Research Article

# Water quality assessment of Loktak Lake, Northeast India using 2-D hydrodynamic modelling

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## Abstract

The paper comprises of an application of a multi-faceted physically based two-dimensional (2D) hydrodynamic model to simulate the transport phenomena of Loktak Lake, including the water quality of Loktak Lake, for which there is consensus that it is deteriorating due to river discharge from sub-catchments carrying sewage loads, soil sediments and agricultural fertilizers, and therefore, has emerged as a serious environmental concern. Accordingly, the study attempts to understand the overall environmental quality of the Loktak system and in particular simulate Loktak Lake water quality (state) variables by coupling through MIKE 21 ECO Lab. The model simulated dissolved oxygen and biochemical oxygen demand throughout the lake.

**Keywords** Hydrodynamic model · Ecological model · MIKE 21 · Loktak Lake · Northeast India

## 1 Introduction

Wetlands can be considered as the most productive ecosystems on the Earth, which provides many ecosystem services. However, they are sensitive to ecological conditions and adaptive systems. Wetlands display various multiplicity rendering to their geographical location, water regime, soil and sediment characteristics, genesis, and dominant species. The worldwide areal extent of the wetland ecosystem ranges from 748, 100,000 to 778,100,000 ha. Globally, wetland ecosystems provide an assessed monetary value of nearly US$15 trillion per year. India, with its varied climatic conditions and topography, supports unique and diverse wetland habitats. The tremendous rise of population and uncontrolled development have led to major pollution impacts on wetlands, affecting the entire ecosystem.

Loktak Lake, a Ramsar designated, is an internationally important wetland system which needs proper management planning. Acknowledging the ongoing ecological modifications, it has been listed in the Montreaux record

[1]. The lake is well known for floating vegetation, popularly known as "Phumdis". An adjoining 40 km$^2$ extent of Phumdis, known as Keibul Lamjao National Park (KNLP) is the only floating national park in the world [2]. This national park is the solitary natural home to the endangered and endemic species of Manipur's brow-antlered deer, commonly known as Sangai. This lake endures rich biological diversity with 132 species of plants and 428 species of animals. It also provides irrigation to about 32,400 ha agricultural area, source of income to about 8,700 fishermen, and supports hydro-power generation [3]. The annual benefits from the lake can be estimated to about 2% of the state's gross domestic product.

Ecological restoration of a wetland is of enormous environmental asset and scientific interest these days. Hydrodynamic (HD) assessment is essential for ecological restoration as it influences the chemical and biological processes. HD variables such as flow magnitude, travel time and degree of mixing affect the assimilative capacity of lakes, thereby impacting the ecological condition of lakes. Therefore, HD assessment plays a significant role

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in the conservation and management of lakes. Physically-based models have emerged as an essential tool in today's planning and management strategy.

HD models may be categorized into one, two and three-dimensional models. In 1D HD models, a river channel is generalized into a number of cross-sections perpendicular to the centreline of a channel and the floodplain is considered as extended cross-sections. Some of the well-known known 1D HD models include MIKE 11 [4], ISIS [5] and HEC-RAS [6]. Some studies which employed MIKE 11 HD model include [7, 8]. On the other hand, 2D HD models are able to provide results not only regarding the spatial information and depth level but also the flow velocities and dynamics of the system over a modeller defined time frame. Hence, 2D models are extensively used among researchers. In the 2D model, modelling fluid is divided into cells. In these cells, each variable is assumed to be constant. All the input and output parameters are assumed to be uniform within a cell. Some of the well-known 2D models are MIKE 21 [9], LISFLOOD-FP [10], TELEMAC-2D [11], SMS [12], Delft FLS [13] and SOBEK [14]. In the 2D model, the vertical variation of flow velocity is usually neglected for two-dimensional approximation. Thus, 2D models are adequate for shallow lakes generally. MIKE 21HD simulates flows and fluctuations in water level according to change of forcing functions in bays, estuaries, coastal areas and lakes. This module has been used for HD assessment in various case studies [15, 16]. However, 3D HD models involve complete representations of flow processes in all three-dimensions. They are capable of providing more accurate results, but also accompanied by complex model structures and time-consuming. Some of the extensively used 3D models are MIKE 3 [17], FLUENT (Fluent Incorporated Company) [18], Delft 3D [13].

Water quality models can be used for simulating and predicting environmental pollution in water resources. Water quality models range from simple theoretical to experimental and to physically based. The selection of model type to be employed for a study area is highly influenced by data availability and the objective/s of the study. Streeter and Phelps model was developed as the first water quality model for analysing water quality of Ohio state located in US [19]. Subsequently, there have been various upgradation in the development of water quality models such as WASP [20], QUAL [21], QUASAR (Quality Simulation Along Rivers) [22], MIKE [23] and EFDC (Environmental Fluid Dynamics Code) [24].

The primary objective of this research is to develop 2D HD model of Loktak Lake using MIKE 21 HD modelling platform and to assess environmental quality. This paper presents a leading attempt for assessment of Loktak Lake based on physically based model. The water quality of the lake is deteriorating as a result from river run-off from sub-catchments carrying sewage loads, soil sediments and agricultural fertilizers, which are of serious environmental concern. The study also attempts to study environmental quality and simulate water quality (state) variables by coupling through MIKE 21 ECO Lab for Loktak Lake. Also, this study presents first attempt to study the water quality of the lake through modelling approach. The paper comprises of the location and climatology of study area, followed by a brief description on methodology and results. The paper concluded with output results and its analysis.

## 2 Study area

The current study area is Loktak Lake, a fresh-water wetland system, located in Manipur, Northeast India (Fig. 1). The lake has been designated under Ramsar Convention due to its international importance. Also, it is listed under Montreaux record due to its ecological modifications [1]. The lake has a catchment area of about 5,040 $km^2$ while the lake extends to around 287 $km^2$. The land use land cover type of the catchment area has been categorised as forest, degraded forest, settlement, agricultural areas, jhum cultivation areas, Phumdis and water bodies. The pH of top layer soil ranges from 4.5 to 5.2 as indicated by field study. The annual average rainfall is 1392 mm with an approximate 150 rainy days [25]. The average temperature varies from about 24 °C (summer) to 14 °C (winter). Hydrologically, the catchment consists of nine sub-catchments namely, Khuga, Western, Nambul, Imphal, Kongba, Iril, Thoubal, Heirok and Sekmai. However, Sekmai and Heirok sub-catchments no longer contributes during lean season due to the construction of barrage for irrigation purposes.

## 3 Materials and methods

### 3.1 Brief description of models

#### 3.1.1 MIKE 21 HD

MIKE 21[9] is a professional hydrodynamic flow transport modelling platform and offers capability ranging from flow simulation, sediments, waves and water quality in estuaries, seas, bays, coastal areas, lakes and rivers. It is particularly useful for problem domain comprising of shallow water bodies where stratification can be neglected. MIKE 21 HD simulates flows and fluctuations of water level according to change of forcing functions in bays, estuaries, lakes and coastal areas. The flows and water levels of the study area are determined on a rectangular grid by providing certain information such as bathymetry, wind data and boundary conditions. The effects of sources and sinks such

**Fig. 1** Location map of Loktak Lake, bathymetry and its source (S1:Thongjaorok; S2:Awang Khujairok; S3:Nambo; S4: Nambul; S5: Kongba; S6: Imphal; S7:Thoubal and Iril) (M1:KLNP; M2:Sendra; M3:Ningthoukhong; M4:Nambul; M5:Thanga; M6:Ithai)
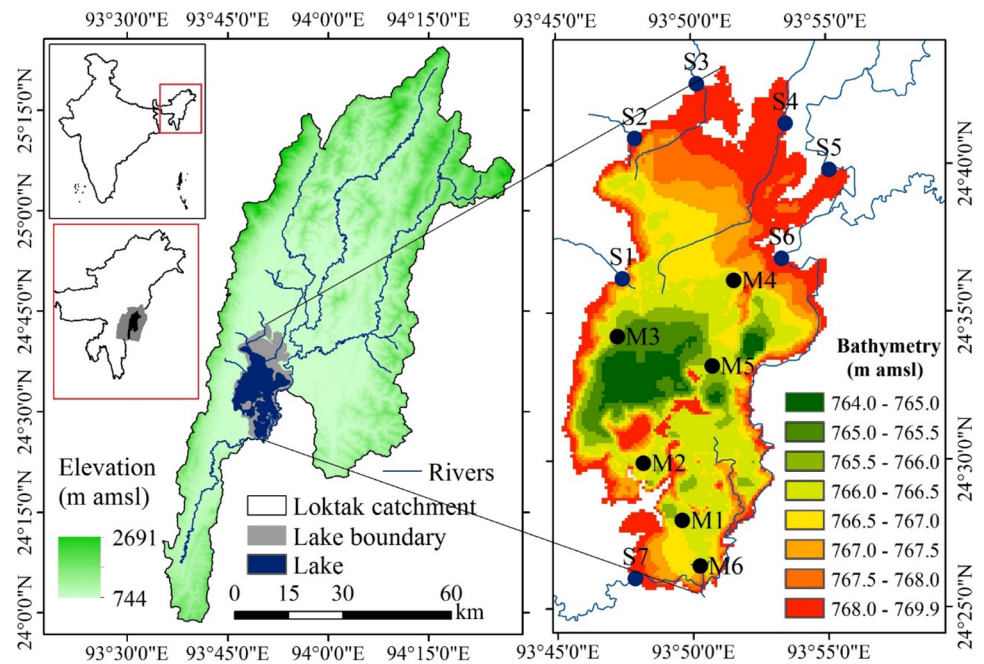
as river discharge, soil water recharge, precipitation, and evaporation are included in the hydrodynamic equations. Further details of MIKE 21 HD module can be found in the literature [9].

### 3.1.2 MIKE 21 ECO Lab

ECO Lab is a module in MIKE, used to model aquatic ecosystem to simulate eutrophication, ecological conditions, water quality and heavy metal distribution. MIKE 21 ECO Lab module can be employed for water quality modelling through solving a set of equations expressing the interactions of various processes involved in organic matter degradation, leading to change of oxygen level and nutrients content in estuaries, lakes, coastal areas and bays. The ECO Lab module is coupled to the hydrodynamic (HD) module by advection–dispersion process. Further details of MIKE ECO Lab can be found from the literature [26].

### 3.2 Models set up

A 2D hydrodynamic and water quality model for Loktak Lake was developed for the time period 2015–2016. MIKE 21 [9], a physically based models of depth-averaged hydrodynamics and water pollution was employed for developing the model. An assumption has been made that there is no interference of Phumdis on the hydrodynamics of the lake. The impact of river discharges from sub-catchments carrying sewage loads and agricultural fertilizers was modelled by considering dissolved oxygen (DO) and biochemical oxygen demand (BOD) which are two important

parameters. Rivers draining into the lake represented as S1 to S7 were modelled using MIKE 11 ECO Lab. Daily flows and water quality variables were simulated for the time period January 2011 to December 2016. Details can be found from the previous work, Khwairakpam et al. [27, 28]. The models were based on field data collection, visual inspections and observed data procured from Loktak Development Authority (LDA) and State Pollution Control Board (SPCB), Manipur.

Loktak Lake and neighbouring wetlands covering an area of about 324 km$^2$ was considered for hydrodynamic model domain. The hydrodynamic model was developed using MIKE 21 HD module. The model domain composed of 18,000 cells and interconnected through a rectangular grid of 180 m. Bathymetry employed in the model is shown in Fig. 1. The map has contours at 0.5 intervals between 764 and 769.9 m amsl. Figure 2 shows flowchart of the models set up employed in the study. Initially, hydrological models of nine sub-catchments namely Khuga, Western, Nambul, Imphal, Kongba, Iril, Thoubal, Heirok and Sekmai using hybrid SHE SWAT were developed. Details can be found in the previous work [27, 28]. Daily discharge simulated from the models were specified as inflows to Loktak Lake. The seven inflow points of the model represents the upper boundary conditions of the lake. The seven inflow points to the lake specified as S1, S2, S3, S4, S5 and S6 and S7 represents discharge from various rivers are shown in Fig. 1. Considering unavailability of present data, daily observed water levels at KLNP station for the time period 2002 to 2003 were used to specify the lake model middle reach boundary condition accounting for hydro-electric
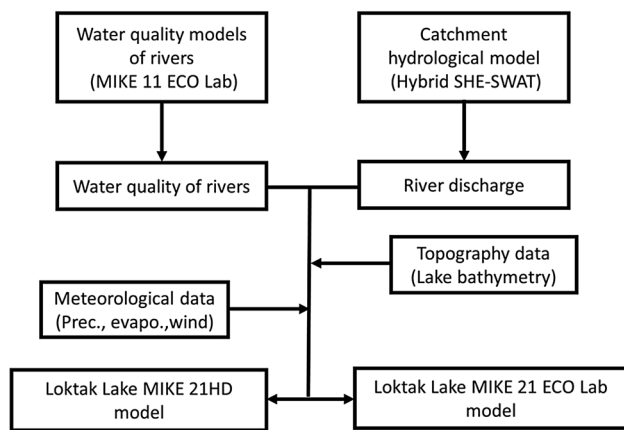
**Fig. 2** Flowchart of the model set up

power generation. The KLNP station data was obtained from LDA through personnel communication. Gridded daily precipitation data (2015–2016) was procured from the Indian Meteorological Department (IMD). Wind data (2015–2016) used in the model was downloaded from the National Oceanic and Atmospheric Administration.

For simulating water quality (state) variables of the lake, MIKE 21 ECO Lab module was incorporated. A predeveloped template in the module were selected for the modelling purpose. During initial stage, EULER (Euler or Linear solution) was used due to comparatively lesser computing time. Later on, RKQC (Fifth order Runge–Kutta with Quality Control) was specified. The time step specified in the model is 60 s. Observed DO and BOD for the time period 2015 to 2016 were procured from SPCB. Simulated water quality of rivers were specified as boundary condition. Water quality (state) variables of rivers were simulated using MIKE 11 ECO Lab in the previous work, Khwairakpam et al. [28] [27]. A field sampling was also done for six monitoring stations M1, M2, M3, M4 M5 and M6 as shown in Fig. 1. The sampling was conducted for two different time periods, during lean (25/1/2016 to 31/1/2016) and rainy (5/8/2016 to 15/8/2016) seasons. Water quality (state) variables observed during field sampling were DO and BOD. DO level was observed using dissolved oxygen probe and BOD level was analysed using five day test for BOD. The model simulated daily DO and BOD for the time period 2015 to 2016.

### 3.3 Calibration and validation of Loktak model

Initially, MIKE 11 ECO lab models for rivers draining into the Loktak Lake were calibrated for the time period 2011 to 2015 using observed water quality data obtained from SPCB, Manipur. Dispersion coefficient (D) and reaeration constant (K) for the rivers were calibrated. The values for

D and K varies from 3 to 7 $m^2 s^{-1}$ and 0.3–0.8 respectively. The models were validated using observed data collected during field survey. Filed sampling was done at every every 1 km of rivers. Models were validated for dry (25–31 January 2016) and wet (5–15 August 2016) seasons. Details can be found from the previous work [27].

The lake model simulated lake depth and water quality (state) variables. Considering unavailability of lake depth, the model was calibrated and validated using water quality data. Observed data procured from SPCB was used for model calibration while data collected during field sampling was employed for validation of the model. Drying depth in the model was given as 0.1 m and flooding depth was specified as 0.3 m. Initially, 32 $m^{1/3}$/s was given as Manning's coefficient (M) [9] which was varied on further calibration. 31 $m^{1/3}$/s is the final calibrated value for M. Eddy viscosity coefficient (E) was estimated using the Smagorinsky concept and a value of 0.5 was specified initially which was further adjusted. 0.8 is the final calibrated value for E. Further, 0.001773 m/s was specified as wind friction. The model simulated depth of the lake on a daily basis for years 2015 to 2016.

The comparison of simulated BOD with observed values during lean season is shown in Fig. 3. Similarly, Fig. 4 shows the comparison of simulated DO with observed values during rainy season. The differences between the two seasons is shown in Fig. 5. The lake model was assessed through indices, mean absolute error (MAE), root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE). BOD during lean period shows MAE of 0.53 mg/L, RMSE of 1.51 mg/L and NSE of 0.94. Similarly, DO during lean period shows MAE of 0.85 mg/L, RMSE of 1.79 mg/L and NSE of 0.97. During rainy period, BOD shows MAE of 0.66 mg/L, RMSE of 1.25 mg/L and NSE of 0.96. Similarly, DO shows MAE of 1 mg/L, RMSE of 2.05 mg/L and NSE of 0.97 during rainy period. The model shows lesser values of MAE and RMSE indicating lower error. It also shows higher NSE in both the seasons indicating higher ability of the developed model. This shows the capacity of the lake model to represent the reality of water quality (state) variables. This indicates that the lake model is successful and can be employed for further study.

## 4 Results and discussions

Results suggest that the model simulation of the lake is successful. Figures 6a show the simulated water depth of the lake during January 2016 (lean) while the simulated water depth during August 2016 (rainy) is shown in Fig. 6b. During lean season, the water depth of the lake is seen to vary from 1.7 to 4.6 m, while the water depth varies from 2.5 to 5.5 m during the rainy season. Figure 3 shows
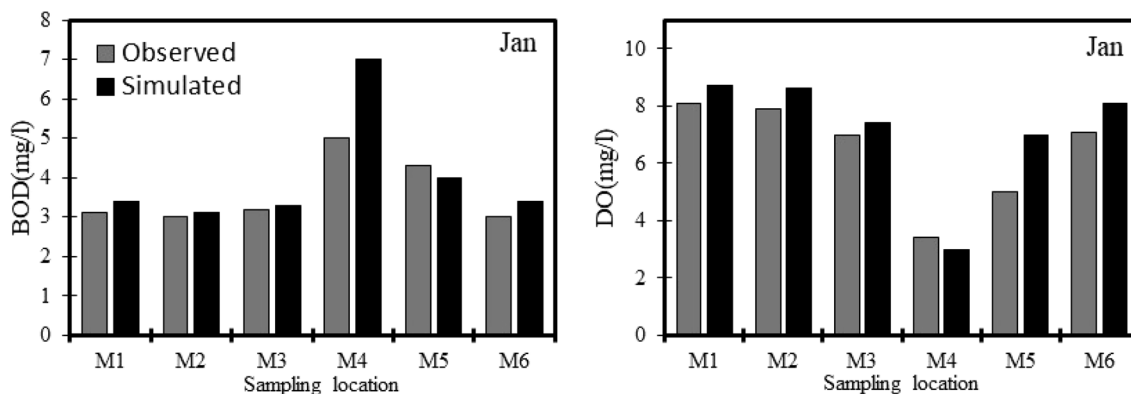
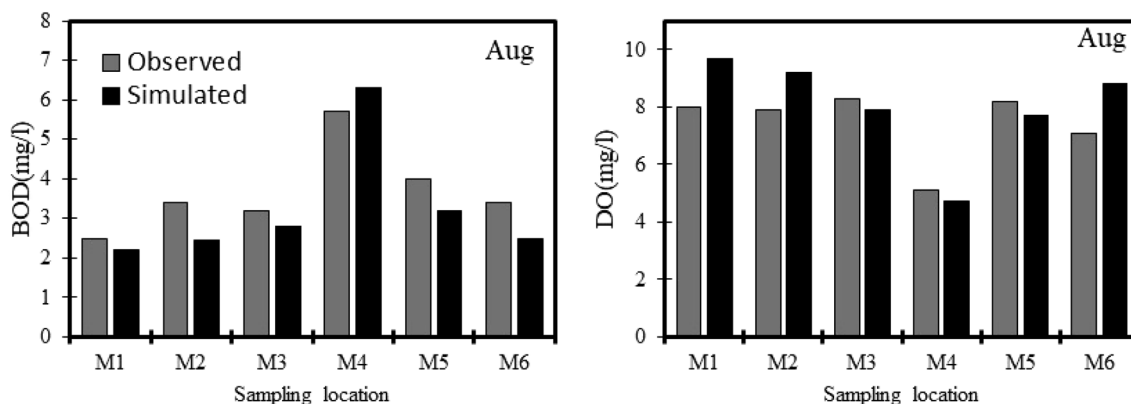**Fig. 3** Observed and simulated BOD, DO during lean season



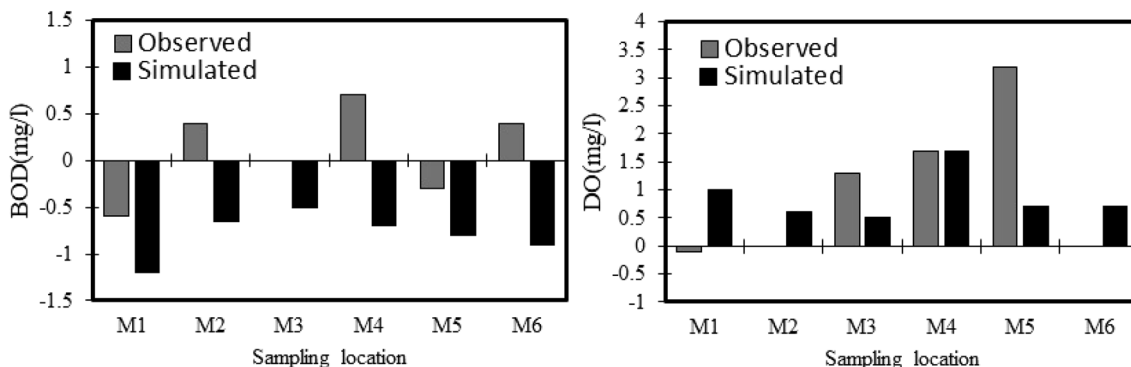**Fig. 4** Observed and simulated BOD, DO during rainy season



**Fig. 5** Difference in BOD and DO between lean and rainy seasons

BOD ranges from 3.1 to 7 mg/L, while DO ranges from 3 to 8.7 mg/L during lean season. There are relatively spatial changes in water quality as shown in the figure. It also shows that DO and BOD are proportional inversely in general. Higher DO and relatively lower BOD indicates better water quality. While lower DO and higher BOD specifies

higher pollution with lower water quality. M4 (where Nambul River drains on the lake) shows lowest DO of 3 mg/L and highest BOD of 7 mg/L indicating highest pollution level among the six sampling locations. This is contributed by excessive use of agricultural pesticides and fertilizers in Nambul River basin, added by dumping of domestic

**Fig. 6** Simulated water depth of Loktak Lake **a** Lean season **b** Rainy season
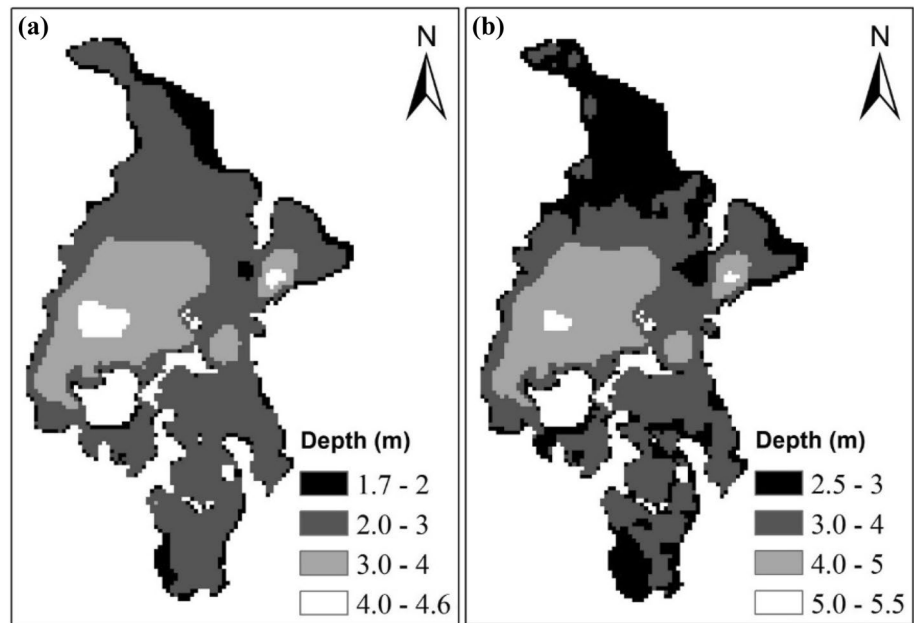


waste from settlement area. The second next water quality is shown by M5 (Thanga) with DO of 7 mg/L and BOD of 4 mg/L.

During rainy season, DO varies from 4.7 to 9.7 mg/L while BOD ranges from 2.2 to 6.3 mg/L (Fig. 4). Comparatively, all sampling sites show better water quality during rainy season. Similarly, M4 (Nambul) shows lowest DO of 4.7 mg/L and highest BOD of 6.3 mg/L. The second next water quality is shown by M5 (Thanga) with DO of 7.7 mg/L and BOD of 3.2 mg/L. Landuse map of the catchment area shows that the majority of land cover in Nambul sub-catchment is occupied by agriculture (Fig. 7). Landuse map was prepared on the basis of data provided by Manipur Forest Department. Out of the total Nambul sub-catchment, agricultural area covers about 47%, constituting about 91 km$^2$. Paddy cultivation, which dominates the cropping pattern, sees extensive use of agricultural pesticides, and nitrogen and phosphorus based fertilizers. This, in turn, contribute return flows that are rich in loadings whose accumulation over time has the potential to lead to eutrophication of Nambul River and Loktak Lake by increasing nutrients. In addition, Nambul River passes settlement areas namely, Imphal, Singjamei and Sagolband with high proportion of generation of domestic waste. This domestic waste are dumped directly to the Nambul River without any treatment. Habitation and urban settlements in Nambul sub-catchment cover about 20 km$^2$ (11%). R. K. B. Singh et al. [29, 30] also observed that DO of Nambul River ranges from 4.5 to 5.6 mg/L while BOD varies from 5.3 to 7 mg/L.

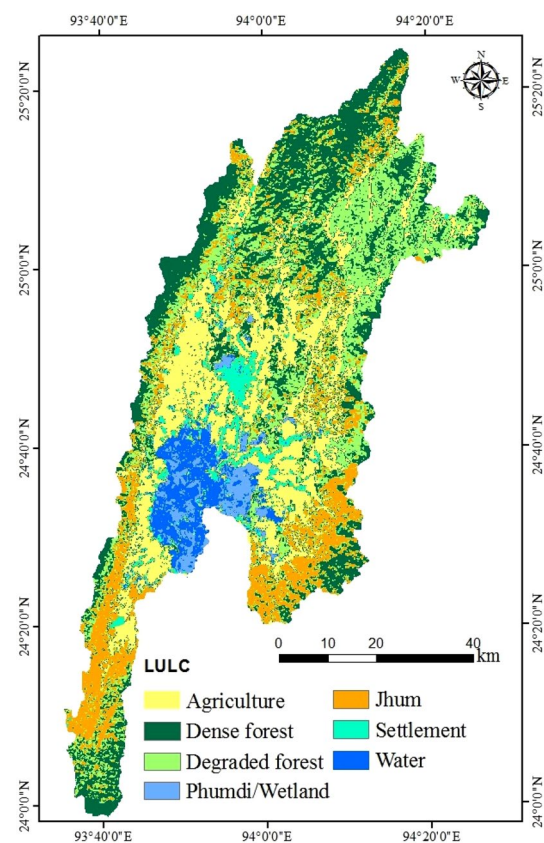The second lowest DO and higher BOD in M5 (Thanga) sampling site during both the seasons is also contributed



**Fig. 7** Landuse map of Loktak sub-catchments

by Nambul River. There is direct dumping of household waste from villagers residing in Thanga Karang. Thanga Karang is an island located inside the Loktak Lake. M6

(Ithai) sampling site depict surface water quality coming throughout the whole Loktak Lake. M6 sampling site shows DO of 8.1 mg/L and BOD of 3.4 mg/L during lean season. Contrasting to water quality of M5, M1 (KLNP) shows better surface water quality with DO of 8.7 mg/L and BOD of 3.4 mg/L during lean season. This is contributed by the presence of KLNP, which is Phumdis. KLNP is a contiguous mass of vegetation which is about 40 km$^2$. Phumdis are known to absorb nutrients and contribute in preserving the Loktak Lake ecosystem [30]. Higher DO and lower BOD are found in the remaining two sampling sites, M4 (Ningthoukhong) and M2 (Sendra). M4 shows DO of 7.4 mg/L and BOD of 3.3 mg/L while M2 shows DO of 7.9 mg/L and BOD of 3.1 mg/L. Tuboi, Irengbam, and Hussain [32] [31] also observed the overall annual water quality of Loktak Lake and Keibul Lamjao National Park in which DO varies from 2.7 to 10.6 mg/L and BOD varies from 2.1 to 10.8 mg/L. Laishram and Dey [33] [32] studied physico-chemical properties of Loktak Lake at five selected villages—three lakeshore villages (Phoubakchao, Laphupat Tera, Nongmaikhong and two island villages—Ithing and Karang). DO was found to vary from 4.05 to 14.18 mg/L and BOD range between 1.51 and 10.65 mg/L. Mayanglambam and Neelam [33, 34] observed physio-chemical parameters in Loktak Lake and found that water quality index for the majority of pre-monsoon period falls under poor category.

Simulated DO of the lake during three different seasons, summer, rainy and winter is shown in Fig. 8. Similarly, Fig. 9 shows the simulated BOD in the lake during summer, rainy and winter seasons. Comparatively, better water quality is observed during rainy season. Throughout the lake, lowest DO and highest BOD is shown in the area where Nambul River drains. This indicates high influence of water quality of Nambul River in the lake. Table 1 shows comparison of BOD and DO of present study with other freshwater lakes located in India. Pandu Bodhan Lake in Andhra Pradesh shows much higher average BOD (60.319 mg/L) than the present study. The other remaining lakes namely, Anchar Lake in Kashmir, Dal Lake in Kashmir Hemkund Lake in Garhwal Himalaya, Khushalsar Lake in Kashmir Kuntbhyog Lake in Himachal Pradesh, Neel Tal Lake in Garhwal Himalaya, Prashar Lake in Himachal Pradesh and Rewalsar Lake in Himachal Pradesh shows generally similar range of BOD as compared to the present study [35–38].

## 5 Conclusions

Water quality of Loktak Lake was assessed based on the use of 2D hydrodynamic modelling using MIKE 21HD coupling through MIKE 21 ECO Lab. The river discharge from sub-catchments carrying agricultural wastes and untreated domestic waste was given as input in the model. The Loktak Lake model was compared with observed BOD and DO procured from SPCB and the field survey. DO and BOD were analysed from six sampling sites for the lean and the rainy seasons during the field survey. The lake model was assessed using various statistical indices which indicate satisfactory performance. The model simulated water depth ranging from 1.7 to 4.6 m during lean season and 2.5–5.5 m during rainy season.

Among the six sampling locations, highest BOD and lowest DO is found in Nambul sampling location. Higher



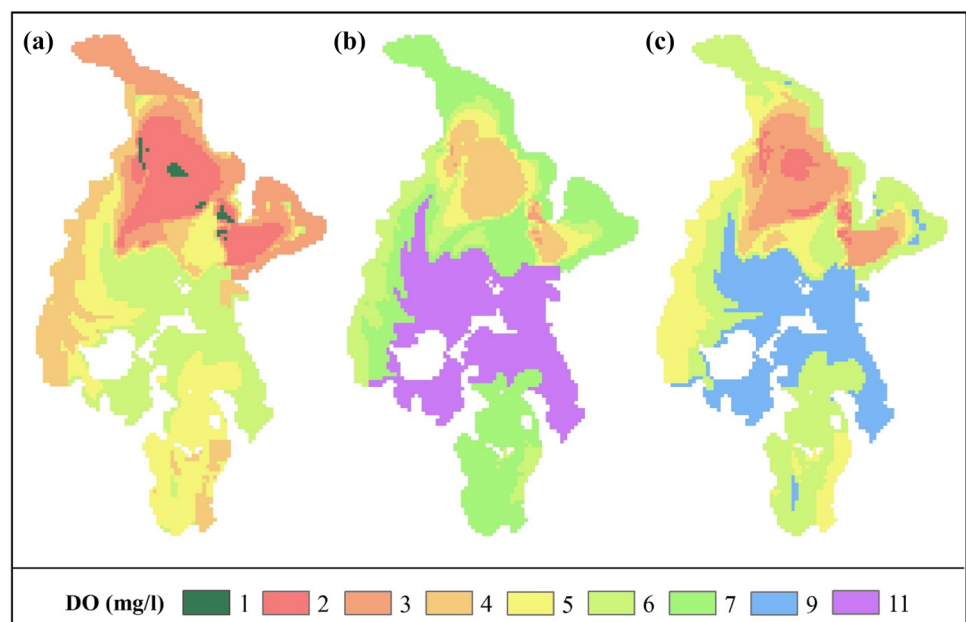**Fig. 8** Distribution of simulated DO throughout the Loktak Lake **a** summer **b** rainy **c** winter seasons

**Fig. 9** Distribution of simulated BOD throughout the Loktak Lake **a** summer **b** rainy **c** winter seasons
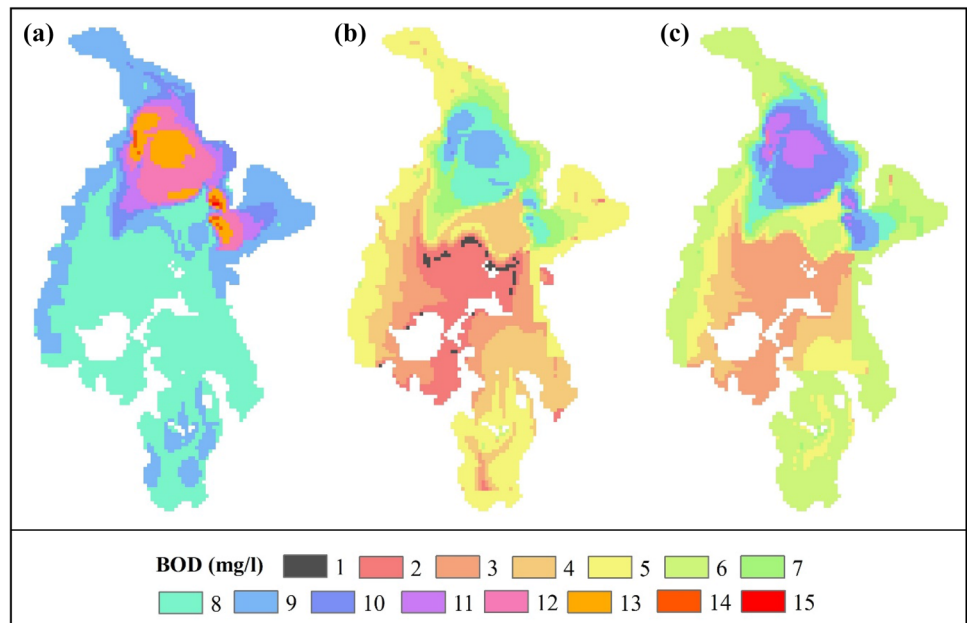


**Table 1** Comparison of BOD and DO of present study with other freshwater lakes in India

| Lake | BOD | DO |
|------|-----|-----|
| Anchar Lake in Kashmir[a] | 2.57 ± 0.4 mg/L | 3.16 ± 0.04 mg/L |
| Dal Lake in Kashmir[a] | 2.74 ± 0.08 mg/L | 3.03 ± 0.06 mg/L |
| Hemkund Lake in Garhwal Himalaya[b] | 3.75 mg/L | 4 mg/L |
| Khushalsar Lake in Kashmir[a] | 3.07 ± 0.09 mg/L | 2.50 ± 0.05 mg/L |
| Kuntbhyog Lake in Himachal Pradesh[c] | 0.00–4.00 mg/L | 7.80–12.32 mg/L |
| Loktak Lake (Present study) | 2.2–7 mg/L | 3–9.7 mg/L |
| Neel Tal Lake in Garhwal Himalaya[d] | – | 4 mg/L |
| Pandu Bodhan Lake in Andhra Pradesh[e] | 60.319 mg/L | 3.937 mg/L |
| Prashar Lake in Himachal Pradesh[c] | 0.52–2.55 mg/L | 6.85–13.21 mg/L |
| Rewalsar Lake in Himachal Pradesh[c] | 2.04–8.21 mg/L | 3.05–7.98 mg/L |

[a]Najar and Khan [34]
[b]Deep et al. [35]
[c]Thakur et al. [36]
[d]Kumar and Sharma [37]
[e]Solanki, Hussain and Raja [38]

BOD and lower DO indicates higher pollution loads, contributing to lower quality and eutrophication of the lake. This is contributed by excessive use of agricultural pesticides and fertilizers in Nambul River basin, added by dumping of domestic waste from settlement area. The second lowest DO and higher BOD in Thanga sampling site is also contributed by Nambul River. There is direct dumping of household waste from villagers residing in Thanga Karang, an island located inside the Loktak Lake. This study presents an initial work towards developing a physically based modelling framework for the Loktak Lake. Further comprehensive investigations of the hydrodynamic and water quality of the Loktak Lake can help towards decision-making bodies in the long run for improving the environmental water quality of the Loktak Lake.

**Declarations**

**Conflict of interest** The authors declare that they have no conflict of interest.

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