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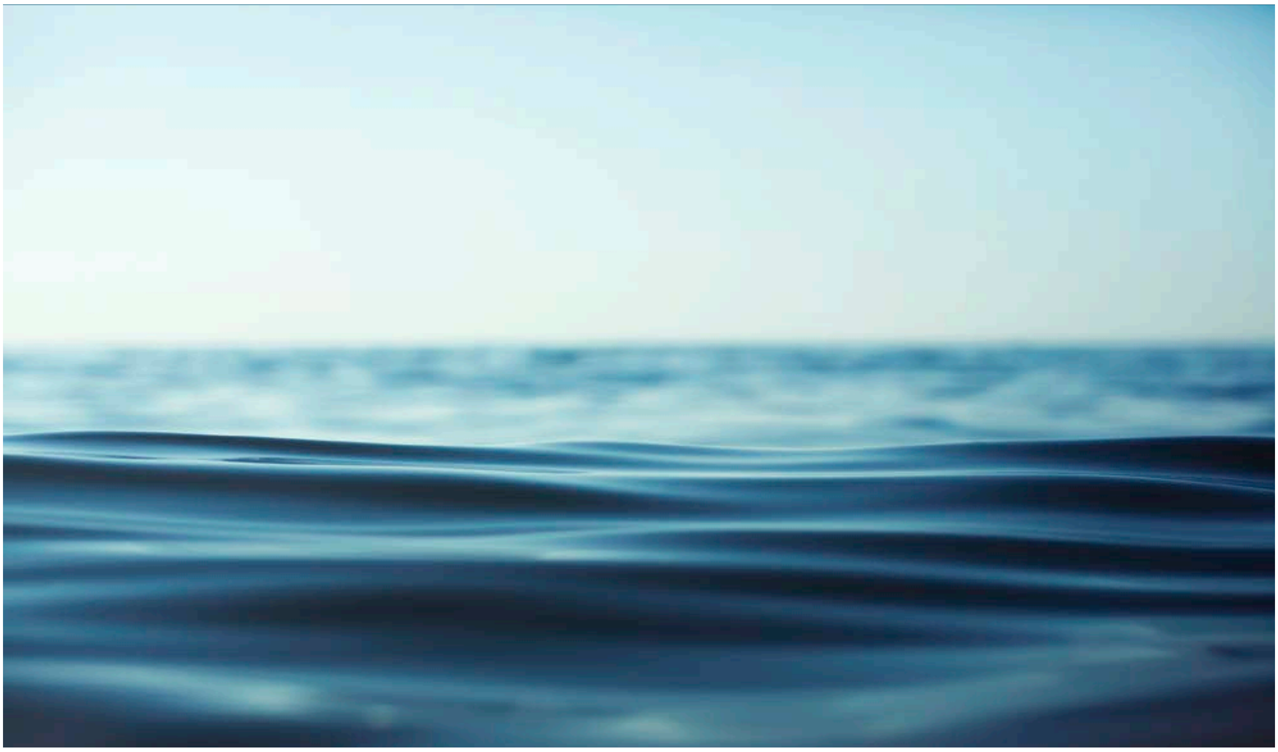
Bradwell Power Station

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 the radioactive components of these waste streams, focusing on the Active Effluent (AE) and fuel element debris (FED). At present these effluents are discharged via the final delay tank and siphon pit / outfall previously used for the power station cooling water. This report describes a study to produce dedicated discharge arrangements.

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 ambient density. Both effluents will be discharged in daily batches of up to 20 m^3.

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

- single port of internal diameter 0.06 m;
- discharging horizontally;
- raised 1 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 AE within 100 m from the outfall for most tidal conditions expected at the site, and for all conditions simulated during the present discharge window.

An outline outfall configuration is suggested for the FED, 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 about 200:1 at 100 m, and 500:1 within about 350 m of the discharge, based on current speeds from the hydrodynamic model, during the discharge window. Comparison with survey data from 2008 and 2012 suggests that actual current speeds may be higher than those predicted by the model, and that in fact the dilution may be better than these values indicate.

Contents

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 the radioactive components of these waste streams, focusing on the Active Effluent (AE) and fuel element debris (FED). At present these effluents are discharged via the final delay tank and siphon pit / outfall previously used for the power station cooling water; this report describes a study to produce dedicated discharge arrangements.

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).

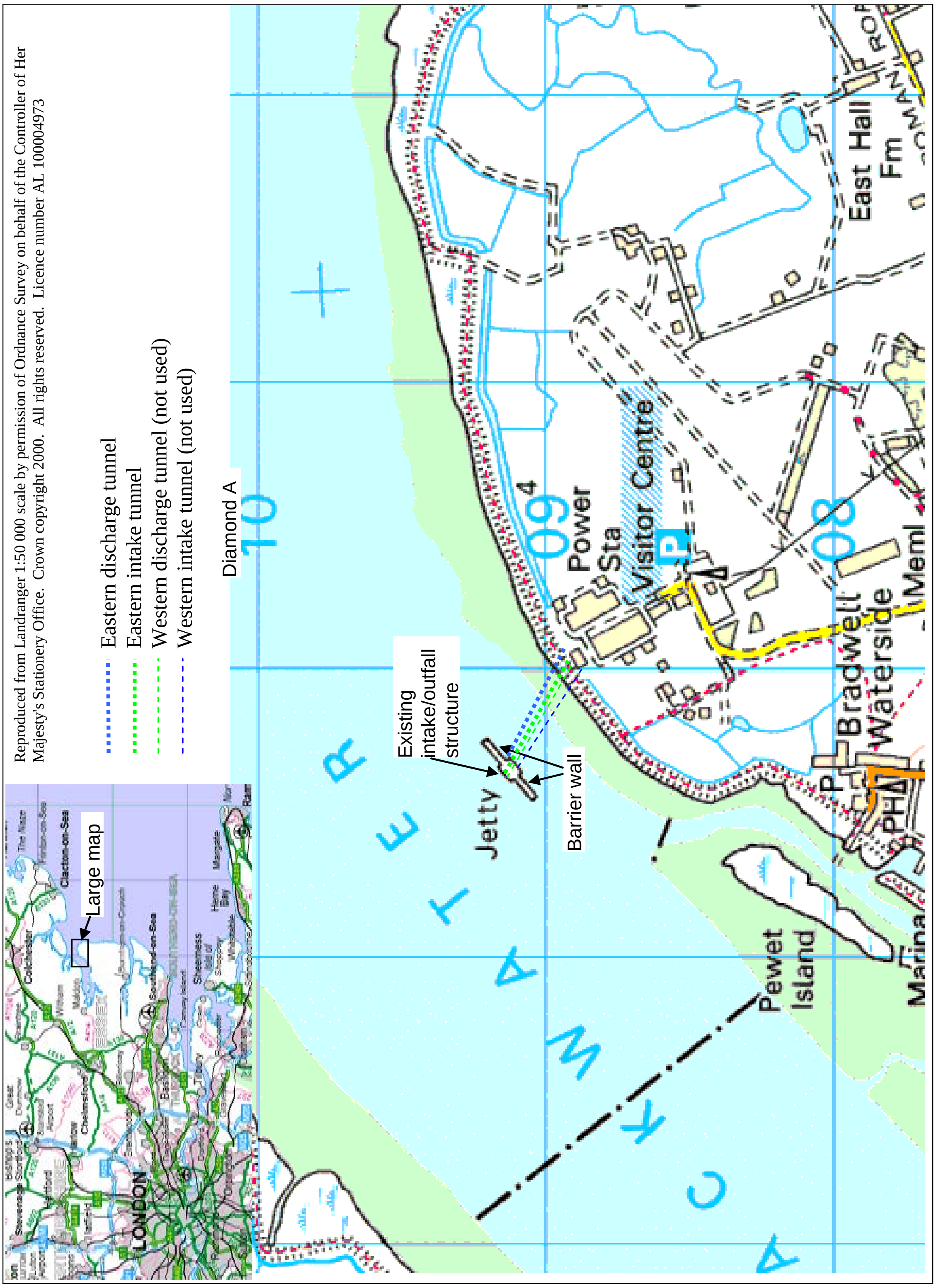

Figure 1.1: Location map

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.

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 water depth varies approximately between 5 m and 11 m, and the peak current speeds between 0.3 m/s and 0.7 m/s.

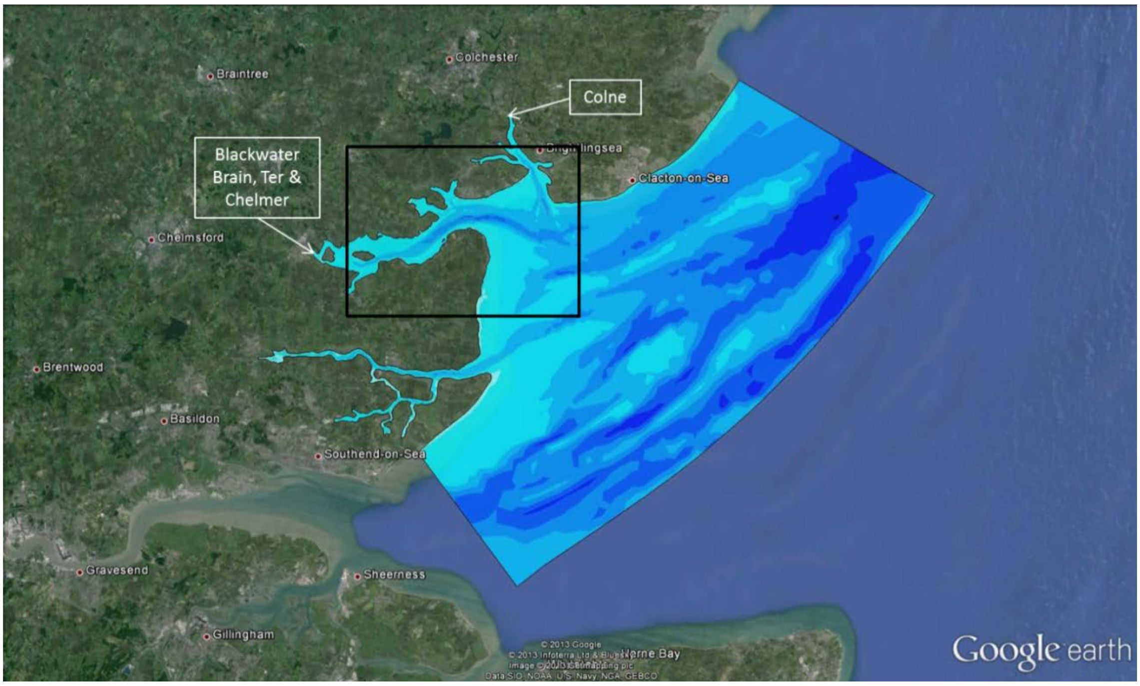

Figure 2.1: Extent of the numerical model

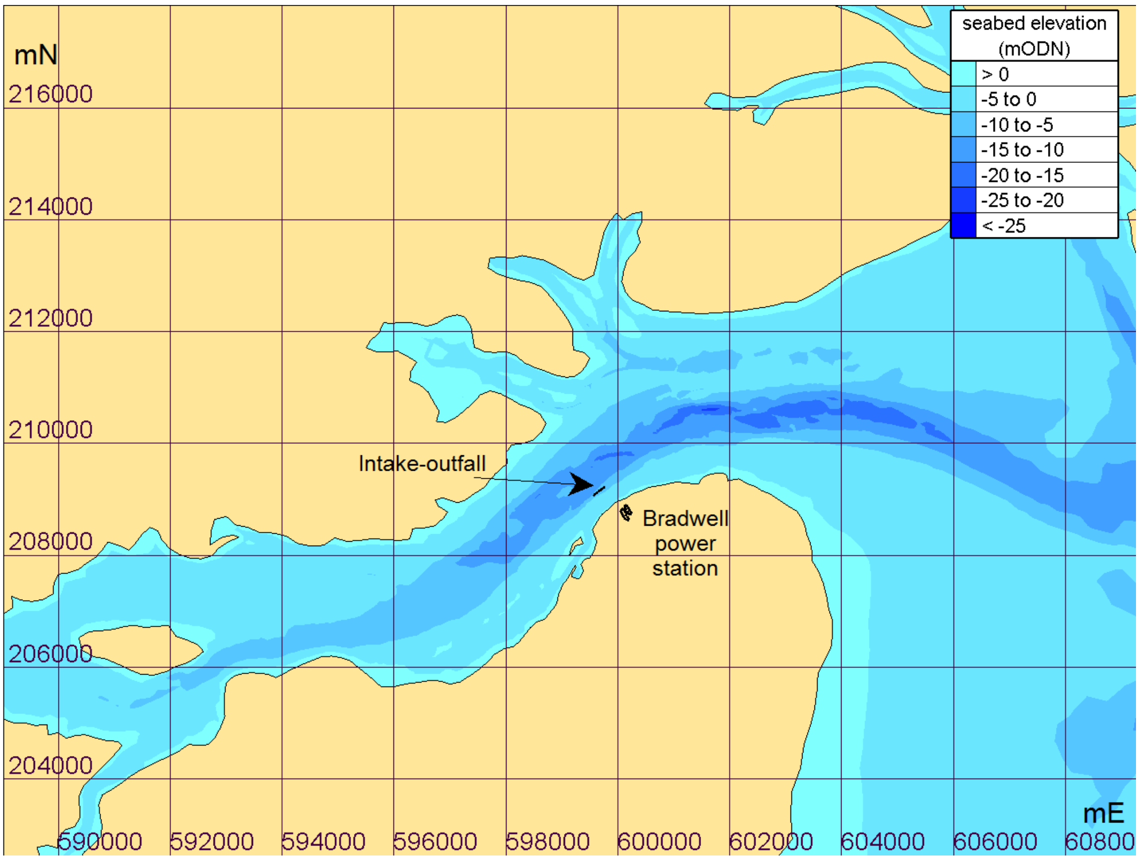

Figure 2.2: Numerical model bathymetry near Bradwell

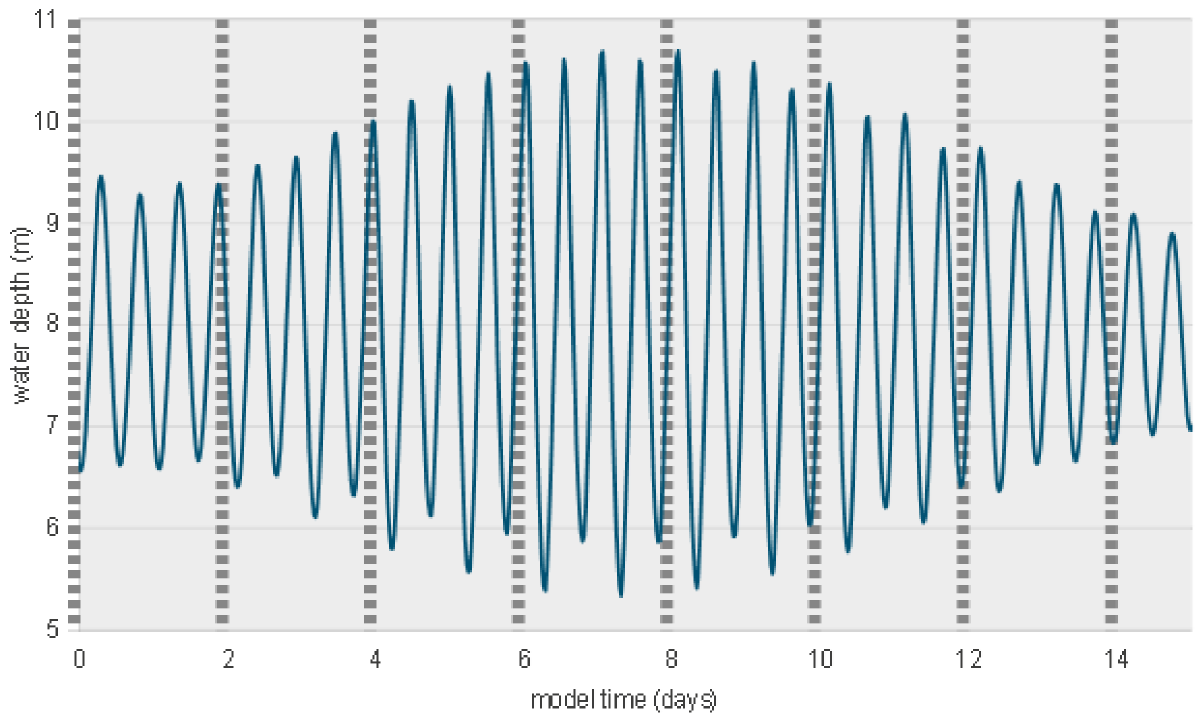

Figure 2.3: Simulated water depth at the outfall location

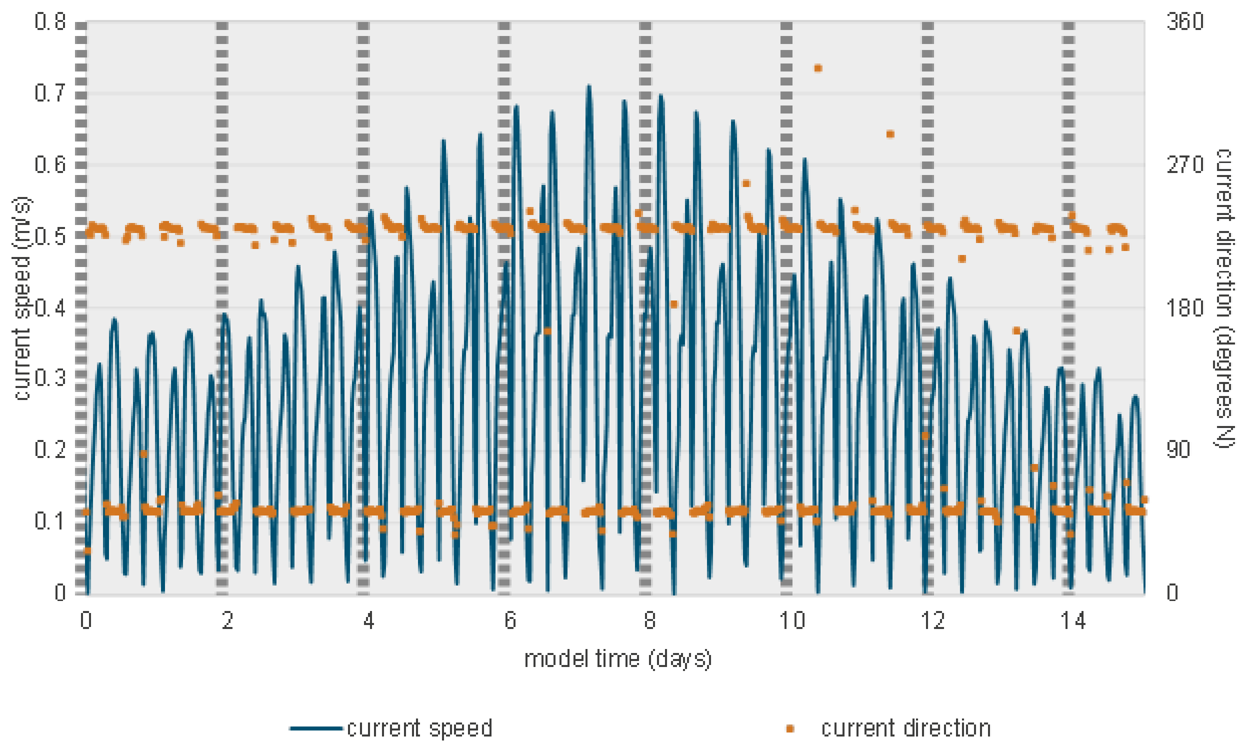

Figure 2.4: Simulated current speed and direction at the outfall location

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) they should not be compared directly with the simulated values shown in Figure 2.3 and Figure 2.4. A more detailed 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. This will tend to lead to conservative dilution and dispersion predictions.

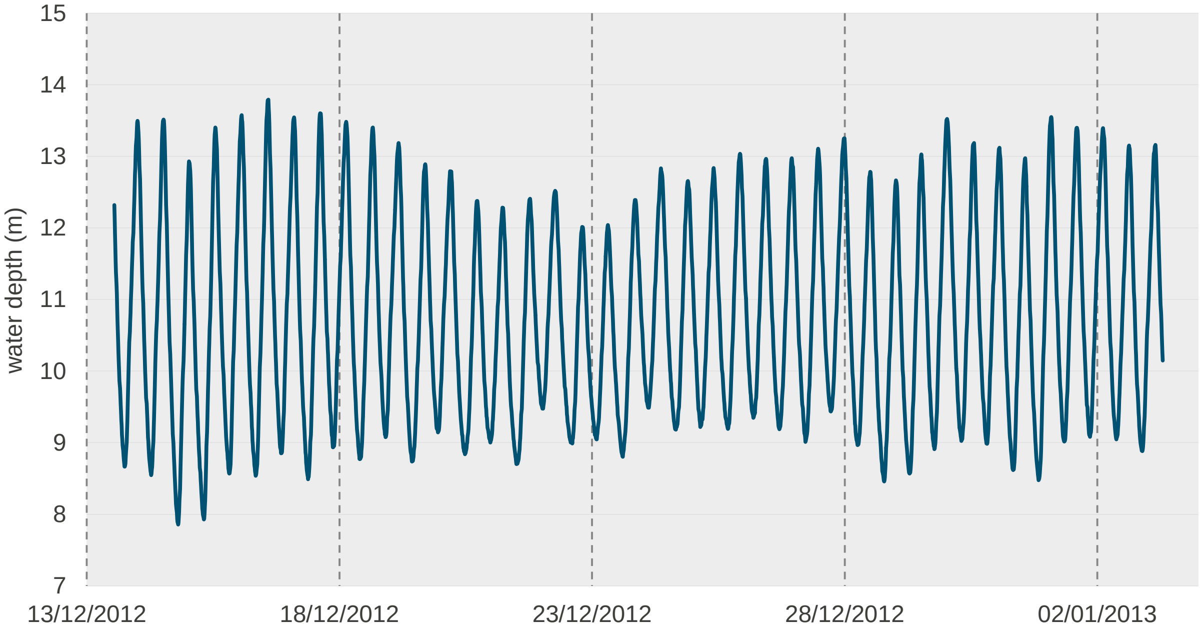

Figure 2.5: Observed water depth near the outfall location

Source: Reference 3

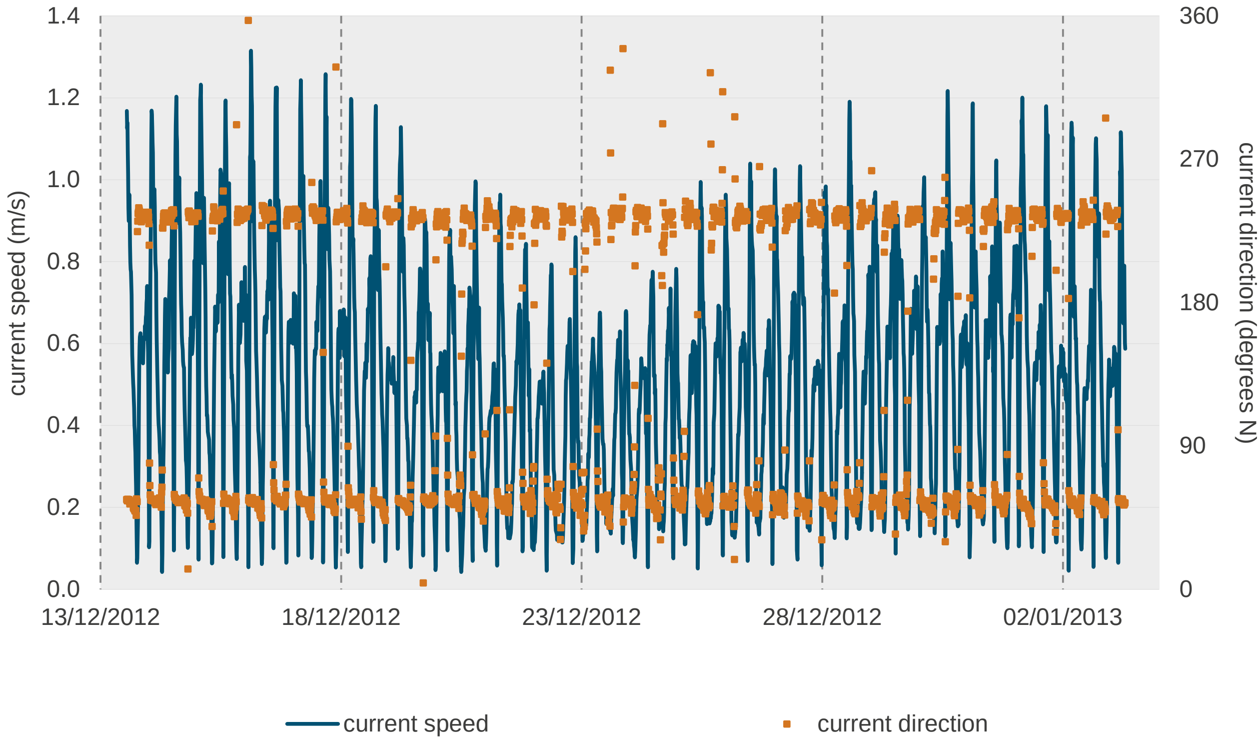

Figure 2.6: Observed current speed and direction near the outfall location

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. It 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. The initial arrangement uses the same discharge facilities as the AE, so that the FED effluent is transferred to the Final Delay Tank and discharged into the siphon pit during its discharge to the estuary. With this arrangement, the FED is expected to 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 is discharged over a period of half an hour, commencing 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 makeup water flow. The undiluted FED effluent will have density of around 1122 kg/m^3. This density is very much higher than the receiving water (around 1030 kg/m^3) and as a result the FED discharge will be negatively buoyant. In contrast, the AE has 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 plumes trapped at the seabed.

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 outfalls 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. However Magnox advised that it would be practicable to locate the outfall high in the water column; 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 ratio of the discharge flow rate, Q (m^3/s), and 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 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 was set so that it remains submerged at LAT, at a height of around 5.5 m above the bed. Initial dilution predictions for the suggested outfall design are presented in section 5.2.

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

A key aim in designing an outfall structure for a buoyant discharge is to increase dilution of the effluent before it reaches the water surface.

We have established and tested a preliminary outfall design for the AE using a similar approach to that described for the FED. The AE discharge flow rate is 0.011 m^3/s. A single port with a diameter of 0.06 m (6.0 cm) would give an exit velocity of 4.0 m/s and a densimetric Froude number around 32, which for many outfalls would be associated with very rapid turbulent mixing.

The outfall was set close to the bed of the estuary, to maximise the rise height before the effluent reaches the water surface. A nominal elevation of 1 m above the bed was used. Initial dilution predictions for the suggested outfall design are presented in section 5.1.

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

- single port of internal diameter 0.06 m;
- discharging horizontally;
- raised 1 m above the bed;
- directed offshore, perpendicular to the tidal current direction.

These outline outfall designs are similar in many respects; the key difference between them is the port elevation, as it is desirable to release a buoyant discharge close to the bed whereas a dense discharge should be released close to the water surface.

The small difference in port diameter between the two specifications has arisen because they were originally derived independently, for different flow rates. The designs have been checked and found to be compatible with the present proposed flow rate. Details such as this should be verified during the detailed design of the outfall system; it may also be appropriate to consider advanced nozzle systems such as duckbill valves, which can help to manage intermittent discharges.

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 AE

We have carried out initial dilution tests for the AE discharge (assuming the outline outfall design established in Section 4.3). Figure 5.1 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.) Dilution factors 500:1 or better are predicted for most conditions within the range studied. Poorer dilution is predicted when the current speeds are greater than about 1.0 m/s (because the discharge is strongly deflected 100 m downstream before significant dilution has occurred), or less than about 0.2 m/s (because insufficient quantities of water are flowing past the discharge), the latter depending also on the water depth.

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 model simulation shown in Figure 2.3 and Figure 2.4. At each of these times, dilution greater than 500:1 is predicted within 100 m of the outfall.

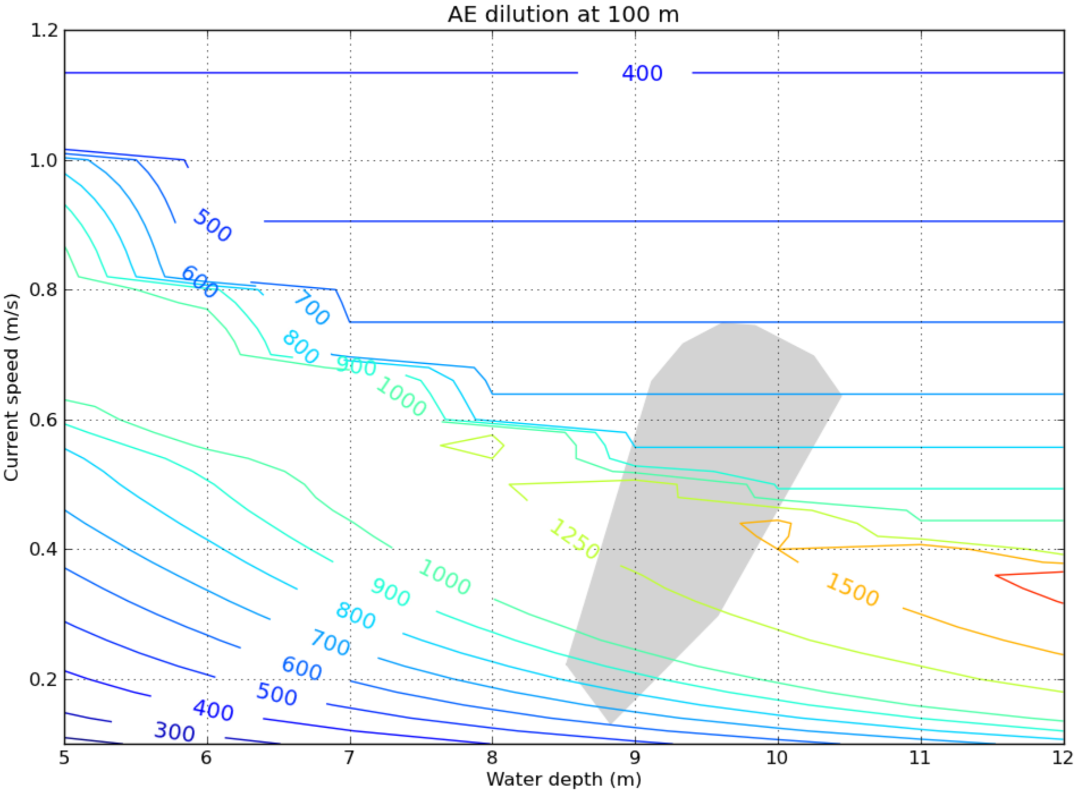

Figure 5.1: Predicted AE dilution 100 m from outfall

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

5.2. Results for FED

We have carried out initial dilution tests for the AE discharge (assuming the outline outfall design established in Section 4.3) 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 and a different form of presentation is used for the FED than for the AE.

The graphs in Figure 5.2 to Figure 5.4 display:

- the predicted minimum dilution 100 m from the outfall;
- the predicted minimum dilution where the plume reaches the bed;
- the distance required to reach a predicted minimum dilution of 500:1.

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 range from roughly 0.13 m/s to 0.75 m/s; at 0.13 m/s, the dilution at 100 m is around 200:1.

Predicted dilutions at the bed are above 250:1 for ambient current speeds above about 0.3 m/s. For ambient current speeds of 0.13 m/s, the minimum predicted dilution at the bed is around 80:1.

Achievement windows have been calculated from the initial dilution predictions, using the model current speeds and the original target dilution. Figure 5.5 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. This figure shows that (as discussed above) there may be days during the neap part of the tidal cycle when there is no significant achievement window for the original target.

We note that the lowest peak speed measured in the survey was around 0.5 m/s, whereas some of the simulated peak speeds are below 0.3 m/s which suggests that the model predictions may be pessimistic. Figure 5.6 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.

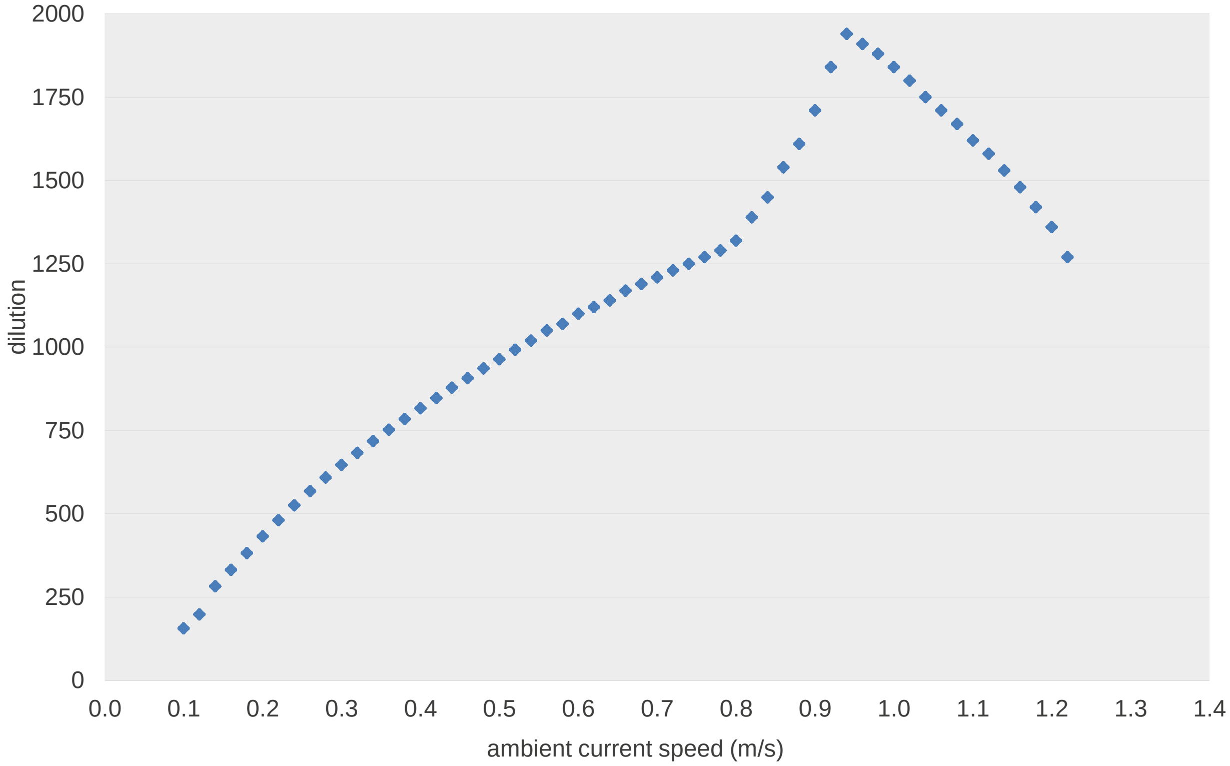

Figure 5.2: Predicted minimum dilution 100m from the outfall

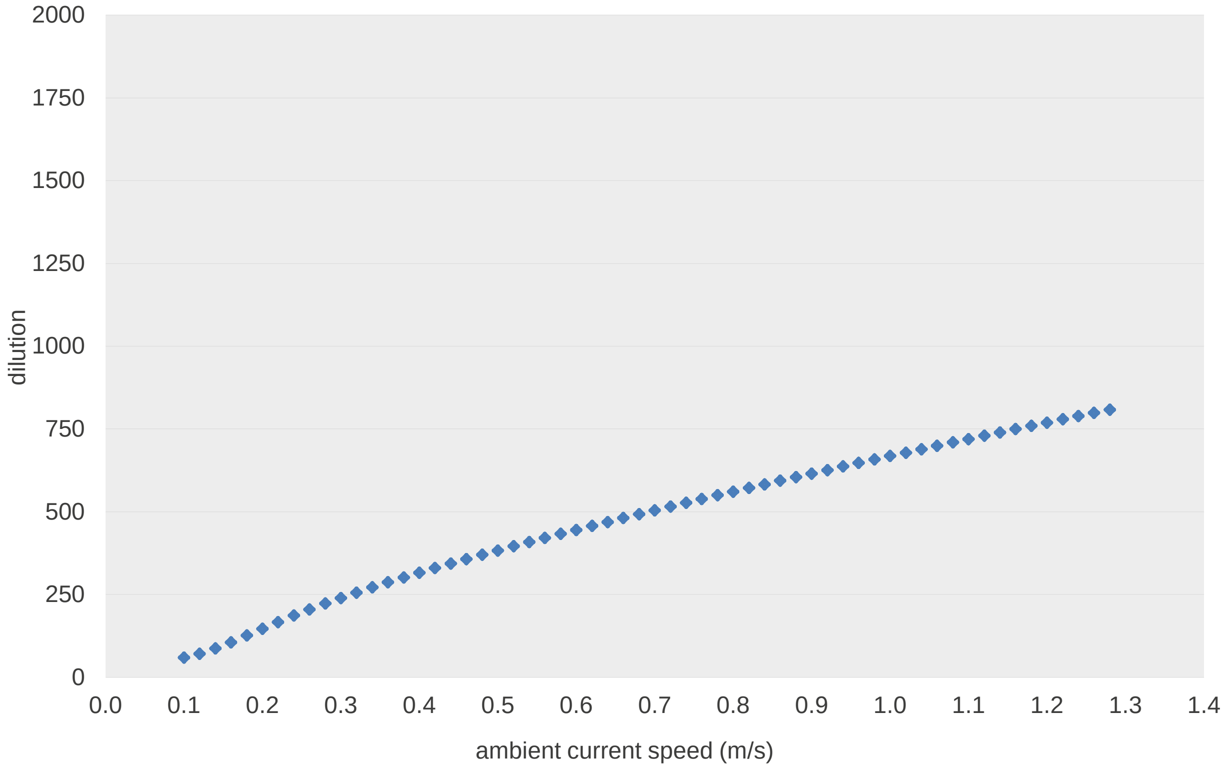

Figure 5.3: Predicted minimum dilution where the plume reaches the bed

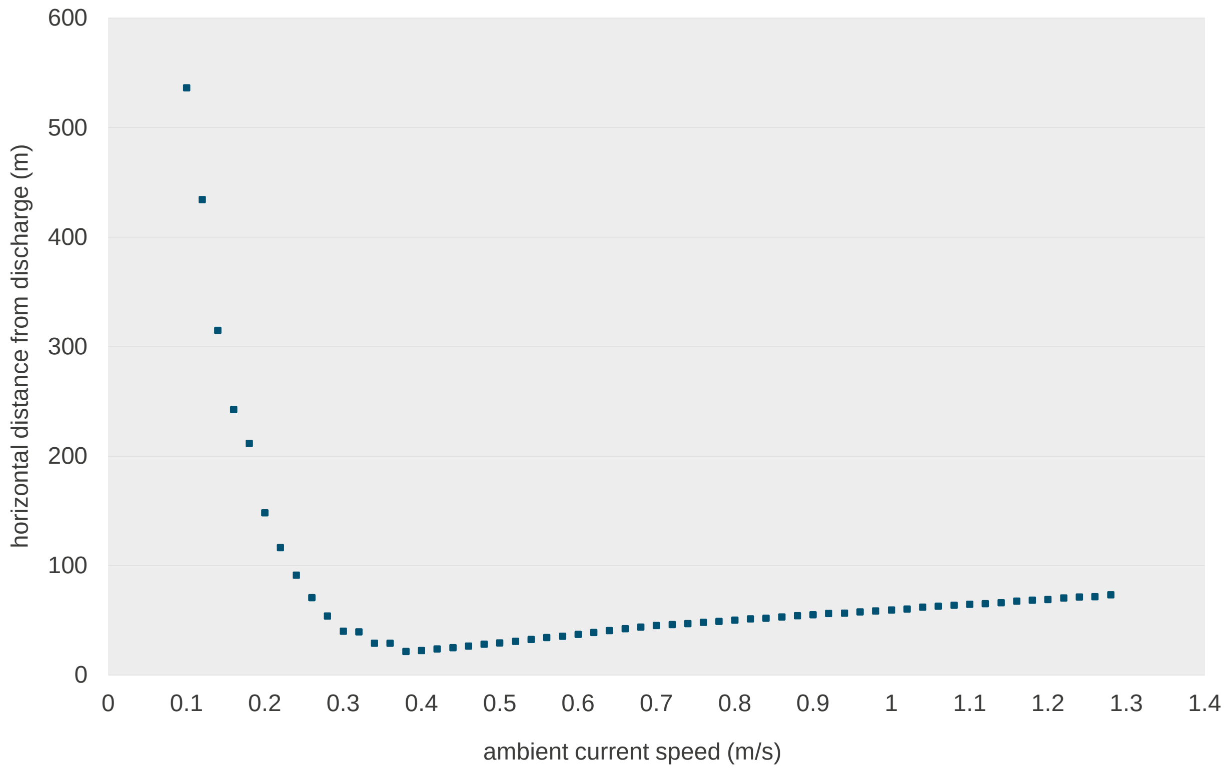

Figure 5.4: Distance required to reach a predicted minimum dilution of 500:1

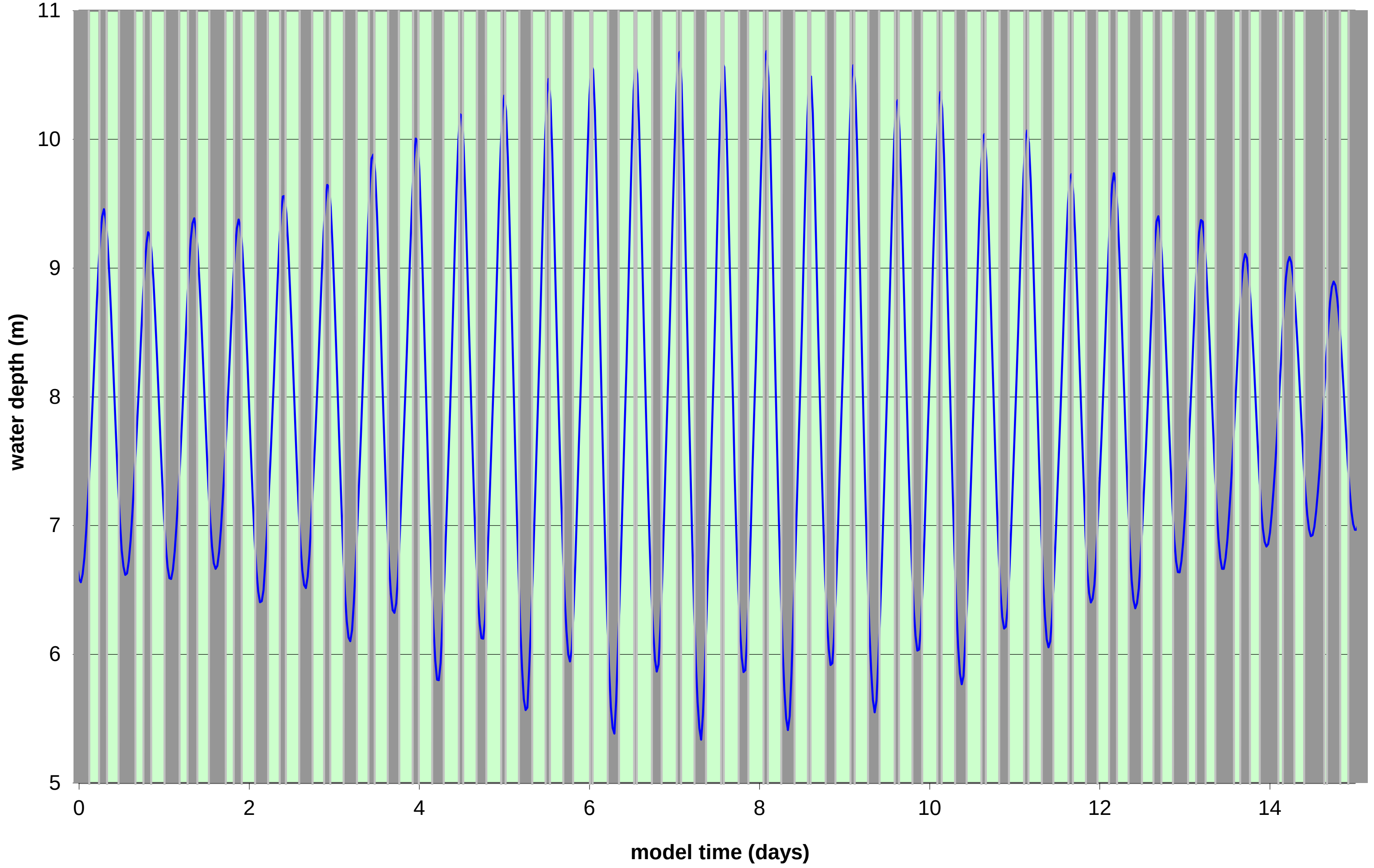

Figure 5.5: Predicted achievement windows (green) for model currents

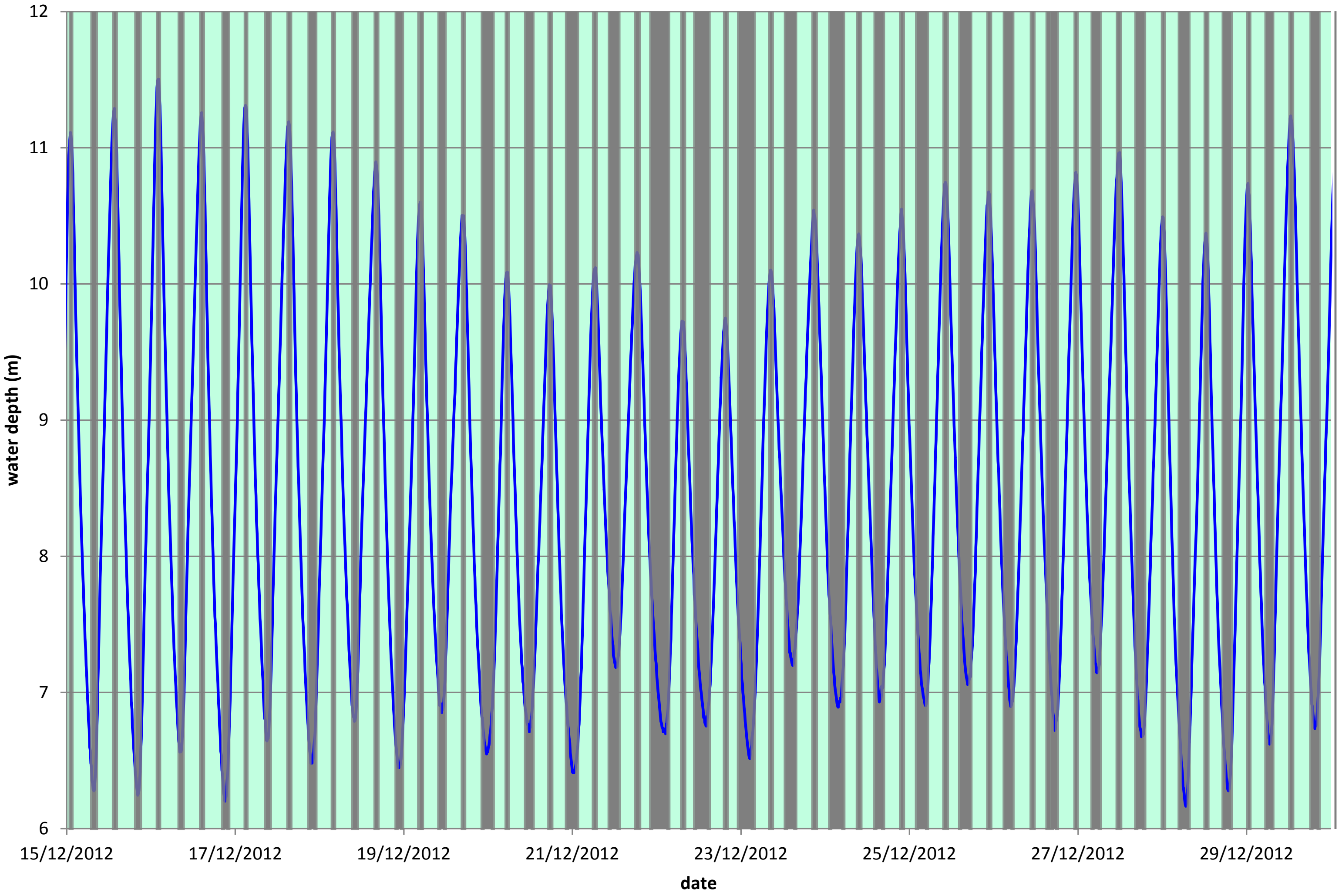

Figure 5.6: Predicted achievement windows (green) for surveyed currents

Note: Water depth has been adjusted to give depth at outfall location

6. Conclusions

Magnox wishes to dispose of active effluent (AE) and dissolved fuel element debris (FED) effluent by discharging to the Blackwater Estuary from dedicated discharge structures, 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 for AE, consisting of:

- single port of internal diameter 0.06 m;
- discharging horizontally;
- raised 1 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 AE within 100 m from the outfall for most tidal conditions expected at the site, and for all conditions simulated during the current discharge window.

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7. References

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HR Wallingford, Howbery Park, Wallingford, Oxfordshire OX10 8BA, United Kingdom
tel +44 (0)1491 835381 fax +44 (0)1491 832233 email info@hrwallingford.com
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