Estimation of Near-field and Far-field dilutions for Site Selection of Effluent Outfall in Coastal Region – A case study.

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ABSTRACT

Site selection for release of industrial effluents is of prime concern for maintaining the marine environmental quality. In this study, an attempt has been made to establish the prevailing ecological conditions and to suggest the suitable location for discharge of the effluents into the sea by using near-field and far-field models. Near-field dilutions were calculated using buoyant jet model while far-field dilutions were estimated using two-dimensional numerical model. As a case study, location of outfall is to be suggested to Vapi Waste and Effluent Management Company Ltd (VWEMCL) for the release of treated effluents. At present, the VWEMCL is discharging effluents into Damanganga river at upstream. As a result, the entire Damanganga estuary has poor water quality. Field studies conducted in 2009 suggested that the Damanganga estuarine segment is more polluted than the coastal waters. Near-field model studies show that the effluent would attain 35 to 70 times dilutions depending on the height of the water column if the release is made at the offshore location. Far-field model study revealed that the effluent would be diluted effectively with ambient currents and the near ambient conditions would prevail at around 100 m distance. The effluent would move along the coast and chances of reaching to the estuary are remote. Rise of the BOD concentration of 2.9 mg/l above ambient is predicted at the release site. The water quality of Damanganga estuary would be restored to the pre-industry period once the outfall is commissioned.

ADDITIONAL INDEX WORDS
Damanganga estuary, currents, water quality, buoyant jet model and two-dimensional numerical model, outfall

INTRODUCTION

Industrial wastewaters are often released into nearby coastal environment through marine outfall system. Site of the outfall is selected so that the effluents released at the location should be dispersed efficiently spatially as well as temporally. Wastewater is subjected to two types of mixing processes, viz, near-field and far-field. Generally the near-field dilutions are estimated basing on the analytical solutions of the momentum equations. CORIMIX program is widely used for the near-field plume analysis (Jirka et al 1991). The near-field mixing zone analysis was carried out by Roberts and Sternau (1997). They have calculated Froude number for near-field dilutions as suggested by Roberts and Toms (1987). The method suggested by
Csandy (1983) was adopted to explain the far-field dilutions. Analytical solution of two dimensional diffusion formulas was used to calculate the spread of the effluent cloud.

In this study, an attempt has been made to estimate the near-field dilution using a buoyant jet model and far-field dilution by a two-dimensional numerical model. These models were applied to suggest ocean outfall location for release of treated effluents at coastal region of Daman, India.

Study Area

Damanganga river originates from Sahyadri hills of Maharashtra state in India and is connected to the Arabian sea at Daman, Union Territory of Government of India (Figure 1). The total length of the river is 131 km. This region experiences high temperatures during 2 seasons, October-November and April-May. The region gets rainfall during southwest monsoon period (June – September) when the basin receives maximum rainfall (2200 mm).

Bathymetry of the region shows that the depths of 2 – 5 m below Chart Datum are available in the Damanganga Estuary while 5.7 m depth is available at the mouth. However, from the mouth to the offshore a large intertidal area (1.8 km) is found. A depth contour of 2 m is found at the distance 3.6 km from High Tide Line (HTL). LISS 3 of Indian Remote sensing Satellite (IRS) data has been processed for this area to identify the mangrove locations. IRS LISS 3 data collected on 06th November 2008 (Figure 2) suggests that the mangroves are present along the both the banks of the estuarine segment of the Damanganga river. A dam is constructed at the railway bridge which is situated around 13 km from the mouth. During spring high water, tidal water reaches upto the dam.

At present, Damanganga estuary (Figure 3) has been receiving industrial effluents from Common Effluent Treatment Plant (CETP) of the Gujarat Industrial Development Corporation (GIDC), Vapi (48000 m$^3$/d) and Khemani Distillery Limited (KD), Kachigam (1050 m$^3$/d) totalling about 49050 m$^3$/d. Industries at Vapi have formed a body called the Vapi Waste and Effluent Management Company Limited (VWEMCL) to handle the issues of CETP. Presently the effluent discharged in the upstream, just below the dam, of the Damanganga estuary has been creating degradation in water quality in the estuary. The google earth image clearly indicates the effluent cloud in the estuarine zone and in the offshore to some extent (Figure 4). According to the Central Pollution Control Board (CPCB), Government of India, this river is one of the pollution hot spots in the country. The Gujarat Pollution Control Board (GPCB) of Government of Gujarat advised the company to shift the discharge location from present upstream location to offshore. The VWEMCL requested the CSIR-National Institute of Oceanography (NIO) to conduct survey in the inshore and offshore waters of Daman and to suggest outfall location for the treated effluents of 100000 m$^3$/d. The following objectives have been identified, (1). To establish the prevailing environmental conditions, and (2). To select a suitable location for outfall in coastal region at Daman.
MATERIALS AND METHODS

The NIO conducted premonsoon and postmonsoon field surveys in April and December 2009 respectively (Anonymous, 2010) to establish the prevailing environmental conditions. The sampling on water quality and biological characteristics were performed at stations as presented in Figure 3. Aanderaa make self-recording current meter was deployed at station 6 from 31st March 2009 to 07th April 2009. Circulation was measured by releasing a neutrally buoyant float at proposed release location and was followed with a GPS. The position of the buoy was recorded at each 30 minutes.

The data pertaining to hydrodynamics (tides, currents and circulation), water quality (Temperature, Salinity, Suspended Solids, Dissolved Oxygen(DO), Biological Oxygen Demand (BOD), Nitrite, Nitrate, Ammonia, Phosphate, Petroleum Hydrocarbons(PhC) and Phenol), sediment quality (trace metals, PhC and organic carbon) and biological characteristics (phytoplankton, zooplankton and macrobenthos) were collected at 13 stations (Figure 3). The procedures of analysis are given in anonymous 2010.

Selection of outfall location is done basing on the considerations, viz, 1. the effluent released at outfall should not reach the release site 2. the effluent should not be transported towards coast, 3. the effluent should attain near ambient conditions at the edge of the mixing zone and 4. the effluent should be sufficiently away from the ecosensitive areas such as mangroves, coral reefs, marine national parks etc. The environmental regulations state the effluent should not be released in the intertidal area and background concentrations of the pollutants should be attained at the end of the mixing zone. In this study, the proposed quantities of VWEMCL (100000 m³/d) and Khemani (2500 m³/d) were considered.

Near-field model

The effluent released from the bottom is subjected to two types of mixing processes, viz, 1. Near-field and 2. Far-field mixing. The domestic or treated effluents for CETP generally are less denser than the ambient seawater. The waters are released with certain velocity (generally 2 m/s). When it is released from the bottom, initially upto certain height the mixing is controlled my momentum forces. Beyond this, the mixing is mainly caused by the buoyancy forces dictated by the density differences until it reaches the surface. This region is called the near-field mixing zone. Once the buoyancy forces are not effective, the mixing is caused by the prevailing currents of the region. The processes involved in this far-field mixing zone are both advection and diffusion.

Generally mixing zone extends a radius of 200 m around the outfall Roberts (1997). The concentration of the contaminants should not exceed the most stringent international criteria for both acute and chronic effects on aquatic life. The BOD of 100 mg/l should reach the near-ambient conditions at the edge of this zone. The excess values should be within the natural variation of the parameter.
Some theoretical representations of initial mixing were given by Rawn et al. (1961) and Abrahams (1930). In these formulations, the near-field mixing was estimated using the analytical formulations. Numerical solutions were given by Fan (1969), McBride (1973) and Featherstone (1984) basing on the entrainment hypothesis. Malacic (2001) applied this model to Bay of Piran, northern Adriatic.

The governing equations for the Buoyant Jet Model are as follows:

\[
\frac{dc}{ds} = \frac{2g \rho}{\rho_o} \frac{dc}{d\rho} \sin \theta - \frac{2x \rho}{b} \\
\frac{dc}{dx} = \frac{2g \rho}{\rho_o} - \frac{dc}{\rho_o} \sin \theta \\
\frac{dc}{dy} = \frac{2g \rho}{\rho_o} - \frac{dc}{\rho_o} \cos \theta \\
\frac{dc}{ds} = \frac{1 + \rho_o}{\rho_o} \sin \theta \frac{dc}{dy} - \frac{2x \rho}{b} \\
\frac{dc}{ds} = \cos \theta \frac{dc}{dy} = \sin \theta
\]

where  
\( g \) = acceleration due to gravity  
\( \rho \) = density of effluent  
\( \rho_o \) = density of coastal water  
\( \alpha \) = constant (0.082)  
\( \lambda \) = entrainment coefficient (1.16)  
\( x \) = horizontal distance from jet orifice  
\( y \) = vertical jet coordinate  
\( u \) = jet velocity  
\( \theta \) = angle of jet orifice with horizontal plane  
\( ds \) = step increment  
also  
\( c, u, b \) = concentration at given time, jet velocity and jet width at given time  
\( c_o, u_o, b_o \) represent concentration/mass density, jet velocity and jet width at time \( t = 0 \).

The model also takes the ambient velocity into account while calculating initial dilution using the equation James A (1978).

Dilution due to ambient currents = dilution in static medium \[ \exp 0.938 \{\log (U_a/U) + 1.107\} \]

Where  
\( U_a \) = ambient current velocity  
\( U \) = jet velocity
Far-Field model

Far-field dilution is estimated using a two-dimensional model which calculates the currents and mass transport in the coastal system after taking inputs of bathymetry, tides and effluent quantity and characteristics.

Modeling of tides and currents

Modelling the hydrodynamic processes is the first important step to quantitatively assess the far-field dilution of contaminants in the receiving water. The two-dimensinal water quality model POLSOFT was used for this purpose Reddy, G. S (1997).

Basic governing equations

The basic governing equations of flow are solved numerically in simulation of tides and currents in the coastal environments. These equations are formulated based on incompressible flow and vertically integrated hydrostatic distribution since the vertical acceleration of the flow is much smaller than the pressure gradient. After applying these assumptions, the basic governing equations of flow momentum can be written in the conservation form as follows:

\[
\frac{\partial u H}{\partial t} + \frac{\partial u^2 H}{\partial x} + \frac{\partial u v H}{\partial y} = f v H - g H \frac{\partial H}{\partial x} + H \frac{\partial}{\partial x} \left( K_x \frac{\partial u}{\partial x} \right) + H \frac{\partial}{\partial y} \left( K_y \frac{\partial u}{\partial y} \right) + \frac{\tau_{wx}}{\rho} - \frac{\tau_{bx}}{\rho}, \quad (6)
\]

\[
\frac{\partial v H}{\partial t} + \frac{\partial u v H}{\partial x} + \frac{\partial v^2 H}{\partial y} = -f u H - g H \frac{\partial H}{\partial y} + H \frac{\partial}{\partial x} \left( K_x \frac{\partial v}{\partial x} \right) + H \frac{\partial}{\partial y} \left( K_y \frac{\partial v}{\partial y} \right) + \frac{\tau_{wy}}{\rho} - \frac{\tau_{by}}{\rho}, \quad (7)
\]

where \( t \) is time; \( \rho \) is the density of sea water; \( f \) is the coriolis parameter; \( g \) is acceleration due to gravity; \( x \) and \( y \) are Cartesian coordinates; \( u \) and \( v \) are depth-averaged velocity components; \( K_x \) and \( K_y \) diffusion coefficients; and \( \tau_{wx}, \tau_{bx}, \tau_{wy}, \tau_{by} \) are wind and bottom stresses in the \( x \) and \( y \) directions respectively.

The horizontal diffusion coefficients \( K_x \) and \( K_y \) are calculated as

\[
K_x = \alpha_x g H \left( \sqrt{u^2 + v^2} \right) \quad C^2 \quad (8)
\]

\[
K_y = \alpha_y g H \left( \sqrt{u^2 + v^2} \right) \quad C^2 \quad (9)
\]
where $\alpha_x = 0.15$ and $\alpha_y = 0.15$ are the depth-averaged eddy viscosity coefficients in the x and y directions. C is the Chezy’s coefficient calculated using the Manning’s roughness ($n$) coefficient as $C = 1/n R^{1/6}$, where $R$ is the hydraulic radius = $A/P$ ($A$ is the wetted area and $P$ is the wetted perimeter) and can be equal to flow depth in shallow waters.

The diffusion coefficients for horizontal exchange of momentum vary in space. The wind stress in the x and y directions ($\tau_{wx}, \tau_{wy}$) can be written as

$$\tau_{wx} = \rho_a C_d U_w \left( \sqrt{U_w^2 + V_w^2} \right)$$

$$\tau_{wy} = \rho_a C_d U_w \left( \sqrt{U_w^2 + V_w^2} \right)$$

where, $U_w$ and $V_w$ are wind velocity components in the x and y directions respectively; $\rho_a$ is air density, $C_d$ is the air-water drag coefficient. The bottom stress in the x and y directions ($\tau_{bx}, \tau_{by}$) can be written as:

$$\tau_{bx} = \rho g u \left( \sqrt{u^2 + v^2} \right) / C^2$$

$$\tau_{by} = \rho g v \left( \sqrt{u^2 + v^2} \right) / C^2$$

where, $\tau_{bx}$ and $\tau_{by}$ are bottom stress components in the x and y directions respectively.

**Boundary-Fitted Coordinate System**

In the present study, the boundary-fitted coordinate (BFC) system was used to resolve complex topography in a horizontal direction. The continuity equation can be written in the BFC system using chain rule transformation

$$\frac{\partial \eta}{\partial t} + \frac{1}{J} \left( X_\xi \frac{\partial (uH)}{\partial \xi} - X_\zeta \frac{\partial (uH)}{\partial \zeta} + X_\eta \frac{\partial (vH)}{\partial \xi} - X_\xi \frac{\partial (vH)}{\partial \zeta} \right) = 0$$

where $x_\xi, y_\xi, x_\zeta, y_\zeta$ are grid transformation parameters and $J$ is the Jacobian transformation. The momentum equations can also be written in the BFC system in the same manner as described previously (Reddy, 1997; Thompson, Thames, and Martin, 1977; Vethamony et al., 2005).

The transformed governing equations of flow have been discretized on a staggered grid and solved using the Alternating Direction Implicit (ADI) finite difference scheme. The scheme splits the time into two intervals. In the first half-time step, derivatives with respect to $\zeta$ are advanced from $t^n$ to $t^{n+1/2}$, and the derivatives involving $\xi$ are held at $t^n$. In the second half-time step, $\zeta$ derivatives are held at $t^{n+1/2}$ and $\xi$ derivatives are advanced from $t^{n+1/2}$ to $t^{n+1}$. Nondervative terms are computed at $t^n$ for both levels. The
transformed equations of flow are discretized using the ADI procedure in the $\zeta$ and $\xi$ directions, arranged in the form of algebraic equations and grouped together to form a tridiagonal matrix, which is then solved implicitly for tides and currents. The time step ($\Delta t$) is chosen based on the Courant stability criteria because, the BFC grid size varies both in the $x$ and in the $y$ direction.

Modeling of BOD Concentration

The basic governing equation of BOD transport in a well–mixed region can be written as

$$
\frac{\partial}{\partial t} (HS) + \frac{\partial}{\partial x} (UHS) + \frac{\partial}{\partial y} (VHS) = \frac{\partial}{\partial x} \left( D_x H \frac{\partial S}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_y H \frac{\partial S}{\partial y} \right) + Q_s \tag{15}
$$

where $S$ is BOD in mg/l, $D_x$ and $D_y$ are the diffusion coefficients which are the function of local currents and water depth, $H$ is the total water depth, $U$ is the velocity component in x direction, and $V$ is the velocity component in y direction, $Q_s$ is source term.

The treated effluent discharge quantities, 100000 m$^3$/d and 2000 m$^3$/d, generated from CETP, Vapi and Daman Distilleries respectively are proposed to be discharged into the coastal waters off Daman at locations, OF-1 and OF-2 respectively (Figure 5). The BOD concentration in the CETP would be 100 mg/l while it is 2500 mg/l in distilleries effluent.

RESULTS AND DISCUSSION

Tides are semi-diurnal type with an appreciable diurnal inequality. The high tide at Daman lags by 120 to 140 minutes by the tide at Mumbai. The maximum tidal amplitude ranged from 6.0 m to 7.4 m depending on the neap and spring conditions. The maximum current speeds varied from 0.4 – 1.2 m/s. The prevailing current direction was parallel to the coast. The float study conducted at station 6 reveals that the excursion lengths of 6 – 15 km in 6 h in flood and ebb directions during neap and spring conditions. The direction of the drift was parallel to the coast.

The annual temperature range off Damanganga varied from 22.7-30.1°C. The average pH off Damanganga ranged from 7.3 to 8.3. The overall variation of suspended solids was less than 518 mg/l. The salinity of the coastal waters ranged from 6.2-35.6 ppt while salinity of the estuary varied over a wide range (6.2 - 20.5 ppt). The overall variation of dissolved oxygen (DO) varied in the range of (2.7 - 5.4 ml/l) indicates well-oxygenated coastal waters. The DO variation (2.9 - 4.9 ml/l) in the estuary with values often below 1 ml/l particularly in the mid-estuary indicates considerable environmental stress due to high loading of anthropogenic organic matter that probably exceeds the assimilative capacity of the estuary (Anonymous, 2010). Biological Oxygen Demand (BOD) was less than 6 mg/l. The concentrations of phosphorous (0.4 to 8.1 µmol/l) in the coastal water were in the range normally recorded for the coastal waters of south Gujarat.
Higher values were recorded in estuary as compared to the coastal area. The values of Nitrate (µmol/l) in the area varied from 1.0 to 23.0 µmol/l. The concentration of Nitrite (µmol/l) ranged from 0.1 to 3.7 µmol/l. The ammonia concentration varied from 0.3 to 54.2 µmol/l and found that the concentration in the Damanganga region was higher than the coastal region. The overall variation in concentration of petroleum hydrocarbon ranged from 0.8 to 445.6 µg/l off Damanganga. The levels of phenols were below 111 µg/l in the coastal waters as well as in the Damanganga estuary.

The coastal subtidal sediment contains silt as the major constituent. The intertidal coastal sediment on the other hand is mainly sandy (>88.4%). The concentrations of trace metals, viz, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn and Hg were low and within the range.

The average chlorophyll a and phaeophytin values during March 2009 were 6.7 and 1.3 mg/m³ respectively. The levels of chlorophyll a during postmonsoon (December 2009) ranged from 0.4 to 4.6 mg/m³ and phaeophytin ranged from 0.1 to 1.9 mg/m³. The phytoplankton cell count for surface water varied from 25.6 to 17740 x 10³/l with high generic diversity. The zooplankton standing stock in March 2009 in terms of biomass and population varied widely from 0.1 to 32.9 ml/100m³ and from 0.05 to 158.5 x10⁷/100 m³ respectively. Coastal waters are more productive than the Damanganga estuary. The macrobenthic standing stock in terms of population and biomass varied from 0 to 1.8 x 10⁴ no/m² and 0 to 38.6 g/m² respectively. Overall the Damanganga estuary was relatively more polluted as compared to the offshore waters.

**Near-field dilutions**

The above nonlinear equations (1-5) were solved explicitly by Runge-Kutta integration scheme. The model calculates the dilutions, plume width, angle of plume at different levels. For lighter effluents, the angle of release is considered as 15° to the horizontal plane instead of 0° to avoid the port clogging due to bottom sediment. The velocity of the effluent at port level is also fixed as 2 m/s to minimize the pipe head losses. The density difference of 23 kg/m³ (salinity difference of 30 ppt) was considered in the effluent. The model was run for different dilutions varying the number of round ports.

The following inputs were used in the model. Effluent quantity = 100000 m³/d, Effluent density = 1000 kg/m³; Seawater density = 1023 kg/m³; Maximum water depth = 8 to 11 m depending on neap and spring; Average current velocity = 0.5 m/s. Concentration of BOD in the treated effluent is 100 mg/l as per the standards of the GPCB. The initial conditions were applied as suggested by Malacic (2001).

The buoyant jet model was run for different port sizes and the results are presented in the Table 1.

Results of the buoyant jet model show that when 100000 m³/d of effluent is released through a 12 port diffuser the plume would attain dilutions of 35 to 70 times depending on the tidal phase viz, spring and
neap, with jet velocities of 2 m/s. Each port should have 0.24 m dia and ports should be separated by 5 m. Angle of the ports should be maintained 15° to the horizontal plane. The total length of the diffuser would be 55 m. The diffuser should be laid perpendicular to the prevailing current regime. With the above dilutions, the increase in BOD levels at release site would be around 2-3 mg/l. The salinity decrease at this location would be around 0.5 to 1.0 ppt.

**Far-field dilutions**

Modeling of far-field dilution involves simulations of hydrodynamics and resultant mass transport. Modeling of tides and currents off Daman was carried out by solving the 2D shallow water equations of continuity and momentum (Equations 5 – 7) on BFC grid system.

Modelling was carried out initially for larger domain for the area between Dahanu and Valsad at the geographical location between 72° 23’ to 72° 55’ E, 20° 0’ to 20° 41’ N (Figure 5). Number of grids in the domain are 150 in x direction while it is 95 in y direction. Time step of the run was 3.19 sec. The tide data of Dahanu and Valsad were prescribed at boundaries. Boundary data at these locations are presented in the Figure 6. Maximum difference in the amplitude is 2 m and the time lag varies between 40 and 60 min. The tides and currents at each grid location were calculated and stored at 1h time steps. Using this data, a smaller domain (72° 39’ - 72° 53’ E 20° 17’ – 20° 32’ N) was selected. The bathymetry data used in the study was obtained from Naval Hydrography Office, India Chart No. 2026. Prescribing the boundary data obtained from the larger domain, the model was again run with finer grid for the tides and currents. The time step used was 1.1s and grid size in x direction is 120.5 m and 120.0 m in y direction.

Now the model was run for hydrodynamics, viz, tides and currents and the results were stored at 1 h interval. The run was started on 25 May 2005 at 0200 h. The model was calibrated with the tide data at Daman collected for the same period (Figure 7). The results show that correlation coefficient (r) between observed and predicted tide is 0.92. The model was again run using boundary data of 2009 for verification of currents collected in April 2009. The results compared with the observed currents at station 6 during April 2009 (Figure 8) reveal that the r is 0.65. Now the model was run for hydrodynamics staring from 31 March 2009 at 0200 h. The simulated currents during spring ebb and flood are presented in the Figures 9 and 10. The current field at proposed release location shows that the flow is parallel to the coast. Maximum currents of 1.9 m/s were found in the model domain. The estuarine currents were relatively smaller than the offshore currents. The model was run by prescribing effluent inputs at locations OF1 (20° 25’ 28” N 72° 46’ 32”) and OF2 (20° 25’ 10” N 72° 47’ 44” E). This location was considered basing on the facts, viz, currents run parallel to the coast, sufficient initial dilutions are available and no ecological sensitive areas are present in the vicinity. Also laying of pipeline in the southern side of the mouth is not possible due to presence of historical Fort on the bank of the estuary. The concentration field of BOD was simulated by solving the 2D advection-diffusion formula (Equation 15). The model was run for two discharges of CETP (OF1) and distilleries
(OF2). The model run started on 31.03.2009 at 0200 h and was allowed to run for 15 days. The BOD concentrations were stored at 1 h interval at different distances from the outfall location as shown in Figure 11. The distances from the outfall to the observational location are given in the Table 2.

The output was also stored for different phases of tidal phases. These results of spring ebb, flood and lowest low water are presented in Figures 12 to 14. The plume would move along the coast during flood and ebb and the concentration of BOD would range from 0.7 to 0.8 mg/l above ambient at proposed CETP release site (OF1). The lowest low water period is considered as the worst case scenario for the discharge. During this period (Figure 14) the BOD concentration would be 2.9 gm/l above ambient. The results of the concentration field show that the both the effluents of OF1 and OF2 run parallel to the coast and do not overlap each other. The temporal variations of BOD concentration obtained at several locations in the model domain in the vicinity of outfall locations as shown in Figure 11 reveal that it would vary between 0.5 and 2.9 mg/l at the release location of OF1(Figure 15). The location which is 214 m away from the release site would experience BOD range of 0.2 to 1.5 mg/l. This shows that the plume would attain near ambient conditions at about 100 m distance. The BOD concentration would be less than 1 mg/l beyond 300 m distance from the outfall location in ebb and flood conditions. The figure 16 illustrates that the BOD concentration would vary between 0.5 and 2.5 mg/l at outfall site of OF2. In this case also the background concentrations would be attained beyond 200 m distances. The plots of these temporal variations also reveal that the regions observed across the flow field, stations 3, 5, 12 and 15 would experience very low BOD concentrations during the release of the effluents. Hence the chances of moving the effluent to the coast are remote. The affect on local biota is limited to the release site only. The chance of entering the effluent into the Damanganga estuary is remote. Hence the treated effluent can be released at a location 20° 25’ 28” N 72° 46’ 32” E with a diffuser system as specified above. The distance from high tide line to the discharge location is about 3.9 km. Shifting of this release location from upstream of the estuary to the offshore location would improve the water quality in the estuarine zone and it is expected that the conditions of pre-industrial period would be restored.

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LITERATURE CITED


Figure 1. Location Map

Figure 2. Satellite image of Damanganga estuary

Figure 3. Sampling locations

Figure 4. Google map showing effluent cloud

Figure 5. Bathymetry contours of model domain

Figure 6. Boundary tide at Valsad and Dahanu

Figure 7. Comparison of observed and modeled tide at Daman

Figure 8. Comparison of observed and modeled currents at Daman

Figure 9. Modeled currents during spring ebb

Figure 10. Modeled currents during spring flood

Figure 11. Modeled currents during spring ebb

Figure 12. Modeled BOD concentration during spring ebb after 12 days of release

Figure 13. Modeled BOD concentration during spring flood after 12 days of release

Figure 14. Modeled BOD concentration during spring slack after 12 days of release

Figure 15. Temporal variations of BOD concentrations at specified locations around OF1

Figure 16. Temporal variations of BOD concentrations at specified locations around OF2
Table 1. Near-field plume model results

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Table 2. Distances of far-field model observational locations from outfalls OF1 and OF2

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