Bradwell power Station

FED discharge dispersion

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Summary

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Magnox is planning to undertake a decommissioning programme at Bradwell in which the magnesium alloy which comprises the fuel element debris (FED) will be dissolved in nitric acid, abated to remove problem constituents and released in a controlled batch operation to the estuary via the final delay tank (FDT) and siphon pit / outfall. The liquors produced will predominantly contain nitrates and trace concentrations of metals.

This report presents the results of a dispersion modelling study for the effluent.

The timing of the pump operation should include:

- Siphon and FDT pumps start at 20 minutes before high water
- FDT pumps stop 9 minutes after high water for $30m^3$ discharge.
- Siphon pumps continue running until 1.5 hours after high water for $30m^3$ discharge.

The concentration of metals in the estuary can be estimated using the dilution and relative concentration values given in this report and multiplying by the Final Delay Tank concentrations to be provided by the process designers.

The modelling results show that the retained nitrate is well diffused, and the discharge does not affect the flow patterns in the estuary to any significant extent, so the most reasonable predictor of the overall increase in concentration in the estuary resulting from the FED discharge would be that the average increase would be in proportion to the increase in load relative to the background load from agriculture and sewage treatment. Magnox would be contributing 5.9% - 7.1% of the N input to the Blackwater and Colne. Thus it is anticipated that overall the average increase in nitrate concentration in the estuary will be less than 10% of the known background. However, local to the discharge point, short-duration peak concentrations of up to 2.2 mg/l as N are predicted within the centre of the plume. In this context, “short duration” means less than half an hour, once per day. These concentrations are based on a maximum total daily discharge of 663 kg as N.

Upon cessation of the Bradwell discharges, the localised peak N concentrations will immediately be eliminated. Residual N concentrations would then reduce at a rate of approximately 30% per month until current background concentrations are generally achieved within 4+ months.

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1. Introduction

Magnox is planning to undertake a decommissioning programme at Bradwell in which the magnesium alloy which comprises the fuel element debris (FED) will be dissolved in nitric acid, abated to reduce certain constituents and released in a controlled batch operation to the estuary via the final delay tank and siphon pit / outfall. The liquors produced will predominantly contain nitrates and trace concentrations of metals.

Following correspondence in August 2010, Magnox commissioned HR Wallingford Ltd to provide a dispersion modelling study for constituents of the discharge, in particular nitrates and metals.

This report presents the results of the dispersion modelling study.

In this report the horizontal co-ordinates are referred to the National Grid and vertical levels to Ordnance Datum Newlyn (ODN). ODN is approximately 0.2m below mean sea level at Newlyn, and 2.68m above Admiralty Chart Datum at Bradwell. In places the report makes reference to dilution relative to a nominal initial concentration rather than absolute concentration. A dilution of, for example, 1000 corresponds to a concentration of one thousandth of the initial concentration within the FED system (i.e. before any pre-dilution with estuary water), or a relative concentration of 10^{-3}. Predominantly the report refers to concentration of nitrate as N in milligrams per litre, assuming a concentration in the final delay dank (FDT) of 22100 mg/l. Concentrations resulting from other concentrations in the FDT can be deduced by rescaling.

Concentrations always refer to depth-average values.

“Month” is used occasionally to refer to the four-week period of the full spring-neap cycle.

The study makes use of information provided and derived in previous investigations carried out for Magnox and BNFL (References 1-4).

2. Background

The site lies on the south side of the Blackwater Estuary in Essex, about 1 kilometre seaward of Bradwell Marina (Figure 1), and has been occupied as a power station since the early 1960s. The power station used a concrete intake-outfall structure situated some 350m offshore. The twin intake tunnels withdrew cooling water from the outer, offshore, face of the structure and the twin outlet tunnels discharged to the inner, inshore side. 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 ebb and flood tidal streams, for some 100m either side of the intake-outfall structure. The barrier wall is still in place, but it is in poor condition and will be removed.

Treated and filtered active effluent from the Power Station is at present retained in a final delay tank prior to being pumped into the station’s cooling water siphon pit and thence to the estuary at the eastern outfall structure. During operation of the power station the active effluent was mixed with the discharged cooling water. Following decommissioning of the main cooling water pumps, pre-dilution of the effluent is now achieved by use of six submersible pumps installed in the cooling water pumping station forebay, and fed with estuary water through the eastern inlet tunnel. The arrangement provides dilution of the effluent by about 50:1 before it is discharged into the Blackwater Estuary.

The timing of the effluent discharge 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.

Details of the tunnels are given on drawings McA/BR/CW/5058 "Arrangement of Barrier Wall & C.W. Inlet and Outlet Structures", 13 September 1957, and BWA/PA120001/E (originally BR/GC/1068 E) "C.W.Tunnels Offshore Bradwell General Arrangement and Grading" supplied by Magnox for a previous study (Reference 3). The concrete-lined cooling water tunnels are of 10 ft (3.05m) internal diameter, bored through the clay stratum below the ground surface to connect to 13 ft (3.96m) diameter vertical risers that lead up to the 32ft (9.75m) diameter intake and discharge towers. The water is discharged into the estuary through openings on the up- and downstream sides of the eastern discharge tower. Each opening occupies one quarter of the circumference of the tower, and is 12ft (3.65m) high with a sill at –25ft (7.62m) (ODN), some 2ft (0.61m) above the seabed. The discharge tunnels have inverts at –43ft (-13.11m) (ODN) at the siphon chamber, sloping down to –94 ft (-28.65m) at the foot of the riser. The culverts remain separate throughout their length and use separate intake and discharge towers. The eastern discharge tunnel is 1520ft (463.3m) long. Active effluent is at present introduced into 'siphon recovery chamber 7' before being discharged through the eastern cooling water tunnel to the discharge structure. Siphon recovery chamber 7 is a circular structure 33ft (10m) in diameter.

The tunnel arrangement is sketched in Figure 2, and relevant details of levels and dimensions are summarised in Table 1.

Because of the volume of the discharge tunnel and the discharge shafts, it is necessary to start pumping some time before the time the effluent is due to emerge into the estuary. Reference 4 showed that for effluent to start emerging at one hour after high water it is necessary to start the effluent discharge pumps at 21 minutes before high water. The sequence of operations to discharge one full final delay tank (68m^3) was calculated to be as follows:

Operating sequence for a full tank of AETP effluent (68m^3)

HW - 0h:21min	Final monitoring and delay tank is full, tunnel is full of seawater. Tank pumps and seawater pumps start. Seawater starts to emerge from discharge structure.
HW + 0h:48min	Tank is empty, landward 84% of tunnel contains pre-diluted effluent, seaward 16% of tunnel contains seawater. Tank pumps stop, seawater pumps continue running. Seawater continues to emerge from discharge structure.
HW + 1h:0min	Landward 16% of tunnel contains seawater; seaward 84% contains pre-diluted effluent. Seawater pumps continue running. Pre-diluted effluent starts to emerge into estuary where it is further diluted by mixing with the tidal flow through the discharge structure.
HW + 2h:8min	Tunnel is full of seawater. Seawater pumps stop.

The situation at high water and at one hour after high water is illustrated in Figure 2.

For the next four hours of the ebb, some seawater will continue to emerge from the discharge structure as the water level in the siphon pit falls: as the tide rises on the next flood a similar quantity of seawater will enter at the discharge structure as the water level in the siphon pit rises.

2.1 DESCRIPTION OF THE FED DISCHARGE

The FED project will use the same discharge facilities as the active effluent, so that the FED effluent will be transferred to the Final Delay Tank.

The Final Delay Tank (FDT) volume discharges into the siphon pit during discharge to the estuary. The pump flow rate for the FDT pump is 60 m^3/h.

The siphon pump rate is 3200 m^3/h.

'Normal' operations indicate approximately 30m^3 of effluent will be discharged once per day. Abnormal operations would be when a smaller amount would be discharged at a higher concentration, without increasing the maximum total daily load.

As the effluent volumes are different from those used in Reference 4, the pumping sequence is also slightly different as follows:

Operating sequence for 30m^3 of FED effluent

HW - 0h:21min	Final monitoring and delay tank contains 30m^3 of FED effluent, tunnel is full of seawater. Tank pumps and seawater pumps start. Seawater starts to emerge from discharge structure.
HW + 0h:09min	Tank is empty, landward 37% of tunnel contains pre-diluted effluent, seaward 63% of tunnel contains seawater. Tank pumps stop, seawater pumps continue running. Seawater continues to emerge from discharge structure.
HW + 1h:0min	Landward 63% of tunnel contains seawater; seaward 37% contains pre-diluted effluent. Seawater pumps continue running. Pre-diluted effluent starts to emerge into estuary where it is further diluted by mixing with the tidal flow through the discharge structure.
HW + 1h:30min	Tunnel is full of seawater. Seawater pumps stop.

2.2 INTENDED CONCENTRATION SCREENING THRESHOLDS

Magnox's screening threshold for the dilution of the FED effluent constituents are based on an increase in metals concentration of not more than 10% of background. For all the metals foreseen in the FED effluent this will be well within the EQS value.

Expected metals concentrations in the delay tank are given separately by Magnox. The expected range of nitrate discharges is given in Table 2. At the highest concentration expected from the plant the maximum daily mass of nitrate would be dissolved in 12m^3 of effluent. However, the bulk of the simulations have been carried out with the intermediate concentration of 22100mg/l as N that would result from the maximum daily discharge in the full 30m^3 of effluent. It should be emphasised that in terms of effect upon the estuary, the mass of N discharged per unit time is of significance, not the variations in concentration within the FDT.

Table 3 summarises the EQS values, observed concentrations and screening threshold including the FED discharge.

2.3 HYDRAULIC ENVIRONMENT

2.3.1 Data from the Blackwater TELEMAC model

An existing TELEMAC-2D calibrated tidal model of the Blackwater Estuary area (Reference 5) was updated with revised bathymetry and mesh for the present study and used to indicate the tidal hydraulic conditions in the vicinity of the proposed new discharge.

TELEMAC-2D is a two-dimensional, depth-averaged, numerical model that uses a finite element solution technique 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 (Reference 6). However, the dispersion model PLUME-RW takes account of the non-uniform velocity profile in its calculations.

The mesh contains triangular elements of variable 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 velocity and water level at the internal nodes in a series of timesteps. The results are stored at intervals for analysis or use in further calculation. TELEMAC has been used in over 100 studies of tidal flow at HR, mostly with verification against field data. It 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 model area includes the three estuaries of the Blackwater, the Colne and the Crouch, and extends 25km along the coast to north and south and 20km offshore. The offshore boundary has been set to follow the general direction of the flood and ebb currents in the North Sea (Figure 3).

The Blackwater Estuary model was set up using bathymetric data from Admiralty charts of the area, together with recent survey data in the vicinity of the intake/discharge structure. 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 (Figure 3).

The model has been verified using published Admiralty tidal stream (Diamond) data and other measurements as described in Reference 5. In particular the model currents were compared with observations close to the discharge point as shown on Figure 3.

Hydraulic conditions have been analysed in the Bradwell area at a range of times, using the finite element model results. The model simulation covered the whole of a spring-neap cycle, commencing with neap tides (range 2.2m), increasing in range to spring tides (range 5.7m) after 7 days, neaps (2.7m) at 14 days, slightly smaller springs (5.3m) at 21 days and then decreasing again to small neap tides (1.8m) after 29 days (Figure 4). These ranges vary from the mean ranges listed in Table 4 because of natural variation in the tidal range through the year.

Figure 5 shows the current patterns at mid ebb and mid flood from the model.

Table 4 shows the current speed and water depth at half-hourly intervals over the first four hours of the ebb tide, for both spring and neap tides. In summary, the water depth varies approximately between 6 m and 10 m, and the current strength between 0.1 m/s and 0.9 m/s. During the proposed discharge period, between 1.0 and 1.5 hours after high water the current is 0.7m/s during spring tides and 0.35m/s during neaps.

2.4 DATA FROM SITE MEASUREMENTS

The values in Table 4 can be compared with the measurements made at the site on 17 August 2000 (Reference 1). These measurements were made near the surface 15-20m offshore and 15-20m onshore of the barrier wall.

Ebb current speeds of 0.9m/s to 1.05m/s were recorded on a tide with a predicted range of 3.5m at Walton-on-the Naze (the local ‘Standard Port’, daily predictions for which are given in the Admiralty Tide Tables).

The mean spring range at Walton-on-the Naze is 3.8m. Rescaling according to the tidal range suggested that the ebb tidal speeds might be 1.14m/s on a mean spring tide. A similar rescaling exercise, suggests that on a mean neap tide (range 2.3m at Walton-on-the-Naze) the ebb speeds might be 0.7ms^{-1}. The results of such rescaling should be treated with caution, particularly when significant differences in range are involved.

If the observations are rescaled according to the tidal ranges at Bradwell, using a predicted range of 4.4m on 17 August 2000, the expected spring and neap tide ebb currents would be 1.17m/s and 0.7m/s. Using either of these scaling factors, it seems likely that the TELEMAC model may underestimate the local currents in the vicinity of the existing intake-outfall structure.

This is likely to be a result of the limited model resolution in the area, and will tend to lead to conservative dilution and dispersion results (that is the model concentrations are likely to be greater than in reality and the model dilutions are likely to be less than in reality).

2.5 DILUTION AND DISPERSION IN THE ESTUARY

The FED effluent in the final delay tank would be denser than the estuary water because of the high nitrate concentration. However, following dilution with the flow from the submersible pumps the density contrast of the effluent would be reduced from about 9% to about 0.15%. With such a small density contrast, buoyancy forces can readily be overcome by turbulence and the effluent can be treated as neutrally buoyant compared with the estuary water. This is discussed in more detail in Reference 4.

Following mixing in the siphon chamber (dilution of 50) there is little further dilution at the interface between the estuary water already in the tunnel and the effluent (Reference 4) and the effluent enters the bottom of the shaft with the some fifty-fold dilution.

There will be turbulence and mixing where the tunnel enters the bottom of the shaft. This will provide some further dilution of the first effluent to emerge into the shaft and thence into the estuary. However, Table 1 shows that the volume of the shaft is equivalent to only six minutes of discharge, so that for the majority of the time that the effluent is emerging the shaft will be completely full of the pre-diluted effluent (dilution of 50) and no further dilution will occur in the shaft.

Once the effluent reaches the top of the shaft and starts to emerge into the estuary, it will mix with the water that flows past and through the discharge structure as part of the tidal stream.

The amount of seawater available for further dilution of the effluent before it emerges from the discharge structure is the tidal flow through the ports in the sides of the shaft. This can be estimated from the port area (6.2m wide by 3.6m high) and the tidal current derived from the TELEMAC model of the estuary (Table 4).

Following emergence from the discharge structure the turbulence naturally present in the tidal stream together with additional turbulence generated by the flow past the structure will rapidly mix the effluent through the full depth of the water. At this stage the amount of water available for dilution can be estimated from the tower width and water depth together with the tidal current from the TELEMAC model (Table 4).

The dilution processes outlined above are clearly dependent on the conditions in the discharge system and close to the discharge tower. The area where this is the case is known as the near field. Dilution in the near field can be estimated on the basis of volume ratios or calculated using a near-field model such as CORMIX.

CORMIX is a widely accepted software system for the analysis, prediction and design of aqueous toxic or conventional pollutant discharges into diverse water bodies (Reference 3). 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 also has some capability for estimating the mid- and far-field dispersion of the effluent. CORMIX has three sub-systems:

- CORMIX 1, for submerged single-port diffuser discharges
- CORMIX 2, for submerged multi-port diffuser discharges
- CORMIX 3, for buoyant surface discharges.

None of the CORMIX sub-systems represents the discharge configuration at Bradwell directly and so the CORMIX results are used in conjunction with hand calculations.

Once the effluent gets more than a few ten of metres from the tower the influence of the geometry of the discharge declines and the dispersion becomes dominated by the flow patterns and turbulence of the natural tidal flow. A more gradual dispersion process will occur in the mid- and far fields. The effluent will move with the tidal stream as a plume. Mixing will continue at the edges of the plume but the mixing rate will now be determined by the turbulence of the ambient current. The mid field plume will be carried to and fro by the tidal stream, moving seaward on the ebb but back up-river on the flood tide, and will eventually be dispersed over a wider area (the far field) by large scale motion, residual tidal, river and wind-driven currents. Dispersion in the mid and far fields can be modelled using a combination of hydrodynamic modelling (TELMAC) and transport modelling (PLUME-RW).

PLUME-RW is a mid-field dispersion model, which simulates the movement of pollutant plumes discharged, for example, from sea outfalls or storm water overflows, using a random walk representation of turbulent dispersion. Pollutant discharges are represented by the release of discrete particles, which move in three dimensions under the influence of mean tidal currents based on the TELEMAC-2D simulations. In this case the TELEMAC hydrodynamic model was the model described in Section 3.1 and Reference 2.

Use of particle tracking in 3D allows the model to take account of the longitudinal dispersion that results from the normal logarithmic velocity profile found in well-mixed tidal streams and allows the model to represent sharp concentration gradients that cannot be represented on the coarser hydrodynamic model grid.

Turbulent motions smaller than the TELEMAC-2D grid (around 200 m in this case) are parameterised as random particle displacements in the horizontal and vertical directions.

Pollutant concentrations are calculated on a square grid of user-defined size, which was here set at 25 m. These are calculated as depth-average concentrations, which is appropriate in this estuary as it is known to be vertically well-mixed (Reference 6).

PLUME-RW has been used extensively by HR for studies of dispersion from sea outfalls over the last ten years. The model has been verified in-situ against both the observed dispersion of dye patches and the observed dispersion of actual effluent. In particular the combination of TELEMAC-2D and PLUME-RW is used by Anglian Water in a planning model for sea outfalls off the Anglian coast and this system has been accepted by the Environment Agency. Similar systems have also been used in studies accepted by the Environment Agency elsewhere in the UK. Details of the PLUME-RW model are given in Appendix 2.

PLUME-RW represents the tidal dispersion and dilution well over a period of a few tides. Longer-term behaviour of the nitrate in the discharge involves chemical reactions that are not represented in the model. However, the model results show that after a period of some weeks, the discharge is spread out to resemble a diffuse source such that the longer term behaviour can be deduced from known behaviour of nitrate that enters the estuary from the rivers.

Thus the PLUME-RW model covers the transition of the discharge from a point source to a diffuse area. Subsequent behaviour of the patch will be similar to the existing material diffused around the estuary.

3. *Model studies*

3.1 SIMULATION CONDITIONS

Dispersion modelling has been undertaken using near-field dilution (hand calculations and CORMIX) and mid field simulations (PLUME-RW) assuming a nominal concentration of a conservative pollutant.

Spring and neap tide simulations have been carried out for the expected discharge configuration:

- Release of 30 m^3 once a day, 1 hour after HW. The effluent tank emptying rate is 60 m^3/h; therefore the discharge lasts for half an hour.
- Sensitivity tests were also carried out to investigate dispersion of a smaller volume ($12m^3$) at a higher concentration in the FDT (55320mg/l as N) and discharged for a shorter time (12 minutes).

The tidal elevation time series used in the dispersion model has been taken from the Bradwell flow model. It covers 33 days of simulation, from 3rd February to 7th March 2008 (Figures 4 and 5). This covers a full spring neap cycle (two sets of springs and two sets of neaps) plus a few days of start-up and continuation. For extended simulations of more than 33 days the sequence is repeated starting from a closely equivalent point to the end (same tidal range and time within the tide).

The spring tide simulation starts on day six of the time series at 1h30 and the neap tide simulation on day 12 at 18h30. Short runs were carried out to identify the behaviour of the recently-discharged material on spring tides and neap tides, and longer runs were carried out for the complete spring-neap cycle. The short runs cover three days of simulation: 3 days with a 30 m^3 discharge per day and a fourth day without any discharge, the fourth day being included to follow the subsequent spreading of the returning effluent. In tests of the sensitivity to concentration and volume in the FDT, these runs were repeated with $12m^3$ discharged at a higher concentration for a shorter time.

Simulations over longer periods of time (spring-neap cycle and one and two month-long runs) have also been carried out to indicate build-up and amount of effluent remaining inside the estuary (more precisely west of x = 602000 m) after a specific length of time. These extended simulations do not include any removal mechanisms other than tidal exchange and are, therefore, conservative. They show how the tidal dispersion spreads the discharge along and across the estuary but their interpretation in terms of actual concentration requires care because of the underlying conservative assumptions.

3.2 PRESENTATION OF RESULTS

3.2.1 *Near field*

Table 5 presents the dilution ratios and Table 6 presents the relative concentrations of the metals and the concentration of nitrate as N at various distances away from the outfall for both spring and neap tide conditions. These were derived as follows:

- At 0m from the discharge: volume ratio for FED flow to siphon pump flow.
- At 10m from the discharge: volume ratio for ambient flow through the discharge structure to effluent discharge.
- At 25m from the discharge: volume ratio for mixing through the full depth across the width of the discharge ports at the appropriate ambient current taking into account the tidal range.
- At 50m from the discharge and further: result taken from the PLUME-RW model.

The dilution ratio calculations are consistent with the CORMIX indications when allowance is made for the additional turbulence associated with flow past and through the discharge towers.

In the case of the results from the PLUME-RW model, it was necessary to take account of the spatial variability within the small discharge plume. At the appropriate distance from the discharge, a number of output positions were analysed across the plume alignment. The values that appear in Tables 5 and 6 are the minimum instantaneous dilutions and the peak instantaneous concentration at the most affected output position.

Table 6 therefore represents the peak concentrations during the discharge period. As the discharge takes place for only 30 minutes per day the average relative concentration at these locations is approximately one forty-eighth of the value in Table 6.

Values of dilution and concentration are given in relation to the concentration in the FDT. Clearly the dilution at and close to the point of discharge is sensitive to the pre-dilution ratio but at distances greater than a few tens of metres changes in pre-dilution would have little effect.

3.2.2 *Mid/far field*

The mid-field model generates the concentration at each point on a 25m output mesh every quarter hour through the simulation. The results are plotted and analysed to summarise this large amount of information. In addition the movement of the plume is shown in animations supplied separately.

Figures show:

- Locations of time-series output points (Figure 6). These are EA monitoring positions 4, 6, 7, 8 and 14, together with additional points 4a, 6a, 7a and 14a, which are the same easting as the corresponding EA positions but moved south to lie on the axis of the discharge plume.
- Contour plots of the average concentrations of nitrate as N in the estuary in normal discharge conditions. They have been calculated using 3 days of daily release during spring tides and neap tides (Figures 7 and 8). These figures show the short-term spread of the discharge under different tidal conditions, excluding build-up, which is considered later in this report.
- Through-tide contour plots of the concentrations of nitrate as N in the estuary for both spring and neap tide simulations. These are snapshots given every 3 hours over the first day, starting once the release has completed (Figures 9 – 24).
- Time series presenting the evolution of the relative concentration and concentration of nitrate as N at various locations in the estuary. These are taken from a full spring-neap simulation, with removal by current only, and show neap tides around days 14 and 28 and spring tides around day 21. The tide curve is shown, with scale on the right hand axis, for reference (Figures 25 – 29).
- Retention of one release of effluent in the estuary over a spring-neap cycle with removal by current only (Figure 30).
- Retention of daily release of effluent over two months with removal by current only (Figure 31).
- Instantaneous concentration field after one month of daily releases with removal by current only (Figure 32).
- Average concentration on a spring tide after 50 days of daily releases with removal by current only (Figure 33).
- Average concentration on a neap tide after 57 days of daily releases with removal by current only (Figure 34).

The contour values in Figures 7 – 24 and 32-34 are chosen (based on Tables 2 and 3) to correspond to the screening threshold for nitrate in the upper, middle and outer estuaries.

That is to say:

Relative concentration	Dilution ratio	Nitrate as N mg/l	Comment
1 x 10^{-6}	1,000,000	0.022	Taken as ‘edge’ of plume
1.584 x 10^{-6}	631,300	0.035	10% of average in Outer Estuary (east of 606,000mE)
1.765 x 10^{-6}	566,600	0.039	10% of average in Middle Estuary (598,000mE to 606,000mE)
3.529 x 10^{-6}	283,400	0.078	10% of average in Inner Estuary (west of 598,000mE)
1 x 10^{-5}	100,000	0.22	Only found close to & during discharge
5 x 10^{-5}	20,000	1.1	Only found close to & during discharge

where the dilution ratio is given relative to the FDT and the nitrate levels are given based on the concentration in the FDT at the maximum value given in Table 2.

Concentration of any discharge constituent can be deduced from Figures 7 to 24 by multiplying the concentration in the Figure by the ratio of (initial concentration in the Final Delay Tank):22100. In the time-series plots the concentration of other constituents can also be calculated by multiplying the initial concentration in the FDT by the relative concentration.

3.3 INITIAL DILUTION

As noted above, these concentrations are found for a limited time per day and the average concentrations at these distances are less than one fortieth (2.5%) of the values shown in Table 6.

It can also be noted that the concentrations shown at up to 50m from the outfall tower are experienced over a very limited width, of the order 20m.

3.4 MID FIELD DISPERSION

The tide in the estuary ebbs past the outfall tower with a velocity of some 0.9m/s during spring tides and 0.3m/s during neap tides. As the discharge progresses it is carried away from the outfall tower to form a plume that stretches away to the east. At the end of the effluent discharge this plume is cut off at the source and becomes a patch moving away from the outfall as the tide falls, but returning toward the estuary as the tide rises. As the plume and patch move with the tide, turbulence in the flow spreads and dilutes the effluent. The actual trajectory and mixing is calculated by the model.

The main purpose of the mid-field studies is to show that the metals are well dispersed from the vicinity of the discharge, and to evaluate the impact of the nitrates. In reality, time-varying wind perturbations and non-tidal currents would be likely to affect the trajectory and spread the impact over a wider area at lower concentrations than discussed below.

3.4.1 Spatial variation of impact

The average impact at any location is the combination of a brief period when the patch may pass directly over, together with a much longer period when there is only indirect impact (residual concentration or returning patch), or no impact. Figures 7 and 8 show that over a three discharge simulation the average impact is most apparent in a long narrow ribbon extending some 10km east of the outfall on a spring tide and 6km east on a neap tide. The ribbon is narrower on the spring tide (250m) than on the neap tide (700m). The concentration of nitrate as N is less than 0.22 mg/l (relative concentration $< 1 \times 10^{-5}$) in all locations in both simulations, i.e. the dilution everywhere is more than 100,000 relative to the FDT. It is noticeable that the maximum average impact is found near the eastern end of the tidal ribbon, in the area where the moving patch slows down and reverses.

The pattern of movement of a single discharge over 24 hours is clearly visible in Figures 9 – 24. These show instantaneous snapshots of the plume or patch position at three-hourly intervals and the instantaneous concentrations are naturally higher than the three day discharge simulation averages shown in Figures 7 and 8. Nevertheless, the instantaneous concentration of nitrate as N is less than 1.1 mg/l (relative concentration $< 5 \times 10^{-5}$ or dilution >20,000) on the ebbing tide and less than 0.22 mg/l (dilution >100,000) on the returning tide.

Figures 7 – 24 show the dispersion of 1 – 3 discharges and demonstrate the transformation of the point source to a diffuse patch over the course of a few tides. They clearly show that the discharge returns to the vicinity of the discharge at a concentration of nitrate as N less than 0.22 mg/l (relative concentration $< 10^{-5}$ of the FDT concentration). There is, however, a gradual spreading of the fraction of effluent that returns.

Figures 7a and 7b show that for the recently discharged effluent the screening threshold of 10% of background nitrate is met over the great majority of the estuary and outer area. All the area coloured grey or white in Figures 7a and 7b is below the screening threshold concentrations.

On the spring tide there is a small area of pale blue in Figure 7a, which indicates that the average nitrate concentration is over 10% of background nitrate for the outer and middle estuary but below 10% of background for the upper estuary. This area is in the outer estuary (east of 606,000mE), near the eastern limit of the area of impact where, as noted, the patch of effluent tends to turn slow down and reverse.

On the neap tide, with its smaller tidal excursion, the area of impact is shorter but concentrations within the footprint are higher. The footprint is confined within the middle estuary (between 598,000mE and 606,000mE). Within the footprint there is an area of pale blue where the nitrate concentration exceeds 10% of background nitrate for the middle estuary but is less than 10% of background for the upper estuary. There is a very small area of darker blue where the concentration is just above 10% of background for the upper estuary.

Figure 8 shows the mean concentration for springs and neaps combined. The concentration does not exceed 10% of the background nitrate for the upper estuary.

Sensitivity testing indicated that the impact of a shorter discharge at a higher concentration is very similar to that shown in Figures 7 - 24.

3.4.2 *Time variation of impact*

The tidal movement of the discharged patch means that impact at any fixed location is intermittent. This can be seen from Figures 9-24 and is further presented in Figures 25-

29, which show the time-variation of the impact at the EA monitoring sites 4, 6, 7, 8 and 14 and corresponding locations within the main plume axis. Graphs are plotted for the first 14 days of the discharge and for days 15-29. The vertical axis is different for the sites off the plume axis, being exaggerated by a factor of ten compared with the sites in the plume axis.

Both the instantaneous value and the daily running mean are shown in Figures 25-29.

Concentrations in the plume axis are generally less than 1.1 mg/l to 1.3 mg/l nitrate as N (relative concentration $<6 \times 10^{-5}$) even at the nearest site to the discharge (site 4a). At the sites outside the main plume axis the impact is typically 5-10 times lower than at the corresponding locations within the axis. The impact peaks are also sharp, particularly at the sites in the plume axis, and drop rapidly as the plume passes over.

It is noticeable that within the plume axis the running mean does not build up significantly during days 15-28 compared with days 1-14. This is because the impact here is dominated by the most recent discharge. Thus no significant further build-up is expected in this area. At the sites, off the plume axis, there is a noticeable build up during the first 14 days as the older discharge becomes more dispersed. There is a small amount of further build-up during days 15-28, which might be expected to continue for some time[1].

Figures 25 – 29 show that:
- The model was run for a sufficient length of time to confirm steady state concentrations along the axis of the plume with repeated daily discharges – i.e. up to 58 days
- The average trend lines demonstrate early initial N concentration build up to day 14 as would be expected but the N concentration across the various sites levels out significantly after this
- The actual peak concentrations within the plume axis downstream of the discharge are predicted to be typically about 1 mg/l nitrate as N (up to 2.2 mg/l) for short 30 minute durations.

3.5 RETENTION OF EFFLUENT IN THE ESTUARY

The dispersion model clearly shows that the effluent is carried right out of the estuary on the ebb tide following discharge from the outfall structure. However, some of the material returns to the estuary highly diluted (with nitrate typically at 0.05 mg/l as N or less) on the returning tide before the next discharge. The question arises: how much build-up might occur over the duration of the FED operation?

3.5.1 Removal by dilution and dispersion over an extended period

Removal of a single discharge

To address this question, the model was run for an extended period and the location of the effluent discharged on the first day (spring tide) was monitored. The fraction of the initial mass remaining in the estuary as the simulation progressed was calculated as a function of time. Here, ‘in the estuary’ means to the west of 602000mE, which is the

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[1] Possibly eventually increasing by a factor of 1.2 to 1.5 compared with the values shown in Figures 25a, 25b, 26a, 26b, 27a, 27b 28a, 28b 29a and 29b in the absence of other removal mechanisms

line crossing the south side of the estuary near its northernmost point, some 2km east of the power station.

The amount of material retained decreased rapidly over the first five days but about 10% was retained after one month (Figure 30) and 6% after two months. The retention fraction varied between spring and neap tides because of the varying tidal prism. This removal in the model represents physical removal by currents, only.

Build up of successive discharges

In the same extended simulation the retention (west of 602000mE) of the total discharged amount (daily release over two months) was also calculated (Figure 31). Figure 31 shows the tide curve (magenta line), the total amount of effluent discharged (stepped red line) and the amount of effluent retained (dark blue line). The variable representing the amount of effluent released and retained is the number of random-walk particles present in the model. Thus the fraction of the total retained at any given time is obtained by comparing the stepped red line and the dark blue line.

In this case 22% of the material released in the first month was retained first month and 18% of the total (two-months discharge) was retained after two months. This implies that a further 8% of the first month's discharge was lost in the second month. Extrapolating forward based on this loss rate[2] it appears that at the end of the discharge period, and ignoring all other loss mechanisms, about 6% of the total nitrate discharged might be present in the estuary west of 602000mE.

Following cessation of discharge, it might be expected (based on the same loss rate) that tidal dispersion alone might remove about one third of the remaining nitrate per month. That is one-third in the first month, leaving two-thirds; one third of this in the second month leaving four-ninths, etc.

It must be understood that this description and simulation of the removal of material by tidal currents and river flow ignores other removal mechanisms including biological and chemical reaction, wind-driven current and non-tidal coastal current. This will result in conservative results (over-prediction of concentration). However, the spread of the discharged water over the estuary should be well represented apart from the effects of wind and tidal perturbations.

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[2] 8% of the first month's discharge was removed in the second month: this constitutes 8/22 of what was present at the start of the second month
So 14/22 of what was present at the start of the second month remains at the end of the second month
Assume this rate of loss of first month's discharge continues: 14/22 x 0.14 = 0.09 is present after 3 months
14/22 x 0.09 = 0.06 is present after 4
Etc
Sum the geometric series for 49 weeks ≈11 months
The result of this is that 5.5% remains after 11 months, which is rounded to 6% above

Obviously this calculation relies heavily on the assumption that 8/22 is lost each month after the first month (which is treated as exceptional because it takes time for the patch to build up). But even if we assume there are no further losses then after 11 months we would expect 22% of the 11th month plus 14% of the previous 10 months or 15% overall.

As a result of the gradual build-up of effluent, a diffuse patch of low concentration develops and spreads across the estuary. In the absence of other removal mechanisms, this would imply a gradually increasing area of impact at 10% above ambient.

This exceedance area builds up steadily over the first month to reach the distribution shown in Figure 32. The build up then levels out and is much less in the second month. This is consistent with the reduced build-up of the total amount retained in the second month. However the area above the threshold is still increasing at the end of 28 days.

The spatial variability of the concentration in the diffused patch is shown in Figure 32, which shows the instantaneous concentration (neglecting losses) after one month. The effluent from the most recent discharge can be seen as a patch of higher concentration centred on site 4a and the area of higher concentration to the southeast of this is the remains of the previous two or three discharges. This does not re-enter the estuary as the tide moves but tends to disperse offshore. There is a wide area of nitrogen spread fairly uniformly over the middle estuary and along the northern side of the outer estuary.

This built-up concentration pattern moves with the tide to produce the daily average impacts shown in Figures 33 (spring tide) and 34 (neap tide).

It is seen that on the spring tide the concentration in the entire upper estuary is less than the upper estuary screening threshold concentration. The average concentration in most of the middle estuary is between the middle and upper estuary screening threshold concentrations. The concentration in most of the outer estuary is less than the outer estuary screening threshold concentration. Only in the narrow line along the axis of the plume does the average concentration exceed the screening threshold concentration for the upper estuary.

On the neap tide the average concentration in the whole of the upper estuary remains below the screening threshold concentration. The average concentration in most of the middle estuary is between the screening threshold concentrations for the middle and upper estuary areas. However, there is an increased area, compared with the spring tide, where the concentration east of the discharge exceeds the upper estuary screening threshold.

3.5.2 Bulk mixing

If we examine the discharge in the context of the overall flows into the estuary and the total volume of the estuary we can estimate the impact of various amounts of retention of the effluent.

The volume of water in the estuary west of 602000mE, estimated from the hydrodynamic model is:

High water spring	269×10^6 m^3.
High water neap	194×10^6 m^3.
Average high water	232×10^6 m^3.

The total volume to be discharged during the 49-week operation can be estimated on the basis of continuous operation as 30x49x7 = 10.3×10^3 m^3 of effluent.

Even if all of this were retained in the estuary there would still be a dilution factor of about 20,000 relative to the concentration in the FDT (22100 mg/l as N) giving nitrate concentrations of the order 0.9 mg/l to1.1 mg/l as N. These values are the average for the whole volume considered, and locally concentrations could be considerably higher, following the patterns shown in Figures 32-34.

If as much as 10% of all the discharge is retained, as suggested in the previous sections, there would be a dilution factor of 200,000 giving average nitrate concentrations for the volume considered of the order 0.09 mg/l to 0.11 mg/l as N. For the middle estuary, this is about 25% of the baseline concentration.

These numbers are calculated using the high tide volume but the implied average concentration applies to all states of the tide. This is because the discharge is always added at high tide. The subsequent outflow of water reduces the total volume but does not increase the concentration.

It can also be noted that according to the National River Flow Archive (http://www.ceh.ac.uk/data/nrfa/data/search.html) the average inflow rate into the estuary from the rivers is:

• Blackwater at Langford	1.33 m^3/s
• Chelmer at Rushes Lock	1.90 m^3/s
• Ter at Crabb's Bridge	0.28 m^3/s
• Brain at Guithavon Valley	0.39 m^3/s

These rivers combine before entering the west end of the estuary proper close to Maldon so

• Total at Maldon	3.94 m^3/s or 340,600 m^3/day

In addition the Colne at Lexden contributes a further 91,900 m^3/day ($1.1m^3/s$), but this is further east than the main impact area of the FED discharge.

On average the river flow into the Blackwater estuary (excluding the Colne) is some 8000 times the effluent discharge volume, and is enough to completely flush the estuary in some 510 days. Thus the rivers will supply a volume equivalent to two-thirds of the water originally in the estuary during the FED discharge, implying that the natural flushing period might be of the order of two years.

3.5.3 *Other removal mechanisms*

The PLUME-RW model calculates dispersion by tidal currents during the period simulated in the hydrodynamic model. This is a period of low residual current in the outer coastal area. In these conditions the same water that leaves the estuary on the ebb tide tends to return on the flood. It is likely that at times during the operation of the FED there will be additional residual currents associated with weather disturbances, etc, that will reduce the volume of "old" water returning to the estuary on the flood tide and replace it with "new" water from the north or the south. This will tend to reduce the build-up of FED effluent in the estuary.

There are also removal processes for the nitrate, corresponding to chemical, biological and sedimentary processes that are not included in the PLUME-RW model. Reference 6 indicates that significant denitrification occurs in the Colne (32-44% of the TOxN entering via the river is removed *en route* to the North Sea), mainly in the upper estuary.

These considerations indicate that, while the PLUME-RW model is an effective tool for investigating the dilution and dispersion of the FED discharge on the first few tides, it omits some important removal processes that affect the long-term build up, which makes the longer term simulations described above over-conservative. The PLUME-RW model is regarded as a reliable simulator of the processes by which the point discharge is transformed into a diffuse concentration field. Figures 32-34 and additional analysis of the model results show that this tidally-dispersed concentration pattern would be fairly uniform.

As the built-up dispersion pattern of the discharge is so widespread and uniform, and as the concentration (without additional removal mechanisms) is of the same order as the existing concentration, the subsequent dispersion and removal of the nitrate in the discharge is expected to be similar to that of the existing nitrate load to the same area. The subsequent behaviour is therefore best determined by considering what is already known about the well-distributed nitrates from other sources, as discussed below.

Evidence from other inputs of nitrate

Reference 6 presents a characterisation of the Essex Estuaries including the Colne and Blackwater Estuaries. The issue of nutrients in the Estuary is covered in section 6.2 of Reference 6. The authors note that, as would be expected, agriculture is the dominant nitrogen source, contributing mainly via run-off in to the freshwater rivers. The agricultural source is supplemented by discharges from sewage treatment works in the river Colne (about 10% of the total load) and to a lesser extent the Blackwater (about 1% of the total load).

In the Colne the main sewage treatment works source is at Colchester Hythe, with smaller sources at Fingringhoe and Brightlingsea. In the Blackwater the sewage treatment works are at West Mersea, Tiptree, Tollesbury, Bradwell and Maldon.

The annual loads of total oxidised nitrogen (TOxN) are estimated as:

- Colne 47.8 x 10^6 moles per year
- 0.669 x 10^6 kg N per year 2.96 x 10^6 kg NO_3 per year
- 1830 kg N per day 8100 kg NO_3 per day

- Blackwater 178.2 x 10^6 moles per year
- 2.49 x 10^6 kg N per year 11.0 x 10^6 kg NO_3 per year
- 6820 kg N per day 30200 kg NO_3 per day

where the NO_3 amounts above are calculated assuming all the oxidised nitrogen is in the form NO_3.

Combining the estimated loads above and the river flow, it can be estimated that the average concentration in the Colne is 1830/91900 = 0.020 kg N per m^3 and the average concentration in the Blackwater is 6820/340600 = 0.020 kg N per m^3. That is, the concentration in both rivers is the same and amounts to 20 mg/l N or 88mg/l NO_3. The processes that reduce these concentrations down to the levels observed in the inner, middle and outer estuary (maximum 4.38 mg/l N to 1.36 mg/l N, average 0.78 mg/l N to 0.35 mg/l N) combine all the tidal and non-tidal dispersion and chemical and biological denitrification processes present in the system.

These loads may be compared with the estimated FED inputs of nitrogen of 555 kg to 663 kg N (2457 kg to 2934 kg NO_3) per day for 49 weeks of operation per year giving an annual load of 0.190 x 10^6 kg N to 0.227 x 10^6 kg N.

The expected annual load from the FED plant is thus of the order 7.7% to 9.1% of the estimated annual load into the Blackwater and 5.9% to 7.1% of the estimated annual load into the Blackwater plus Colne, (where the load into the Blackwater and Colne can be regarded as contributing to the middle and outer estuary).

If we allow for denitrification of 32% to 44% in the upper estuary (say 40% on average), as indicated in the previous section we can conclude that the FED discharge might amount to 7.7% to 9.1% of the load entering the upper estuary and about 10% of the load entering the middle and outer estuary.[3]

As the retained nitrate is well diffused and the discharge does not affect the flow patterns in the estuary to any significant extent, the most reasonable predictor of the overall increase in concentration in the estuary resulting from the FED discharge would be that the increase would be in proportion to the load: 8% to 10% depending on location within the estuary.

As indicated above, tidal dispersion would be expected to decrease this by about one-third per four weeks after discharges cease. Therefore the increase would be expected to decrease to less than 5% above background within about three months of cessation of discharge.

3.6 REMOVAL OF THE WING WALL

The wing wall is aligned with the flow and does not affect the flow patterns significantly. There might be more turbulence around the discharge tower without the wing wall, which would enhance mixing and dilution.

The intake is situated upstream of the discharge and the intake flow is a small fraction of the natural flow past the structure. It is not considered likely that the intake will recirculate the discharged water.

The conclusions of this study are considered to apply equally to the situation after removal of the wing wall.

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[3] Based on the statement in Reference 6 (p92, para 2) that about 40% of the load in the Colne is lost by denitrification “en route to the North Sea” and “mainly in the upper estuary”. Assuming this to mean that 40% is lost before reaching the middle and outer estuary (and assuming that 40% is lost in the upper Blackwater estuary as well as the upper Colne estuary), this implies that, the real Blackwater + Colne contribution to middle and outer is only (1-0.4)x(2.49e6+0.669e6) so the FED plant “share” is increased by 1/(1-0.4) from (5.9% - 7.1%) to (9.8% - 11.8%) ≈ 10% - 12%. However, considering the relative contribution to the upper estuary, the calculation uses only the Blackwater source and ignores the denitrification loss.

Applying all, rather than most of the loss to the upper estuary gives a conservative estimate of the ratio of plant load to background load. It is probably also conservative to apply a 40% loss to the upper Blackwater estuary when the estuary report only gives the value for the Colne and implies it might be higher in the Colne than the Blackwater. Thus 10% seems a reasonable value.

4. Conclusions and recommendations

This report has examined discharge and dilution of the FED discharge using the same arrangement as is currently in place for the FDT discharge.

The timing of the pump operation is set out in Section 2 and should include:

- Siphon and FDT pumps start at 20 minutes before high water.
- FDT pumps stop 9 minutes after high water for $30m^3$.
- Siphon pumps continue running until 1.5 hours after high water for $30m^3$ discharge.

The concentration of metals in the estuary can be estimated using the dilution and relative concentration values given in Tables 5 and 6 and multiplying by the Final Delay Tank concentrations to be provided by the process designers.

The modelling results show that the retained nitrate is well diffused, and the discharge does not affect the flow patterns in the estuary to any significant extent, so the most reasonable predictor of the overall increase in concentration in the estuary resulting from the FED discharge would be that the average increase would be in proportion to the increase in load relative to the background load from agriculture and sewage treatment.

Magnox would be contributing 5.9% - 7.1% of the N input to the Blackwater and Colne. There are significant N reductions due to the natural loss mechanisms within the estuary of approximately 40% on average in addition to the natural dispersion and outflow effects demonstrated by the model. Ignoring these loss mechanisms, we would expect that the discharges from Bradwell would increase the current background N concentrations in proportion to the scale of the contribution i.e. 5.9-7.1%. As the loss mechanisms in the upper estuary result in some decrease in the background load reaching the discharge area, the FED load represents a higher proportion of the local background, estimated as 10% if the maximum daily output were sustained all year.

Thus it is anticipated that overall the average increase in nitrate concentration in the estuary will be less than 10% of the known background.

There will however be localised areas within the plume which will exceed the 10% threshold. Close to the discharge point and within the path of the plume, short-duration peak concentrations of up to 2.2 mg/l as N (typically 1 mg/l) (site 4a) are predicted within the centre of the plume. In this context, “short duration” means less than half an hour, once per day. These concentrations are based on a maximum total daily discharge of 663 kg as N.

Upon cessation of the Bradwell discharges, the localised peak N concentrations will immediately eliminated. Residual N concentrations would then reduce at a rate of approximately 30% per month until current background concentrations are generally achieved within 4+ months.

5. References

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5. Tidal and wind-induced flow modelling of the Blackwater Estuary. Report EX 3870, HR Wallingford Ltd, 1998
6. Characterisation of the European Marine Sites: Essex Estuaries European Marine Site. Chessman BS, Burt GR and Langston WJ, Marine Biological Association of the United Kingdom Occasional Publication (17), (ISSN:02602784), 2006

Tables

Table 1 Tunnel and shaft details

Based on Drawing McA/BR/CW/5058 13 Sept 1957 (shows levels in feet relative to Newlyn Datum, 1m = 3.281ft)			Based on BNFL data provided for Reference 3	
Extreme HW	14.4 ft OD	4.39 m OD		
HW OST			7.8 ft OD	2.38 m OD
Low water	-8.3 ft OD	-2.53 m OD		
LW OST			-7.9 ft OD	-2.41 m OD
Discharge port soffit	-13 ft	-3.96 m		
Discharge port invert	-25 ft	-7.62 m		
Tunnel soffit at shaft	-84 ft	-25.60 m		
Tunnel invert at shaft	-94 ft	-28.65 m		
Tunnel soffit at pit	-33 ft	-10.06 m		
Tunnel invert at pit	-43 ft	-13.11 m		
Shaft diameter	13 ft	3.96 m		
Tunnel diameter	10 ft	3.05 m		
Tunnel length	1520 ft	463.30 m		
Pit diameter	33 ft	10.06 m		9.7 m
Tunnel gradient	0.0336	0.0336		
Tunnel gradient:	1 : 29.80	1 : 29.80		
Tunnel area	78.54 ft^2	7.30 m^2		
Tunnel volume	119380.5	3380.48 m^3		
Shaft area	132.73 ft^2	12.33 m^2		
Shaft volume (at MSL)	11149.51 ft^3	315.72 m^3		
Pit area		79.46 m^2		73.90 m^2
Volume of one tank		68 m^3		
Tidal volume of seal pit				353.63 m^3

Tidal levels from Admiralty Tables	m OD
Mean High Water Spring	2.6
Mean High Water Neap	1.5
Mean Low Water Neap	-1.4
Mean Low Water Spring	-2.3

Table 2 Expected nitrate concentration in the discharge

	Total daily discharge (kg) as N		Concentration in the delay tank (mg/l) as N	
	As NO_3	As N	As NO_3	As N
Maximum	2934	663	97800 in 30m^3	22100 in 30m^3
			244800 in 12m^3	55320 in 12m^3
Minimum	2457	555	81900	18500

Table 3 EQS values, observed concentrations and screening thresholds including discharge

Determinand	EQS	Monitoring Site	Max baseline estuary	Average baseline estuary	Average baseline +10%
Boron	7000 µg/l	Upper Estuary	5030 µg/l	3999 µg/l	4399 µg/l
Cadmium	5 µg/l	Upper Estuary Mid Estuary Salcott/Strood	0.507 µg/l 0.101 µg/l 0.183 µg/l	0.068 µg/l 0.05 µg/l 0.047 µg/l	0.075 µg/l 0.055 µg/l 0.052 µg/l
Chromium	15 µg/l	Upper Estuary Mid Estuary Salcott/Strood	6.5 µg/l 0.5 µg/l 2.2 µg/l	0.72 µg/l 0.43 µg/l 0.52 µg/l	0.792 µg/l 0.473 µg/l 0.572 µg/l
Copper	5 µg/l	Upper Estuary Mid Estuary Salcott/Strood	3.39 µg/l 1.79 µg/l 2.24 µg/l	1.52 µg/l 1.34 µg/l 1.36 µg/l	1.672 µg/l 1.474 µg/l 1.496 µg/l
Iron	1000 µg/l	Upper Estuary	100 µg/l	49.54 µg/l	54.494 µg/l
Lead	25 µg/l	Upper Estuary Mid Estuary Salcott/Strood	1.12 µg/l 0.131 µg/l 0.71 µg/l	0.15 µg/l 0.078 µg/l 0.11 µg/l	0.165 µg/l 0.0858 µg/l 0.121 µg/l
Nickel	30 µg/l	Upper Estuary Mid Estuary Salcott/Strood	5.03 µg/l 1.43 µg/l 1.7 µg/l	1.47 µg/l 1.1 µg/l 0.16 µg/l	1.62 µg/l 1.21 µg/l 0.18 µg/l
Silver	n/a	Upper Estuary Mid Estuary Salcott/Strood	1.81 µg/l <1 µg/l <1 µg/l	1.011 µg/l <1 µg/l <1 µg/l	1.112 µg/l 1.1 µg/l 1.1 µg/l
Zinc	40 µg/l	Upper Estuary Mid Estuary Salcott/Strood	29 µg/l 6.1 µg/l 18.7 µg/l	5.78 µg/l 3.25 µg/l 3.65 µg/l	6.358 µg/l 3.575 µg/l 4.015 µg/l
Nitrate Filtered as N	Grade 1 (GQA)	Upper Estuary Mid Estuary Outer Estuary	4.38 mg/l 2.02 mg/l 1.36 mg/l	0.78 mg/l 0.39 mg/l 0.35 mg/l	0.086 mg/l 0.429 mg/l 0.039 mg/l

Table 4 Depth-average current speeds and water depth near the intake structure from the Blackwater model

Time (hours)	Mean Spring Tide (range 4.9m)		Mean Neap Tide (range 2.9m)	
	depth (m)	current (m/s)	depth (m)	current (m/s)
HW	10.1	0.1	8.3	0.1
HW+0.5	9.7	0.7	8.3	0.1
HW+1	8.8	0.9	8.1	0.3
HW+1.5	7.7	0.7	7.9	0.3
HW+2	7.0	0.6	7.6	0.3
HW+2.5	6.6	0.5	7.2	0.3
HW+3	6.1	0.4	6.9	0.3
HW+3.5	5.8	0.3	6.6	0.2
HW+4	5.6	0.3	6.4	0.2

Table 5 Dilution ratios at peak concentration relative to tank at different distances from the discharge

Distance from outfall (m)	0	10	25	50	100	250	500
Dilution spring – relative to FDT	50	1100	2900	5100	9400	12200	14600
Dilution neap – relative to FDT	50	500	1300	2800	5700	8100	9800

Table 6 Peak concentrations relative to tank and as N at different distances from the discharge

Distance from outfall (m)	0	10	25	50	100	250	500
Concentration spring – rel. to FDT	0.02	9.1e-4	3.4e-4	2.0e-4	1.1e-4	8.2e-5	6.8e-5
Concentration spring - as N (mg/l) [1]	440	20	7.5	4.4	2.4	1.8	1.5
Concentration neap – rel to FDT	0.02	2.0e-3	7.7e-4	3.6e-4	1.8e-4	1.2e-4	1.0e-4
Concentration neap – as N (mg/l) [1]	440	44	17	8.0	4.0	2.7	2.2

[1] Assuming 22100 mg/l in the FDT

Figures

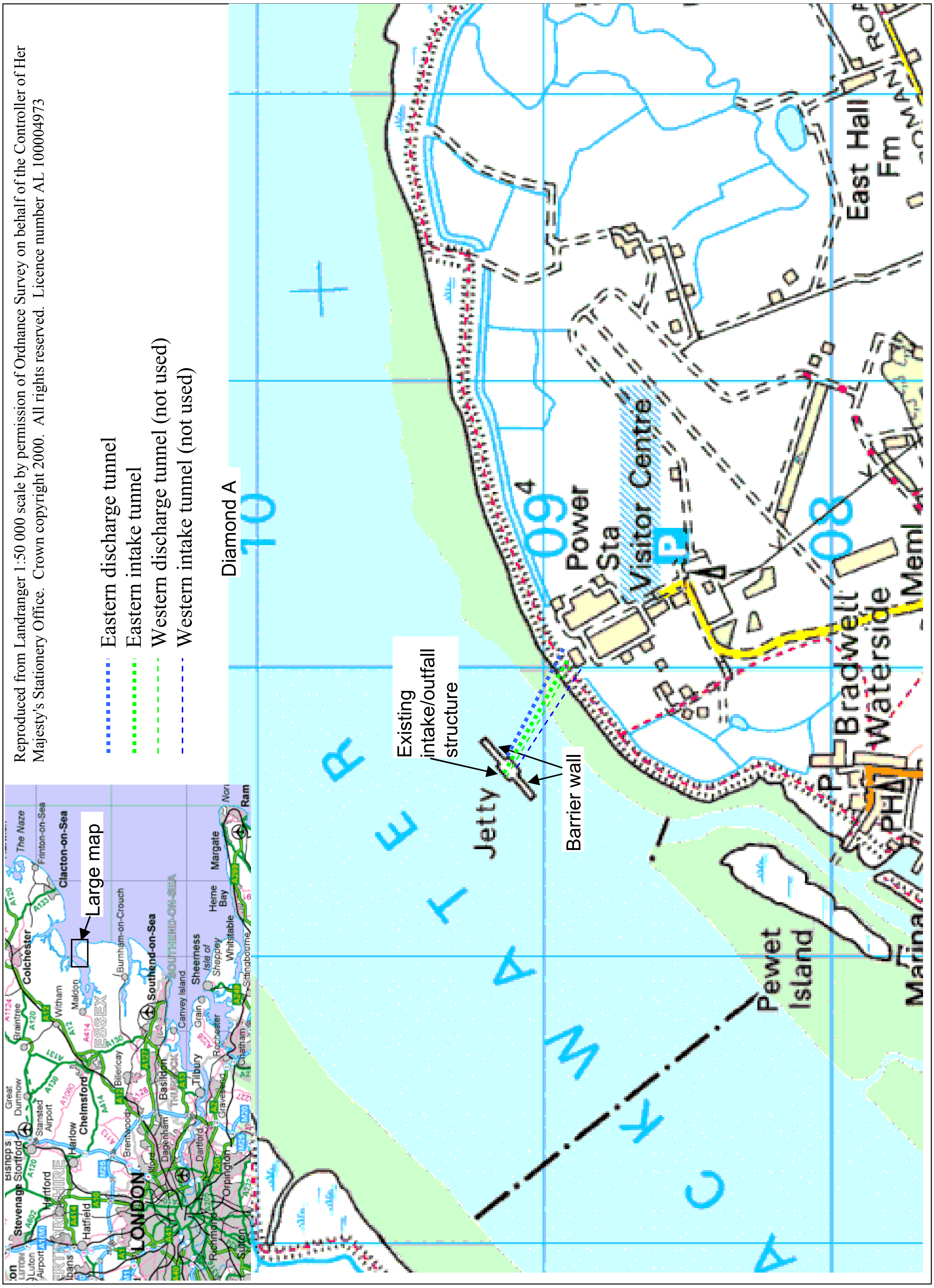

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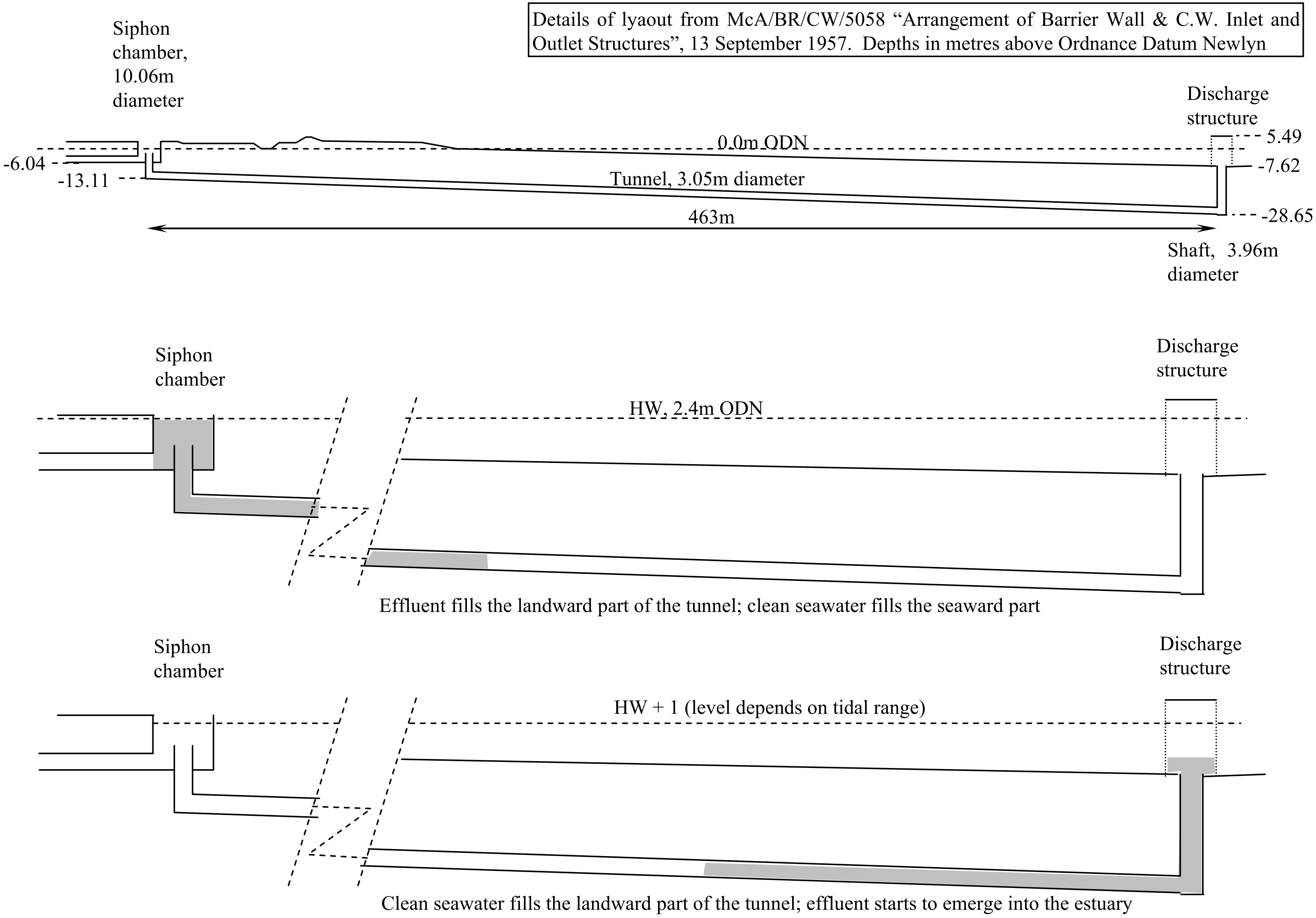
Figure 1 Location map



Details of lyaout from McA/BR/CW/5058 “Arrangement of Barrier Wall & C.W. Inlet and Outlet Structures”, 13 September 1957. Depths in metres above Ordnance Datum Newlyn

Effluent fills the landward part of the tunnel; clean seawater fills the seaward part

Clean seawater fills the landward part of the tunnel; effluent starts to emerge into the estuary

Figure 2 Layout of the discharge

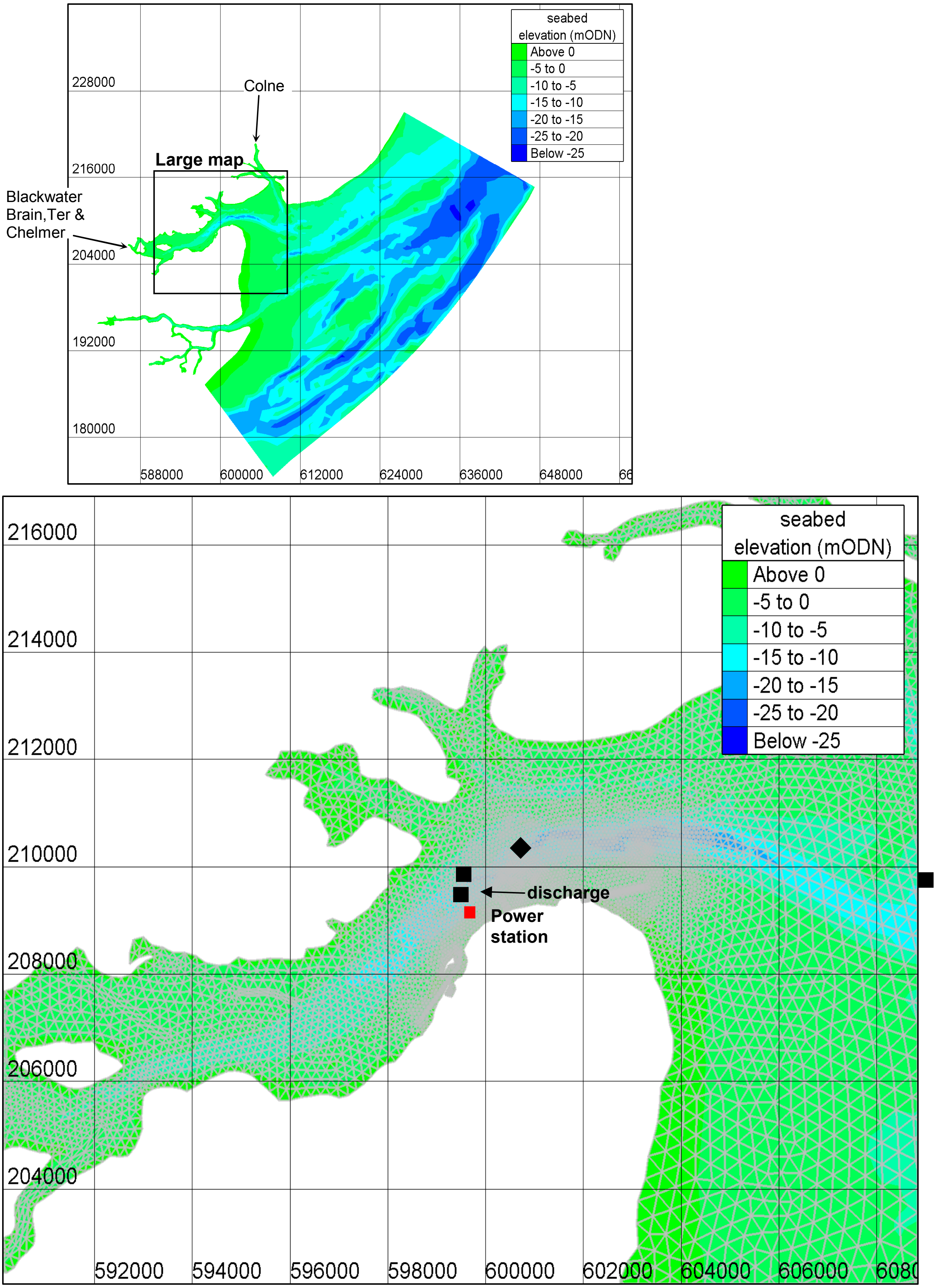


Figure 3 Model bathymetry and mesh showing nearest calibration points

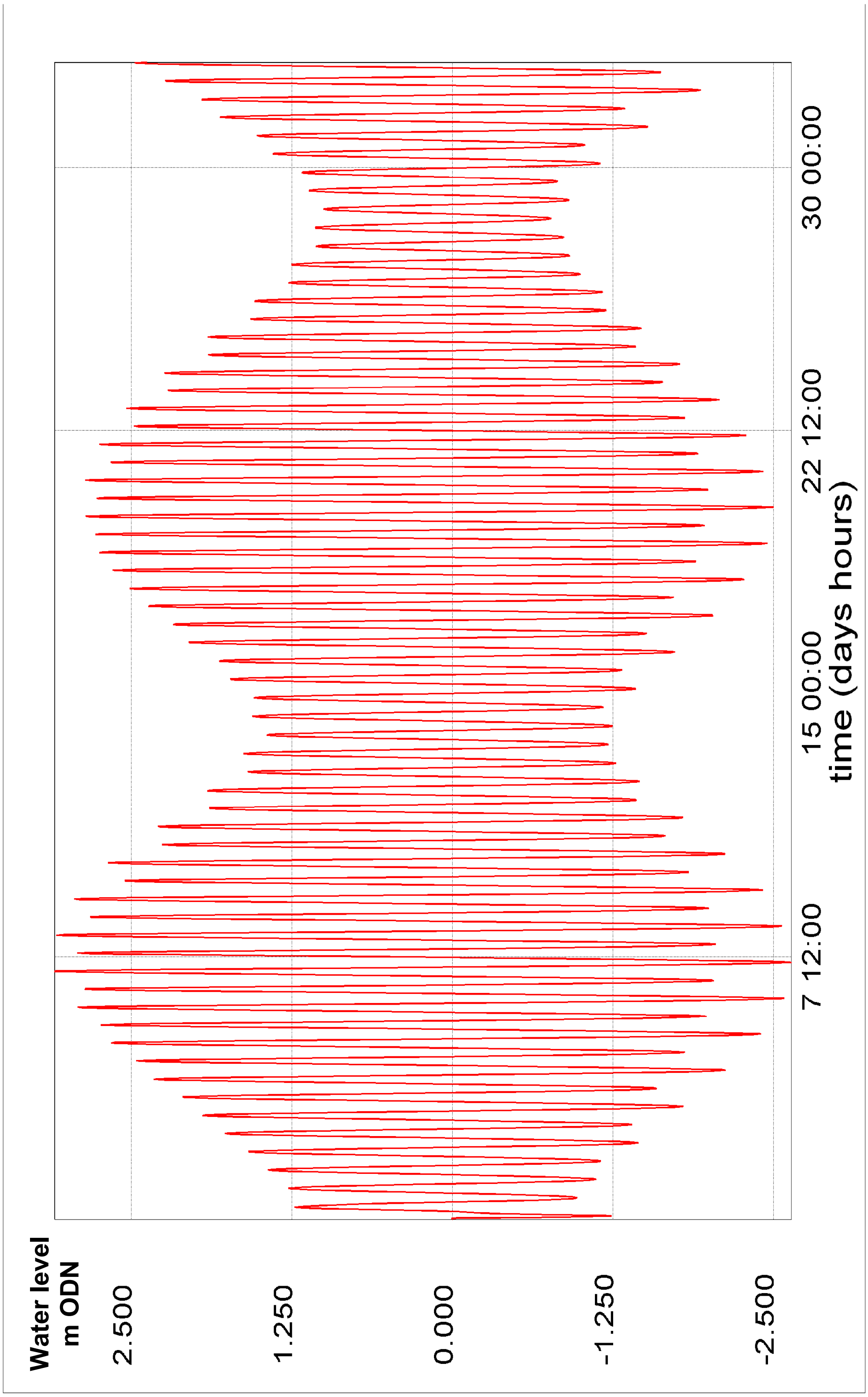


Figure 4 Tidal variation in the estuary

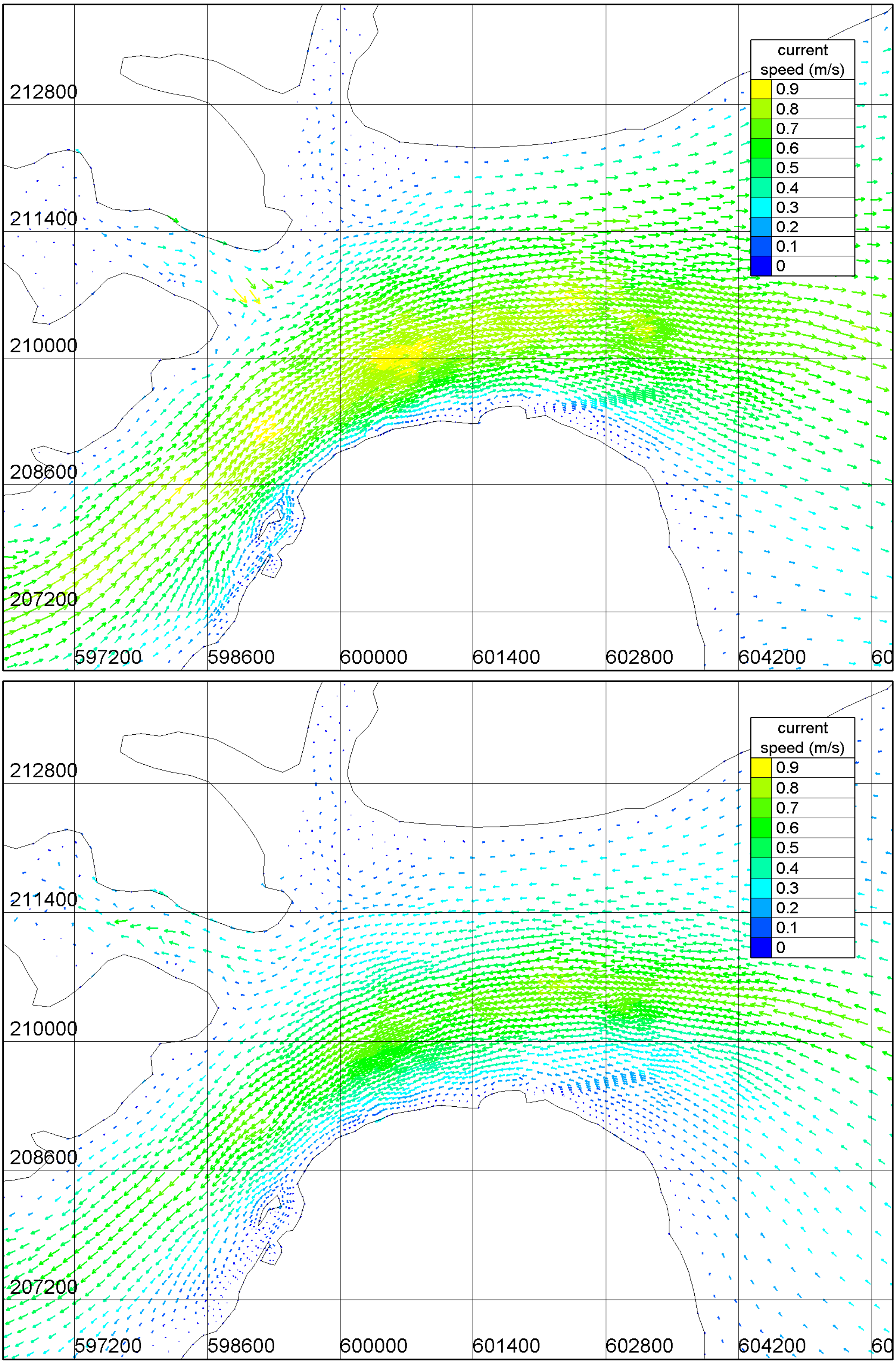


Figure 5 Currents in the estuary

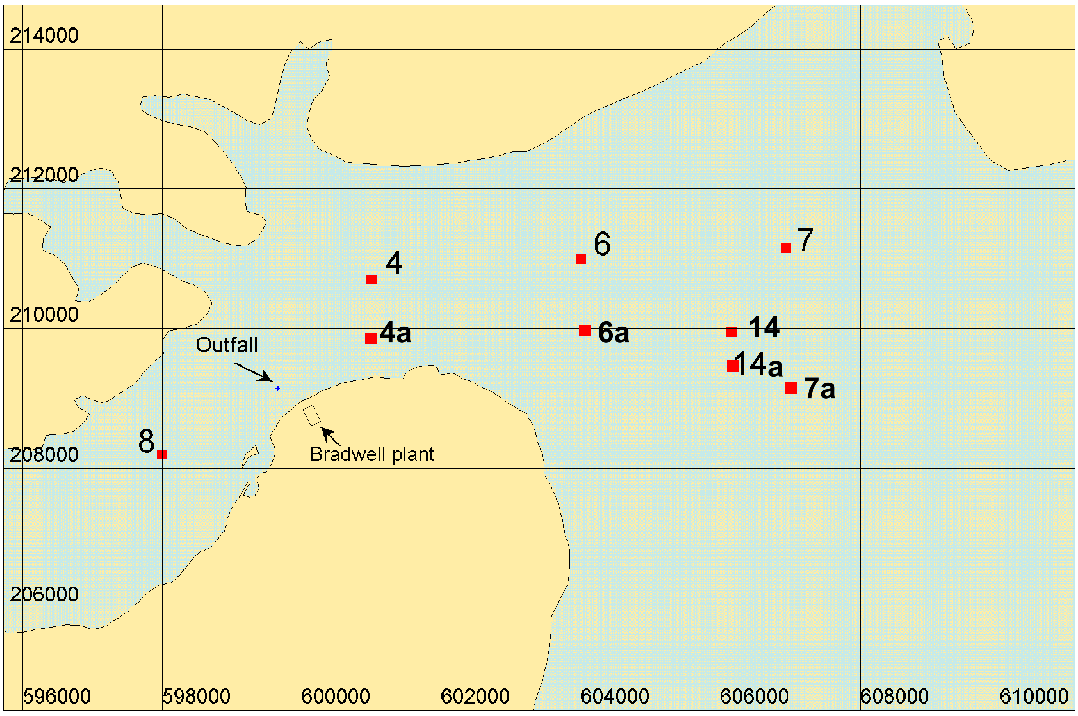


Figure 6 Location of the outfall, the plant and the monitoring sites where results have been extracted

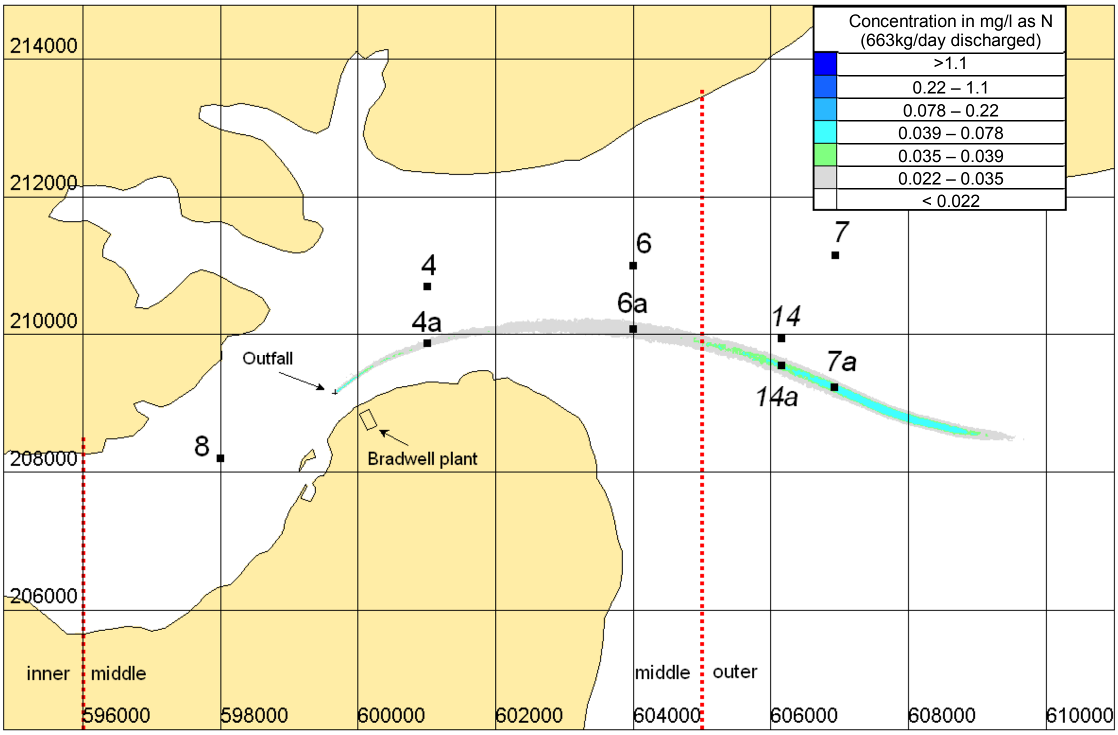


Figure 7a Average concentrations of recently discharged effluent – three days of release around spring tide

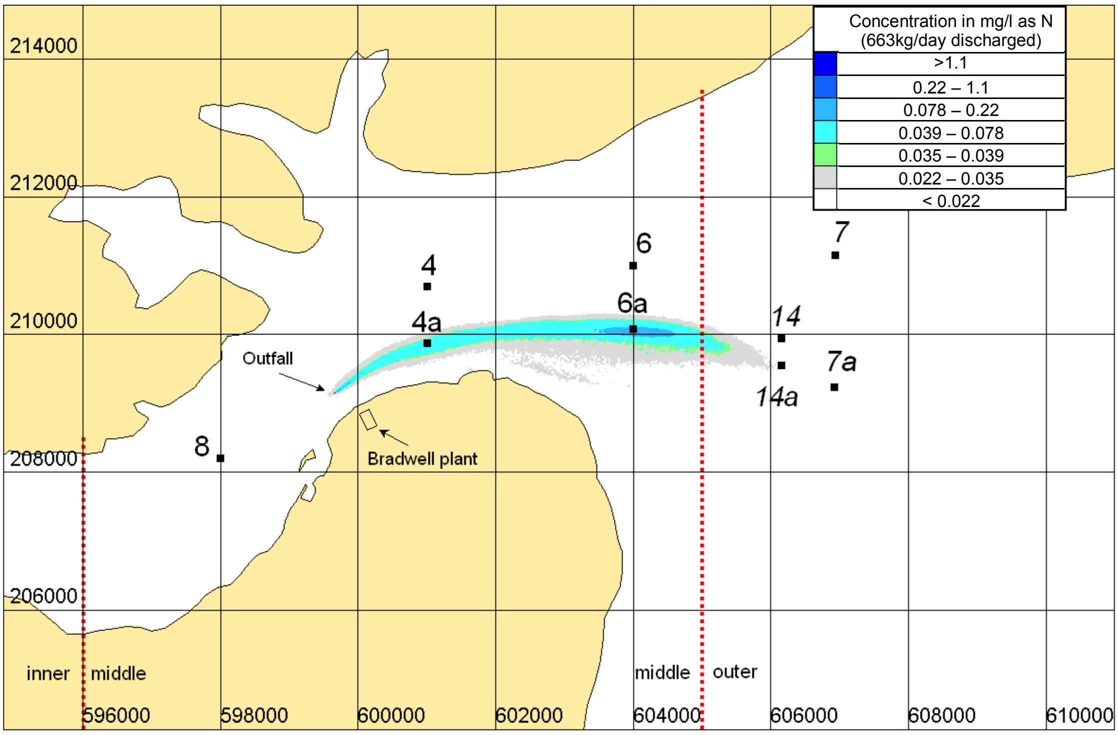


Figure 7b Average concentrations of recently discharged effluent – three days of release around neap tide

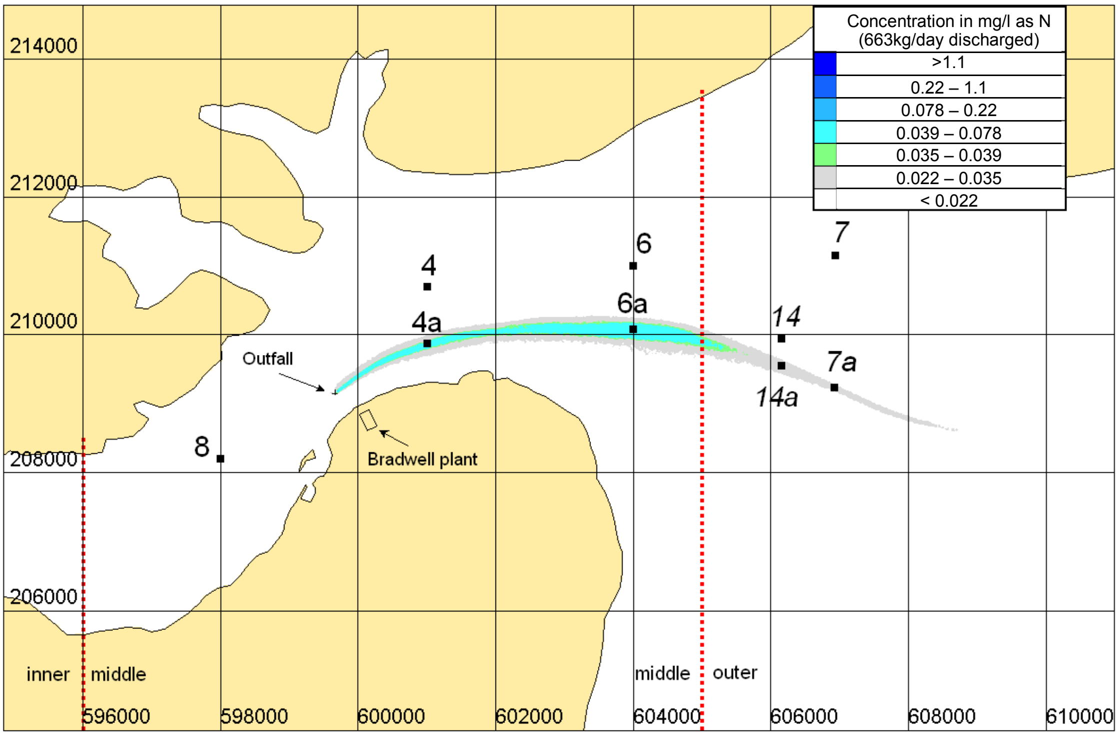


Figure 8 Average concentrations of recently discharged effluent – average of figures 7a and 7b

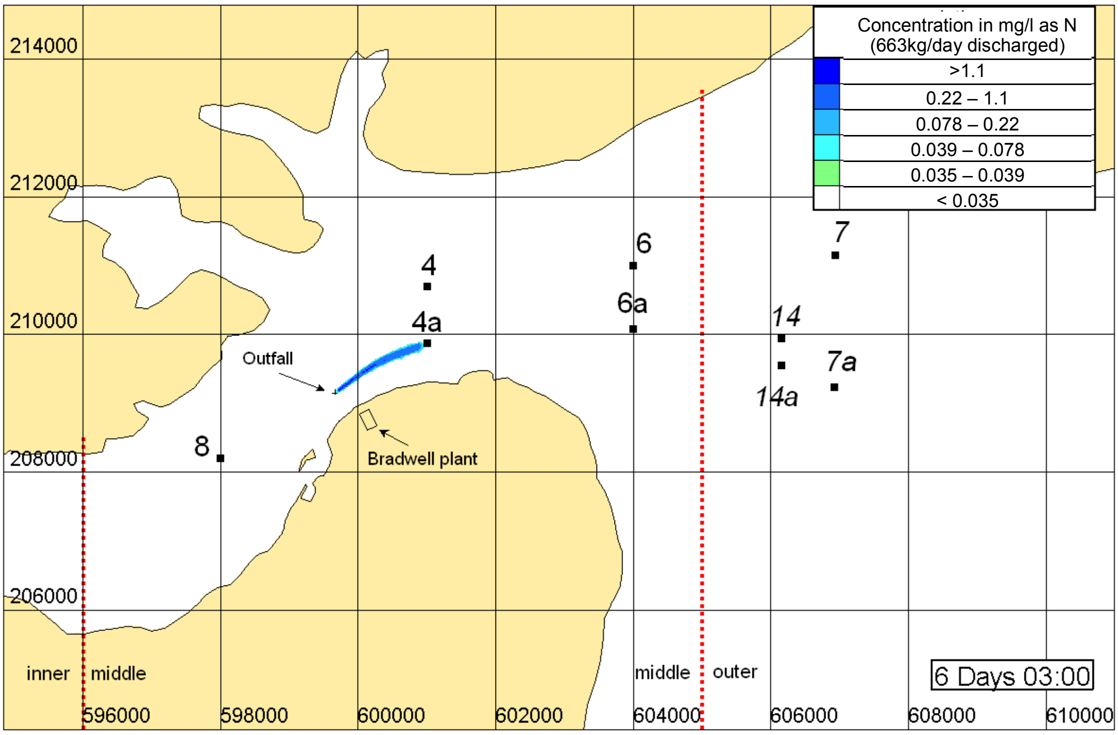


Figure 9 Concentrations of recently discharged effluent – single release, spring tide, 30m^3 discharge, at 6days 3h

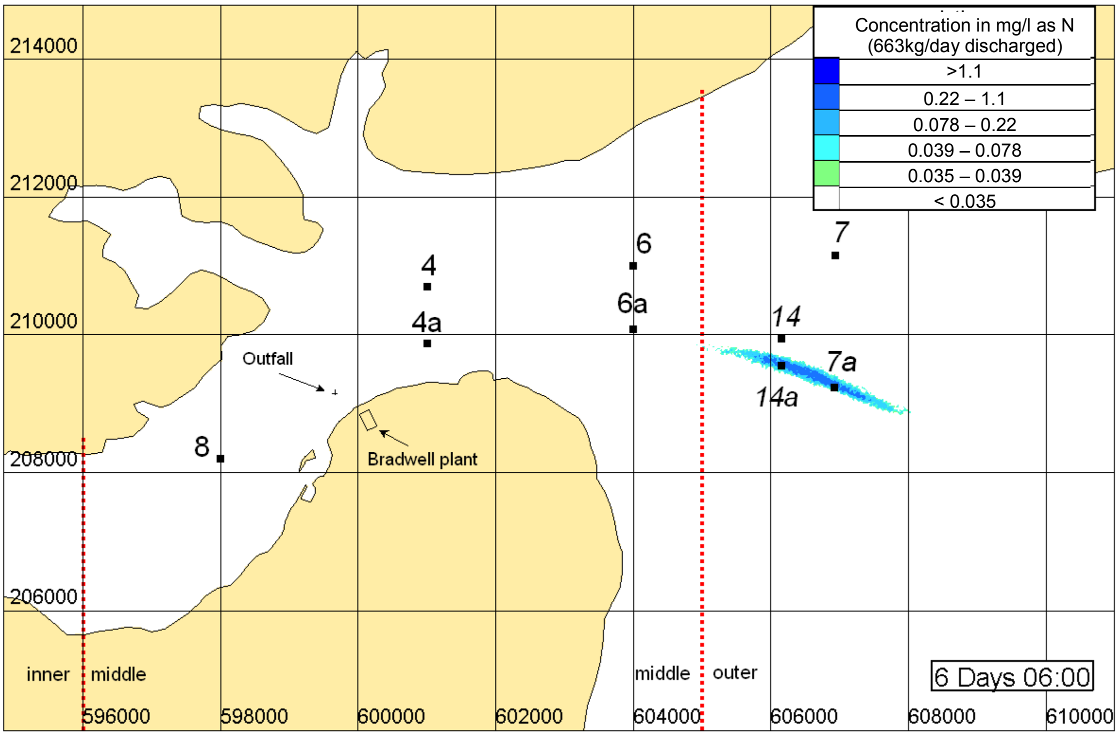


Figure 10 Concentrations of recently discharged effluent – single release, spring tide, 30m^3 discharge, at 6days 6h

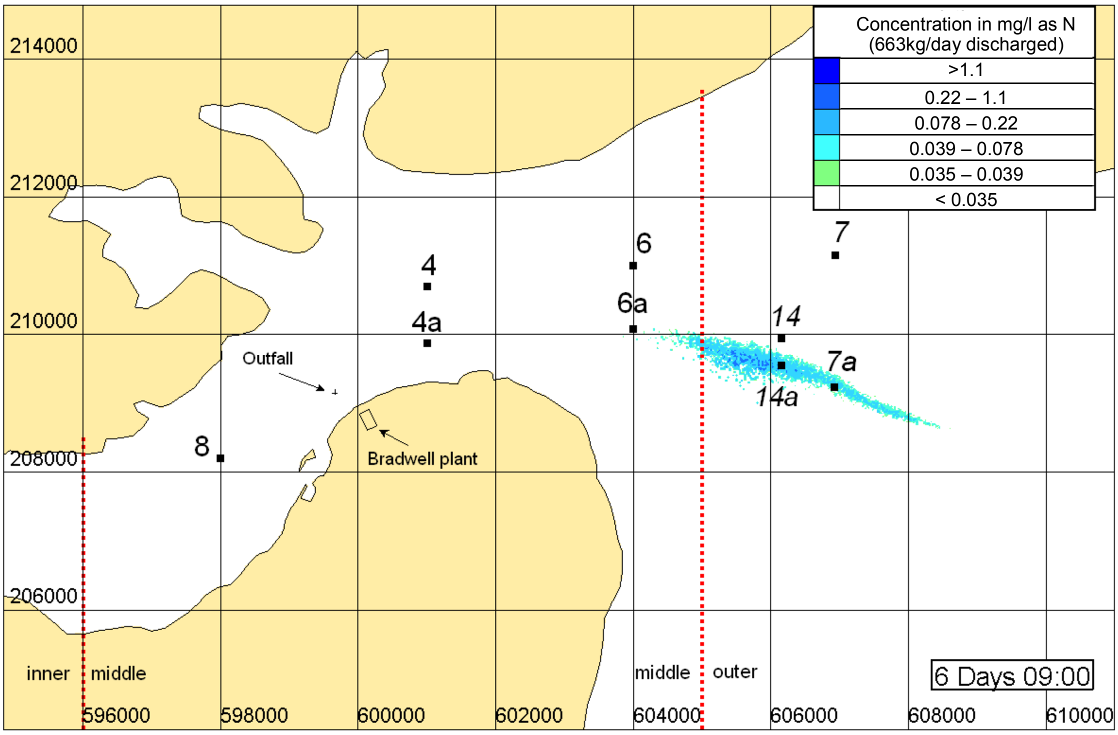


Figure 11 Concentrations of recently discharged effluent – single release, spring tide, 30m^3 discharge, at 6days 9h

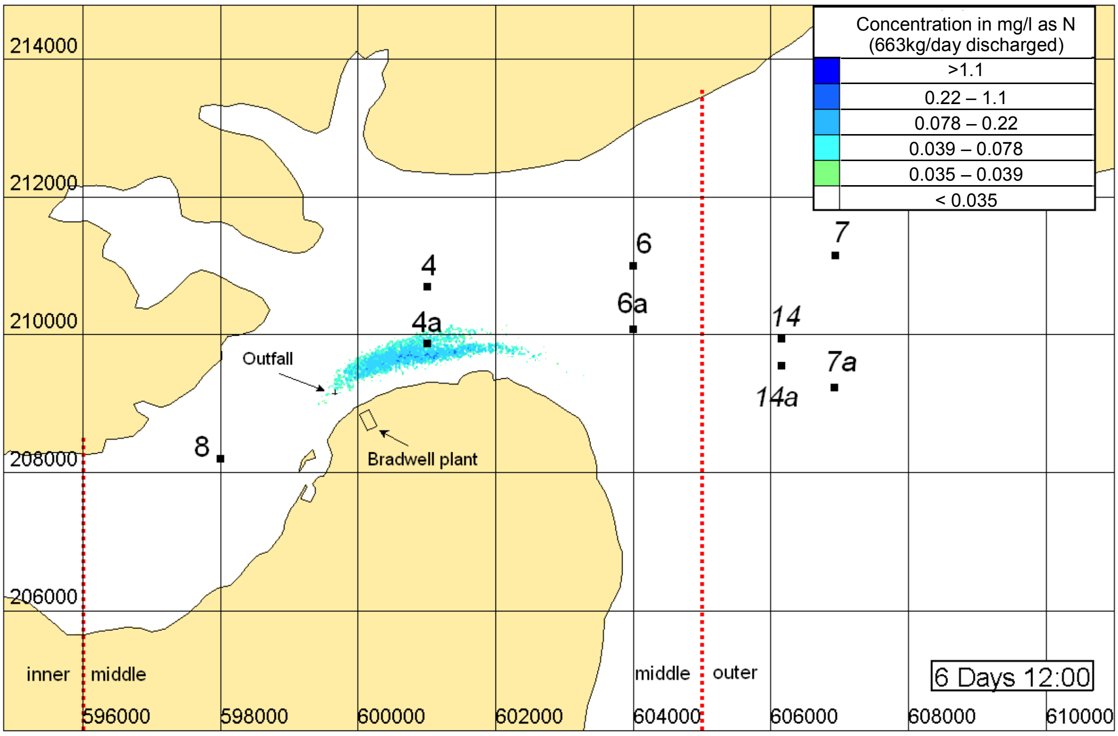


Figure 12 Concentrations of recently discharged effluent – single release, spring tide, 30m^3 discharge, at 6days 12h

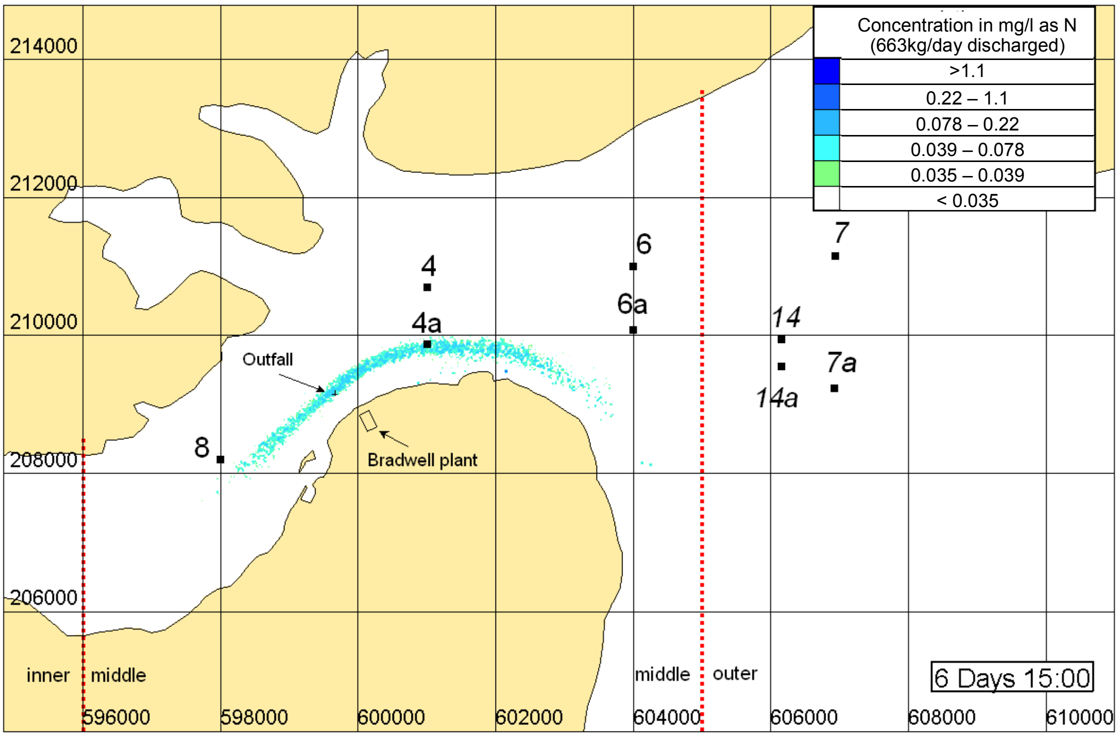


Figure 13 Concentrations of recently discharged effluent – single release, spring tide, 30m^3 discharge, at 6days 15h

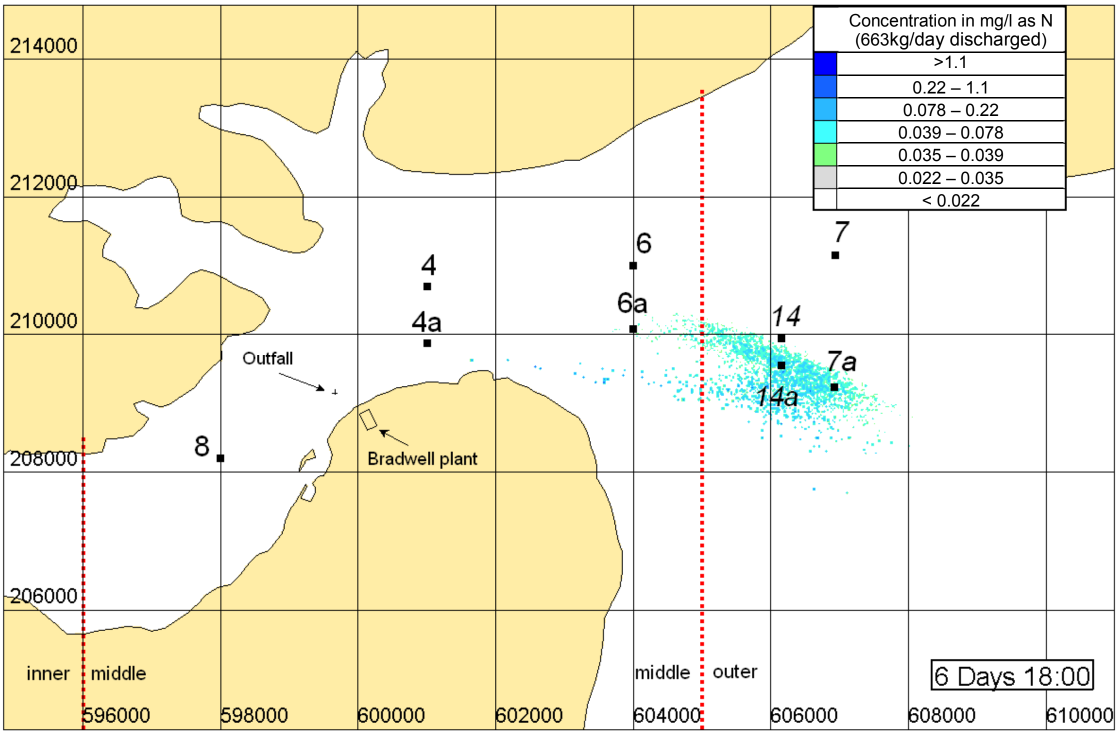


Figure 14 Concentrations of recently discharged effluent – single release, spring tide, 30m^3 discharge, at 6days 18h

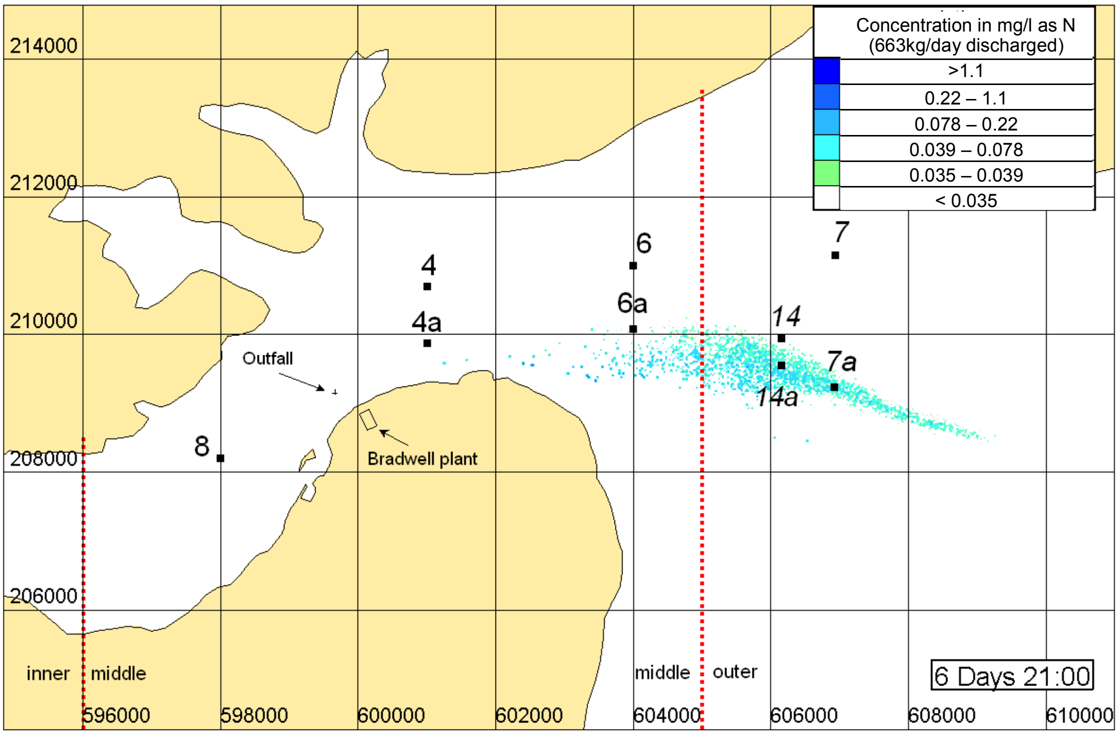


Figure 15 Concentrations of recently discharged effluent – single release, spring tide, 30m^3 discharge, at 6days 21h

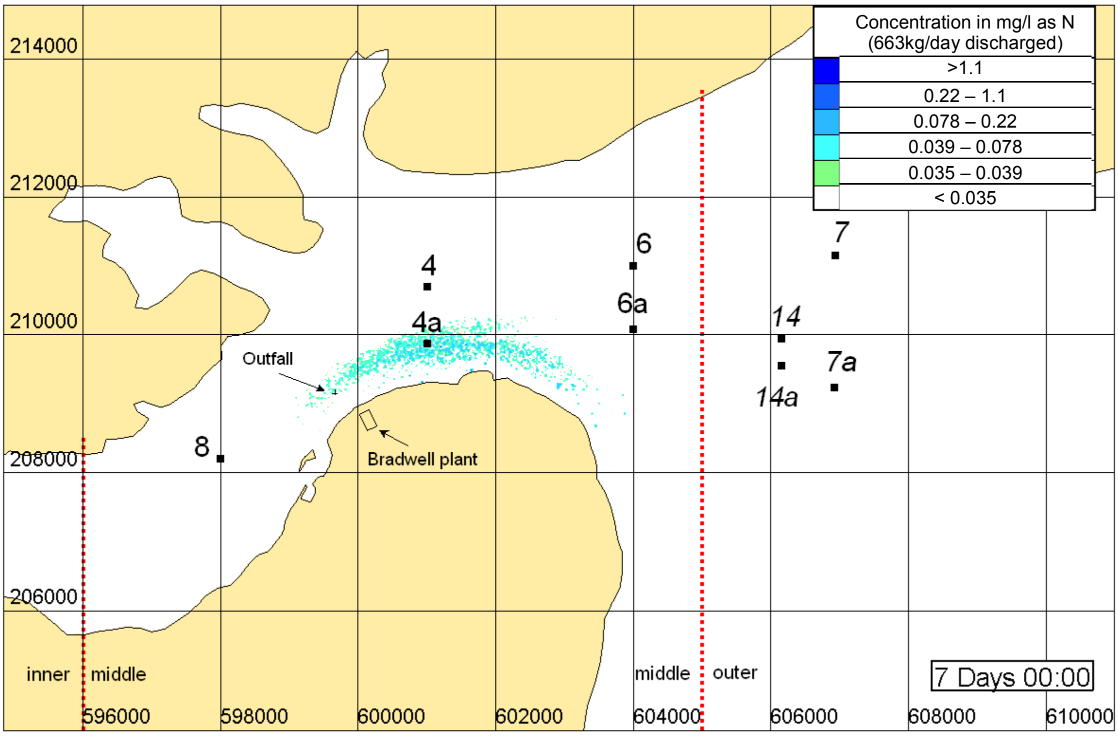


Figure 16 Concentrations, of recently discharged effluent – single release spring tide, 30m^3 discharge, at 7days 0h

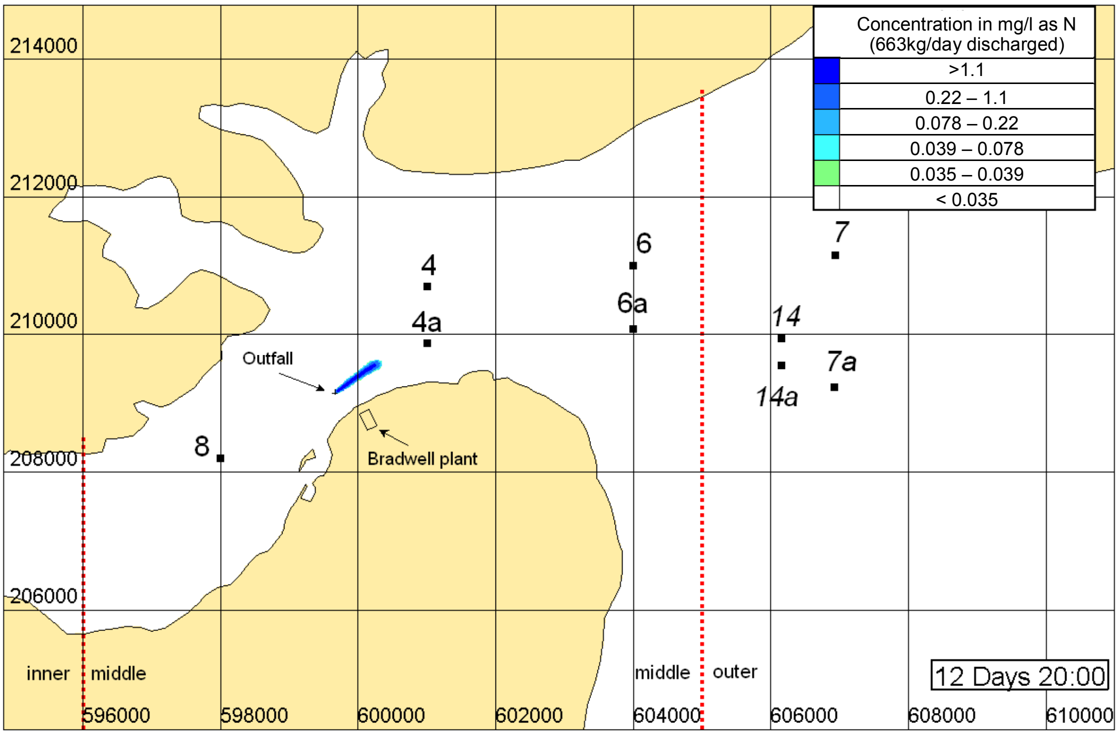


Figure 17 Concentrations of recently discharged effluent – single release, neap tide, 30m^3 discharge, at 12days 20h

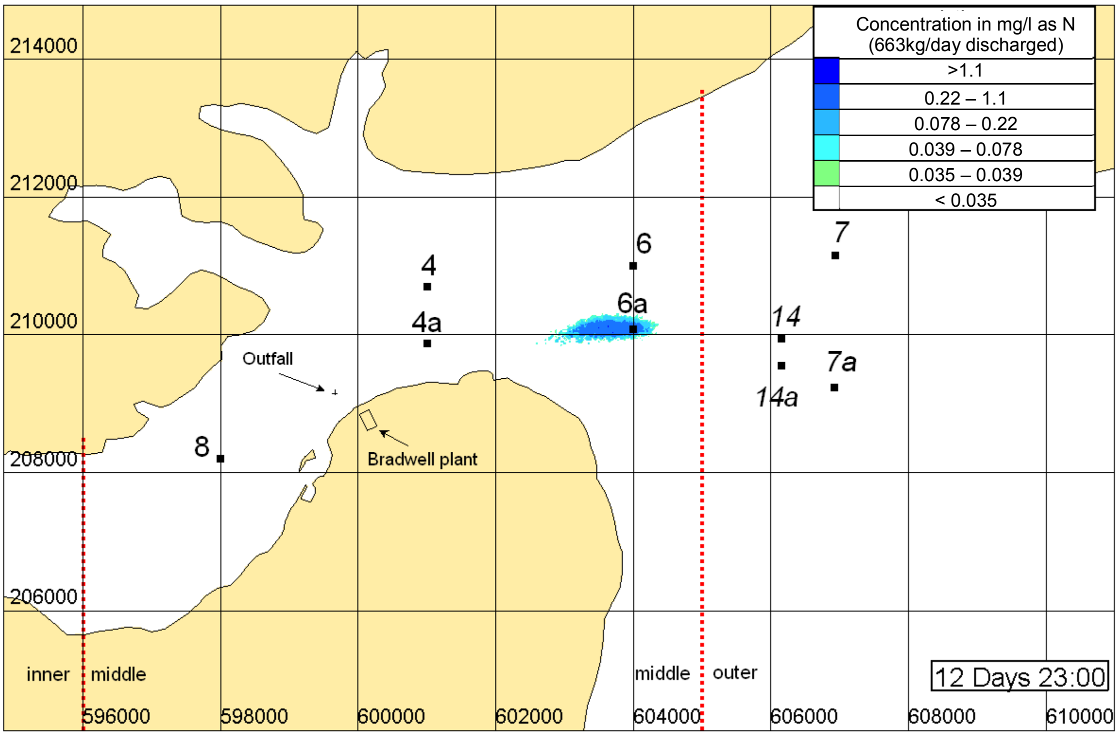


Figure 18 Concentrations of recently discharged effluent – single release, neap tide, 30m^3 discharge, at 12days 23h

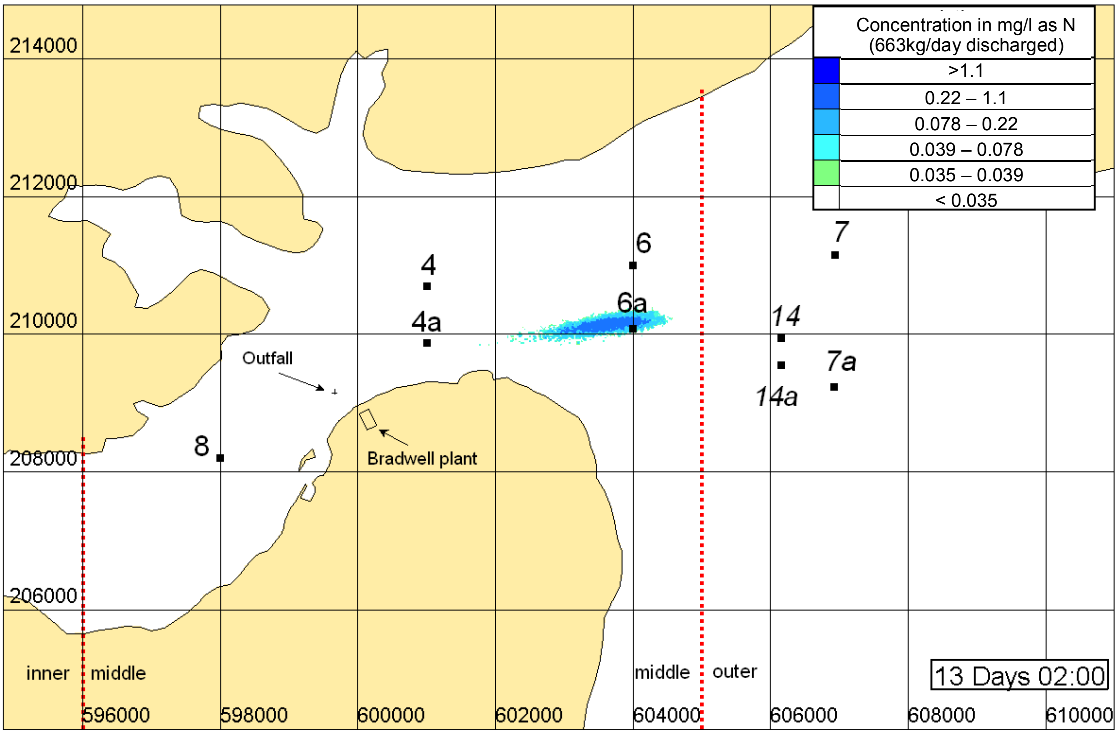


Figure 19 Concentrations of recently discharged effluent – single release, neap tide, 30m^3 discharge, at 13days 2h

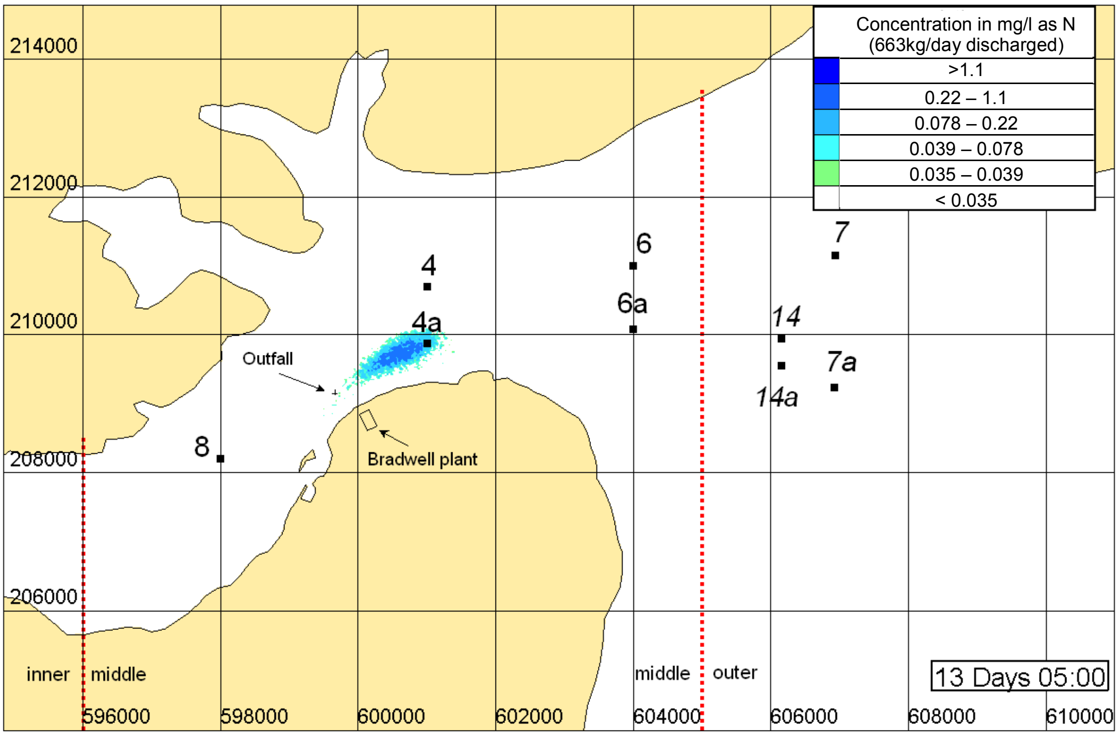


Figure 20 Concentrations of recently discharged effluent – single release, neap tide, 30m^3 discharge, at 13days 5h

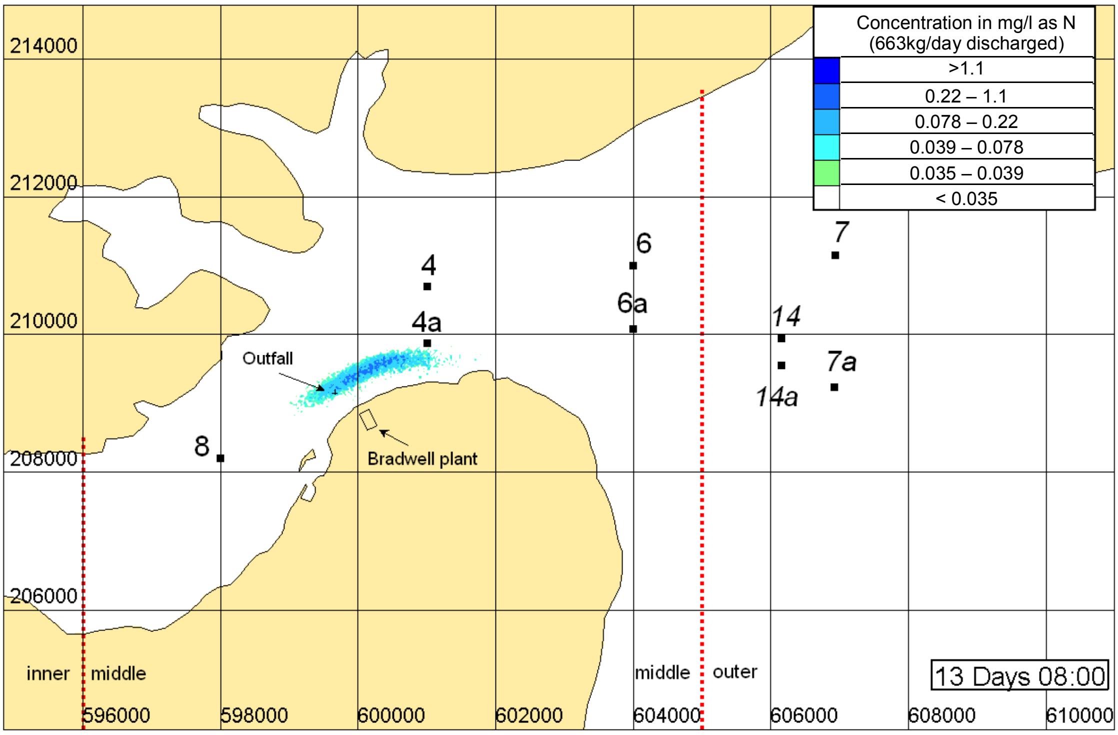


Figure 21 Concentrations of recently discharged effluent – single release, neap tide, 30m^3 discharge, at 13days 8h

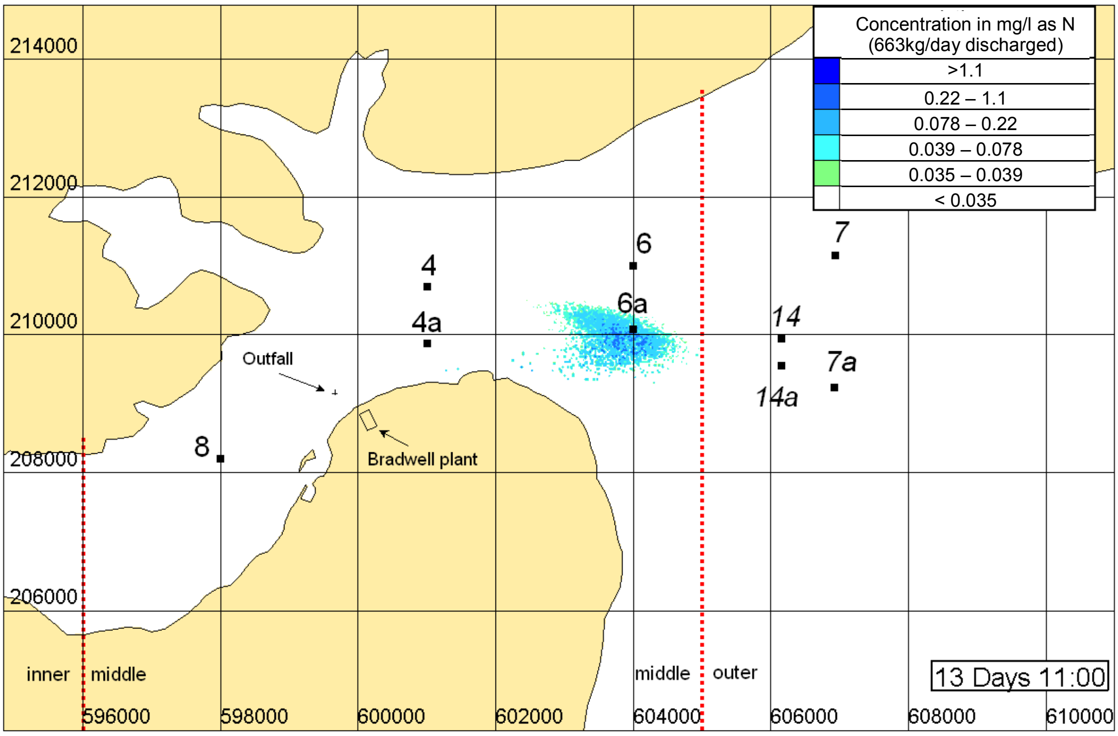


Figure 22 Concentrations of recently discharged effluent – single release, neap tide, 30m^3 discharge, at 13days 11h

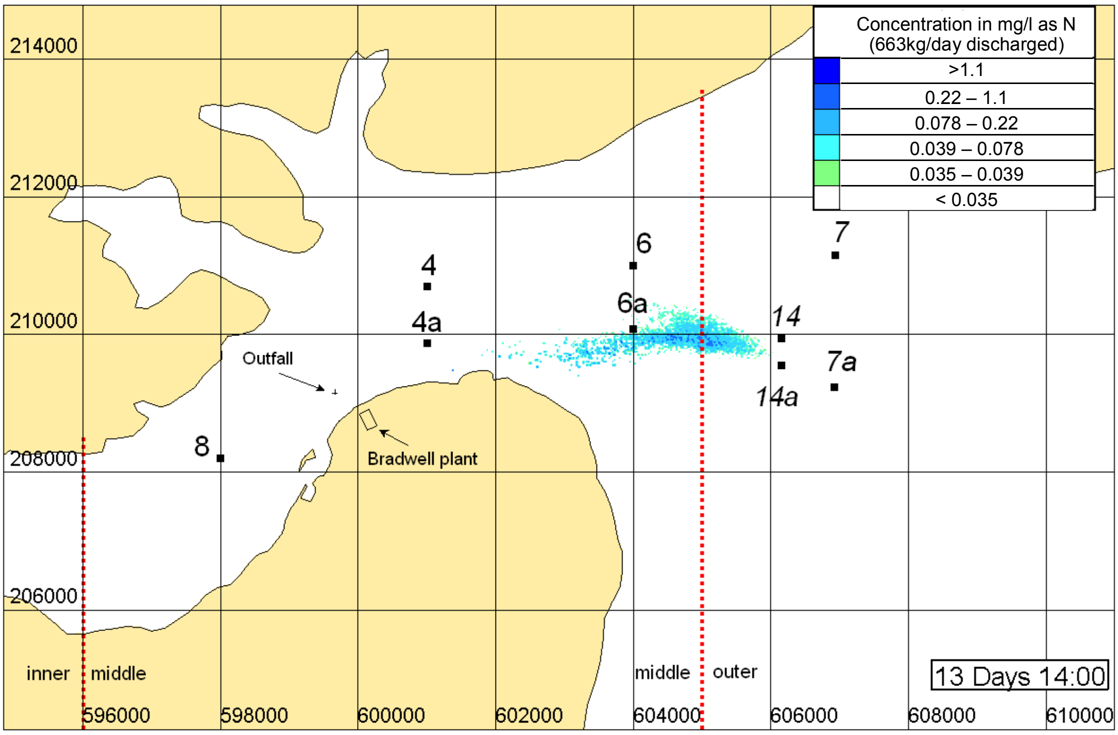


Figure 23 Concentrations of recently discharged effluent – single release, neap tide, 30m^3 discharge, at 13days 14h

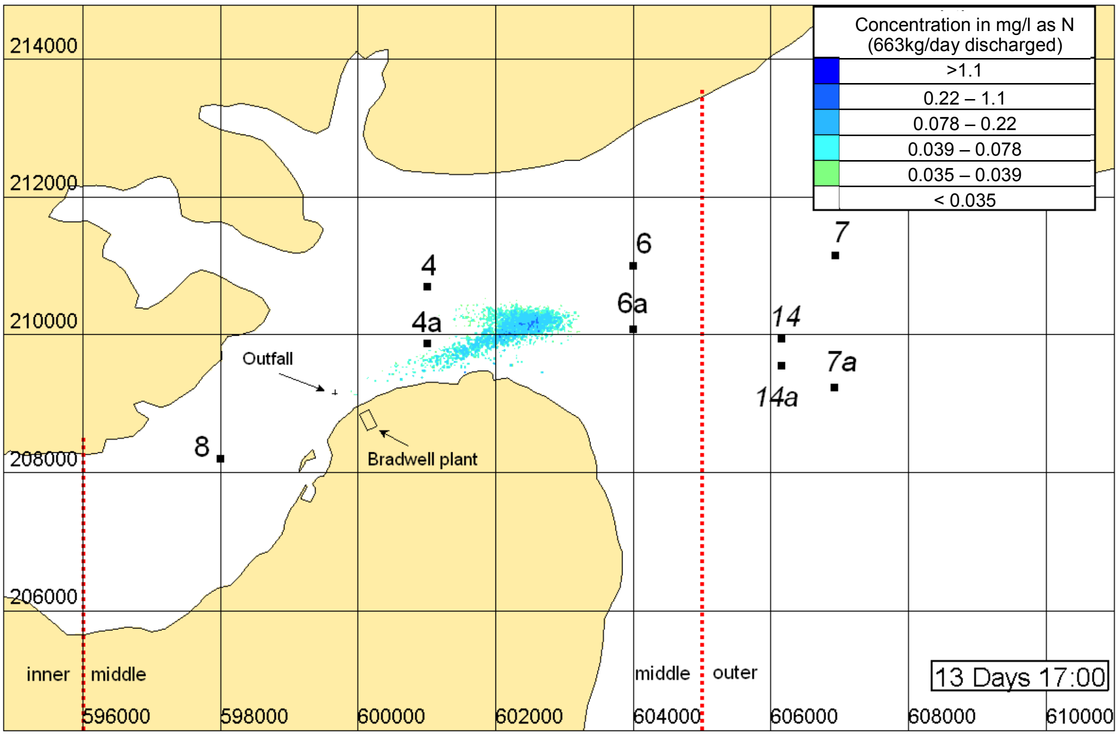


Figure 24 Concentrations of recently discharged effluent – single release, neap tide, 30m^3 discharge, at 13days 17h

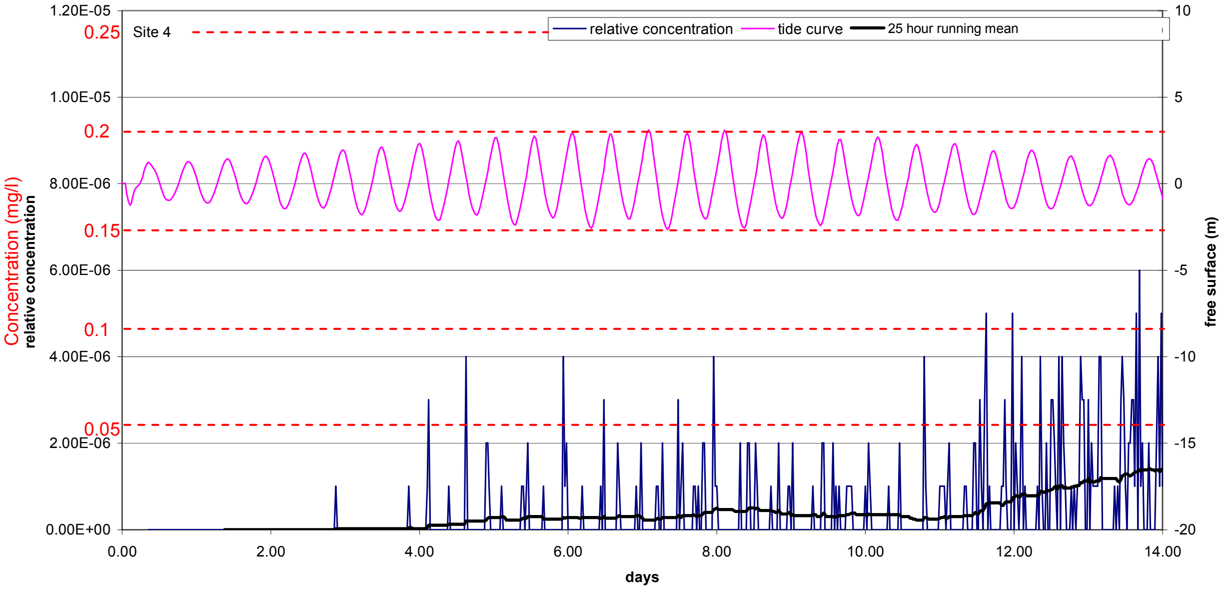


Figure 25a Concentration (N) evolution, daily release, between 1 and 14 days, site 4 (663kg/day)

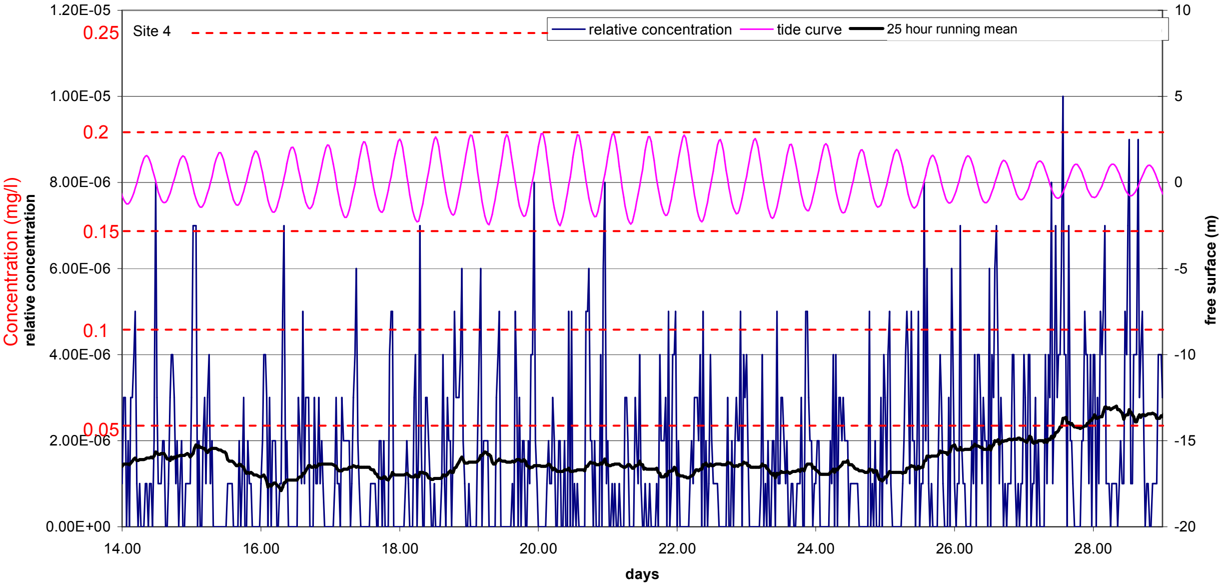


Figure 25b Concentration (N) evolution, daily release, between 14 and 29 days, site 4 (663kg/day)

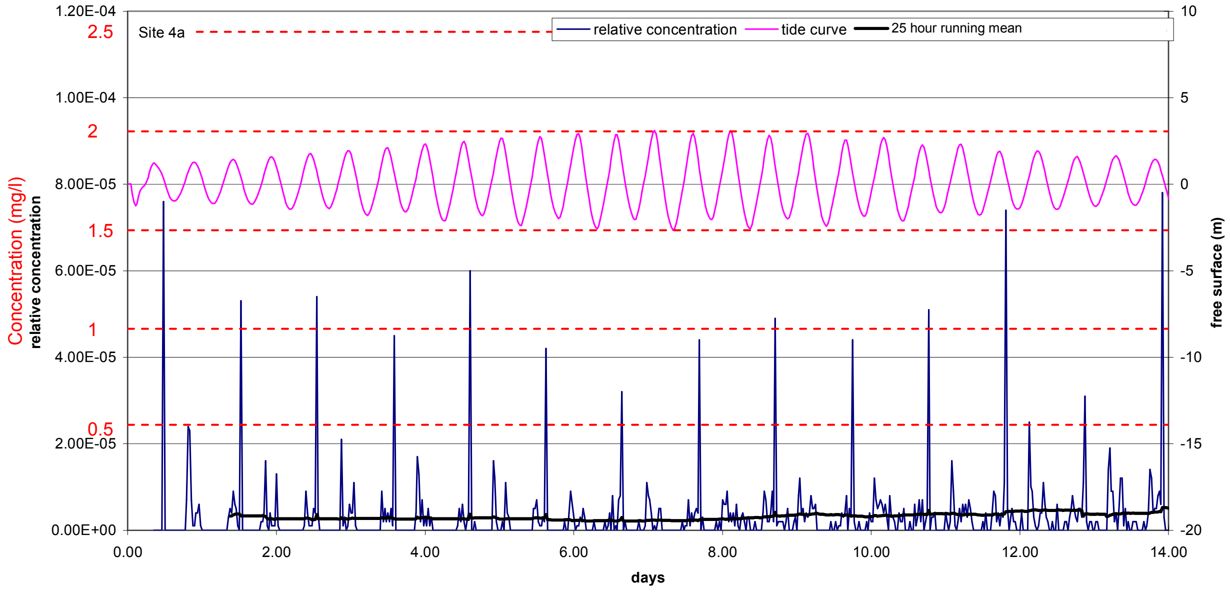


Figure 25c Concentration (N) evolution, daily release, between 1 and 14 days, site 4a (663kg/day)

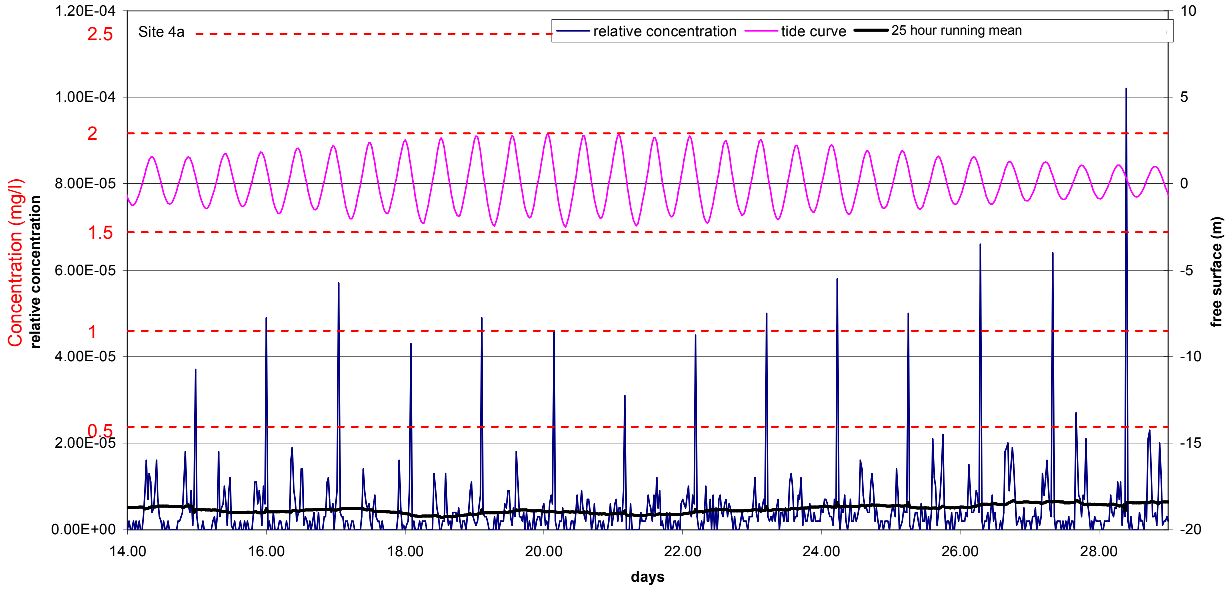


Figure 25d Concentration (N) evolution, daily release, between 14 and 29 days, site 4a (663kg/day)

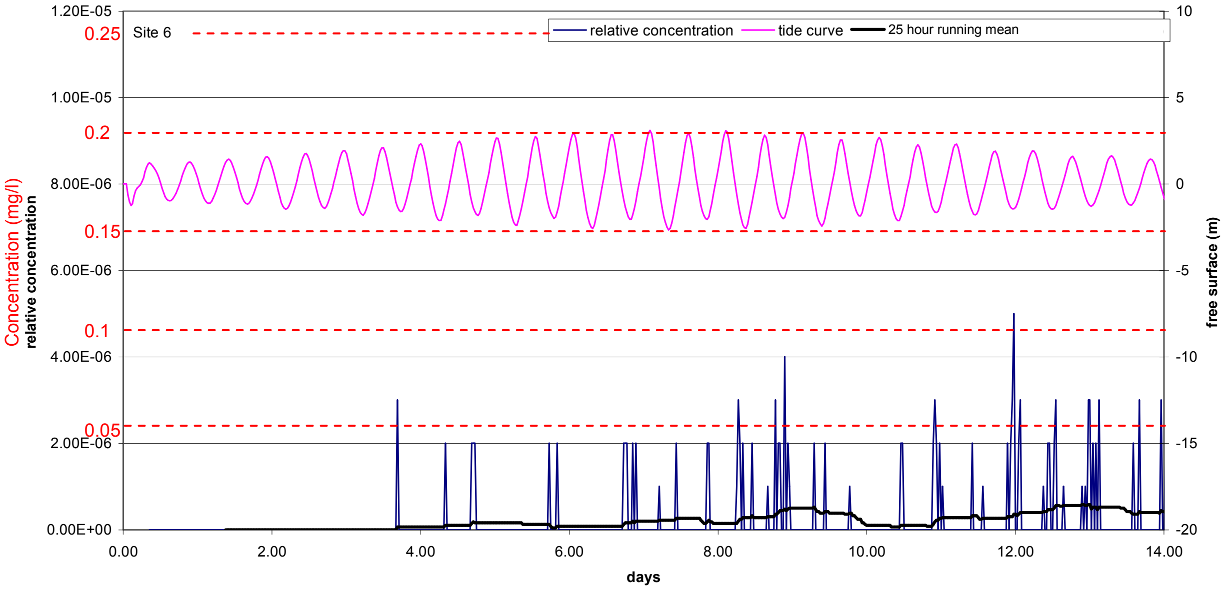


Figure 26a Concentration (N) evolution, daily release, between 1 and 14 days, site 6 (663kg/day)

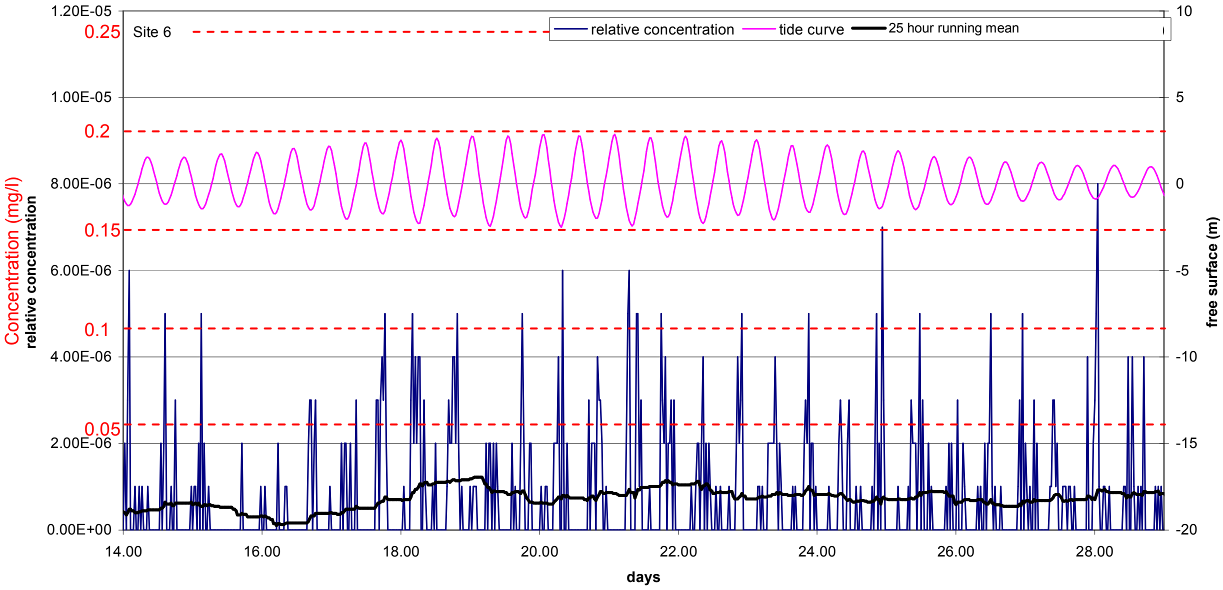


Figure 26b Concentration (N) evolution, daily release, between 14 and 29 days, site 6 (663kg/day)

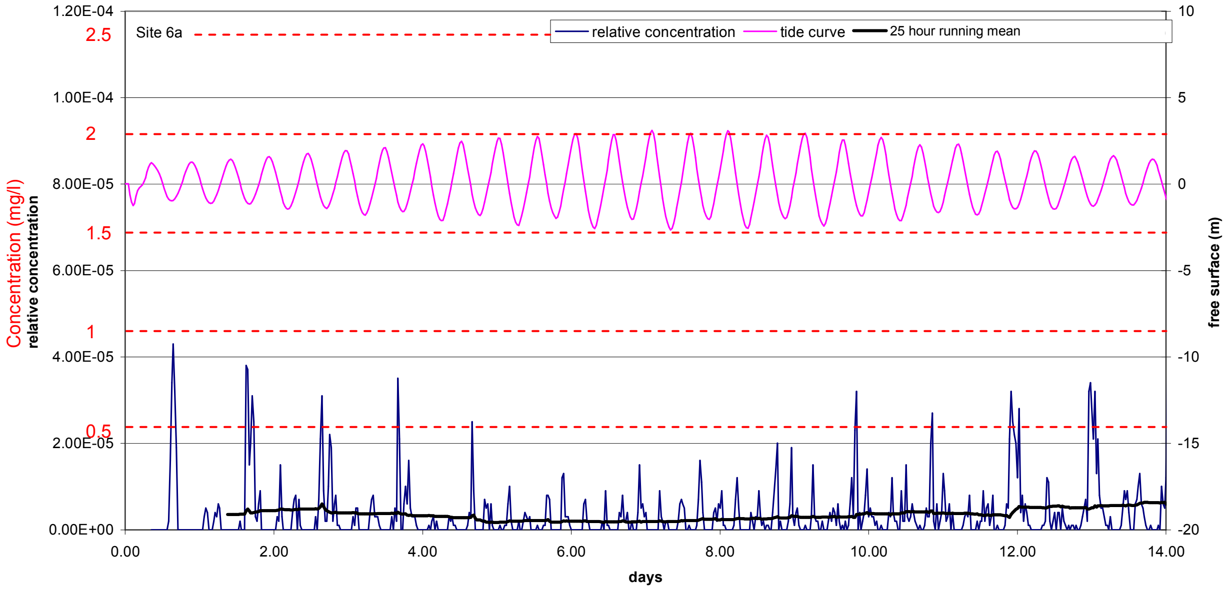


Figure 26c Concentration (N) evolution, daily release, between 1 and 14 days, site 6a (663kg/day)

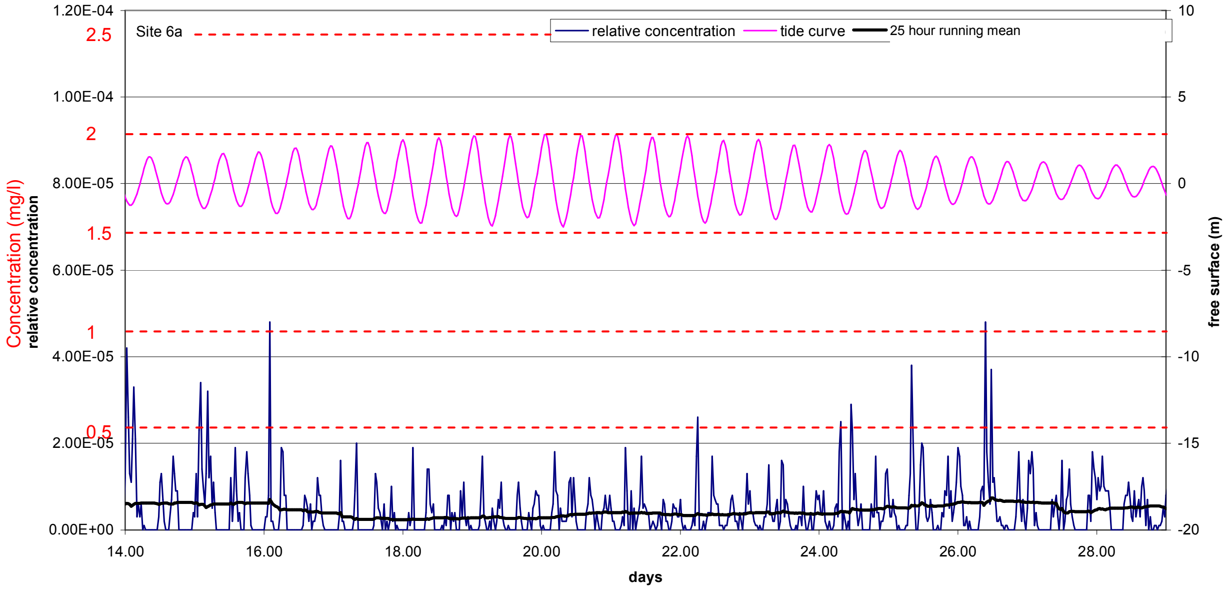


Figure 26d Concentration (N) evolution, daily release, between 14 and 29 days, site 6a (663kg/day)

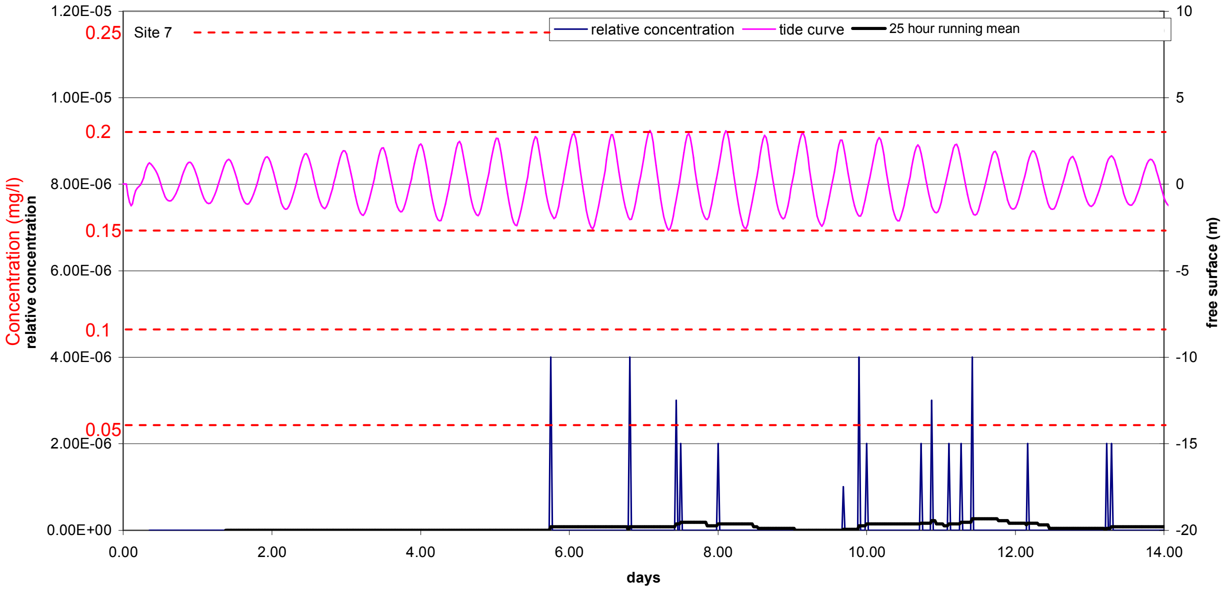


Figure 27a Concentration (N) evolution, daily release, between 1 and 14 days, site 7 (663kg/day)

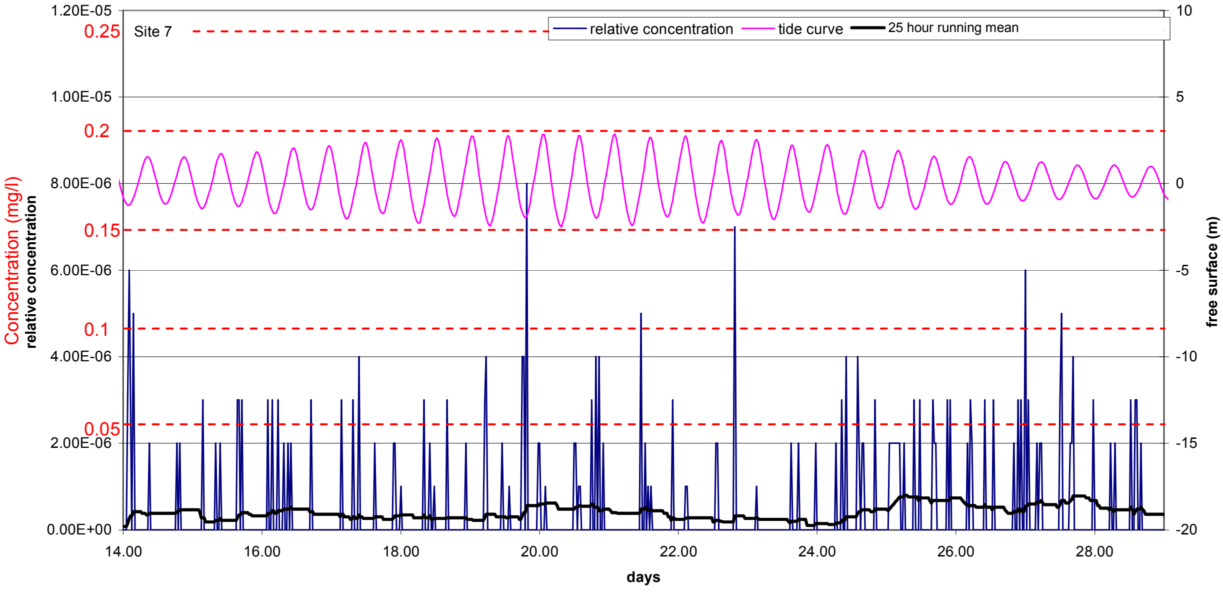


Figure 27b Concentration (N) evolution, daily release, between 14 and 29 days, site 7 (663kg/day)

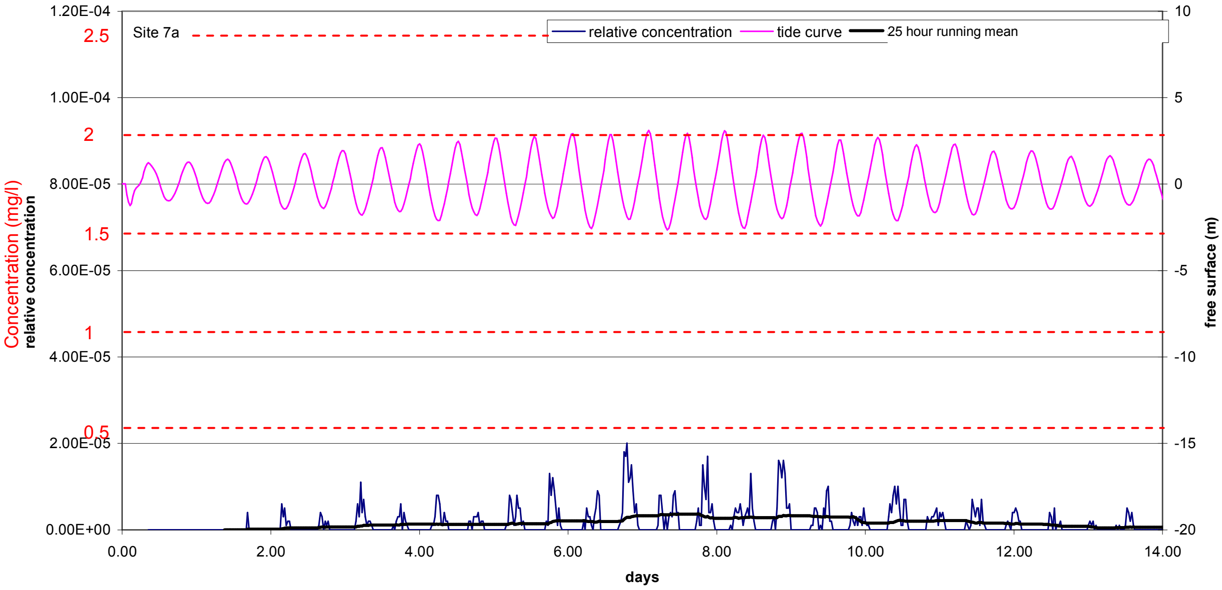


Figure 27c Concentration (N) evolution, daily release, between 1 and 14 days, site 7a (663kg/day)

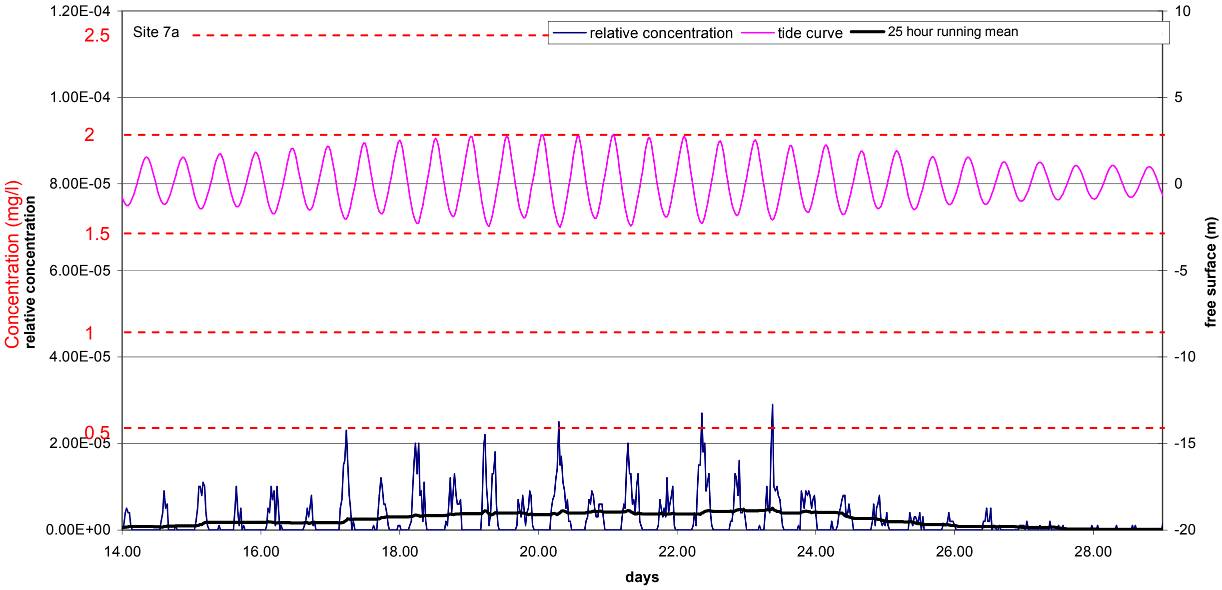


Figure 27d Concentration (N) evolution, daily release, between 14 and 29 days, site 7a (663kg/day)

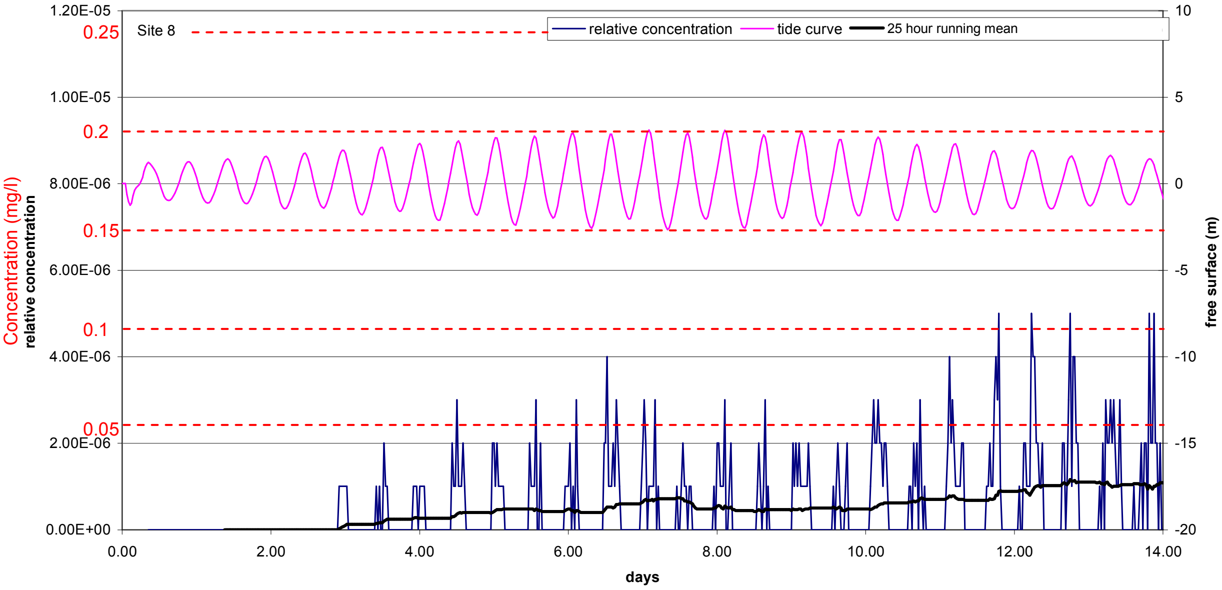


Figure 28a Concentration (N) evolution, daily release, between 1 and 14 days, site 8 (663kg/day)

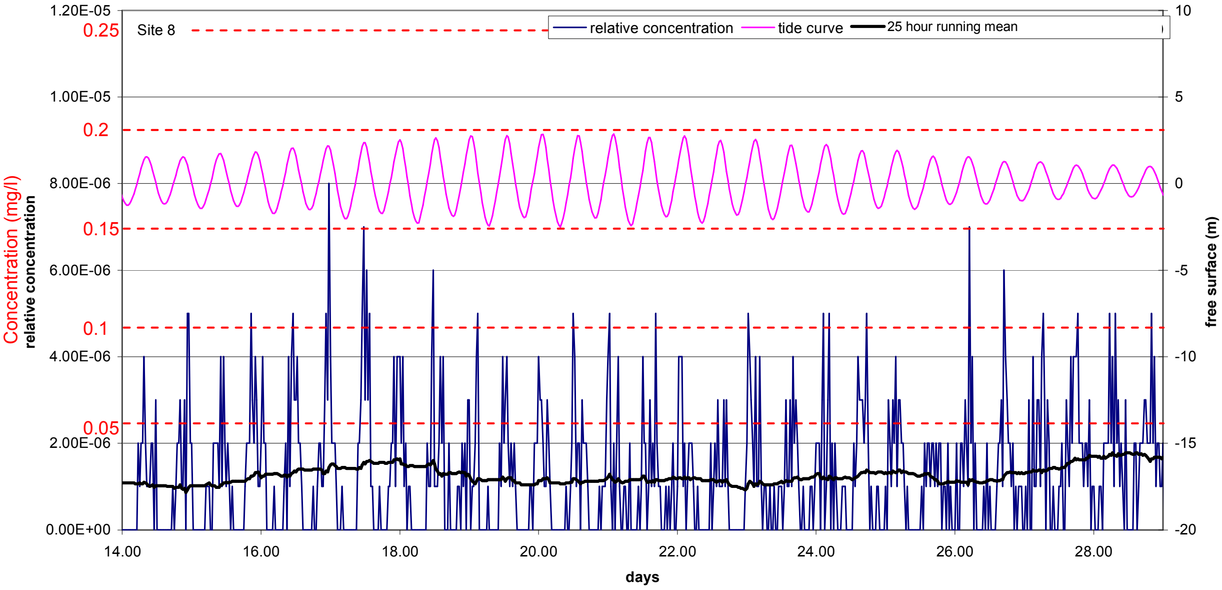


Figure 28b Concentration (N) evolution, daily release, between 14 and 29 days, site 8 (663kg/day)

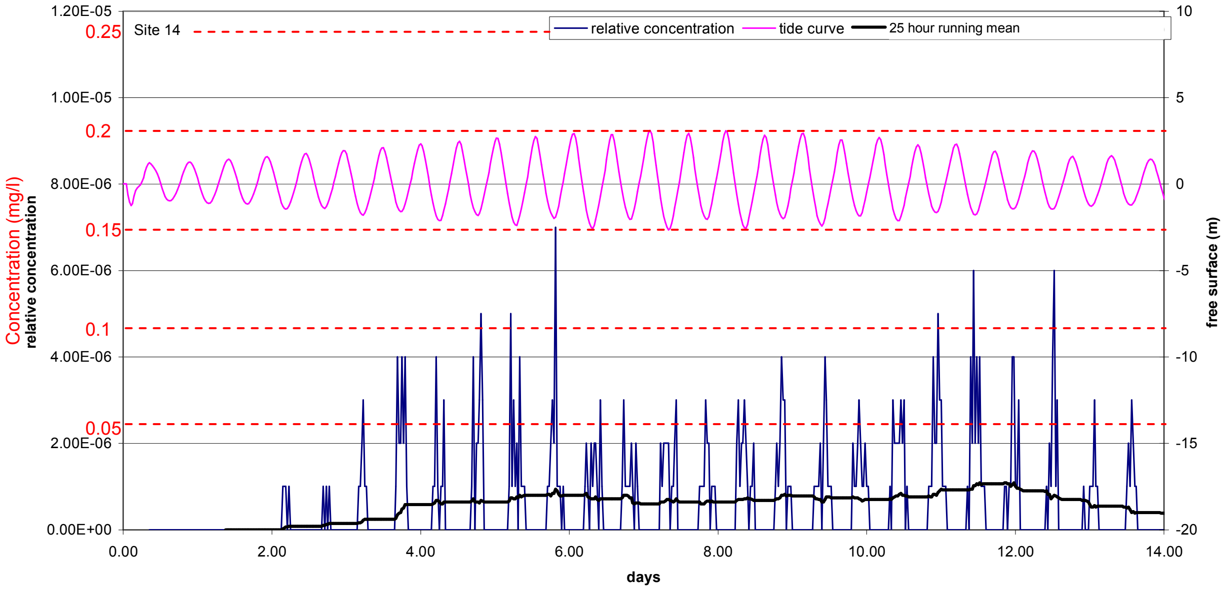


Figure 29a Concentration (N) evolution, daily release, between 1 and 14 days, site 14 (663kg/day)

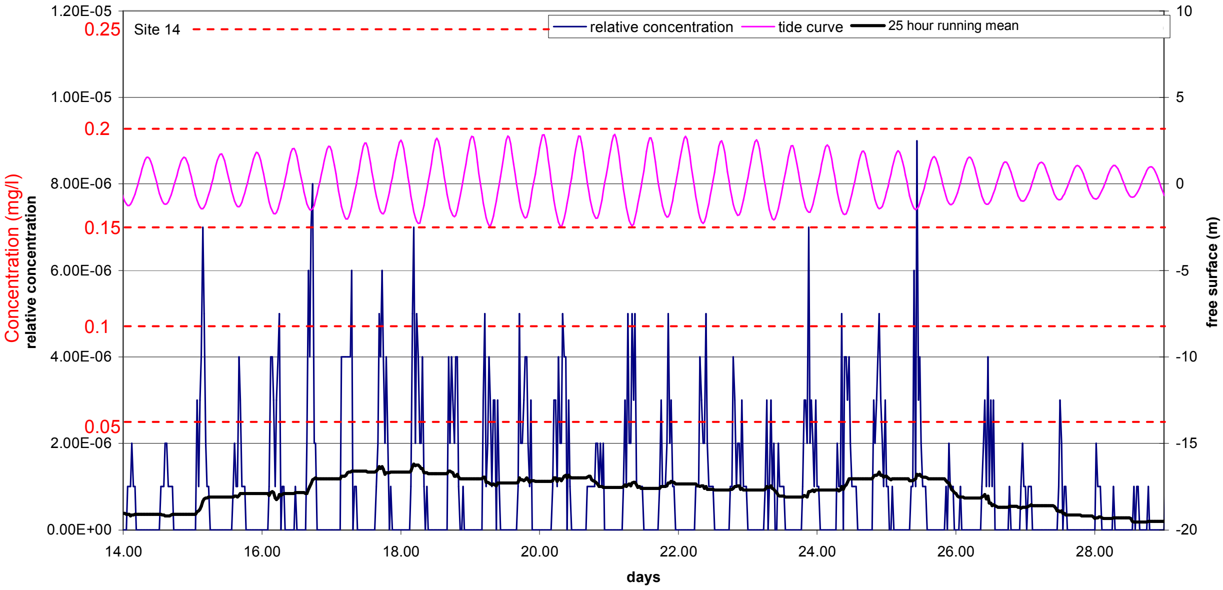


Figure 29b Concentration (N) evolution, daily release, between 14 and 29 days, site 14 (663kg/day)

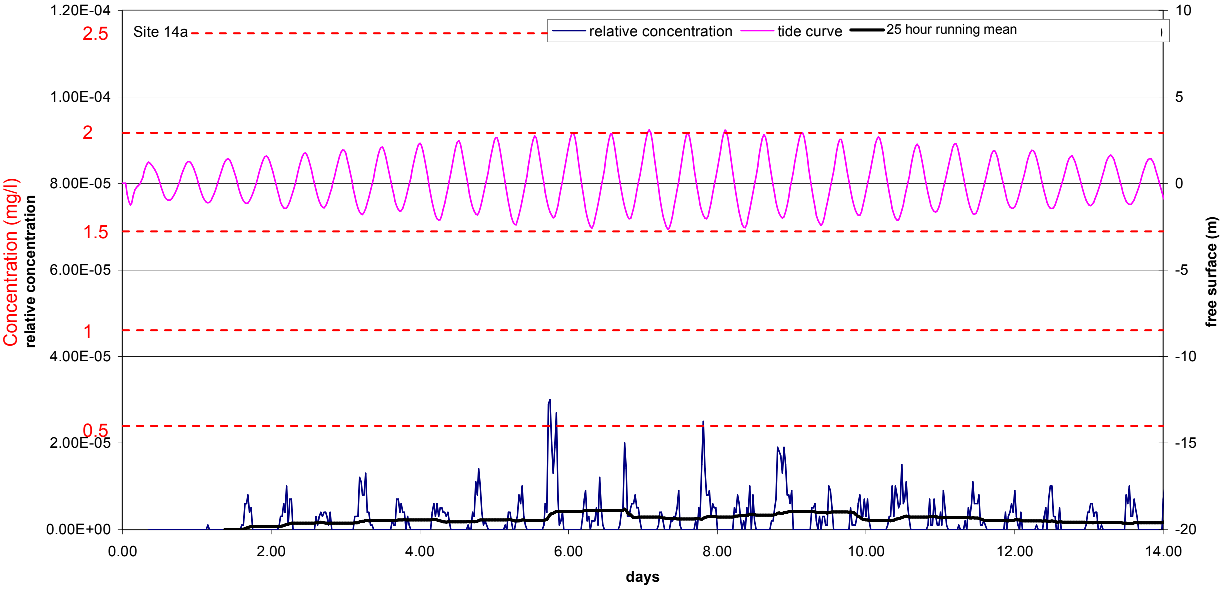


Figure 29c Concentration (N) evolution, daily release, between 1 and 14 days, site 14a (663kg/day)

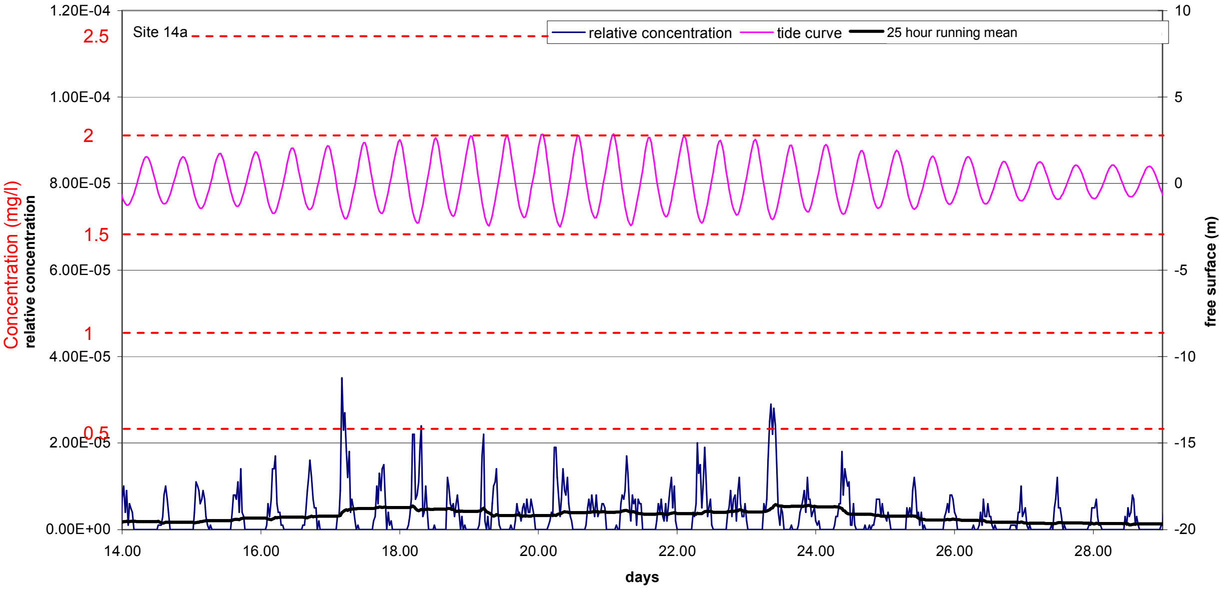


Figure 29d Concentration (N) evolution, daily release, between 14 and 29 days, site 14a (663kg/day)

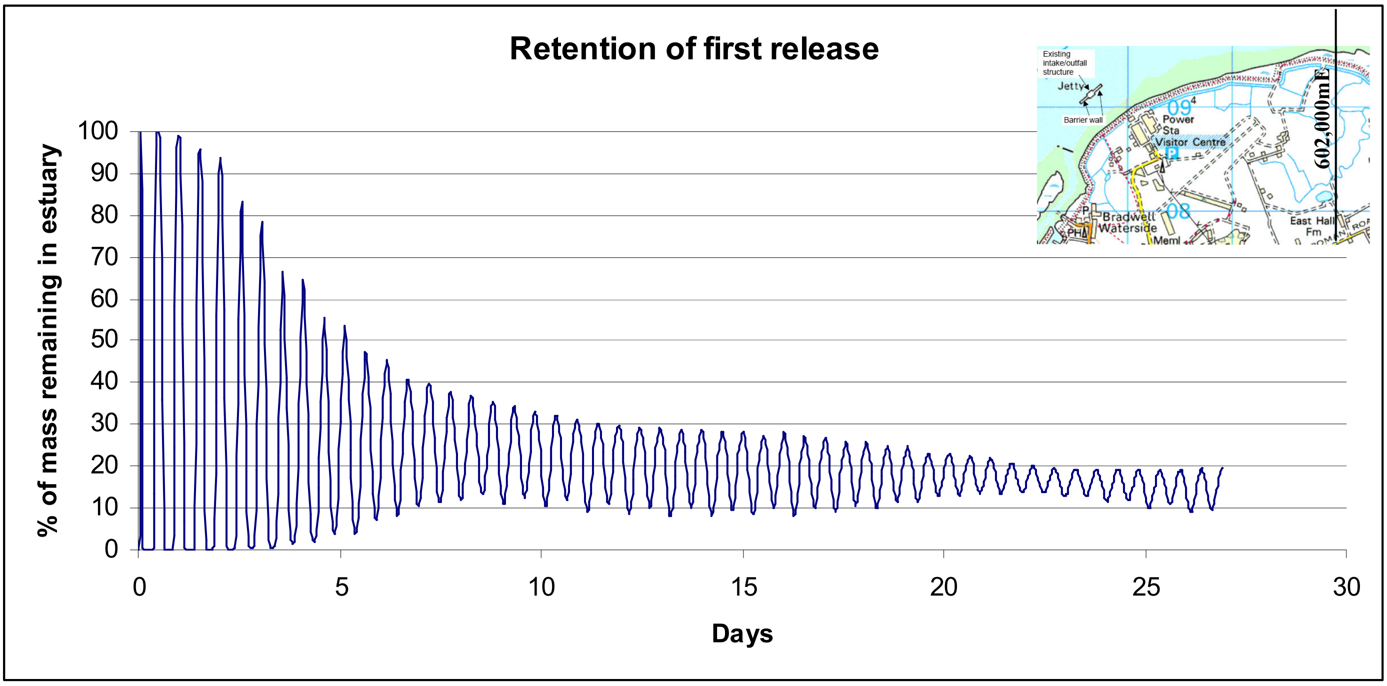


Figure 30a Retention of one discharge within the estuary – single release on a spring tide

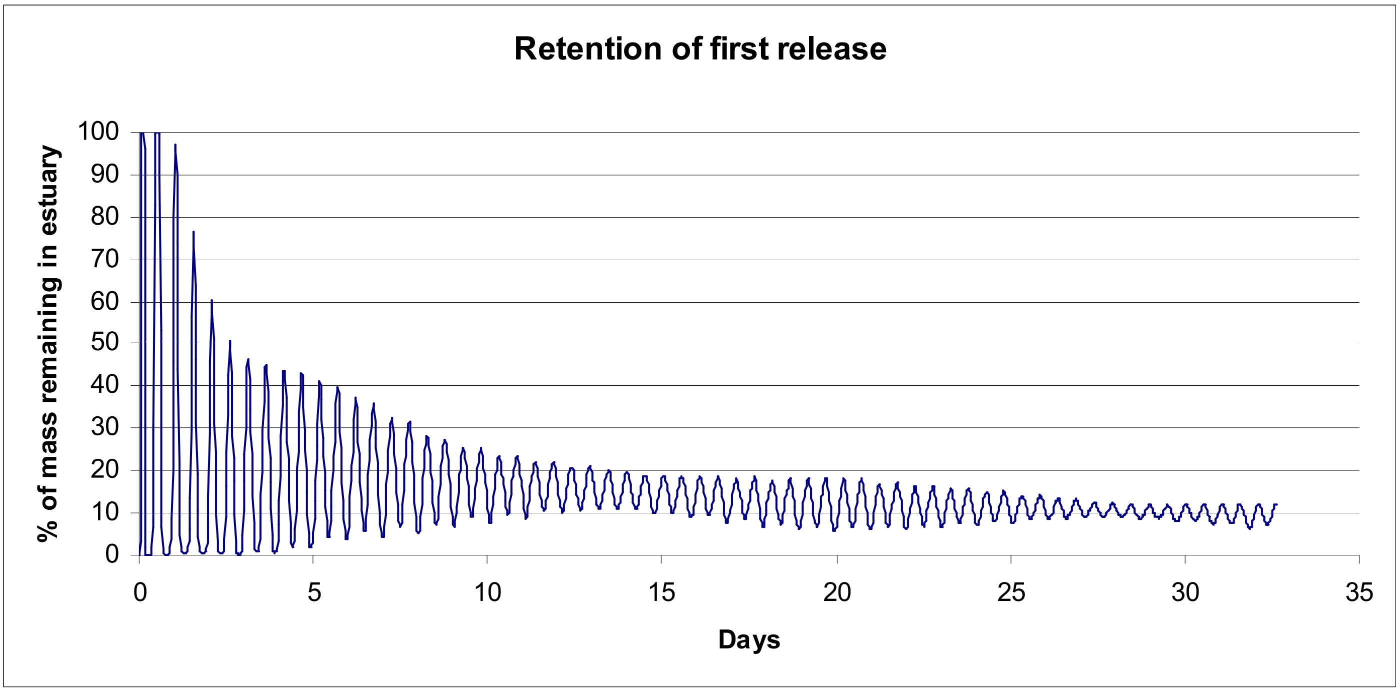


Figure 30b Retention of one discharge within the estuary – single release on a neap tide

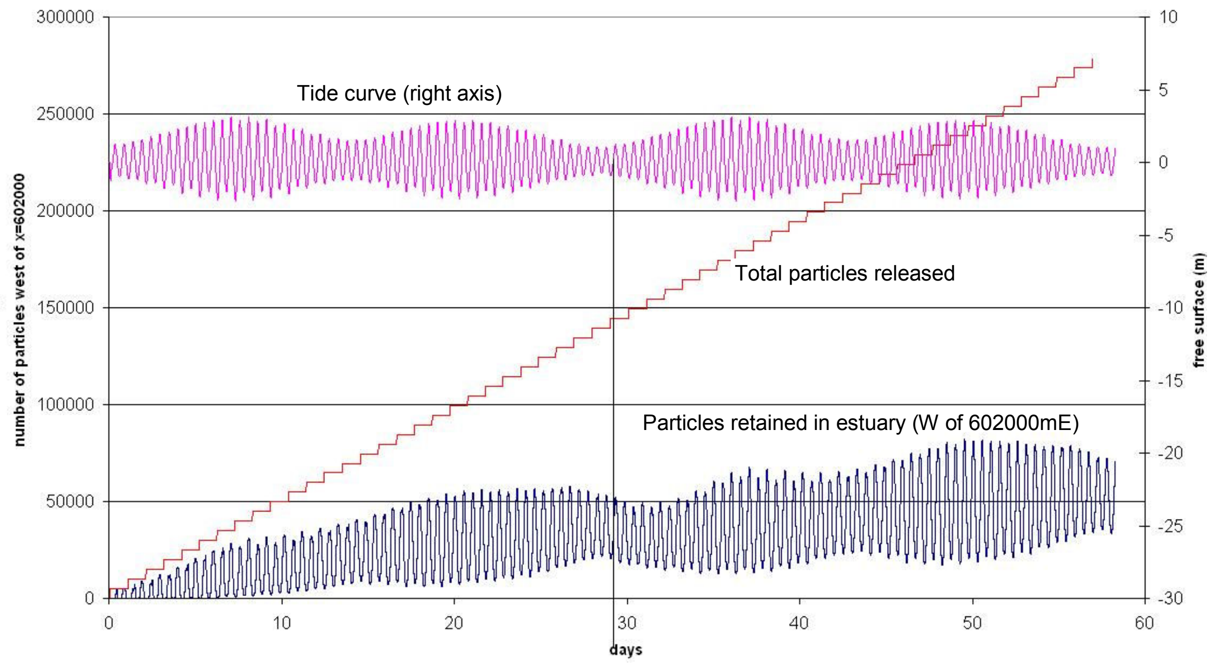


Figure 31 Retention of discharge within the estuary - daily release over two months

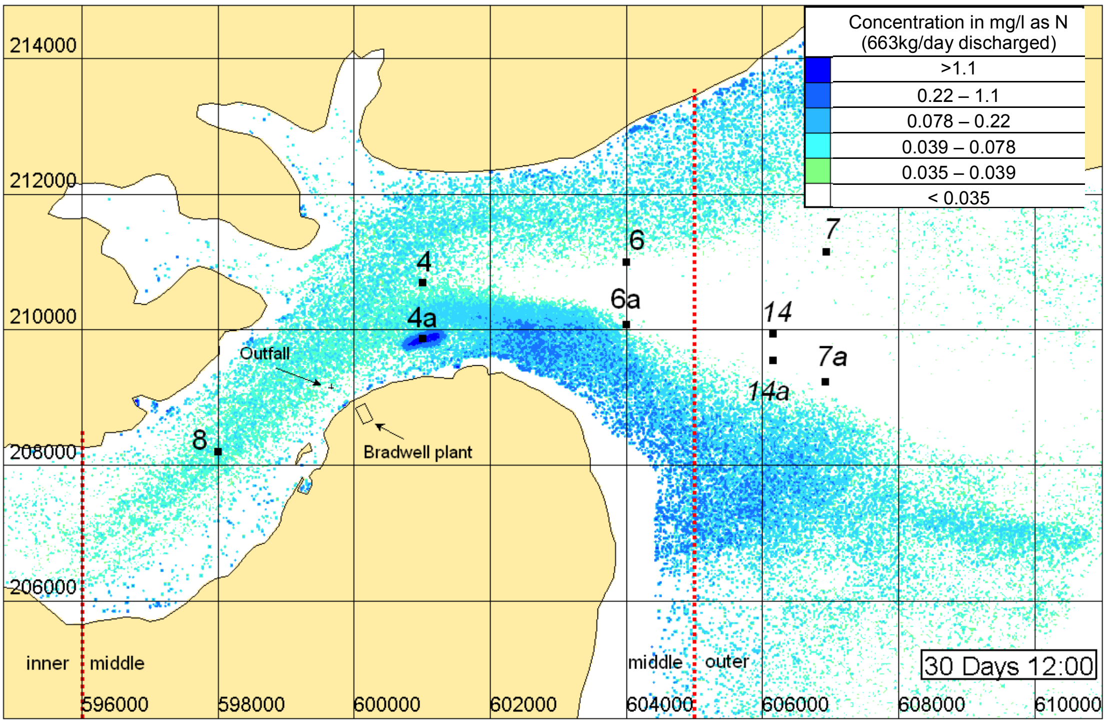


Figure 32 Instantaneous concentration after 1 month of daily discharge

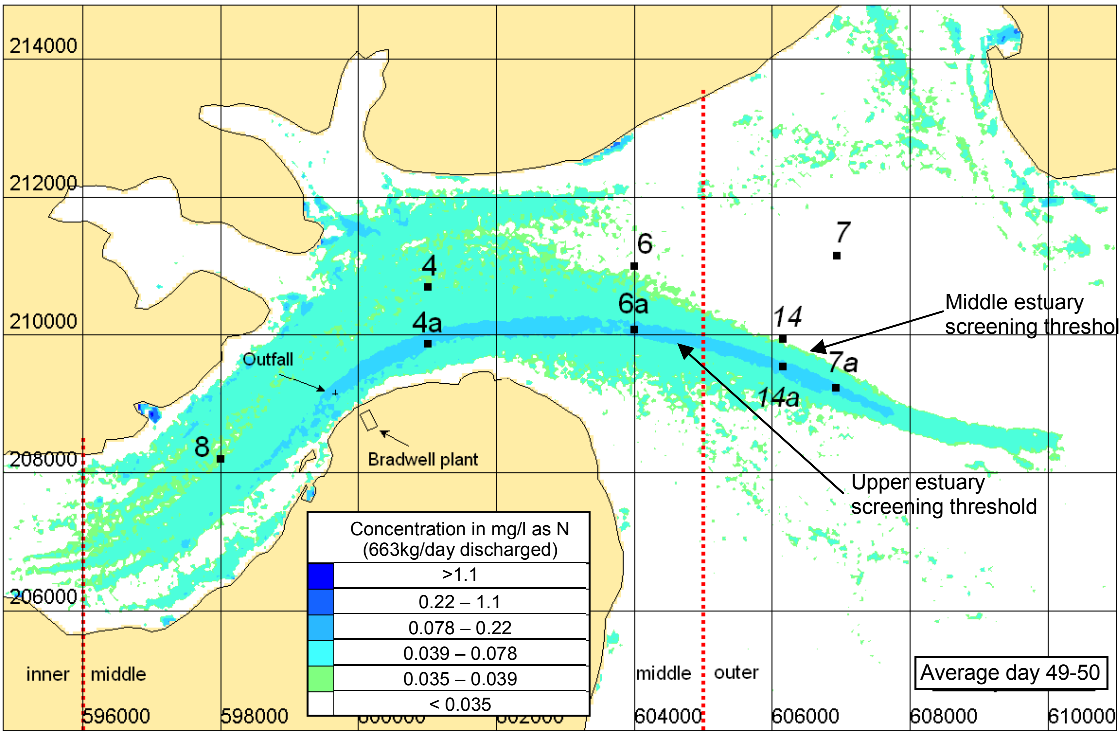


Figure 33 Daily average concentration on a spring tide after 50 days of daily discharge

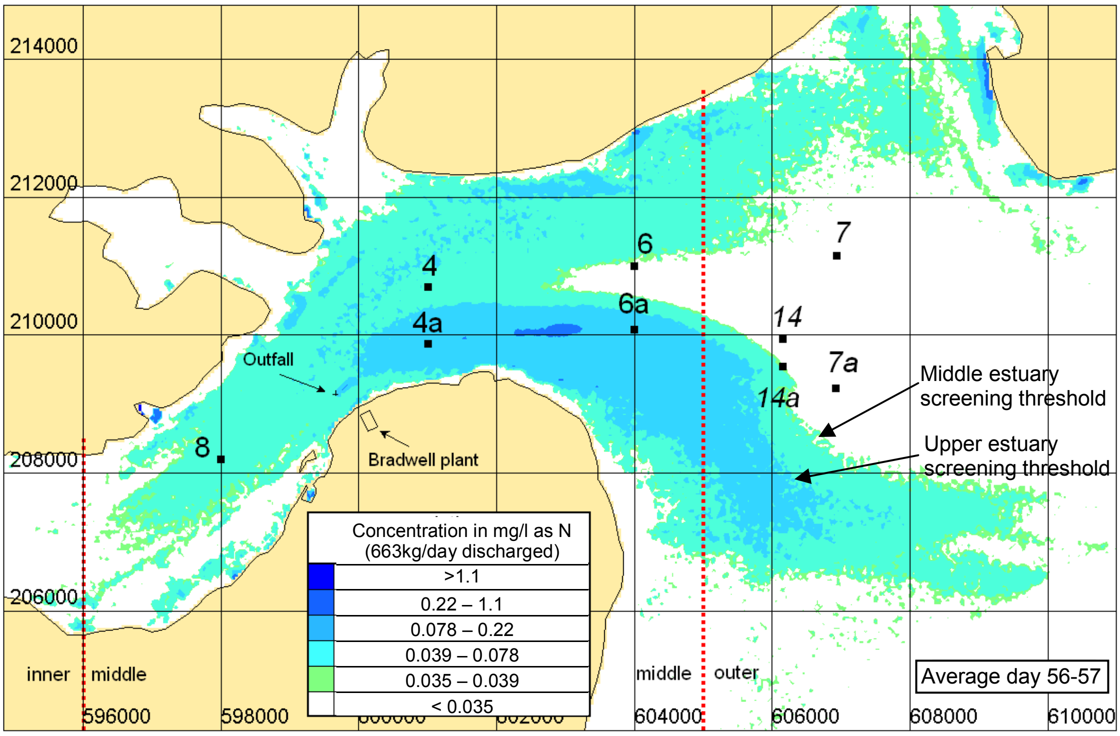


Figure 34 Daily average concentration on a neap tide after 57 days of daily discharge

Appendices

Appendix 0 Construction Design and Management Regulations (CDM 2007)

OPTION 1 – UK/EU project location: No design element by HRW and nothing unusual about the site

The Construction (Design and Management) Regulations 2007 (CDM 2007) require consideration to be given in the design of a project to health and safety during construction, maintenance, cleaning and demolition of any works. It is essential that a competent designer and principal contractor are selected to undertake this work. It is also important to highlight and record the impacts of the works on health, safety and welfare which should feed into both the Health and Safety Plan and Health and Safety File.

We note that this project consists of desk assessments and or modelling work which may be used by others in the design process. No design work has been undertaken by HR Wallingford and, in our professional opinion, there are no particular issues that should be drawn to the attention of a competent designer and principal contractor. It is assumed that the designer will review the information produced in this study when assessing the risks to those involved in the works.

Appendix 1 TELEMAC-2D Model Description

Description of model and main areas of application
TELEMAC-2D is a sophisticated flow model, which was originated by LNH in Paris, for free surface flows. It solves the 2D depth-integrated shallow water equations that are used to model flows in rivers, estuaries and seas. It uses finite element techniques so that very flexible, unstructured triangular grids can be used. It has been developed under a quality assurance system including the application of a standard set of validation tests.

The model can simulate depth integrated tidal flows in estuaries and seas including the presence of drying banks. It can also simulate flows in rivers including turbulence structures resulting from flow obstructions and transcritical flows.

The advantage of using finite elements lies primarily in the possibility of using a very flexible grid. This is superior to using an orthogonal curvilinear grid as the user has far more complete control over grid refinement with a finite element system.

The applications of TELEMAC have included studies of tidal flows, storm surges, floods in rivers, dam break simulations, cooling water dispersion and infill of navigation channels.

Theoretical background and solution methods
TELEMAC solves the shallow water equations on an unstructured finite element grid (usually with triangular elements). The various variables (bed elevation, water depth, free surface level, and the **u** and **v** velocity components) are defined at the nodes (vertices of triangles) and linear variation of the water and bed elevation and of the velocity within the triangles is assumed.

When the model is used a time-step is chosen and the computation is advanced for the required number of time-steps. There is no particular limit on the time-step for a stable computation but it is best to ensure that the Courant number based on propagation speed is less than about 10. It is found that if the solution is nearly steady then few computational iterations are required at each step to achieve the required level of accuracy, which in TELEMAC is computed according to the actual divergence from the accurate solution. The computation at each time-step is split into two stages, an advective step and a propagation-diffusion step.

The advective step
The advective step is computed using characteristics or stream-wise upwind Petrov-Galerkin. The characteristic step makes it possible for the code to handle such problems as flow over a bump giving rise to locally supercritical flow and eddies shedding behind flow obstructions.

The propagation/diffusion step
The finite element method used is based on a Galerkin variational formulation. The resulting equations for the nodal values at each time-step are solved using an iterative method based on pre-conditioned conjugate gradient (PCG) methods so that large problems are solved efficiently. Several PCG solvers are coded and a selection is available to the user. The complete matrix is not assembled. Instead an element by element method is used so that most of the operations are carried out on the element matrices; this is computationally more efficient, both in speed of execution and in memory requirements. Rather than using Gauss quadrature exact analytical formulae are used for the computation of matrices. Symbolic software was used to draw up the formulae used. The software makes it possible to carry out a second iteration of the solution at each time-step in order to represent the non-linear terms in a time centred way, otherwise these terms are treated explicitly.

Boundary conditions

Boundary conditions are applied at solid boundaries where a "zero normal flow" and either a slip or non-slip boundary condition are applied. At open boundaries a selection of possibilities can be invoked depending on whether the flow is subcritical or supercritical or whether a wave absorbing boundary using a Riemann invariant is needed. A water discharge along a boundary segment can also be applied and the software distributes the flow along the segment chosen. This facility is valuable when running models of river reaches and the discharge in a cross section may be known rather than the velocity at each point in the cross-section.

Grid selection

The model can be run with a Cartesian grid for modelling rivers, estuaries and small areas of sea, with the possibility to apply a uniform Coriolis parameter, or on a spherical grid for larger areas of sea in which case the Coriolis parameter is computed from the latitude at each node. The effect of a wind blowing on the water surface and causing a set-up or wind induced current or of an atmospheric pressure variation causing an inverted barometer effect can be included, as can a k-epsilon model of turbulence if required.

Friction

The bed friction can be specified via a Chezy, Strickler or linear coefficient, or a Nikuradse roughness length. A variable friction coefficient over the model area is a possibility. Sidewall friction can also be included if wanted. Viscosity can be imposed as a given eddy viscosity value or a k-epsilon model can be used if needed.

Tracer calculation

TELEMAC-2D includes also the capability to simulate the transport of a tracer substance. The tracer is again computed using an advective step followed by a propagation/diffusion step. Tracer boundary conditions can be applied at model inflow boundaries. The tracer calculation has been used in order to simulate cooling water dispersion and mud transport. Sources of water and/or of tracer can be specified in terms of the discharge required and the x and y co-ordinates of the location.

INPUTS

TELEMAC requires as input a finite element grid of triangles covering the area to be modelled. Bathymetric data from which the bed elevation at each node can be computed is also required covering the area. A file of keyword values is used to steer the computation (supplies bed roughness, time-step, duration of run etc).

OUTPUTS

Output parameters

The user can select from a range of output parameters including u and v velocity, u and v discharge, water level, bed level, water depth, tracer concentration and Froude number.

GENERAL

Interaction and compatibility of the model with other models

The TELEMAC suite includes a bed load transport model (TSEF) and a suspended load model (SUBIEF). Also a wave model ARTEMIS that solves the mild slope equation.

The TELEMAC modelling suite also includes a quasi-3D random walk model for pollution transport modelling and a detailed water quality model with many water quality parameters including dissolved oxygen balance and particulates.

Quality Assurance
The software has been developed under the quality assurance procedures required by the French Electricity Industry. This has included the production of an extensive dossier of validation tests.

Validation
Validation tests on TELEMAC include:

- Simulation of eddies produced behind bridge piers. This test case includes the ability of the model to produce an unsteady solution from steady boundary conditions (von Karman vortex street).
- Drying on a beach.
- Simulation of the tides on the continental shelf including the Bay of Biscay. This model has been closely compared with the observed tides at coastal sites.
- Flow over a step in the bed with critical flow and a hydraulic jump. This solution is compared with the analytically known solution to this problem.

Appendix 2 Detailed description of PLUME-RW

1. Purpose

PLUME-RW is designed to compute the three-dimensional dispersion of pollutant released from sea outfalls and storm water overflows under the influence of tidal or residual currents and wind-driven flows. The model can use flow fields computed by tidal flow models, such as TELEMAC, as input data. Simulated pollutant can be conservative or can decay at user-specified rates, and the model can represent multiple pollutants in a single model run. Plumes can be simulated in stratified or well-mixed waters.

2. Method

Flow in a coastal region usually consists of large-scale tidal motion, wind-driven currents and small-scale turbulent eddies. In order to model the dispersion of pollutant in such a region the effects of these flows on pollutant plumes must be simulated.

When simulating the relatively small scale plumes discharged from sea outfalls and storm water overflows, PLUME-RW interpolates flows computed by numerical flow models onto fine square grids, on which pollutant concentrations are computed. In order to correctly model plumes in this way, the effects of turbulence on pollutant dispersion must be represented. PLUME-RW is based on the random walk principle, which represents turbulent diffusion as random displacements from the purely advective motion described by the turbulent mean velocities computed by flow models, such as TELEMAC.

2.1 Representation of pollutant discharge

In PLUME-RW the discharge of pollutant into coastal waters is represented as a regular discharge of discrete particles. Particles are released throughout a model run to simulate constant or continually varying pollutant discharges or for part of the run to simulate pollutant discharge over intervals during the tidal or diurnal cycle. At specified outfall sites a number of particles are released in each model time-step and, in order to simulate pollutant discharges, the total pollutant released at each site during a given time interval is divided equally between the released particles. Particles can be released either at the precise coordinates of the outfalls, or at random points within circles centred on the outfall coordinates. This latter approach represents the lateral spreading of a buoyant plume rising from an outfall on the sea bed, but PLUME-RW results are generally insensitive to the initial spreading radius.

During a model run the amount of pollutant represented by each particle (the particle "mass") can be either constant for conservative pollutant, or can decrease at a specified decay rate, e.g.

$$m(t) = m_o \exp(-kt) \qquad (1)$$

where:

$m(t)$ is particle "mass" at time t ("mass" units)
m_o is the initial particle "mass" at the outfall site ("mass" units)
k is a decay constant (s^{-1}).

In simulations of decaying effluent, m will represent a number of bacteria and k bacterial mortality. k can be related to specified T_{90} values (hours) through the equation

$$k = 6.4 \times 10^{-4}/T_{90} \qquad (2)$$

The T_{90} values specified in PLUME-RW can vary diurnally between maxima and minima specified by the model user, in order to represent the effects of incident sunlight variation on bacterial mortality.

2.2 Large-scale advection

a) Tidal or residual currents
TELEMAC simulates depth-averaged flows in coastal waters. In order for particles in a PLUME-RW run to simulate the movement of plumes in three dimensions, it is necessary to include a representation of the depth structure of tidal currents in the model.

$$U(z) = \frac{(U_*)_T}{k_o} \log_e \left(\frac{30.1\,z}{k_s}\right) \qquad (3)$$

The depth structure of currents in coastal waters is given by the well-known logarithmic velocity profile:

where

U = current velocity (ms^{-1})
$(U_*)_T$ = friction velocity for a current (ms^{-1})
k_o = von Karman's constant
z = distance above the sea bed (m)
k_s = roughness length (m).

k_o is equal to 0.41 and the roughness length, k_s, is related to the size of protuberances on the sea bed, either directly in the form of particle sizes (especially in the case of shingle and stones etc) or indirectly in the form of ripple lengths (in the case of fine particles, ripple lengths are about 1000 times median grain size). Typical values of k_s vary from around 0.2m for fairly stony, rough coastal regions, to 0.003m or smaller for muddy, smooth areas. Equation (3) can be integrated over the water depth to give the following equation for $(U_*)_T$.

$$(U_*)_T = \frac{\overline{U}\,k_o}{\log_e(30.1\,d/\,k_s\,e)} \qquad (4)$$

where

$\overline{U}$ = depth-averaged velocity (ms^{-1})
d = water depth (m)
e = 2.72.

In PLUME-RW, depth-averaged velocities are interpolated to the positions of individual particles, before being used in equation (4) to derive friction velocities. These are then used in equation (3) to compute velocities at the depth of each particle. Vertical particle motions are computed in PLUME-RW by assuming that, as particles move through areas of varying water depth, each particle moves vertically so that its depth below the sea surface remains a constant fraction of the total water depth. By moving particles through the flow field at the computed horizontal and vertical velocities, in addition to wind-driven and turbulent velocities, the advection of pollutant plumes by large-scale mean currents is simulated.

b) Wind-driven currents
In addition to advection by mean currents, plumes in coastal waters move in response to wind-driven currents. In order to incorporate the effects of wind on pollutant plumes, PLUME-RW computes a surface wind-driven current velocity from a specified wind speed or time-history of wind data. It is assumed that the surface wind-driven current is parallel to the wind vector with a speed given by:

$$S = \alpha w \tag{5}$$

where

S = surface wind-driven current speed (ms^{-1})
α = an empirical constant
w = wind speed at 10m above the sea surface (ms^{-1}).

In Reference 1, a value of approximately 0.03 is given for α, based on the results of many observations of surface drift currents. Having computed S, a wind-driven current speed at any depth in the water column can be computed from:

$$U_w(z) = S(3(1-z/d)^2 - 4(1-z/d) + 1) \tag{6}$$

where

U_w = wind-driven current velocity (ms^{-1})
d = water depth (m).

Equation (6) is derived in Reference 2 and gives rise to a parabolic wind-driven velocity profile, which includes downwind flow in the upper third of the water column and upwind flow at greater depths. The effects of winds on pollutant plumes are simulated in PLUME-RW by the addition of the wind-driven current vector at the depth of each particle to the tidal or residual current vector when computing particle advection by the mean flow.

2.3 Turbulent diffusion

In order to simulate the effects of turbulent eddies on pollutant plumes in coastal waters, particles in PLUME-RW are subjected to random displacements in addition to the ordered movements which represent advection by mean and wind-driven currents. The motion of simulated plumes is, therefore, a random walk, being the resultant of ordered and random movements. Provided the lengths of the turbulent displacements are correctly chosen, the random step procedure is analogous to the use of turbulent diffusivities in depth-averaged pollutant transport models.

a) Lateral diffusion
The horizontal random movement of each particle during a time-step of PLUME-RW consists of a displacement derived from the parameters of the simulation. Whilst the direction of movement in the horizontal plane is random, the length of the displacement is determined from a specified lateral diffusivity. The relationship between the spatial displacement, the time-step and the diffusivity is defined in Reference 3 as:

$$\frac{\Delta^2}{\Delta t} = 2D \tag{7}$$

where

Δ = turbulent lateral displacement (m)
Δt = time-step (s)
D = lateral diffusivity (m^2s^{-1}).

In a PLUME-RW simulation, a lateral diffusivity is specified, which the model reduces to a turbulent displacement using equation (7). No directional bias is required for the turbulent movements, as the effects of shear diffusion are effectively included through the use of depth structure in the mean current profile. Pollutant concentration fields simulated by PLUME-RW are, in fact, relatively insensitive to variations in D over a range of physically-realistic values, as dispersion in the sea is dominated by current shear.

b) Vertical diffusion

Whilst lateral movements associated with turbulent eddies are satisfactorily represented by the specification of a constant diffusivity, vertical turbulent motions can vary significantly horizontally and over the water depth, so that vertical diffusivities must be computed from the characteristics of the mean flow field, rather than specified as constants. In neutral conditions, the vertical diffusivity, K_z, is given by:

$$K_z = 0.16\, z^2 \left(1 - \frac{z}{d}\right) \left|\frac{U_*}{k_o\, z}\right| \qquad (8)$$

where U_* is the total friction velocity associated with wind-driven and tidal or residual currents, whilst in stratified conditions, vertical mixing can be represented by equations given in Reference 4, which include the effects of vertical temperature and salinity variations on vertical mixing. Where pollutant plumes near sea outfalls form buoyant surface layers, K_z values calculated using equation (8) can be damped to reduce mixing downward from the sea surface. In such situations, the degree of damping applied is usually defined by calibrating the model using observations of the dispersion of a tracer, such as dye.

2.4 Settling and deposition

As well as simulating plumes of dissolved pollutant in coastal waters, PLUME-RW can simulate the dispersal of particulate effluent by including gravitational settling and deposition at the sea bed. Settling velocities can either be specified as constants, or derived from the simulated pollutant concentration field using an equation of the following form:

$$w_s = \beta\, c^n \qquad (9)$$

where

w_s = settling velocity (ms^{-1})
c = computed pollutant concentration ("mass" units/m^3)
β,n = empirical constants

Settling velocities are used to compute downward particle displacements in each timestep of a model simulation. Under conditions of low bed shear stress, model particles which impinge on the sea bed can become inactive, that is stationary at their point of impact, in order to represent deposition of particulate effluent. Particulate deposits formed in this way can become re-suspended subsequently if the shear stress is sufficiently high at other times.

2.5 Computation of pollutant concentrations and deposit distributions

In PLUME-RW, pollutant concentrations and deposit distributions are computed on a square grid, the dimension of which is chosen to resolve the essential features of relatively small-scale plumes. In each PLUME-RW grid cell, depth-averaged concentrations are derived by assuming that the total pollutant represented by all the particles in each cell is evenly distributed over the water depth. Similarly, near-surface concentrations can be calculated from the pollutant represented by the near-surface particles and the volume of a user-defined surface layer. Deposit distributions are calculated similarly, by assuming that the pollutant represented by the inactive (deposited) model particles in each cell of the output grid is evenly distributed over the cell area.

3. References

mg/l as N (based n 22g/l N in FDT)
>1.1
0.22 – 1.1
0.078 – 0.22
0.039 – 0.078
0.035 – 0.039

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