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CALIBRATION AND VALIDATION OF FAR FIELD DILUTION MODELS FOR OUTFALL AT WORLI, MUMBAI

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Abstract. The city of Mumbai, India with a population of 15 million discharges about 2225 MLD of domestic wastewater after partial treatment to adjoining marine water body. Under the Mumbai Sewage Disposal Project Scheme, sewage is being disposed to the west coast at Worli and Bandra through 3.4 kms long submarine outfalls. A field study was conducted at recently commissioned outfall diffuser location at Worli, at the onset of neap flood tide to study the dispersion patterns and measure the far field dilutions using radio and dye tracers. Estimated dilutions using different tracers were compared with outputs from an empirical model (Brooks) and a 2D numerical model (DIVAST). Validation using parameters such as BOD and FC, indicated a good match for BOD in near field compared to FC. The radiotracer ^{82}Br and Rhodamine WT generally gave good correlation with Brooks' and DIVAST models for nearfield, however at further distances predictions were not accurate.

Keywords: far field dilution, tracer studies, calibration, validation

1. Introduction

Ocean disposal is typically accomplished by submarine outfalls that consist of a long section of pipe to transport from shore and a diffuser section to dilute the wastewater with seawater. Diffusers offer an attractive engineering solution to the problem of managing wastewater discharges in an environmentally sound way. During the past 50 years multi port diffusers have been used by many coastal cities for the disposal of municipal sewage water into oceans or large lakes (Roberts, 1991). In the United States as well as other countries large outfall installations for sewage disposal after primary and secondary treatment are currently in operation in Boston, San Diego, and Sydney. Of 25 mega cities in the World, 17 are coastal cities with 25% of world population, which use ocean for waste disposal. However, the problem occurs when wastewater discharges are concentrated in a limited area instead of dispersing them over large areas and at longer distances away from the coastal cities. Studies carried for near shore sewage disposal indicate that sewage toxicity can lead to aberration in micro anatomical structures of some fish species (Kumta and Kumar, 1998).

The city of Mumbai, India is presently confronted with deteriorating marine water quality due to disposal of about 2225 million litres of sewage per day from the seven drainage zones. Of these, five drainage zones directly or indirectly discharge wastewater onto the west coast as shown in Figure 1. At Worli and Bandra, sewage is being disposed to the west coast through 3.4 kms long submarine outfalls with a diffuser system at the end. Sewage is discharged through the outfall after preliminary treatment in the form of screening and degritting.

The hydrodynamics of an effluent continuously discharging into a receiving water body can be conceptualized as a mixing process occurring in two separate regions. In the first region, the momentum flux, buoyancy flux and outfall geometry influence the jet trajectory and mixing. This region is referred to as near field. In this near field region, outfall designers can improve the initial mixing characteristics through appropriate manipulation of design variables. At the end of the initial mixing region the waste field is established. Conditions existing in the ambient environment will control trajectory and dilution of the turbulent plume through buoyant spreading motion. This region is referred to as far field or dispersion zone.

This paper presents the findings of investigations carried out on dispersion patterns at farfield of wastewater released into the ocean through marine outfall at Worli, Mumbai by using tracer techniques employing radiotracer ^{82}Br and chemical tracer Rhodamine WT. These results were compared with the outputs of two mathematical models, viz Brooks' model (Brooks, 1959) and DIVAST (Depth Integrated Velocity and Solute Transport) Model (Falconer, 1984, 1986).

1.1. BROOKS' MODEL

A continuous line discharge of a conservative solute gives rise to a wastefield of initial concentration C_0 and width w_0, which enters the current of speed U perpendicular to the line of source. As the effluent moves downstream, it spreads laterally due to diffusion. The plume width, w_0 increases with distance x from the source. The peak concentration $C_{\max}$ as a result decreases with the increasing x.

Beyond the assumption of a constant current speed normal to the line source Brooks made the following assumptions in solving for the concentration of contaminant at any downstream location.

- Vertical mixing is negligible
- Mixing in the direction of the current is negligible
- Effluent moves with the current system
- Mixing in the lateral direction can be described by the diffusion process with variable D_y given by

$$D_y = a w_0^n \tag{1}$$

where D_y is the diffusion coefficient and α is a constant.

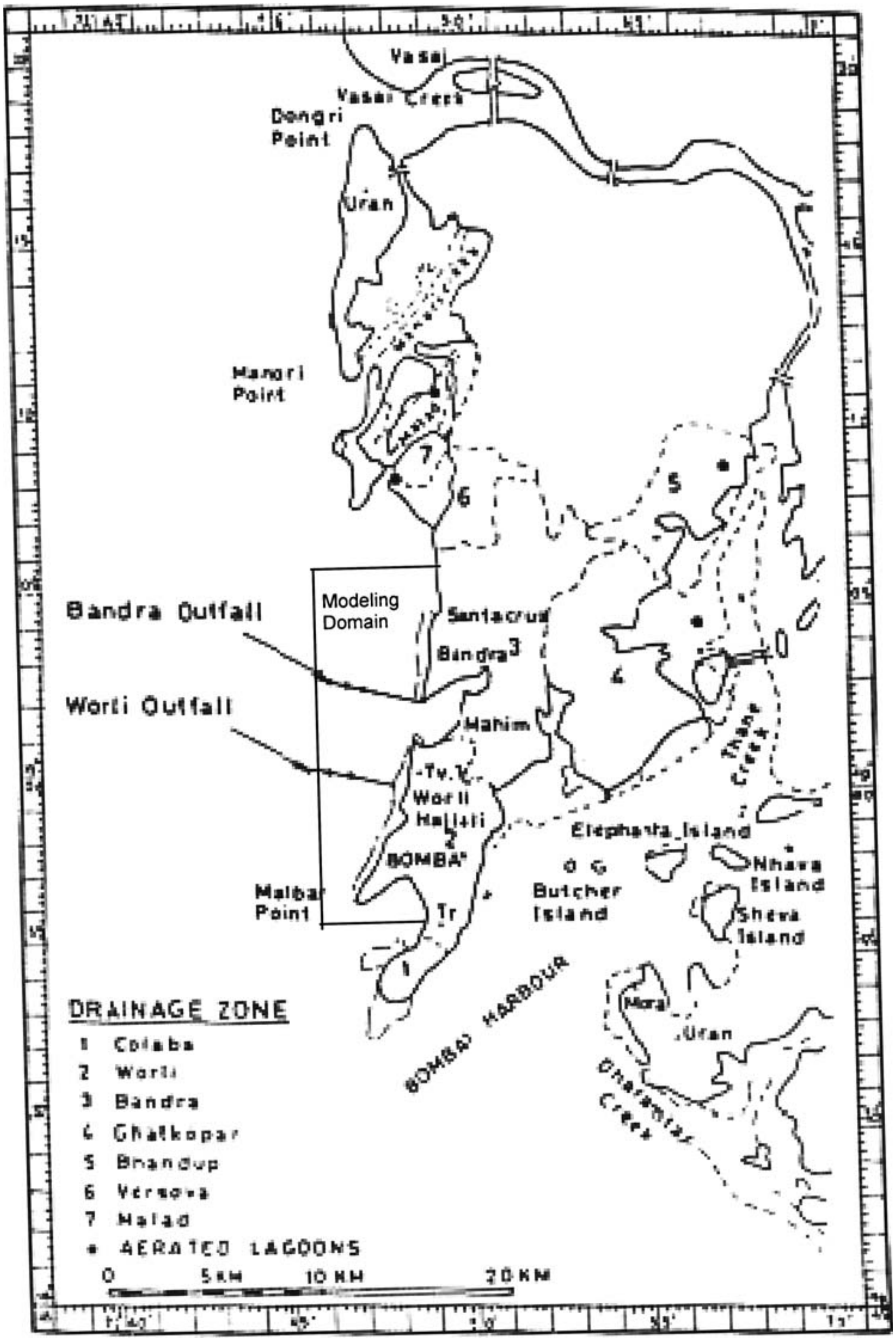

Figure 1. Locations of different sewage disposal points, Worli outfall and modelling domain.

Three different values in the exponent n; 0, 1, and 4/3 were considered by Brooks. The first component corresponds to constant diffusion coefficient; the second is consistent with coast line situation and the latter conforms to Richardsons law.

Let β be a dimensionless number given by

$$\beta = 12D_{y_0}/U_{w_0} \tag{2}$$

The plume dilution due to dispersion is mathematically expressed as follows:

$$S_2 = \mathrm{erf}\,\{[1.5/[(1 + 2\beta x/3w_0)^3 - 1]]^{1/2}\} \tag{3}$$

where $\mathrm{erf}\,\{a\} = \frac{2}{\sqrt{\pi}} \int_0^a \exp(-t^2)\,\mathrm{d}t$.

Tables of error function are available such as in Abramowitz and Stegun (1964). However, the error function can be evaluated from more convenient common tables of normal distribution probability (e.g., Hoel, 1976).

Let S_1 = average dilution at the end of near field. Therefore, total dilution is given by

$$S = S_1 \times S_2 \tag{4}$$

Also, for comparison of far field dilution factor, the simplified equation derived from advection diffusion model with variable (depending on the distance from the outfall) coefficient of turbulent diffusion given by Gardanoc (1995) is used.

$$S_2 = \left(w_0^{2/3} + 0.08x/U\right)^{3/2}\big/w_0 \tag{5}$$

Model output includes the unknown 3D jet trajectory, and at any elevation the average dilution, the plume half-width and average velocity, density deficit/pollutant concentration.

2. DIVAST Model

Currently there are several models available which can be used for hydraulic studies in the coastal area. MIKE 21 can model wave transformation, currents due to wave and tides, advection and dispersion, water quality, mud and sand transport. DIVAST (Depth Integrated Velocity and Solute Transport) developed by Falconer (1984, 1986) can model currents due to waves and tides and also predict water quality parameters from outfalls. Both MIKE 21 and DIVAST models were appropriate for the simulation of tidal conditions and water quality parameters. For the present study, 2-D numerical model DIVAST was used.

The modeling study undertaken for the study warranted data collection for bathymetry, ocean current and tidal elevations. Bathymetry data was collected during an earlier study (Kumar *et al.*, 2000) on oceanography and water quality modeling. Current and tidal elevation data was collected using current meters and tide gauges. Current meters were placed at north, south and west boundaries and one close to the diffuser location. Tidal observations were made at the southern boundary and near the diffuser location.

The resolution of the bathymetry data was 200 × 200 m. The bathymetry of modeling domain shows a gradual slope on western and southern sides. It was observed that the currents are semidiurnal (two high cycles and two low cycles) primarily aligned alongshore. Their direction of rotation is counter clockwise.

2.1. Description of the DIVAST model

The DIVAST model simulates two dimensional distribution of current, water surface elevations and various water quality parameters within the modeling domain as a function of time, taking into account the hydraulic characteristics governed by the bed topography, surface wind effects and boundary conditions. The equations governing fluid motion are based on the conservation of mass and momentum. The hydrodynamic equations, which describe the flows, are depth integrated form of three dimensional Reynolds equations.

The model considers two dimensional depth integrated advective diffusion equation for solute transport processes and is given by

$$\frac{\partial \mathrm{HS}}{\partial t} + \frac{\partial \mathrm{HUS}}{\partial x} + \frac{\partial \beta \mathrm{VS}}{\partial y} = \frac{\partial}{\partial x}\left[D_{xx} H \frac{\partial S}{\partial x} + D_{xy} \frac{\partial S}{\partial y}\right] + \frac{\partial}{\partial y}\left[D_{xx} H \frac{\partial S}{\partial x} + D_{yy} \frac{\partial S}{\partial y}\right] + \varphi_s \tag{6}$$

in which, H is the total water depth; S is depth averaged solute concentration (unit/volume); U and V are depth averaged velocity components in the x and y directions respectively; $D_{xx}, D_{xy}, D_{yx}, D_{yy}$ are the depth averaged dispersion-diffusion coefficients in the x, y directions respectively; φ_s represents source sink including contributions from outfalls.

In the model the area of coverage is divided into uniform rectangular grid. The tidal forcing at the open boundaries is specified by defining the water elevation or flows obtained through field observations at relevant locations.

The finite difference scheme used in DIVAST is based on the Alternating Directions Implicit technique which involves the sub division of each time step into half time steps. With the boundary conditions included, the resulting finite difference equations for each time step are solved using Gauss elimination and back substitution methods.

While solving the hydrodynamic and solute transport equations, boundary conditions of water elevations or flows for the hydrodynamic and solute values for the solute transport processes need to be specified both at the lower and upper boundaries throughout the simulation period at all the open boundaries. The coast lines are treated as closed boundaries and water surface boundary is treated as open boundary. A refined drying and flooding routine is used in the model where iterative checks are done (Chen and Falconer, 1992)

3. Sampling and Analytical Techniques

Radiotracer ^{82}Br and dye tracer Rhodamine WT were used to carry out field experiments during the neap tide to assess the movement of waste field. The 3.5 Km long outfall diffuser location was taken for field investigation. The diffuser of 240 m length consists of 10 risers having east pole towards shore side at 19° 00.14′N and 72° 47.26′E and west pole towards seaside at 19° 00.18′N and 72° 47.105′E. About 2.5 km^2 of area around the diffuser was considered for the observations of various parameters like Biochemical Oxygen Demand (BOD), bacterial density, concentrations of radiotracer and dye.

During the experiment, a controlled wastewater discharge of 5 m^3/s was maintained. Two different tracers viz. radiotracer ^{82}Br ($t_{1/2} = 36$ h) in the form of aqueous NH_4Br and fluorescent tracer (Rhodamine WT) were injected simultaneously to determine the dilution and dispersion of the wastewater discharged through the diffuser section at a distance of about 3.4 km on the west coast.

Rhodamine WT dye tracer was used for the experiment because of its stable nature and solubility in water. Samples collected at various interval and locations were brought to the laboratory for analysis on spectrofluorometer (Shimadzu RF 5000) at BARC. Radiotracer concentration measurements were measured in-situ by waterproof scintillation detectors. Analysis of DO, BOD and Bacterial density were performed using Standard Methods (20th edition), 1998. S4 Current Meter (Inter Ocean) was employed to measure the temporal variation of the ambient current velocities. Lateral transects at various longitudinal distances from the diffuser section were covered to monitor the levels of radiotracer.

The experiment was conducted at the onset of neap flood tide. The tidal range during the experiment was 2.65 m with the low water slack of 1.01 m at 10:30 h. About 74 GBq (2 Ci) of ^{82}Br was diluted in 45 L of water and injected into the effluent channel of Worli Pumping Station at the rate of 625 ml/min using a Master flux Peristaltic Pump. About 3 kg of Rhodamine WT in 100 L of water was also simultaneously and continuously injected at the rate of 6 L/ min with a concentration of 600 ppb.

4. Modeling Details

The modeling domain has been defined by 3 open boundaries. The north boundary is at 19°1.63′N Latitude near Bandra. The south boundary is at 18°55.5′N Latitude

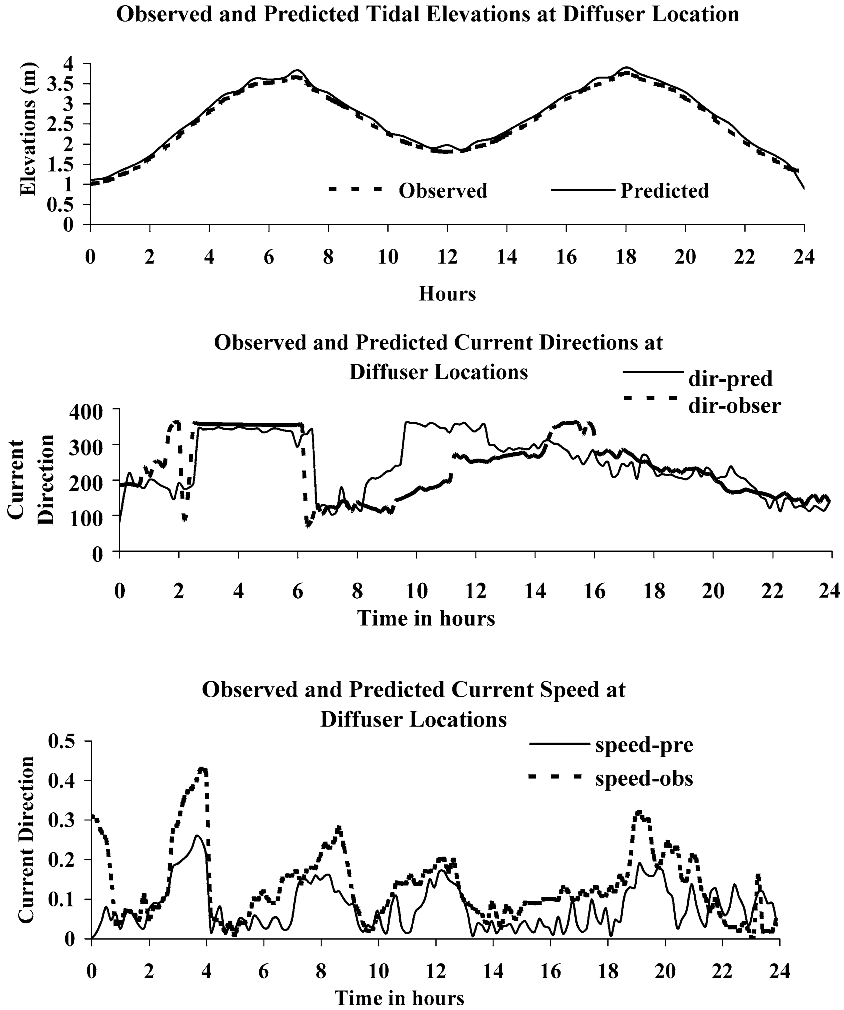

Figure 2. Calibration curve for tidal elevation, current direction and current speed at diffuser location.

and the western boundary is at 72° 46.47′E longitude. The northern and western boundary have been taken as flow boundary and the southern boundary has been taken as the elevation boundary. The validation of the model was carried out to reproduce the agreement between the predicted water surface elevations, current velocity and directions and that observed by direct measurements. Figure 2 gives the calibration curves for a specific location. It was observed that the model predicted tidal heights matched very well with the observed data. However, predicted current velocities and directions did not match so well with the field data. The model considers same wind speed through out the simulation period which governs the advection of pollutants. The model assumes vertical variation in flow is insignificant but in actual case it is different. These assumptions lead to differences in predicted and observed current directions and speed.

The model was fine tuned by varying the shear coefficients and BOD removal rate. The BOD decay rate coefficient was taken as 1.0 per day. The model considered that carbonaceous organic matter and ammonical-N removal is governed by the first order kinetics. The oxygen balance in a water body depends on the capacity of the body to re-aerate itself. This capacity is a function of advection and diffusion processes, which occur within the system and sinks of oxygen. The sinks of oxygen include biochemical oxidation of carbonaceous and nitrogenous organic matter (CBOD and NBOD), benthic oxygen demand and oxygen utilized by algae respiration. Owen's relation was used to adjust the re-aeration coefficient in the model for varying water depths and velocities. The coefficient for SOD (sediment oxygen demand) and ammonical-N removal were selected based on the published values in literature for coastal waters receiving municipal wastewater. These were adjusted to 6 g/m^2/day and 0.4 per day respectively. Removal of Fecal Coliforms (FC) were considered to be governed by decay rates. Since sunlight plays an important role in decay of FC, different decay rates for different times of the day (24 h) have been considered. Decay coefficients for FC in coastal waters were selected form the study carried out earlier. Thus decay coefficient was 5.52 per day in the day time and 2.88 per day at night. The background water quality parameters were taken as BOD: 2 mg/L, DO: 4 mg/L and FC: 1500 counts/100 ml.

To validate the model for water quality parameters, the results of the model simulation were compared with the observed values. The observed FC count was about 1×10^5 counts/100 ml near the diffuser location at high tide while the predicted FC count was about 5×10^4 counts/100 ml. BOD was observed to be 10 mg/L near the diffuser location at high tide, while the predicted BOD was 7.5 mg/L. Figure 3 depicts the concentration contours of BOD and FC during high tide.

Table I gives the comparison of the output of far field models of Brooks and DIVAST with the radiotracer and dye experiments. The range of dilution obtained by radiotracer experiment is less than the corresponding values obtained by dye experiment showing that the radiotracer gives a more consistent value. Table II gives the percentage difference. The dilution results indicate that for a nearer distance of about 225 m from diffuser, all the observed values as well as predicted values are close. However, as the distance from diffuser goes on increasing, the observed values of tracers show high variance in the results compared to predicted estimates. The variation of Brooks' model estimate could be attributed to it being an empirical model, does not consider the actual hydrodynamic characteristics of the region. Whereas the difference in the results of DIVAST could be due to some of the basic assumptions which are intrinsic to the models but field conditions may not be supporting them such as depth integrated, wind contribution etc. One of the major factor could be the assumptions of completely mixed un stratified waters in case of DIVAST.

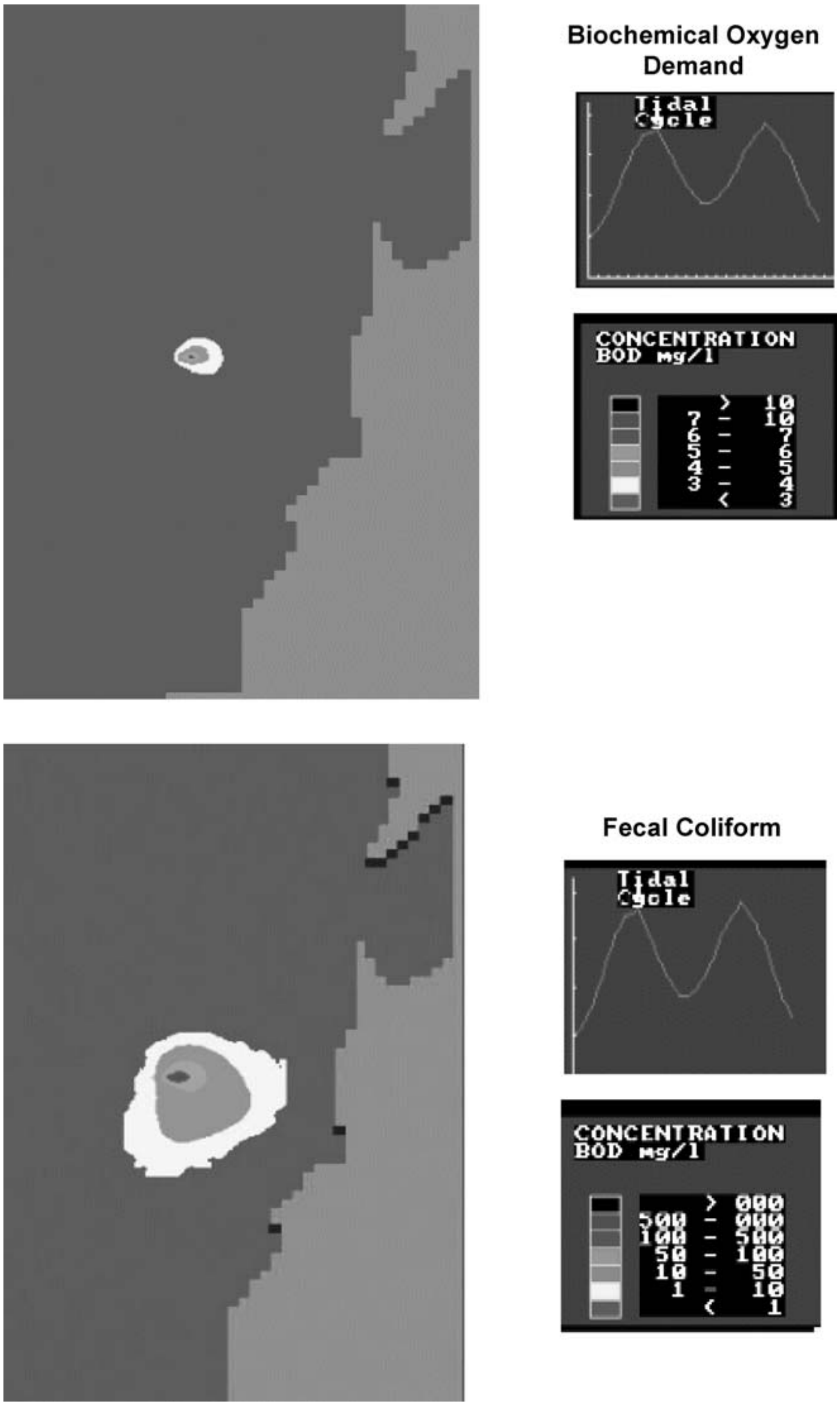

Figure 3. Bio-chemical oxygen demand and fecal coliform contours at Worli outfall at high tide.

TABLE I
Comparison of far field dilutions obtained from DIVAST, brooks, radiotracer and dye.

Serial no	Dilution observed by radiotracer expt.	Dilution observed by Dye expt.
Distance = 225 m, Dilution obtained by Brooks = 62; Dilution obtained by DIVAST = 64		
1	60.9	65.9
2	85.2	62.5
3	71.0	69.0
4	60.9	72.3
5	47.3	61.2
6	71.0	65.2
7	47.3	93.8
8	53.2	34.1
9	71.0	65.9
Average	63.08	65.6
Distance = 625 m, Dilution obtained by Brooks = 70; Dilution obtained by DIVAST = 108		
1	85.2	109.1
2	85.2	101.7
3	71	82.2
4	85.2	75.9
5	85.2	85.7
6	106.5	87.0
7	85.2	76.9
8	106.5	61.2
9	106.5	61.9
10	85.2	51.7
Average	90.15	79.33
Distance = 930 m, Dilution obtained by Brooks = 87; Dilution obtained by DIVAST = 124		
1	100.8	87.0
2	93.5	90.0
3	87.2	54.1
4	117.3	48.4
5	121.8	89.6
6	137.3	56.1
7	121.8	75.9
8	146.7	74.1
9	107.6	98.4
10	99.3	97.6
11	100.8	125.0
12	100.8	127.7
Average	113.3	85.3

TABLE II
Percentage difference of dilutions obtained from radiotracer, Dye, DIVAST and Brooks

	Percentage difference					
Dilution at distance	Radiotracer-Dye	Radiotracer-Brooks	Radiotracer-DIVAST	Dye-Brooks	Dye-DIVAST	Brooks-DIVAST
225	4.5	1.6	1.6	6.1	3.0	3.1
625	12.2	22.2	16.7	11.4	26.8	35.2
930	24.8	23.0	8.9	2.3	31.5	29.8

5. Conclusions

Various experiments conducted under the study provided useful insight into the suitability of radioisotopes as well as use of chemical tracers in polluted water. Radioactive ^{82}Br as well as Rhodamine WT gave comparable results in the region of 200 to 300 m. Large variations were noticed for distances 600 m and more. Most of these estimate indicate that Brooks' model as well as DIVAST model may not be adequate for far field prediction due to varied assumptions intrinsic to model formulation. However, near diffuser location, these models predict reasonably well.

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