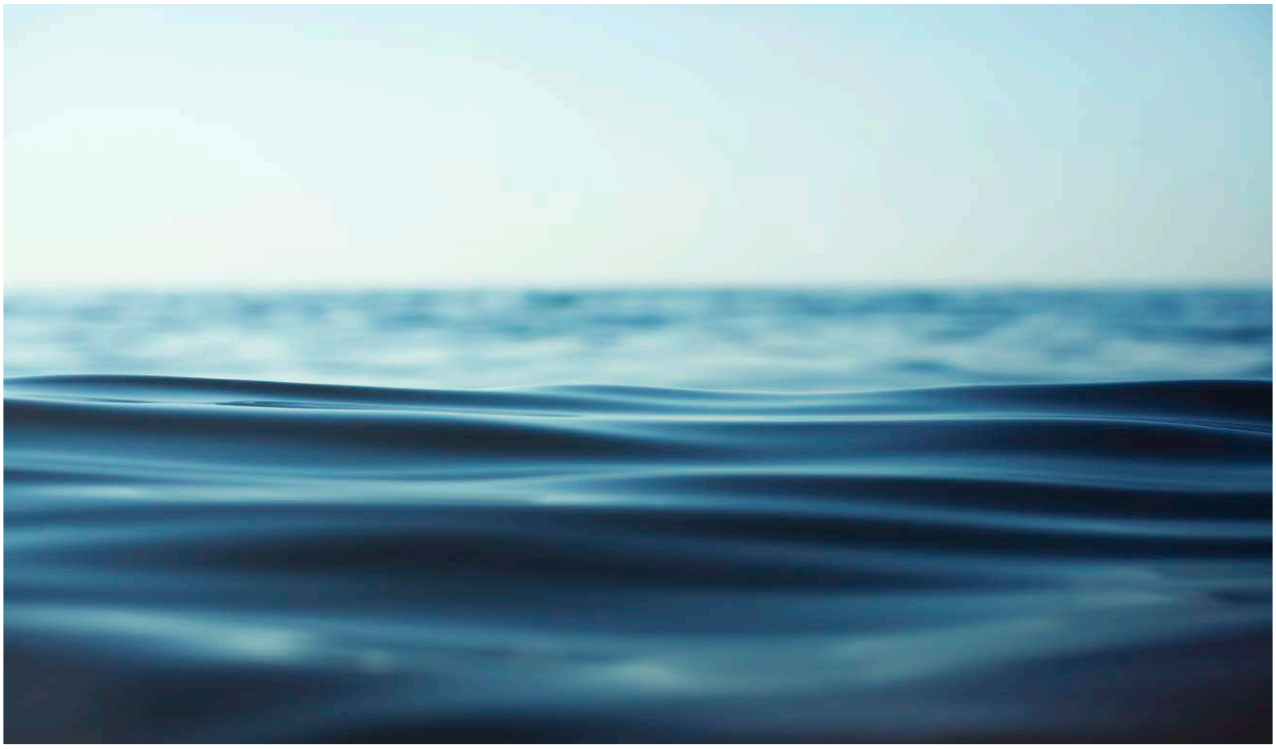
HR Wallingford
Working with water

Bradwell Power Station

Effluent discharge arrangements: Initial dilution



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Summary

Magnox is undertaking a decommissioning programme at Bradwell nuclear power station. During decommissioning several waste streams will be generated and released in a controlled batch operation to the Blackwater Estuary. This report considers two components of these waste streams: the Active Effluent (AE) and the abated fuel element debris (FED) effluent. In its initial concept, Magnox expected that these effluents would be discharged via the final delay tank and siphon pit/outfall previously used for the power station cooling water. This report describes a study to assist Magnox in developing dedicated discharge arrangements for the effluents.

The AE has a density close to that of fresh water. The FED effluent is expected to have a nitrate concentration of around 22,000 mg/l as N, and a density of 1122 kg/m^3, which is significantly higher than the density of the receiving water. Both effluents will be discharged in daily batches of up to 20 m^3.

An outline outfall configuration is suggested for the FED and AE, consisting of:

- single port of internal diameter 0.065 m;
- discharging horizontally;
- raised 5.5 m above the bed;
- directed offshore, perpendicular to the tidal current direction.

This outfall configuration is predicted to give an initial dilution of 500:1 or better for FED within 100 m from the outfall for most tidal conditions expected at the site. On occasional smaller tides it is predicted to achieve at least 300:1 at 100 m, and 500:1 within about 260 m of the discharge, based on current speeds from the hydrodynamic model, during the discharge window.

For the AE, dilution at 100 m of 500:1 or better is predicted when the current speed is greater than about 0.4 m/s (around half the simulated tides). For the lowest current speed during the discharge window, the predicted dilution is around 240:1 at 100 m and 500:1 is achieved around 260 m from the outfall. Dilution of 500:1 or better is achieved for more than 60% of the simulated tides (and 400:1 or better for 80%) at 100 m from the discharge point.

Contents

Summary

Figures

Tables

1. Introduction

Magnox is undertaking a decommissioning programme at Bradwell nuclear power station. During decommissioning several waste streams will be generated and released in a controlled batch operation to the Blackwater Estuary. This report considers two components of these waste streams: the Active Effluent (AE) and the abated fuel element debris (FED) effluent. In its initial concept, Magnox expected that these effluents would be discharged via the final delay tank and siphon pit/outfall previously used for the power station cooling water. This report describes a study to assist Magnox in developing dedicated discharge arrangements for the effluents.

The site lies on the south side of the Blackwater Estuary in Essex, approximately one kilometre seaward of Bradwell Marina (Figure 1.1), and has been occupied as a power station since the early 1960s.

1.1. Report conventions

In this report the horizontal co-ordinates are referred to the British National Grid and vertical levels to Ordnance Datum Newlyn (ODN). ODN is approximately 0.2 m below mean sea level at Newlyn, and 2.68 m above Admiralty Chart Datum (CD) at Bradwell; CD is approximately the level of the Lowest Astronomical Tide (LAT).

Most of the report refers to rates of dilution rather than absolute concentrations. This allows the dilution predictions to be extended to other constituents of the effluent not directly considered, because all dissolved components are expected to behave in the same way. For example, a dilution of 1000:1 corresponds to a concentration of one thousandth (1/1000) of the initial concentration, or a relative concentration of 0.001.

The study makes use of information provided and derived in previous investigations carried out for Magnox and BNFL, and summarises HR Wallingford’s previous studies of the AE and FED effluent.

Dispersion in the wider estuary area is discussed in a companion report to this document (Reference 5).

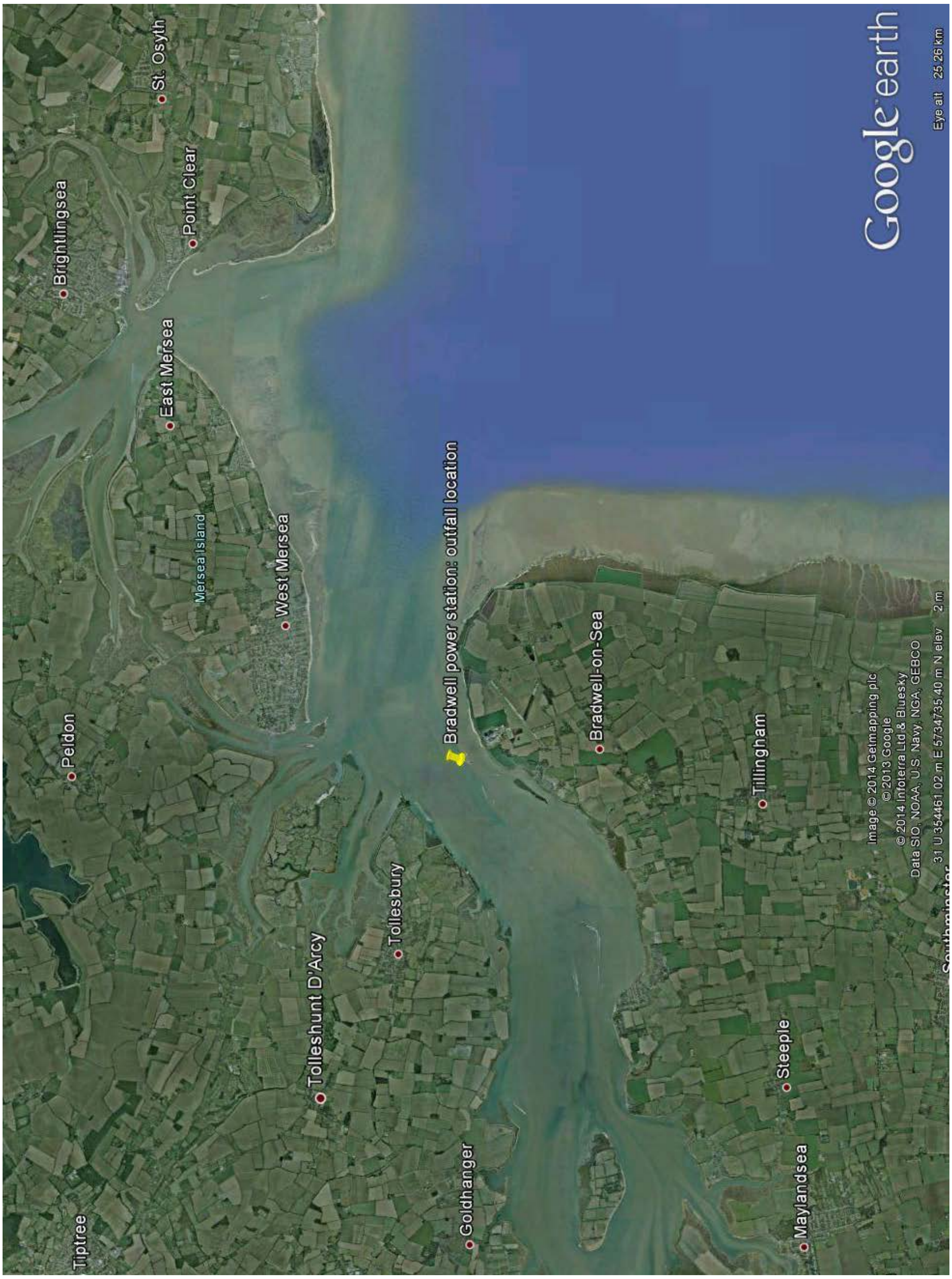

Figure 1.1: Location map

2. Environmental conditions

The Blackwater Estuary is a significant tidal estuary on the east coast of England. It receives freshwater inputs from the rivers Blackwater, Colne and Crouch, together with other smaller streams. The mean tidal range at Walton-on-the-Naze (an Admiralty Standard Port near the mouth of the estuary) is 3.8 m on spring tides and 2.3 m on neap tides. The tidal range at Bradwell is somewhat larger: around 4.8 m on spring tides and 2.9 m on neap tides, according to the Admiralty Tide Tables.

2.1. Data from the Blackwater TELEMAC model

HR Wallingford holds an existing calibrated TELEMAC-2D tidal model of the Blackwater Estuary area, which was established for previous studies at Bradwell (References 1 and 2). The model extent and bathymetry are presented in Figure 2.1 and Figure 2.2.

TELEMAC-2D is a two-dimensional, depth-averaged, numerical model that uses the well-established finite element method to determine water depths and depth-averaged velocities at each node in the computational network or ‘mesh’. A depth-averaged model is appropriate in this case as the Blackwater Estuary is observed to be well mixed and unstratified. The model mesh contains triangular elements of varying size and orientation, allowing wide spatial coverage using small elements in the area of interest and larger elements in the remoter areas. The elements can be aligned with physical features to give a highly accurate representation of the layout. The model is supplied with boundary conditions in the form of water level and/or current velocity, and calculates the corresponding velocity and water level across the domain. The results are stored at intervals for analysis or use in further calculation. TELEMAC has been established as a highly effective model for simulation of well-mixed estuaries and HR Wallingford’s TELEMAC models of coastal areas, including the Anglian and Northumbrian coastlines, have been accepted by the Environment Agency as the basis of discharge planning studies for many sea outfalls.

The Blackwater Estuary model was set up using bathymetric data from Admiralty charts of the area, together with survey data in the vicinity of the intake/discharge structure. The model area includes the three estuaries of the Blackwater, the Colne and the Crouch, and extends 25 km along the coast to north and south and 20 km offshore. The offshore boundary has been set to follow the general direction of the flood and ebb currents in the North Sea. Boundary conditions were provided as water levels at the seaward boundaries, synthesised from published harmonic constituents in a similar way to the predictions published in the Admiralty tide tables.

River inputs were represented as average discharges at Maldon (Rivers Blackwater, Brain, Ter and Chelmer) and at the River Colne.

The model has been verified using published Admiralty tidal stream (Diamond) data and other measurements. In particular the model currents were compared with observations close to the discharge point (Reference 1).

Figure 2.3 and Figure 2.4 show the modelled variation of water depth, and current speed and direction near the outfall structure. In summary, the simulated water depth varies approximately between 5 m and 11 m, and the simulated peak current speed between 0.3 m/s and 0.7 m/s.

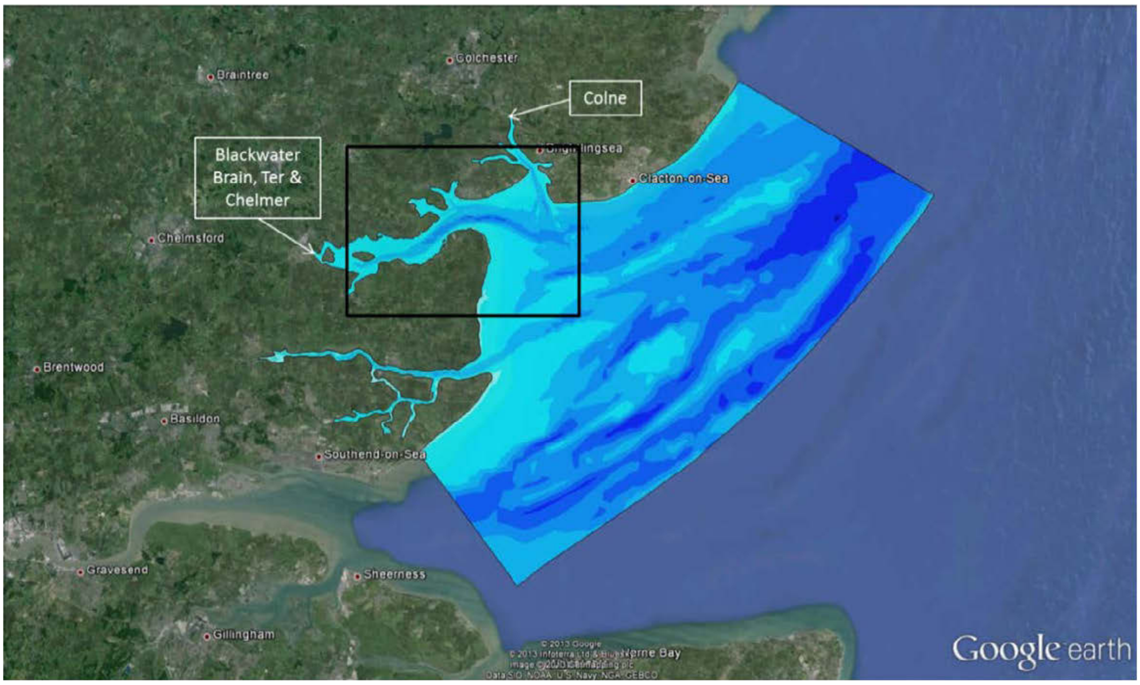

Figure 2.1: Extent of the numerical model

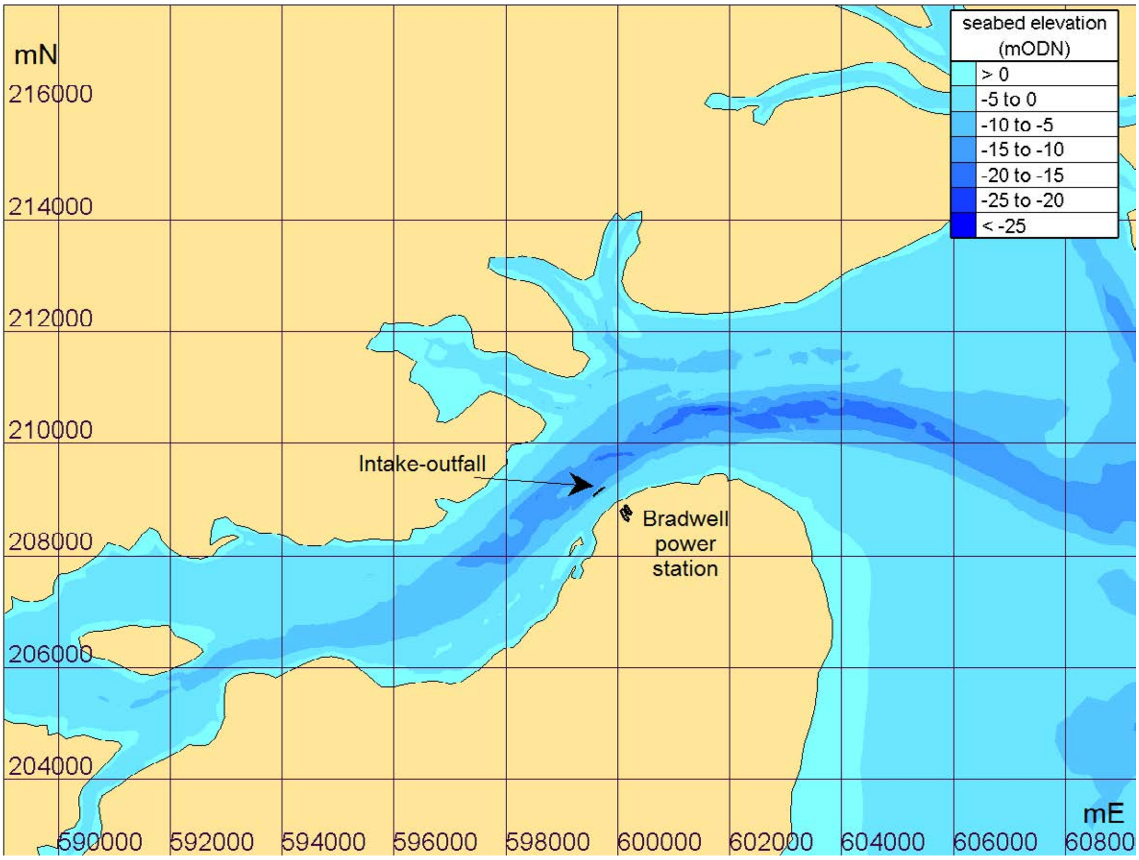

Figure 2.2: Numerical model bathymetry near Bradwell

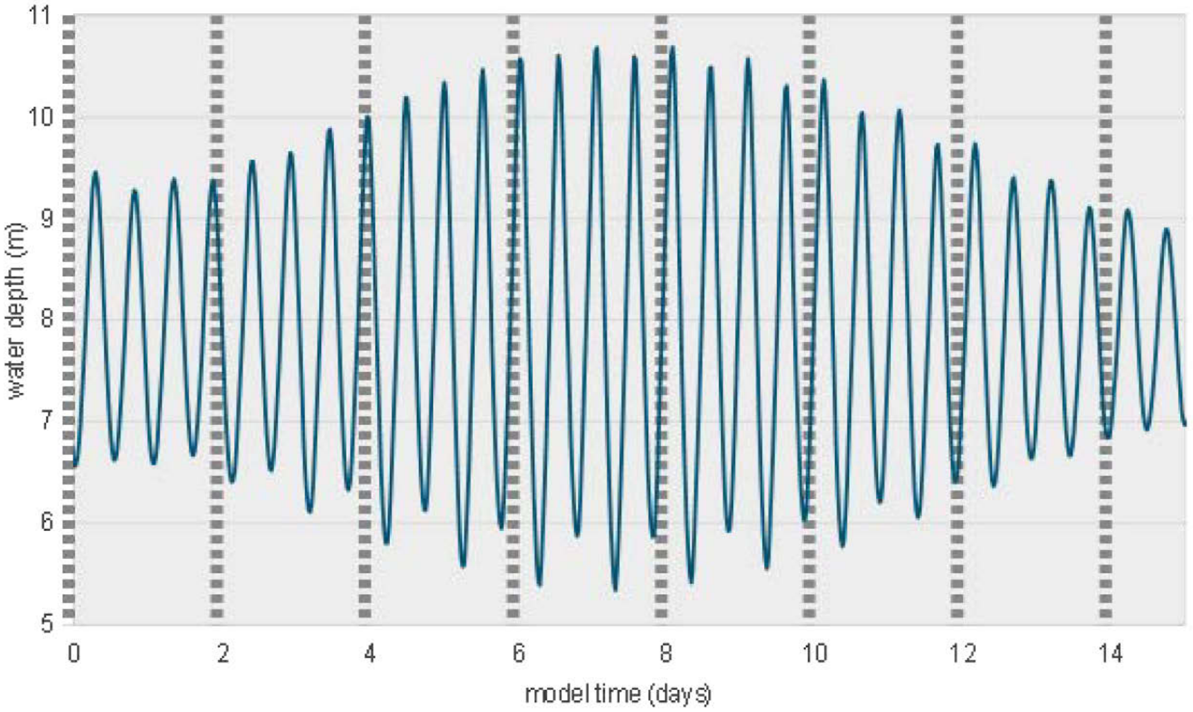

Figure 2.3: Simulated water depth at the outfall location

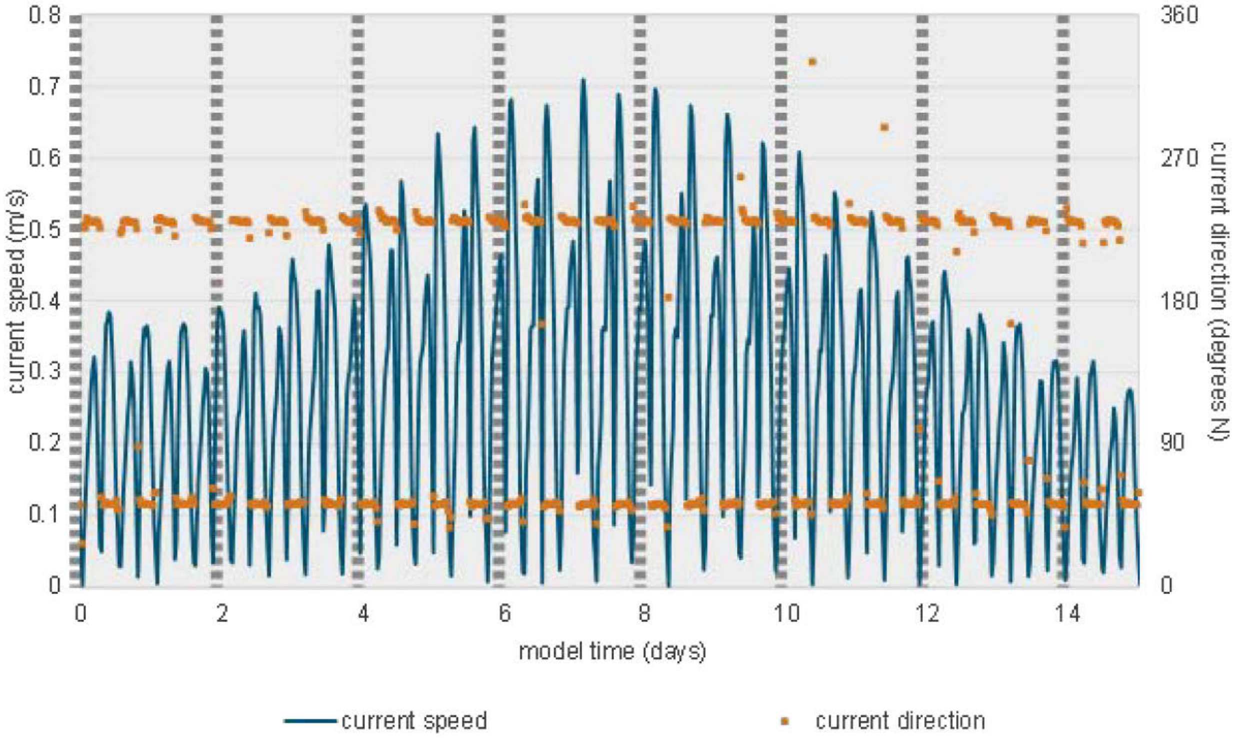

Figure 2.4: Simulated current speed and direction at the outfall location

2.2. Data from site measurements

The hydrodynamic model calibration is described fully in Reference 1. The values above can also be compared with the measurements made at the site in December 2012 (Reference 3) by the Port of London Authority. The latter measurements were made around 90 m offshore of the barrier wall. Ebb-tide current speeds of 0.5 m/s to 1.1 m/s were recorded. Measured water depths and current speeds and directions are shown in Figure 2.5 and Figure 2.6.

Note that since these measurements were made at a different place (where tidal flows are stronger) and for a different period, they should not be compared directly with the simulated values shown in Figure 2.3 and Figure 2.4. Comparison of the model predictions with measurements from the two surveys (References 1 and 3) suggests that the TELEMAC model may underestimate the current speeds in the vicinity of the existing intake-outfall structure, which will tend to lead to conservative dilution and dispersion predictions.

2.3. Lowest current speeds

Some of the neap tides in the simulation described here are smaller than the mean neap range quoted by the British admiralty. In particular, the tide on day 14 (the final tide shown on Figure 2.3) has a range of 1.8 m.

Analysis of long-term tidal records and tidal harmonics indicates that the smallest expected neap tide at Bradwell Waterside is around 2.0 m, compared with the mean neap range of 2.9 m. Thus the tidal range here is comparable to the smallest astronomical tide that may be expected, but perhaps smaller by about 10%. The smallest astronomical tide would be expected to occur rarely – perhaps only once in the entire duration of the planned FED process – but there are likely to be other small tides close to the minimum range.

We consider that this tide gives a reasonable representation of an extreme condition, but taken together with the underestimate of current speeds (noted above) it may lead to unrealistically pessimistic dilution predictions. For this reason, we have discarded some of the lowest predicted current speeds in analysing the initial dilution calculations. The lowest predicted current speed during the discharge window (as described in Chapter 5) is 0.13 m/s. We have increased this to 0.15 m/s for the purposes of the initial dilution calculations described in this report, an increase of 15%. For the 15 day period shown, this corresponds to discarding two tides.

The smallest tide remaining in the simulation has a discharge window current speed of 0.16 m/s and tidal range of about 2.3 m.

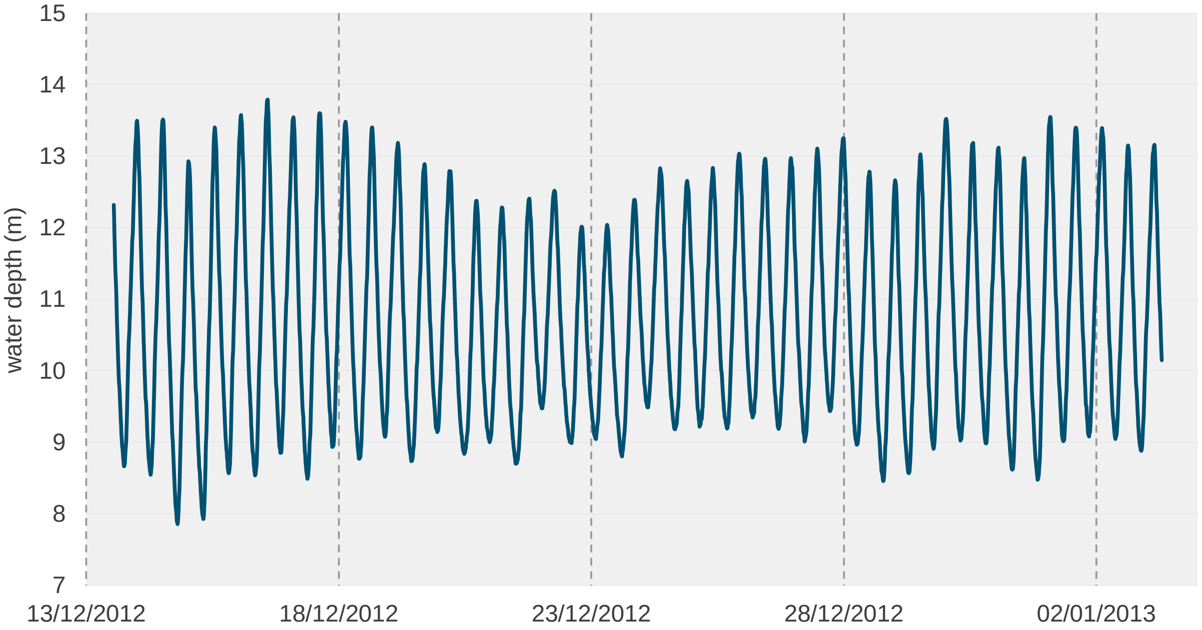

Figure 2.5: Observed water depth near the outfall location

Source: Reference 3

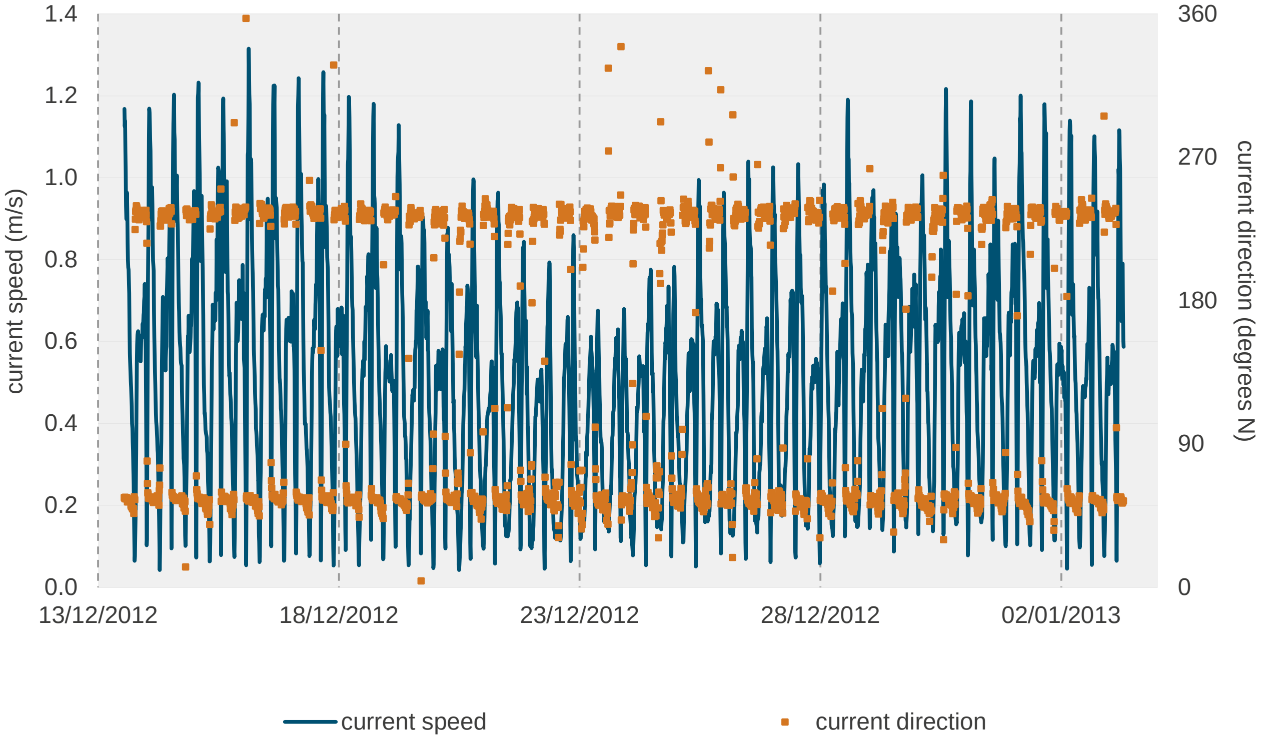

Figure 2.6: Observed current speed and direction near the outfall location

Source: Reference 3

3. Power station discharges

During operation, the power station discharged cooling water and active effluent to the Blackwater Estuary. The FED effluent is one of a class of new discharges produced during the decommissioning process. This chapter describes these three discharges.

3.1. Cooling water discharge

The power station used a concrete intake-outfall structure situated around 350 m offshore. The twin intake tunnels withdrew cooling water from the offshore face of the structure and the twin outlet tunnels discharged to the inner, inshore side. The cooling water flow rate during operation was around 15,000 m^3/h (4.2 m^3/s). Since the station ceased generating, the cooling water flow has been stopped.

Direct recirculation of the cooling water from the discharge to the intake was prevented by a barrier wall. This was constructed from sheet piles and extended, parallel to the coast and to the main direction of tidal flow, for approximately 100 m either side of the intake-outfall structure. This wall has now been removed.

3.2. Active effluent

Treated and filtered active effluent (AE) from the power station was retained in a Final Delay Tank (FDT) prior to being pumped into the station's cooling water siphon pit and then to the estuary at the eastern outfall structure. During power station operation the active effluent was mixed with the cooling water, which provided a dilution of around 500:1 before discharge into the Blackwater Estuary. When the cooling water flow was turned off, an alternative water flow was provided to give a dilution around 50:1 before discharge.

The timing of the effluent release is set so that it emerges into the estuary on the early ebb tide, in order to maximise the offshore advection and dispersion of the effluent and minimise the impact on the middle and upper estuary. Because AE has been discharged during power station operation, it is convenient to use its dispersion behaviour as a reference in the present study.

3.3. FED discharge

The FED is expected to have a nitrate concentration of around 22,000 mg/l as N in the final delay tank, and will be discharged in batches of up to 20 m^3. Initially a discharge of one batch per day is anticipated, with a lower rate of discharge later on in the process. Magnox initially expected to use the same discharge facilities as the AE, so that the FED effluent would be transferred to the Final Delay Tank and discharged into the siphon pit during its discharge to the estuary. With this arrangement, the FED would have a similar level of dilution to the AE; that is, around 50:1 prior to discharge, and around 500:1 within a short distance of the outfall.

One batch of 20 m^3 would be discharged over a period of half an hour, so that it would start to enter the estuary on the early ebb tide (specifically, starting one hour after high water), once per day.

3.4. Future discharge arrangements

Magnox wishes to establish a method to discharge the AE and FED without the pre-dilution water flow. The undiluted FED effluent will have a density of around 1122 kg/m^3. This density is very much higher than that of the receiving water (around 1030 kg/m^3) and as a result the FED discharge will be negatively buoyant. In contrast, the AE has a density close to that of freshwater and is positively buoyant.

After an initial phase where the motion of the discharge is dominated by the outfall characteristics and its momentum, a negatively buoyant (often called ‘dense’) effluent will tend to sink towards the bed of the estuary and may flow down bed gradients. The weight of the effluent will cause it to spread out into a thin stable layer (or density current). The plume may be deflected by ambient currents, but once it has reached the seabed the interaction between the plume and ambient water is generally weak.

A positively buoyant (or simply ‘buoyant’) effluent will experience a similar initial phase dominated by outfall characteristics, and will then tend to float towards the water surface. Positively buoyant plumes floating at the water surface are generally more strongly affected by ambient currents and wind effects than dense plumes at the seabed.

Magnox wishes to establish a single outfall structure to be used for both discharges. Because Magnox regards the FED as the higher hazard effluent, Magnox has instructed HR Wallingford to optimise the design for FED, and then check the dilution performance for AE discharge. Since the present discharge arrangement gives a dilution around 500:1 close to the outfall, we have used this dilution as a target value for the AE and FED during this assessment.

4. Outline outfall design

4.1. The CORMIX system

Potential locations and configurations for the AE and FED outfall were assessed using the CORMIX mixing zone model. CORMIX is an internationally accepted software system for the analysis, prediction and design of aqueous discharges into diverse water bodies. It incorporates an expert system that uses the characteristics of the discharge (flow rate and configuration) and of the receiving water (depth, width, current speed, etc.) to determine a class for the discharge jet. It then calculates the centre-line trajectory and dilution rate of the jet to the edge of the near-field area.

CORMIX cannot represent detail such as spatially varying bathymetry or current patterns, but provides approximations for uniform environments.

CORMIX has three sub-systems:

- CORMIX1, for single-port discharges;
- CORMIX2, for submerged multi-port diffuser discharges;
- CORMIX3, for surface discharges.

Further details of the CORMIX system are given in Reference 4.

4.2. Appropriate discharge structure for FED

A key aim in designing an outfall structure for a dense discharge is to increase dilution of the effluent before it reaches the bed. Generally, this is done by arranging for the effluent to mix through as much depth in the receiving water as can be achieved, in order to maximise dilution in the initial stages of its trajectory.

The overall length of the trajectory before impact on the bed can be increased by discharging upwards at some depth below the water surface, so the jet rises and then falls, without interacting with the water surface. Usually, practical considerations make it difficult to discharge from high up in the water column, so in general both positively and negatively buoyant effluents tend to be discharged near the bed.

In practice, it is difficult to project a very dense discharge high above the discharge point without using a high velocity discharge, which may require significant pumping energy, or an impractically small outlet diameter. For the FED discharge it was found that a near-bed outfall would only provide limited initial dilution as the rise height was too severely restricted by the effluent's high density. It would be preferable to locate the outfall high in the water column. Magnox advised that this would be practicable, as the new discharge port can be fixed to the existing intake/outfall tower; therefore our subsequent investigations have used this concept. It was also determined that using a horizontal discharge, with the active effluent jet directed perpendicular (cross-flowing) to the main ambient current direction, improved the predicted dilution at 100 m. Furthermore, a horizontal discharge directed offshore might also reduce the chance of effluent reaching the shallower waters closer to the shore.

Key parameters for the design of discharge outlets are:

- the exit velocity, U_0 (m/s), which is the discharge flow rate, Q (m^3/s), divided by the outlet cross-sectional area, $\pi d_0^2/4$, where d_0 (m) is the port diameter;
- the densimetric Froude number, $F = U_0 / (g' d_0)^{1/2}$, where for a discharge of density ρ_0 into ambient water of density ρ_A, $g' = g(\rho_0 - \rho_A)/\rho_A$ is the initial reduced gravity of the discharge (m/s^2).

Higher exit velocities and densimetric Froude numbers are generally associated with more rapid turbulent mixing.

The FED discharge flow rate corresponding to 20 m^3 in 30 minutes is 0.011 m^3/s. A single port with a diameter of 0.065 m (6.5 cm) would give an exit velocity of 3.3 m/s and a densimetric Froude number around 14, which for many outfalls would be associated with rapid turbulent mixing.

The preliminary outfall design was tested and refined using a series of sensitivity tests in CORMIX. The outfall height was set so that it remains submerged at all times. Our data indicate that the bed level close to the outfall tower is generally around 5.8 m below Lowest Astronomical Tide (LAT). To allow a margin for error we have therefore taken the outfall at a height of around 5.5 m above the bed. (We understand that there is substantial accretion of sediment around the base of the outfall tower, following removal of the barrier wall – this height should be understood to disregard that local change in bed level.) Initial dilution predictions for the suggested outfall design are presented in section 5.

In summary, the following outline outfall configuration is suggested for the FED:

- single port of internal diameter 0.065 m;
- discharging horizontally;
- raised 5.5 m above the bed;
- directed offshore, perpendicular to the tidal current direction.

4.3. Appropriate discharge structure for AE

The AE will be discharged using the same outfall as the FED.

5. Initial dilution

Initial dilution tests were carried out for both effluents for the range of hydrodynamic conditions likely to be found near the outfall location, with a range of current speeds and water depths representative of the whole tide.

5.1. Results for FED

We have carried out initial dilution tests for the FED discharge (assuming the outline outfall design established in Section 4.2) for the range of hydrodynamic conditions likely to be found near the outfall location. The results were found to be insensitive to the water depth, so long as the outfall is submerged. For this reason, a single representative depth was assumed for all tests.

The graphs in Figure 5.1 to Figure 5.3 display:

- the predicted minimum dilution at the plume centreline, 50 and 100 metres from the outfall;
- the predicted minimum dilution at the plume centreline, where the plume reaches the bed;
- the distance required to reach a predicted minimum dilution of 500:1 at the plume centreline.

Dilution factors of at least 500:1 are predicted about 100 m away from the point of discharge when ambient current speeds are higher than about 0.23 m/s. The simulated current speeds during the discharge window (as discussed in Section 2.3) range from roughly 0.15 m/s to 0.75 m/s. At 0.15 m/s, the dilution at 100 m is around 300:1.

At 0.13 m/s (the lowest current speed without the adjustment discussed in Section 2.3), the dilution at 100 m is around 240:1; this more conservative value was used for the other constituents of the FED discussed in Reference 5.

Predicted dilutions at the point where the plume reaches the bed are above 250:1 for ambient current speeds above about 0.3 m/s. For ambient current speeds of 0.15 m/s, the minimum predicted dilution at the bed is around 100:1.

Achievement windows have been calculated from the initial dilution predictions, using the model current speeds and the original target dilution. Figure 5.4 shows the times during the tidal cycle when the target dilution of 500:1 (or better) is predicted at 100 m from the outfall. The achievement windows are the green shaded areas; the rest of the tidal period is shaded grey.

Figure 5.5 shows the same analysis, using the survey data as input. The period has the same length as that shown for the model, but note that here the neap tide is in the middle, rather than at the end. For the surveyed current speeds, the longest non-achievement window is around 6 hours. These figures show that most days contain an achievement window, but this does not necessarily coincide with the consented discharge window.(Nevertheless, the existing discharge window is favourable for flushing the effluent out of the estuary as a whole, even if greater initial dilution might be obtained at other phases of the tide. This is discussed in Reference 5.)

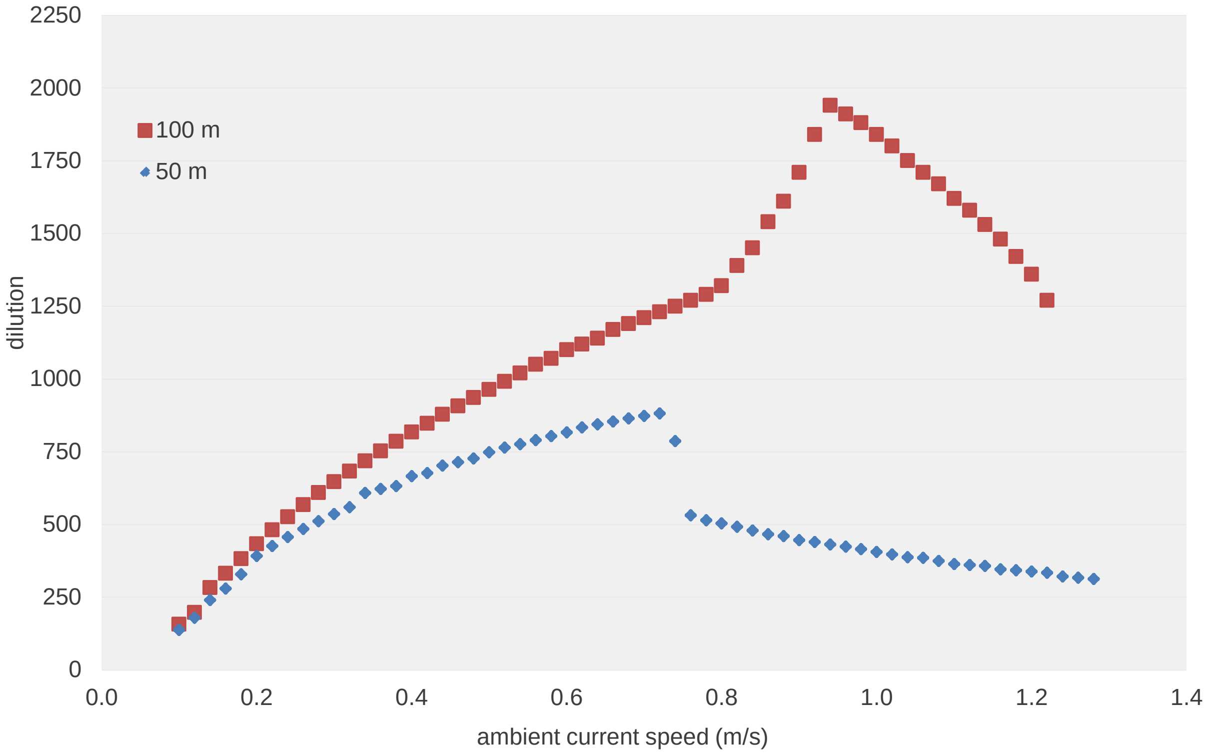

Figure 5.1: Predicted minimum dilution 50 m and 100 m from the outfall

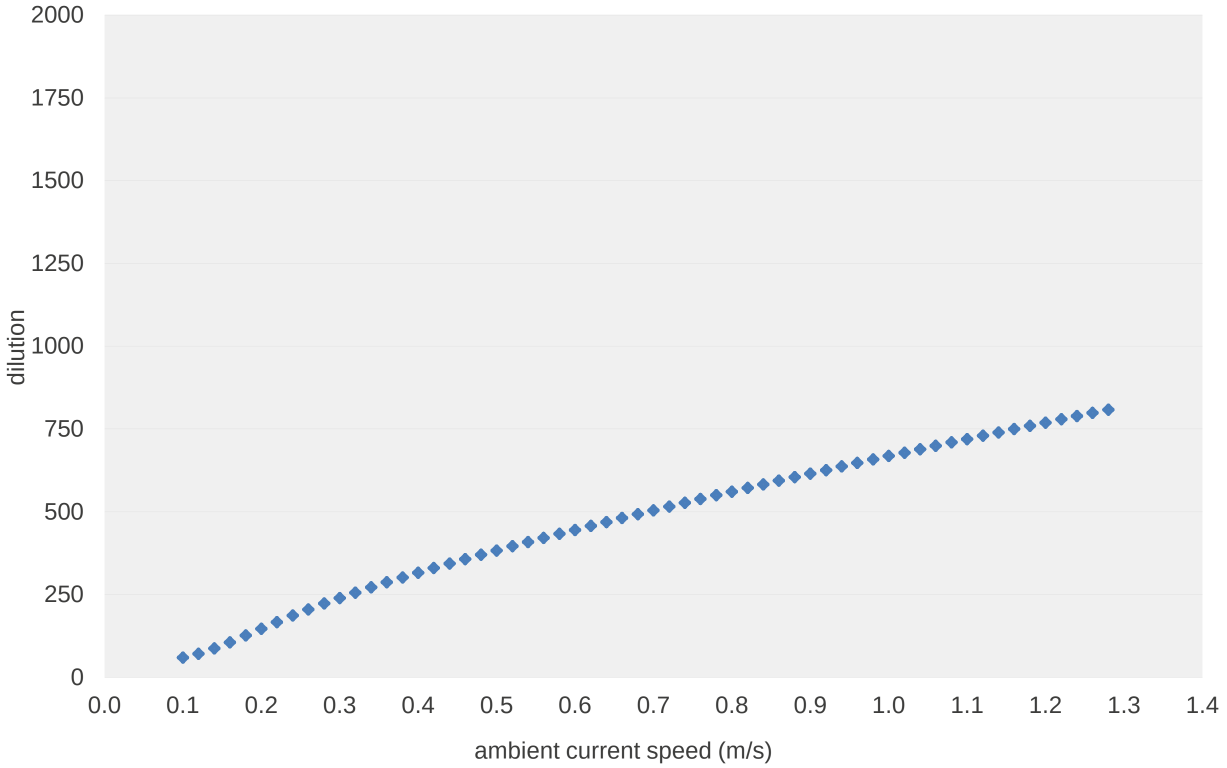

Figure 5.2: Predicted minimum dilution where the plume reaches the bed

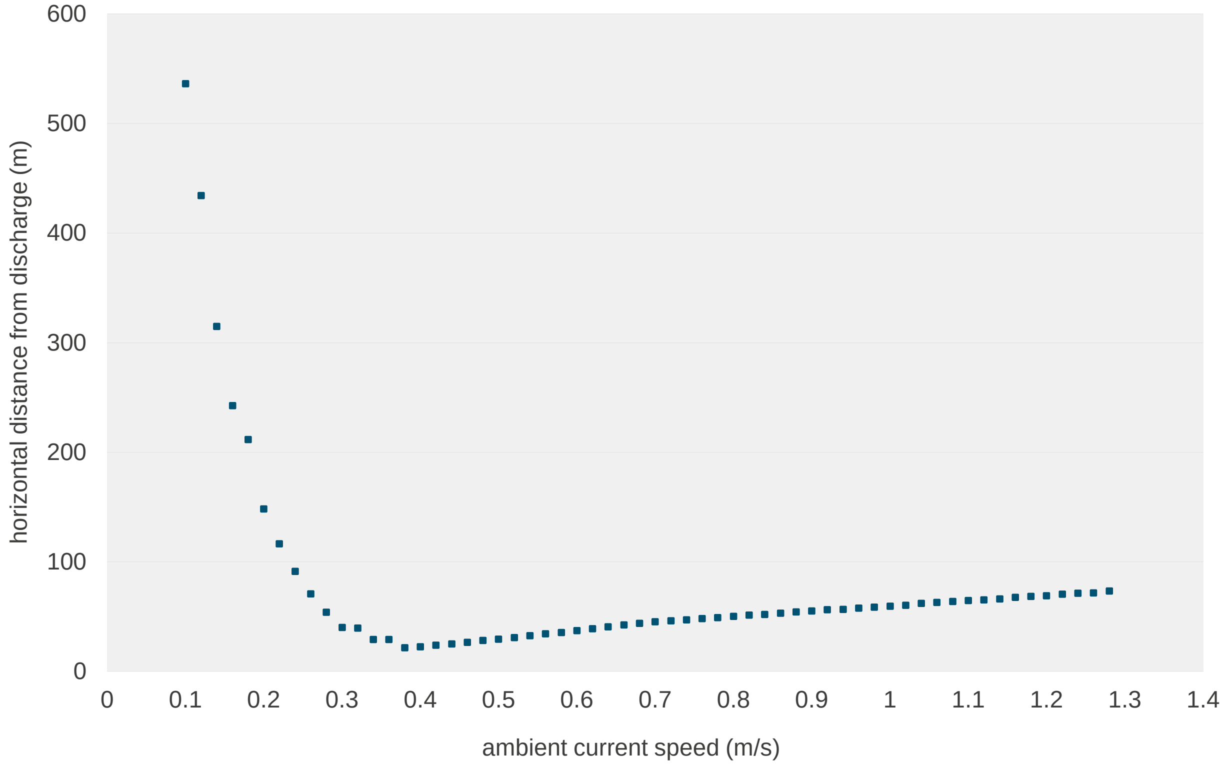

Figure 5.3: Distance required to reach a predicted minimum dilution of 500:1

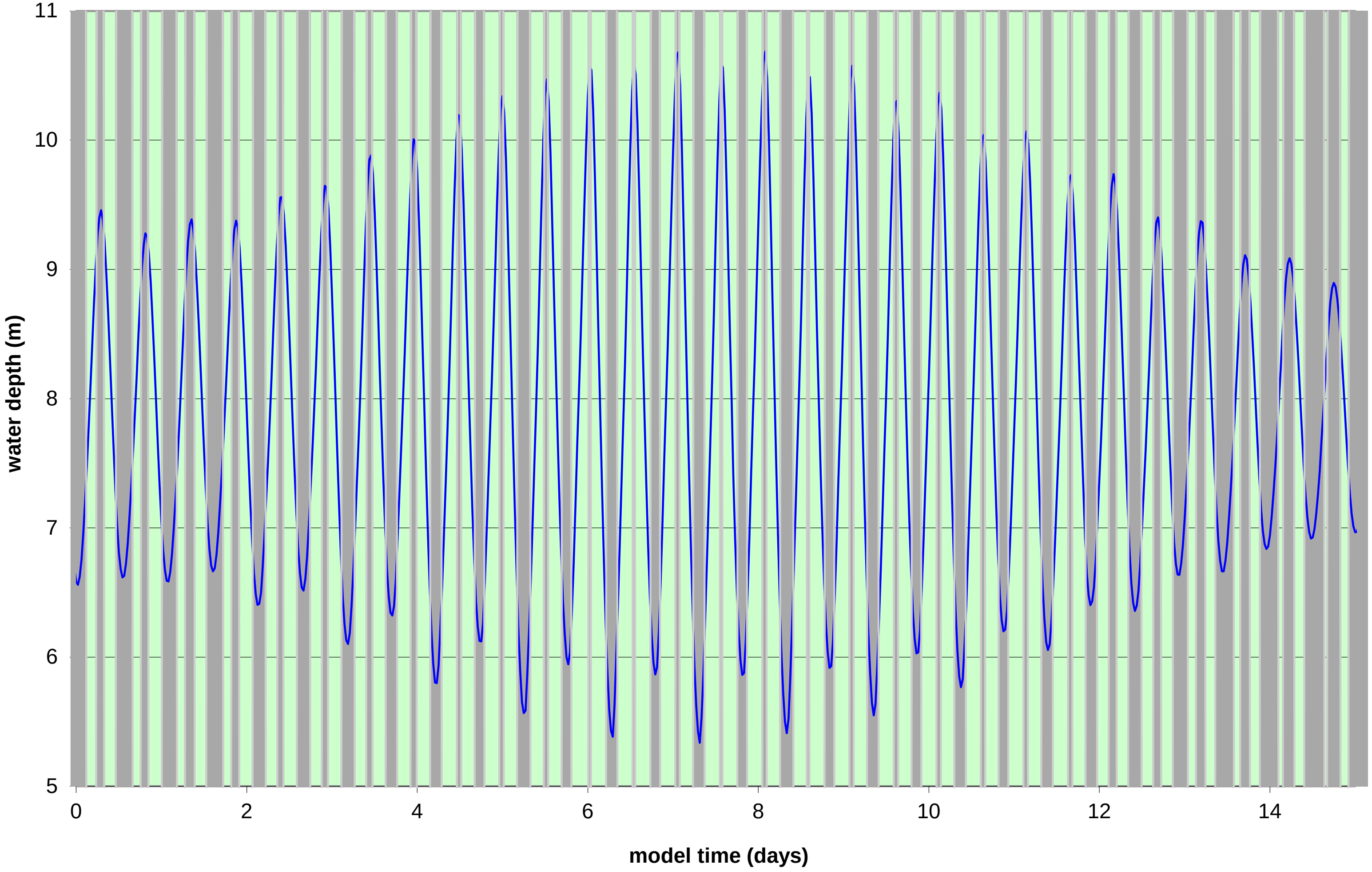

Figure 5.4: Predicted achievement windows (green) for model currents

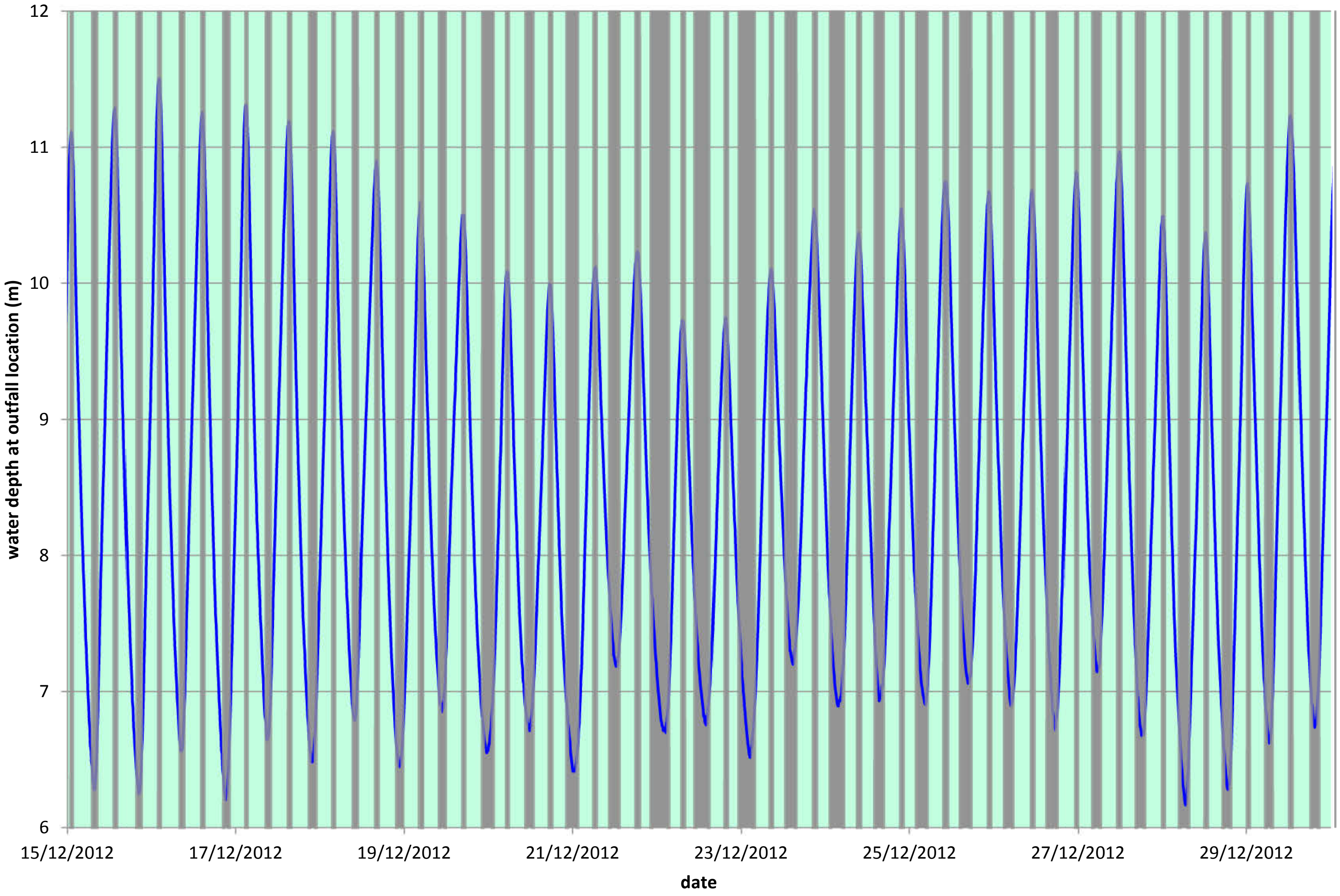

Figure 5.5: Predicted achievement windows (green) for surveyed currents

5.2. Results for AE

We have carried out initial dilution tests for the AE discharge (assuming the outline outfall design established in Sections 4.2 and 4.3). Figure 5.6 shows the dilution predicted at 100 m from the outfall for a range of water depth and current speed. (The range selected represents all tidal conditions at the site.) For the water depths expected at discharge, dilution factors 500:1 or better are predicted when the current speed is greater than about 0.4 m/s.

The conditions corresponding to the discharge window (HW+1 to HW+1.5) are marked by the grey shaded area on the figure, using values from the full model simulation, part of which is shown in Figure 2.3 and Figure 2.4. The most frequently-occurring current speeds are towards the upper end of the grey patch where dilution greater than 500:1 is predicted within 100 m of the outfall. The lower end of the grey patch corresponds to the smaller neap tides from the simulation.

For the lowest current speed during the discharge window (0.15 m/s), the predicted dilution is around 250:1 at 100 m and 500:1 is achieved around 260 m from the outfall.

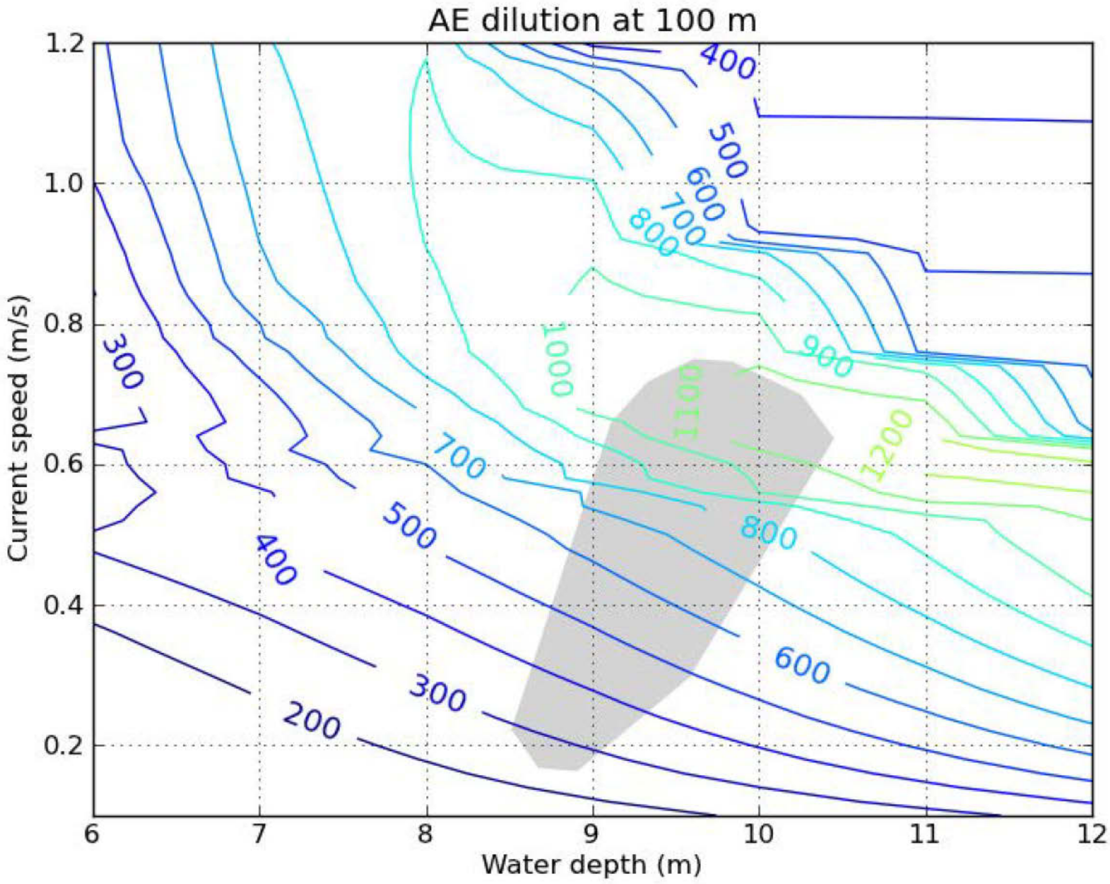

Figure 5.6: Predicted AE dilution 100 m from outfall

Grey shaded area denotes conditions predicted to occur during the discharge window.

Table 5.1: AE dilution at 100 m (simulated tides)

Dilution factor	Number of occurrences	% Occurrence
above 1000	24	23
500 to 1000	41	39
400 to 500	19	18
300 to 400	13	12
200 to 300	9	8
Total	*106*	*100*

Table 5.1 gives more detail of the predicted dilution factors for the simulated tides. Dilution of 500:1 or better is achieved for more than 60% of the simulated tides (and 400:1 or better for 80%).

5.3. Oyster beds

Magnox has identified two oyster beds in the vicinity of Bradwell, at the locations shown in Figure 5.7: Oyster beds. These locations are around 600 m and nearly 8 km from the outfall, both of which are well outside the area of initial dilution. Effluent concentrations at the oyster beds are discussed in the far-field dispersion report, Reference 5.

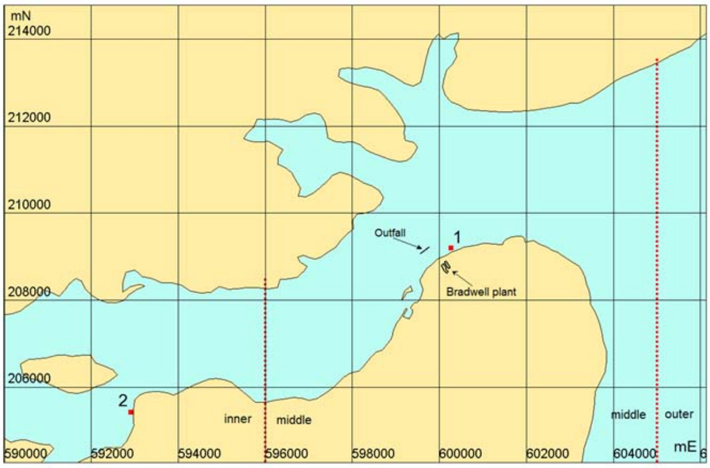

Figure 5.7: Oyster beds

1: Bradwell Pacific Oysters; 2 Pacific oysters, Cock Clarks

6. Conclusions

Magnox wishes to dispose of active effluent (AE) and dissolved fuel element debris (FED) effluent by discharging to the Blackwater Estuary from a single dedicated discharge structure, independent of the existing discharge tunnel. The AE has a density close to that of fresh water. The FED effluent is expected to have a nitrate concentration of around 22,000 mg/l as N, density 1122 kg/m^3. Both effluents will be discharged in daily batches of up to 20 m^3.

An outline outfall configuration is suggested:

- single port of internal diameter 0.065 m;
- discharging horizontally;
- raised 5.5 m above the bed;
- directed offshore, perpendicular to the tidal current direction.

This outfall configuration is predicted to give an initial dilution of 500:1 or better for FED within 100 m from the outfall for most tidal conditions expected at the site. On occasional smaller tides it is predicted to achieve at least 300:1 at 100 m, and 500:1 within about 260 m of the discharge, based on current speeds from the hydrodynamic model, during the discharge window.

For the AE, dilution at 100 m of 500:1 or better is predicted when the current speed is greater than about 0.4 m/s (around half the simulated tides). For the lowest current speed during the discharge window, the predicted dilution is around 250:1 at 100 m and 500:1 is achieved around 260 m from the outfall. Dilution of 500:1 or better is achieved for more than 60% of the simulated tides (and 400:1 or better for 80%).

7. References

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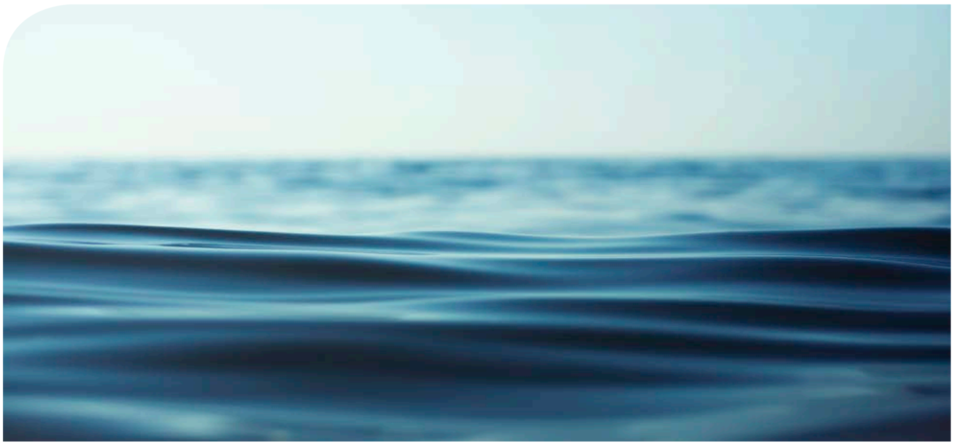

HR Wallingford is an independent engineering and environmental hydraulics organisation. We deliver practical solutions to the complex water-related challenges faced by our international clients. A dynamic research programme underpins all that we do and keeps us at the leading edge. Our unique mix of know-how, assets and facilities includes state of the art physical modelling laboratories, a full range of numerical modelling tools and, above all, enthusiastic people with world-renowned skills and expertise.

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