Mapping and Dilution Estimation of Foz do Arelho Outfall Plume using an Autonomous Underwater Vehicle

Patrícia Ramos
INESC Porto
Campus da FEUP, Rua Dr. Roberto Frias, 378
4200-465 Porto, Portugal
ISCAP, Rua Jaime Lopes Amorim, s/n
4465-004 S. Mamede de Infesta, Portugal
pramos@inescporto.pt

Nuno Abreu
INESC Porto
Campus da FEUP, Rua Dr. Roberto Frias, 378
4200-465 Porto, Portugal
nabreu@inescporto.pt

Abstract— **In this work geostatistics is used to model and map the spatial distribution of temperature and salinity measurements gathered by an Autonomous Underwater Vehicle in a monitoring campaign to Foz do Arelho outfall, with the aim of distinguishing the effluent plume from the receiving waters, characterizing its spatial variability in the vicinity of the discharge and estimating dilution. The results demonstrate that this methodology provides good estimates of the dispersion of effluent and it is therefore very valuable in assessing the environmental impact and managing sea outfalls.**

I. INTRODUCTION

A. MARES AUV

Autonomous Underwater Vehicles (AUVs) have been used efficiently in a wide range of applications. They were first developed with military applications in mind, for example for mine hunting missions. Later on, scientists realized their true potential and started to use them as mobile sensors, taking measurements in difficult scenarios and at a reasonable cost ([1][2]). MARES (Modular Autonomous Robot for Environment Sampling) AUV has been successfully used to monitor sea outfalls discharges ([3]) (see Fig. 1). MARES is 1.5 m long, has a diameter of 8-inch and weighs about 40 kg in air. It features a plastic hull with a dry mid body (for electronics and batteries) and additional rings to accommodate sensors and actuators. Its modular structure simplifies the system's development (the case of adding sensors, for example). It is propelled by two horizontal thrusters located at the rear and two vertical thrusters, one at the front and the other at the rear. This configuration allows for small operational speeds and high maneuverability, including pure vertical motions. It is equipped with an omnidirectional acoustic transducer and an electronic system that allows for long baseline navigation. The vehicle can be programmed to follow predefined trajectories while collecting relevant data using the onboard sensors. A Sea-Bird Electronics 49 FastCAT CTD had already been installed onboard the MARES AUV to measure conductivity, temperature and depth. MARES' missions for environmental monitoring of wastewater discharges are conducted using a GUI software that fully automates the operational procedures of the campaign ([4]). By providing visual and audio information, this software guides the user through a series of steps which include: (1) real time data acquisition from CTD and ADCP sensors, (2) effluent plume parameter modeling using the CTD and ADCP data collected, (3) automatic path creation using the plume model parameters, (4) acoustic buoys and vehicle deployment, (5) automatic acoustic network setup and (6) real time tracking of the AUV mission.

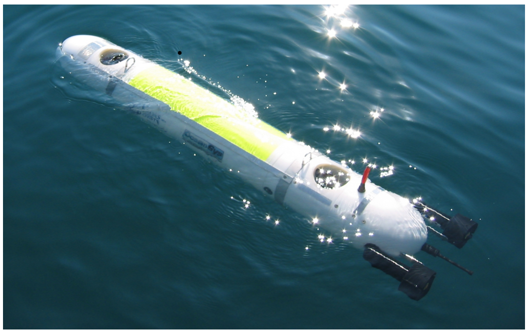


Fig. 1. MARES AUV.

B. Data processing

Data processing is the last step of a sewage outfall discharge monitoring campaign. This processing involves the ability to extrapolate from monitoring samples to unsampled locations. Although very chaotic due to turbulent diffusion, the effluent's dispersion process tends to a natural variability mode when the plume stops rising and the intensity of turbulent fluctuations approaches to zero ([5]). It is likely that after this point the pollutant substances are spatially correlated. In this case, geostatistics appears to be an appropriate technique to model the spatial distribution of the effluent. In fact, geostatistics has been used with success to analyze and characterize the spatial variability of soil properties, to obtain information for assessing water and wind resources, to design sampling strategies for monitoring estuarine sediments, to study the thickness of effluent-affected sediment in the vicinity of wastewater discharges, to obtain information about the spatial distribution of sewage pollution in coastal sediments, among others. As well as giving the estimated values, geostatistics provides a measure of the accuracy of the estimate in the form of the kriging variance. This is one of the advantages of geostatistics over traditional methods of assessing pollution. In this work, universal kriging method [6] is used to model and map the spatial distribution of temperature and salinity measurements gathered by an AUV on a Portuguese sea outfall monitoring campaign. The aim is to distinguish the effluent plume from the receiving waters, characterize its spatial variability in the vicinity of the discharge and estimate dilution.

II. Geostatistical Analysis

A. Study site

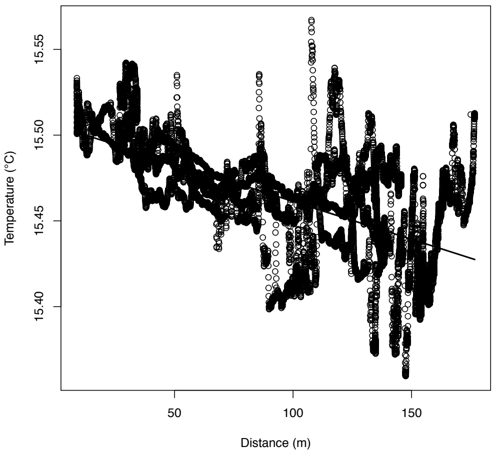
Foz do Arelho outfall is located off the Portuguese west coast near Óbidos lagoon. In operation since June 2005, is presently discharging about 0.11 m^3/s of mainly domestic wastewater from the WWTPs of Óbidos, Carregal, Caldas da Rainha, Gaeiras, Charneca and Foz do Arelho, but it can discharge up to 0.35 m^3/s. The total length of the outfall, including the diffuser, is 2150 m. The outfall pipe, made of HDPE, has a diameter of 710 mm. The diffuser, which consists of 10 ports spaced 8 or 12 meters apart, is 93.5 m long. The ports, nominally 0.175 m in diameter, are discharging upwards at an angle of 90° to the pipe horizontal axis; the port height is about 1 m. The outfall direction is southeast-northwest (315.5° true bearing) and is discharging at a depth of about 31 m. In that area the coastline itself runs at about a 225° angle with respect to true north and the isobaths are oriented parallel to the coastline. A seawater quality monitoring program for the 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. During the campaign the discharge remained fairly constant with an average flowrate of approximately 0.11 m^3/s. The operation area specification was based on the outputs of a plume prediction model [5] which include mixing zone length, spreading width, maximum rise height and thickness. The model inputs are, besides the diffuser physical characteristics, the water column stratification, the current velocity and direction, and the discharge flowrate. Information on density stratification was obtained from a vertical profile of temperature and salinity acquired in the vicinity of the diffuser two weeks before the campaign. The water column was weakly stratified due to both low-temperature and salinity variations. The total difference in density over the water column was about 0.13 σ-unit. The current direction of 110° was estimated based on predictions of wind speed and direction of the day of the campaign. A current velocity of 0.12 m/s was estimated based on historic data. The effluent flowrate consider for the plume behavior simulation was 0.11 m^3/s. According to the predictions of the model, the plume was spreading 1 m from the surface, detached from the bottom and forming a two-layer flow. The end of the mixing zone length was predicted to be 141 m downstream from the diffuser. The AUV operation area (specified according to the model predictions) was mainly in the northeast direction from the diffuser, covering about 20000 m^2. The vehicle collected CTD data at 1.5 m and 3 m depth, in accordance to the plume minimum dilution height prediction. During the mission transited at a fairly constant velocity of 1 m/s (2 knots) recording data at a rate of 16 Hz. Maximum vertical oscillations of the AUV in performing the horizontal trajectories were less than 0.5 m (up and down).

B. Exploratory analysis

In order to obtain elementary knowledge about the temperature and salinity data sets, conventional statistical analysis was conducted. At the depth of 1.5 m the temperature ranged from 15.359°C to 15.562°C and at the depth of 3 m the temperature ranged from 15.393°C to 15.536°C. The mean value of the data sets was 15.463°C and 15.469°C, respectively at the depths of 1.5 m and 3 m, which was very close to the median value that was respectively 15.466°C and 15.472°C. The coefficient of skewness is relatively low (-0.309) for the 1.5 m data set and not very high (-0.696) for the 3 m data set, indicating that in the first case the distribution is approximately symmetric and in the second case that distribution is only slightly asymmetric. The very low values of the coefficient of variation (0.002 and 0.001) reflect the fact that the distributions do not have a tail of high values. At the depth of 1.5 m the salinity ranged from 35.957 psu to 36.003 psu and at the depth of 3 m the salinity ranged from 35.973 psu to 36.008 psu. The mean value of the data sets was 35.991 psu and 35.996 psu, respectively at the depths of 1.5 m and 3 m, which was very close to the median value that was respectively 35.990 and 35.998 psu. The coefficient of skewness is not to much high in both data sets (-0.63 and -1.1) indicating that distributions are only slightly asymmetric. The very low values of the coefficient of variation (0.0002 and 0.0001) reflect the fact that the distributions do not have a tail of high values. Fig. 2 shows the temperature measurements at depth of 1.5 m (top) and 3 m (bottom) versus distance to the middle point of the diffuser fitted by a linear model. A similar behavior was found for the salinity measurements. These figures show that although some variability there is a certain relation between the measurements and the distance between its location and the middle point of the diffuser. For this reason, universal kriging method was applied.

C. Variogram modeling

For the purpose of this analysis, the temperature and the salinity measurements were divided into a modeling set (comprising 90% of the samples) and a validation set (comprising 10% of the samples). Modeling and validation sets were then compared, using Student's-t test, to check that they provided unbiased sub-sets of the original data. Furthermore, sample variograms for the residuals of the modeling sets were constructed using the Matheron's method-of-moments estimator (MME) and the Cressie and Hawkins estimator (CRE) [6]. The CRE estimator was chosen to deal with outliers and enhance the variogram's spatial continuity. An estimation of semivariance was carried out using a lag distance of 2 m. Table I and Table II show the parameters



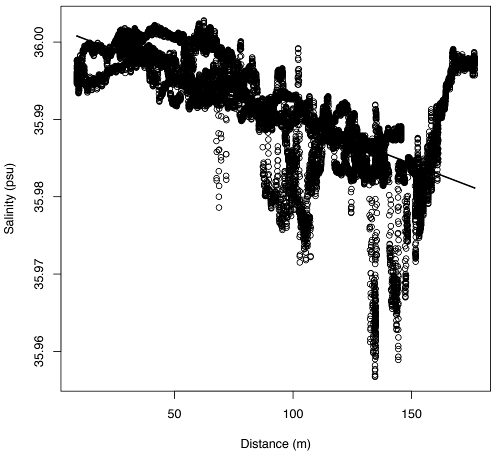


Fig. 2. Temperature measurements at depth of 1.5 m (top) and 3 m (bottom) versus distance to the middle point of the diffuser fitted by a linear model.

of the fitted models to the omnidirectional sample variograms constructed using MME and CRE estimators (for salinity measured at depths of 1.5 m the sample variogram constructed using CRE could not be fitted by any model). All the variograms were best fitted to Matern models. The range value (in meters) is an indicator of extension where autocorrelation exists. The autocorrelation distances are always larger for the CRE estimator (with the exception to temperature at depth of 1.5 m) which may demonstrate the enhancement of the variogram's spatial continuity. All variograms have very low nugget values which indicates that local variations could be captured probably due to the high sampling rate and due to the fact that the variables under study have strong spatial dependence. Anisotropy was investigated by calculating directional variograms. However, no anisotropy effect could be shown.

D. Cross-Validation

The block kriging method was preferred since it produced smaller prediction errors and smoother maps than the point

TABLE I

PARAMETERS OF THE FITTED VARIOGRAM MODELS FOR TEMPERATURE MEASURED AT DEPTHS OF 1.5 AND 3.0 M.

Depth	Variogram Estimator	Model	Nugget	Sill	Range
1.5	MME	Matern $(\nu = 0.2)$	0.000	0.001	453.7
	CRE	Matern $(\nu = 0.3)$	0.000	0.001	130.3
3.0	MME	Matern $(\nu = 0.3)$	0.000	0.0001	18.0
	CRE	Matern $(\nu = 0.3)$	0.000	0.00015	83.3

TABLE II

PARAMETERS OF THE FITTED VARIOGRAM MODELS FOR SALINITY MEASURED AT DEPTHS OF 1.5 AND 3 M.

Depth	Variogram Estimator	Model	Nugget	Sill	Range
1.5	MME	Matern $(\nu = 0.2)$	0.000	3.086	95.9
3.0	MME	Matern $(\nu = 0.2)$	0.000	1.522	35.2
	CRE	Matern $(\nu = 0.3)$	0.000	1.459	70.7

kriging. Using the 90% modeling sets of the two depths, a two-dimensional universal block kriging, with blocks of 10×10 m^2, was applied to estimate temperature at the locations of the 10% validation sets. The validation results for both parameters measured at depths of 1.5 m and 3 m depths are shown in Table III and Table IV. At both depths temperature was best estimated by the variogram constructed using CRE. Salinity at the depth of 3 m was also best estimated using CRE. The difference in performance between the two estimators: universal block kriging using the MME estimator (MUBK) or universal block kriging using the CRE estimator (CUBK) is not substantial.

TABLE III

CROSS-VALIDATION RESULTS FOR THE TEMPERATURE MAPS AT DEPTHS OF 1.5 AND 3 M.

Depth	Method	R^2	ME	MSE	RMSE
1.5	MUBK	0.9134	1.1910e-4	8.5402e-5	9.2413e-3
	CUBK[a]	0.9167	1.1348e-4	8.2147e-5	9.0635e-3
3.0	MUBK	0.8753	0.8940e-4	3.6141e-5	6.0117e-3
	CUBK[a]	0.8757	0.8868e-4	3.6045e-5	6.0038e-3

[a] The preferred model.

TABLE IV

CROSS-VALIDATION RESULTS FOR THE SALINITY MAPS AT DEPTHS OF 1.5 AND 3 M.

Depth	Method	R^2	ME	MSE	RMSE
1.5	MUBK[a]	0.9423	4.5058e-5	3.2216e-6	1.7949e-3
3.0	MUBK	0.8931	-6.8442e-5	4.1108e-6	2.0275e-3
	CUBK[a]	0.8973	-6.6000e-5	3.9511e-6	1.9877e-3

[a] The preferred model.

III. RESULTS

A. Mapping

Fig. 3 shows the block kriged maps of temperature on a 2×2 m^2 grid using the preferred models. Fig. 4 shows the block kriged maps of salinity on a 2×2 m^2 grid using the preferred models. In the 1.5 m kriged map the temperature ranges between 15.382°C and 15.525°C and the average value is 15.469°C (measured range 15.359°C–15.562°C and average 15.463°C). In the 3 m kriged map the temperature ranges between 15.432°C and 15.502°C and the average value is 15.466°C (measured range 15.393°C–15.536°C and average 15.469°C). We may say that estimated values are in accordance with the measurements since their distributions are similar (identical average values, medians, and quartiles). The difference in the ranges width is due to only 5.0% of the samples in the 1.5 m depth map (2.5% on each side of the distribution) and only 5.3% of the samples in the 3.0 m depth map (3.1% on the left side and 2.2% on the rigth side of the distribution). These samples should then be identified as outliers not representing the behaviour of the plume in the established area. In the 1.5 m kriged map the salinity ranges between 35.965 psu and 36.004 psu and the average value is 35.992 psu, which is in accordance with the measurements (range 35.957psu–36.003psu and average 35.991 psu). In the 3 m kriged map the salinity ranges between 35.984 psu and 36.004 psu and the average value is 35.996 psu, which is in accordance with the measurements (range 35.973psu–36.008psu and average 35.996 psu). As predicted by the plume prediction model, the effluent was found dispersing close to the surface. From the temperature and salinity kriged maps it is possible to distinguish the effluent plume from the background waters. It appears as a region of lower temperature and lower salinity when compared to the surrounding ocean waters at the same depth. At the depth of 1.5 m the major difference in temperature compared to the surrounding waters is about -0.116°C while at the depth of 3 m this difference is about -0.073°C. At the depth of 1.5 m the major difference in salinity compared to the surrounding waters is about -0.044 psu while at the depth of 3 m this difference is about -0.027 psu. It is important to note that these very small differences in temperature and salinity were detected due to the high resolution of the CTD sensor. [7] observed temperature and salinity anomalies in the plume in the order, respectively of -0.3°C and -0.1 psu, when compared with the surrounding waters within the same depth range. The small plume-related anomalies observed in the maps are evidence of the rapid mixing process. Due to the large differences in density between the rising effluent plume and ambient ocean waters, entrainment and mixing processes are vigorous and the properties within the plume change rapidly [7][8]. The effluent plume was found northeast from the diffuser beginning, spreading downstream in the direction of current. Using the navigation data, we could later estimate current velocity and direction and the values found were, respectively, 0.4 m/s and 70°C, which is in accordance with the location of the plume. Fig. 5 shows

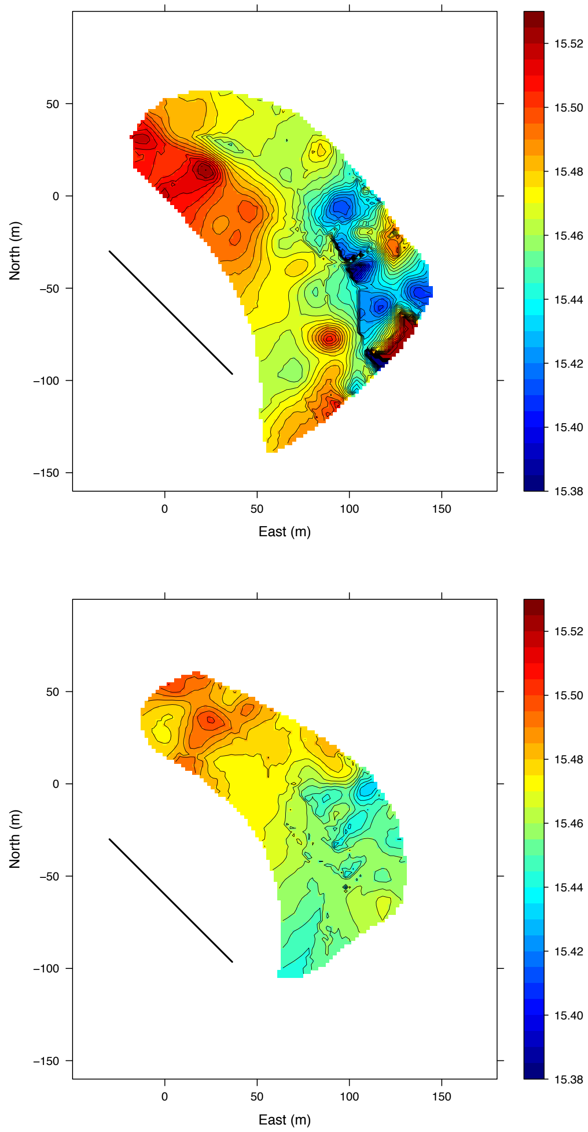


Fig. 3. Prediction map of temperature distribution at depths of 1.5 m (top) and 3 m (bottom).

the variance of the estimation error (kriging variance) for the maps of temperature distribution at depths of 1.5 m and 3 m. The standard deviation of the estimation error is less than 0.03404°C at the depth of 1.5 m and less than 0.00028°C at the depth of 3 m. It's interesting to observe that, as expected, the variance of the estimation error is less the closer is the prediction from the trajectory of the vehicle. The dark blue regions correspond to the trajectory of MARES AUV.

B. Dilution estimation

Using salinity distribution at depths of 1.5 m and 3 m dilution was estimated according to [9] (see the contour maps in Fig. 6). The minimum dilution estimated at the depth of 1.5 m was 778 and at the depth of 3.0 m was 1503 which is in accordance with Portuguese legislation that suggests that

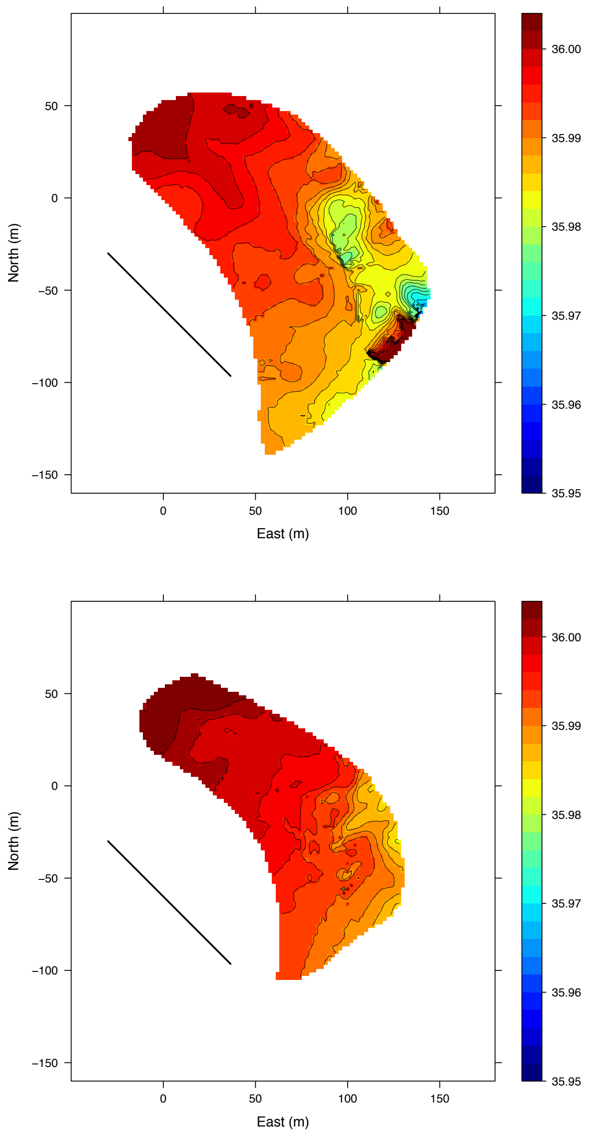


Fig. 4. Prediction map of salinity distribution at depths of 1.5 m (top) and 3 m (bottom).

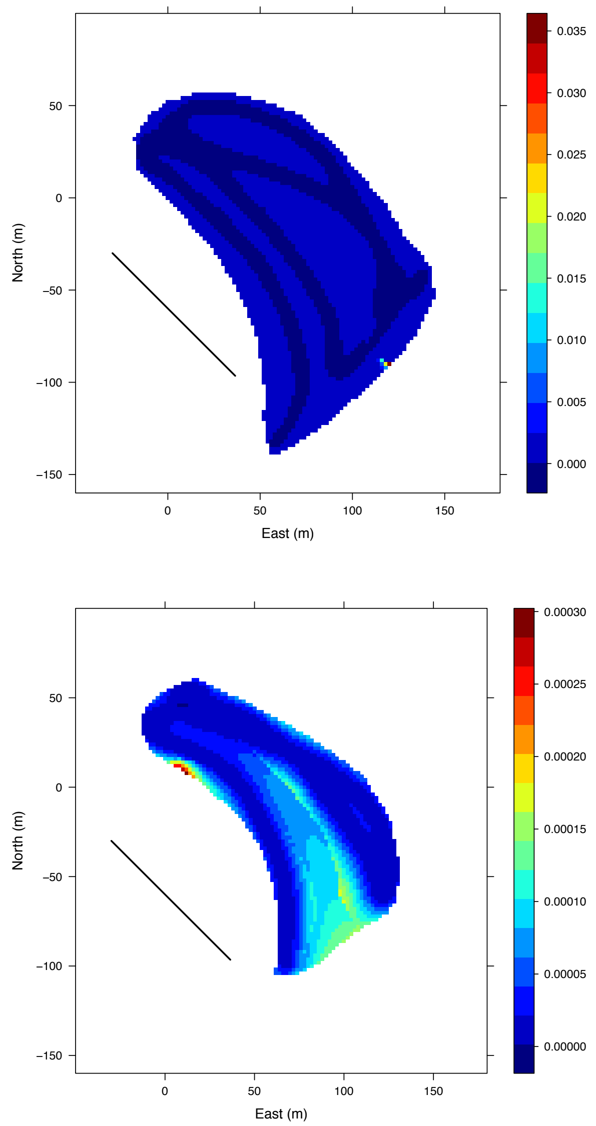


Fig. 5. Variance of the estimation error for the maps of temperature distribution at depths of 1.5 m (top) and 3 m (bottom).

outfalls should be designed to assure a minimum dilution of 50 when the plume reaches surface [10]. (Since dilution increases with the plume rising we should expect that the minimum values would be greater if the plume reached surface [5]).

IV. CONCLUSIONS

Through geostatistical analysis of temperature and salinity obtained by an AUV at depths of 1.5 m and 3 m in an ocean outfall monitoring campaign it was possible to produce kriged maps of the sewage dispersion in the field. The Matheron's classical estimator and Cressie and Hawkins' robust estimator were then used to compute the omnidirectional variograms that were fitted to Matern models. The performance of each competing model was compared using a split-sample approach. In the case of temperature, the validation results, using a two-dimensional universal block kriging, suggested the Matern model ($\nu = 0.3 - 1.5$ m and 3.0 m) with semivariance estimated by CRE. In the case of salinity, the validation results, using a two-dimensional universal block kriging, suggested the Matern model ($\nu = 0.2 - 1.5$ m and $\nu = 0.3 - 3.0$ m) with semivariance estimated by MME, for the depth of 1.5 m, and with semivariance estimated by CRE, for the depth of 3 m. The difference in performance between the two estimators was not substantial. Block kriged maps of temperature and salinity at depths of 1.5 m and 3 m show the spatial variation of these parameters in the area studied and from them it is possible to identify the effluent plume that appears as a region of lower temperature and lower salinity when compared to the surrounding waters, northeast from the diffuser beginning, spreading downstream in the direction of current. Using salinity distribution at depths of 1.5 m and 3 m we estimated dilution at those depths. The values found are in accordance with Portuguese legislation. The results presented demonstrate that geostatistical methodology can provide good estimates of the dispersion of effluent that are very valuable in assessing the environmental impact and managing sea outfalls.

REFERENCES

[1] J. Bellingham, "New Oceanographic Uses of Autonomous Underwater Vehicles," *Marine Technology Society Journal*, vol. 31, no. 3, pp. 34–47, 1997.

[2] X. Yu, T. Dickey, J. Bellingham, D. Manov, and K. Streitlien, "The Application of Autonomous Underwater Vehicles for Interdisciplinary Measurements in Massachusetts and Cape Cod Bayes," *Continental Shelf Research*, vol. 22, no. 15, pp. 2225–2245, 2002.

[3] P. Ramos and N. Abreu, "Using an AUV for Assessing Wastewater Discharges Impact: An Approach Based on Geostatistics," *Marine Technology Society Journal*, vol. 45, no. 2, 2011.

[4] N. Abreu, A. Matos, P. Ramos, and N. Cruz, "Automatic interface for AUV mission planning and supervision," in *MTS/IEEE International Conference Oceans 2010*, Seattle, USA, September 20-23 2010.

[5] C. D. Hunt, A. D. Mansfield, M. J. Mickelson, C. S. Albro, W. R. Geyer, and P. J. W. Roberts, "Plume tracking and dilution of effluent from the Boston sewage outfall," *Marine Environmental Research*, vol. 70, pp. 150–161, 2010.

[6] P. Kitanidis, *Introduction to geostatistics: applications in hydrogeology*, C. U. Press, Ed., New York (USA), 1997.

[7] L. Washburn, B. H. Jones, A. Bratkovich, T. D. Dickey, and M.-S. Chen, "Mixing, Dispersion, and Resuspension in Vicinity of Ocean Wastewater Plume," *Journal of Hydraulic Engineering, ASCE*, vol. 118, no. 1, pp. 38–58, Jan. 1992.

[8] A. A. Petrenko, B. H. Jones, and T. D. Dickey, "Shape and Initial Dilution of Sand Island, Hawaii Sewage Plume," *Journal of Hydraulic Engineering, ASCE*, vol. 124, no. 6, pp. 565–571, June 1998.

[9] H. B. Fischer, J. E. List, R. C. Y. Koh, J. Imberger, and N. H. Brooks, *Mixing in Inland and Coastal Waters*. Academic Press, 1979.

[10] INAG, *Linhas de Orientação Metodológia para a Elaboração de Estudos Técnicos Necessários para Cumprir o Artï¿½ 7ï¿½ do D.L. 152/97. Descargas em Zonas Menos Sensíveis*, Instituto da Água. Ministério do Ambiente, Lisboa, Março 1998.

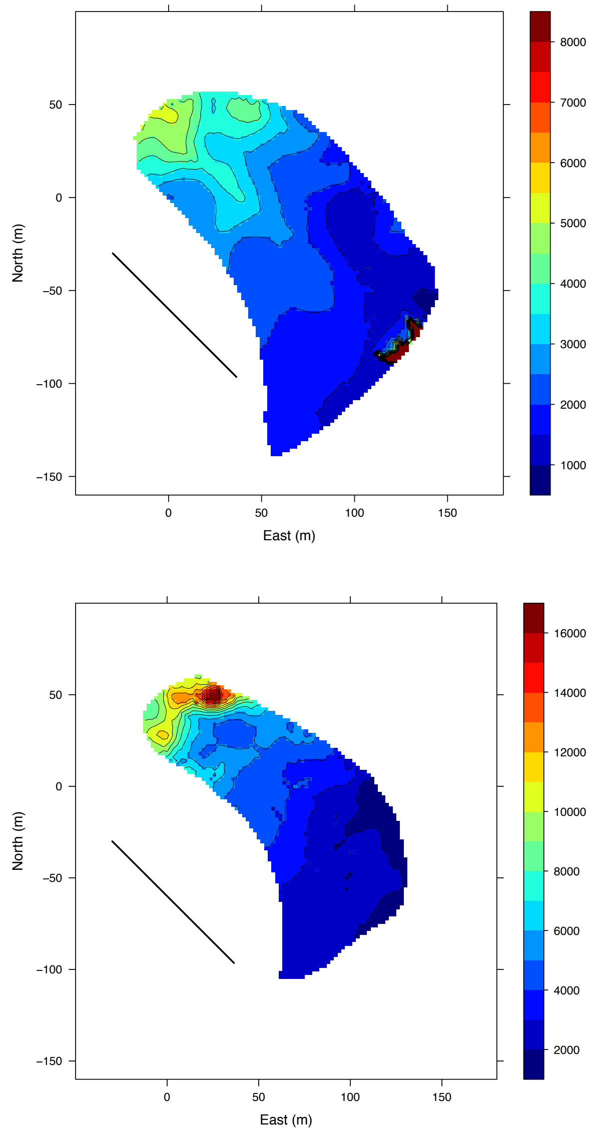


Fig. 6. Dilution maps at depths of 1.5 m (top) and 3 m (bottom).