Dye tracers as a tool for outfall studies: dilution measurement approach.

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Abstract
Dye tracer technique is well established and of wide application for assessment of outfalls and for delineation of the near field and of the far field extension. Common goals of a tracer study include the measurement of the dilution factor, the estimation of the dispersion coefficients, the measurement of the effluent discharge and the calibration of the transport model. Slug injection on the surface of the water body is used for preliminary dispersion studies aiming at diffusers positioning. During the operational phase of the outfall, continuous injection of dye tracer is used to determine the effluent dilution under different scenarios. This paper presents a brief review on the main methods involving the use of dye tracer for outfall assessment and illustrates the methodology of slug release and continuous injection based on two real cases of campaigns carried out on coastal waters of Brazil.

Keywords
Dilution measurement; dye tracer; injection methods; outfall.

INTRODUCTION

At the metropolitan area of Rio de Janeiro city, southeast region of Brazil, are located the coastal outfalls of Ipanema and Barra da Tijuca and the outfall of Icarai inside the Guanabara Bay. Other systems are in the implementation or in preliminary phases. A general overview of the area highlighting the Ipanema Beach and the Guanabara Bay is shown in **Figure 1**.

The Submarine Sewage Outfall of Ipanema (SSOI) – built during the decade of the 70's – has a submerged pipeline with 4,325 m in length and diffusers on the last 450 m in a place with 28 m in depth. The labels ① and ② mark the approximated position of the Guanabara Bay main channel. Near the point ① the depth ranges between 15 m and 20 m and near the point ② depths are around of 20 m. The point ② indicates the position for the planned but not implemented Submarine Sewage Outfall of Alegria (SSOA). The Submarine Sewage Outfall of Icarai (SSOIC) is located around the point ③. An animation of the SisBaHiA´s transport model for the outfalls operating at Rio de Janeiro can be viewed on http://www.sisbahia.coppe.ufrj.br/Animacao/Emissarios_RIO.htm.

Sea currents off the coast are parallel to the shoreline with a pattern depending on the cold fronts reaching the region and also present a modulation due to tides. As a general behaviour, the region is particularly prone to upwelling during the summer producing a water column with a high degree of stratification. During the winter, with prevailing winds coming from directions between southwest and southeast, the water column is normally non-stratified. Oceanographic data gathered close to the outfall of Ipanema (Roldão et al., 2001) have shown, however, that water column can change from a homogeneous to a stratified condition and vice versa in a matter of few days along the seasons as shown in **Figure 2**.

Inside the Guanabara Bay, tidal flow dominates the circulation. Tide follows a semidiurnal cycle with a excursion of 1.55 m between the lowest and the highest astronomical tide rising up to 0.35 m due to storm surge based on the data available for the tidal station of Ilha Fiscal during the year of 1997. However, during neap tide strong winds can significantly affect the sea current pattern.

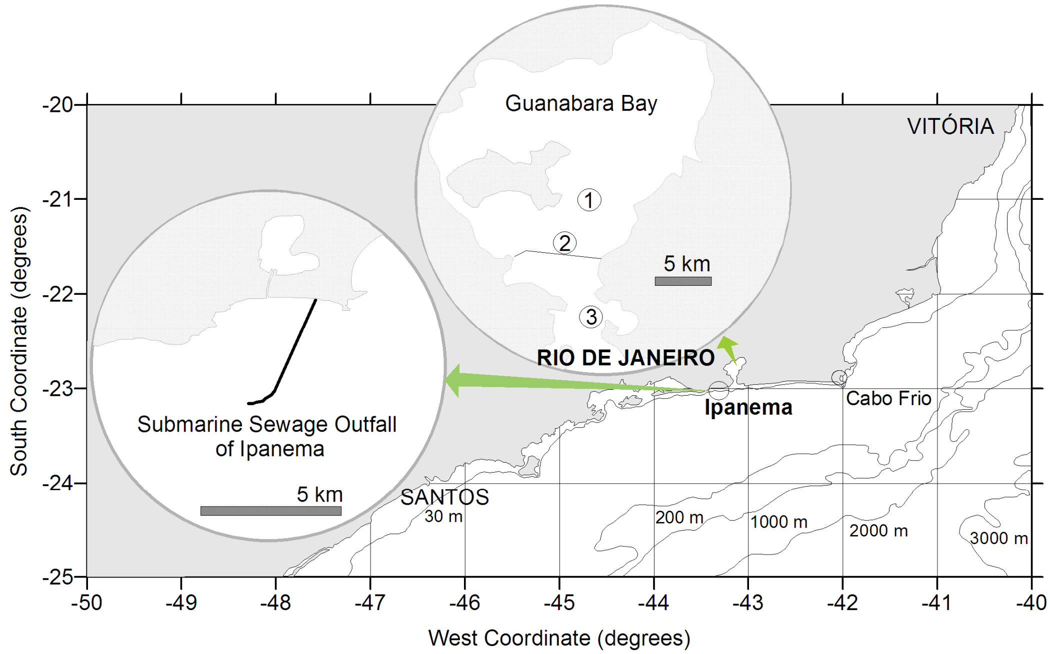

Figure 1. Location of the Submarine Sewage Outfall of Ipanema at Rio de Janeiro and of the Guanabara Bay. Note the different scales associated with the coastlines details near to SSOI and around the Guanabara Bay.

Coastal water temperature and influence inside the bay

Two thermistors string manufactured by Aanderaa were deployed near to the SSOI ① and near to the point planned for sitting the diffusers of the SSOA ② inside of the bay. Time series for the water temperature at the upper and the lower bins both for SSOI and SSOA are presented in **Figure 2** for September 1997 (typical spring conditions in the south hemisphere). The behaviour resembles the action of a low pass filter. Strong coastal thermal stratification due to upwelling did not reach the SSOA region as a result of a slow exchange with the bay inner waters.

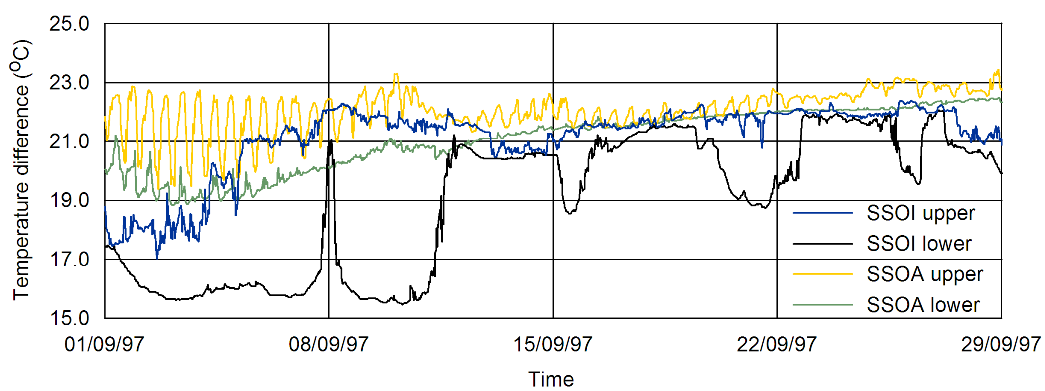

Figure 2. Temperature time series of the upper and lower water layers at Ipanema (SSOI) and inside the Guanabara Bay (SSOA) during September 1997.

From coastal water dataset over a whole year, minimum differences between the upper and lower layers occurred in June 1997 while the maximum temperature as well the maximum difference between the upper and lower layers were observed in January 1998. Temperature differences between the upper and lower layers higher than 5 °C occurred 20% within the observed period while differences higher than 8 °C occurred 10% within the period.

There are periods when the coastal waters are non-stratified while the inner waters present thermal stratification following a strong tidal modulation. The higher differences at the SSOA station are due to the shallower and warmer waters flowing during the ebb tide probably as a result of the solar radiation and air temperature patterns.

Field studies with dye tracers

The Submarine Sewage Outfall of Ipanema (SSOI) is an old structure launching effluents *in natura* on coastal waters of Rio de Janeiro. As part of a monitoring program, a set of 4 field campaigns were carried out during the years of 1996 and 1997 under stratified and non-stratified water column conditions. This work presents a brief revisit to the dye tracer dataset gathered on March 20, 1996 (under stratified conditions) and on September 25, 1997 (under near homogeneous conditions) as an example of continuous injection of dye tracers. Slug injection was employed for a preliminary study inside the Guanabara Bay on December 8, 2010 during neap tide. As the hydrodynamic pattern is dominated by tides, field campaigns were planned to cover specific moon phases.

METHODOLOGY

The basic dye injection methods are the instantaneous release which will generate a cloud or the continuous release which will generate a plume. Instantaneous release near to the water surface or slug method is used to determine the transport and dispersion of a labelled volume. Continuous injection method underwater is the main method to determine the dilution field of a plume along the advection path. The water volume labelled with dye is detected by instruments along transects, profiles or in fixed positions acquiring concentration time series.

Field monitoring campaigns with different levels of complexity are found in the literature. Pritchard and Carpenter (1960), Brooks (1960) and Okubo (1971) presented works on the turbulent diffusion process in estuarine and coastal waters. Bailey (1966) describes the use of the slug and continuous method of dye tracing for studying the transport and diffusion characteristics of estuaries. Pioneer works for outfall´s assessment are presented by Seligman (1955), Harremoës (1966) and Hansen (1970). Regarding the plume tracking methods Murray and Venezia (1982) discussed about sensors for horizontal and vertical profiling and effluent detection. Hodgins (1989) describes a sampling strategy of navigation along the transects while cycling the detection instrument (in a towed mode) vertically through the dye cloud. Processing and contouring the dye tracer data yields a 3D representation of the plume. Ramos et al. (2005) describe an autonomous underwater vehicle (AUV) for monitoring the shape and estimate initial dilution of an outfall using a temperature–salinity diagram. Regarding the time scale, field studies range from short duration (Roldão et al., 1997) to long duration (Obropta and Hires, 2007; Hunt et al., 2010).

The dilution factor

The average dilution factor S_a for each pollutant in a plume, considering its nonzero ambient concentration, can be expressed by the definition of Baumgartner et al. (1994) as

$$S_a = \frac{c_e - c_a}{c_p - c_a} \qquad \text{(Equation 1)}$$

where c_e is the concentration in the effluent (mg/m^3), c_p is the concentration in the plume (mg/m^3) and c_a is the concentration in the ambient water (mg/m^3).

Tracer selection

The dye tracer selected was Amidorhodamine G Extra (Color Index 45220) due to its characteristic highly conservative: low sensitivity to temperature and pH, low adsorption onto organic solids and low photodecay. Such dye tracer also presents high solubility in water as well as low ecotoxicological effects (Behrens et al., 2001). The detection threshold, by using spectrofluorometric techniques, is around 0.01 mg/m^3. For in situ measurements, by using field fluorometers, the detection limit is between 0.1 mg/m^3 and 0.3 mg/m^3 allowing real time data collection of samples used for evaluating dilution factors up to 10^3.

Continuous injection and plume tracking

The effluent is labeled with Amidorhodamine G Extra continuously injected at the sewage pump station during a period of 6 hours for sites with semidiurnal tide pattern. An apparatus for continuous injection was designed and can be adjusted to keep the average tracer concentration inside the outfall between 300 and 600 mg/m^3 and to keep injection rate steady. As a basic requirement, the effluent release rate should be kept steady during the field injection period. Effluent samples are used to determine the tracer concentration inside the outfall and also the operational discharge rate (Kilpatrick and Cobb, 1985; ISO, 1992).

Despite of injection method – slug or continuous – two monitoring boats are used for monitoring the dilution field. One boat is equipped with pumping system, field fluorometers, GPS and portable computers. The plume detection is performed along navigation lines perpendicular to the average flow with the help of a navigation software. Sea water is continuously pumped from the defined depths through the continuous flow cell of field fluorometers. A second boat is equipped with pumping apparatus, field fluorometers, GPS and CTD. While the first boat performs transects for delineating the labelled effluent, the second boat monitors tracer and CTD vertical profiles.

Along the transects water samples are collected for measurements in the laboratory by using the spectrofluorometric method. Also during the navigation, some points with singular concentration readings are marked with buoys. The marking buoys indicate the points adequate for vertical profiling of dye tracer, CTD data or other parameters by the second boat.

Slug injection and cloud detection

Eulerian monitoring method is normally used in narrow streams where samples are collected in fixed points as a function of the time. In this work, it was used a kind of Eulerian method for detecting the dye cloud. Transects should start and finish at background levels and are repeated until the dye tracer concentration – at the cloud centerline – reaches its background value. A new positioning "downstream" is defined and the process is repeated as fast as possible.

Trajectory transformation

As a strategy for data processing, the maximum concentration along the transects are identified. Then, the average water speed between consecutive transects is estimated based on the position and time associated with the points of maximum concentration. When available, water current data measurements can be used on this step. The average water speed is used for translating the position of each sample along the original navigation lines to new coordinates calculated by using

$$x_{i\ \mathrm{new}} = x_i + u\ (t_i - t_0) \qquad \text{(Equation 2)}$$

$$y_{i\ \mathrm{new}} = y_i + v\ (t_i - t_0) \qquad \text{(Equation 3)}$$

where $x_{i\ \mathrm{new}}$, $y_{i\ \mathrm{new}}$ are the east and north translated positions, respectively; x_i , y_i are the east and north original positions, respectively; u, v are the east and north components of average water speed, respectively and $(t_i - t_0)$ is the difference between original and the cloud central time.

Processing and data analysis

Although the pre-processing phase of the tracer dataset obtained with the slug and with the continuous release differs, contour generation follows the same basic steps. For the dataset visualization, contour maps are drawn by using the kriging method (Oliver and Webster, 1990). Although the use of geostatistics techniques for contour map generation uses an underlying hypothesis of stationarity (which is not the case), the kriging was chosen because it is an optimum estimator and, as so, can provide a good tool for comparison of different contour plots.

RESULTS AND DISCUSSION

The field work with continuous dye tracer injection was carried out on the Submarine Sewage Outfall of Ipanema (SSOI) on September 25, 1997. The dataset for the campaign comprises 4025 samples of tracer concentration for 3 monitored depths. The samples were acquired with a data collection platform based on the OEM Tattletale datalogger. A specific piece of software was designed and coded for saving all samples gathered and its associated geographic positions latter on transformed to the Universal Transverse Mercator (UTM) projection. Further details about the monitoring campaigns carried out on SSOI are presented by Pecly (2000), Roldão et al. (2001) and Carvalho et al. (2002).

Slug injection was employed for a preliminary study inside the Guanabara Bay on December 8, 2010 during neap tide. Instantaneous tracer release of a solution prepared with 1 kg of Amidorhodamine G was done on the water surface 1 hour after the high slack water. Addition of alcohol to the solution prepared with fresh water was done to change its density to a value close to the sea water density. Sea water was continuously pumped from the depth of 0.5 m below surface through the continuous flow cell of one field fluorometer. The dataset for the cloud presented in in **Figure 3** comprises 811 samples of tracer concentration acquired with a data collection platform based on the OEM ZWorld datalogger running a piece of software designed and coded for saving all samples gathered and its associated geographic positions latter on transformed to the Universal Transverse Mercator (UTM) projection.

Contour maps

The plates in **Figure 3** are used for comparing some results of the plume tracking method employed inside the Guanabara Bay (upper) and around the SSOI (lower). The upper plates show preliminary data about the transformed navigation lines (left) and a resulting dye cloud (right). The elapsed time between the first and last sample acquired is 1 hour. The lower panels show the navigation lines (left) and a resulting dye plume (right). The tracking time between the start and the end of the navigation around SSOI was 6 hours and 24 minutes. Although the time scales are different, the spatial scales for the cloud and for plume illustrated in **Figure 3** are the same.

The plume monitored on September 25, 1997 (lower right plate in **Figure 3**) represents a specific condition with very low sea currents ranging between 2 and 14 cm/s to northwest (into the shore direction) near to neap tide. Water temperature profiles indicated values between 21 and 22 ^{o}C over the whole water column. With these conditions, the field work was carried during Spring under homogeneous water column conditions with the effluent reaching the sea surface as shown in **Figure 4.** Based on a detection limit for the dye tracer of 0.1–0.2 mg/m^3 it was possible to delineate an area with dilutions between 1:3,000 and 1:2,000.

As the dye cloud monitored on December 8, 2010 spreads over three dimensions, the data analysis is difficult (Okubo, 1971; Hayakawa, 2003). A practical approach assumes a horizontal concentric shape adjusted by an analytical formulation in order to estimate dispersion coefficients (Roldão et al., 1996). This kind of analysis should still be undertaken.

The behaviour of the labelled volume along the vertical dimension deserve additional comments.

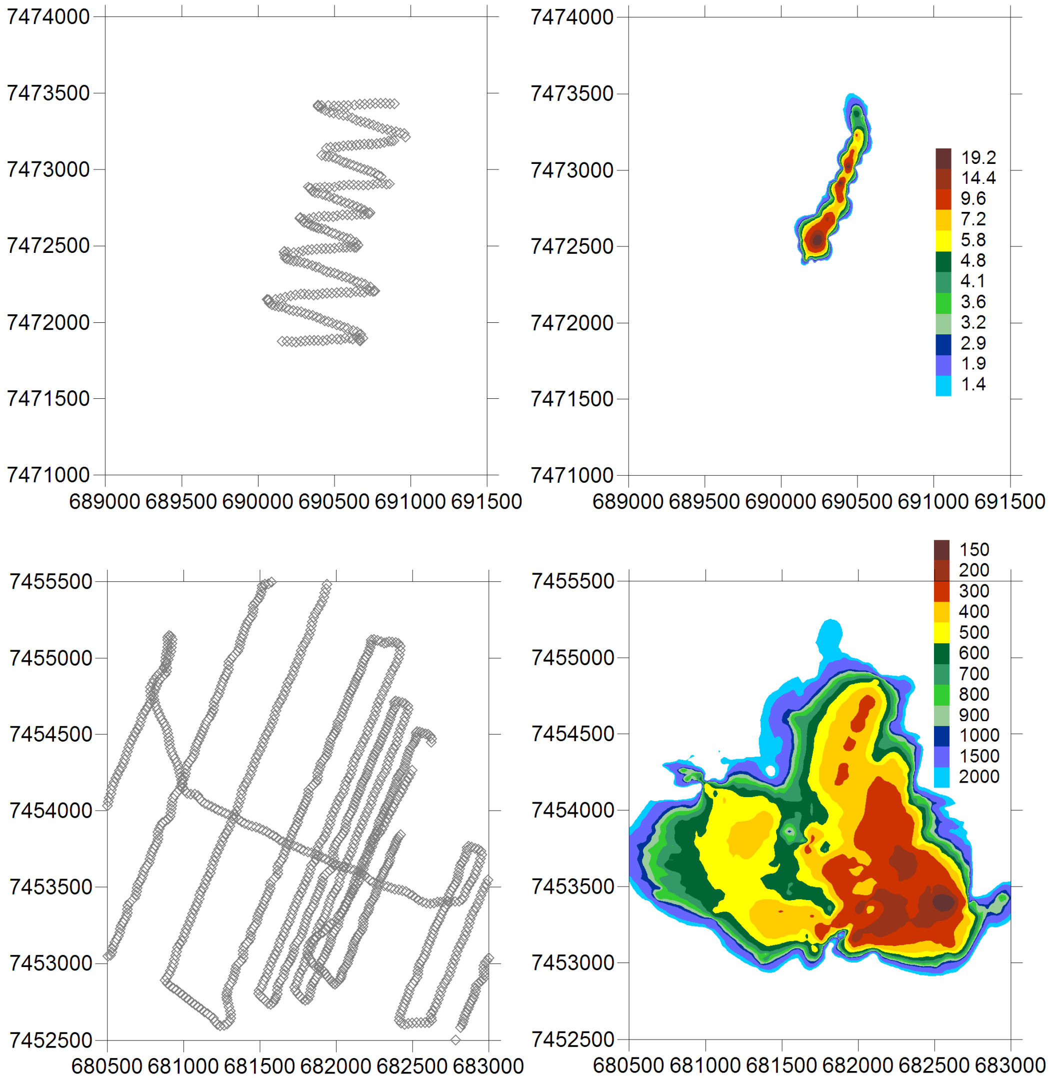

Figure 3. Sampling points and contour maps for the case studies: navigation lines inside the bay (*upper left*); dye cloud concentration (in mg/m^3) at 0.5 m below surface inside the bay (*upper right*); navigation lines around SSOI (*lower left*) and dilution factor isolines (dimensionless) from the dye plume 2 m below surface (*lower right*). Vertical and horizontal axes are North and East UTM coordinates respectively. Note that all plates have the same spatial scale but different time scales.

Four between several vertical profiles were chosen to illustrate the vertical mixing pattern of the effluent plume. The profile P1 (UTM coordinates 7453493 N, 682173 E) and the profile P2 (UTM coordinates 7453376 N, 681952 E) shown in **Figure 4** indicated a spreading of the effluent over the higher half of the water column during a non-stratified condition during the Spring of 1997 while the profile P3 (UTM coordinates 7453001 N, 682770 E) and the profile P4 (UTM coordinates 7453407 N, 682434 E) indicate a plume of the effluent trapped below the thermocline during the summer of 1996.

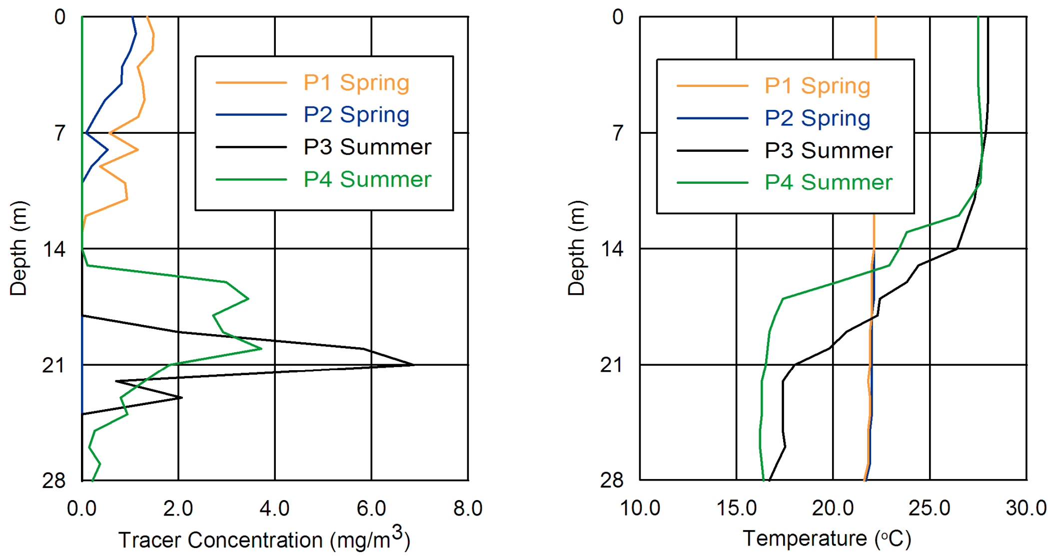

Figure 4. Vertical profiles of dye tracer concentration near to the diffusers of SSOI under stratified (Summer) and homogeneous (Spring) conditions.

For illustrating the vertical mixing pattern of the volume labelled inside the bay, two between several vertical profiles were chosen. The profile P5 (UTM coordinates 7474641 N, 691054 E) and the profile P6 (UTM coordinates 7472293 N, 689940 E) shown in **Figure 5** indicate a cloud limited above the level of lower density water.

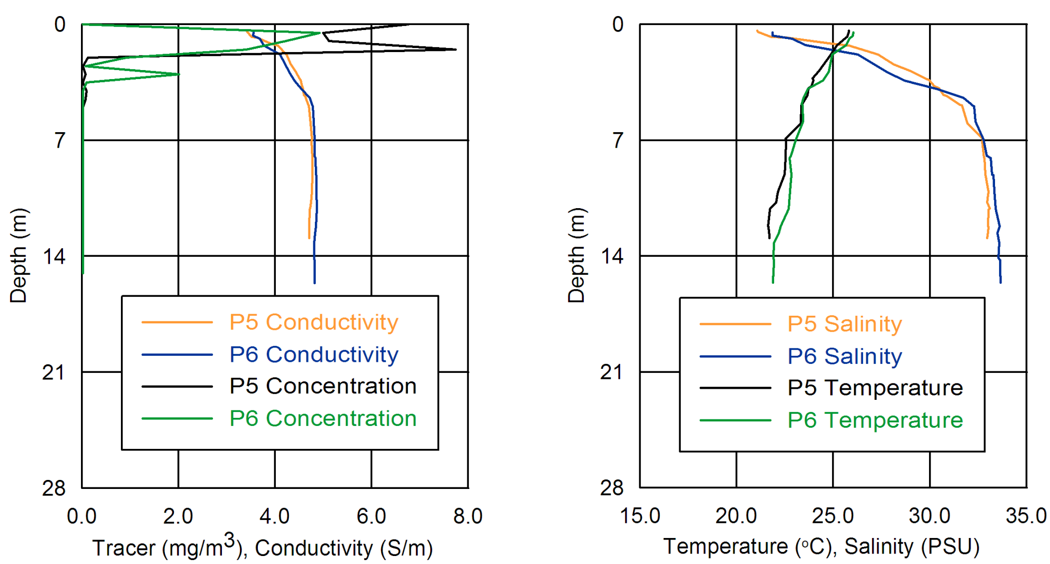

Figure 5. Vertical profiles of dye tracer concentration and CTD data inside the Guanabara Bay. Data suggest a "trapping" level near to surface.

CONCLUSIONS

A common task related to a program for monitoring an outfall in estuarine and coastal waters is the dilution field assessment. Modelling is commonly used for mixing zone studies but it requires calibration against *in situ* measurement of dye tracer data for increasing confidence in results.

The dye tracer Amidorhodamine G Extra was introduced in the water as a method to identify the transport and dispersion of pollutants in two selected water bodies. The dye tracer was continuously injected into the pipeline of the Submarine Sewage Outfall of Ipanema (SSOI) and the plume tracking was performed along the lines transversal to the average flow. The same dye was used on the tidal channel of the Guanabara Bay. Tracer performance and chemical compatibility evaluation was carefully undertaken.

Basically, one should determine the horizontal dimensions, thickness and depth of the effluent. On coastal waters, under very low oceanic currents, the spatial variability presented an isotropic behavior while on a tidal channel the variability was strongly anisotropic as expected. The obtained dataset showed the ascension tendency of the plume due to a non-stratified water column and the presence of a trapping level depending on the degree of stratification.

The temperature dataset gathered on coastal water of Rio de Janeiro showed not only seasonal dependence but also a variability inter-annual. The transfer function between temperatures observed on coastal and inner waters resembles the behavior of a low pass filter. Cold water due to upwelling last several days for changing the inner water temperatures.

Slug release is a method particularly useful in case we expect narrow and fast advecting dye clouds when diffusion is considered small between transects. One should not that non-stationarity or flow inversion pose additional difficulties to its application. Although it represents a quite simple method which allows a course contour drawing, modeling can benefit with calibration based on comparison between sections of the modeled cloud and the translated transects. Additional limitations are due to wind stress (Wu, 1969) and sea state which, acting over a surfaced cloud during the moments past the dye release, can lead to different transport and mixing patterns.

The dye tracer represents a robust tool for monitoring outfalls although it brings the requirements of an expert team in field measurement and data interpretation and a specialized set of instruments.

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