Prediction Studies for an AUV Monitoring Mission Plan

Patrícia Ramos[1,2], Nuno Cruz[1], Aníbal Matos[1],
Mário V. Neves[1], Fernando L. Pereira[1]

[1]Faculdade de Engenharia da Universidade do Porto
Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
Tel. + 351-225081539   Fax. +351-225081440

2 Instituto Superior de Contabilidade e Administração do Porto
Rua Padre Costa, 4465-111 S. Mamede de Infesta, Porto, Portugal
Tel. + 351-229050000   Fax. + 351-229025899

E-mail: {patricia, nacruz, anibal, mjneves, flp}@fe.up.pt

Abstract

Wastewater plumes show to be very difficult to observed in detail. The several field studies already conducted exhibit very complex and patchy structures both in vertical and horizontal sections. It is not clear yet if this plume patchiness is due to physical processes or measurement limitations. Rapid tow-yo sampling is expected to reduce the time variability during and between transects. The AUVs may be a useful instrument to detect and map wastewater plumes.

This paper presents several prediction studies using time series files of actual in-situ measurements integrated in the UM3 near field model. The model predictions of the plume characteristics at the end of near field support the definition of the best sampling strategy for an AUV monitoring mission in a Portuguese west coast outfall.

Introduction

Several field studies using different types of techniques were already performed in order to map and detect sewage plumes (Washburn et al., 1994), (Petrenko et al., 1998)

and (Carvalho et al. 2001). In all these studies, the very complex found structures showed to be very difficult to identify with the classic picture of the buoyant plume. It is not proved yet if the patchiness of these structures is real and due to physical processes or measurement limitations. These studies are very important since, besides giving a better understanding of the plume behavior under certain conditions, can be used to be checked against prediction models.

Autonomous Underwater Vehicles (AUVs) have shown to be a very useful instrument in this case since they enable the efficient collection of data required to detect and map the plume. But the success of outfall monitoring missions using AUVs depends crucially on the efficiency of a sampling strategy.

This paper presents an exhaustive prediction study of the sewage plume of S. Jacinto outfall using time series files of actual in-situ measurements of flowrate, density profiles and current speed and direction. The UM3 model predictions of the plume characteristics at the end of near field, which include rise height and dilution, support an AUV sampling strategy for a monitoring mission. Simulations of the pollutant concentration in the far field are also predicted using Brooks solution.

The paper is organized as follows. In section II we describe the study area, giving some details about the S. Jacinto outfall and the seawater quality monitoring program that has already started in September 2000. In Section III, we give a short presentation of the Isurus AUV focussing on the monitoring operation aspects. In Section IV we present the in-situ measurements already collected in three campaigns conducted in September 2000, January and June 2001. Then in Section V, after a brief description of the data used in a plume behavior prediction model, the results are discussed. In section VI we present an AUV mission plan for monitoring the S. Jacinto outfall based on the obtained results. Finally, in Section VII we give some perspectives for future work.

Study Site

The bathymetry of the Aveiro coast and the mouth of its estuary, the oceanographic instrumentation sites and the S. Jacinto outfall are shown in Fig. 1.

This Portuguese outfall, in operation since May 2000, is presently discharging about 0.7 m3/s of mainly industrial wastewater. Its total length, including the diffuser, is 3378 m (first 3135 m with a diameter of 1600 m and last 243 m with a diameter of 1200m). The diffuser, consisting of 72 ports alternating in each side, 0.175 m diameter, is 332 m long. Presently only 20 of the 72 ports are working. These are discharging upwards at an angle of 30º above the horizontal axis. The outfall has a bearing direction of 290º and is discharging at a depth of about 15 m.

A seawater quality monitoring program for this outfall has already started in September 2000. Its main purposes are to evaluate the background seawater quality both in the offshore and nearshore locations around the vicinity of the sea outfall and to follow the impacts of wastewater discharge in the area. In this monitoring program, measurement and sampling sessions are organized four times a year, being once per season. Three measurement sessions were already conducted in the following dates: September 2000, January 2001 and June 2001.

The location of the offshore measurement and sampling stations established at different depths around the outfall is shown in Fig. 1. The letter A and a number, e.g. A2, identify the stations, except the reference one, which is indicated, with REF letters. A1 station is at 15 m depth, located almost above the end of the diffuser. At different distances from the diffuser but at the same depth are stations A3, A5, A6 and A7. In the outfall line are stations A2 and A4 respectively at 19 m and 13 m depth. The reference station, REF, is located at 37 m depth, at 6000 m of distance from the end of the outfall.

Fig. 1. Bathymetry, outfall and oceanographic instrumentation sites in Aveiro coast.

The Isurus AUV

Isurus (Fig. 2) is a REMUS (Remote Environment Measuring UnitS) class AUV, built by the Woods Hole Oceanographic Institution, MA, USA, in 1997 (Alt et al.,1994). The Systems and Underwater Technology Lab (LSTS) at the University of Porto has been operating and customizing it for the past 4 years. Several missions were already performed

with great success namely in the estuary of Minho River in the border between Portugal and Spain, and also in the Douro River (Ramos et al., 2000).

These vehicles are low cost, lightweight AUVs specially designed for coastal waters monitoring (maximum depth of 200m). The reduced weight and dimensions makes them extremely easy to handle, requiring no special equipment for launching and recovery, such as winching systems. Isurus has a diameter of 20 cm and is about 1.5 meters long, weighting about 30 kg in air. Its maximum forward speed is 4 knots, being however the best energy efficiency achieved at about 2 knots. At this velocity, the energy provided by a set of rechargeable Lithium-Ion batteries may last for over 20 hours (i.e., over 40 nautical miles). Although small in size, this vehicle can accommodate a wide range of oceanographic sensors, according to mission objectives. For the missions mentioned above two specific sensors were integrated: a CTD (Conductivity, Temperature, Depth), OS200 model from Ocean Sensors, CA, USA, and an altimeter, from Imagenex, Canada, but several successful tests have been performed in the past with ADCP (Acoustic Doppler Current Profiler), Optical BackScatter, Sidescan Sonar, etc.
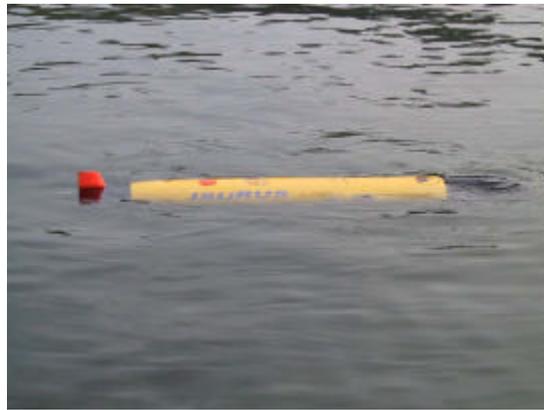

Fig. 2. The Isurus AUV.

In-Situ Measurements

In-situ measurements in the all stations were obtained for the three campaigns already conducted: September 2000, January 2001 and June 2001, with the exception of A7 which was not performed in January due to bad weather. The locations of the measured stations were determined by DGPS (Differential Global Positioning System). Data were collected from a sensor (OCEANSEVEN 316 manufactured by IDRONAUT-Italy) incorporated in a twelve bottle Rosette. This sensor measured, between the surface and the bottom, several physicochemical parameters, including pressure, temperature, salinity, dissolved oxygen, pH and turbidity. Real time sampling visualization of these parameters was accomplished with a RS232 Interface.

For the three campaigns, the vertical temperature and salinity profiles for the measured stations, are respectively in the first and second plots of Fig. 3, Fig. 4 and Fig. 5. The vertical temperature and salinity profiles of the January and June 2001 campaigns were obtained with a 0.2 meter resolution, while the September ones were obtained with 1 meter resolution. The seawater density profile presented in the third place of Fig. 3, Fig. 4 and Fig. 5 was computed from the temperature and salinity measurements.

As expected, the density difference over the water column for the three campaigns, in the stations that are able to better characterize the backgroundwaters and influence the plume behavior, which are A3, A5 and A6, is slightly different and varying along the seasons. The maximum observed value was obtained in the January campaign and is about 1.8 σt-units. This density difference is mainly influence of the salinity difference, which reaches its maximum value, approximately 2.5 PSU in A5 station. In the following seasonally campaigns the density difference decreases being approximately 1.2 σt-units in June and 0.5 σt-units in September. The significance of this is discussed in the next section, were we present the model results.

Additionally, measurements of currents were also obtained from 2 electromagnetic current meters moored at 17 and 27 meters depth and operating from January 17th to April 5th, 2001. This equipment was set to record current speed and direction at twenty minutes intervals. Its location in the study area at the 17 m and 27 m depth is identified in Fig. 1 respectively with C2 and C1 points. The stick plots of the currents measured at C2 point are shown in Fig. 6. As expected, the stronger and predominant current directions are NNW and SSE, parallel to the local bathymetry. The stronger current velocities at the 17 m depth in the NNW and SSE directions, for the period above mentioned, were around respectively 0.7 m/s and 0.5 m/s, being the average values much weaker.

Seawater samples at the different depths were also collected from the eleven bottles of the Rosette and properly stored in order to perform precise chemical and microbiological analysis.
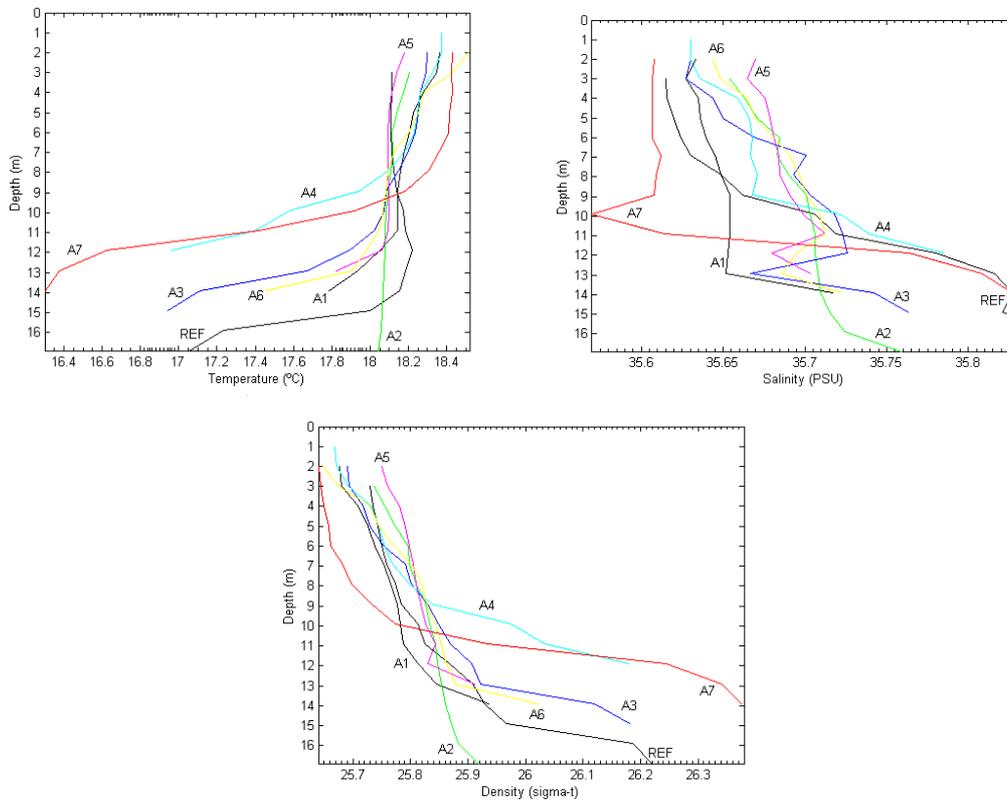
Fig. 3. Temperature, salinity and density profiles at all stations for the September 2000 campaign.
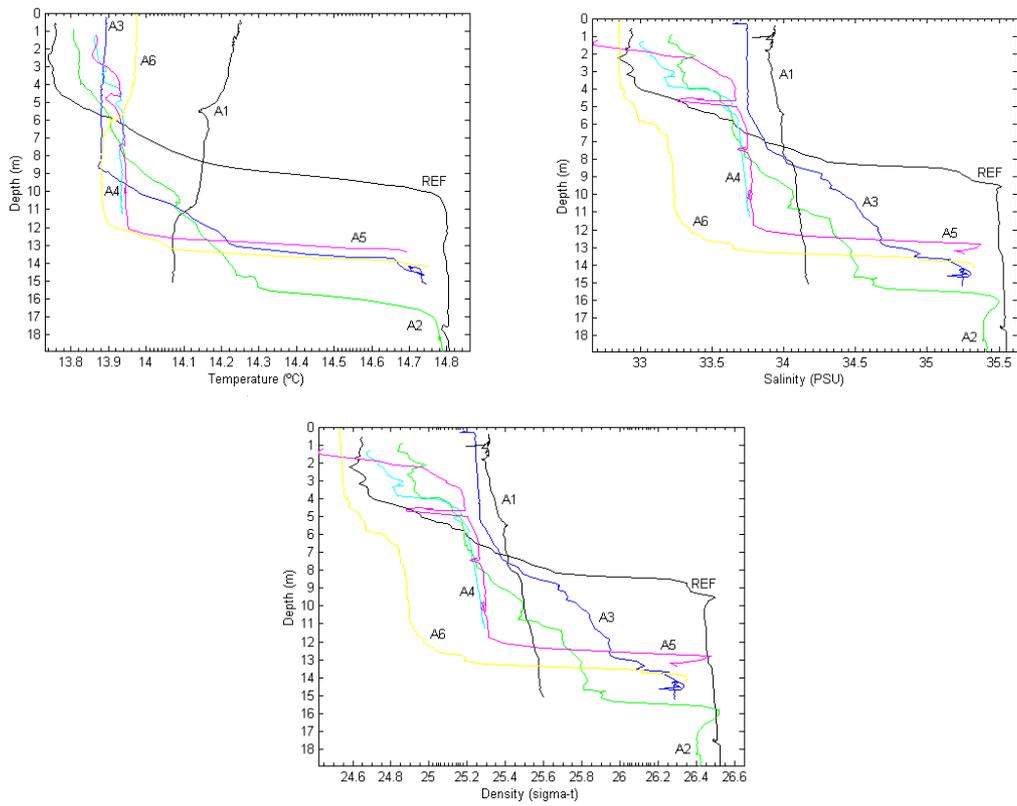
Fig. 4. Temperature, salinity and density profiles at all stations for the January 2001 campaign.
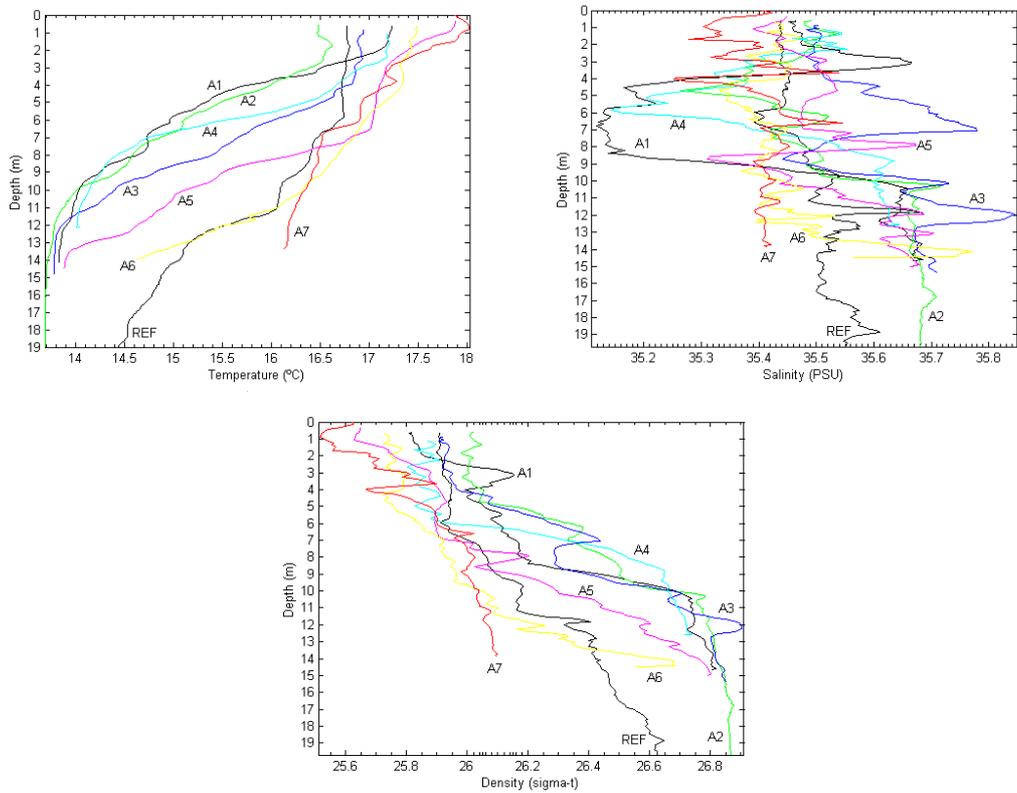

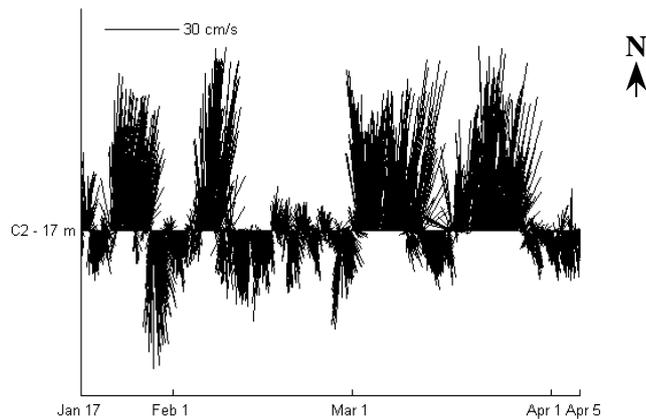Fig. 5. Temperature, salinity and density profiles at all stations for the June 2001 campaign.

Fig. 6. Stick plots of currents at point C2 measured by an electromagnetic current meter between January 17th and February 27th, 2001.

Model Results

The wastewater is mixed by physical, chemical and biological processes that occur over a wide range of length and time scales. The initial mixing zone, where intense turbulence generated by the buoyancy and momentum of the discharge occurs, is called the near field. This first zone ends where, due to density stratification, the plume stops rising, reaching a level of neutral buoyancy, starting to spread laterally. Then this established wastefield drifts with the ocean current and is diffused by oceanic turbulence in a region called the far field. The rate of mixing in the far field is much slower than in the near field.

In order to define the best sampling strategy to detect and map the sewage plume of S. Jacinto outfall, several prediction studies of its behavior in the near field were performed using UM3 model. UM3 is a three-dimensional plume model for simulating single and multi-port submerged discharges, available in the Environmental Protection Agency interface "Visual Plumes" (VP) (Frick et al., 2000). In this Lagrangian model, the equations for conservation of mass, momentum, and energy are solved at each time step, giving the dilution along the plume trajectory. To determine the growth of each element, UM3 uses the shear (or Taylor) entrainment hypothesis and the projected-area-entrainment hypothesis. The flows begin as round buoyant jets issuing from one side of the diffuser and can merge to a plane buoyant jet (Carvalho et al. 2001). The model output consists of plume characteristics along its trajectory such as centerline dilution, width and centerline height.

VP application allows to run UM3 with long time series files of actually recorded data. This capability, particularly useful to adequately describe performance of outfalls under a range of conditions, was actually one of the main reasons because UM3 model was chosen for this study.

As any other initial mixing plume model, UM3 predictions are based on ambient water column data, which include temperature and salinity, current speed and direction. Effluent flowrate data and diffuser configuration are also needed. In this study, temperature and salinity profiles of stations A3 and A5 were chosen to characterize the background waters of the three different seasons. A1, A2, and A4 profiles were excluded since these stations are too close to the diffuser and may naturally be influenced by it. The

profiles of A6 and mostly A7 were not considered since they are very different from the remaining stations in the same bathymetry line. The influence of increased tidal mixing or outflow of waters heated in the estuary over a tidal cycle may contribute to its elevated temperatures and reduced gradient. Specially in the January campaign, the reference station profile is also quite different from the others, since the layer of cold and less saline water is considerably thicker for the shallow-water stations, and the deep layer below the thermocline, that begins at just 10 m, is not evident at the other sites.

The currents from the C2 point shown in Fig. 6 were chosen for the UM3 predictions since its measurement depth is almost the same of the discharge. The flow rate data, obtained from the treatment plant in an 8-hour interval, were considered for the same time period of current, mainly because this is a quite good reasonable representation of the data conditions and makes density profiles the only parameter variable between different simulations. The flowrate data plot is shown in Fig. 7.
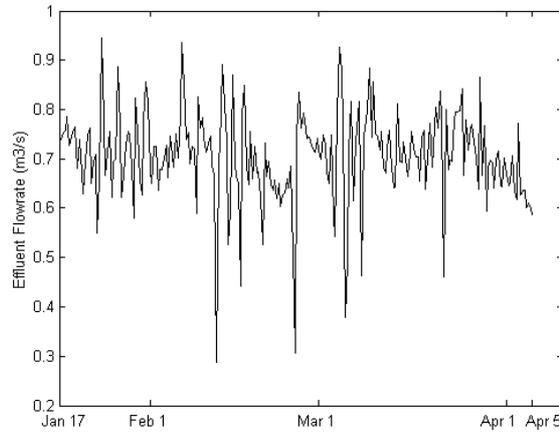

Fig. 7. Effluent flowrate between January 17th and February 27th, 2001.

All these data were input into the model at twenty minutes intervals and long time series of predicted near field plume characteristics were generated. Note that in each step of A3 and A5 stations simulation, the same temperature and salinity profiles were used for the three seasons. Far field calculations based on UM3 outputs were also performed using the constant eddy diffusion model proposed by Brooks and available in the VP interface. The constant eddy diffusion model gives approximate far field dilutions in both open coastal and inshore sites. The equation relating pollutant concentration to distance travelled can be expressed as:

$$C_{FFCL} = C_{NFCL} \, erf \sqrt{\frac{Uab^2}{16eX}}$$

where C_{FFCL} is the pollutant concentration in the center of the waste field at the end of the far field, C_{NFCL} is the pollutant concentration and b is the width of the waste field, both at the end of the UM3 calculations, erf is the standard error function, U_a is ambient velocity, e is the lateral eddy diffusivity and X is the distance traveled from the end of the mixing zone to the end of the far field. A far field dispersion coefficient a of 0.0003 $m^{2/3}$/s was used in the simulations. This dispersion coefficient is related to waste field size and eddy diffusity by $a = e/b^{4/3}$ (Davies, L., 1999).

Simultaneously, measured flow rate, density stratification, and current speed and direction should be preferentially used at each step of a model simulation, in order to predict the actual plume behaviour during the time period considered. This was impossible to do in this study since we have no such data, even in the January campaign, but the main purpose was accomplished since we were able to perform simulations in a wide range of reasonable conditions for each season and certainly were considered the best and the worst situations.

Among other plume variables, centerline dilution, width and centerline height in the end of the initial mixing zone were obtained for each A3 and A5 season profiles using the 17 m current and the flow rate measured between January 17th and February 27th, 2001. Far field centerline pollutant concentrations at 5000 m distance from the diffuser downstream were also predicted using the same 17 m current speed and direction. Plots of these time series results for September and January campaigns can be found in Fig. 8 and Fig. 9.
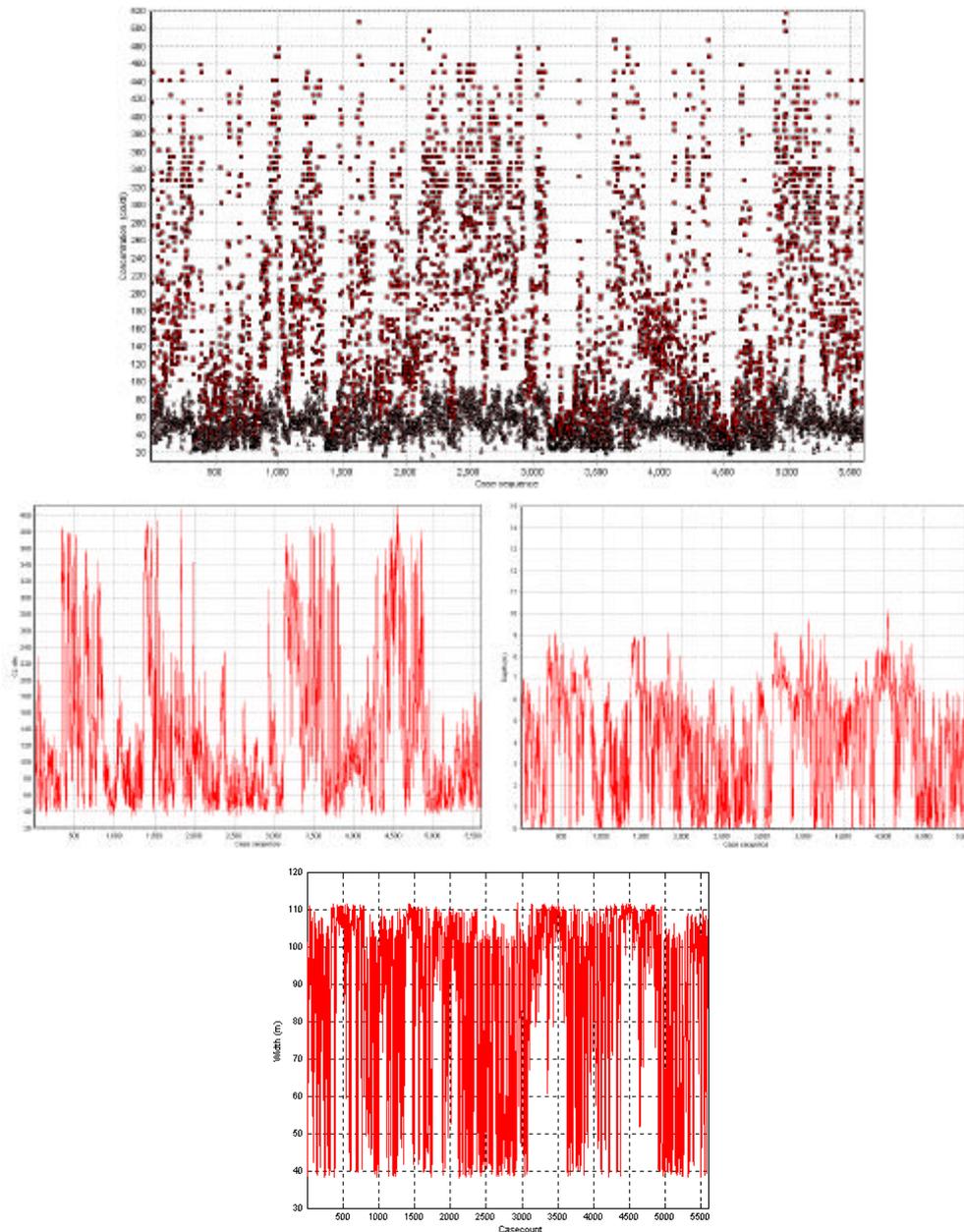

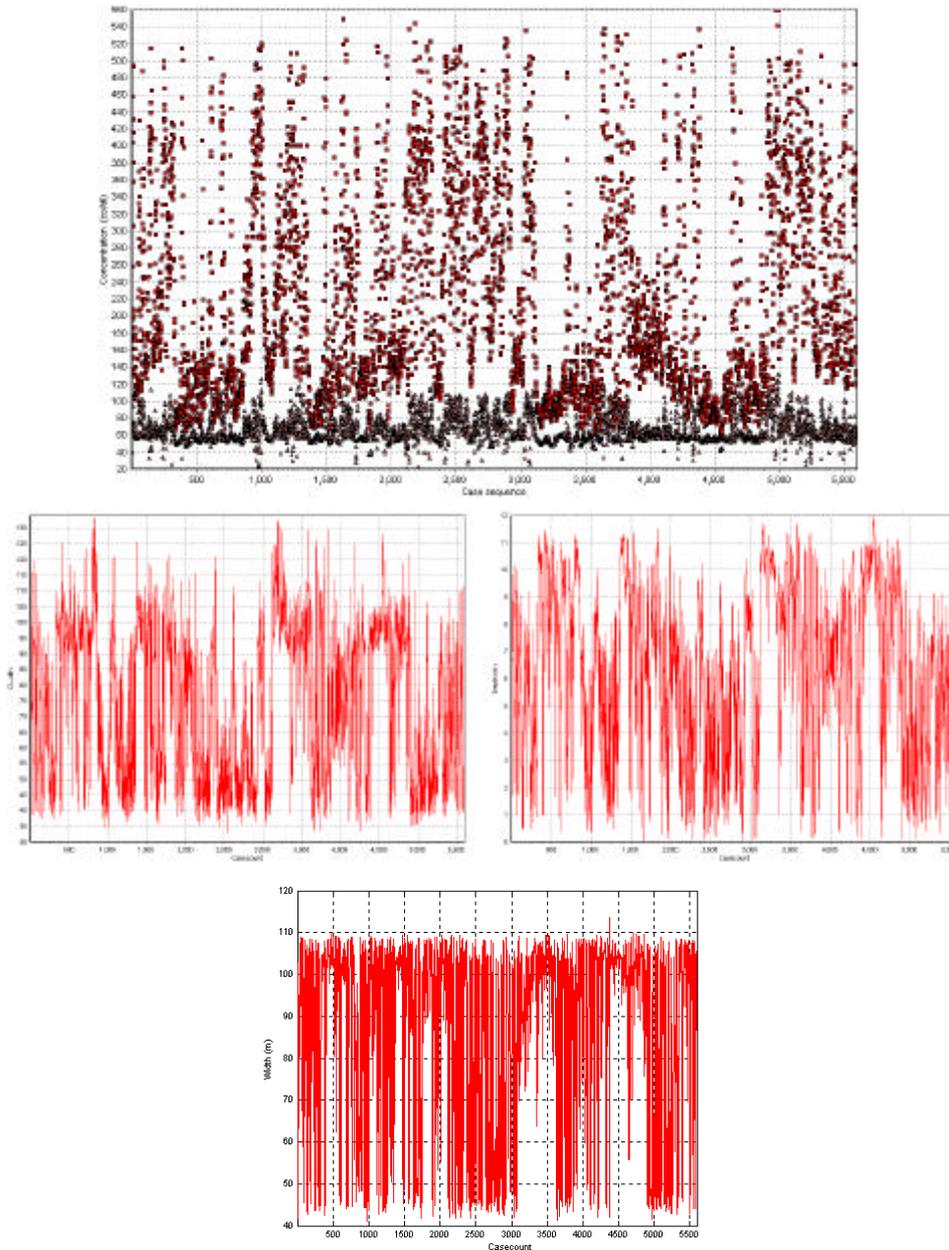Fig. 8. Simulation results for A3 station of the September 2000 campaign.

Fig. 9. Simulation results for A5 station of the January 2001 campaign.

Since in UM3 the discharge is only from one side of the diffuser, half reduced port spacing was considered in order to preserve the total diffuser length and the discharge per unit diffuser length, recommendation of reference (Frick et al., 2000). The reported results are considered at the plume terminal rise height considering any further mixing that occurs in the spreading layer up until the end of near field.

No significant difference was found in the simulation results of A3 and A5 profiles for the same campaign, but important differences were found between the three seasons. Higher plume centerline heights reaching a maximum value of 12 m are found in the January campaign where the plume tends to be more frequently submerged. The range variation of this plume parameter decreases slightly in the June simulation (not showed) and reaches the lowest values in the September results, between 7 m and the surface.

Consequently, the higher dilutions occur in September when the plume is always at the surface. The centerline dilution plot for this month (Fig. 8) indicates maximum values around 1:380 while in January this value is less than 1:130. Inversely, slightly higher average pollutant concentrations at the end of near field, given by the rectangles in the concentration plots, are found in the January simulations reaching maximum value of 560 col/dl. The far field centerline pollutant concentrations predicted at 5000 m distance from the diffuser (the distance to the mouth of the estuary) are given by the triangles in the concentration plots. These concentrations are similar to the all results and range between 20 and 100 col/dl. Stronger and weaker density stratification over the water column demonstrated to play an important role in the plume behavior for the three seasons. This parameter controls the centerline height of the plume affecting average and centerline dilution.

Mission Plan

Monitoring missions using the Isurus AUV are being prepared for the S. Jacinto outfall. Until now the seawater quality standards, in the stations considered, have been achieved but there is no real knowledge of the impacts of wastewater discharge in the area. We expect to be able to detect and map the plume using the CTD measurements of the missions that the vehicle will be able to perform in the vicinity of the outfall. If possible, the graphical representation of temperature and salinity on a T-S diagram with initial mixing lines between wastewater and ambient waters will be used to estimate plume dilution in the near field (Petrenko et al., 1998).

This large amount of simulations considering a wide range of oceanographic and flowrate conditions gave us a better idea of the plume behavior in this three times of the year. We can expect the initial mixing zone length to be always less than 200 m (Ramos et al., 2001), the near field width of the plume under 110 m and the centerline height to be between 12 m and the surface, which are suitable operational conditions for Isurus. Vertical sections, were the Isurus vehicle can perform yo-yo shaped transects, are not particularly useful in this case of near field monitoring. With a 10º-dive angle the vehicle can perform minimum cycles of 150 m in yo-yos of 13 m amplitude. So, horizontal transects at different depths with a 3 m resolution performed in the first 250 m downstream seem to be a right choice for these specific conditions. The horizontal trajectories of 150 m length will be spaced of 50 m. The high frequency sampling of the CTD sensor, around 3.6 Hz, will provide enough horizontal and, when necessary, vertical resolution for characterizing the dispersal of the outfall plume in reasonable spaced transects.

Conclusions

Plume models do not predict the wastefields patchiness that has been observed in field tests. Advanced field instrumentation is expected to better understand and model the mixing process under real oceanic conditions. The Isurus AUV can certainly be a very useful instrument since enables efficient data collection required in this case but its successful use depends crucially on a sampling strategy. In this paper we presented an efficient monitoring mission plan for S. Jacinto outfall supported by a near field prediction study using UM3 model. This study gave us a better understanding of the wastefield behavior in three different times of the year.

During the Isurus mission, in addition to flowrate, simultaneous measurements of the oceanographic conditions will be collected, namely density and current velocity and direction over the all water column. These data will be integrated into some commonly used near field mathematical models such as UM3 (Frick et al., 2000), RSB (Roberts et al., 1989) and CORMIX (Akar et al., 1991). The sampled results of the Isurus mission can be easily compared with the predictions of those models in order to evaluate its performance under the considered conditions, bringing significant improvements to ocean outfall plume behavior prediction.

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