Dye tracers as a tool for submarine outfall studies associated with Mathematical Modeling

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Abstract
This work presents a short review of the use of artificial tracers in studies related to the experimental evaluation of transport and dispersion characteristics of domestic and industrial effluents disposed through submarine outfalls in Brazil.
In addition describes how LT-COPPE/UFRJ has evolved from studies performing instantaneous injection of radioactive tracer (meanly ^{82}B) to more complete studies by performing continuous injection of fluorescent dye tracers with simultaneous measurement of both meteorological and oceanographic parameters to provide data required for Mathematical Modeling.

Keywords
Fluorescent dye tracer; field studies, submarine outfalls, modeling

INTRODUCTION

During the 1960s decade several research institutions across the world, mostly supported by the International Atomic Energy Agency - IAEA (Vienna), developed the basic tracer techniques, involving the injection of slug containing a short-lived radioactive isotope (in general ^{82}Br). In the earliest studies, the tracer was injected at the surface or the subsurface of the receiving water body, never directly into the pipeline or close to the diffusers.

The evolution of the tracer cloud was then measured in the receiving water body using radioactive detectors immersed in the sea water. The general goal of those studies was to help making decisions regarding the final position of the outfalls' diffusers.

The techniques developed at the Danish Isotope Center (DIC) and the pioneer works of Harremöes (1967) and Hansen (1971) had a great influence on the early studies performed in Brazil by the research groups at I.E.A. (Instituto de Energia Atomica - São Paulo-Brazil) and I.P.R. (Instituto de Pesquisas Radioativas - Belo Horizonte-Brazil).

Field experiments using radioactive tracers were performed by Gauthier (1976) in France, Spain, by White (1976) in England and by Hansen (1970) in Denmark, by scientists hosted by Nuclear Research Institutes in early 1970s.

In pioneer studies along São Paulo State coastline, several instantaneous injections of ^{82}Br were performed in order to help in the final decision regarding the location of the diffusers of important submarine outfalls at the towns of Guarujá, Santos and Ilha Bela. The paper published by Agudo et al. (1976) may be considered a good example of a series of publications (*in Portuguese*) concerning the applications of radiotracers related to submarine outfalls in Brazil during this decade.

A synthesis of similar research studies produced by I.P.R. was presented by Marri (1973), describing the field work performed in the vicinity of the already existing Ipanema's submarine outfall and in the vicinity of the future Barra da Tijuca's submarine outfall, both situated on the coast of Rio de Janeiro city.

One important practical limitation concerning the use of short-lived ^{82}Br and other gamma-emitting tracers in submarine outfall studies was the near impossibility of performing continuous injection due to radioprotection considerations. The increasing global restrictions for using radioactive tracers in open waters also seriously contributed to make impossible the labeling of large amounts of waste waters, which are typical in submarine outfall studies.

These limitations were overcome by the introduction of fluorescent dye tracers in submarine outfall studies where continuous injection of selected dyes could be performed for several hours, with practically no toxicological or eco-toxicological concerns.

By 1989, the Tracer Laboratory at the Federal University of Rio de Janeiro (LT-COPPE/UFRJ) was also using instantaneous injection of ^{82}Br combined with the dye Rhodamine WT as tracers to label the thermal waste water of Angra dos Reis Nuclear Power Plant at Rio de Janeiro State.

Later on, the LT-COPPE/UFRJ has started the development of a suitable methodology, based on field studies carried out by Murthy and Miners (1978), to use a continuous injection of fluorescent dye tracer to evaluate the efficiency of submarine outfalls in operation along Brazilian coast.

Table 1. Basic information concerning field experiments performed by the LT-COPPE/UFRJ in Brazilian submarine outfalls employing fluorescent dye tracers.

City (Site)	Type	Year (NE)	NO	Depth (m)	LS (km)	TFR (m^3/s)	DL (m)	NP
Maceió (Salgema)	(I)	1988-89 (3)	1	17	1.8	1.1	250	1
Rio de Janeiro (Ipanema)	(I)	1996-97 (3)	1	28	4.3	6.0-6.2 4.8-5.7	450	3
Salvador (Rio Vermelho)	(D)	1995 (2)	1	27	2.0	0.95-1.1	75	2
	(D)	1999 (2)	1	27	2.0	4.0	75	3
Aratú (Dow Chemical)	(I)	2002-03 (2)	1	15-25	0.15	2.0	10	1
Aracruz (Fibria)	(I)	1993 (4)	2	17	2.0	2.5	200	2
	(I)	2010 (2)	3	17	2.0	2.2	200	2
Guamaré (PETROBRAS)	(I)	2008 (4)	2	6	5.7 7.2	1.0	100 250	1
Rio de Janeiro (Guanabara Bay)	(-)	2009 (1)	(-)	(-)	(-)	(-)	(-)	1
Rio de Janeiro (Maricá)	(-)	2009 (1)	(-)	(-)	(-)	(-)	(-)	1

NOTE: Type = (I) Industrial Effluent, (D) Domestic Effluent NE = Number of Experiments
NO = Number of submarine Outfalls LS =Length of the Submerged pipeline
TFR = Total Flow Rate DL =Diffusers Length ND = Number of Pumping depths
(-) planned submarine outfall and tracer injection performed close to the sea surface

In early studies the main objective was simply to evaluate the real response of submarine outfall in-operation by tracking the plume path and by measuring dilution factors in order to establish the value of the minimum dilution factor and the affected area under the so-called “representative” environmental conditions dictated by Brazilian Environmental Authorities.

During 1996 and 1997, a set of four field campaigns with tracer were carried out at the Submarine Sewage Outfall of Ipanema (SSOI), the oldest and the biggest in operation in Brazil.

Due to the importance of the SSOI which discharges *in natura* domestic effluents close to tourist interest beaches of the city of Rio de Janeiro, the environmental authorities responsible for the operation of the SSOI have been convinced to sponsor long term measurements of oceanographic data in conjunction with tracer studies.

Very reliable information were then gathered about the temperature of the water column (by using Aanderaa thermistor strings) and about the local sea currents (by using ADCPs).

The gathered data during the tracer and oceanographic studies were later used for the calibration process of the SisBaHia (Sistema Base de Hidrodinanamica Ambiental), a computational model developed by Rosman (1998) at COPPE-UFRJ (see http://www.sisbahia.coppe.ufrj.br/). A rich dataset was used to support MSc and PhD theses at COPPE/UFRJ and reported by Pecly (2000), Roldão et al. (2001) and Carvalho et al. (2002).

BASIC DYE TRACER METHODOLOGY

The measurement of the actual dilution factor is a basic requirement for the performance assessment of an outfall during its operational phase. The fluorescent tracer methodology is especially suitable to evaluate “on duty” submarine outfall transporting domestic or industrial effluent.
The basic hypothesis states that the dilution characteristic of the selected tracer reproduces the dilution characteristics of the soluble aqueous portion of the effluent, which in practice is not very restrictive.

The dilution factor

The dilution factor S_a here seen as the reciprocal of the volume fraction of effluent v_e contained in the diluted plume follows the definition of Baumgartner et al. (1994) and can be expressed as the ratio between the sum of effluent volume v_e with the volume of ambient dilution water v_a and the effluent volume v_e , i.e.:

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

Using the continuity equation and rearranging 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).

Tracer selection

The dye tracer usually adopted by the LT-COPPE/UFRJ for field works in surface waters is Amidorhodamine G Extra (Color Index 45220). This fluorescent possesses very good solubility in water and has proved to be very conservative in domestic and industrial effluents. It has low sensitivity to temperature fluctuations and to pH changes as well strong resistance against photo-decay, low adsorption onto suspended solids and low biodegradability. This dye tracer is safe both from toxicological and eco-toxicological points of view (Behrens et al. 2001). Another important practical aspect derives from the fact that the tracer is sold as an easily soluble and concentrated powder, simplifying the dilution and transport efforts.

In special situations when, for any specific reason, it appears to be interesting to use a second tracer the fluorescent dye Sodium Fluorescein (Color Index 45350) is the usual choice. This tracer is advised to be used in field studies of short duration due its fair sensitivity to photo-decay and to biodegradation.

Laboratory procedures using proper spectrofluorometric technique permits their detection in water samples containing Amidorhodamine G Extra and Sodium Fluorescein.

The detection threshold by using spectrofluorometers in laboratory is around 0.01 mg/m^3. For *in situ* measurements, by using field fluorometers, the detection limit lies between 0.1 mg/m^3 (clear sea water) and 0.3 mg/m^3 (river or turbid sea water).

Tracer injection

The injection flow rate is general kept constant, but in situations when the effluent flow rate varies the injection flow rate can be adjusted to keep constant the tracer concentration in terrestrial pipeline.

The concentration of the tracer to be injected in a terrestrial pipeline use to be around 10% (above the limit of solubility) and total mass of the dye to be injected will depend on the flow rate of the effluent and on the duration the injection (typically between 6-8 hours).

The dye concentration in the terrestrial pipeline (c_e), after complete mixing of the dye in the effluent is reached is typical around 300-500 mg/m^3 allowing to measure the maximum value of dilution factor (S_a) in the range 1000-3000 (depending on the optical characteristics of the local sea water).

Figure 1. Continuous injection of the fluorescent dye tracer at the inlet of a terrestrial pipeline.

As a rule, at every 15 minutes, a sample of dye solution which is being injected is taken for later determination of the concentrated dye. At the same time the injection flow rate is measured by volumetric method using a graduated cylinder and a chronometer.

Tracer concentration of the dye tracer in the terrestrial pipeline

A sampling protocol needs to be established in order to obtain an average value for the dye concentration (c_e). The sampling site should be located in a place in which the complete mixing between the dye and the effluent is guaranteed. A typical sampling location is the place where the terrestrial pipeline has its transition to the submerged pipeline.

Figure 2. Sampling in a place where the dye tracer is completely mixed with effluent

As a by-product, the flow rate of the effluent can be determined by using the Mass Balance Method when a conservative dye tracer is been used.

Continuous monitoring the tracer plume in the sea

The tracer concentrations after the effluent is dispersed in the sea by the outfall's diffusers (c_p) is detected and measured with the help of suitably equipped boat, named Boat #1.

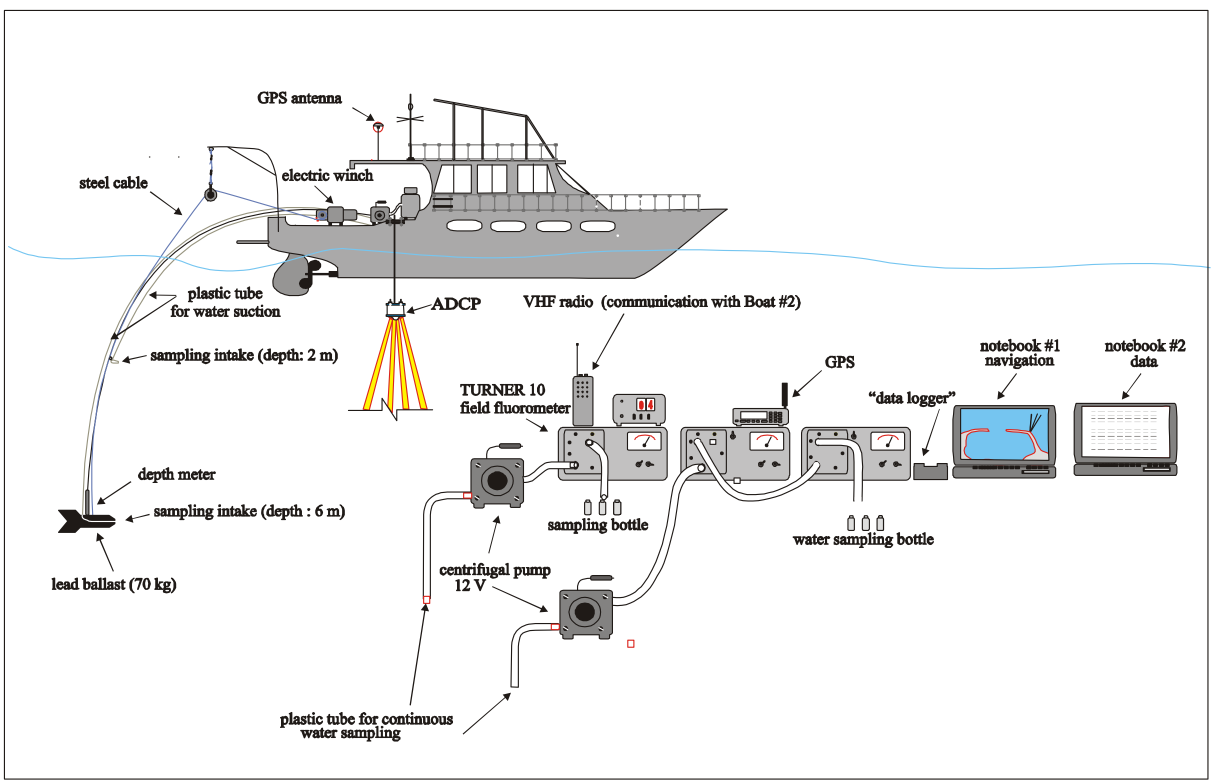

Figure 3. Basic equipment used for continuous monitoring the dye tracer plume in the sea.

Sea water is continuously pumped from the selected depths to the deck of the boat through ½" reinforced plastic tubing by using 12 VDC centrifugal pumps.

The deepest pumping intake is kept in the right vertical position by heavy ballast (from 30-75 kg) whereas the vertical position can be adjusted by an electric winch.

Depending on the length of water column, the expected vertical plume thickness and the existence of stratifications in the water column, one, two or three pumping depths are adopted. The choice of three pumping depths, offers a quasi "three dimensional" picture of the tracer plume.

LT-COPPE/UFRJ still uses the Turner field fluorometers model 10 which are robust and reliable instruments. The measured fluorescence data by each fluorometer are transformed in concentrations by its own calibration curve and are digitally recorded by a "homemade" datalogger based on the OEM Tattletale. A specific piece of software was designed and coded for saving all the gathered dye concentrations and its associated geographic positions in Universal Transverse Mercator (UTM) coordinates.

Prior to every field campaign a navigation plan is drawn based on the geographic positions associated to the beginning and the end of the diffusers of the submarine outfall(s).

Before starting the navigation a set of variable are evaluated in order to select which will be the main direction (axis), the moment to start the navigation, the distance between transects and the pumping depths.

The main variables to be estimated/measured are the current direction (either by instruments or visually), the wind direction, information obtained by vertical profiling of the tracer cloud (in general performed by a second boat, named Boat # 2), estimated transit time of the injected tracer between the injection site and the diffuser and a waiting time till the tracer plume spreads.

Commercial navigation software is normally used to assure a proper navigation along the planned transects.

Figure 4. Monitoring boat: navigation along a transects and sample collection for calibration.

A small set of water samples are collected along the navigation lines which are later analyzed in the laboratory to compare the tracer concentrations and to check the calibration curves of the fluorometers aboard.

An example of the recorded data along a set of navigation lines (transects) is shown in **Figure 5**, in which the variable *index* is associated to geographic position in UTM coordinates.

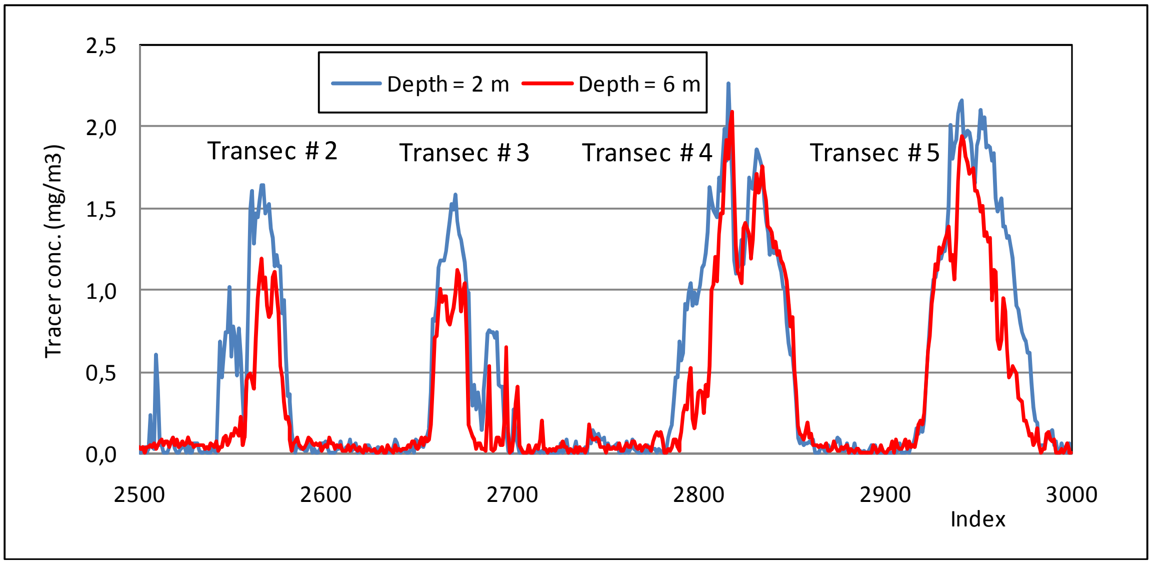

Figure 5. Variation of the dye concentration along navigation lines (transects).

Processing the data – Navigation Lines and Contour Maps

The spatial variation of the dye concentration measured along the navigation lines is then converted to spatial variation of the dilution factor by using **Equation 2**.

A well known method for visualizing the whole dataset is the drawing of contour maps representing the dilution factors. In many cases a contour map is drawn by using the Kriging Method which is a moving average weighting method aiming to interpolate points which were not directly sampled.

An important assumption inherent to the Kriging Method is that all data has been measured under a steady situation, which is not true in the sea. Depending on the total duration of a given field campaign and how dynamic the local oceanographic variable are, drawing a contour map, as shown in **Figure 6**, may be rather inaccurate.

Nevertheless the measured data along each navigation line (transect) can be considered as obtained under a "steady situation" since the duration of each transect takes just a few minutes.

It seems that drawing contour maps, despite its limitations, is still important for having an overview of the direction of transport and a more general picture of the dilution plume from a submarine outfall.

The modeling team should be interested in using a more direct and more accurate result offered by the set of individual navigation line, where the temporal and spatial variations are more reliable.

Locations where 7 (seven) vertical profiles of dye tracer concentration, temperature, conductivity and turbidity were performed by the anchored Boat # 2 are depicted with red dots in **Figure 6**. These locations were materialized by buoys released by the crew of Boat # 1 which has a more complete and "real time" idea about how the study progresses.

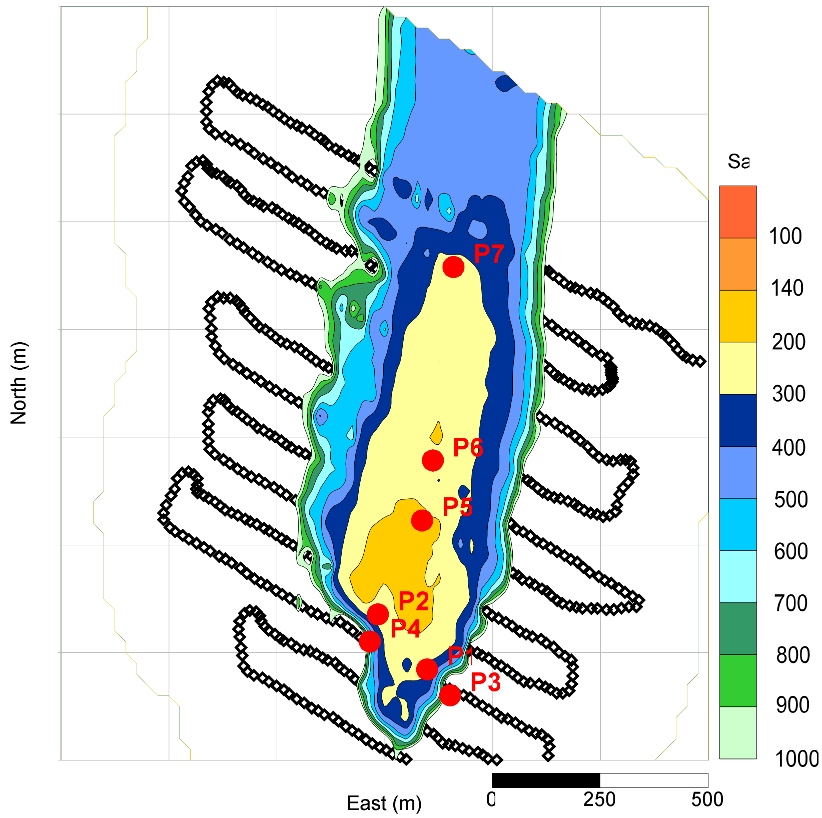

Figure 6. Navigation lines, location of vertical profiles (P) and contour lines of a dye tracer plume.

CONCLUSIONS

The prediction of the transport and the dilution of sewage or industrial effluent discharged in the sea by submarine outfalls can be obtained by using of a suitable mathematical model that requires transport and dilution data that should be obtained with the help of an independent and reliable tool such as the tracer technique.

Nevertheless tracer studies have intrinsic limitations. They need some time to be planned, they are relatively expensive, they still need a specialized team and a set of electronic instruments and due to safety reasons they cannot be conducted under rough oceanographic conditions (mainly strong winds and big waves).

The result of short tracer campaigns (each one lasting a few hours) can be extrapolated for long periods of time (several days) by using a calibrated model, in which is also possible to simulate several "extreme" scenarios in which a tracer study could never be performed.

The possibility of using data generated by models can also be helpful when the tracer campaign is being planned. Even preliminary results generated by mathematical modeling can provide valuable hints on operational requirements for instance, the number of simultaneous pumping depths, the distance between navigation lines (transects), an estimate of the length of a typical navigation line and the distance along the plume axis to be covered by the monitoring boat.

Hints can also be valuable to select the operational questions which are more related to a secondary (vertical profiling) boat, such as the number of locations to be sampled/measured and the vertical spacing between each sampled depth.

A better integration between the tracer monitoring team and the modeling team could even consider the planning of the navigation lines more suitable to the model meshes and other mutual benefits.

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