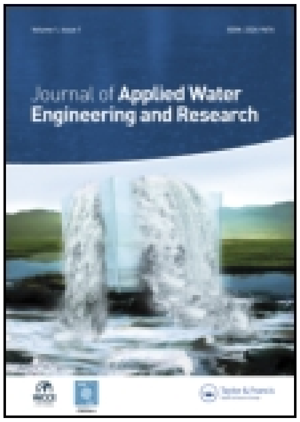

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Coupling bacterial decay and hydrodynamic models for sewage outfall simulation

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Coupling bacterial decay and hydrodynamic models for sewage outfall simulation

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The evaluation of wastewater concentrations in coastal environments has to be accurate for water quality control. The description of the physical process in a comprehensive model is a complex task. Due to the different spatial and temporal scales involved, the use of different numerical models is required: far-field hydrodynamic models; near-field and pollutant transport models. In this paper, a coupled application of these models is described. Capabilities and limitations of modelling techniques applied to wastewater mixing and dispersion from submerged multiport discharges are discussed for environmental impact analysis. The recommended procedure combines a near-field mixing zone model, such as NRFIELD, with the Lagrangian far-field flow and water quality models within SisBaHia® (http://www.sisbahia.coppe.ufrj.br/). The results showed that the model coupling improves the description and analysis of treated wastewater discharges over large scales. This allows a more realistic evaluation of the environmental impact due to domestic sewage discharges in coastal waters.

Keywords: submarine outfalls; model coupling; bacterial decay; solar radiation

1. Introduction

Submarine outfalls have been employed to discharge and disperse urban effluents in the receiving waters, providing a high dilution capacity, thus reducing pollutant concentrations to acceptable levels and further improving natural degradation processes. Most coastal outfall projects apply concentrations of indicators of faecal pollution, such as thermo-tolerant coliform bacteria, as main water quality criteria. The modelling of sewage dispersion through submarine outfalls is an issue of extreme relevance in the assessment of the environmental impact of these effluents in coastal waters and for taking decisions related to the optimal discharge position, type of diffuser and its orientation in regard to hydrodinamical field. The dispersion of contaminants in the marine environment can be described considering two different regions: the near field and the far field. The near field is governed by the initial mixing between the buoyant effluent jets and seawater, and the far field by the passive mixing driven by ocean currents and the contaminant kinetics. The space and time scales of the processes differ significantly in the near field and far field, which makes it almost impossible to include all processes in a single model. In order to overcome these hurdles, Zhang and Adams (1999), Hillebrand (2003) and Bleninger (2006) proposed a coupling methodology between near-field and far-field models, which essentially consist of a passive, one-way, offline coupling approach, where pollutant mass fluxes computed by a near-field model are inserted as a source within far-field models. These methodologies are suitable for small volume fluxes, such as most sewage discharges, which do have almost no influence on the far-field circulation patterns. However, for large volume fluxes or discharges into enclosed receiving waters, such as cooling water discharges, the passive coupling methodology does not consider the dynamic effects of the near-field mixing processes on the far-field circulation. The latter case requires a dynamic or active, online, two-way coupling methodology, as described in Morelissen et al. (2013), which provides a continuous exchange of data between the models, which run in parallel and not separately as in the previous cases. Besides those methodologies focussing on an optimized hydrodynamic consideration of the discharge situation, the additional modelling of the pollutant kinetics, which further depends on the hydrodynamic features, is underrepresented in most discharge studies or not even considered.

The established waste-field properties determined by near-field models, such as thickness and height are predominantly ruled by the receiving waters density profile. According to this profile the buoyant effluent will rise

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towards the surface, and the plume rise height is established by the position where the density difference between effluent and the surrounding water becomes neutral, being either at the surface or within the water column. Considering the influence of solar radiation on bacterial die-off, the determination of rise height and thickness is extremely relevant in the subsequent far-field modelling of wastewater discharges.

In modelling studies of bacteria transport, the decay, rate is commonly represented by the parameter T_{90} describing the time required to reduce the bacteria population by 90% of its original concentration. Basically in the marine environment, variations in solar radiation, temperature and salinity are considered as major parameters determining bacterial decay rates. According to Feitosa et al. (2013) amongst the formulations presented in literature (Bellair et al. 1977; Chamberlin & Mitchell 1978; Canteras et al. 1995; Christoulas & Andreadakis 1995; Sarikaya & Saatçi 1995; Guillaud et al. 1997; Yang et al. 2000), Mancini's (1978) formulation was adopted because it is in better agreement with field data.

In fact, solar radiation has been found to be more influential on the bacterial decay rate than other environmental parameters (Fujioka et al. 1981; McCambridge & McMeekin 1981; Canteras et al. 1995; Christoulas & Andreadakis 1995; Sarikaya & Saatçi 1995). Solar radiation in the water column can be computed by a numerical model parameterized by a set of input parameters such as date; latitude; cloud cover; atmospheric conditions and water light extinction coefficient. A commonly used calculation methodology is described in McCambridge and McMeekin (1981).

For the coupled modelling approach, the methodology proposed by Roberts (1979) and Roberts et al. (1989) was used for the near-field model, providing source data for a Lagrangian far-field flow and water quality model within SisBaHia®. This model is a result of a cooperation between the Coastal and Oceanographic Engineering Area (Oceanic Engineering Program) and the Database Area of Systems Engineering (Computer Science Program), both from the Department of Engineer Grauduate Programs (COPPE), Federal University of Rio de Janeiro (UFRJ).

The model produces current patterns in water bodies, where density gradients are not relevant. It enables working with a bi-dimensional current field or a tridimensional field where the current profile is influenced by the tension of friction on the surface and bottom. The plume's advection and turbulent dispersion is performed by the advective–diffusive transport model which uses the current field based on the hydrodynamic model. For a complete description of the modes see www.sisbahia.coppe.ufrj.br/.

This paper presents the coupled application of a near-field plume model with a far-field model together with a bacterial decay and solar radiation models.

2. Mixing processes

The mixing process between the sewage and the seawater comprises two different regions according to their space and time scales. The first region is the near-field active mixing zone that occurs close to the diffuser. In this turbulent region, the hydrodynamics are influenced by the effluent jet momentum. The buoyant force due to the effluent's density (in case of a sewage effluent discharge in a marine environment), contrasting with the seawater, deflects the jet upwards, forming plumes which are deflected downstream by ocean currents. The ejected plume mixes with the surrounding water, reaching its ultimate position in the water column (neutral buoyancy level) where there is no difference anymore between the mixed effluent and surrounding water densities (which is typically the water surface in case of no ambient stratification). In the latter region, named far-field or neutral mixing zone, the effluent is passively transported by ocean currents where due to the longer time scale bacteria decay kinetics take place. Due to the differences between the active and passive mixing zones, specific modelling methodologies are adopted for each zone.

2.1. *Modelling of the mixing zone in the near-field*

There are many models developed for near-field modelling. The Visual Plumes Suite provided by the USEPA (United States Environmental Protection Agency) (Frick 2001) has the NRFIELD models implemented. The NRFIELD model is based on the experiments carried out by Roberts (1979) and Roberts et al. (1989) for homogeneous and density stratified waters, respectively. Another model, widely used in practice is the CORMIX model ('Cornell Mixing Zone Expert System', www.cormix.info, Doneker & Jirka 2007), which is composed of a jet integral model combined with multiple routines to simulate the mixing including boundary interactions and far-field spreading. NRFIELD and UM3 allow as input arbitrary density profiles, which are also performed in the sub-module CorJet within CORMIX; however, general applications of CORMIX use schematized profiles with four types: uniform, linear, two layers and a constant surface layer followed by a density jump and a linear profile.

Carvalho et al. (2002) performed field observations of the Ipanema sewage outfall in Rio de Janeiro, Brazil, by adding dye tracers to the effluent and simultaneously measuring oceanographic conditions. This outfall discharges at a depth of 27 m about 6 $m^3\ s^{-1}$ of domestic wastewater from the southern zone of Rio de Janeiro. It is 4326 m long, 2.4 m in diameter and the last 449 m is the diffuser, consisting of 90 ports (170 mm diameter) on each side, spaced 5 m apart.

The results showed that the three aforementioned models can reasonably predict near-field characteristics. However according to plume rise height results, NRFIELD presented the best fit between observed and calculated values. Additionally, this model showed good results in the

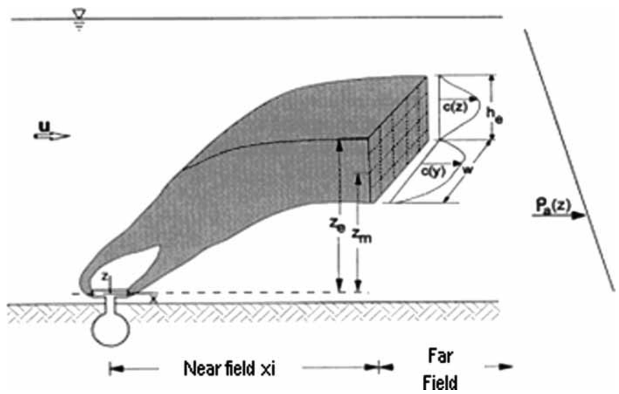

Figure 1. Characteristics of the plume in the near-field.

near-field study of the Boston outfall (Roberts et al. 2002), as long as boundary interactions are negligible, which is usually the case for deeply submerged discharge situations.

Considering solar radiation intensities for different plume positions as one of the most important factors in determining bacterial decay rates, the NRFIELD methodology was adopted in the present work.

NRFIELD is a dilution model for effluent discharges that determines the geometric characteristics of the established waste-field (Figure 1), such as the rise height (z_e); the minimum initial dilution at the end of the initial mixing region (S_m); the thickness (h_e) and the length of the initial mixing region (x_i).

2.2. *Modelling the passive mixing zone in the far field*

Downstream of the near-field region the effluent is passively transported by surrounding currents. In this passive mixing zone (far field), the contaminant concentrations in water depend on hydrodynamic processes and bacterial decay kinetics.

As mentioned before, the decay of the bacteria is a function of a number of parameters that are described by a decay rate called k. This rate is empirical and varies as a function of the environment conditions where the bacteria are developing (see Feitosa et al. 2013 for a complete description).

The bacteria concentration over time, considering a first-order kinetic die-off, where C is the time concentration; C_0 the initial concentration; k the bacterial decay rate and t the time, is given by the equation:

$$C = C_0 \, e^{-kt}. \tag{1}$$

In numerical modelling studies, the decay rates k are also expressed by the parameter T_{90}, which corresponds to the time required to reduce the bacterial population by 90% of its original amount. In this case, the previous equation can be written as follows:

$$0.1C_0 = C_0 \, e^{-kT_{90}}, \quad T_{90} = \frac{2.3}{k}. \tag{2}$$

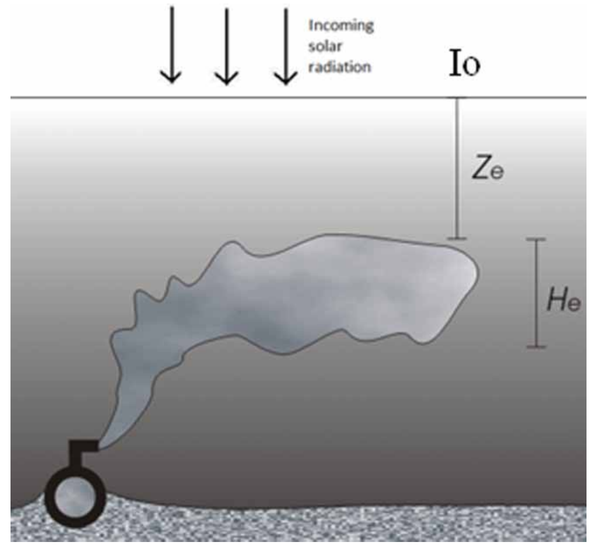

Figure 2. Representation of the solar radiation penetration along the water column.

The role of solar radiation in bacterial decay depends on light intensity at the plume position (Figure 2).

Carvalho et al. (2006) proposed an adaptation where solar radiation is averaged between the top and the bottom of the plume (Equation (3)):

$$\bar{I} = \frac{I_0}{H_e K_p} e^{-K_e Z_e} [1 - e^{-K_p H_e}], \tag{3}$$

where I_0 is the incoming solar radiation on top of the plume; H_e is the thickness of the plume; Z_e is the depth of plume and K_e and K_p are the light extinction coefficient for sea water and wastewater plume, respectively (m^{-1}).

High values of these coefficients show a strong light attenuation in the water column. A rough estimate of K_e and K_p is related to the Secchi depth Z_s according to the following equation:

$$K_{e,p} = \frac{1.8}{Z_s}. \tag{4}$$

If turbidity information is available or being modelled, more detailed estimates can be done accordingly. The formulation proposed by Mancini (1978) provides numeric estimate of coliform decay rates (k), considering the combined effects of solar radiation, salinity and temperature (Equation (5)). This methodology is considered by Manache et al. (2007) as one of the most complete models of faecal coliform decay:

$$k = [0.8 + 0.006 \times (\%\text{seawater}) \times 1.07^{(T-20)} + \bar{I}], \tag{5}$$

where the decay rate (k) is represented in day^{-1}, solar radiation in Langley[1] h^{-1}, T corresponds to temperature in °C and seawater salinity (35) is equivalent to 100%.

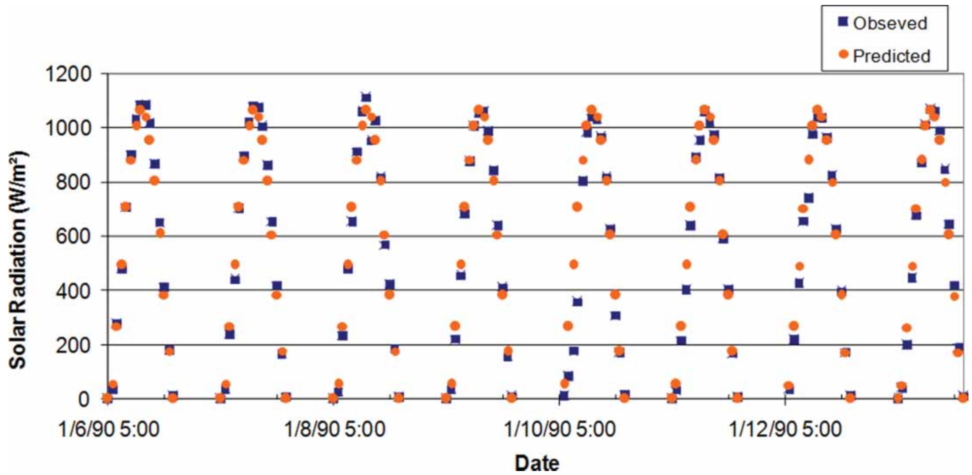

Figure 3. Comparison between solar radiation data as measured and that which was calculated by the model. Measurements carried out during the 1989 summer by the IEAPM (Brazilian Navy, pers. comm.) – Arraial do Cabo – RJ.

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3. Solar radiation model

The determination of solar radiation levels is extremely important for coliform modelling. The model proposed by Martin et al. (1999) was used in the calculation of solar radiation levels within the plume. This model considers the variation of geographic, seasonal and meteorological parameters. The first two parameters are represented by the latitude and by the seasons of the year that will influence the angle of incidence of the sun rays on the atmosphere. The third parameter is represented by cloud cover condition. The model input data are date, latitude, longitude, dew point temperature, hour of day and cloud cover percentage.

The solar radiation model in the present case was validated with field measurements performed in the city of Arraial do Cabo, RJ, by the IEAPM Institute (Brazilian Navy, pers. comm.). Figure 3 shows the comparison between measured and predicted values.

The solar radiation values predicted by the proposed model are in close agreement with field data. This allows the use of this model to estimate solar radiation levels without direct measurements.

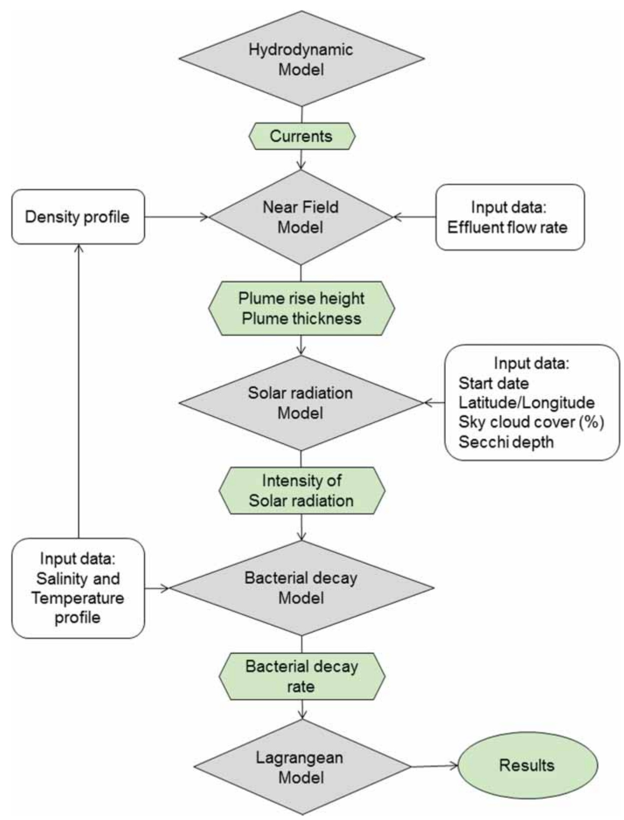

Figure 4. Flow-chart for applied one-way coupling of near-field/far-field modelling, with consecutive solar radiation, and bacterial decay simulation.

4. Coupling of the models

Model coupling intends to perform the coliform modelling in the marine environment in more realistic conditions. The information exchange between the near- and the far-field models provides more realistic predictions for the evaluation of the plume thickness and plume rise height. Figure 4 is a flow chart for the applied methodology.

The horizontal current distribution provided by the hydrodynamic model is used for the pollutant advection in the far field and is also used as input data for the near-field model. Primary results of the near-field model are characteristics of the plumes, such as thickness and rise height. These characteristics are indispensable for the quantification of solar radiation in the sewage plume. The hourly variations in solar radiation levels, salinity and temperature are used for the bacterial decay model, which provides the die-off kinetics for the far-field transport model. Below, a description of each step is discussed.

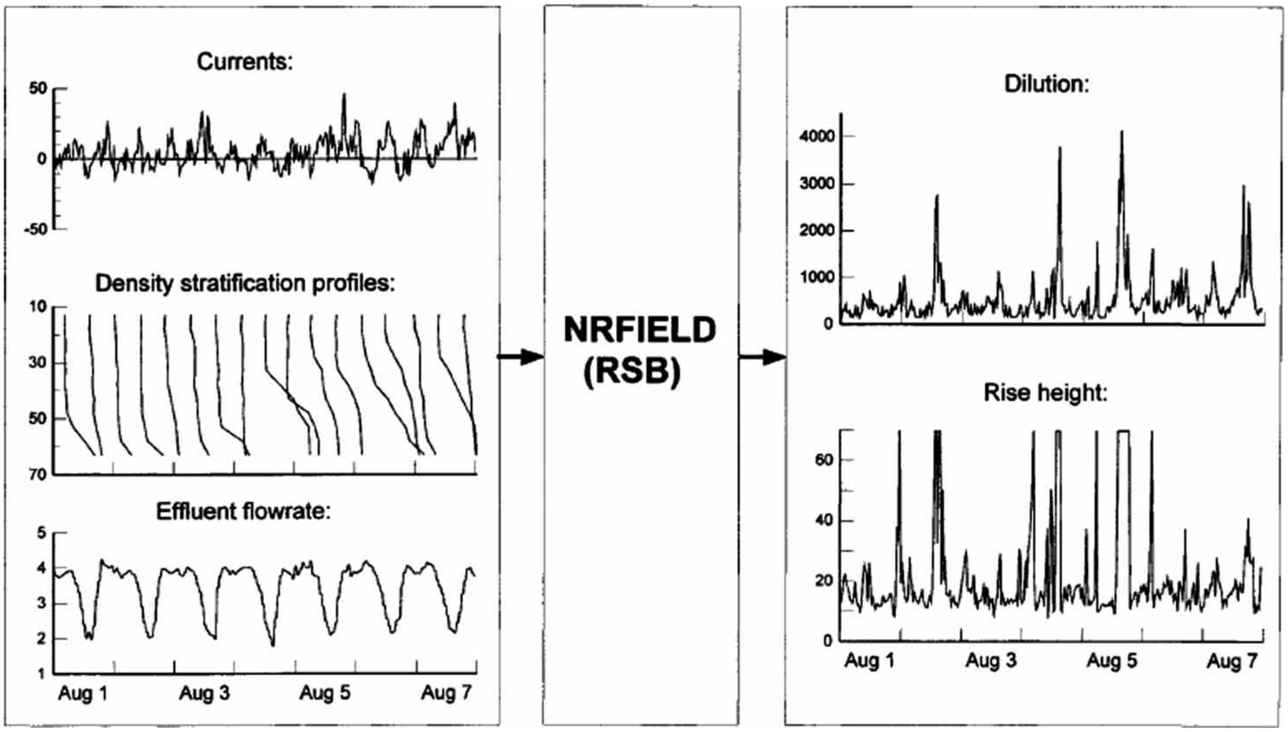

Figure 5. Main entry data of the near-field model.
Note: Adapted from Roberts (1999)

4.1. *Coupling between far-field and near-field hydrodynamic models*

A coupling scheme example is shown in Figure 5 (from Roberts 1999).

The current's action is considered through the coupling between hydrodynamic (SisBaHiA) and NRFIELD models. The effluent flow rate and density profile variations, generated by the combination of temperature (T) and salinity (S) profiles in the water column according to Eckart formula, are provided to the near field (NRFIELD) as additional input files:

$$\begin{aligned} \rho(S,T) &= 1000\frac{1+A}{B+0.698A}, \\ \text{where} \quad A &= 5890 + 38T - 0.375T^2 + 3S, \\ B &= 1779.5 + 11.25T - 0.0745T^2 \\ &\quad - (3.8 + 0.01T)S. \end{aligned} \tag{6}$$

4.2. *Coupling between the near-field and far-field transport models*

The near-field model provides the plume thickness and plume rise height for the far-field transport model (within SisBaHiA® – www.sisbahia.coppe.ufrj.br). These characteristics allow estimating the incoming solar radiation levels within the plume and consequently the bacterial decay rates.

SisBaHia® is a Lagragean transport model for simulation of the advective–diffusive transport of different types of contaminants with kinetic reactions. This model is especially suited to evaluate the behaviour of sewage and oil spill plumes in natural water bodies. The contaminant is represented as a cloud of particles, which is advected by the current field generated by the hydrodynamic module. The mass loss of the particles is computed according to the decay rates adopted in the modelling.

The contaminant decay depends on the simultaneous variation of solar radiation, salinity and temperature provided as input data. It is supposed that faecal coliform follows a first-order decay law as shown in the following equation:

$$M(t) = M_0 \exp(-k\ t_v), \tag{7}$$

where M_0 is the initial mass of the contaminant, t is the time after the release of the contaminant and k is the decay rate calculated from the formulation of Mancini (1978).

Considering the importance of solar radiation on contaminant die-off, the bacterial decay model calculates decay rates according to incoming solar radiation, salinity and temperature levels on plume's position. This fact introduces in the modelling a more sensitive performance in the estimation of the contaminant mass variation over time, according to environmental conditions.

In the next item the coupling procedure is illustrated through a hypothetical simulation that assesses the influence of variations of plume characteristic for the far-field modelling.

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5. Case study

The influence of density stratification is evaluated based on a comparison between two different scenarios during 108 h simulations. Both simulations started at 0:00 h of 16 January and covers a 4.5-day period (108 h). The start date is a relevant input in the modelling for determining solar radiation levels in the period of the simulation.

The first scenario (Figure 6) does not consider the hydrodynamic coupling of the models, and the top of the plume remains in free surface, during the whole simulation period. Thus, the intensity of the solar radiation on the free surface and on top of the plume is the same.

As shown in Figure 6, whenever the hydrodynamic parameter variations are not included (no coupling), T_{90} follows a cyclic pattern along the entire simulation. This is because no data interchange between near- and far-field hydrodynamic models exists, and currents and density profiles are supposed constant in the near-field modelling. As a result, the plume is considered in the same depth and with the same thickness for the whole time period, and the solar radiation on the plume only varies due to its hourly variations.

The second scenario (Figure 8) considers the one-way coupling of the hydrodynamic near-field and far-field models with bacterial decay, and solar radiation models. Thus, the decay rates can be computed with values of solar radiation, salinity and temperature on plume's position in the water column. During the simulation, the water density profiles varied according to what is shown in Figure 7, moving from a nearly homogeneous to stratified condition capable of establishing the submerging of the plume.

As shown in Figure 8, apart from the hourly variations of solar radiation on the free surface, the coupling incorporates the light attenuation according to the plume rise height. As a result it is possible to verify that bacterial decay (T_{90}) no longer varies in cycles. During the night period the

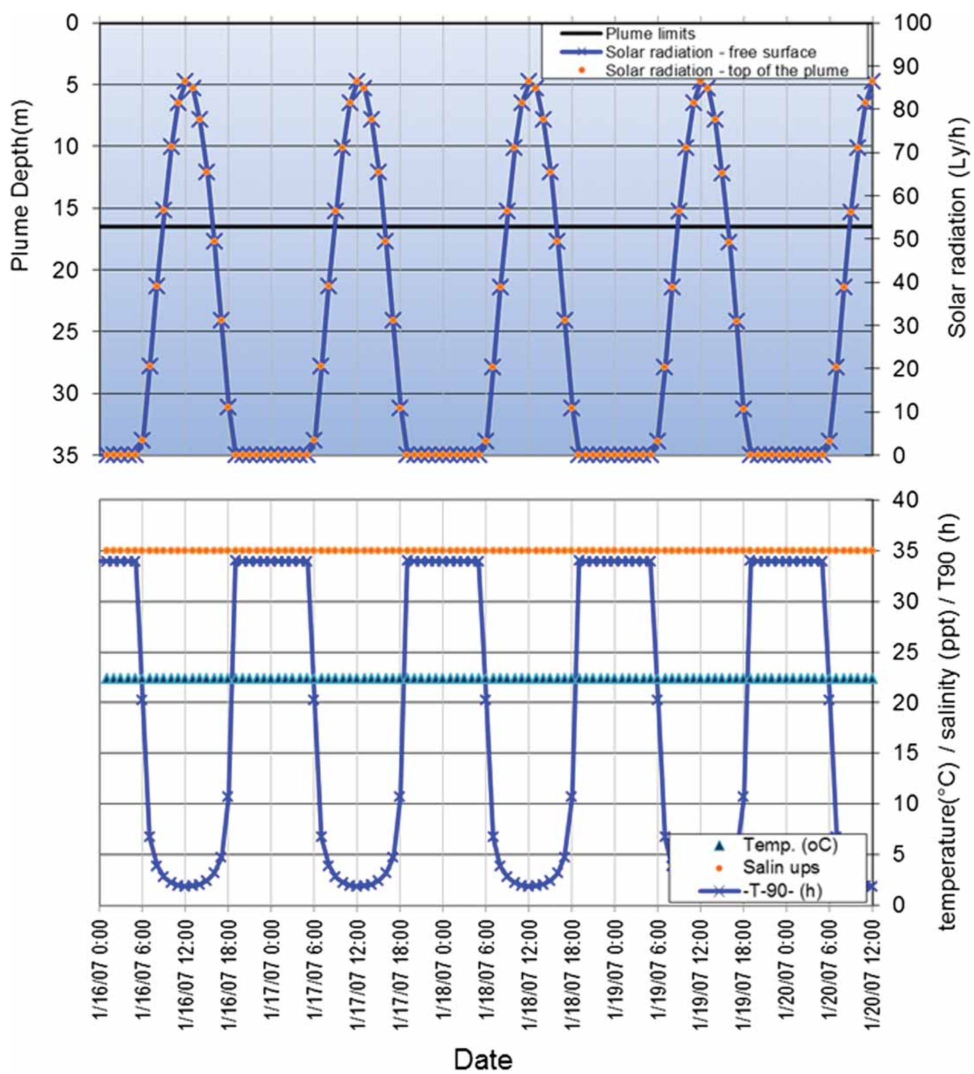

Figure 6. Surface plume condition. The upper illustration shows the intensity of solar radiation, whilst the lower one shows the T_{90} variation.

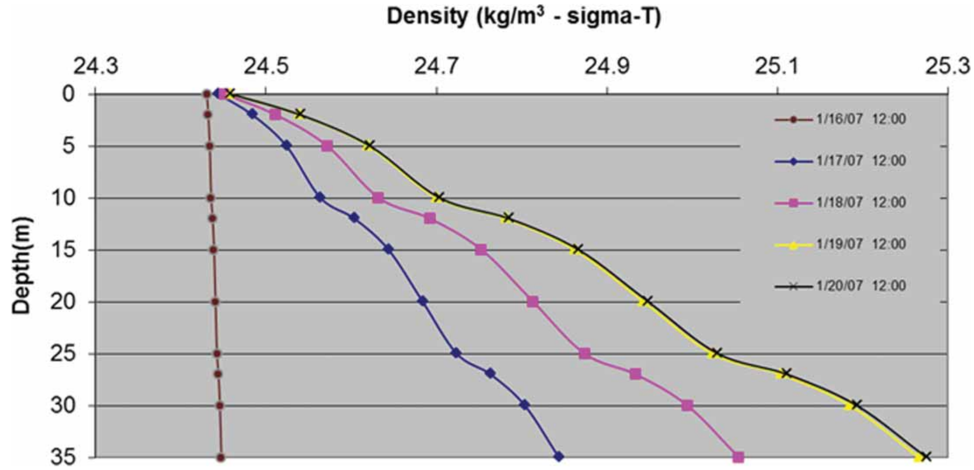

Figure 7. Density profiles variation along the period simulated.

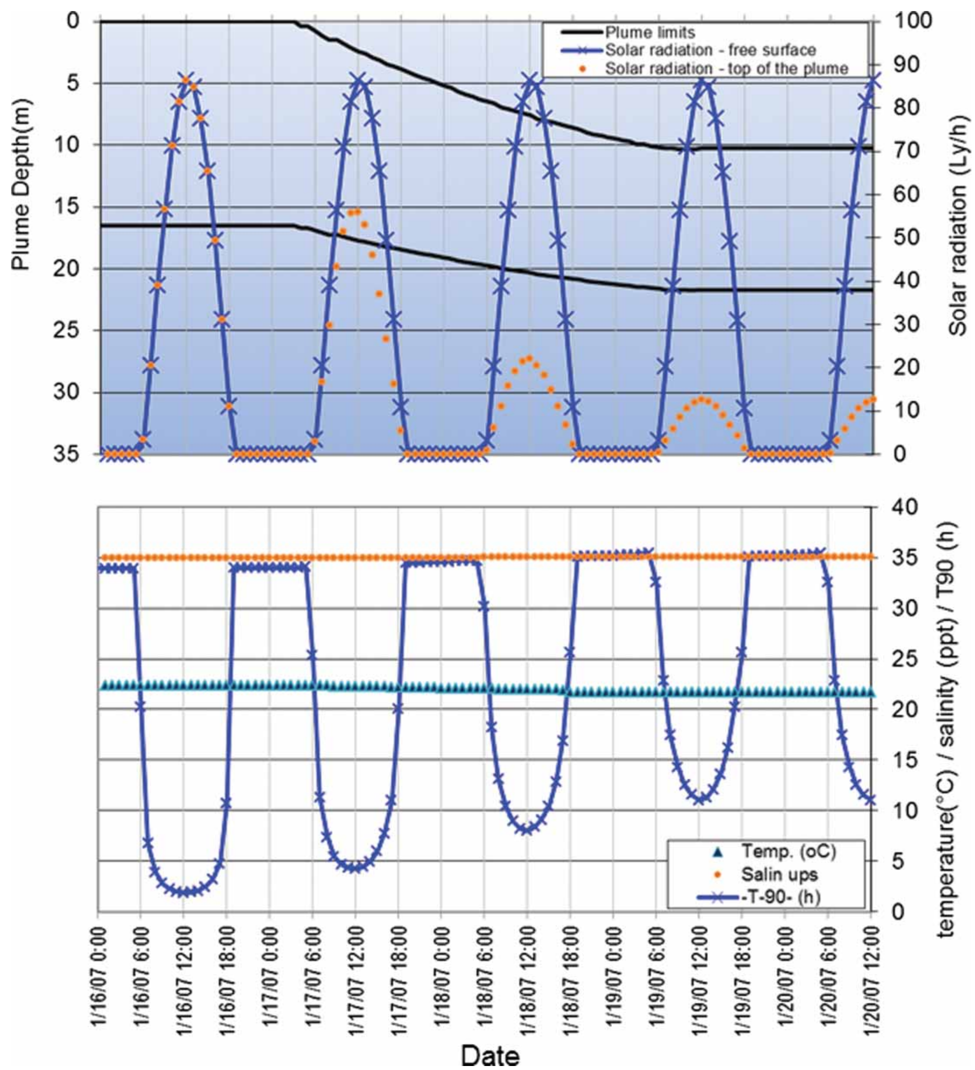

Figure 8. Submerging plume. The upper illustration shows attenuation of solar radiation due to the submersion of the plume, whilst the lower one shows the T_{90} variation as a result of temperature, salinity, and depth of plume.

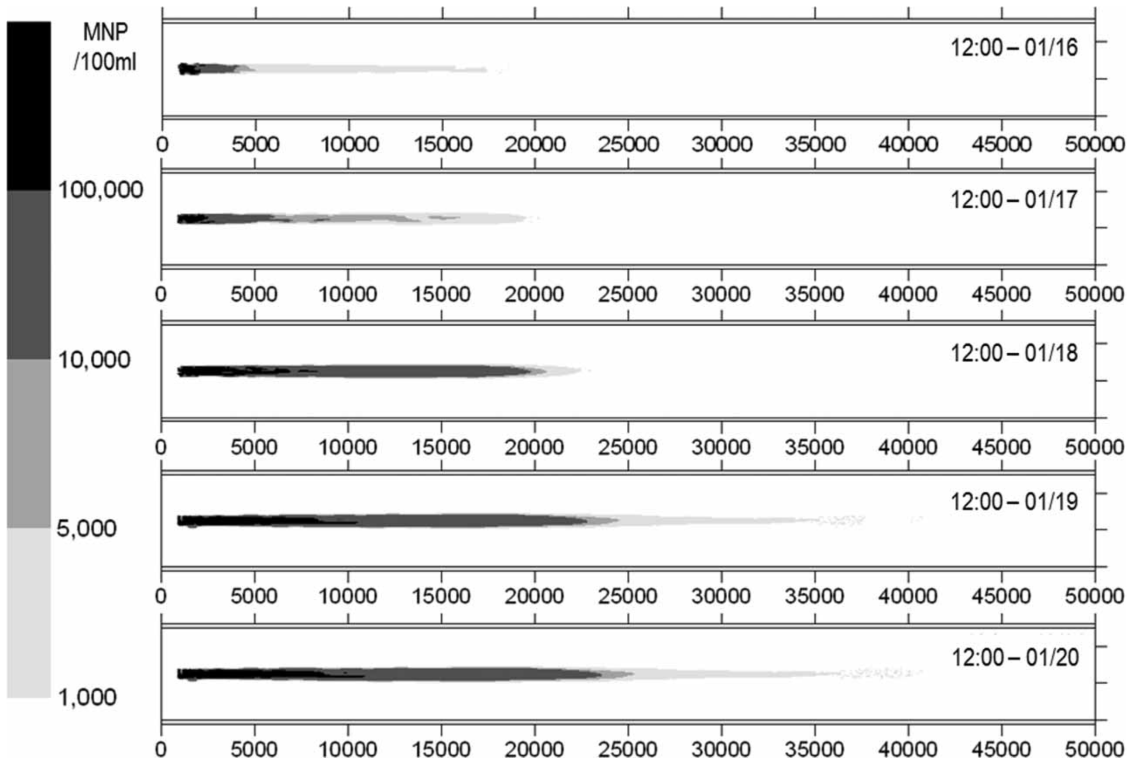

Figure 9. Top view of isolines for faecal coliform concentrations in a rectangular canal (5000 m wide and 50,000 m long) at five different simulation moments under day time conditions. The horizontal scales refer to the distance in metres.

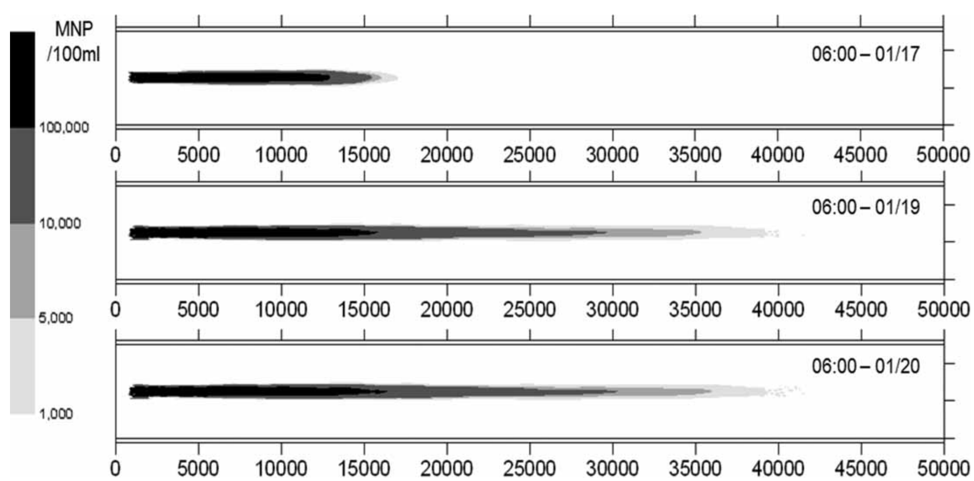

Figure 10. Top view of isolines for faecal coliform concentrations in a rectangular canal (5000 m wide and 50,000 m long) at three different moments in the end of night period. The horizontal scales refer to the distance in metres.

simultaneous action of the temperature and salinity in the decay rates becomes more evident. All the factors capable of reducing solar radiation start to have a more relevant role in the bacterial decay. The cloud cover conditions, and seawater turbidity, which regulates the light intensity, become important for the modelling of coliform plumes.

As a consequence of the increasing stratification, the initial surface waste-field has its thickness gradually vary from 17 to 12 m until it establishes its position at 10 m depth in the last 30 h of the simulation. The variations in plume rise height and thickness, represented by the solid lines, during the simulation are plotted in Figure 8. Decay rates, represented by T_{90} parameter, salinity, temperature and solar radiation levels are also shown.

Figure 8 shows the reduction in incoming solar radiation levels on the plume as it submerges and an increase in T_{90} values. The variations in temperature and salinity have significant influence on bacterial die-off only during

Table 1. Simulation parameters.

Geographic position			
Latitude		Longitude	
23°	S	43°	W
Start date			
Hour	Day	Month	Year
15	15	01	2007
Diffuser characteristics			
No of ports	Port diameter (m)	Port spacing (m)	Discharge depth (m)
180	0.17	5	33
Effluent			
Density (kg/m^3)	Flow rate (m^3/s)	Concentration (MPN faecal coliform/100 ml)	
998	6	1.10^8	
Metheoceanographic conditions			
Cloud cover (%)		Secchis depth (m)	
0		10	
Ambient waters conditions			
Currents (m/s)		Density profile	
0.25		Depicted in Figure 7	

the night period. Under the action of solar radiation these parameters become less relevant. Thus, the model coupling incorporates the simultaneous action of the environmental parameters involved in the modelling of wastewater outfall plumes into a marine environment.

Figures 9 and 10 show the coliform concentration levels, based on decay rates exposed in Figure 8, considering the release of the effluent in a 50 km long and 5 km wide canal, under the action of a steady flow (0.25 m s^{-1}). The results are presented in two sets that represent daytime and night-time conditions. The density profile varies over time according to Figure 7, and Table 1 gives an overview of the parameters used in the simulation.

The determination of coliform levels is extremely important to define the spatial limits, where these levels are higher than those established by local regulations.

According to the decision of the National Environmental Agency (Brasil 2000), which regulates Brazilian water quality standards, faecal coliform concentrations over 1000 MPN 100 ml^{-1} are considered as inadequate.

Figure 9 shows the top view of coliform plume in a rectangular canal at five different moments of the simulation, under daytime conditions. It was intentionally considered instant shots at the same hour in subsequent days, in order to evaluate the light attenuation due the submergence of the plume. The initial surface plume, under a nearly uniform density profile (16 January), starts to submerge gradually until it reaches its stability at a depth of 10 m for the last two days of simulation (19 and 20 January). As a result, the extension of the plume increases from approximately 17 (16 January) to 35 km (19 and 20 January).

The bacterial decay in the absence of solar radiation is ruled by temperature and salinity variations. In the simulation herein presented, the higher concentrations observed during the night time occur due to the temperature decrease in the lower layers of the water column.

Figure 10 shows the faecal coliform concentrations at the end of the night period, when is expected to have the higher concentration levels. Three different moments, related to 06:00 h, respectively, for 17, 18 and 20 January are compared.

Similar to daytime results, a substantial increase of the plume extension from the beginning (17 km – 16 January) to the end of the simulation (40 km – 19 and 20 January) is also observed. However, compared with the previous results presented in Figure 9, it is seen that higher concentration levels of coliform can extend farther away from the effluent release point. This can be explained by background concentration from previous times. Once plume is submerged there is a relevant reduction of bacterial decay even during the daytime, which leads to a mass accumulation of the contaminant with the subsequent periods.

The general results show the importance of the coupling between near-field and far-field models. If the model coupling were not taken into account it would result in cyclic patterns of coliform concentrations, due to the periodic variation of the decay rate (T_{90}) shown in Figure 6. As a result, the diurnal concentration levels (12:00 16 January) observed in Figure 9 would be repeated in the subsequent days (12:00 17–20 January).

The same premise is true for the end of night period, meaning that all concentration observed at 6:00 would follow the same pattern observed in Figure 10 (6:00 of 17 January).

6. Conclusions

Considering the diversity of variables involved in the modelling, only the light attenuation due to plume submersion was assessed. However, with the combined modelling approach, it becomes possible to simultaneously incorporate additional parameters that affect light incidence, such as values for Secchi's depth and cloud cover.

The results show a strong correlation between faecal coliform concentration and solar radiation levels. All the meteorological and oceanographic parameters responsible for light attenuation are extremely relevant in the modelling of the coliform plume. Thus, the coupling of near-field, far-field and bacterial decay models succeeds to make a more realistic approach of coliform plume modelling.

Solar radiation is considered one of the most important factors controlling the survival of faecal coliforms in seawater. Studies carried out by Chamberlin and Mitchell (1978) and field observations made by Gameson and Gould (1975) and Foxworthy and Kneeling (1969) (Chamberlin & Mitchell 1978) produced convincing evidence that the coliform die-off in seawater can be first attributed to the light intensity and other factors that influence its propagation through atmosphere and water. Through the waste-field positioning along the water column, the near-field model plays a fundamental role in determining the incoming solar radiation that reaches the coliform plume. This is the basis for establishing accurate bacterial decay rates. It should also be highlighted that light attenuating factors, such as turbidity, meteorological and geographical position and season of the year, are of great relevance in the modelling of sewage plumes from submarine outfalls.

Unfortunately, there is no field data available in the literature or engineering reports providing a base to validate the presented coupling method and its consequences. However, all used modelling tools and transformation equations are intensively validated by laboratory and field studies, thus it is expected that their combination represents representative results too. Deviations of results between models and measurement studies are generally associated with missing calibration to predict the absolute values correctly. However, models in general are doing very well when comparing the results of two alternatives or two methods (relative values), which was the case presented here. In any case, the results show the necessity for improvements of bacterial decay models, water quality model formulations in general and a more holistic view on model improvements. This is especially of concern looking on previous works which focussed more on improvements of turbulence models and higher order numerical schemes than on the correct implementation of bacterial decay models, though inaccuracies in the latter part were orders of magnitude larger, thus demand for more investigations. In any case, it is strongly recommended to undertake field studies to explore those processes and modelling approaches in more detail.

It is also important to emphasize that the validation of the model herein presented is not a simple task, since simultaneous field campaigns would be necessary to evaluate the spatial coliform concentrations between those predicted by the model and those observed in the field. This would require time sequence measurements of all environmental conditions involved in modelling, such as density profile, currents, cloud cover, water light extinction coefficient, etc. Additionally a precise monitoring of effluent characteristics such as flow rate and coliform concentration would be required, since it also plays a fundamental role in the modelling.

Note

1. Langley (Ly) = calorie/cm^2.

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