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Hydrodynamic and Advection-Dispersion Simulation of Cool Seawater Discharges from an LNG Facility

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The impact of cool seawater discharge in the coastal waters from a Liquefied Natural Gas (LNG) plant has been simulated using MIKE21. In this work, hydrodynamics conditions of the coastal waters were calibrated and corroborated to predict the cool seawater discharge under two plant design scenarios by selecting flow rate 15 m^3/s and 10 m^3/s with a temperature drop of 5 °C and 7 °C, respectively. The simulations were carried out under different scenarios, to arrive at the best possible case to minimize the potential impact on the coastal environment. Both the simulated scenarios complied with the available World Bank guidelines for LNG facilities. However, the designed scenario of flow rate 10 m^3/s with a temperature drop of 7 °C between inlet and outlet presents a better choice as it reduces the pumping power of seawater intake. As there are no Indian guidelines for cool seawater discharges from LNG plant, the present work can support the policymakers and regulators to formulate coherent discharge standards.

[**Keywords***:* Advection-dispersion, Cool seawater discharges, Hydrodynamics, LNG, MIKE21]

Introduction

With the growing world prosperity, the industrial developments have transcended to coastal zones of India[1]. Presently, most of the industrial outfalls into the coastal waterbody are executed through a designed diffuser[2]. This economically important industrial development should not come at the expense of environmental deterioration. Therefore, environmental modelling and simulations have nowadays become an effective decision-making tool for environmental issues and quantitative impact assessment[3-5]. Such simulations reveal the hydrodynamics and other relevant processes well before any field implementation of the technology or process begun and thus making the project more techno-economically feasible.

Significant advancements have been made in the area of environmental simulations and modelling covering the ecological aspects[5-6] and water quality deterioration caused by industrial discharges[7-9]. Numerical models like MIKE, UM3, RSB and CORMIX were used to simulate and predict the behaviour of the industrial discharges in the coastal environment[10-11]. These numerical models have wide applicability and capabilities to predict the ambient water temperature changes in coastal seawaters[12].

The temperature of the discharged effluents is one of the key variables that affect the aquatic communities structure and their distribution[13-14]. With increasing industrial activities near the shores, the coastal waters are now facing ever-increasing environmental stresses[15]. Therefore, it is important to access the variation of the seawater temperature in the coastal areas by numerical simulations considering the interface between the hydrodynamics characteristics and thermal diffusion of Liquefied Natural Gas (LNG) cool seawater discharges. Such thermal recirculation of cool seawater will directly impact the operational efficiencies of the upcoming industrial plants in the coastal regions. Hence, it becomes essentially important to systematically evaluate and plan these industrial discharges specific to coastal sites[12]. The objective of the study is to reduce the likely impact of coastal cool seawater outfalls from an LNG facility by appropriately selecting the design parameters of discharge flow rate and temperature between inlet and outlet. Therefore, the hydrodynamic and advection-dispersion simulation was carried out under two different plant design scenarios to select eco-friendly and energy-efficient discharge criteria for cool seawater discharges.

Materials and Methods

Model domain

To address the growing demand of natural gas in India and facilitated by a conducive and proactive environment, various LNG gasification terminals have been proposed in Gujarat, India. The present study area is situated on the northern shore of the Gulf of Kutch at approximately 300 km South-West of Gandhinagar in Gujarat. Researchers have carried out numerous studies in the coastal areas of Gulf of Kutch to understand the tides, tide-driven currents and the influence of anthropogenic activities on the environmental ecology[16-19]. The study area for the proposed site of the LNG facility lies between 22° 42’ N to 22° 46’ N latitude and 69° 38’ E to 69° 43’ 30’’ E longitude covering an area of approx. 28.4 km^2.

The base map of the study area along with the bathymetry contours was delineated using ArcGIS 10.220. The base map of the study area provides the spatial location of the proposed plant site, inlet and outlet and depth and height contours w.r.t. Chart Datum (CD) (Fig. 1). The study area was divided into square grids of size 25 m x 25 m amounting to a total of 45,360 computational grids. Based on the bathymetry model; the inlet and outlet depths w.r.t. CD is approximately 9.5 m and 2.1 m, respectively. During the field visit in the month of July 2013, variations in surface seawater temperature were observed to range from 29 °C to 30.5 °C. The seawater density was expressed as a function of temperature. Salinity was also considered as forcing function affecting density as 33 Practical Salinity Unit (PSU).

Model description

The flow and thermal dispersion of discharge were simulated in the study area using a hydrodynamic (HD) and advection-dispersion (AD) module of MIKE21, respectively[21].

The system was modelled based on the numerical solution of incompressible Reynolds Averaged Navier-Stokes (RANS) equations in 2-D. The modelling system was computed under the assumptions of hydrostatic pressure and Boussinesq. The model equation comprised of the mass balance equation, momentum balance equation and transport equation for salinity and temperature. The explicit scheme was used for the time integration of the functions over the computation grids, wherein the density was represented as a function of salinity and temperature. The continuity equation is written as Eq. 1[21].

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \dots (1)$$

where the flow velocity is denoted as u and v for respective x and y coordinates. The x and y component of the momentum equations is presented in Eq. 2[21] and Eq. 3[21], respectively.

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial vu}{\partial y} = fv - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial x} + F_u + u_s S \quad \dots (2)$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial y} + \frac{\partial uv}{\partial x} = -fu - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho_0}\frac{\partial p_a}{\partial y} + F_v + v_s S \quad \dots (3)$$

where, t - time, g - gravitational acceleration, F - diffusion term, ρ_0 - density, p_a – atm. pressure and S - net source term. The transport-diffusion of temperature (T) and salinity (s) follow Eq. 4[21] and Eq. 5[21], respectively.

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} = F_T + \hat{H} + T_s S \quad \dots (4)$$

$$\frac{\partial s}{\partial t} + \frac{\partial us}{\partial x} + \frac{\partial vs}{\partial y} = F_s + s_s S \quad \dots (5)$$

Model Calibration and setup

HD simulated flow dynamics and the variation in the water levels with a multitude of forcing functions in coastal areas. The input parameters for the HD simulation included the system boundary conditions (BC), the bathymetry of the study area, the period of simulation, heat source and sinks along with the discharge flow rates (Q). HD BC was specified w.r.t. spatial and temporal tidal variations and zero in-out fluxes at open model boundaries (Fig. 2). The model was simulated for a period of 15 days. Several trial runs of the hydrodynamic model were made by varying the phase difference in the tidal boundary conditions as well as varying Manning bed roughness to get the observed flow field. All the model inputs such as tide and current are derived from secondary measurements in the area; moreover, the simulation is calibrated using tide and current data acquired during a field visit in the month of July 2013. The model was validated with the observed available secondary tide and current data inside the model domain.

The validated hydrodynamic model was corroborated to simulate and predict the AD scenarios based on the discharge seawater temperature at varied flow rates. AD describes the transport and dispersion of seawater discharge into the study area. For setting the simulations, the heat sink was defined in terms of the discharge seawater temperature at the outlet of the plant and constant ambient temperature of the coastal seawater were specified for the AD model boundary.

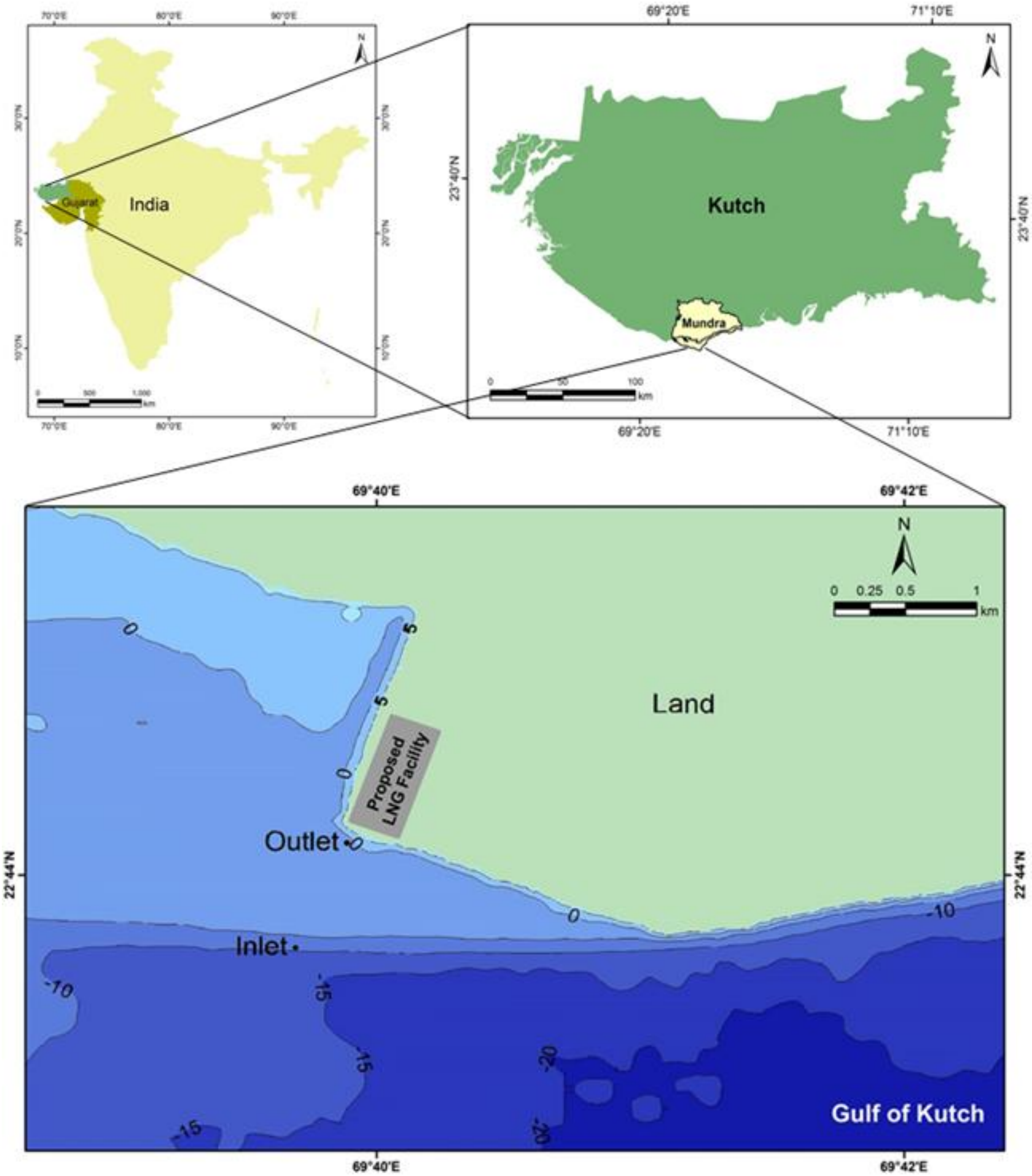

Fig. 1 — Details of the study area with bathymetry

Currently, there are no Indian guidelines on cold water discharge from an LNG facility. Therefore, the temperature drop of 5 °C and 7 °C between inlet and outlet for the present simulation was selected in analogy with Central Pollution Control Board (CPCB), New Delhi guidelines, which state the temperature limit for the discharge of effluents and condenser cooling water in marine coastal environment[22]. The heat dissipation was modelled using plant design temperature of 30 °C, which is the ambient seawater temperature and Q of 15 m^3/s and 10 m^3/s with a temperature drop (ΔT) of 5 °C and 7 °C, respectively. The dispersion coefficients were assumed proportional to current ranging from 1 m^2/s to 1.5 m^2/s. The model was accessed to comply with available guidelines for discharges from an LNG facility.

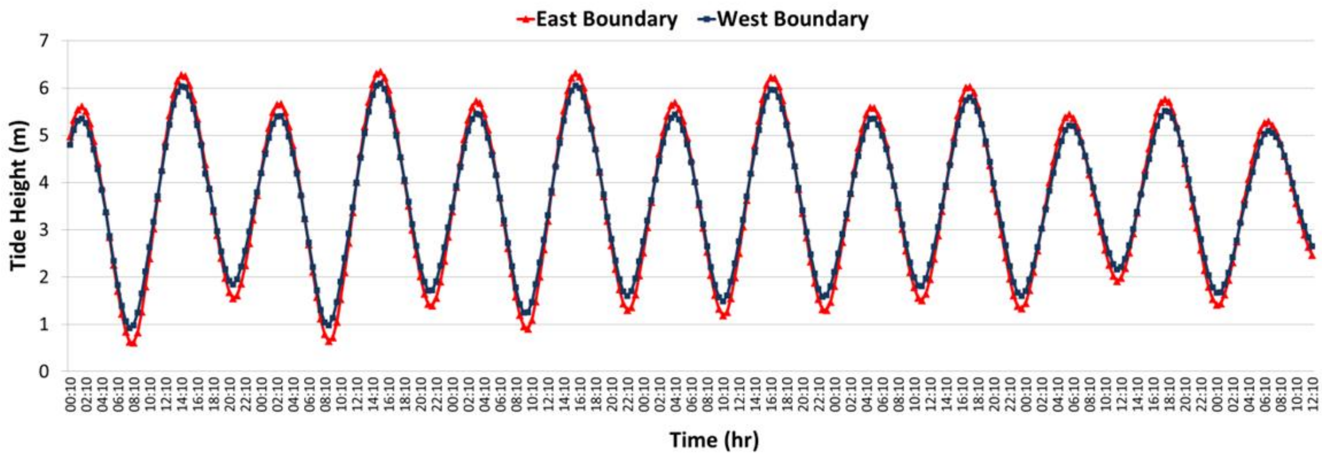

Fig. 2 — Astronomical tide data for a period of 7 days in July 2013

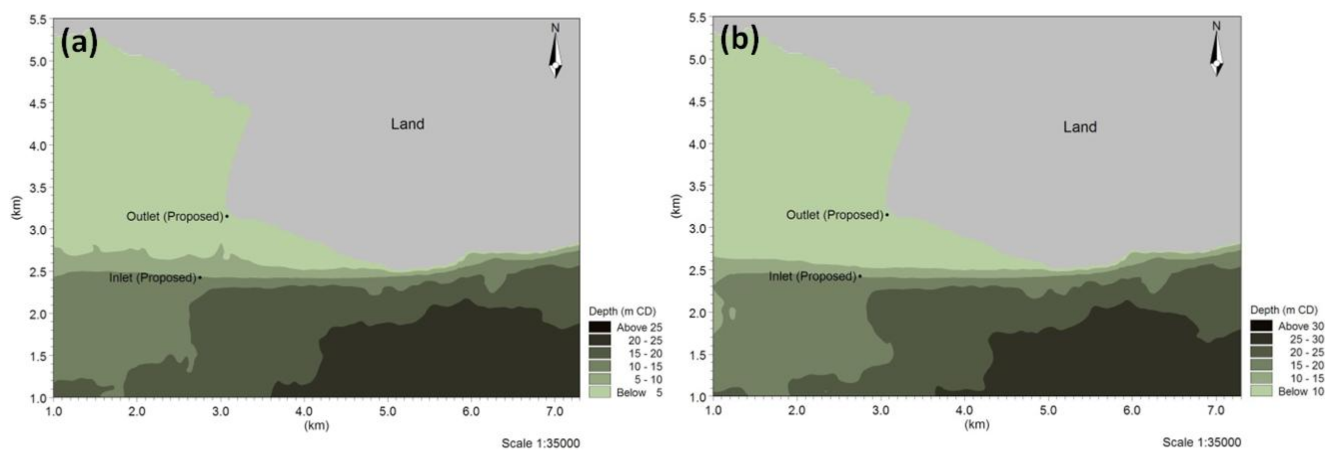

Fig. 3 — Water depth profile at present condition (a) lowest low tide (b) highest high tide

Model limitation

The limitation of the model is that it gives vertically averaged currents and temperature rise or fall at each grid point under the assumption of well-mixed condition. The effect of a turbulent cascade over the depth is neglected. As a large region can be simulated by this model, it can give guidelines for refinement by three dimensional mathematical or physical models.

Results and Discussion

The hydrodynamics of the seawater was simulated and calibrated for existing conditions at the proposed site location i.e. no intake of seawater considering tidal variations in the model domain. The spatio-temporal variations in the depth of seawater are presented in Fig. 3a and 3b, respectively. Due to variation in the tidal heights, the water depths at inlet and outlet was found to vary from 10.3 m to 14.8 m and 3.1 m to 7.5 m, respectively. It was also observed that the tidal current ranges from 0 to 1 m/s and are prominent towards the east and westward side. The unidirectional flow was also observed in the open seawaters (either eastern or western). The observed water depth was compared with the simulated depth to validate the hydrodynamics model and, current speed and direction at 10 m bathymetry contour inside the model domain. Variation in observed and simulated water depth is shown in Fig. 4a. Similarly, the observed and simulated current velocities were compared at identical locations as depicted in Fig. 4b and Fig. 4c. Significant correlations are observed for current speeds, directions and water depths, which are found to be 0.91, 0.86 and 0.98, respectively. This suggests that the current hydrodynamic simulations can help predict the advection-dispersion case scenarios of cool seawater discharge.

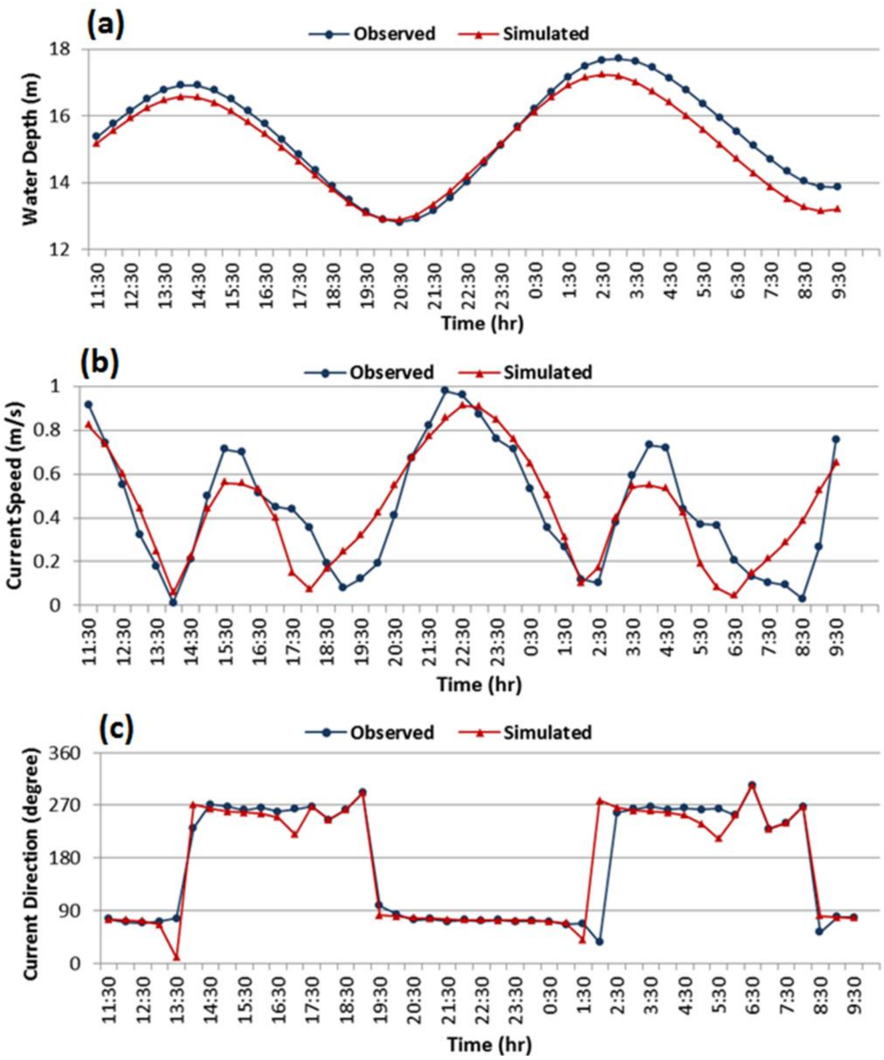

Fig. 4 — Comparison between observed and simulated hydrodynamics (a) water depth (b) current speed and (c) current direction

Scenario 1: Q = 15 m^3/s and ΔT = 5°C

In this case, the HD and AD phenomenon was simulated for withdrawal and discharge of seawater at Q = 15 m^3/s with a temperature difference of 5 °C between seawater plant inlet and outfall (outlet) w.r.t. ambient seawater temperature. The change in the depth of water at inlet and outlet was observed to be negligible w.r.t. present condition as the ratio of discharge (or withdrawal) to the available volume at these locations was very less. The spatio-temporal variations in the temperature drop of the seawaters due to withdrawal and discharge of cooled seawater during the lowest low tides are presented in Fig. 5a, whereas Fig. 5b presents these variations during the highest high tides. Different levels of the legends were used to delineate the variations in the water temperature drop and any temperature drops value below 0.1 °C is considered as ambient temperature. From the dispersion scenario, a temperature drop of 0.2 °C is detected at the seawater plant inlet during the lowest low tidal conditions. This temperature drop does not last long and attains ambient values within one hour, due to the tidal influence. The structure of the thermal plume is mainly driven by the advection. The variation in temperature at the inlet and outlet due to withdrawal and discharge of seawater, respectively are shown in Fig. 5c. At the seawater discharge outlet, the drop in temperature is found to be significant owing to the cool seawater discharge with outlet temperature ranging from 28.0 °C to 29.5 °C with a temperature drop of 0.5 to 2.0 °C w.r.t lowest low and highest high tidal conditions. To study the effect of mixing of water and status of recirculation, the simulated temperature values were recorded at 100 m

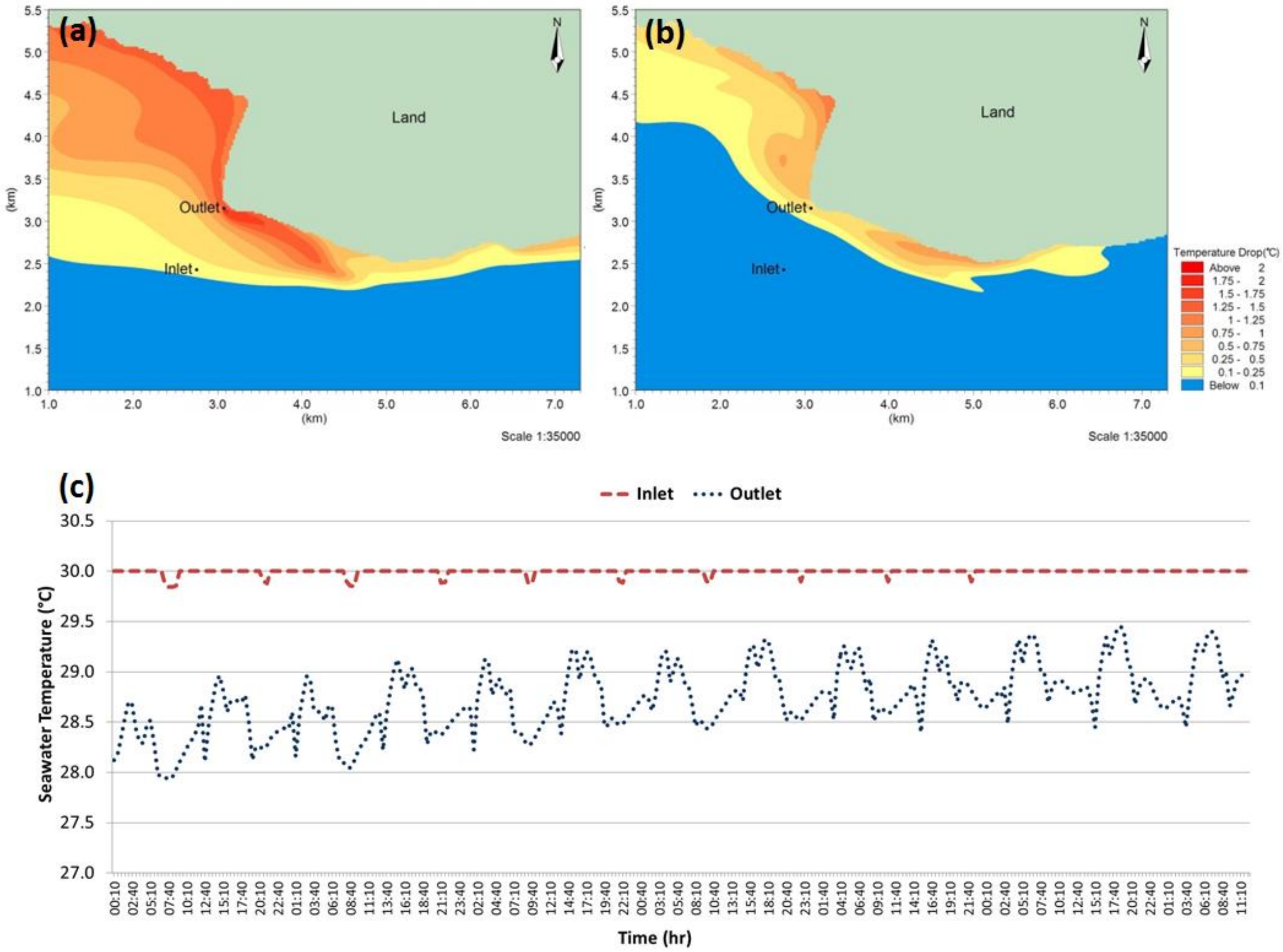

Fig. 5 — Seawater temperature drop for Scenario 1 (Q = 15 m^3/s and ΔT = 5 °C) (a) Lowest low tide (b) Highest high tide (c) Variation in temperature at inlet and outlet

from the seawater outlet. These simulated temperature values were found to range from 28.3 °C to 28.6 °C with a drop between 1.4 °C and 1.7 °C from seawater ambient temperature.

Scenario 2: Q = 10 m^3/s and ΔT = 7°C

In this case, the HD and AD phenomenon was simulated for withdrawal and discharge of seawater at Q = 10 m^3/s with a temperature difference of 7 °C between seawater plant inlet and outfall (outlet) w.r.t. ambient seawater temperature. The result of hydrodynamic simulation shows similar behaviour as Scenario 1 in terms of water depth variation at seawater plant inlet and discharge outlet. The spatio-temporal variations in the temperature drop of the seawaters due to withdrawal and discharge of cooled seawater during the lowest low tides are presented in Fig. 6a, whereas Fig. 6b presents these variations during the highest high tides. From the dispersion scenario, a temperature drop of 0.2 °C is detected at the seawater plant inlet during the lowest low tidal condition as similar to Scenario 1. This temperature drop again attains ambient values within an hour. The variation in temperature at the seawater inlet and discharge outlet due to withdrawal and discharge of seawater respectively, is shown in Fig. 6c. At the discharge outlet, the drop in temperature due to discharge of cool seawater was more prominent as compared to Scenario 1. At the seawater discharge outlet, the drop in temperature is found to be significant owing to the cool seawater discharge with outlet temperature ranging from 27.5 °C to 29.5 °C with a temperature drop of 0.5 to 2.5 °C w.r.t lowest low and highest high tidal conditions. The simulated temperature values at 100 m from the seawater outlet were found to range from 28.1 °C to 28.7 °C with a

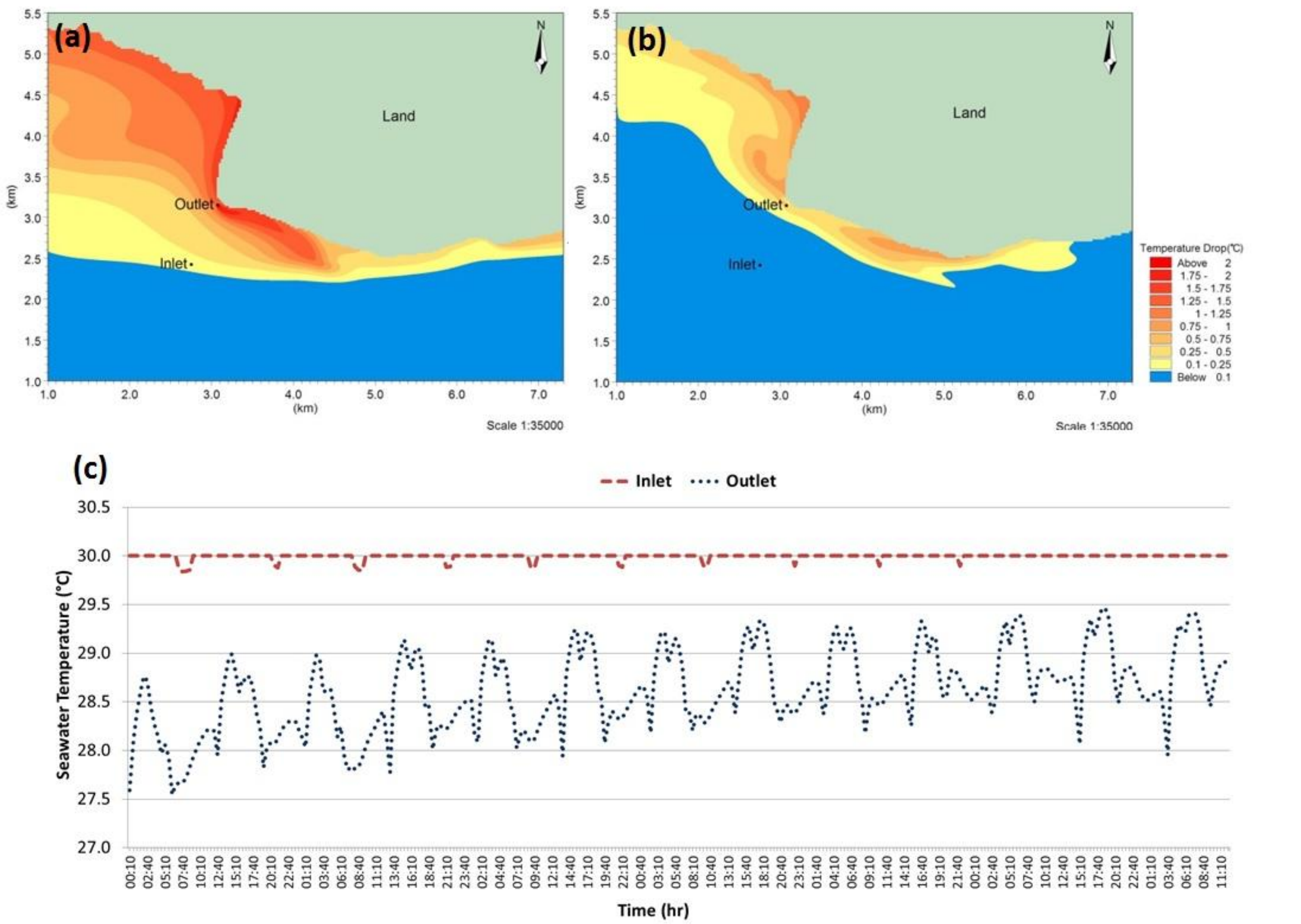

Fig. 6 — Seawater temperature drop for Scenario 2 (Q = 10 m^3/s and ΔT = 7 °C) (a) Lowest low tide (b) Highest high tide (c) Variation in temperature at inlet and outlet

drop between 0.9 °C and 1.3 °C from ambient seawater temperature.

At the present condition, as there is no discharge of cool seawater from the proposed LNG facility, it is difficult to validate the dispersion model against the observed values. The predicted scenarios of cool seawater discharge are assessed to meet the available Environmental, Health, and Safety (EHS) guideline for LNG facilities[23]. The predicted results show that the mixing and cooling of the seawater discharge for both the scenarios are below 1.7 °C of ambient seawater temperature within 100 m of the discharge outlet. Hence, the simulated scenarios comply with the international guidelines to ensure that the cool seawater discharge temperatures are within 3 °C of seawater ambient temperature at all times and at the edge of mixing zone or within 100 m of the discharge point.

Conclusion

The hydrodynamics and advection-dispersion simulations were performed under varying flow rates and temperatures at inlet and outlet from proposed LNG cool seawater discharges. Hydrodynamic simulations were validated using the secondary data on tides and current within the model domain, which was then used to predict the cool seawater discharge under two plant design scenarios. The simulations were carried out under different scenarios, to arrive at the best possible case in order to minimise the adverse impacts on the coastal marine environment. Both the simulated scenario complied with the available EHS guidelines for cool seawater discharges at the LNG outlet as well as at the edge of the mixing zone. Therefore, the plant design scenarios studied in the analysis deems fit for seawater discharges. However, Scenario 2 presents a better choice as it may reduce the pumping power of seawater intake for the LNG facility. Research findings of this paper can be used as an input by Indian regulators and policymakers to develop coherent discharge standards for such cool water discharges into coastal environments.

References

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

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

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

4 Liang, S., Xie, J., Sun, Z. et al., Development of a regional coastal management decision-aided system. Part A: Establishment of an automatic numerical simulation program, *Ocean Coast Manag.,* 96 (2014), pp. 173-180.

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

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

7 Vijay, R., Sardar, V., Dhage, S., *et al*., Hydrodynamic assessment of sewage impact on water quality of Malad Creek, Mumbai, India, *Environ. Monit. Assess.,* 165 (2010), pp. 559–571.

8 Palomar, P., Lara, J.L., Losada, I.J., *et al*., Near field brine discharge modelling part 1: Analysis of commercial tools, *Desalination,* 290 (2012), pp. 14–27.

9 Kumar, D. and Kumar, N., Identification of Optimum Outfall Location for Desalination Plant in the Coastal Waters off Tuticorin, India, *Int. J. Environ. Res.,* 8 (2014), 1, pp. 69–78.

10 Panigrahi, J.K. and Tripathy, J.K., Numerical Simulation of Advection-Dispersion for Monitoring Thermal Plume Re-Circulation in a Shallow Coastal Environment, *Appl. Ecol. Environ. Res.,* 9 (2011), pp. 341–354.

11 Paliwal, R., & Patra, R. R., Applicability of MIKE 21 to assess temporal and spatial variation in water quality of an estuary under the impact of effluent from an industrial estate, *Water Sci. & Technol.,* 63 (2011), 9, pp. 1932-1943.

12 Gupta, A., Vijay, R., Kushwaha, V.K., *et al*., Identification of inlet and outlet locations for cool seawater discharges from an LNG facility, *Int. J. Environ. Res.,* 8 (2014) ,4, pp. 953-960.

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

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

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

16 Shirodkar, P.V., Pradhan, U.K., Fernandes, D. *et al*., Influence of anthropogenic activities on the existing environmental conditions of Kandla Creek (Gulf of Kutch), *Curr.ent Sci.,* 98 (2006), 6, pp. 815-828.

17 Ramaswamy, V., Nath, B.N., Vethamony, P. et al., Source and dispersal of suspended sediment in the macro-tidal Gulf of Kachchh, *Mar. Pollut. Bull.,* 54 (2007), pp. 708–19.

18 Kankara, R.S., Subramanian, B.R. and Sampath, V., Validation of a Deterministic Hydrodynamic Model in the ICZM Framework for Gulf of Kachchh, India, *J Coast Res.,* 235 (2007), pp. 1324–1331.

19 Vethamony, P., Babu, M.T., Ramanamurty, M. V. *et al*., Thermohaline structure of an inverse estuary-The Gulf of Kachchh: measurements and model simulations, *Mar. Pollut. Bull.,* 54 (2007), pp. 697–707.

20 ESRI, ArcGIS 10.2., *Environmental Systems Resource Institute*, Redlands, California, 2013

21 User Guide and Reference Manual for MIKE21, *Reference Manual*, Danish Hydraulic Institute, Agera Alle, Horsholm, Denmark, 2001, pp.70

22 Central Pollution Control Board (CPCB), *India, Pollution Control Acts, Rules, Notifications issued thereunder, New Delhi: CPCB*, Ministry of Environment and Forests. Sixth edition, 2010, pp. 484, 545

23 World Bank Group, *Environmental, Health, and Safety Guidelines for Onshore Oil and Gas Development*, 2007, pp. 22