m/s), probably having some influence on the transport of the drifters shoreward. However, the size of the drifters is quite big and the wind velocity does not seem to be sufficiently high to explain the differences between the model results and the observations. Other sources of uncertainty may be related to the leeway due to waves, a misrepresentation of the complex coastal bathymetry by the model, etc.

If we compare these results with the ones corresponding to the previous validation report (BEEMS Technical Report TR229), we observe a completely different behaviour. Whereas the previous version of the model lead to the underestimation of the observed trajectories for the ebb phase of the spring tide, the present version seems to overestimate it for SE1 release.

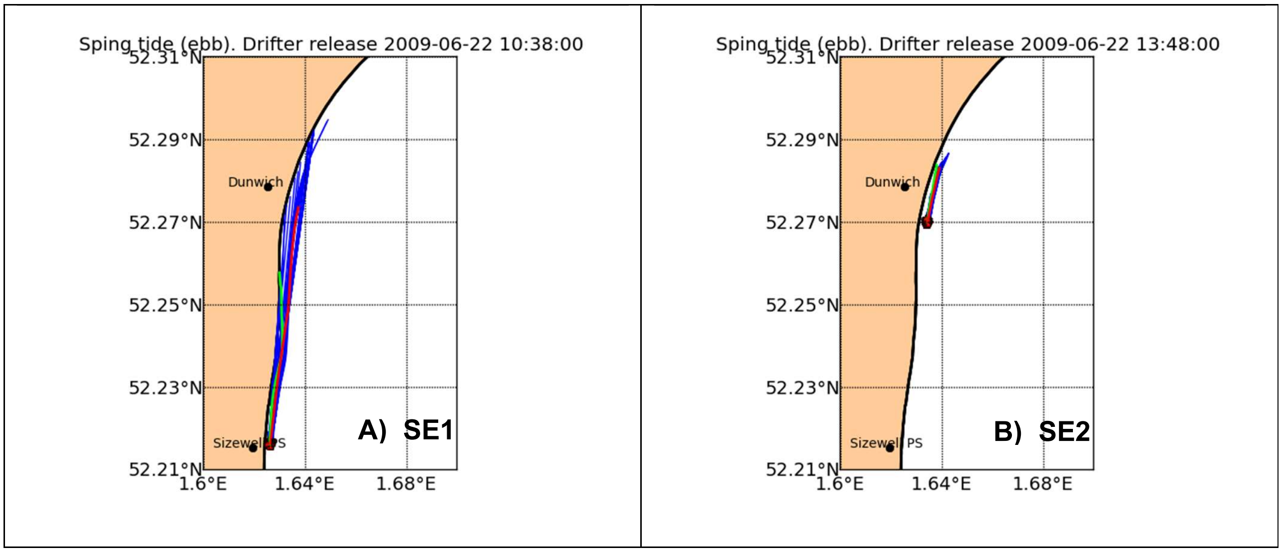


Figure 30: Modelled and observed particle trajectories released at Spring tide (ebb phase). The plot corresponds to the release SE1 in Table 15. Simulated trajectories in blue, centre of mass in red and observations in green.

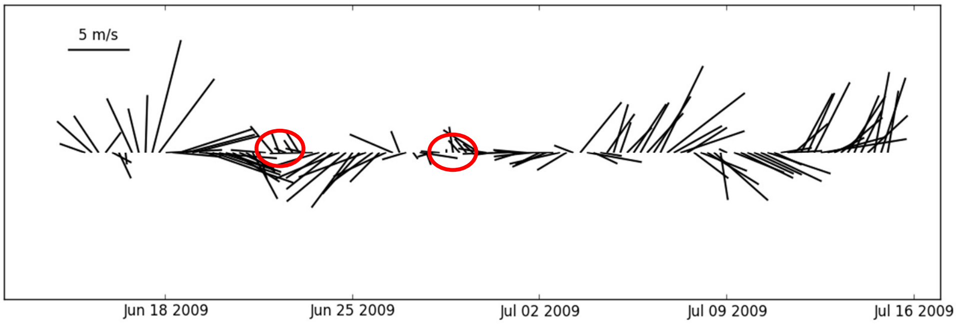
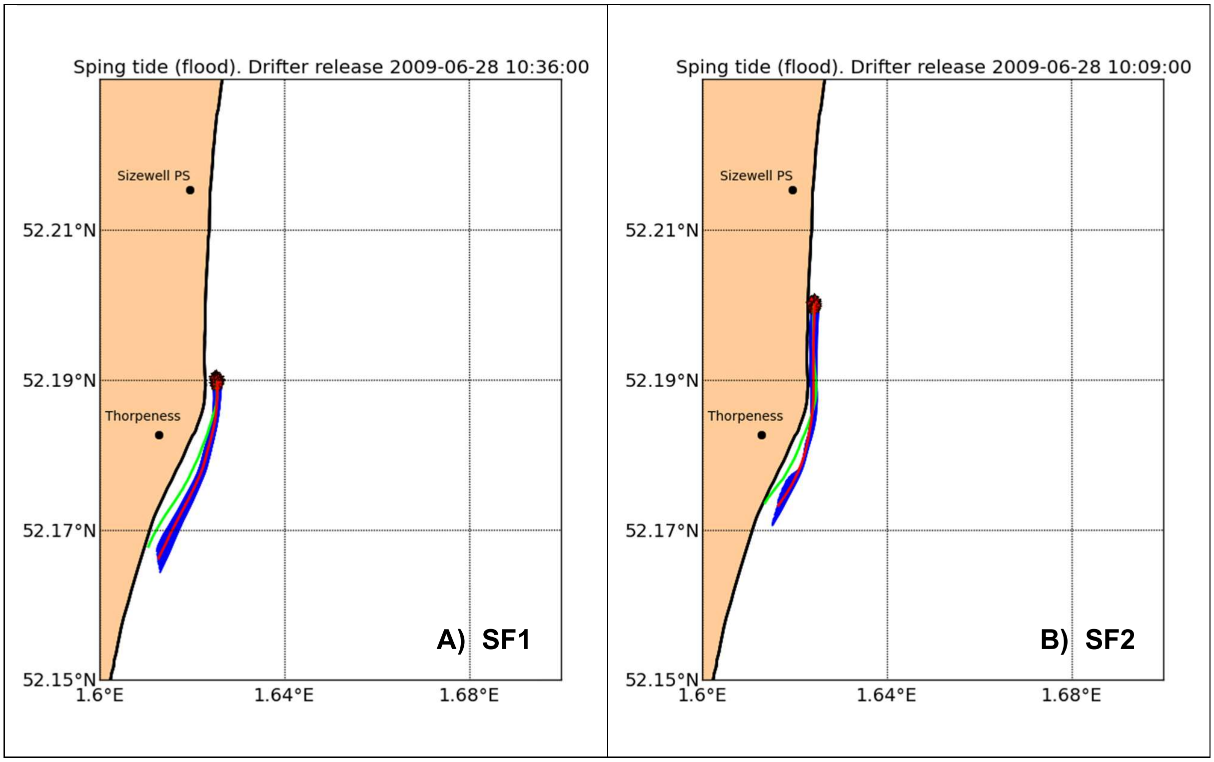


Figure 31: Wind conditions (ECMWF-operational product) before and after the simulated period. We highlight in red the wind conditions for the 2009/06/22 (left) and the 2009/06/28 (right).

A.3.4 Spring tide flood phase

Three simulations corresponding to the positions and dates denoted by SF1-3 in Table 15 were run. Particles were followed for 2 hours for SF1 and SF2 and for 3 hours for SF3. Figure 32 shows that the model presents a good ability to reproduce the observed trajectories for all the experiments, both in extension and shape. The only difference is related to a slightly more offshore pathway of the modelled trajectories with respect to the observations. This fact could be somehow related to the weak onshore component of the wind this day (see Figure 31, right red circle. The average wind speed is 3.8m/s).

There is a clear improvement on the model results with respect to the previous version of the model for this period of time (see BEEMS Technical Report TR229).



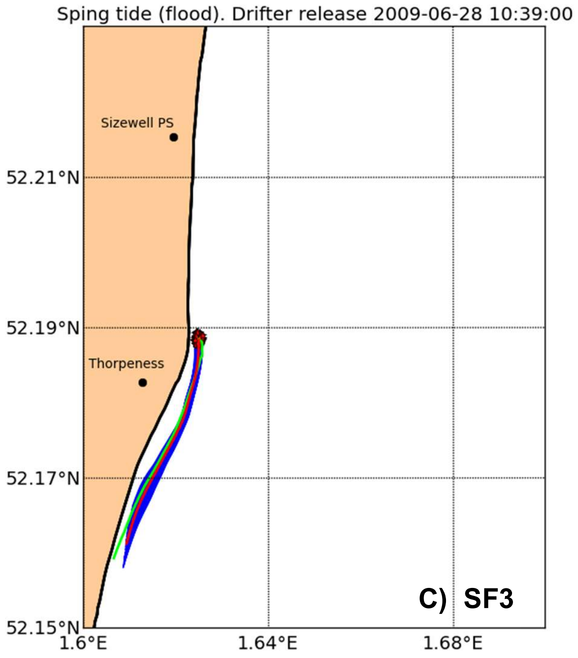


Figure 32: Modelled and observed particle trajectories released at Spring tide (flood phase). The plot corresponds to the releases SF1-3 in Table 15. Simulated trajectories in blue, centre of mass in red and observations in green.

A.4 Conclusions

The Lagrangian model was able to reasonably reproduce most of the observed trajectories during the ebb and flood phases, during both spring and neap tides. The hydrodynamic model updates described in Section A.2 led to an improvement in the representation of the coastal currents with the consequent improvement in the particle trajectories. This is made clear when comparing the results shown in this report with those shown in BEEMS Technical Report TR229.

However, some differences persist (see for example Section A.3.3). Among the sources of discrepancy BEEMS Technical Report TR229 points out the difficulties in reproducing the most relevant features of the bathymetry at the model resolution, especially in shallow water, where the drifters were released.

The GPS drifters used in this experiment could have been affected by leeway drift caused by wind or waves, although in this particular case the wind conditions were fairly weak. Including this effect in the Lagrangian model could lead to a better representation of the observed trajectories but only at the expense of considerable complexity.