Dye tracers as a tool for outfall studies: dilution measurement approach
J. O. G. Pecly and J. S. F. Roldão

ABSTRACT
Dye tracer technique is well established and of wide application for assessment of outfalls and for delineation of near field and far field extensions. Common goals of a tracer study include the measurement of the dilution factor, estimation of the dispersion coefficients, measurement of the effluent discharge and calibration of a contaminant transport model. This paper presents a brief review of the methods involving the use of dye tracer for outfall assessment and illustrates the methods of slug release and continuous injection based on two real cases of campaigns carried out on Brazilian coastal waters. Slug injection on the surface of the water body was used for preliminary dispersion studies aiming at outfall positioning. During the operational phase of an outfall, the continuous injection of dye tracer was used to determine effluent dilution in different seasons. In coastal waters of Rio de Janeiro city, sea current pattern, tidal modulation and thermal stratification explained the main features of the dilution field.

Key words | dilution measurement, dye tracer, injection methods, outfall

INTRODUCTION
Dilution field assessment is one of the important tasks of an outfall monitoring programme in estuarine and coastal waters. Modelling is commonly used for mixing zone studies but it requires calibration against in situ measurement of tracer data to increase the reliability of the results.

Common goals of a tracer study include the measurement of the dilution factor, estimation of the dispersion coefficients, measurement of the effluent discharge and calibration of a contaminant transport model. Field monitoring campaigns using tracer techniques with different levels of complexity are described in the literature. Brooks (1960), Pritchard & Carpenter (1960) and Okubo (1971) present 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. Seligman (1955) and Harremoës (1966) present pioneer studies of outfall assessment. With regard to plume tracking methods, Murray & Venezia (1982) discussed 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 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 (Hunt et al. 2010).

Positioning outfalls in sites with high transport and dilution capacity can minimize the risk of infection, illness, and adverse environmental impact. These aspects require studies for delineating the mixing zone around the outfall location.

Slug injection on the surface of the water may be used for preliminary dispersion studies aiming at outfall positioning. The outcome is the estimation of transport and dispersion of pollutants limited to surface layers. It is not possible to simulate the behaviour of a real diffuser installed on the bottom. During the operational phase of an outfall, the continuous injection of dye tracer can be used to determine effluent dilution under different hydrodynamic conditions. The goal for both methods is to determine the horizontal dimensions, thickness and depth of the dilution field.
field and its dependence on local currents and water temperature profiles.

To assess the effect of thermal stratification in open waters, its influence on inner waters and how these trends relate to the vertical mixing pattern, a combined case study is presented. The Submarine Sewage Outfall of Ipanema (SSOI) is an old structure launching effluents in *natura* on the coastal waters of Rio de Janeiro. This paper 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. Also discussed are some results of a preliminary tracer study inside the Guanabara Bay on December 8, 2010 during neap tide using slug injection. The study using tracers inside the Guanabara Bay was only possible in 2010 based on the expectation of siting a new outfall near its main channel.

**SITE DESCRIPTION**

The coastal outfalls of Ipanema and Barra da Tijuca and the outfall of Icarai inside the Guanabara Bay are located at the metropolitan area of Rio de Janeiro city, in the southeast region of Brazil. Other systems are in phase of 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 SSOI – built during the 1970s – has a submerged pipeline with 4,325 m in length and diffusers on the last 450 m in a site 28 m deep. The Barra da Tijuca outfall is located about 10 km west of Ipanema Beach. The Submarine Sewage Outfall of Alegria (SSOA) was planned, but not yet built, for siting near the Guanabara Bay main channel. The location of the Icarai outfall is close to the mouth of the Guanabara Bay.

Sea currents off the coast are parallel to the shoreline, present a pattern that depends on the cold fronts reaching the region and a modulation due to tides. Inside Guanabara Bay, tidal flow dominates the circulation. However, during neap tide strong winds can significantly affect the sea current pattern. Tide follows a semidiurnal cycle with a variation of 1.55 m between the lowest and the highest astronomical tide based on the data available for the tidal station of Ilha Fiscal located inside Guanabara Bay.

**Coastal water temperature**

The coastal region is prone to upwelling during the summer producing a water column with a high degree of thermal stratification. During the winter, with prevailing winds coming from between the southwest and southeast directions, the water column is normally non-stratified. To monitor these trends and their influence inside the bay, two thermistor strings Model TR7 manufactured by Aanderaa were deployed near the SSOI and near the point planned for siting the SSOA inside the bay.
The water temperature dataset gathered near the SSOI over a whole year (Roldão et al. 2001), shows that 20% of the temperature differences between the upper and lower layers were higher than 5°C while differences higher than 8°C occurred in 10% of the measurements over that period.

**DILUTION FIELD ASSESSMENT**

The basic dye injection methods are the instantaneous method (slug release), which generates a tracer cloud, and the continuous injection method, that generates a tracer plume. Instantaneous release near the water surface was used to study the transport and dispersion of a labelled volume aiming at the siting of an outfall. Continuous injection underwater was the main method used to determine the dilution field of an outfall under operational conditions. The volume of water labelled with dye was detected by instruments along the transects and profiles or in fixed positions acquiring concentration time series. The main features on effluent labelling and sampling and on dilution assessment are summarized in Table 1, followed by a descriptive summary of its topics.

**Importance of oceanographic conditions**

Field campaigns should be planned to cover different oceanographic conditions that determine the effluent dilution pattern. Hydrodynamic pattern is related to the transport and diffusion of the effluent while thermal stratification is related to vertical mixing. For preliminary outfall siting studies, local oceanographic data can be used for probabilistic modelling as it was done for Barra da Tijuca Outfall (Roberts 1989). For the SSOI case, a monitoring programme included a set of four field campaigns carried out during the years of 1996 and 1997 in different seasons, including stratified and homogeneous water column conditions. The campaign carried out inside Guanabara Bay in December 2010 was planned to cover the ebb period during neap tide, which means the water flushing out of the bay under lower tidal range. Under neap tide, with currents of small magnitude driven by a small tidal range, a small dispersion of the tracer cloud was expected.

**Tracer selection**

The dye tracer selected was Amidorhodamine G (Colour Index 45220) due to its conservative characteristics: 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, using spectrofluorometric techniques, is about 0.01 mg/m³. For in situ measurements, using field fluorometers, the detection limit lies between 0.1 and 0.5 mg/m³ allowing data acquisition of tracer samples in real time.

**Slug injection and cloud detection**

A field campaign inside Guanabara Bay was planned for an ebb period during neap tide, because the local hydrodynamic pattern is tide-dominated. Under neap tide, a small cloud dispersion represents the worst case scenario for effluent dilution. A volume of 50 L of water was labelled with 1 kg of Amidorhodamine G and released at the sea surface. Ethyl alcohol was added to the tracer solution prepared with fresh water to change its density to a value near to that of the sea water. The Eulerian monitoring method is normally used for cloud detection in narrow rivers and streams where samples are collected in fixed points as a function of time. In the Eulerian method, the flow and concentration of a given substance are described at a frame fixed in space (Rybak & Huybrechts 2003; Lauritzen 2005), but the method suffers from restrictions on the sampling time. In this study, a kind of Eulerian method was used for detecting the dye cloud. Transects (navigation lines perpendicular to the mean flow used for gathering samples equally spaced

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**Table 1 | Summary of the methods, main tasks and application to studied sites**

<table>
<thead>
<tr>
<th>Site</th>
<th>Inside Guanabara Bay</th>
<th>Ipanema (SSOI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanographic study</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Monitoring period</td>
<td>One tidal cycle for both methods</td>
<td></td>
</tr>
<tr>
<td>Dye tracer</td>
<td>Amidorhodamine G for both methods</td>
<td></td>
</tr>
<tr>
<td>Outfall in operation</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Injection method</td>
<td>Slug</td>
<td>Continuous</td>
</tr>
<tr>
<td>Sampling strategy (see Figure 3)</td>
<td>Transects repeated until concentration reached background</td>
<td>Transects in zigzag pattern over the dye patch</td>
</tr>
<tr>
<td>Trajectory correction</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Vertical profiles</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Boat payload</td>
<td>Same instruments for both methods</td>
<td></td>
</tr>
<tr>
<td>Data processing</td>
<td>Contour maps by kriging for both methods</td>
<td></td>
</tr>
<tr>
<td>Dilution ratio estimative</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
in time) along dye patch should start and end at background levels and are repeated until the tracer concentration – at the cloud centreline – reaches its background value. After the cloud spreading, a new transect ‘downstream’ is defined (at a position where the cloud has not yet reached) and the process is repeated (Roldão et al. 1996). In case of fast-spread clouds, the long duration of one transect implies in dye patch dimensions that vary while the navigation line is performed. The positioning of the transects (following global positioning system (GPS) readings) is rapidly selected based on a rough estimation of the transit time, on the measured concentration levels of previous transects and on the judgment of the researchers on board of the monitoring boat.

Whichever the injection method – slug or continuous – two boats with similar instrument payloads were used and similar tasks were performed during the cloud or the plume tracking (details are given in the section Continuous injection and plume tracking below).

**Trajectory transformation (slug method)**

The maximum concentrations along the transects were identified as a first step for data processing. Then, the mean water velocity between consecutive transects was estimated based on the position and on the time associated to the points of maximum concentration. Such estimated values of velocity or, when available, measurements of the mean water velocity were used for translating the position of each sample along the original navigation lines to new coordinates (Figure 3(a)) calculated by

\[ x_{\text{new}} = x_i + u(t_i - t_0) \]  
\[ y_{\text{new}} = y_i + v(t_i - t_0) \]

where \( x_{\text{new}}, y_{\text{new}} \) 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 mean water speed, respectively, and \( (t_i - t_0) \) is the difference between the original \( t_i \) and central \( t_0 \) time of the cloud.

**Continuous injection and plume tracking**

The SSOI effluent was labelled with Amilorhodamine G injected into the outfall pipeline during a period of 6 hours because the site experiences a semidiurnal tide pattern. An apparatus for continuous injection was designed and could be adjusted to keep the average tracer concentration in the effluent between 300 and 600 mg/m³ and to keep injection rate steady. Effluent samples – collected after reaching a good mixing distance – were used to determine the tracer concentration inside the outfall and the effluent flow rate (Kilpatrick & Cobb 1985; ISO 1992). The effluent release rate was kept steady during the injection period as required.

Two boats were used for monitoring the dilution field. One boat was equipped with pumping system, Turner 10AU field fluorometers, GPS and portable computers. The plume detection was performed along the navigation lines perpendicular to the average flow (Figure 5(c)) with the help of navigation software. Sea water was continuously pumped from the defined depths through the continuous flow cell of field fluorometers connected to a data collection device running a software designed and coded for gathering samples to determine tracer concentration and its associated geographic positions, which were then transformed to the Universal Transverse Mercator (UTM) projection. Some water samples were collected along the transects for measurement of dye concentration in the laboratory by the spectrofluorometric method.

Also during the navigation, some points with singular concentration readings were marked with buoys. The marking buoys indicated the points chosen for vertical profiling of dye tracer, conductivity-temperature-depth (CTD) data and other parameters (typically dissolved oxygen and water turbidity) by a second boat equipped with pumping apparatus, Turner 10AU field fluorometers, GPS and CTD (SeaBird SBE37) instruments.

**Data processing and analysis**

Although the pre-processing phase of the tracer dataset obtained by the slug and the continuous release differed, contour generation followed the same basic steps. For the dataset visualization, contour maps can be drawn from interpolated values by the kriging method (Oliver & Webster 1990). Although the geostatistical techniques use an underlying hypothesis of stationarity (which is not the case in the sea) for contour map generation, the kriging method was chosen because it is an optimum estimator and, as thus is a good tool for comparison of different contour plots.

**The dilution factor (continuous injection)**

The average dilution factor \( S_a \) calculated with the tracer data, considering its nonzero ambient concentration, can
be expressed by the definition of Baumgartner et al. (1994) for the case of continuous injection as

\[ S_a = \frac{c_e - c_a}{c_p - c_a} \quad (3) \]

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

As the concentration of Amidorhodamine G can be detected in the sea water down to a range between 0.1 and 0.3 mg/m\(^3\), this dye is adequate to evaluate dilution factors up to \( 10^3 \) using the values of \( c_p \) gathered during the plume tracking.

**RESULTS**

**Temperature**

Time series for the water temperature at the upper and the lower layers for both SSOI and SSOA during September 1997, typical spring conditions in the coast of Rio de Janeiro State, are shown in Figure 2. Temperature data gathered near the outfall of Ipanema showed, however, that the water column changed from a homogeneous to a stratified condition and vice versa in a matter of a few days due to upwelling (Figure 2(a)). In September, cold water moved away from shore on September 8 and from September 11 onwards being replaced by warmer waters.

The transfer function between temperatures observed on coastal (Figure 2(a)) and inner (Figure 2(b)) waters resembles the action of a low pass filter. Strong coastal thermal stratification due to upwelling did not reach the SSOA region because of a slow exchange with the inner waters. 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.

**Tracers**

A slug injection was employed for a preliminary study inside Guanabara Bay on December 8, 2010. Instantaneous release of a solution of Amidorhodamine G was performed on the water surface 1 hour after the high slack water during neap tide. Sea water was continuously pumped from a depth of 0.5 m below the surface through the continuous

![Figure 2](https://iwaponline.com/wst/article-pdf/67/7/1564/440794/1564.pdf)

**Figure 2** | Temperature time series of the upper and lower water layers at (a) Ipanema (SSOI) and (b) inside Guanabara Bay (SSOA) during September 1997.
flow cell of a Turner 10AU field fluorometer. It was possible to detect two dye clouds separated about 2 km along the flow direction. The dataset for the first cloud – presented in Figure 3 – comprised 811 samples of tracer concentration acquired with a data collection platform based on the OEM (original equipment manufacturer) ZWorld datalogger. A summary of the results related to both clouds is presented at the end of this section.

The fieldwork with continuous dye tracer injection was carried out on the SSOI on September 25, 1997. The dataset for the campaign comprised 4,025 samples of tracer concentration at three monitored depths (2, 4.5 and 6.5 m). The samples were acquired with a data collection platform based on the OEM Tattletale datalogger. More details about the monitoring campaigns carried out on SSOI have been presented by Roldão et al. (2001) and Carvalho et al. (2002).

**Contour maps**

The plates in Figure 3 were used for comparing some results of the tracking method employed inside Guanabara Bay (upper) and around the SSOI (lower). The upper plates show preliminary data about the transformed navigation lines (left) and the resulting dye cloud (right). The elapsed time between the acquisition of the first and the last sample was 1 hour. The lower panels show the navigation lines (left) and the resulting dye plume (right) for the

![Figure 3](https://iwaponline.com/wst/article-pdf/67/7/1564/440794/1564.pdf)
tracer data gathered 2 m below surface. The tracking time between the start and the end of the navigation around SSOI was about 6.5 hours. Although the spatial scales for the cloud and for the plume illustrated in Figure 3 are the same, the campaigns were carried out on different dates.

The dilution plume of the SSOI monitored on September 25, 1997 (lower right plate in Figure 3) represents a specific condition with low sea currents ranging between 2 and 14 cm/s to northwest (into the shore direction) near the neap tide. Based on a detection limit for the dye tracer of 0.15 mg/m³ it was possible to delineate an area with dilutions about 1:2,000.

Vertical mixing

Among several vertical profiles, two were chosen to illustrate the vertical mixing pattern of the volume labelled inside Guanabara Bay. The data of the profile P1 (UTM coordinates 7474641 N, 691054 E) and of the profile P2 (UTM coordinates 7472293 N, 689940 E) show a cloud limited above the level of lower density water (Figure 4). Data suggest a ‘trapping’ level near the surface related to the thickness of the fresh water layer found inside Guanabara Bay.

Four vertical profiles were chosen, among several, to illustrate the vertical mixing pattern of the effluent plume near the SSOI. The data of the profile P3 (UTM coordinates 7453493 N, 682173 E) and the profile P4 (UTM coordinates 7453376 N, 681952 E) showed a homogeneous condition in the spring of 1997 with values of temperature ranging between 21 and 22 °C over the water column. Under this homogeneous condition, a spreading of the effluent over the higher half of the water column was observed. The data of the profile P5 (UTM coordinates 7453001 N, 682770 E) and the profile P6 (UTM coordinates 7453407 N, 682434 E) show a thermal stratification with water temperature varying from 27 °C down to 16 °C about mid-depth and a plume of the effluent trapped below the thermocline in the summer of 1996 (Figure 5).

Summary of results

The main aspects and results about the dilution assessment at the studied sites are summarized in Table 2, followed by a short description of its topics.

Results in Table 2 are shown for the slug (dye released at the surface) and for the continuous injection (injection inside the pipeline, with the dye released near the sea bed) methods. For the slug release, some parameters are shown for the first and for the second cloud detected inside Guanabara Bay. For Ipanema, some results are shown for spring and summer campaigns, representative of homogeneous and stratified water columns, respectively. Then, some aspects related to the vertical and horizontal dimensions of the dye patch are included. Dye tracer was detected below the dye patch depth and each patch presented a different thickness. Among the presented cases, only the summer plume is trapped below the thermocline positioned 15 m deep. The length and width of the dye patch represent dimensions along and across the main flow, respectively. The length higher than 2,000 m of the summer plume
means that the patch was not completely detected due to time limitation. The distance and elapsed time values were calculated from the injection point up to the location of maximum concentration for the clouds inside Guanabara Bay. The dye patches inside Guanabara Bay were modelled using a 2D analytical solution for the advection-diffusion equation. The values of dispersion coefficients (longitudinal and transversal) were estimated by the comparison of the dimensions of the modelled dye patches and of the detected dye patches. For the Ipanema study, the effluent flow rate was calculated by the dilution method and used to evaluate the minimum dilution rate of the SSOI.

**DISCUSSION**

Slug release is a method particularly useful in case one expects narrow and fast advecting dye clouds when diffusion...
is considered small between transects. As for the continuous injection case, non-stationarity or flow inversion pose additional difficulties to its application. Although it represents a simple method, which allows a course contour drawing, modelling can be benefitted with calibration based on comparison between sections of the modelled cloud and the translated transects (Obropta & Hires 2007). Additional limitations are due to wind stress (Wu 1969) and sea state which, acting over a surfaced cloud during the moments after the dye release, can lead to different transport and mixing patterns.

Data analysis is difficult (Okubo 1971; Hayakawa 2003), as the dye cloud monitored on December 8, 2010 near the SSOA (upper right plate in Figure 3) spread over three dimensions. A practical approach assumes a horizontal concentric shape adjusted by an analytical formulation to estimate horizontal dispersion coefficients (Roldão et al. 1996). Water salinity profiles suggest density stratification along the water column during the ebb period. Under these conditions, the observed dye cloud was near the sea surface (Figure 4).

Continuous injection of tracer allowed us to estimate the near and the far concentration fields of SSOI. Within a navigation period of 4–5 hours, it was possible to track an area of 3 km by 3 km in the ocean with high spatial resolution. The dilution field, as well as the effluent flow rate, were calculated using the concentration data of samples gathered from the inland pipeline. Inside the above mentioned area, it was possible to evaluate dilution factors up to $10^3$.

In this paper, the term anisotropy describes the dependence of the dilution field on the direction of dispersion. The anisotropy ratio is dependent on the local flow pattern, which affects the proportion between the advective and diffusive flux. Regarding pollutant transport (simulated with dye tracer), the longitudinal dispersion near the SSOA was much larger than the transversal dispersion. On the other hand, near the SSOI and under low sea currents, the longitudinal and transversal dispersion were of the same order of magnitude. Based on the dilution patterns observed around SSOI, it is possible to define an optimized frame for water quality monitoring.

**CONCLUSIONS**

In the coastal area of Rio de Janeiro city, the dye tracer Amilorrhodamine G was injected in the water as a method to evaluate the transport and dispersion of pollutants in two selected sites. The dye tracer was instantaneously released on the tidal channel of Guanabara Bay at the sea surface and the cloud was tracked along lines transversal to the average flow. The same dye was continuously injected, on another date, into the pipeline of the SSOI and the plume tracking was also conducted along lines transversal to the average flow.

The analysis of the tracer data allowed the horizontal dimensions, thickness and depth of the cloud generated by the slug release to be determine. For the plume generated by the continuous tracer injection, the dilution field was also determined. On the tidal channel, the spatial variability was strongly anisotropic whereas on coastal waters, under low oceanic currents during the spring campaign, the spatial variability presented an isotropic behaviour as expected. The obtained dataset showed the tendency for ascension of the plume due to a homogeneous water column and the presence of a trapping level below the thermocline due to a stratified water column.

The SSOI operated under good initial dilution ratios (higher than 1:120 under homogeneous water column) and the general transport is parallel to the shore. Under thermal stratification, dilution ratios as low as 1:28 were observed. The dilution pattern observed on September 25, 1997 – into the coastline direction – is prone to occur with a small probability (Figure 3(d)). Regarding the planned SSOA, the weak tidal flushing (associated with the high residence time inside Guanabara Bay) must be considered in case of effluent disposal at this site.

Dye tracer technique constitutes a robust tool for monitoring outfalls although its use requires an expert team in field measurement and data interpretation and a specialized set of instruments. The continuous injection method can be used for environmental impact evaluation and regulatory action as a tool for assessing the effluent dilution field under operational conditions.

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