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BOD–DO modeling and water quality analysis of a waste water outfall off Kochi, west coast of India

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Abstract

Water quality scenarios around an offshore outfall off Kochi were simulated using MIKE21 water quality model, assuming a high Biochemical Oxygen Demand ($\text{BOD} = 50\ \text{mgl}^{-1}$) effluent discharge. The discharge is introduced into the model through an outfall located at a distance of 6.8 km from the shore at a depth of 10 m. Three scenarios were simulated with different discharge rates such as 2, 5 and 10 $\text{m}^3\ \text{s}^{-1}$, with BOD load of 8640, 21,600 and 43,200 kg day^{-1} respectively. Model simulations were carried out to estimate the assimilation capacity of the waters off Kochi for the three discharge rates. The results show that for 10 $\text{m}^3\ \text{s}^{-1}$ effluent discharge, the initial BOD of 50 mg l^{-1} reduced to 3.33 mg l^{-1} at the outfall after 48 h. High BOD values were confined to an elliptical area of $\sim 8\ \text{km}^2$ around the outfall. Based on this, the assimilative capacity of the waters off Kochi in terms of BOD can be estimated as 38,000 kg day^{-1}. It is suggested that offshore waters could be used as a feasible alternative to the Kochi backwaters for the disposal of treated effluent.

Keywords: BOD; Water quality; Kochi

1. Introduction

Kochi (Cochin), situated along the west coast of India, is the largest industrial city of Kerala state. It has a major historic sea port known as Cochin Port located along 10°N latitude in the eastern Arabian Sea (Fig. 1). The Cochin Backwater is a unique estuarine system formed by the confluence of six rivers (Balachandran et al., 2003). It encompasses an area of $\sim 256\ \text{km}^2$ of brackish waters, connected to the Arabian Sea through a narrow opening called the Cochin gut. It is the largest backwater system on the west coast of India and a major tourist destination, primarily due to its scenic beauty and pristine waters. But, of late it is heading towards an ecological degradation because of large-scale pollution, indiscriminate exploitation of its resources, encroachments and reclamation of land. Interestingly, in Cochin, the industries are situated in the hinterland area, bank of the rivers or near the backwaters itself (Sankaranarayan et al., 1986). No industry is discharging directly into the coastal sea; the industrial and municipal wastes are discharged either into the Cochin backwaters or in the upstream area of the rivers. About 16 major industries such as oil refineries, fertilizer plants and chemical industries discharge nearly 0.104 $\text{Mm}^3\ \text{day}^{-1}$ of wastes containing organic matter into the backwaters (Balachandran et al., 2003). The backwaters act as a reservoir, receiving the industrial and urban sewage in the upstream and transfer part of the waste load into the Arabian Sea through the Cochin gut. A large volume of organic matter and pathogenic microorganisms reach the backwaters and at times the sewage quantities are beyond the assimilative capacity of the backwaters. However, the waste load reaching the shallow lagoons of backwaters eventually gets flushed out offshore by tidal currents and river flow during southwest monsoon. Most of the organic particulate matter in the waste water settles down in the lagoon during slack tide, thereby causing eutrophication in the backwaters.

There is an abnormal rise in faecal coliform count and as a result contamination of water is very high in certain areas. Heavy load of organic material released into the backwaters is responsible for the decrease of dissolved oxygen in the backwaters, especially during lean periods when river run-off becomes minimal. The release of waste water into the lagoons causes serious environmental problems, both aesthetic and

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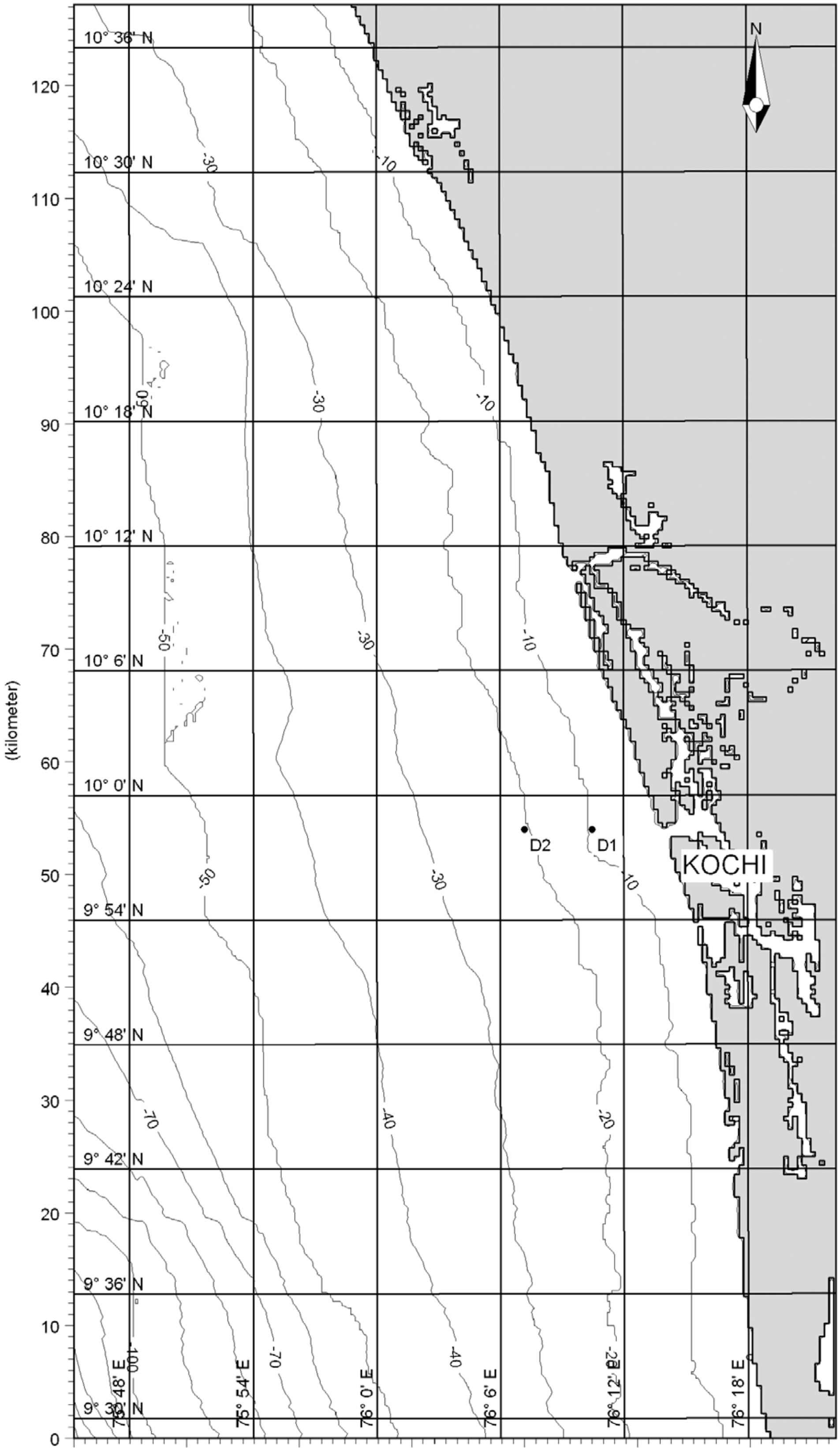


Fig. 1. Study area and model domain off Kochi (depth contours are in metres).

hygienic, in the backwaters. It is obvious that the backwaters are unable to assimilate the waste discharged into it. A study on trace metals of the Cochin backwaters indicated that the backwaters receive a large quantity of phosphate and nitrate from the rivers, but export less than half of it to the coastal waters (Nair et al., 1990). Several studies have indicated that due to decline in the water quality the backwaters are already showing indications of ecological degradation. Fish diseases and mortality has been observed on several occasions in some parts of the backwaters (Nair et al., 1991; Pillai, 1991).

Studies related to estimation of waste assimilative capacity of the coastal/river waters in India are limited to the Ganga–Yamuna rivers (Bhargava, 1983) and Thane Creek, Mumbai (Gupta et al., 2003) only. Most of the studies carried out in the Cochin backwaters are related to biology, fisheries and hydrodynamics. In order to prevent the Cochin backwater system from pollution, it is proposed to seek an alternate option of discharging the treated sewage into the coastal waters away from the lagoons. In this context, a hypothetical case study is taken up by modeling the DO around a marine outfall. The objective of the study is to estimate the waste assimilation capacity of the coastal waters of Kochi with respect to urban and industrial sewage using a 2-D water quality model.

2. Methodology

BOD and DO are the two important water quality parameters required to assess the waste assimilative capacity of the coastal waters (Thomann and Mueller, 1987). DO is affected largely by the waste influx, especially the organic particulate matter, which causes depletion of DO in the process of organic degradation. BOD is employed as a gross measure of the oxygen demanding potential of the effluent. Assimilative capacity varies in accordance with variations in hydrodynamic conditions and other ecological processes. During southwest and northeast monsoon seasons (June–September and November–January/February), the coastal currents are quite high (50–60 cm s^{-1}) and this would increase the assimilative capacity of the area. Therefore, in the present study a transition period (February–March 1999) with weak currents is selected. Parameters such as temperature, salinity, pH, DO, BOD, NO_2–N, NH_4–N, PO_4 and SiO_4 have been collected from near-surface and near-bottom waters from 45 stations in the study region and described in detail by Balachandran (2004). Based on the measured data, the average values of BOD and DO have been estimated as 0.9 and 4.9 mg l^{-1} respectively and these are used in the model as initial values. Time series data on currents measured in March 1999 by mooring Aanderaa (RCM-7) current meters at two locations (10 and 15 m depths; denoted by D1 and D2 in Fig. 1) off Kochi have been used for model validation.

2.1. The model

MIKE21 hydrodynamic (HD) and water quality (WQ) modules were used to simulate tides, currents, DO and BOD off Kochi for estimating the assimilative capacity of the region. It is a standard modeling software used for advanced numerical modeling of HD, WQ, waves, sediment transport and ecological modeling (MIKE21 user guide and reference manual, 2001). The model provides a transient solution for shallow water bodies and it can accommodate irregular coastline, complex bathymetry and open boundaries. This model has been widely used for modeling the hydrodynamics, transport of pollutants, thermal plumes and water quality parameters in coastal waters. The model has been applied to simulate tidal residual circulation, salinity variability and storm surge studies (Madsen and Jacobsen, 2004; Babu et al., 2005; Chubarenko and Tchepikova, 2001). The water quality module (WQ) takes into account the degradation of dissolved, suspended and settled organic material of nutrients and chlorophyll by applying the following DO balance equation:

B_1	Sediment oxygen demand
C_s	Saturation concentration of DO
K_2	Re-aeration constant
NH_3	Ammonia
K_3	BOD decay rate
K_4	BOD decay rate for nitrification
P	Photosynthesis
R_{20}	Respiration
T	Temperature
Y_1	Yield factor for DO used for nitrification
θ_2	Temperature coefficient for respiration
θ_3	Temperature coefficient for BOD decay
θ_4	Temperature coefficient for nitrification

$$\begin{aligned}\frac{\mathrm{dDO}}{\mathrm{d}t} &= K_2(C_s-\mathrm{DO})-K_{d3}\mathrm{BOD_d}\theta_{d3}(T-20)\\ &\quad -K_{s3}\mathrm{BOD_s}\theta_{s3}(T-20)-K_{b3}\mathrm{BOD_b}\theta_{d3}(T-20)\\ &\quad -Y_1K_4\mathrm{NH_3}\theta_4(T-20)-R_{20}\theta_2(T-20)+P-B_1\end{aligned} \tag{1}$$

where subscripts d, s, and b represent dissolved, suspended or settled

In the present analysis a simple BOD–DO model formulation of WQ model has been used considering only the dissolved BOD. Hence the equation can be simplified as follows:

$$\begin{aligned}\frac{\mathrm{dDO}}{\mathrm{d}t} &= K_2(C_s-\mathrm{DO})-K_{d3}\mathrm{BOD_d}\theta_{d3}(T-20)\\ &\quad -R_{20}\theta_2(T-20)+P-B_1.\end{aligned} \tag{2}$$

The model calculates the oxygen balance without taking into account the nutrients or the suspended part of BOD; the DO depletion is directly related to the dissolved BOD in the water column.

2.2. Model domain and bathymetry

The model domain has been selected with the southern boundary lying along 9°29′N and the northern boundary along 10°37′N (Fig. 1). The maximum depth in the model domain is 120 m in the southwestern boundary. The eastern boundary of the domain is kept along the coastline, where the depth is zero. The depth values have been digitized from the bathymetry chart of the region east of 76°46′E. In order to carry out simulation, the domain of the region has been divided into 170 × 319 elements with a grid size of 400 m × 400 m, thereby covering a distance of 68.0 km towards offshore and 127.6 km along the coast.

2.3. Model parameters

The zonal (u) and meridional (v) components of the currents were derived from the measured currents of March 1999 and used for the validation of model results. Calibration of the model has

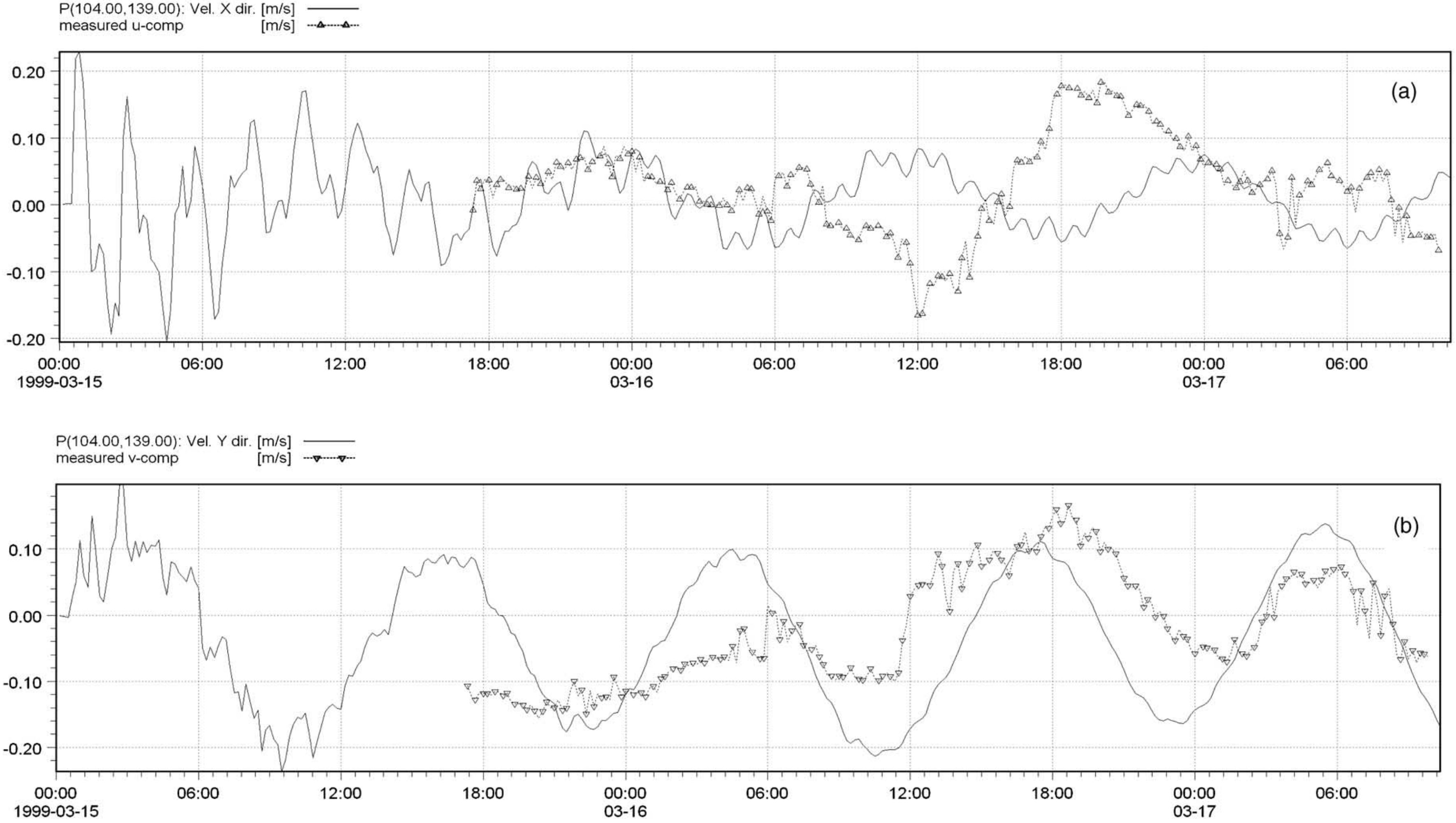


Fig. 2. Comparison between measured and modeled currents, (a) *u*-component and (b) *v*-component (dotted lines indicate measured currents and solid line modeled currents).

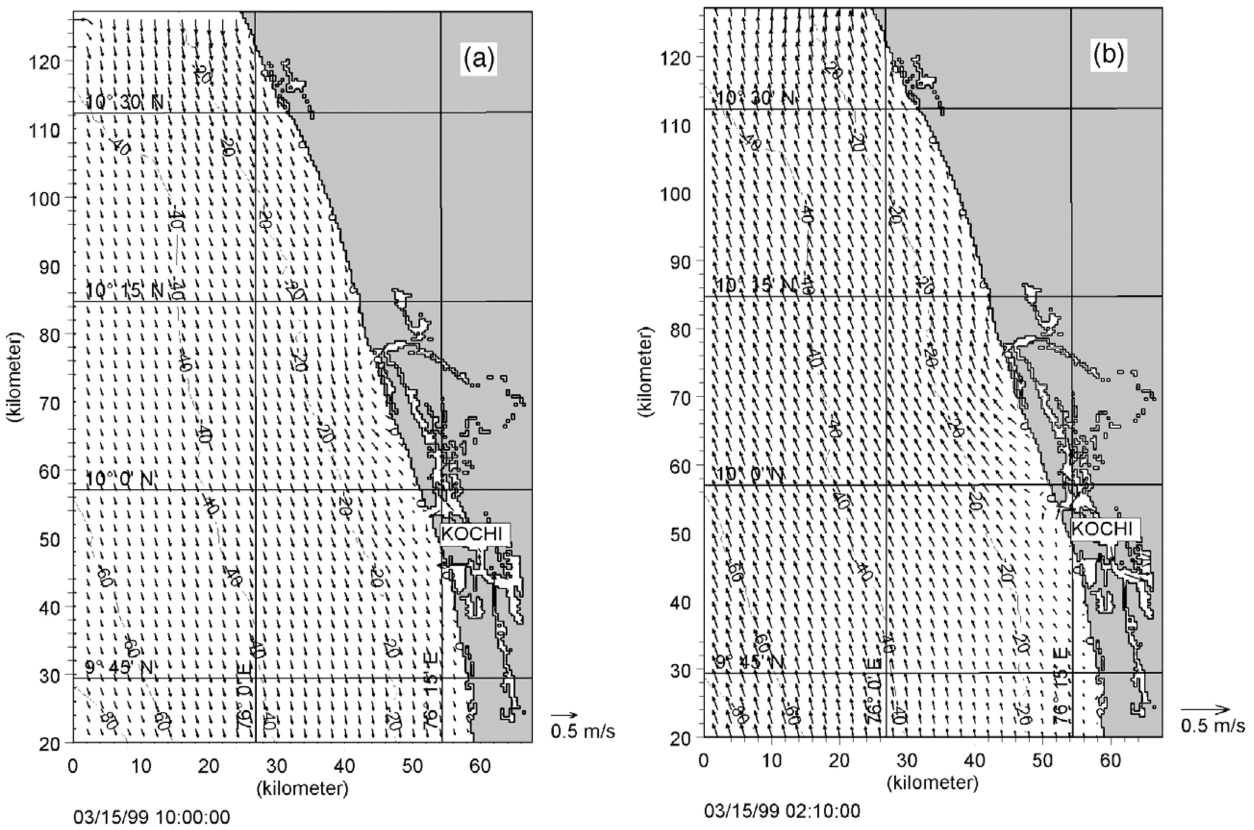


Fig. 3. Typical model simulated current patterns off Kochi during (a) ebb and (b) flood tides.

been carried out using the frictional stress at the bottom (t_b). The southern, western and northern boundaries are kept open and the water level variations (h) at these boundaries are prescribed based on the predicted tides given in the Indian Tide Tables (Anonymous, 1999). Tides from these Tables are also used to provide the initial condition. The wind speed and direction and temperature flux at the surface are given as input based on the measured data.

The measured currents during March 1999 exhibited tidal oscillation in the southeast–northwest direction. The u-components vary between -0.16 and 0.18 m s^{-1} and v-components between -0.15 and 0.16 m s^{-1}. Though the simulated currents show variations in the same range as the measured currents (Fig. 2a and b), a phase shift is noticed in the current components. In general, the currents flow parallel to the coast in a northward or southward direction depending on the tide. Typical current patterns during flood and ebb tides are given in Fig. 3a and b. Average values of BOD and DO measured in the vicinity of the outfall point (0.9 and 4.9 mg l^{-1}, respectively) have been used as the initial and boundary values. A constant decay rate of 0.03 day^{-1} is assumed for BOD (Tyagi et al., 1999). The primary productivity in the Arabian Sea varies between 770 and 1782 mg C m^{-2} day^{-1} (Prasanna Kumar et al., 2002). From this range the minimum value of primary productivity can be estimated as 1.7 gO_2 m^{-2} day^{-1}. This value is used for case2 model runs. Respiration rate was calculated as a percentage of the maximum rate of photosynthesis. Lower respiration rates of the order of 1.5% are estimated in regions of low primary productivity (Kromkamp and Peene, 1995). Since the study area is one of the highly productive regions of the eastern Arabian Sea, a constant value of 0.425 g O_2 m^{-2} day^{-1} (25% of the primary productivity) is assumed for respiration rate.

3. Results and discussions

Simulation of BOD and DO were carried out for two cases. In case 1, DO production through photosynthesis is excluded and in case 2 average DO is included. These two different situations were studied to assess the variability of BOD in the absence of DO production through photosynthesis. In both cases, model runs were carried out with three different scenarios assuming hypothetical

Table 1
BOD maximum and DO minimum obtained at the outfall for different discharge rates (effluent BOD=50 mg l^{-1}; outfall depth=10 m)

Discharge quantity (m^3 s^{-1})	BOD load (kg day^{-1})	BOD maximum (mg/l) at the outfall (initial BOD=0.9 mg l^{-1})		DO minimum (mg/l) at the outfall (initial DO=4.9 mg l^{-1})	
		Case 1	Case 2	Case 1	Case 2
2.0	8640	1.33	1.33	4.63	4.82
5.0	21,600	2.06	2.06	4.53	4.71
10.0	43,200	3.33	3.33	4.36	4.53

effluent quantities of 2, 5 and 10 m^3 s^{-1} (Table 1). BOD load corresponding to each discharge rate is introduced into the model as a continuous flow at the outfall (grid point D1: 113,135) where the water depth is 10 m (Fig. 1).

3.1. CASE 1: without DO from photosynthesis

Model runs were carried out to simulate the variation of DO at the outfall assuming a hypothetical situation in which no oxygen is produced through photosynthesis. The runs were continued for a period of 7 days with discharge rates of 2, 5 and 10 m^3 s^{-1} having a BOD of 50 mg l^{-1}. BOD maximum and DO minimum obtained at the outfall for the above conditions are given in Table 1 and their variations in Fig. 4a and b. Oscillations in BOD and DO values are seen in phase with the tidal variations. The initial value of DO (4.9 mg l^{-1}) decreases to 4.36 mg l^{-1} after 7 days for an effluent flow rate of 10 m^3 s^{-1}. The DO values exhibit continuous decrease due to the absence of DO input. BOD values show oscillation in tune with the north–south oscillation of coastal currents and BOD increases upto 3.33 mg/l from the ambient level of 0.9 mg l^{-1}. The spread and concentration of BOD obtained around the outfall for the three scenarios after 48 h of discharge are given in Fig. 5a–c. A plume of higher BOD value is seen at the outfall advecting towards south, parallel to the coast with a meriodional axis of about 6–8 km, spreading over an area of 8 km^2. BOD at the outfall increased proportionately with higher discharge quantities (Table 1), but the effective area of higher BOD (BOD > 0.9) remained the same.

3.2. CASE 2: with DO input through photosynthesis

In order to study the variation of BOD in the presence of DO input from photosynthesis, an average DO of 1.7 g O_2 m^{-2} day^{-1} has been introduced in the model based on the primary productivity observations (Prasanna Kumar et al., 2002). Temporal variations of BOD and DO at the outfall location for a period of 7 days are given in Fig. 6a and b. Simulation results show that BOD variation is the same as in case 1 (Figs. 4a and 6a), but the DO level increased due to the input of additional DO into the system (Table 1).

The maximum level of BOD for sea water type 2 (SW2) designated for bathing and commercial fisheries is 3.0 mg l^{-1} (Central Pollution Control Board of India, CPCB, 1993). Since Kochi is an active fishery zone, it would be healthier to keep the BOD level at SW2 itself. In the present analysis, the maximum level of BOD for a discharge of 10 m^3 s^{-1} at 10m depth after 7 days is about 3.33 mg l^{-1}. From the variation of BOD for various discharge scenarios, it is estimated that the maximum discharge that can be allowed off Kochi is 8.8 m^3 s^{-1} so that SW2 water quality criteria of 3 mg l^{-1} would be satisfied. Based on the above calculations, the assimilative capacity of approximately 8 km^2 area of the coastal waters off Kochi can be estimated as 38,000 kg day^{-1} of BOD load for the hydrodynamic conditions that prevailed during March 1999.

4. Conclusions

We have selected a transition season in terms of hydrodynamic conditions to study the water quality around an effluent outfall off Kochi. A simple BOD–DO WQ model is used to simulate the BOD–DO fields. The model results indicate that if the effluent is discharged at 10 m depth off Kochi, the DO available in the area of about 8 km^2 can assimilate BOD load up to 38,000 kg day^{-1}, keeping SW2 water quality criteria of BOD 3.0 mg l^{-1}. Uncertainties due to several factors, including interaction of water quality parameters with ecological processes make the estimation of assimilative capacity a demanding task. In the model, constant values are assumed for

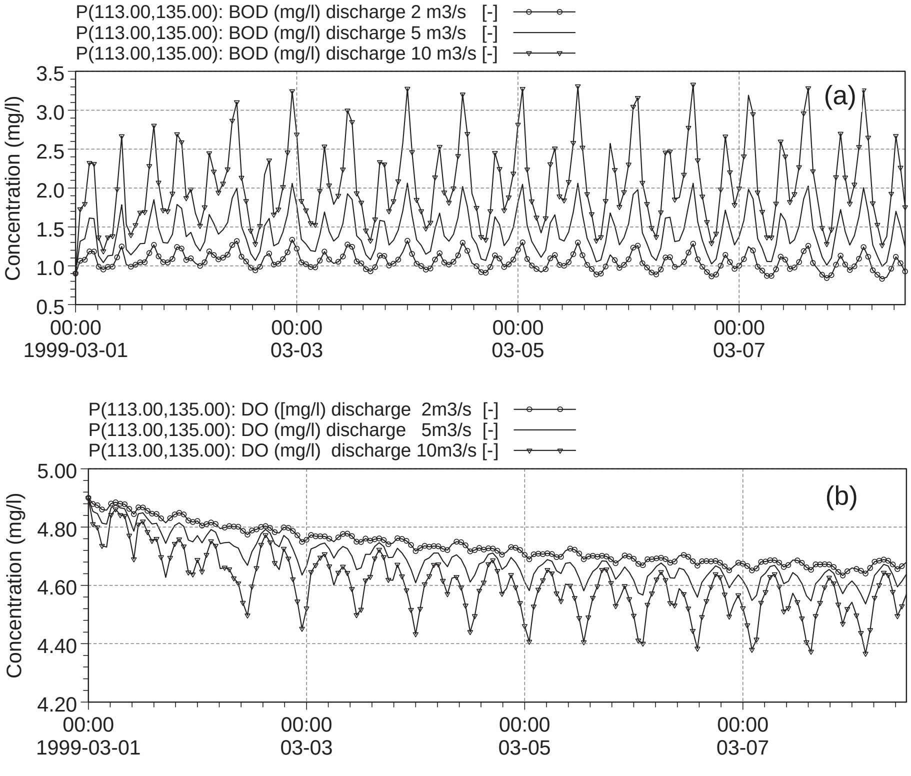
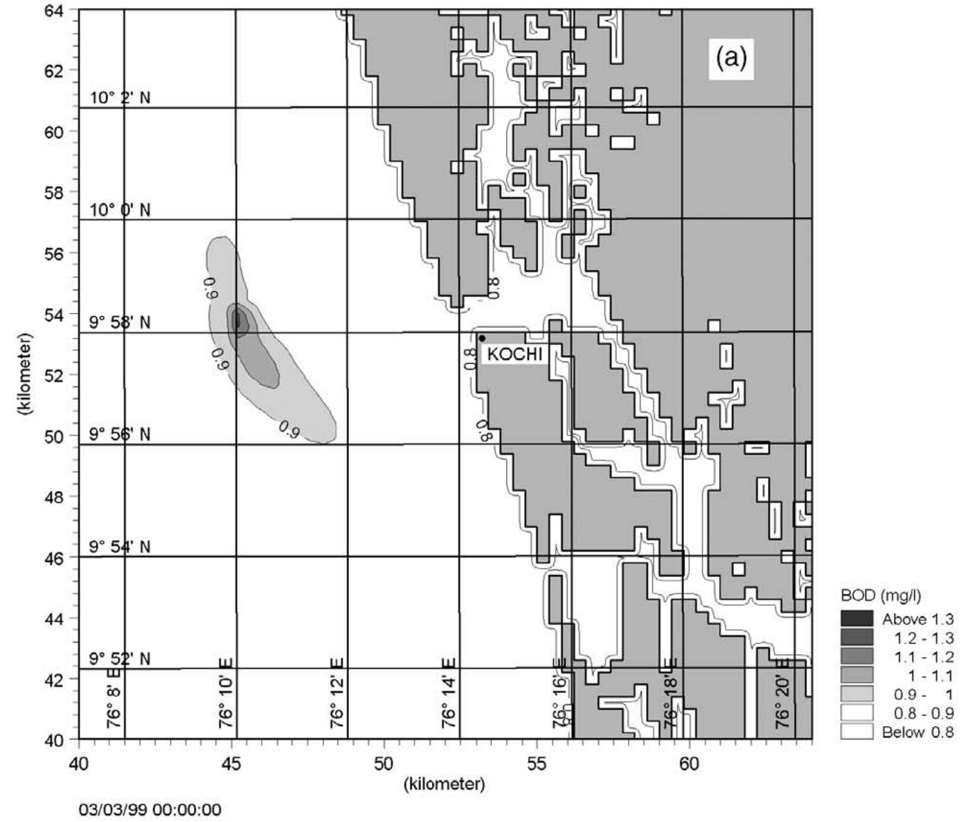


Fig. 4. Variation of (a) BOD and (b) DO at the outfall for case 1: for different discharge rates without oxygen input through photosynthesis (outfall depth = 10 m).



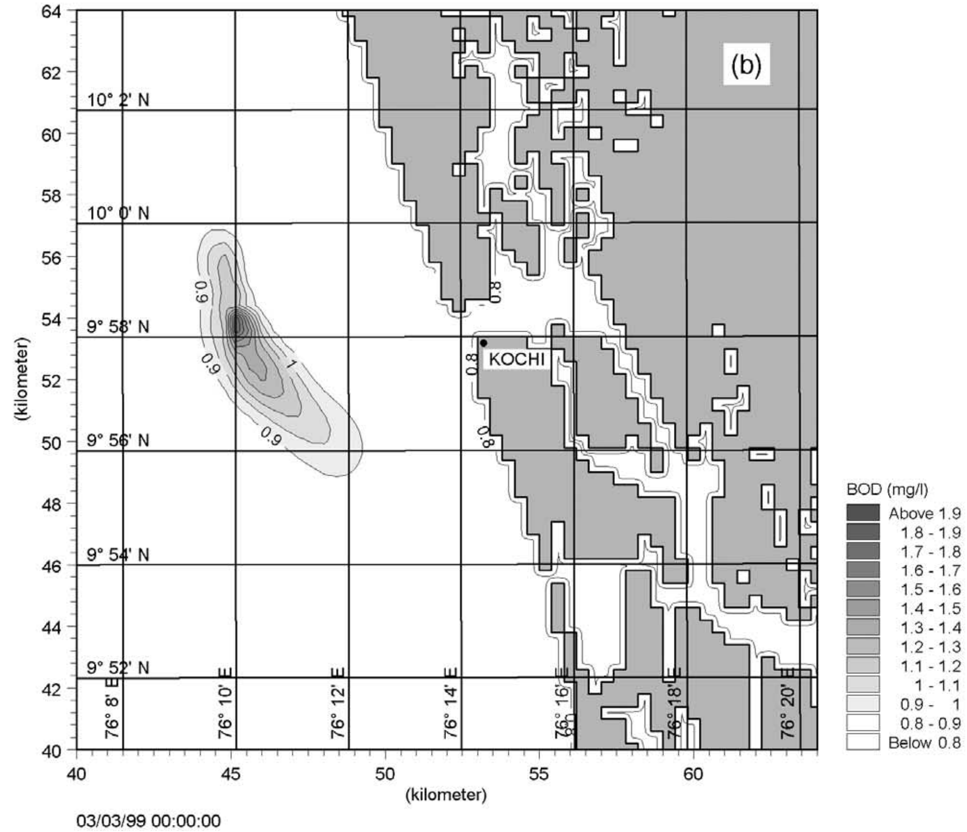


Fig. 5. Distribution of BOD (mg l^{-1}) after 48 h discharge at the rate of (a) 2 m^3 s^{-1}, (b) 5 m^3 s^{-1} and (c) 10 m^3 s^{-1} for case 1.

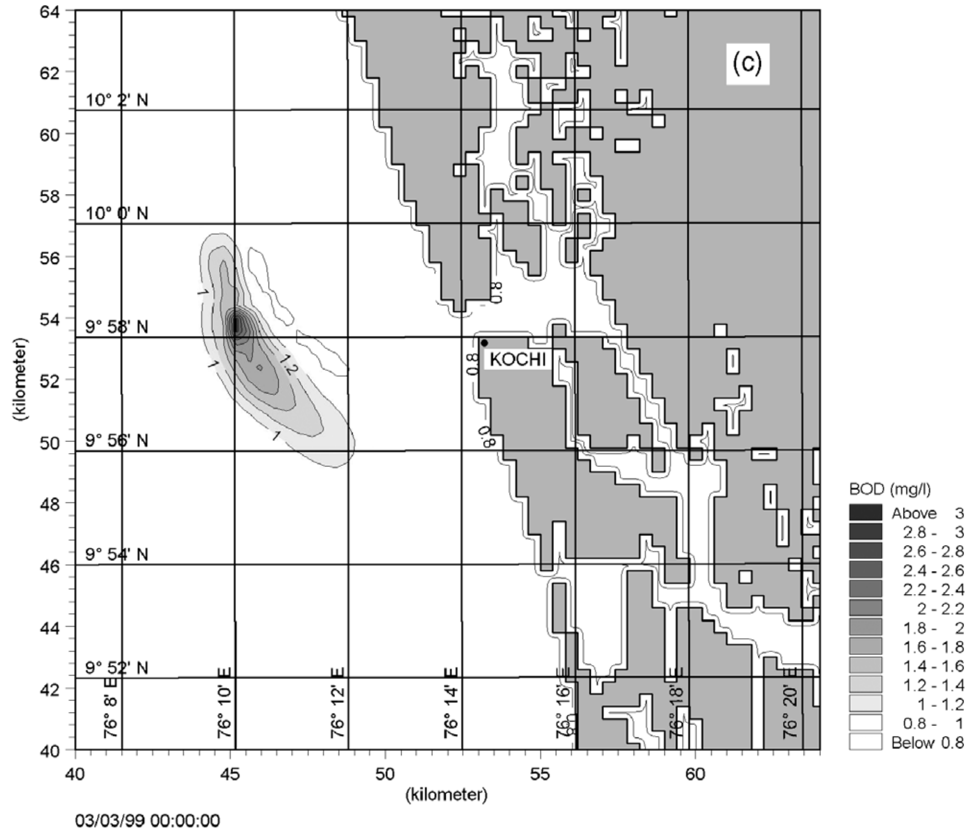


Fig. 5 (*continued*).

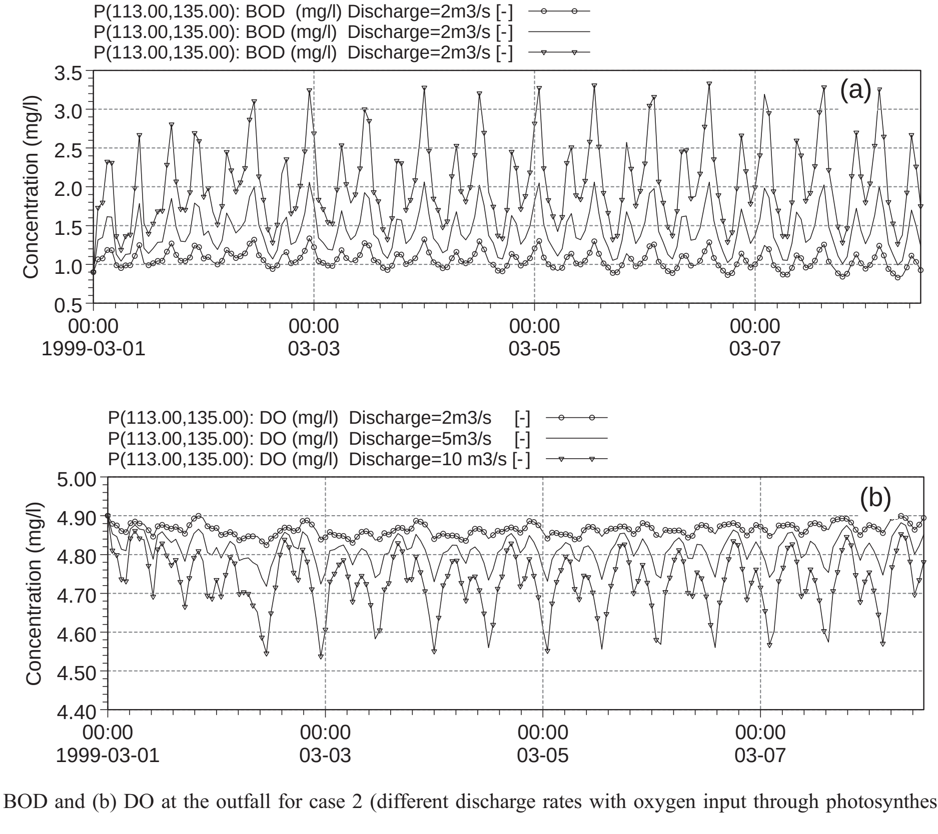


Fig. 6. Variation of (a) BOD and (b) DO at the outfall for case 2 (different discharge rates with oxygen input through photosynthesis, outfall depth = 10 m).

respiration and BOD decay rate because of lack of field data. BOD and DO values could not be validated in the field, as the assumed situation of high BOD outfall is a hypothetical one. Also, it is necessary to include the effect of nutrients for fine-tuning the assimilative capacity estimates. In spite of all these uncertainties, the model results can be used to provide an approximate estimate of the BOD and DO field in the event of an outfall discharge with excess amount of BOD.

An important aspect to be considered while discharging organic waste into the coastal sea is eutrophication of the coastal waters as the sewage contains significantly high amount of nutrients. Recently there have been several events of red tide and fish mortality at different locations along the southwest coast of India. These can be minimized through proper pre-treatment of the effluent before releasing it into the sea. Also a necessary balance is to be attained between the level of industrialization/urbanization and the exploitation of coastal zone environment so that the coastal ecosystem can be preserved. It can be achieved by adopting a suitable waste load allocation strategy for effluent disposal in the ecologically fragile zones along the Indian coasts through the application of water quality modeling coupled with field measurements. The model results could act as a guide to help the managers establish the limits for pollution load that can be released at any location. It can be achieved by estimating the assimilative capacity of the coastal waters and the inter-linked water bodies.

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References

Anonymous. Indian Tide Tables, Survey of India, Dehra Dun, India; 1999.

Babu MT, Vethamony P, Desa Ehrlich. Modelling tide-driven currents and residual eddies in the Gulf of Kachchh and their seasonal variability: a marine environmental planning perspective. Ecol Model 2005;184: 299–312.

Balachandran KK. Does subterranean flow initiate mud banks off the southwest coast of India. Estuar Coast Shelf Sci 2004;59:589–98.

Balachandran KK, Joseph Thresiamma, Nair KKC, Nair Maheswari, Joseph PS. The complex estuarine formation of six rivers (Cochin backwater system) on west coast of India)—Distribution of trace metals. The second international symposium on the management of large rivers for fisheries—sustaining livelihoods and biodiversity in the new millennium; Phnom Penh, Kingdom of Cambodia, February, 2003.

Bhargava DS. Most rapid BOD assimilation in Ganga and Yamuna rivers. J Environ Eng, ASCE 1983;109:174–87.

Chubarenko Irina, Tchepikova Irina. Modelling of man-made contribution to salinity increase into the Vistula Lagoon (Baltic Sea). Ecol Model 2001; 138:87–100.

CPCB (Central Pollution Control Board). Criteria for classification and zoning of coastal waters, Coastal Pollution Coastal Series, COCOS/6/1993, CPCB, New Delhi, India; 1993.

Gupta Indrani, Shivani Dhage, Chandorkar AA, Anjali Srivastav. Numerical modeling for Thane creek. Environ Model Softw 2003;19(6):571–9.

Kromkamp J, Peene J. Possibility of net phytoplankton primary production in the turbid Schelde Estuary (SW Netherlands). Mar Ecol Prog Ser, MEPS 1995;121:249–59.

Madsen Henrik, Jacobsen Flemming. Cyclone induced storm surge and flood forecasting in the northern Bay of Bengal. Coast Eng 2004;51:277–96.

MIKE21 user guide and reference manual. Horsholm, Denmark: DHI, Danish Hydraulic Institute; 2001.

Nair SM, Balchand AN, Nambisan NPK. Metal concentrations in recently deposited sediments of Cochin backwaters, India. Sci Total Environ 1990; 97/98:507–24.