Using the effluent turbidity as an environmental tracer: application to a domestic sewage outfall and comparison with dye tracer data.

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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. In order to evaluate the alternative use of the effluent turbidity to delineate the dilution field of a domestic submarine outfalls, a field work comprising continuous dye tracer injection with simultaneous monitoring of the effluent turbidity was carried out on the Submarine Sewage Outfall of Ipanema (SSOI). A laboratory assessment was carried out with an effluent sample of SSOI whose turbidity was measured by the nephelometric method before and during a successive dilution process using distillate water. During a field campaign on SSOI, under non-stratified water column condition, the dye tracer was monitored with field fluorometers and the turbidity was observed with an optical backscattering sensor both interfaced to an OEM data acquisition system. Circa of 4 thousand samples were gathered covering an area of around 2 km x 2 km near to the outfall diffusers. The dye tracer plume presented strong correlation with the turbidity plume drawn on the near field region, as the higher dilution values were adequately evaluated by using the turbidity data. At the far field – where it was noted a drift of the plume into the coastline direction – the effluent plume was adequately labelled by the dye tracer. However, the turbidity plume was biased due to higher and variable background of the sea water near to the coastline.

Keywords
Dye tracer; field measurement; outfall; turbidity

INTRODUCTION

The Submarine Sewage Outfall of Ipanema (SSOI) is an old structure launching effluents *in natura* on coastal waters of Rio de Janeiro, southeast region of Brazil. As part of a monitoring program, a set of 4 field campaigns were carried out during the years of 1996 and 1997 as reported by Pecly (2000), Roldão et al. (2001) and Carvalho et al. (2002). The rich dataset archived is still being studied nowadays. This work presents a revisit to the dye tracer and turbidity datasets gathered on September 1997 when was observed a homogeneous water column condition.

Figure 1 shows the general location of the SSOI and a detail of the study area. Total length of the submerged pipeline is 4,325 m with diffusers on the last 450 m in a place with 28 m in depth. 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 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.

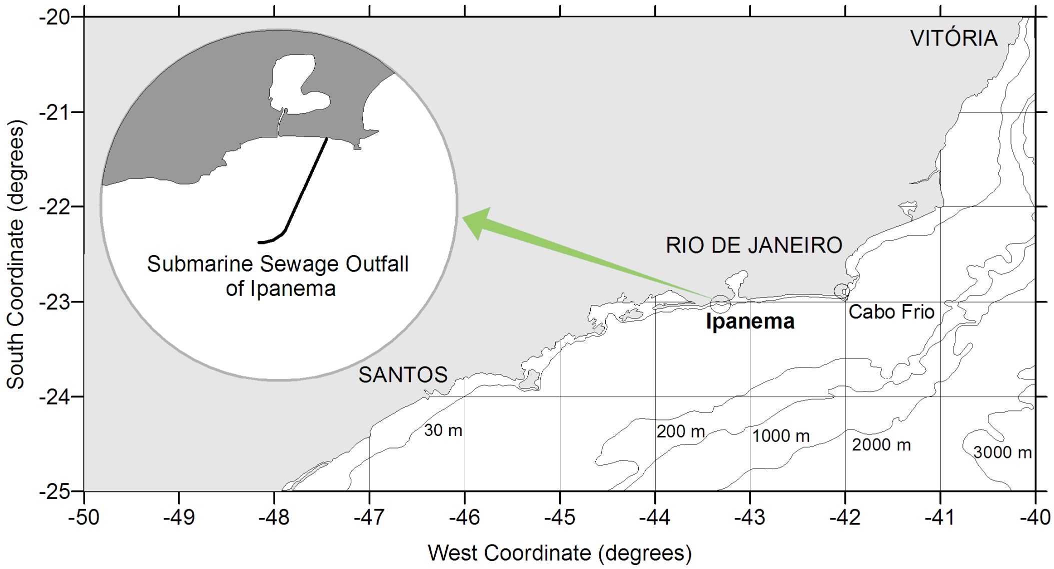

Figure 1. Location of the Submarine Sewage Outfall of Ipanema at Rio de Janeiro.

METHODOLOGY

A common task related to a program for monitoring a submarine outfall in coastal waters is an assessment of the effluent dilution. Based on the measured dilution levels it is possible to determine the dilution field coverage area.

The dilution factor

The average dilution factor S_a is the reciprocal of the volume fraction of effluent v_e contained in the diluted plume following the definition of Baumgartner et al. (1994) and can be expressed as the ratio of the sum of effluent volume v_e with the volume of ambient dilution water v_a to the effluent volume v_e as

$$S_a = \frac{1}{\dfrac{v_e}{v_e + v_a}} = \frac{v_e + v_a}{v_e} \qquad \text{(Equation 1)}$$

Using the continuity equation and rearranging the terms, the average dilution factor S_a for each pollutant in a plume, considering its nonzero ambient concentration, can be expressed as

$$S_a = \frac{c_e - c_a}{c_p - c_a} \qquad \text{(Equation 2)}$$

where

c_e is the concentration in the effluent (mg/m^3);

c_p is the concentration in the plume (mg/m^3);

c_a is the concentration in the ambient water (mg/m^3).

The measurement of the dilution factor is a basic requirement for the performance assessment of an outfall during its operational phase. Under typical operational conditions, the dilution field can be determined *in situ* by using tracing techniques. Successful works include the use of artificial tracers (Roldão et al., 2001; Obropta and Hires, 2007; Hunt et al., 2010) as well as environmental tracers (Wilander et al., 1974; Kaye and Haddad, 1992). It was not found in the literature a systematic approach for outfall assessment by using the effluent turbidity as an environmental tracer.

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.

The effluent turbidity as an environmental tracer

As a preliminary task it was collected an effluent sample in order to evaluate the use of the turbidity as an environmental tracer. Sample turbidity was measured in laboratory during a successive dilution process with distilled water. For the turbidity measurement, the nephelometric method (Turner, 1979) was employed by using an optical backscattering meter (branded SeaPoint Turbidity Meter). **Figure 2** summarize the relationship between the turbidity of the diluted sample and the value of dilution applied to the sample.

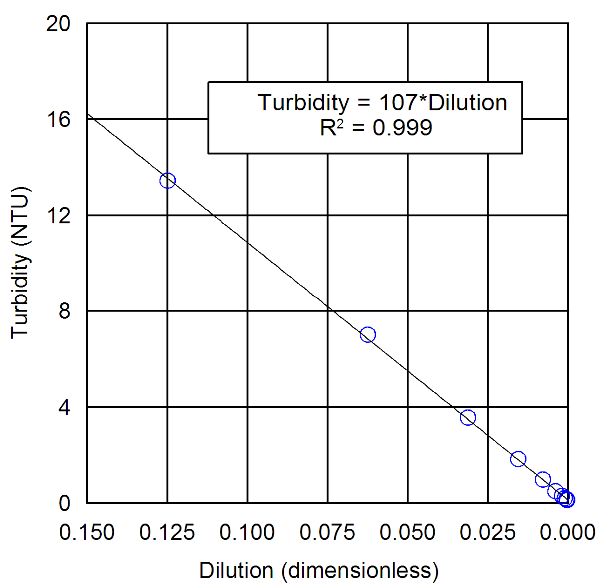

Figure 2. Linear relationship after regression of sample turbidity data and applied dilution. Determination coefficient is close to unity.

The highly linear behavior of the test and the possibility of detection of turbidity values as lower as 0.1 NTU indicated the possibility of measurement of dilution factors up to 10^3. These numbers have shown that is possible to measure the dilution of outfalls under homogeneous water column and under low turbidity background. However, under stratified conditions, with the plume trapped in higher depths, the turbidity measurements can be masked by sediment resuspension due to bed stress induced by natural events (Morris and Howarth, 1998) or even by anthropogenic action (Schoellhamer, 1996).

Continuous injection and plume tracking

The effluent was labeled with Amidorhodamine G Extra continuously injected at the sewage pump station during a period of 6 hours. The apparatus for continuous tracer injection was designed and adjusted to keep the average tracer concentration inside the outfall around 300 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.

The plume detection was performed along navigation lines perpendicular to the average flow with the help of a navigation software. Sea water was continuously pumped from the depths of 2 m, 4.5 m and 6.5 m below surface through the continuous flow cell of three field fluorometers and one optical backscattering meter. The turbidity measurements were carried out 6.5 m in depth. For simplification, the dataset for the depth of 4.5 m is not presented here.

The dataset for the campaign analyzed in this work comprises 4025 samples of tracer concentration for each monitored depth and 4025 samples of turbidity data. 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).

Processing and data analysis
A small set of physical samples collected along the navigation lines was analyzed in the laboratory for measuring the tracer concentrations and compared with the respective data gathered by the datalogger showing very good agreement. The whole dataset gathered was checked against non-consistency and detrended empirically on a line-by-line basis.

For the dataset visualization contour maps were drawn by using the kriging method. The kriging is a moving average weighting method for interpolating points not physically sampled based on the knowledgement of the spatial relationship present on the measured dataset (Matheron, 1963; Krige, 1976; Oliver and Webster, 1990). Such spatial relationship is obtained by the variogram modeling.

An estimator $2\gamma^*$ for the variogram function is the mean of squared differences between two experimental measurements taken on two points separated by the vector h (Journel and Huijbregts, 1993) and can be expressed as

$$2\,\gamma^*(h) = \frac{\sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2}{N(h)} \qquad \text{(Equation 3)}$$

where

$\gamma^*(h)$ is the semivariogram at lag distance h;
$z(x_i)$ is the sample observation at point x_i;
$z(x_i+h)$ is the sample observation at point x_i+h;
$N(h)$ is the number of pairs of observations with lag distance $|h|$;

Although there are a lot of software applications to calculate the experimental semivariogram, the model adjustment requires interpretation and judgement from the user. For the case study of SSOI the adjustment with isotropic models presented higher determination coefficients than anisotropic models.

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 comparing the different contour plots for dye tracer and turbidity data.

Table 2 presents a summary of the results obtained after the experimental variogram analysis for the dye tracer and turbidity datasets. The values of sill and range for the selected isotropic models were used for generating a regularly gridded dataset with a 25 m spacing. The gridded data were used for contour map drawing shown on section Results and Discussion of this work.

Table 2. Values adjusted after experimental variogram analysis of the dye tracer and turbidity datasets.

	Depth	Model	Parameters		
Dataset	(m)	Isotropic	Sill	Range (m)	R^2
Dye tracer	2.0	Spherical	0.30	1000	0.98
Dye tracer	6.5	Exponential	0.15	560	0.98
Turbidity	6.5	Exponential	0.12	530	0.95

RESULTS AND DISCUSSION

The observed plume represents a specific condition with very low sea currents ranging between 2 and 14 cm/s to northwest 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 under homogeneous water column conditions with the effluent reaching the sea surface**.** Two profiles were chosen to illustrate the vertical mixing pattern of the effluent. The profile 1 (UTM coordinates 7453493 N, 682173 E) and the profile 2 (UTM coordinates 7453376 N, 681952 E) shown in **Figure 3** indicated a spreading of the effluent over the higher half of the water column.

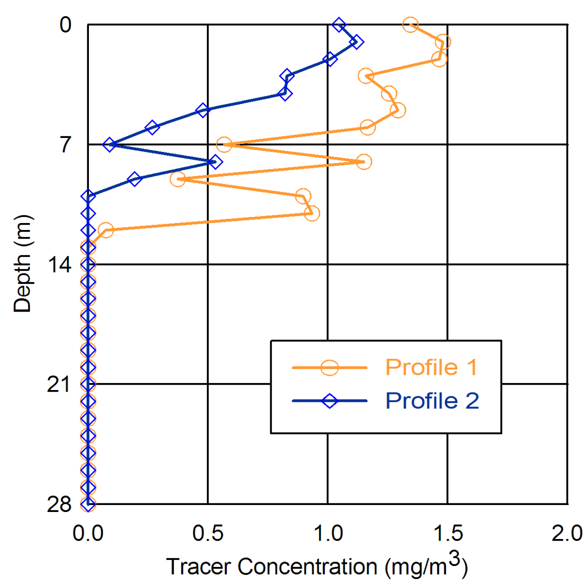

Figure 3. Vertical profiles of dye tracer concentration near to the diffusers.

The average effluent flow rate was calculated as 5.7 m^3/s by using the dilution method (Kilpatrick and Cobb, 1985). The value of the dye concentration inside the pipeline was measured as 288 mg/m^3 and used to estimate the *in situ* dilution factors. Due to an instrument fault, the effluent turbidity was not measured during the field work. So, the dilution field obtained by using the turbidity dataset was based on the sample turbidity used for laboratory assessment.

Contour maps

The dilution factors used for drawing the contour maps are presented in **Table 3** which also includes the values used for drawing the turbidity isolines and a color code for a better understanding of the plumes shown in **Figure 4**. The dynamic range of observed values was divided into 12 class intervals.

Table 3. Values associated to the contour lines of **Figure 4**. Dye tracer isolines are expressed as dilution factor (dimensionless) while turbidity isolines are expressed in Nephelometric Turbidity Units (NTU).

		Dye tracer	Turbidity (NTU)	
Color	Code	Dilution factor	measured	detrended
dark brown	12	160	1.50	1.50
brown	11	200	1.37	1.10
red	10	300	1.12	0.84
orange	9	400	0.87	0.60
yellow	8	500	0.74	0.48
dark green	7	600	0.67	0.40
green	6	700	0.62	0.35
light green	5	800	0.58	0.31
faded green	4	900	0.56	0.29
blue	3	1000	0.54	0.27
light blue	2	1500	0.52	0.25
cyan	1	2000	0.45	0.20

The plates in **Figure 4** can be used for comparing the behaviour of the dye tracer data against the sea water turbidity. The upper plates show evidence of the plume ascension in agreement with data of **Figure 3**. The lower panels show the comparison between the measured and detrended turbidity datasets. The upper right and the lower right panels show the comparison between the dye tracer and turbidity data at 6.5 m in depth indicating strong correlation near to the diffusers.

For a dilution value of 1:200, such as adopted in the design of the Barra da Tijuca Outfall (Roberts, 1989), one can obtain an affected area inscribed in a circle of approximately 600 m in diameter for the dye tracer monitored 2 m in depth. Such value is comparable with the range obtained from the variogram analysis for the dye tracer (560 m) and turbidity (530 m) data monitored 6.5 m in depth.

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. However, considering a detection limit of 0.2–0.3 NTU for the turbidity data (based on a noisy background) it was possible to delineate areas associated with dilutions of 1:1,000. Into the northwest direction, the turbidity plume is masked possibly due to sediment resuspension.

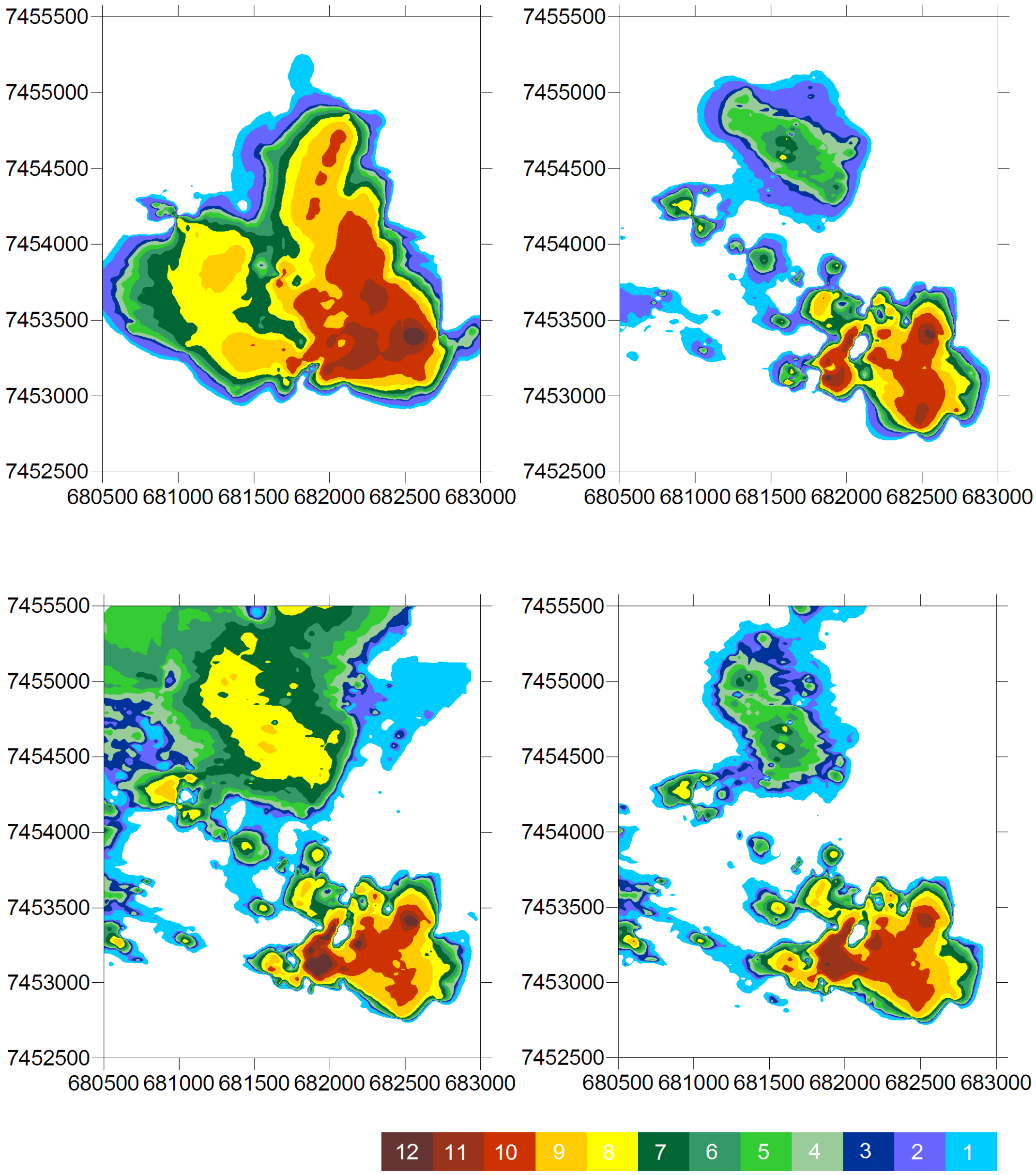

Figure 4. Contour maps for the effluent of SSOI: dye tracer at 2 m below surface (*upper left*); dye tracer at 6.5 m below surface (*upper right*); turbidity at 6.5 m below surface (*lower left*) and detrended turbidity at 6.5 m below surface (*lower right*); colour code is found on **Table 3**. Vertical and horizontal axis are North and East UTM coordinates respectively.

CONCLUSIONS

The field campaign was carried out during the spring season of 1997. The dye tracer Amidorhodamine G Extra 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. An optical backscattering sensor was also used for monitoring the turbidity levels on the studied area. The turbidity levels found in the studied area are too low for affecting fluorescence measurements.

The analysis of the whole dataset showed the ascension tendency of the plume due to a non-stratified water column. Variogram analysis for both dye tracer and turbidity dataset were used for contour generation by the kriging method. Under very low oceanic currents, the spatial variability presented an isotropic behaviour as verified by the variogram analysis.

The use of the turbidity as an environmental tracer allowed to delineate the dilution field near to the diffusers for a non-stratified water column. Although both dye tracer and turbidity allowed to delineate isolines of dilution factor up to 10^3, the effluent turbidity data is masked in areas into the coast line direction probably due to sediment resuspension.

As expected, the dye tracer represents a more robust tool for monitoring outfalls although it brings the requirements of an expert team and specialized set of instruments.

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