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Identification of Inlet and Outlet Locations for Cool Seawater Discharges from an LNG Facility

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ABSTRACT: Two-dimensional hydrodynamic and advection-dispersion simulations were carried out to identify the appropriate locations of inlet and outlet for cool seawater discharges from the proposed Liquefied Natural Gas (LNG) terminal using MIKE-21 suites of software. The model simulations were validated by comparing the observed and simulated hydrodynamics in terms of water depths, current speeds and directions. The model is satisfactorily correlated with coefficients 0.98, 0.86 and 0.91 for water depth, current speed and direction, respectively. The validated model was extended to predict the advection-dispersion phenomena for the two scenarios based on positions of inlet and outlet and their discharges. The predicted results of cool water discharges were compared to the existing Environmental Health and Safety, World Bank guidelines for LNG discharge facilities. It was observed that a trade-off is required before taking engineering decisions for selecting an environmentally acceptable and energy efficient option for such cool water discharges from an LNG facility.

Key words: Hydrodynamics, Advection-Dispersion, Cool seawater discharges, LNG, Simulation

INTRODUCTION

For decades, the ocean has been the ultimate sink for industrial water-borne waste products. The anthropogenic threats that result from industrial activities are influenced by activities on land (terrestrial and freshwater), along coasts, and in oceans (Halpern *et al*., 2008). As industrial development continues along the coastal zones, near-shore waters are subjected to increased environmental stress. Due to the ocean's high dilution capabilities, multiport submerged diffusers are nowadays considered the most practical solution for industrial discharge (Ahmad and Baddour, 2014). Modelling the costal seawater environment can provide a cost effective solution which can reveal the hydrodynamics and other related processes well before taking investment decisions. Mathematical modelling has thus become an effective tool in decision-making related to environmental issues and quantitative environmental impact assessment (Jorgensen and Bendoricchio, 2001; Gertsev and Gertseva, 2004; Babu *et al*., 2005; Lattemann and Höpner, 2008; Vijay *et al*., 2010a). A few modelling studies have been carried out in India to understand some of the issues relating to water quality deterioration caused by the disposal of urban sewage and industrial effluents (Gupta *et al*., 2004; Desa *et al*., 2005; Vethamony *et al*., 2005; Vijay *et al*., 2010b). Numerical Modelling has also been used to predict the change in ambient temperature in coastal zones (Valeo and Tsanis, 1994) and to evaluate the design of diffuser for the cool seawater discharge from the Liquefied Natural Gas (LNG) Plant using CORMIX (Nigam *et al*., 2013). Temperature is one of the most important environmental variables, which affects the survival, growth and reproduction of aquatic organisms (Langford, 1990; Hughes, 2009). Investigations have revealed the effects of thermal effluent on aquatic communities' structure and their distribution (Lee, 2003; Roberts and Tian, 2004; Poornima *et al*., 2005). The main factors that affect the recirculation of such water are; the distance between inlet and outlet, the spreading behaviour of the warmed water from the outlet, the heat budget in the bay, the tidal action, the wind stress and its direction, the configuration and the depth of the bay etc. (Wada, 2000). Hence, the discharges to coastal waters have to be adapted to be site specific and optimum. In effect, the discharge plumes should get dissolved by the action of the prevailing currents in the coastal marine environment (Quetin and De Rouville, 1986).

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Therefore, potential impacts to the marine environment can be minimized by appropriately planning and selecting the suitable outfall location (Panigrahi and Tripathy, 2011). Due to increased imports of LNG, various gasification terminals have been proposed in the coastal zone of India (Nigam *et al*., 2013; Vivoda, 2014). It is, therefore, an important problem to predict the variation of the sea surface temperature in the bay for the development of upcoming plants in the coastal areas. Such recirculation of water has great influence on the efficiency of operation of LNG terminal. Keeping this in view, a modelling study has been carried out to assess the hydrodynamics and advection-dispersion of the LNG-Open Rack Vaporiser (ORV) outlet seawater discharge. The objective of the study is to identify and select an optimum location of LNG-ORV seawater discharges by simulating two inlet outlet scenarios. In this study, the tide induced flow and the advection-dispersion of ORV discharge plume is simulated in the vicinity of the Gulf of Kutch using MIKE-21 suite of programs (User Guide and Reference Manual for MIKE21, 2001).

MATERIALS & METHODS

The present study is pertinent to the Mundra, Gulf of Kutch, Gujarat which is a semi-enclosed marine embayment located in the north-eastern part of the Arabian Sea. The study area lies between the latitude 22° 42' 57'' N to 22° 45' 25'' N and longitude 69° 38' 40.5'' E to 69° 42' 22'' E with an area of 4.5 x 6.3 km^2. The base map of the plant site was prepared using GPS (Trimble Juno SD) and delineated on Geographical Information System (GIS) platform with ArcGIS 10.2 (ESRI, 2013). The location map provides the details regarding proposed plant site and locations of inlet and outlet as shown in Figure 1. The study area was discretised into 45,360 grids with grid size of 25 m x 25 m. Figure 2 depicts the bathymetry that shows the contours of depth and height with reference to Chart Datum (CD) in spatial domain of the study area. The heights above CD are categorised into two classes varying from 0 to above 5 m and the depths below CD are divided in five classes from 0 to below -20 m. The depths available at the proposed inlet and outlet are approximately -9.5 m and -2.1 m CD respectively based on the bathymetry model. Variations in surface seawater temperature was not much pronounced near the studied area and observed to range from 29.0 °C to 30.5 °C in the month of July 2013. Water salinity values did not fluctuate much and varied from 33 to 35 Practical Salinity Unit (PSU).

In order to minimize environmental sensitivity and take appropriate engineering decision for confirming set of inlet and outlet locations, advection-dispersion modelling are performed coupling Hydrodynamic (HD) and Advection-Dispersion (AD) model of MIKE-21

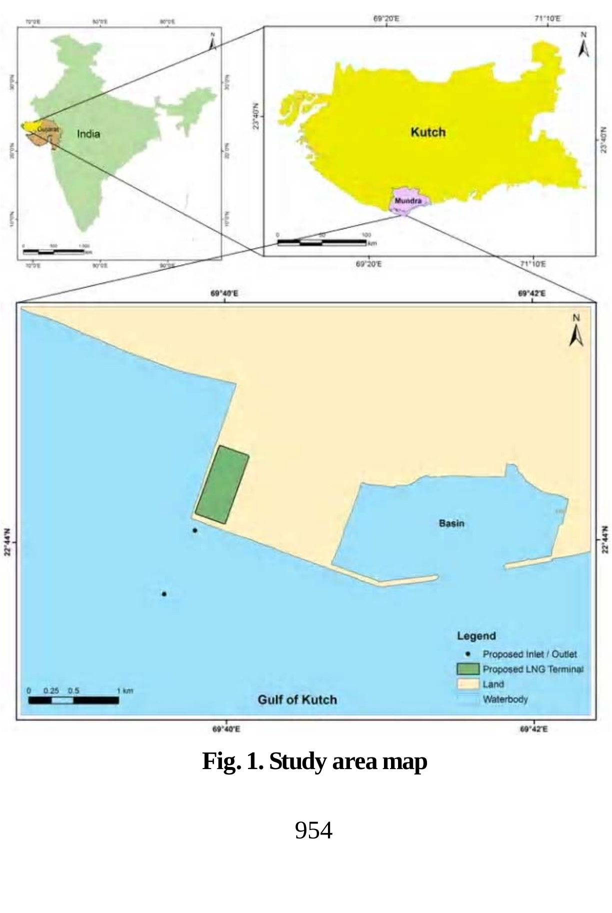


Fig. 1. Study area map

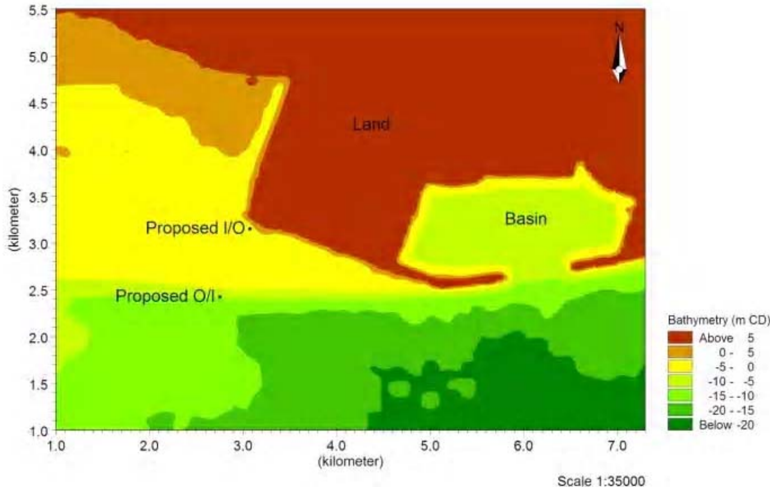


Fig. 2. Bathymetry of the study area

suites of programs. The modelling system is based on the numerical solution of the 2-D incompressible Reynolds Averaged Navier-Stokes equations subject to the assumptions of Boussinesq and hydrostatic pressure. The resulting model conceptualisation consists of conservation of mass, momentum, transport of temperature, salinity and state of matter equations. The density is expressed as a function of temperature and salinity only. The time integration is performed using an explicit scheme. The governing equations are presented using Cartesian coordinates. The continuity equation is written as Eq. 1.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad \text{(Eq.1)}$$

where, u, v and w denotes the flow velocity component in x, y and z Cartesian coordinates, respectively. The generalised momentum equations for the x- and y-component are presented in Eq. 2.

$$\left[\frac{\partial}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right](u,v)$$

$$=f(u,v)-g\frac{\partial \eta}{\partial (x,y)}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial (x,y)}- \qquad \text{(Eq.2)}$$

$$\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial (x,y)}dz+F_{u,v}+\frac{\partial}{\partial z}\left(v_t\frac{\partial u}{\partial z}\right)+S.(u_s,v_s)$$

where, t is time, g is gravitational acceleration, F is diffusion term, p_0 is density, p_a is atmospheric pressure and S denotes the net source term. Calculations of the transports of temperature, T, and salinity, s follow the transport-diffusion equations as depicted in Eq. 3.

$$\left[\frac{\partial}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right](T,s)= \qquad \text{(Eq3)}$$

$$F_{T,s}+\frac{\partial}{\partial z}\left(D_v\frac{\partial}{\partial z}\right)(T,s)\ +(T_s,s_s).S$$

The water levels and flows are resolved on a rectilinear grid covering the area of interest. HD was established with input parameters which include bathymetry, simulation period, boundary conditions, heat source and sink with seawater discharge flow rate around 15 m^3/s. Hydrographic boundary conditions are specified in terms of tidal variations (in time and space) and flux boundary at each of the open model boundaries. Concurrent tidal and current data for a period of 14 days in the month of July 2013 with frequency resolution of 30 min were used as boundary conditions. Table 1 presents the tidal variations near the site location w.r.t. neap and spring tide timings. An

Table 1. Tidal data at site location

Tidal conditions	Depth
Lowest Astronomical Tide (LAT)	0.6m
Mean Low Water Spring (MLWS)	1.2m
Mean Low Water Neap (MLWN)	1.8m
Mean Sea Level (MSL)	3.6m
Mean High Water Neap (MHWN)	5.3m
Mean High Water Spring (MHWS)	5.9m
Highest Astronomical Tide (HAT)	6.4m

All the levels are w.r.t. Chart Datum

initial free surface level is mapped over the entire model domain. The model was validated and calibrated against the observed and simulated tide and current within the model domain. The validated model was extended for AD modelling to simulate the two scenario based on the location of inlet and outlet for the cool seawater discharge. The AD simulation was set up by defining the discharge temperature of the seawater at the plant outlet as heat sink. The heat dissipation was incorporated using the ambient seawater temperature as plant design seawater temperatures around 30 °C and discharge seawater temperature with difference of 5 °C colder from seawater temperature. The dispersion coefficient was specified in both longitudinal and transverse directions. The model was simulated for a period of 14 days.

RESULTS & DISCUSSION

The hydrodynamic model was conceptualized and simulated for present conditions. The results of hydrodynamic simulation in terms of water depth profiles are depicted in Figure 3 under lowest low and highest high tide conditions. The water depth at proposed inlet/outlet and outlet/inlet varies in the range of 10.3 m to 14.8 m (seaward) and 3.1 m to 7.5 m (near shore), respectively due to tidal influence. It is observed in the open sea at the site that the flow is unidirectional (either eastern or western). The tidal current as per simulation was observed to be prominent in westward and in between north-east and eastward directions with current speed in the range of 0 – 1 m/s. The validation of the model was performed by comparing the hydrodynamics at the mouth of the basin (water depth, current speed and direction) with the observed values for 24 hours with an interval of 30 min. The correlation coefficients for water depth, current speed and direction are found to be 0.98, 0.86 and 0.91 respectively based on observed and simulated values. The scatter plots of water depth, current speed and direction are presented in Figure 4 a, b and c respectively. The calibration and validation of the model was found to be satisfactory indicating that the hydrodynamic output can be further extended to predict the plant design scenarios of cool water discharges under two scenarios based on the locations of inlet and outlet of seawater. The HD and AD simulations of scenarios are explained below.

Scenario 1: In this scenario, the inlet and outlet are located at a distance of 1000 m and 100 m from the shore, respectively. Based on the hydrodynamic

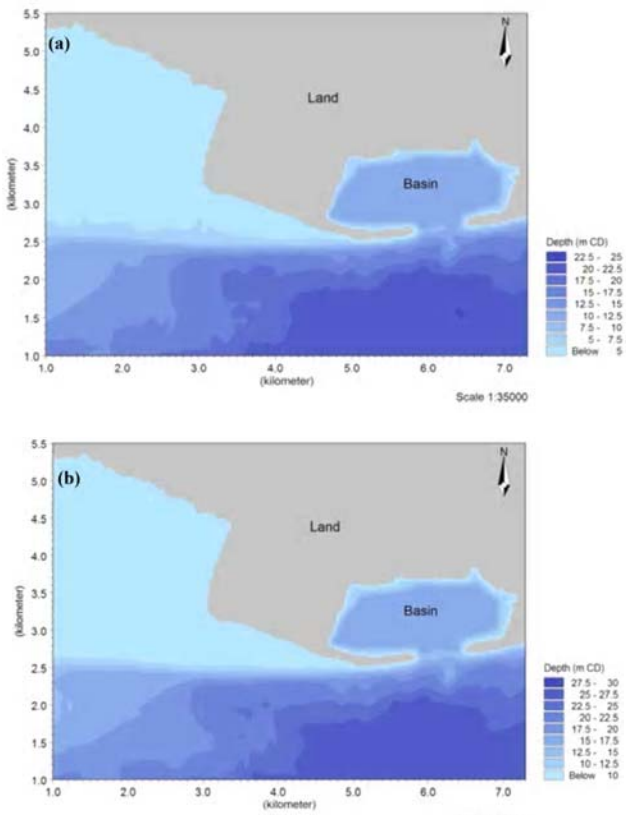


Fig. 3. Water depth profile (a) lowest low tide (b) highest high tide

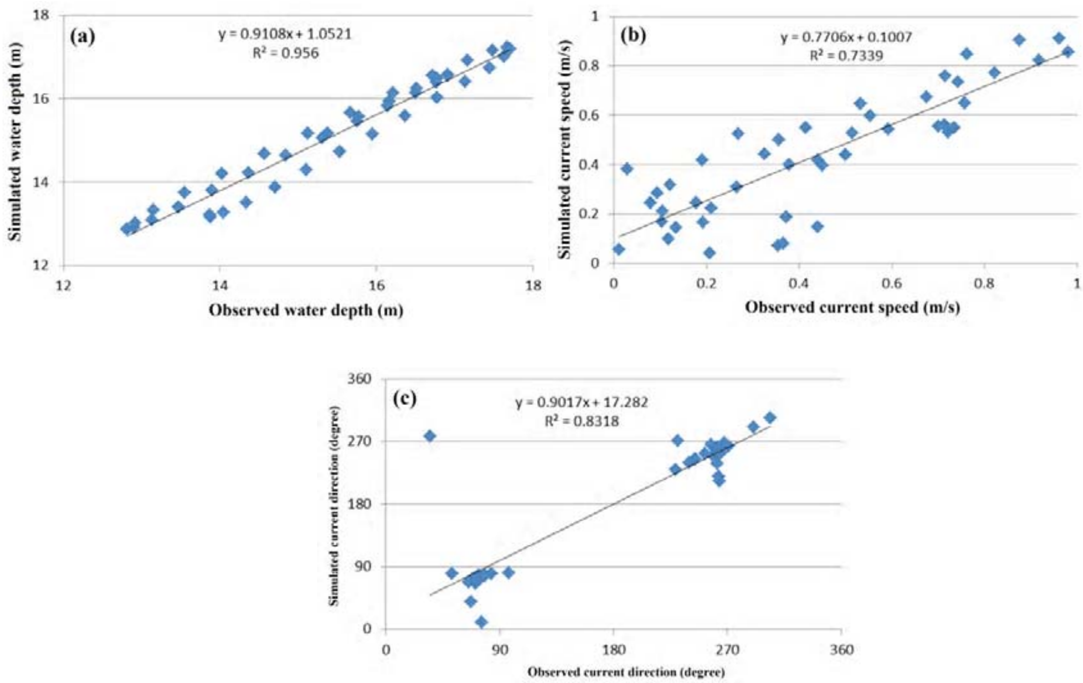


Fig. 4. Scatter plots of observed and simulated hydrodynamics a) water depth b) current speed and c) current direction

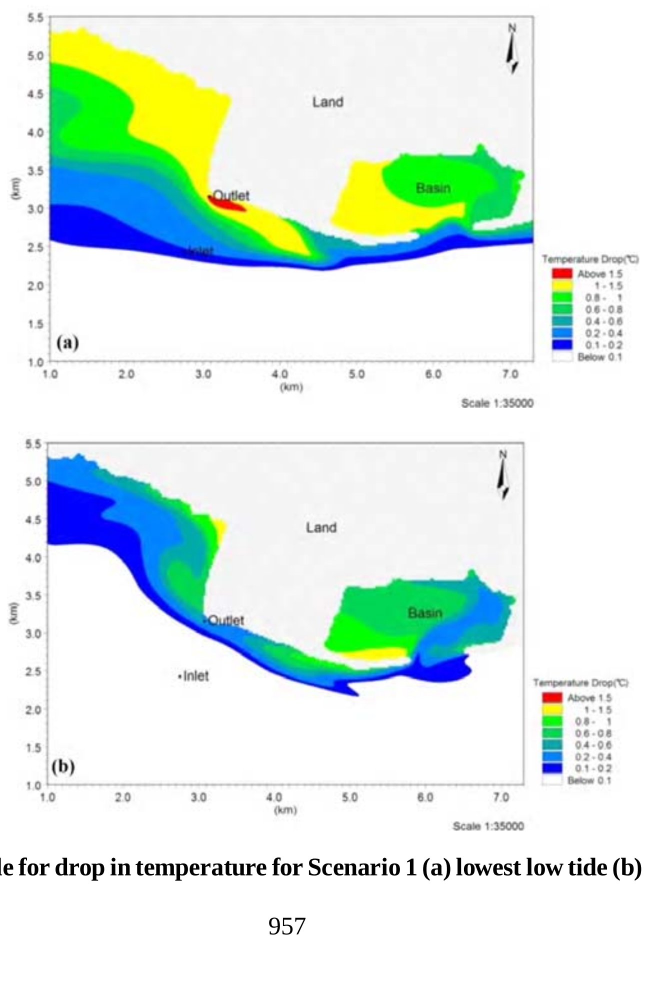


Fig. 5. Dispersion profile for drop in temperature for Scenario 1 (a) lowest low tide (b) highest high tide

simulation, water depths at inlet and outlet vary in the range of 10.3 m to 14.8 m and 3.1 m to 7.5 m, respectively during lowest low to highest high tide conditions. Dispersion phenomenon was simulated for 5 °C drop in temperature between inlet and outlet from ambient seawater temperature with withdrawal of seawater for LNG terminal and discharge of seawater into the coastal environment. The spatial and temporal variations in the seawater temperature drop due to discharge of cooled water during lowest low and highest high tides are presented in Figure 5a and Figure 5b, respectively. Legends are provided to assess the variations in the seawater temperature drop with levels below 0.1 °C and above 1.5 °C. Temperature values below 0.1 °C are considered as ambient seawater temperature. Based on the dispersion scenario, during lowest low tide, a temperature drop of 0.2 °C at the inlet is observed which regains ambient temperature within a span of half an hour to one hour due to tidal influence. No influence of cool seawater discharge is observed at inlet during highest high tide condition. A significant drop in temperature is observed at outlet due to discharge of cool water and low water levels. The temperature at outlet is found to be in the range of 28 °C to 29.5 °C with a drop of 0.5 °C to 2 °C with reference to lowest low and highest high tide conditions. The minimum seawater temperatures at recirculation distance of 100 m from outlet were observed to vary from 28.3 °C to 28.6 °C with a drop of 1.4 °C to 1.7 °C from ambient seawater temperature.

Scenario 2: In this case, the locations of the inlet and outfall were reversed where the outlet is located away from the shore. The simulation condition was kept same as for Scenario 1. Based on hydrodynamic simulation, negligible change in water depth was observed at inlet and outlet. The spatial and temporal variations in the seawater temperature drop due to discharge of cooled water during lowest low and highest high tides are delineated in Figure 6a and Figure 6b, respectively. Based on the dispersion scenario, during lowest low tide, a temperature drop of 1 °C occurs at the inlet which does not regain its ambient temperature even during highest high tide. This drop

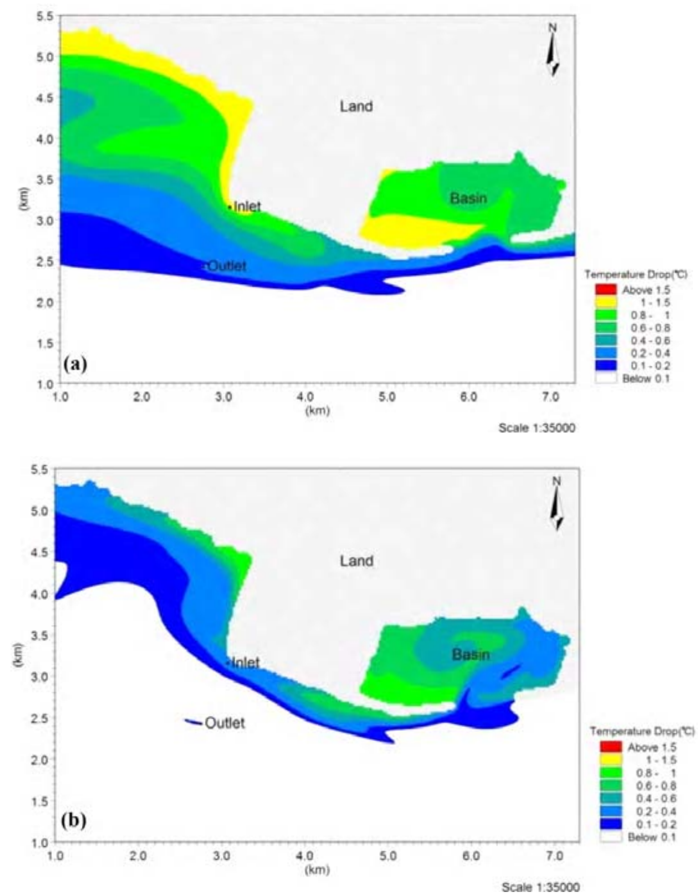
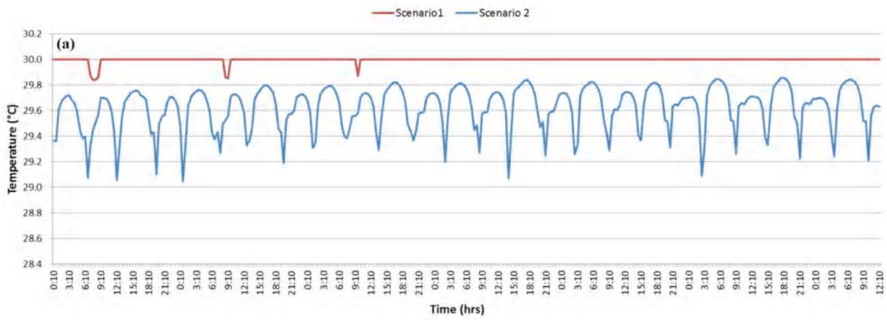


Fig. 6. Dispersion profile for drop in temperature for Scenario 2 (a) lowest low tide (b) highest high tide



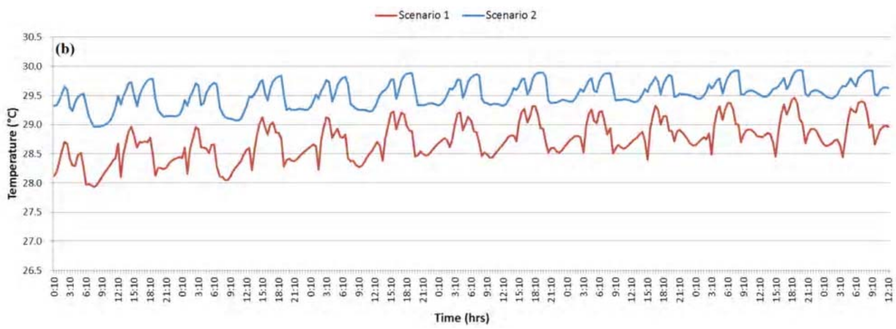


Fig. 7. Comparison of seawater temperature variations at (a) Inlet (b) Outlet

in temperature at the inlet may be attributed to its proximity to the shore and low water levels for dilution. The minimum seawater temperature at inlet during lowest low tide and highest high tide were observed as 29 °C and 29.8 °C, respectively. A drop in temperature is observed at outlet due to discharge of cool water. The temperature at outlet is found to be in the range of 28.9 °C to 29.9 °C with a drop of 0.1 °C to 1.1 °C with reference to lowest low and highest high tide conditions. The minimum seawater temperatures at recirculation distance of 100m from outlet were observed to vary from 29.5 °C to 29.8 °C with a drop of 0.2 °C to 0.5 °C from ambient seawater temperature.

The comparison of variation in temperatures at the inlet and outlet for both the scenarios are shown on Figure 7a and b, respectively. The predicted results of cool seawater discharges in coastal environment were assessed to comply with the EHS Guidelines for LNG Facilities which state that "cooling or cold water should be discharged to surface waters in a location that will allow maximum mixing and cooling of the thermal plume to ensure that the temperature is within 3 °C of ambient temperature at the edge of the mixing zone or within 100 meters of the discharge point" (WBG, 2007). In the existing situation, this is no discharge from proposed LNG terminal. Hence the dispersion model cannot be calibrated and validated against observed data. However, the important parameters used in the dispersion model are dispersion coefficients D_x and D_y in x and y directions respectively. After making sensitivity analysis, dispersion coefficients were assumed to be proportional to the current in the range of 1 m^2/s to 1.5 m^2/s for x and y directions.

CONCLUSION

The hydrodynamic and dispersion simulations were carried out by considering two scenarios of inlet and outlet locations to identify a suitable seawater discharge location which does not have any adverse effect on the coastal zones. The model was validated for the present hydrodynamics with respect to tidal height, current speed and directions. The validated model was extended to predict the temperature dispersion of cooled seawater plume. The cold seawater discharge from proposed LNG terminal for both the simulated scenarios complies with available international guidelines. The drop in seawater temperatures from ambient was observed to be higher at a recirculation distance of 100 m from outlet in scenario 1. Whereas, a higher temperature drop at inlet was observed for Scenario 2. This shows that Scenario 2 is more environmentally benign as compared to Scenario 1 but will hamper the operational efficiency of the proposed LNG terminal. So, it is necessary to have a trade-off between the environmentally friendly and energy-efficient options. In this study, Scenario 1 meets the international guidelines and does not affect the operational efficiency of the LNG terminal; thus presents a better choice for cool seawater discharges from an LNG facility.

REFERENCES

Ahmad, N. and Baddour, R. E. (2014). A review of sources, effects, disposal methods, and regulations of brine into marine environments. Ocean Coast Manag, **87**, 1–7.

Babu, M. T., Vethamony, P. and Desa, E. (2005). Modelling tide-driven currents and residual eddies in the Gulf of Kachchh and their seasonal variability. Ecol. Modell., **184**, 299–312.

Barnes, R. S. K. and Hughes, R. N. (2009). An Introduction to Marine Ecology. (John Wiley & Sons)

Desa, E., Zingde, M.D., Vethamony, P., *et al*. (2005). Dissolved oxygen-a target indicator in determining use of the Gulf of Kachchh waters. Mar. Pollut. Bull., **50**, 73–9.

ESRI, (2013). ArcGIS 10.2. Environmental Systems Resource Institute, Redlands, California.

Gertsev, V. and Gertseva, V. (2004). Classification of mathematical models in ecology. Ecol. Modell., **178**, 329–334.

Gupta, I., Dhage, S., Chandorkar, A.A. and Srivastav, A. (2004). Numerical modeling for Thane creek. Environ. Model. Softw., **19**, 571–579.

Halpern, B. S., McLeod, K. L., Rosenberg, A. A. and Crowder, L. B. (2008). Managing for cumulative impacts in ecosystem-based management through ocean zoning. Ocean Coast Manag., **51**, 203–211.

Jorgensen, S. E. and Bendoricchio, G. (2001). Fundamentals of ecological modelling.Vol. 21. Elsevier.

Langford, T. E. (1990). Ecological effects of thermal discharges. Elsevier Applied Science, Elsevier Science Pub. Co., London; New York, USA

Lattemann, S. and Höpner, T. (2008). Environmental impact and impact assessment of seawater desalination. Desalination, **220**, 1–15.

Lee, C. (2003). The effects of thermal effluent on marine diatoms and bacteria. Malaysian Journal of Science, **22**, 23–27.

MIKE21, (2001). User Guide and Reference Manual, Reference Manual. Danish Hydraulic Institute, Agera Alle, Horsholm, Denmark, 70 pp.

Nigam, S., Rao, B. P. S. and Srivastava, A. (2013). Effect of Thermal Discharge of Cool Water Outfall from Liquefied Natural Gas (LNG) Plant into Sea Using CORMIX. Computer and Communications, 1–5.

Panigrahi, J. K. and Tripathy, J. K. (2011). Numerical Simulation of Advection-Dispersion for Monitoring Thermal Plume Re-Circulation in a Shallow Coastal Environment. Applied Ecology and Environmental Research, **9**, 341–354.

Poornima, E. H., Rajadurai, M., Rao, T. S., Anupkumarb, B. Rajamohanb, R. Narasimhanb, S.V. Rao, V.N.R. and Venugopalan, V. P. (2005). Impact of thermal discharge from a tropical coastal power plant on phytoplankton. J. Therm Biol., 30, 307–316.

Quetin, B. and De Rouville, M. (1986). Submarine sewer outfalls-A design manual. Mar. Pollut. Bull., **17**, 133–183.

Roberts, P. J. W. and Tian, X. (2004). New experimental techniques for validation of marine discharge models. Environ. Model. Softw., **19**, 691–699.

Valeo, C. and Tsanis, I. K. (1994). Two case studies of dilution models applied to thermal discharges. Can. J. Civ. Eng., **23**, 193-201.

Vethamony, P., Reddy, G.S., Babu, M. T., Desa, E. and Sudheesh, K. (2005). Tidal eddies in a semi-enclosed basin: a model study. Mar. Environ. Res., **59**, 519–32.

Vijay, R., Khobragade, P. and Sohony, R. A. (2010). Water quality simulation of sewage impacts in west coast of Mumbai, India. Water Science and Technology, **62 (2)**, 279-287.

Vijay, R., Sardar, V. and Dhage, S. Kelkar P. S. and Gupta A. (2010). Hydrodynamic assessment of sewage impact on water quality of Malad Creek, Mumbai, India. Environ. Monit. Assess., **165**, 559–571.

Vivoda, V. (2014). LNG import diversification in Asia. Energy Strateg Rev., **2**, 289–297.

Wada, A. (2000). A study on phenomena of flow and thermal diffusion caused by outfall of cooling water. Technical Laboratory, Central Research Institute of Electric Power Industry ,pp. 1388-1411.

WBG, (2007). World Bank Group, Environmental, Health, and Safety Guidelines for Onshore Oil and Gas Development. p 22.