Foz do Arelho Outfall Plume Predictive Study

P. Ramos[1,2], S. Carvalho[3]
patricia@fe.up.pt; s.carvalho@aguasdooeste.com
[1]Faculty of Engineer of University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[2]Institute of Accountancy and Administration of Porto, Dept. of Mathematics
R. Jaime Lopes Amorim, 4465-004 S. M. Infesta, Portugal
[3]Águas do Oeste, S.A., Convento de S. Miguel das Gaeiras, 2510-718 Óbidos, Portugal
Phone: +351 960084473, Fax: +351 225081443

***Abstract*-A seawater quality monitoring program for Foz do Arelho outfall has already started in May 2006 to evaluate the background seawater quality around the vicinity of the sea outfall and to follow the impacts of wastewater discharge in the area. Seven monitoring campaigns were already performed between 2006-2007 in which CTD and ADCP measurements were obtained in the vicinity of the wastewater discharge. Predictions of the plume behavior for several times of the year were obtained using a near field model with the monitoring data as input. The plume behavior was mostly influenced by density stratification. During stratified conditions the plume was trapped with dilutions always above 270 to 1. During unstratified conditions the plume was surfacing with dilutions above always 375 to 1. It is concluded that the outfall is behaving as expected.**

I. Introduction

Typically, the behavior of a sea outfall discharge is a process that can be described as follows. The wastewater is usually ejected as an array of turbulent buoyant jets from ports spaced along the outfall diffuser. These turbulent buoyant jets generate intense mixing with the ambient seawater, usually resulting in rapid reductions of contaminant concentrations [1]. The seawater present around coastal outfalls is often density stratified with density increasing with depth. The discharge, whose density is close to fresh water, is lighter than the surrounding ambient and the plumes rise due to buoyant forces until they reach a level of neutral buoyancy where the effluent spreads laterally, creating an horizontal spreading layer. This moment is called the end initial mixing region, or the end of near field. Depending on the strength of seawater stratification, currents and other variables, the horizontal spreading layer may be submerged and will not be visible at the water surface. If the receiving waters are homogeneous or weakly stratified, the plumes will reach the surface and spread horizontally away from the source [2].

Águas do Oeste authority has been monitoring the coastal environment since the beginning of Foz do Arelho outfall operation, to better understand the extents of the wastefield under different ambient conditions, and to evaluate the potential impacts of the plume in the area [3]. Several monitoring campaigns were already conducted in which were obtained in-situ measurements of current speed and direction, with a downward-looking Acoustic Doppler Current Profiler (ADCP) (Workhorse Sentinel 600kHz model), and CTD (conductivity, temperature, depth) vertical profiles.

One way to better understand the evolution of an effluent plume in the near field is to simulate it by using an appropriate model that accounts for influences such as the outfall configuration, characteristics of the discharge, bathymetry of the coastal environment, and ambient conditions. By using monitoring data to help generate input to the model, when all the information needed has been specified, the model would predict the spatial evolution of the plume under the conditions of interest [4,5].

In this paper we present an extensive modeling study of the Foz do Arelho outfall sewage plume, using representative ambient conditions of each time of the year effectively measured, to understand how the wastewater plume actually migrates and dissipates in the coastal environment under continually evolving seasonal influences. The near field mathematical model used was RSB.

RSB is a plume dispersion model based on the extensive experiments on multiport diffusers in density-stratified currents of arbitrary direction [6]. It is a length scale model that uses semiempirical formulations based on the relative magnitudes of the dominant length scales of the problem. The model output consists of the plume characteristics (dilution, rise height, and wastefield thickness) at the end of the near field [7].

The paper is organized as follows. In section II we describe the study area, giving some details about the Foz do Arelho outfall and the seawater quality monitoring program that has already started in May 2006. In Section III we present the in-situ measurements collected in seven campaigns conducted in 2006 and 2007, in May 4, 2006; July 27, 2006; October 30, 2006; March 16, 2007; July 17, 2007; September 13, 2007 and November 14, 2007. Then in Section IV we give details about the modeling and present the plume behavior prediction results. We end with Section V giving the conclusions.

II. Study Syte

The study site is shown in Fig. 1. The Foz do Arelho outfall is located off the Portuguese west coast near the Óbidos lagoon. In operation since June 2005, is presently discharging about 0.11 m^3/s of mainly domestic wastewater from the WWTPs of Óbidos, Carregal, Caldas da Rainha, Gaeiras, Charneca and Foz do Arelho, but it can discharge up to 0.354 m^3/s. The outfall, made of HDPE, is 2150 m long, 710 mm diameter. The last 93.5 m is the diffuser, consisting of 10 ports nominally 110 mm diameter, spaced 8 or 12 meters apart. These are discharging upwards at an angle of 90º to the horizontal axis; the port height is about 1 m. The outfall is oriented SE-NO (~315.5º true bearing) and is discharging at a depth of about 31 m. In that area the coastline itself runs at about a 225º angle with respect to true north and the isobaths are oriented parallel to the coastline.

A seawater quality monitoring program for this outfall has already started in May 2006. Its main purposes are to evaluate the background seawater quality both in 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, sampling sessions are organized four times a year, once per season. In 2006 and 2007, seven monitoring campaigns were conducted in the following dates: May 4, 2006; July 27, 2006; October 30, 2006; March 16, 2007; July 17, 2007; September 13, 2007 and November 14, 2007. The location of the five measurement points established at different depths around the outfall is shown in Fig. 1. Measurement point P_1 (N 39.4478º, E -9.2463º) is located at the offshore extremity of the diffuser. Measurement points P_2 (N 39.4569º, E -9.2349º) and P_3 (N 39.4406º, E -9.2563º) are distanced, respectively, 1.4 km north and 1.1 km south of the diffuser end at the same depth. Measurement points P_4 (N 39.4443 º, E - 9.2423 º) and P_5 (N 39.4514 º, E - 9.2505 º) are distanced 0.5 km, respectively east and west of the diffuser end.

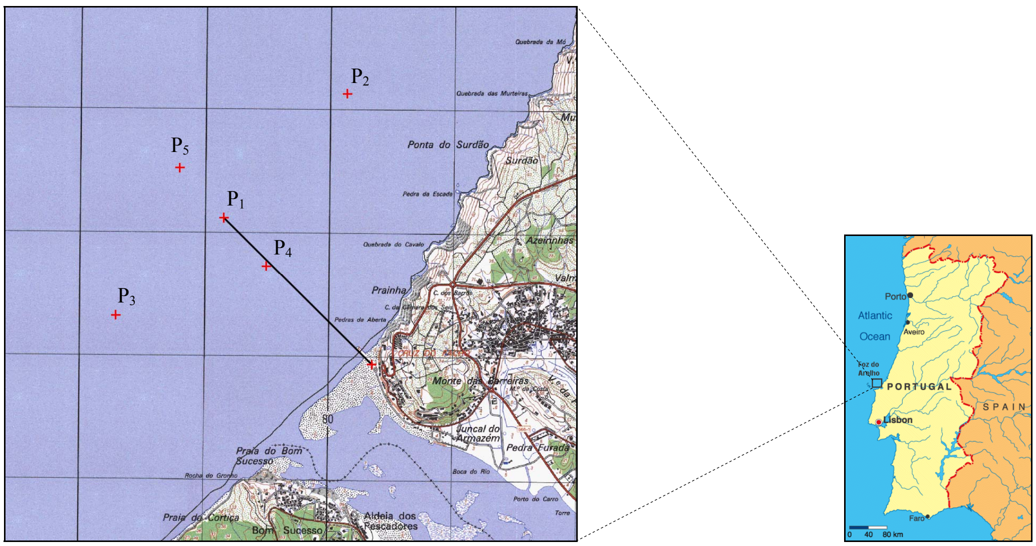

Fig. 1 Map of Foz do Arelho outfall and current measurement points.

III. Oceanographic Measurements

In all the monitoring campaigns in-situ measurements of temperature, salinity, dissolved oxygen, chlorophyll, turbidity and pH were obtained in some or in all the sampling points.

In May 4, 2006 were obtained measurements at sampling points P_2 and P_3; in July 27, 2006 were obtained measurements at sampling points P_1 – P_5; in October 30, 2006 were obtained measurements at sampling points P_1 and P_3; in March 16, 2007 were obtained measurements at sampling points P_1, P_2, P_4, and P_5; in July 17, 2007 were obtained measurements at sampling points P_1 – P_5; in September 13, 2007 were obtained measurements at sampling points P_1, P_3, and P_5; in November 14, 2007 were obtained measurements at sampling points P_1 – P_5. In July 27, 2006, October 30, 2006, March 16, 2007 and July 17, 2007 campaigns, measurements of currents were also obtained near the offshore extremity of the diffuser using an Acoustic Doppler Current Profiler (ADCP) RDI Sentinel® 600-kHz broadband. In July 27, 2006 the ADCP was set to record current speed and direction at 5-minutes intervals from 2.5 to 29.5 m depth in bins spaced 1.5 m apart. In October 30, 2006 it was set to record current speed and direction at 3-minutes intervals from 2.0 to 30.0 m depth in bins spaced 1.0 m apart. In March 16, 2007 it was set to record current speed and direction 1-minute intervals from 2.0 to 30.0 m depth in bins spaced 1.0 m apart. In July 17, 2007 it was set to record current speed and direction at 3-minutes intervals from 2.0 to 25.0 m depth in bins spaced 1.0 m apart.

A. Unstratified Conditions

Experiments of May 4, 2006; October 30, 2006; March 16, 2007 and November 14, 2007

The campaigns on May 4, 2006, October 30, 2006, March 16, 2007 and November 14, 2007 were performed to study the behavior of the plume under unstratified conditions. The vertical profile measurements of temperature, salinity and density obtained at the sampled points are shown in Fig. 2 – 5. The profile measurements associated to a sampling point are plotted with the same color: P_1 – P_5 data were plotted respectively in black, green, blue, red and magenta. For a better comparison of the same parameter in different campaigns, measurements of the same parameter were plotted using the same scale.

The temperature and salinity differences over the water column are of most interest, as they affect the strength of the density stratification. The temperature difference between the bottom and the surface was about 1.4ºC on May 4, 2006, about 1.0ºC on October 30, 2006, between 0.4 – 0.9ºC on March 16, 2007, and between 0.1 – 0.4ºC on November 14, 2007. Salinity differences over the water column were very low in all the campaigns. They were about 0.11 psu on May 4, 2006, between 0.02 – 0.05 psu on October 30, 2006, between 0.04 – 0.10 psu on March 16, 2007, and between 0 – 0.08 psu on November 14, 2007. The little density difference between the bottom and the surface in all the campaigns was then mostly due to temperature variations. The total density difference over the water column was about 0.4 σ_t on May 4, 2006, about 0.3 σ_t on October 30, 2006, between 0.2 – 0.3 σ_t on March 16, 2007, and between 0.15 – 0.18 σ_t on November 14, 2007. (A σ_t unit is a density difference of 1 kg/m^3.) We may say that on November 14, 2007 the water column was completely homogeneous. Time and depth variation of current vectors measured by the ADCP on October 30, 2006 and March 16, 2007 campaigns are shown in Fig. 6. The depth-averaged currents profile of October 30, 2006 campaign reveals that surface waters, down to a depth of about 21 m, move generally to the SSE at speeds between 5 and 8.5 cm/s; the deeper currents are slower, with speeds generally between 2.5 to 5 cm/s, and move to the ESE. The average current velocity and direction over the whole water column was 5.9 cm/s and 144º. The depth-averaged profile of March 16, 2007 campaign shows again weak currents with speeds up to 9 cm/s that move between SE and SW. The measurements at the uppermost level were considered unreliable due to surface effects. The average current velocity and direction was 5.1 cm/s and 172º over the whole water column, excepting for the uppermost level.

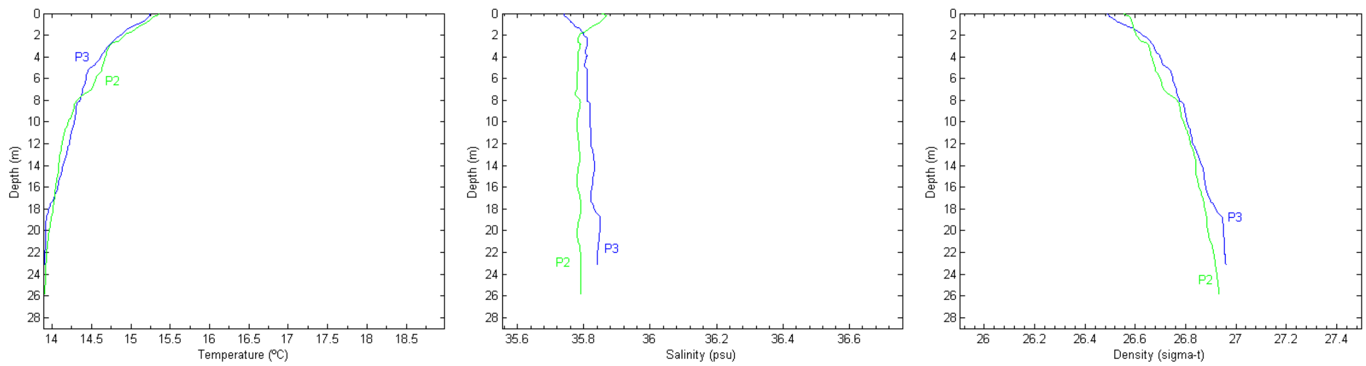

Fig. 2 Temperature, salinity and density at sampled points during May 4, 2006 campaign.

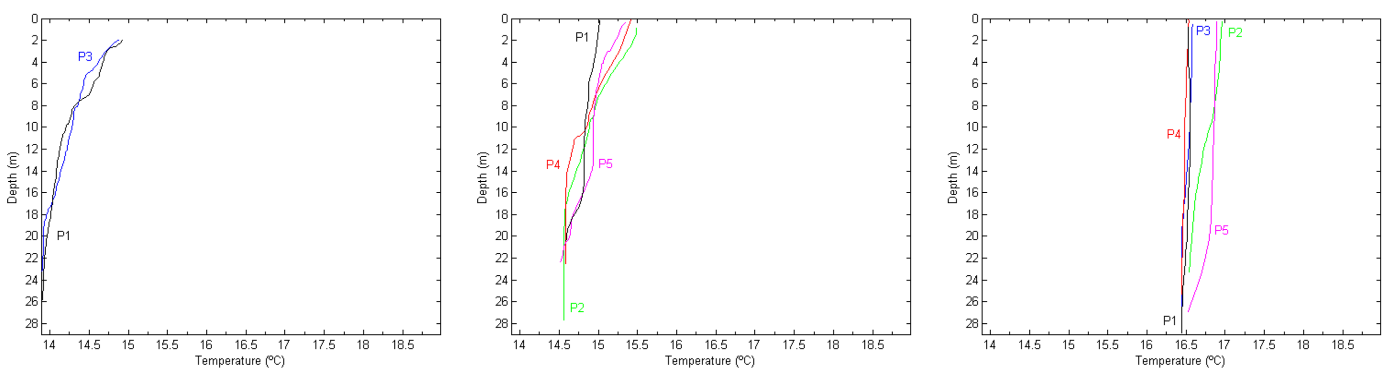

Fig. 3 Temperature at sampled points during (from left to right) October 30, 2006, March 16, 2007 and November 14, 2007 campaigns.

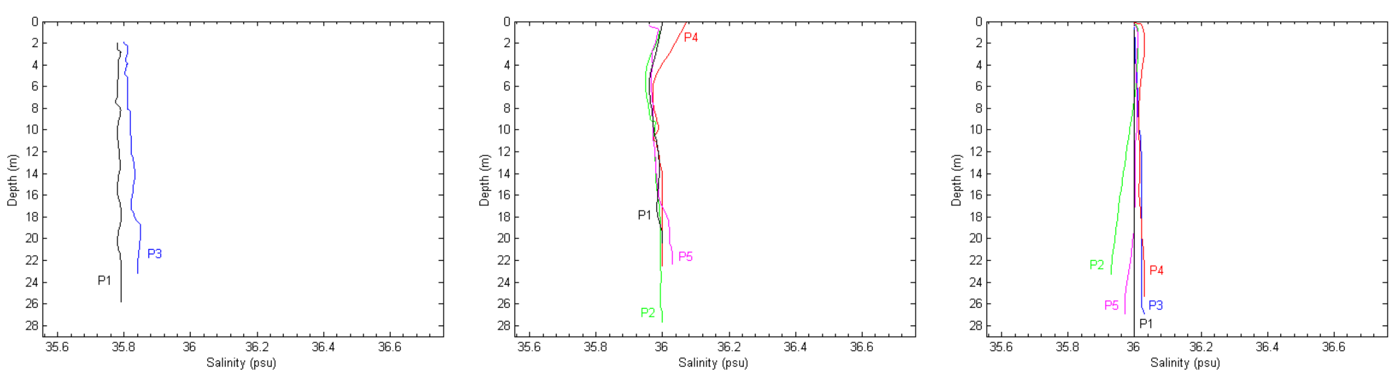

Fig. 4 Salinity at sampled points during (from left to right) October 30, 2006, March 16, 2007 and November 14, 2007 campaigns.

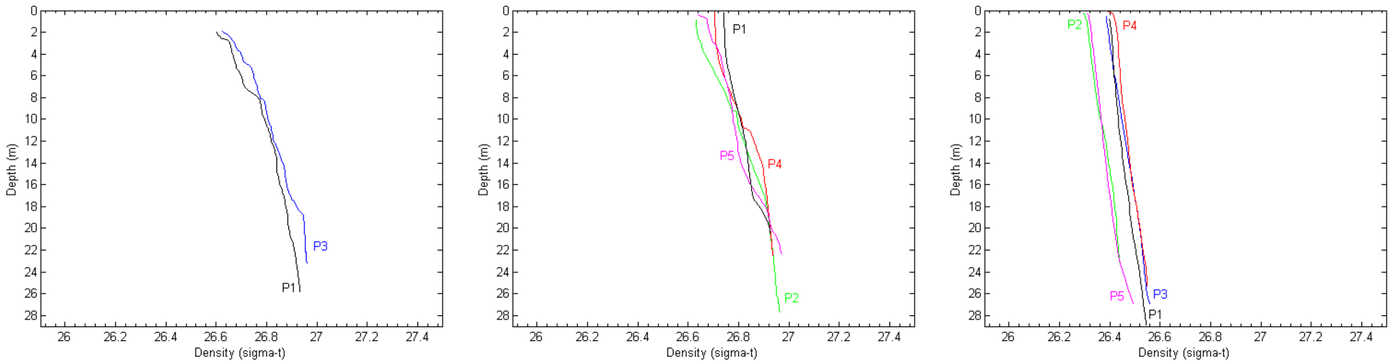

Fig. 5 Density at sampled points during (from left to right) October 30, 2006, March 16, 2007 and November 14, 2007 campaigns.

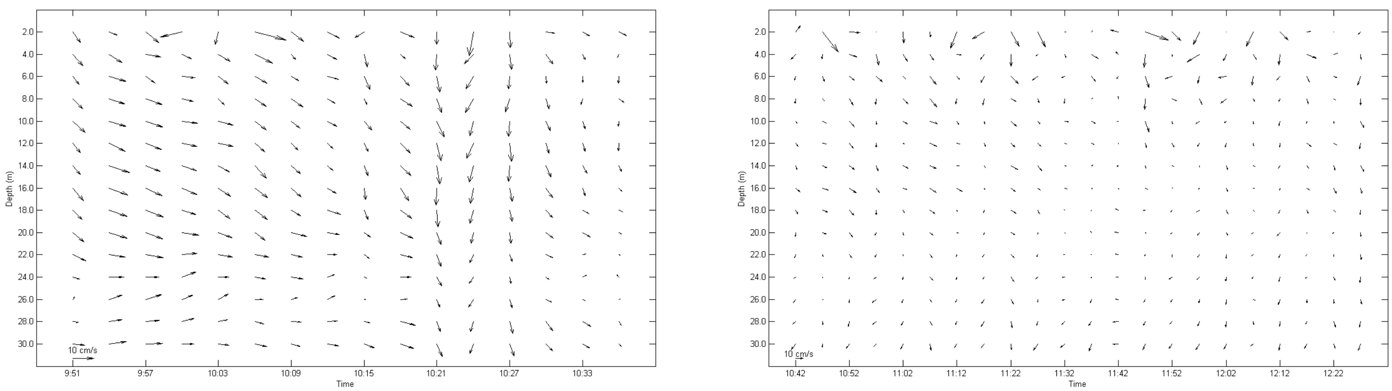

Fig. 6 Time and depth variation of current vectors measured by the ADCP on (from left to right) October 30, 2006 and March 16, 2007 campaigns.

B. Stratified Conditions

Experiments of July 27, 2006; July 17, 2007 and September 16, 2007

The campaigns of July 27, 2006, July 17, 2007 and September 13, 2007 were performed to study the behavior of the plume under stratified conditions. The vertical profile measurements of temperature, salinity and density obtained at the sampled points are shown in Fig. 7 – 9. In all the three campaigns the water column was stratified mainly due to temperature variations. Total temperature differences were, between 1.7 – 2.2ºC on July 27, 2006, between 3.0 – 3.2ºC July 17, 2007, and between 3.4 – 3.7ºC on September 13, 2007, with variations extending almost over the water column. Salinity variations between the bottom and the surface were between 0.08 – 0.13 psu on July 27, 2006, between 0.17 – 0.43 psu July 17, 2007 and about 0.05 psu on September 13, 2007. Density differences over the water column were about 0.5 σ_t on July 27, 2006, between 0.5 – 0.7 σ_t on July 17, 2007 and about 1.0 σ_t on September 13, 2007. Time and depth variation of current vectors measured by the ADCP on July 27, 2006 and July 17, 2007 are shown in Fig. 10. During July 27, 2006 campaign, surface waters down to a depth of about 14.5 m move generally to the South at speeds up to 30 cm/s; the deeper currents are slower, with speeds generally between 1 to 12 cm/s, and move to the WNW. The depth-averaged profile shows speeds between 8 and 30 cm/s above 14.5 m depth and speeds less than 8 cm/s for the deeper waters. The average current velocity and direction over the whole water column was 8.8 cm/s and 198º. The depth-averaged profile of July 17, 2007 campaign shows weaker currents. The predominant currents directions were to the south above 10 m depth. Deeper currents move generally to N and NE. The average current velocity and direction over the whole water column was 2.2 cm/s and 93º.

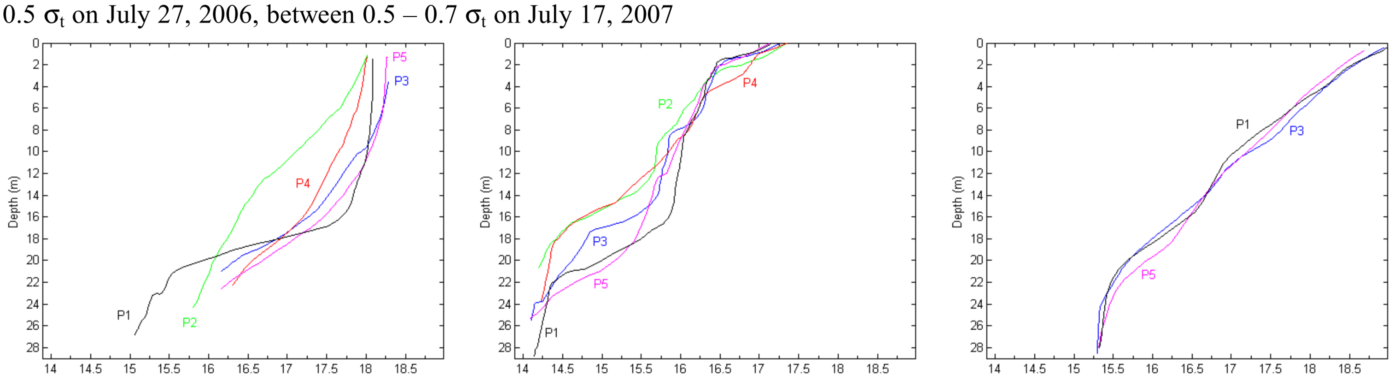

Fig. 7 Temperature at sampled points during (from left to right) July 27, 2006, July 17, 2007 and September 13, 2007 campaigns.

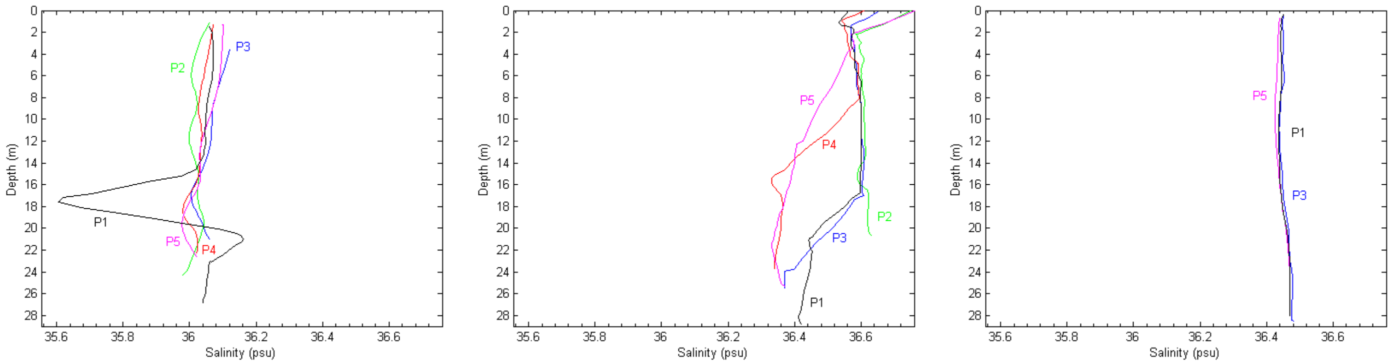

Fig. 8 Salinity at sampled points during (from left to right) July 27, 2006, July 17, 2007 and September 13, 2007 campaigns.

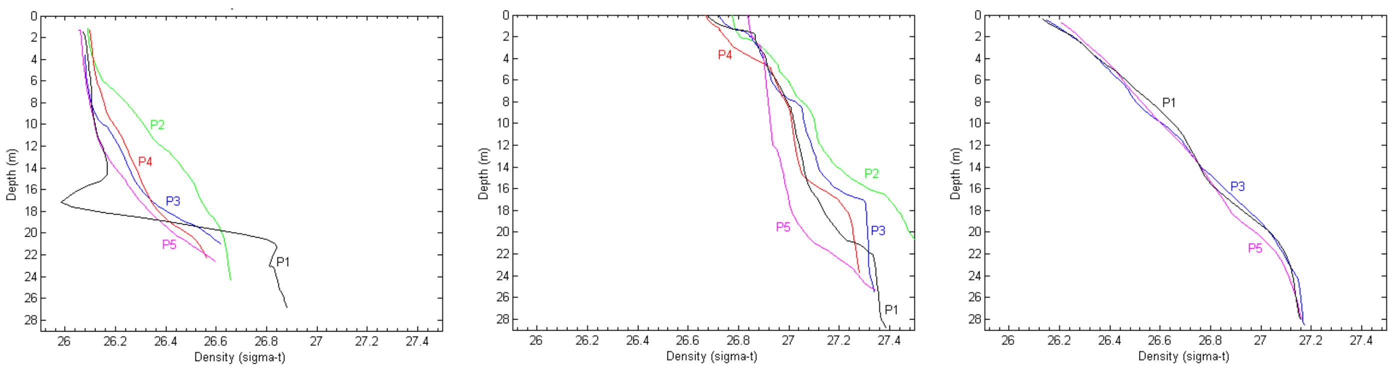

Fig. 9 Density at sampled points during (from left to right) July 27, 2006, July 17, 2007 and September 13, 2007 campaigns.

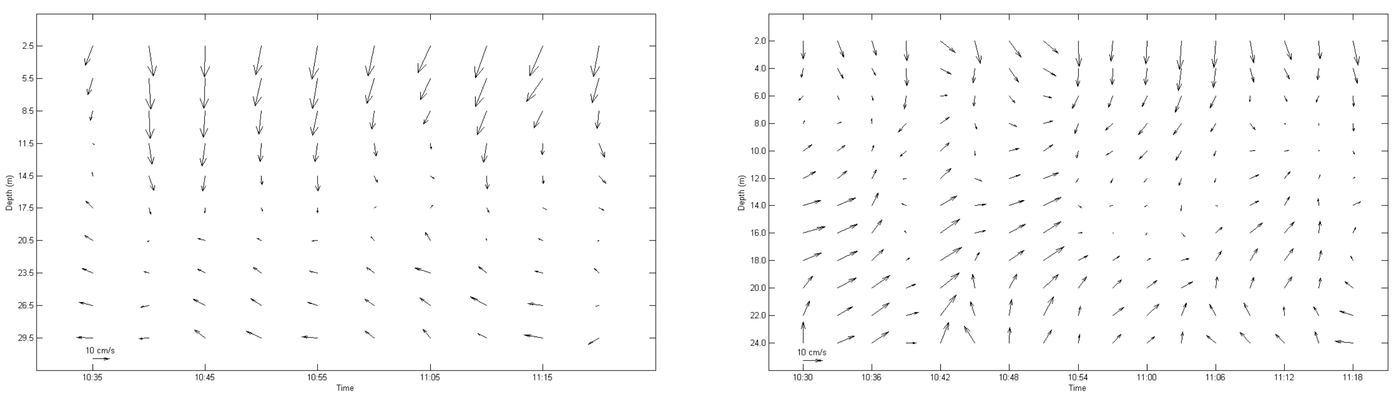

Fig. 10 Time and depth variation of current vectors measured by the ADCP on (from left to right) July 27, 2006 and July 17, 2007 campaigns.

IV. Modeling Results

RSB integrates equations based on experimental work on multiport diffusers. These experiments incorporate the most important hydrodynamic aspects of ocean outfalls, including the effects of arbitrary current speed and direction (including parallel currents), stratification, port spacing, source momentum flux, discharges from both sides of the diffuser and the resulting merging of the plumes from both sides, re-entrainment and additional mixing in the spreading layer, direct plume impingement in parallel currents, and lateral gravitational spreading [8]-[12]. In addition to the laboratory data, the model has been validated against other data, including data from the field tracer and laboratory experiments for the San Francisco outfall [13], from the field tests in the Whites Point, Los Angeles outfall [14] and in the Sand Island, Hawaii outfall [15], and more recently from the field tracer of the Boston outfall [16].

The model predictions are the plume characteristics at the end of near field, which include minimum dilution, S_m, rise height to the top of the wastefield, z_e, spreading layer thickness, h_e, the height to the level of minimum dilution, z_m, and length of the near field, x_i (see Fig. 11).

Simultaneously measured flow rate, density stratification, and current speed and direction should be preferentially used in a model simulation, in order to predict the actual plume behavior during the time period considered.

Simultaneously measured density stratification and current speed and direction were used in the modeling simulation of July 27, 2006; October 30, 2006; March 16, 2007 and July 17, 2007 conditions. In the modeling simulation of May 4, 2006;

September 13, 2007 and November 14, 2007 conditions, that was not possible, since on those campaigns currents were not measured. To be able to perform simulations in a wide range of reasonable conditions considering the best and the worst situations, density stratification conditions of those campaigns were combined with the four ADCP current profiles available.

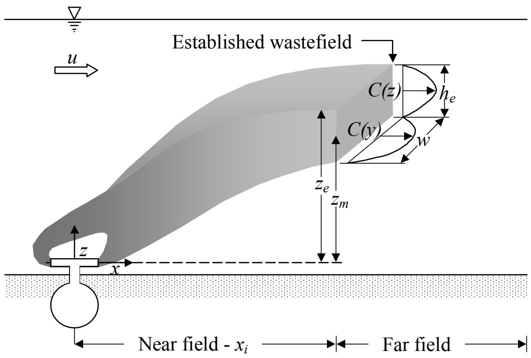

Fig. 11 Wastefield details (adapted from [2]).

Actual flow measurements of a typical day (April 27, 2006) obtained from AdO authority were used (see Fig. 12). The average value of flow on that day, used in the modeling simulations, was 0.11 m^3/s.

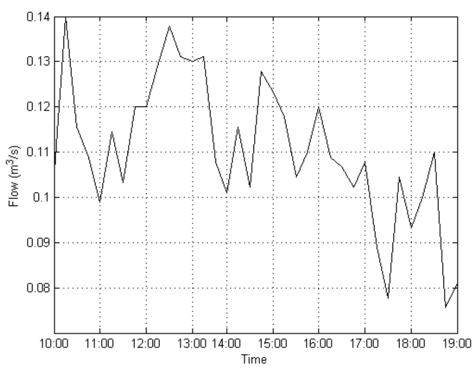

Fig. 12 Effluent flow measured on April 27, 2006.

TABLE I
SUMMARY OF RSB MODELING CONDITIONS

Effluent:	
Flow rate (m^3/s)	0.11
Temperature (ºC)	19
Salinity (psu)	2.3
Discharge depth (m)	30
Diffuser:	
Nº of ports	10
Ports spacing (m)	23.4
Ports diameter (m)	0.11
Orientation of diffuser axis to North (º)	135.5

Some assumptions are required for the model inputs [7]. The diffuser variables are given in Table I. The port depths were assumed to be at 30 m depth, with each port discharging equally. The currents were assumed constant and uniform over the plume rise height and equal to the depth-averaged current vector over the water column (for surfacing situations), and over part of the water column (for submerge situations). Since RSB assumes ports discharging horizontally from both sides of the diffuser, the port spacing was doubled. This approximation, done in order to preserve the total diffuser length and the discharge per unit diffuser length, is recommended in [17].

The modeled plume characteristics at the end of near field, obtained for the several times of the year simulated, are summarized in Table II. The predicted characteristics are the plume minimum depth ($30 - z_e$), the thickness of the spreading layer, h_e, the minimum dilution depth ($30 - z_m$), the length of the near field, x_i, the near field dilution, S_m, and the plume heading. Also shown is the value of the Froude number, $F = u^3 / b$ (u is the ambient current speed and b is the buoyancy flux per unit length). For long multiport ocean outfall diffusers, F is one of the most important parameters governing the dynamics and mixing of the flow in the near field. Experiments on diffusers in both unstratified [9, 10] and stratified [6, 11, 12] flows show that for Froude numbers less than about 0.1, the effect of the current on dilution is negligible. As the current speed is increased only slightly $(F \approx 0.1)$ the upstream layer is expelled and all of the flow is swept downstream. Increasing the current speed further to $F \approx 1$ causes the plumes from opposite sides of the diffuser to rapidly merge, and the wastefield takes on a wave-like form that does not appear at smaller or larger values of F. A change in the mixing process occurs as the current speed increases further. At low current speeds (e.g. at $F \approx 0.1$) the flow has the normal plume-like pattern with the plume bent downstream. At higher current speeds (e.g. at $F \approx 10$) the plume cannot entrain all of the incoming flow while maintaining the free plume pattern and the wastefield bottom stays at the nozzle level. This is known as the forced entrainment regime, and it occurs when the current Froude number exceeds a value which lies somewhere between 1 and 10. The rise height and thickness of the wastefield decrease with increasing current speed in the forced entrainment regime.

According to modeling results, on July 27, 2006, July 17, 2007 and September 13, 2007 during stratified conditions, the plume was submerged. During unstratified conditions, on May 4, 2006, October 30, 2006, March 16, 2007 and November 14, 2007, the plume was predicted to be surfacing or near the surface.

On July 27, 2006, with a density difference over the whole water column of about 0.5 σ_t, the plume was submerged between 10.1 m and 13.6 m with a thickness between 13.7 m and 16.6 m. The minimum dilution occurred between 16.7 m and 19.0 m, which is in accordance with salinity profile measure at point P_1 at the offshore extremity of the diffuser (see the plot on Fig. 8). The minimum dilution was between 297 and 341. The RSB predicts the length of the near field to be within about 36 – 42 m from the diffuser.

TABLE II

SUMMARY OF NEAR FIELD MODELING RESULTS

Campaign	Sampled Points	Froude Number	Minimum Depth (m)	Spreading Layer Thickness (m)	Minimum Dilution Depth (m)	Near Field Length (m)	Near Field Dilution	Current Velocity (cm/s)	Direction of Dispersion (º)
May 4, 2006	**P2**	0.07-0.70	4.2	19.3-23.0	12.7	14-60	375-579	2-7-5.9	34, 137-178, 269
	P3	0.07-0.70	4.2	19.3-23.0	12.7	14-60	375-579	2-7-5.9	34, 137-178, 269
July 27, 2006	**P2**	0.38	10.1	16.6	16.7	42	341	4.8	304
	P3	0.38	12.7	14.5	18.4	36	298	4.8	304
	P4	0.38	10.6	16.2	17.0	40	332	4.8	304
	P5	0.60	13.6	13.7	19.0	38	297	5.6	305
October 30, 2006	**P1**	0.52	4.2	21.2	12.7	60	451	5.4	137
	P3	0.52	4.1	21.3	12.7	61	453	5.4	137
March 16, 2007	**P1**	0.45	0.0	26.3	0.0	54	560	5.1	172
	P2	0.24	5.1	22.0	13.3	36	424	4.2	178
	P4	0.27	0.4	26.0	10.2	46	510	4.3	173
	P5	0.25	3.4	23.5	12.2	39	453	4.2	176
July 17, 2007	**P1**	1.11	14.1	14.1	19.4	42	450	7.0	29
	P2	1.17	13.7	14.5	19.1	44	465	7.1	27
	P3	0.92	8.1	19.5	15.3	48	521	6.5	32
	P4	0.92	7.6	20.0	15.0	49	533	6.5	32
	P5	1.18	15.8	12.7	20.5	39	407	7.1	27
September 13, 2007	**P1**	0.28-1.27	13.5-15.8	12.6-14.7	18.9-20.5	25-40	276-409	4.4-7.3	25, 122-194, 305
	P3	0.28-1.27	13.8-15.3	13.1-14.4	19.2-20.2	24-41	270-423	4.4-7.3	25, 122-194, 305
	P5	0.28-1.27	13.4-15.5	12.9-14.0	18.9-20.3	25-41	277-417	4.4-7.3	25, 122-194, 305
November 14, 2007	**P1**	0.04-2.30	0.0	22.5-26.7	0.0	16-106	434-963	2.2-8.8	93-198
	P2	0.04-2.31	0.0	22.5-26.7	0.0	16-106	434-962	2.2-8.8	93-198
	P3	0.04-2.30	0-1.7	22.4-26.3	0-11.0	16-100	434-908	2.2-8.8	93-198
	P4	0.04-2.30	0.0	22.5-26.7	0.0	16-106	434-963	2.2-8.8	93-198
	P5	0.04-2.31	0-1.8	22.5-26.3	0-11.1	16-100	434-906	2.2-8.8	93-198

On July 17, 2007, with a density difference over the whole water column between about 0.5 – 0.7 σ_t, the plume was submerged between about 7.6 m and 15.8 m with a thickness between 12.7 m and 20.0 m. The minimum dilution occurred between 15.0 m and 20.5 m and varied between about 407 and 533. The length of the near field predicted was within about 39 – 49 m from the diffuser.

On September 13, 2006, with a density difference over the whole water column of about 1.0 σ_t, the plume was submerged between 13.4 m and 15.8 m with a thickness between 12.6 m and 14.8 m. The minimum dilution occurred between 18.9 m and 20.5 m and varied between 270 and 423, with the higher values occurring induced by the stronger currents (July 17, 2007) and the lower values occurring induced by the weaker currents (October 30, 2006). Note also that, in general, the length of the near field is shorter for the weaker currents and longer for the stronger currents, ranging from 24 – 41 m.

On May 4, 2006, with a density difference over the whole water column of about 0.4 σ_t, the plume was found always at 4.2 m depth with the minimum dilution occurring always at 12.7 m depth, even considering different current profiles. Notice that the results obtained using the density profiles from measurement points P_2 and P_3 were the same, since there is almost no difference between these two profiles. The wastefield thickness predicted was between 19.3 m and 23.0 m. The higher values of minimum dilution and near field length occurred induced by stronger currents, and the lower values occurred induced by the weaker currents, varying respectively, between 1:375 and 1:579, and 14 m and 51 m.

On October 30, 2006, with a density difference over the whole water column of about 0.3 σ_t, no significant differences where found on the results obtained using the density profiles from measurement points P_1 and P_3. The plume was found almost surfacing at ~4.2 m depth with minimum dilution value of about ~451 occurring at 12.7 m. The spreading layer thickness at about 60 m from the diffuser was ~21.2 m.

On March 16, 2007, with a density difference over the whole water column between 0.2 – 0.3 σ_t, the plume was found surfacing or almost surfacing, between 0 and 5.1 m depth, with a thickness between 22.0 m and 26.3 m. The minimum dilution occurred between 0 and 13.3 m and varied between about 424 and 560. The RSB predicts the length of the near field to be within about 36 – 54 m from the diffuser.

On November 14, 2007, with a density difference over the whole water column between 0.15 – 0.18 σ_t, the plume was found surfacing for almost all of the current profile conditions simulated, with few exceptions induced by stronger currents and slightly higher stratifications. The spreading layer thickness ranged between 22.5 m and 26.7 m, with the lower value associated with the weaker current and the higher value associated with the stronger current. The same situation occurs for minimum dilution values and near field lengths with the higher value of minimum dilution and near field length occurring induced by the stronger current, and the lower value occurring induced by the weaker current, ranging respectively, between 1:434 and 1:963, and 16 m and 106 m. Notice that when Froude numbers were less then about 0.1, currents had little effect on dilution.

V. CONCLUSIONS

The near field behavior of Foz do Arelho sea outfall plume was simulated using effective in-situ measurements of currents and stratification. Density stratification over the water column demonstrated to play an important role in the plume behavior. This parameter controlled plume rise height and thickness, affecting dilution and the length of the near field. On July 27, 2006, July 17, 2007 and September 13, 2007, during stratified conditions, the plume was found submerged. On May 4, 2006, October 30, 2006, March 16, 2007 and November 14, 2007, during unstratified conditions, the plume was found surfacing or near the surface. During stratified conditions the plume is trapped between about 8m to 16 m depth. During unstratified conditions, the plume surfaces or is near the surface above ~4 m depth. Dilution is always high and above 270:1 for submerged conditions and 375:1 for surface conditions. Note that the length of the near field is quite short for these weak currents. RSB predicts it to be always below 60 m. We may conclude that the outfall appears to be well designed and working well, with dilutions always above the reference value of 50:1 for both submerged and surface conditions.

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