Mixing Zone Case Study

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National Rivers Authority

MIXING ZONE CASE STUDY

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EXECUTIVE SUMMARY

The control of industrial discharges to fresh and saline waters requires the setting of appropriate consent conditions. In the UK this is done by applying the Environmental Quality Objective/Environmental Quality Standard (EQO/EQS) approach and, in the case of discharges into tidal waters, by the designation of a 'mixing zone' within which it is recognised that the EQS may be exceeded. It is the responsibility of the NRA, as the pollution control authority, to determine whether a mixing zone is of an acceptable size or not. The setting of the mixing zone in tidal waters will often entail the use of mathematical models of the discharge which must be capable of predicting the distribution of contaminants brought about by tidal movements and dispersion. There must, therefore, be confidence in the models produced, or at least knowledge of the level of certainty associated with predictions.

The objective of this project was to test, by case study field surveys, the efficacy of a mathematical model in defining the mixing zone around the Tioxide Ltd outfall on the Humber estuary. This was achieved through the addition of a conservative tracer to the effluent, and by the subsequent comparison of measured tracer concentrations within the estuary with those predicted by the mathematical model. It proved to be very difficult to reliably sample the effluent plume during the two case studies, partially due to the vertical stratification of the effluent but also to the relative narrowness of the plume and the variability of its location relative to the outfall over the tidal cycle. A comparison of observed and predicted tracer concentrations during the first study indicated that over the ebb sampling period, the overall average observed and predicted concentrations were very similar. This suggests that a sampling programme to examine one extremity of a mixing zone would find an average concentration close to that estimated by the model. However, during the remaining part of the first study and during the second study it was found that observed concentrations (depth averaged) were generally much lower than those predicted by the model. The model was, therefore, not adequately validated by the results of these latter surveys.

This study has demonstrated that the depth-averaged concentration was not the most appropriate statistic on which the mixing zone should be judged, because at this site the highest tracer concentrations were found near the bed. If the zone to be protected includes the water near the bed, this should be considered when estimating the size of mixing zone to be expected from the design of the discharge hardware. Even though the case studies had limited success in validating the model for the Tioxide discharge, the employed method potentially offers the best opportunity for validating the mixing zone around other discharges. For this strategy to work successfully the boat would have to be moored within the plume. This would be aided by the use of tracer which could be measured *in situ* or by the measurement, *in situ*, of a component of the discharge.

KEY WORDS

Mixing zones, tidal waters, case studies, compliance assessment, monitoring strategies.

1. INTRODUCTION

The control of industrial discharges to fresh and saline waters requires the setting of appropriate consent conditions. In the UK this is done by applying the Environmental Quality Objective/Environmental Quality Standard (EQO/EQS) approach and, in the case of discharges into tidal waters, by the designation of a 'mixing zone' within which it is recognised that the EQS may be exceeded. It is the responsibility of the NRA, as the pollution control authority, to determine whether a mixing zone is of an acceptable size or not.

The setting of the mixing zone will often entail the use of mathematical models of the discharge which must be capable of predicting the distribution of contaminants brought about by tidal movements and dispersion. There must, therefore, be confidence in the models produced, or at least knowledge of the level of certainty associated with predictions.

The objective of this project was to test, by case study field surveys, the efficacy of a mathematical model in defining the mixing zone around a specific estuarine industrial discharge. The first study was undertaken in July 1991 and was fully reported in an interim report (Nixon *et al*, 1991). This R&D Note draws together the conclusions from the case studies, compares the results with those obtained by routine monitoring and makes more general comments about the use of mathematical models to set mixing zones. A detailed description and results of the field work programme are given in Project Record 224/7/A available from the NRA Project Leader.

2. THE MIXING ZONE CONCEPT

There are many practical problems of monitoring for compliance with EQSs in estuarial waters, mainly due to the very large variability shown by quality in estuarial waters but exacerbated by the extreme skewness of that variability (Ellis 1989). The more skewed the distribution of the determinand is, the greater the number of samples needed before this skewness is ironed out of the sample mean. Theoretically even as many as 200 samples taken at random over a number of tidal cycles might pin down the true mean concentration only to within ±27% of the true value (with a 90% confidence interval). In many cases, therefore, the estuarial monitoring of mean quality to test for compliance with EQSs is not a practicable option. An alternative approach is to use a suitable mathematical model which, with details of pollutant loads and hydrodynamic data from the receiving waters, can be used to define an acceptable mixing zone. Assessment of compliance might, therefore, require less sampling effort.

The Water Authorities Association published guidelines on the use of mixing zones for the control of industrial discharges to surface waters (WAA 1988). A general recommendation was that there should be no adverse effect on the general and visible amenity of the area, and any area of acute toxicity immediately adjacent to the discharge must be minimised, within the constraint of reasonable cost. In addition, it was recommended that suitable models were used for tidal waters to establish what would be the best option for a mixing zone.

It is also stated in the WAA booklet (1988) that in view of the large uncertainties in model predictions, substantial safety factors would need to be incorporated and model calibration carried out when mixing zones and consent conditions were first set. Calibration may be effected by determining the contaminant concentration along transects across the plume of the discharge, or by using a tracer as a surrogate for the contaminant. The second approach to calibration was adopted for this project.

3. RATIONALE BEHIND THE CASE STUDY

3.1 The use of a tracer

It was proposed that the case study would be undertaken by adding a conservative tracer to a suitable industrial effluent discharging to tidal waters and for which there was a mathematical model. The tracer would be added to the effluent being discharged from the outfall over a tidal cycle, and the subsequent dispersion and dilution in the receiving waters measured. The observed results would then be compared with the predictions of the mathematical model, and the degree of model validation assessed. The use of a tracer as a surrogate for contaminants within an effluent negates the possible requirement of adding 'decay factors' to the model predictions. For example, high pH may be rapidly buffered to normality and ferrous iron may be precipitated out rapidly in saline waters. The tracer would, therefore, represent the 'worst case' in terms of dispersion of contaminants in the water column.

3.2 The choice of case study site

After an initial meeting with the NRA project leader it was decided to carry out the case studies on the Tioxide outfall in the Humber estuary. It was potentially suitable as a mathematical model (BANKER) developed by WRc had been used in the siting of the new outfall which had relatively recently been constructed (1988). In addition, surveys had been undertaken previously to monitor and test the mixing zone.

An initial visit was made to Tioxide Ltd in November 1990 with the local NRA pollution control officer with the view of determining the suitability of using the outfall, from a logistic point of view, for the study, and to discuss the proposals with Tioxide personnel. The site proved suitable for the study and formal permission was sought and received from Tioxide (UK) Ltd to undertake the study from their premises.

It was originally proposed to undertake the initial study in the first year of the contract (1990/1991) but due to the late commencement of the contract and other logistic problems the first study was not undertaken until July 1991.

3.3 The Tioxide discharge

The two principal pollutants in the Tioxide discharge arising from the production of titanium dioxide are ferrous iron and acid. EQSs of 1 mg l^{-1} for soluble iron (expressed as an annual average) and of pH 6.0 for acid (expressed as a 95 percentile) had been used to characterise the boundary of the mixing zone (NRA 1989a). The NRA is responsible for implementing the EC Titanium Dioxide Directives, including the 1982 Monitoring Directive. This latter Directive expands the monitoring provisions of the main Directive and requires:

- the water around the outfall to be analysed three times a year;

- the life around the outfall to be examined once a year;
- the sediment around each outfall to be examined once a year.

The EC Directive provided the stimulus for the reduction of the pollution from the discharge and detailed investigations were carried out to quantify the impact of the two discharges. Following this work in 1984, it was decided to replace the existing pipes with longer outfalls. The Tioxide discharge was relocated to the main deep water channel at a distance of approximately 2.2 km from the shore. At the discharge point this channel is at least 5 m deep at low water and can be up to 12 m deep at high water on spring tides. No diffuser was fitted as modelling work predicted little advantage in having one in a channel where good mixing should occur.

3.4 The mathematical model

The model used to define the mixing zone around the Tioxide outfall was the WRc model BANKER. The model was developed in 1979, initially for the Laporte (SCM) discharge on the Humber. It has since been applied to coastal dischargs in Cumbria, discharges to the Tees estuary and a number of outfalls on the Humber, including Capper Pass. It is a 2-dimensional depth-averaged (plan) model and uses information on water level and longshore currents over a tidal cycle together with bed-level profile on a line perpendicular to the bank to calculate the tidal average concentration field generated around an outfall. For calculation of concentrations in this study, the model cells are 20 m wide by 50 m long and the effluent dispersion is calculated transversally and longitudinally in steps throughout the tidal cycle. The tidal cycle is broken down into 1000 segments of time. In each time segment the discharge load is injected into the boxes which find themselves opposite the outfall. The boxes then move with the tide and some of the pollution diffuses into neighbouring boxes. Only one tide is simulated to estimate a tidal average and no carry over or build up of contaminants over a series of tides is accounted for. The model may, therefore, be unsuitable for use in locations where discharges are contributing significantly to 'background' contaminant levels and where 'background' levels are close to EQS values. In this case a model that simulates accumulative and steady-state levels might be required. Also as the EQS is usually expressed as an annual average the accepted practice is to average the results of a mean spring and a mean neap tide. The model also assumes that the contaminants are entirely conservative.

The area (in hectares) of the mixing zone defined by the EQS values for iron and acid around the Tioxide outfall was predicted to be as follows.

	Iron	Acid
1984	550	160
1989	44	0

As a comparison the estimated mixing zone in 1984 for the former discharge point is also given. The pattern of distribution of the mixing zone can vary substantially between spring and neap tides.

4. PREVIOUS MONITORING SURVEYS

Previous surveys to confirm the mixing zone and for assessment of compliance with the EC Titanium Dioxide Directives had encountered a number of problems (NRA 1989b).

1. The topography of the estuary bed gives rise to local variations in current velocity.

2. The discharge plume stratifies in the water.

3. The extent of the soluble iron plume cannot be assessed in the field making it difficult to determine representative sample points along the transect.

4. Plume shape varies continuously with time from slack water, i.e. with current velocity and direction.

5. Wind speed and direction are variable and the plumes may well be affected by wind.

6. Pools of concentrated effluent are formed around slack water which distort the plume shape immediately afterwards.

Intensive surveys have been undertaken to assess the impact and mixing zone around the new discharge point. These have included detailed surveys of the water column and of the sediment. For example, measurement of pH around the outfall on a neap tide in 1989 indicated that the acidic plume was between 100 and 200 m wide and detectable 900 m upstream and 1200 m downstream of the outfall (NRA 1989b). Water with pH <6.0 was also detectable 900 m upstream and 400 m downstream of the outfall. Surveys of soluble iron concentrations around the outfall showed that the plume was not as narrow or as consistent in width as that for pH. Values in excess of the EQS value for soluble iron (1 mg l^{-1}) were found 983 m upstream and 1253 m downstream. During the iron surveys two samples were taken, one at the surface the other subsurface, ranging from mid-depth to near bottom. Typically higher concentrations were found subsurface than at the surface.

In addition, a macrobenthic survey undertaken around the Tioxide outfall a year after coming on line indicated that there were two identifiable impoverished areas which might be impacted by the discharges (NRA 1989b). It is possible that the changes relate to a weak impact of the effluent on the benthos on the north east side of the outfall. However, by 1989 there had been no evidence of enrichment of sediments around the outfall by metals in the effluent.

5. FINDINGS FROM THE CASE STUDIES

The details of the first study undertaken in July 1991 have been fully reported in the interim report (Nixon *et al*, 1991). The second study undertaken in December 1991 is reported in Appendix A of this report. For both studies a radiotracer, tritium as tritiated water, was added to the Tioxide effluent over a period of approximately 12 hours. Samples were subsequently taken over a tidal cycle from a boat moored downtide of the outfall and from a mobile boat undertaking transects across the effluent plume. It was important that the position of both sampling boats was known with a precision and accuracy consistent with the cell size of the model (20 m). A microfix navigation system (or equivalent) was needed for this study and would be for any undertaken in the future. The measured tritium concentrations were then compared to those predicted by the BANKER model.

5.1 First study, July 1991

The observations showed that the effluent plume from the outfall was still stratified within about 400 m of the outfall, with highest concentrations near the bed.

As has been previously described, the model used to simulate dispersion from the outlet is depth-averaged and cannot look at the vertical structure of concentration, so comparisons were made with the average of concentration measurements taken at several depths.

The predicted tidal range for the tide sampled on 9 July 1991 was 4.3 m, intermediate between spring and neap. The tidal data for the model were available only for mean spring and mean neap tides, so the tide of the experiment was simulated by averaging the velocities and water levels from the two available tides. This was a tide of 4.54 m range and thus reasonably close to the tide sampled.

The boat's position varied during the sampling about a mean distance of about 350 m from the outfall on the downstream side, seawards on the ebb and landwards on the flood tide. In the model, concentration was output on transects along rows of cells centred at 325 m landwards and seawards of the outfall.

Even when averaged over depth, the observed concentrations showed considerable variations between consecutive measurements (usually at 15 minute intervals) and, therefore, for ease of comparison the data were mostly averaged over periods of one hour. The variability of the measurements illustrated the turbulence of the plume and hence the difficulty of sampling in the middle of the plume. The model cells were 20 m wide and the concentration used for comparison with the observations was the average of that in the peak cell and one cell on each side of it, thus representing an average over a 60 m width at the peak of the traverse. During the sampling periods the centre cell was virtually fixed in position. It was hoped that this might give a better representation of what was observed in the field.

The modelled and observed data, in averaged form, are shown in Figure 5.1 against time of day. The observations over the first hour were more than twice the predicted level, and no explanation is obvious. Over the next two hours, to the end of the ebb tide, the observations were below the predictions and this could be explained by the sampling missing the centre of the plume, though this could not be corroborated without an even bigger sampling exercise. Over the ebb sampling period, the overall average concentration was 205 Bq l^{-1} (observed) and 195 Bq l^{-1} (predicted), suggesting that a sampling programme to examine one extremity of a mixing zone would find an average concentration close to that estimated by the WRc BANKER model. At the sampling position on the flood tide, most of the samples were taken right outside the plume, confirming the problem of sampling without being able to measure at the same time. Some tracer was found later on in the sampling, near to high water, but still at levels well below those predicted.

5.2 Second study, December 1991

Comparison between model and observations

The predicted tidal range during the second survey was 3.1 m, similar to the range of a mean neap tide (3.2 m). The model BANKER was run to simulate a mean neap tide; the currents at this site (Tioxide) had been estimated prior to these studies by a hydrodynamic model of the Humber estuary for mean spring and mean neap tides.

In the model the maximum current speed had been assumed to be 0.64 m s^{-1} on the flood and 0.74 m s^{-1} on the ebb tide; measured currents from the fixed boat showed a similar maximum on the flood tide while the readings seemed reliable, but higher values were found later in the flood when the direction readings became unrealistic; during the ebb tide higher currents were observed near the surface though the depth-averaged values were only slightly higher than assumed in the model. In summary, the model was based on good estimates of the principal dispersion features, the current speed and water depth near the end of the outfall.

In the first survey the stratification of the tracer was a notable feature, though excluded from the scope of the depth-averaged model. Because the model estimates depth-averaged concentrations, it should be compared with estimates of observed depth-averaged concentrations, and the average of consecutive samples taken over the depth offers the best available estimate. Even these estimates (usually from sets of four samples) vary greatly between consecutive sets, and several have been combined (averages over periods of about 40 minutes) for plotting in Figure 5.2 to ease the comparison with the model.

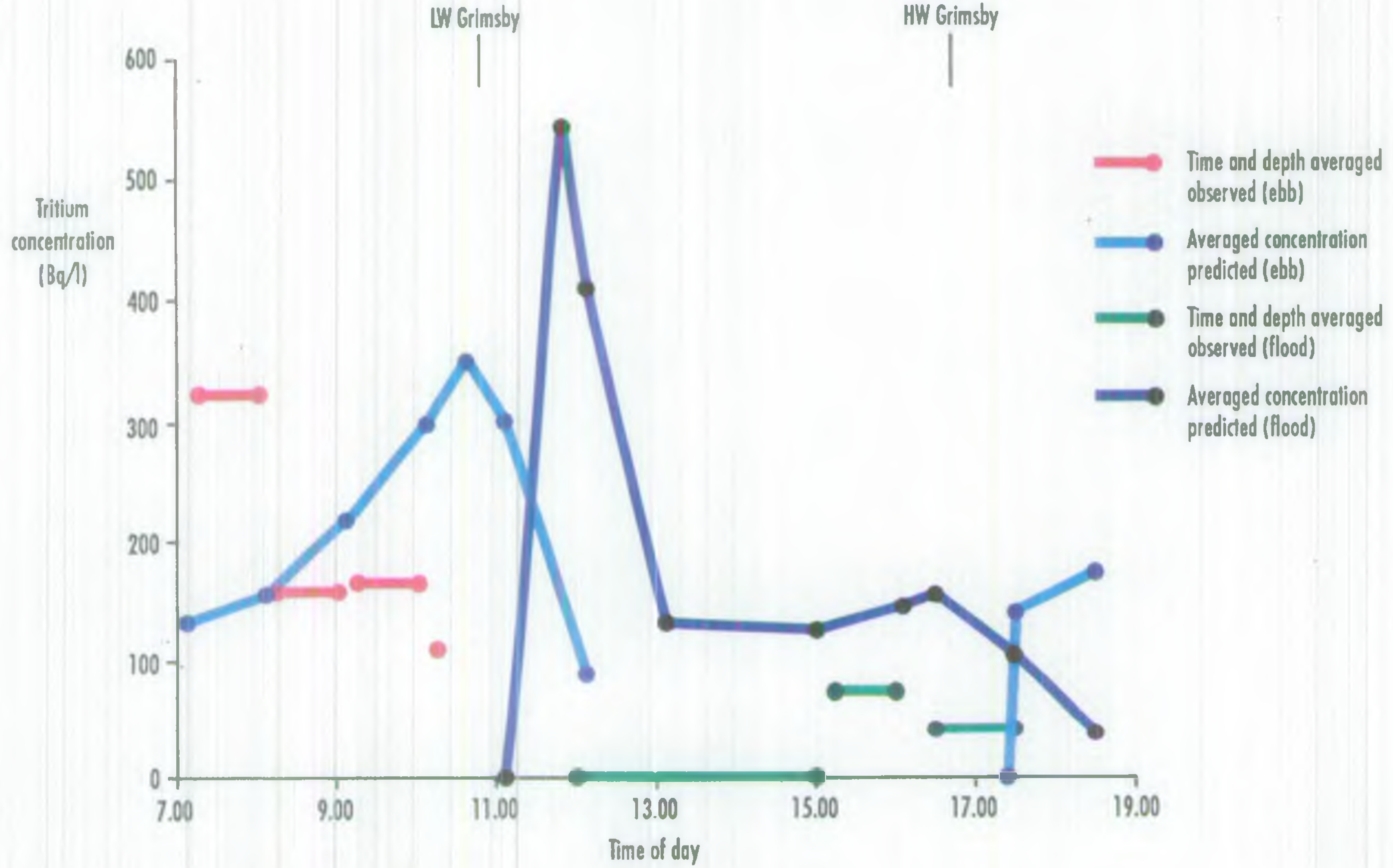

Figure 5.1 Mixing zone case study, July 1991. Comparison of observed and predicted tracer concentrations around the Tioxide outfall

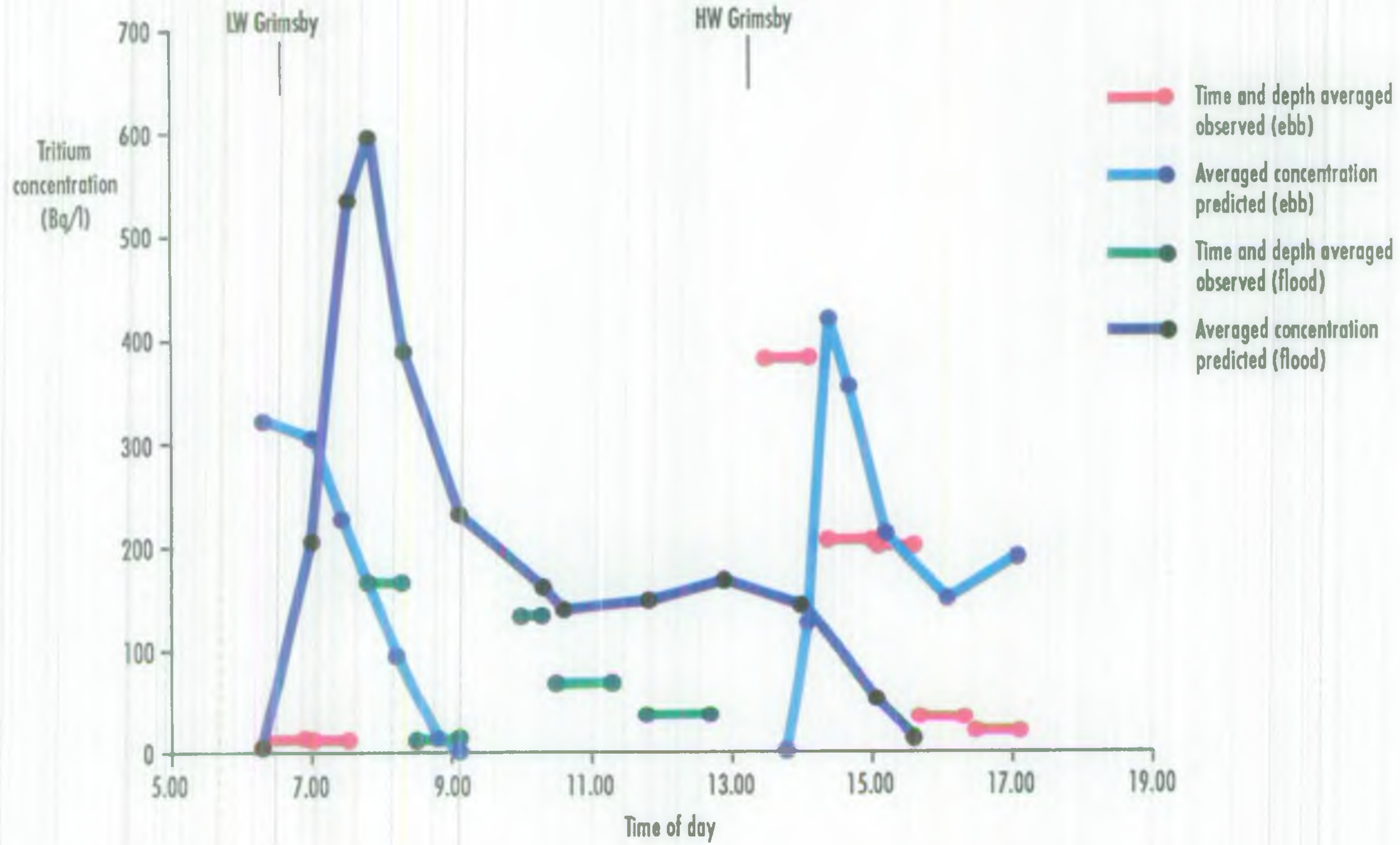

Figure 5.2 Mixing zone case study, December 1991. Comparison of observed and predicted tracer concentrations around the Tioxide outfall

Detailed comparison

The earliest samples of the survey, taken during the last third of the ebb tide, showed that observed tracer concentrations at the fixed boat were mostly near background. During this period the moving boat took one set of samples nearer the outfall and also seemed to miss the tracer. The model predictions for this period were well above background, as may be seen from Figure 5.2. There is no obvious reason for the low tracer recoveries here - it is an illustration of the difficulty of sampling a turbulent plume close to its source when it cannot be seen or even detected *in situ.*

During the flood tide, higher tracer concentrations were observed occasionally, especially nearer the bed, but on the whole the observed concentrations were less than the predictions. The moving boat was more successful at finding the plume, though the sampling methodology of stopping at several points on a transect across the plume resulted in fewer samples at any single point, a drawback when it is considered that the objective is to estimate statistics at particular points within the plume. Unfortunately because the location of the plume moves over the tidal cycle it may not be possible to stay in one place.

On the subsequent ebb tide, high concentrations were observed at the very start before the model expected any tracer to be moving seawards. Examination of the current meter record at that time does not offer an explanation of how the tracer got there. For most of the ebb the observed concentrations were less than the predictions. Again the moving boat provided interesting information on the plume; in this case it showed a wider plume over about three hours, explaining in part the fact that the observed concentrations were lower than the predictions.

5.3 Discussion

Unlike the first survey, when over the ebb tide sampling period the average observed tracer concentration was similar to that predicted by the model, the observations on the December survey showed a generally lower level of tracer than predicted. Certainly the real turbulent system is considerably more complex than the modelled scenario of a current varying in strength slowly over a tidal cycle of about 12.5 hours and a diffusion process to gradually widen the plume with distance downstream from the source. Perhaps sampling would need to be fairly continuous to reduce the stochastic element introduced by discrete sampling, and also it may need to be at several fixed points to improve the chances of being near the critical positions. Observations of visible tracers in such turbulent flow would help to elucidate the sampling problem - a comparative example closest to everyday experience being smoke from a chimney, though any quantitative similarity may be difficult to establish. For the quantitative measurement required when investigating a mixing zone near the discharge point, a tracer which can be measured *in situ* seems essential.

The study has demonstrated that the depth-averaged concentration may not be the most appropriate statistic on which the mixing zone should be judged, because at this site the highest tracer concentrations were found near the bed. If the zone to be protected includes the water near the bed, this should be considered when estimating the size of mixing zone to be expected from the design of the discharge hardware. A model that considered the buoyancy and initial momentum of the discharge and described the ensuing plume in three dimensions would be superior to the present BANKER model for flagging such possibilities as a more concentrated plume attached to the estuary bed. However, now that the possibility is revealed, the design of the outlet could be considered in simpler models to ensure that the most sensitive part of the water column is protected, say in this case by jetting the effluent from the pipe on the estuary bed towards the surface. In the case of Tioxide, the outfall pipe is inclined upward but there is no diffuser. Then a depth-averaged concentration would be an underestimate of the concentration near the bed, at least in the vicinity of the discharge.

6. DISCUSSION

Relationship between model and monitoring data

As has been already discussed in this report the NRA undertakes surveys to determine the soluble iron and pH concentrations around the outfall (NRA 1989b). As an example, the results obtained during a flood tide survey undertaken on 8 October 1989 are illustrated in Figure 6.1. The results represent concentrations of soluble iron found in samples taken along transects across the plume at increasing distances from the outfall. The results indicate (as had the tracer studies) that the effluent plume was not always successfully sampled. As can also be seen there is a very wide variation in the concentrations found and such randomly taken results would not in themselves validate the model or the mixing zone. To do so model predictions would have to be obtained for each of the lateral and longitudinal cells sampled during the survey. It is likely that a plot of observed against predicted concentrations would give a wide scatter of points from which no conclusions as regard to the efficacy of the model could be made. These sample points would also represent only a single snapshot in time and space, they would not necessarily represent the average situation within the mixing zone.

However, the NRA results indicate that iron was found above the EQS value at 1 km downtide of the outfall. If, as the tracer and pH survey data have indicated, the plume is approximately 200 m wide and concentrations in excess of the EQS value are found 1 km either side of the outfall, then the particular mixing zone (under these specific tidal conditions) might be 40 hectares. This is close to the annual average mixing zone of 44 hectares set for the discharge but no conclusions can be drawn from this as to what the annual average mixing zone would be. In general, therefore, the model would be better validated by obtaining more data at particular points to obtain a tidal average, and thereby an annual average, concentration.

Monitoring requirements for compliance assessment

This case study had limited success in validating the model for the Tioxide discharge. However, the employed method potentially offers the best opportunity for validating the mixing zone around other discharges. Obtaining more samples at relatively few fixed points, rather than fewer samples from points over a greater spatial area is probably the best strategy. An appropriate strategy might, therefore, be to moor a boat close to the longitudinal limit of the mixing zone and take frequent samples (e.g. every 15 minutes over a tidal cycle). For this strategy to work successfully the boat would have to be moored within the plume which is difficult to achieve. In addition, samples should be taken less frequently at points along a transect across the plume closer to the discharge point.

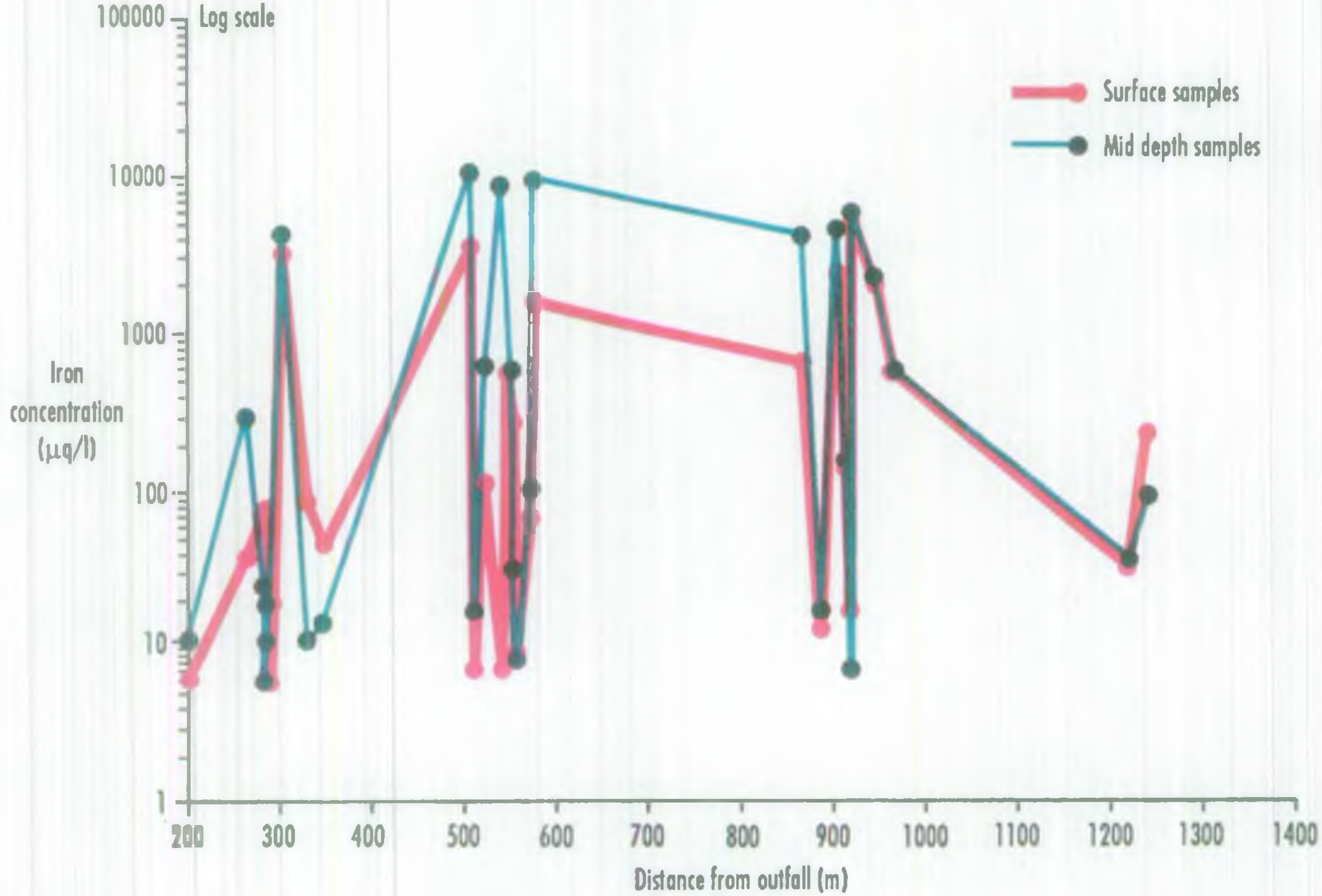

Figure 6.1 The concentration of soluble iron samples taken around the Tioxide outfall on 8 October 1989

An alternative sampling strategy worthy of field assessment would be to take an integrated sample from the fixed boats to obtain an average sample through time and depth. This could be achieved through the continuous pumping of water from several depths. In all of these examples, it would always be essential to obtain, where possible, an *in situ* measurement of the effluent (e.g. pH), as both the tracer and routine monitoring surveys have indicated that it is easy to miss the plume and 'waste' sampling effort.

Any monitoring programme should also consider site-specific factors, such as stratification of effluent, in order to obtain a representative, depth-averaged in the case of the Tioxide, sample concentration.

The use of tracers as a surrogate for effluent is a useful technique for validating models used to define mixing zones. The main shortcoming of this study was the fact that the tracer could not be detected *in situ*, thereby increasing the possibility of not sampling the plume representatively. In the case of the Tioxide effluent the use of such a tracer was not possible - dye was denatured by the effluent and the required quantities of a gamma emitting radiotracer would been have too great to handle with ease. But for other mixing zones these types of tracer should be considered. Validating the model on a conservative substance rather than on the contaminants within the effluent, the latter which may have decay characteristics that further decreases their concentration in the water column, adds a further safety margin to the application of the mixing zone.

Applicability of model to other discharges

The BANKER model would be generally applicable to other outfalls after the provision of certain site-specific data. Most importantly data on tidal currents would be required not only at the point of discharge but also at a number of other sites closer to and further away from the shore. Current data would be required over a tidal cycle for a mean neap and a mean spring tide. In many cases bathymetric data of the area around the outfall would also be of use in setting up the model. However, whereas the model might be generally applicable for relatively small mixing zones and discharges, where there is a large mixing zone the model may not adequately represent important features such as variable depth cross-sections or split channels. In these cases truly 2-dimensional models may be required. For some applications the accumulative or steady-state effect of the discharge might have to be accounted for. In all cases site-specific factors such as stratification and the 'Uses' requiring protection should always be considered when setting mixing zones and an appropriate margin of safety, to cover uncertainties or limitations, applied.

Implications to the definition of EQSs and mixing zones

The WAA guidelines on setting mixing zones suggest that other 'Uses' of the controlled waters must not be compromised or adversely impacted by the mixing zone. An example given is that the zone should not cover the whole width of an estuary when the passage of migratory fish might be inhibited. In these case studies the effluent was stratified within the water column and occurred at far higher concentrations close to the bed than in the surface layers. If in other situations a 'Use' was to protect benthic communities (e.g.

Special Ecosystem) then clearly the potential of stratification would have to be considered in setting the mixing zone to ensure that the Use was not compromised. In the case of the Tioxide outfall the impact on an already naturally impoverished benthic community appears to be minimal (NRA 1989b, Appendix 13). The situation around other outfalls may of course be different.

7. CONCLUSIONS

1. Two case studies were undertaken from the Tioxide Ltd outfall discharging into the Humber estuary. The first study was undertaken during July 1991, when tidal conditions were intermediate between neap and spring, and the second was completed in December 1991 under mean neap tidal conditions.

2. The Tioxide effluent was found to be stratified within the water column with the highest tracer concentrations often being found close to the bed.

3. It proved to be very difficult to reliably sample the effluent plume, partially due to the vertical stratification of the effluent but also to the relative narrowness of the plume and the variability of its location relative to the outfall over the tidal cycle.

4. A comparison of observed and (model) predicted tracer concentrations during the first study indicated that over the ebb sampling period, the overall average concentration was 205 Bq l^{-1} (observed) and 195 Bq l^{-1} (predicted). This suggests that a sampling programme to examine one extremity of a mixing zone would find an average concentration close to that estimated by the WRc BANKER model.

5. During the remaining part of the first study and during the second study it was found that observed concentrations (depth averaged) were generally much lower than those predicted by the model. The model was, therefore, not adequately validated by the results of these latter surveys.

8. RECOMMENDATIONS

1. The study has demonstrated that the depth-averaged concentration may not be the most appropriate statistic on which the mixing zone should be judged, because at this site the highest tracer concentrations were found near the bed. If the zone to be protected includes the water near the bed, this should be considered when estimating the size of mixing zone to be expected from the design of the discharge hardware.

2. This case study had limited success in validating the model for the Tioxide discharge. However, the employed method potentially offers the best opportunity for validating the mixing zone around other discharges. Obtaining more samples at relatively few fixed points, rather than fewer samples from points over a greater spatial area is probably the best strategy for validation as this would reduce the stochastic element introduced by discrete sampling. For this strategy to work successfully the boat would have to be moored within the plume.

3. Any monitoring programme should also consider site-specific factors, such as stratification of effluent, in order to obtain a representative (depth-averaged in the case of the Tioxide) sample concentration.

4. The use of tracers as a surrogate for effluent is a useful technique for validating models used to define mixing zones. The main shortcoming of this study was the fact that the tracer could not be detected *in situ,* thereby increasing the possibility of not sampling the plume representatively. Validating the model on a conservative substance rather than on the contaminants within the effluent adds a further safety margin to the mixing zone.

5. The BANKER model would be generally applicable to other outfalls after the provision of certain site-specific data. Most importantly data on tidal currents would be required not only at the point of discharge but also at a number of other sites closer to and further away from the shore. In many cases bathymetric data of the area around the outfall would also be of use in setting up the model. However, whereas the model might be generally applicable for relatively small mixing zones and discharges, where there is a large mixing zone the model may not adequately represent important features such as variable depth cross-sections or split channels. In these cases truly 2-dimensional models may be required. For some applications the accumulative or steady-state effect of the discharge might have to be accounted for. In all cases site-specific factors such as stratification and the 'Uses' requiring protection should always be considered when setting mixing zones and an appropriate margin of safety, to cover uncertainties or limitations, applied.

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