HYDROLOGICAL MODELLING FOR LAKE MANAGEMENT: A CASE STUDY OF LOKTAK LAKE, NORTHEAST INDIA

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ABSTRACT: The amount of water discharged to a lake is vital for framing of conservation and management plan of the lake. Loktak Lake is one among the Indian Ramsar site included in Montreux Record due to anthropogenic influence and alteration of the lake ecosystem. Covering an area of 287 km², with an average depth of about 2.7 m, the lake is situated in Manipur, Northeast India. A distinctive characteristic of Loktak Lake is the extensive occurrence of floating vegetation mass called "*Phumdis*". These Phumdis are integral part of the lake ecosystem and a critical determinant of the lake ecosystem. The catchment area of the Loktak Lake is approximately 5,040 km^2, covering about 22 % of the Manipur state and it comprises of nine sub-catchments. The present study develops hydrological models of three gauged sub-catchments (i.e., Nambul, Iril and Thoubal) using couple MIKE SHE-MIKE 11. The models simulate daily discharge, which has been validated using observed daily discharge. The simulation of daily discharge will help various stakeholders to develop management approaches for the conservation of the entire Loktak ecosystem.
KEY WORDS: Loktak; Hydrological modelling; MIKE SHE; Discharge simulation

Effective lake management demands an integrated strategy that connects catchment management with sustainability principles, ensuring a holistic understanding of environmental impacts and potential usage alternatives (Zerga, 2025). The main inflows of water can be from river in catchment, thereby, its precise estimation would be of great help towards framing of various management strategies.

Effective conservation and management planning of lakes require accurate estimation of discharge within the catchment area. To achieve this, hydrological models are developed to simulate river flow and to gain insights into the catchment's hydrological behaviour. These models help simplify complex natural processes, allowing for better prediction of water responses and clearer understanding of the interactions between various hydrological inputs, outputs and events. This understanding is vital for assessing the impact of hydrological changes and for formulating appropriate management strategies (Du and Pechlivanidis, 2025; Parra et al., 2018). Despite using the same input data and study area, different models may yield varying results (Shi et al., 2011). Consequently, identifying a suitable modelling approach for a particular region can be challenging for hydrologists and planners (Wood et al., 2004; Najafi et al., 2011). Therefore, selecting the most appropriate hydrological model is essential for accurately representing regional hydrological processes (Vansteenkiste et al., 2013).

Physically based models are considered to offer more accurate representation of hydrological processes and thus more precise simulation compared to other modelling approach (Refsgaard and Knudsen, 1996). Several physically based models have been introduced over time to improve the precision of hydrological evaluations. Commonly used models include TOPMODEL (Zhu et al., 2025), HBV (Berge et al., 2025), Soil and Water Assessment Tool (SWAT) (Mei et al., 2025) and MIKE SHE (Sharma et al., 2025).

Among the hydrological models, the fully distributed MIKE SHE models (Beven et al., 1986), is extensively used to simulate hydrological processes in diverse environments. Numerous studies have applied MIKE SHE to analysed hydrological impacts of land use and climate change, develop irrigation strategies, assess the effects of forest fires, support forest management, ensure sustainable groundwater use, and guide hydrological interventions in wetland ecosystems (Thompson et al., 2004; Sharma et al., 2025). The present study will develop hydrological models of the three gauged sub-catchments of Loktak Lake using coupled MIKE SHE- MIKE 11 model. The hydrological models will simulate discharge from Loktak sub-catchments which will help in understanding the hydrological regime of the catchment area.

Loktak Lake in north eastern India is a designated Ramsar site (Ramsar, 2025). It is also listed in the Montreux Record due to ecological changes over time (Ramsar, 2025). The lake lies in Manipur between 93°46′–93°55′ E longitudes and 24°25′–24°42′ N latitudes (Figure 1). The lake covers an area of about 287 km² (Eliza et al., 2020) with Iis depth ranging from 0.5 to 4.6 m with minimum during dry summer and maximum in the monsoon (Khwairakpam et al., 2021). A peculiar characteristic of Loktak Lake is the

presence of floating vegetation, popularly known as Phumdis, which seasonally sink and rise to sustain nutrient cycles. The Keibul Lamjao National Park (KLNP), a 40 km² area of Phumdis, is the world's only floating wildlife sanctuary and endemic habitat of endangered Sangai deer (*Rucervus eldii eldii*). The lake's catchment area spans about 5,040 km² which is roughly about 22% of Manipur's total area, lying between 23°58′33″–25°24′30″ N and 93°35′16″–94°27′47″ E. The catchment consists of nine sub-catchments namely, Nambul, Iril, Khuga, Sekmai Western, Heirok, Imphal, Kongba and Thoubal (Figure 1). Except for Kongba, all sub-catchments have both hilly and valley terrains. Iril is the largest (26.55%, 1338.8 km²), while Kongba is the smallest (123 km²). The lake is primarily fed by nine rivers, including Khuga, Thoubal, Imphal, Iril, Kongba, and others in the Western sub-catchment.

MATERIALS AND METHODS

3.1 **Model description of MIKE SHE**

MIKE SHE is a comprehensive physically-based hydrological model designed to simulate the full water cycle in a catchment area (Thompson, 2004). It originates from the System Hydrologique European (SHE) model developed by Beven et al., (1986). It incorporates various hydrological processes including rainfall, evapotranspiration, overland and channel flow as well as water movement through unsaturated and saturated zones, accounting for their interactions.

Rainfall acts as the main driving component for generating runoff (DHI, 2007). Interception is represented through a storage layer dependent on leaf area index (LAI). Kristensen and Jensen method is used for estimating actual evapotranspiration (ETa), which modifies potential evapotranspiration based on vegetation characteristics and moisture present in root zone. The rates of transpiration are influenced by density of green vegetation (LAI), soil water content within the root area and root distribution. It is expressed as follows.

$$ET_a = f(LAI * S * R * PET) \qquad (1)$$

Where ET_a is actual evapotranspiration; LAI is leaf area index; S is soil moisture; R is root distribution; PET is potential evapotranspiration.

Saint Venant equations are employed for calculating overland and channel flows. A two-dimensional diffusive wave approximation of the Saint Venant equation is used for modelling overland flow within each grid cell. In contrast, one-dimensional equation is used for simulating the channel flow within the stream network. Continuity equation is used for calculating the surface detention storage, as expressed in Equation (2).

$$d_2 = d_1 + (q_s - q) + \Delta T \qquad (2)$$

Where d_2 is detained storage volume at the end of the time step; d_1 is detained storage volume at the start of the time step; q_s is the amount of water being added to overland flow during the time step; q is overland flow during the time interval.

MIKE 11HD (Hydrodynamic) is integrated to simulate river hydraulics, which allows for one-dimensional dynamic modelling of river flow and water levels using the full Saint Venant equations (DHI, 2003). Details of MIKE SHE and MIKE 11 can be found from the literature (DHI, 2007; DHI, 2007)

3.2 Data inputs and model development

The hydrological models of the sub-catchments namely Nambul, Iril, and Thoubal were developed using MIKE SHE covers the period from June 1991 to May 2003 and a daily simulation time step was set. For all the three sub-catchments, a uniform grid size of 500 × 500 meters was applied. Input datasets for model setup were gathered from various sources, as listed in Table 1. Daily rainfall records from seven meteorological stations, along with evapotranspiration (ET) values obtained from four stations are interpolated using the Thiessen polygon method to generate the necessary spatio-temporal data. To ensure consistency, input data were evaluated using double mass curve analysis. Precipitation data was obtained from India Meteorological Department (IMD) for the time period 1991 to 1999 in gridded form. The three models used Shuttle Radar Topography Mission (SRTM) DEM with 30-meter resolution.

The hydrological models used land use land cover (LULC) map obtained from State Forest Department, Government of Manipur. The digital LULC map consists of six different classes such as degraded forest, dense forest, Phumdis, Jhum, water bodies and agriculture. The temporal leaf area index (LAI) of various LULC class was obtained from the MODIS MOD15 product. The average LAI values for these land cover types are presented in Figure 2. Root depths for the six LULC classes were referred from existing literature (FSI, 2003; LDA and WISA, 1998). For the land use classes such as degraded forest, dense forest, Phumdis and Jhum, root depth was assumed to be constant, whereas root depth in agricultural zones varied seasonally depending on crop type. Residential and water body areas were assigned a root depth of zero year-round. Initial surface water depth was set to zero in the overland flow simulations. The valley region has an average groundwater level of 1.79 m below the surface (CGWB, 2013), indicating relatively shallow groundwater. The models specified two-layer unsaturated zone with uniform soil properties considering the shallow water table and limited data. Zero-flux boundary conditions were applied at the outer limits of each model domain.

Irrigation abstractions and water management practices were incorporated using data obtained from Irrigation and Flood Control Department, Government of Manipur. Hydrodynamic flow in rivers draining the three sub-catchments was simulated using MIKE 11 HD model, with outputs feeding into the corresponding MIKE SHE models. The river network was obtained from Soil and Water Assessment Tool (SWAT) model. MIKE 11 Geographic Information System (GIS) platform was used to generate additional cross-sections data at various points in the river network.

3.3 Model calibration

Hydrological models were developed for the three gauged sub-catchments namely, Nambul, Iril and Thoubal for the time period June 1991 to May 2003 with daily time step. The initial eight years from 1991 to 1999 were utilized as spin up and the remaining were used for calibration and validation of the developed model. The three hydrological models were calibrated using the observed discharge. Observed discharge are available at the outlets (Hiyangthang, Moirang Kampu and Thoubal) of each sub-catchment (Nambul, Iril and Thoubal) respectively.

Previous studies have identified several key parameters for calibrating coupled MIKE SHE-MIKE 11 include Manning’s roughness coefficients of channel and overland flows, initial surface water depth for overland flow, detention storage, hydraulic conductivity for the unsaturated zone both in horizontal and vertical, bulk density, drainage time constant for the saturated zone, specific yield and specific storage (Doummar et al., 2012; Xevi et al., 1997). In this study, calibration was carried out for horizontal and vertical hydraulic conductivity for the saturated zone, saturated hydraulic conductivity for the unsaturated zone and Manning’s coefficients for overland and channel flow.

Initially, the saturated hydraulic conductivity for unsaturated zone was specified as 5×10^{-7} m/s as referred from the literature (NBSS and LUP, 2001; PWD, 1976; Stibinger, 2014). A single uniform layer was assumed for the saturated zone, with initial hydraulic conductivity of 3×10^{-7} m/s for both vertical and horizontal directions (PWD, 1976). Initially, a uniform Manning’s coefficient of 0.037 s $m^{-1/3}$ was specified for overland flow as referred from the literature (PWD, 1976; Singh, 2010). For channel resistance, a Manning’s coefficient of 0.035 s $m^{-1/3}$ was specified across the river network as suggested by Chow, (1959). These parameter values were finely tuned during calibration, and the final values are summarized in Table 2.

RESULTS AND DISCUSSION

The three hydrological models were developed for the gauged sub-catchments Nambul, Iril, and Thoubal for the time period June 1999 to May 2003 with an initial eight-year spin-up period. Coupled MIKE SHE-MIKE 11 was employed for developing the models. Model performance was assessed using standard indicators such as coefficient of determination (R^2), Root mean square error (RMSE) and Nash–Sutcliffe Coefficient (NSE). In the Nambul sub-catchment, the model demonstrated a strong ability to simulate hydrological processes. Notably, it accurately captured high discharge flows during the monsoon months, reflecting its capability to model seasonal variations. The RMSE during the spin-up and validation phases was 3.322 cumecs/month and 3.826 cumecs/month, respectively. Calibration results show R^2 and NSE values of 0.816 and 0.803, while validation yielded 0.791 and 0.702 respectively, indicating good model accuracy and reliability. The model outputs closely matched observed high and low flows across seasons, as illustrated in the corresponding figure, further confirming the model's robustness in simulating variable hydrological conditions as shown in Figure 3.

The statistical performance of coupled MIKE SHE- MIKE 11 model for Iril is summarized in Table 3. Hydrographs generated by the model indicate that it effectively captured the overall patterns of rising and falling discharge trends, aligned with the temporal flow characteristics, as illustrated in Figure 3. Seasonal variations in flow are also well-represented, demonstrating the model’s capability to simulate seasonal hydrological dynamics. The model successfully reproduces peak flows throughout calibration and validation periods, with R^2 values of 0.811 and 0.861 respectively. High performance of the model is reflected by RMSE values of 11.592 and 10.088 cumecs/month during calibration and validation respectively. The model also shows high NSE values of 0.864 (calibration) and 0.869 (validation). Despite these strong results, the model shows a tendency to underestimate lean season flows. This underestimation may be attributed by different time intervals used for observed discharge collection during calibration and validation phases.

The coupled MIKE SHE-MIKE 11 model of Thoubal sub-catchment is also assessed by statistical indicators as shown in Table 3. The analysis show that the model is successful in simulating river discharge as also shown in Figure 3. During the calibration period, it shows R^2 and RMSE of 0.803 and 13.628 respectively, while the validation phase shows values of 0.812 and 15.758 respectively. The model also shows NSE of 0.864 and 0.839 during calibration and validation respectively. As illustrated in Figure 3, the simulated discharge closely aligns with the observed data, which indicates the model ability to replicate actual flow regime during lean and rainy seasons.

Results demonstrate that coupled MIKE SHE-MIKE 11 models for the three sub-catchments, namely Nambul, Iril, and Thoubal perform successfully. Nonetheless, the models may face challenges during periods of high flow and frequent peak events. The higher accuracy of coupled MIKE SHE-MIKE 11 models can be attributed to its capacity to represent spatially diverse hydrological conditions in response to different temporal flow regime. This highlights the model's potential for extended applications. Given its physically based framework, MIKE SHE is well-suited for simulating river discharge at various points along the river, making it a valuable tool for river basin planning and management. Such simulations can support policy makers in making informed, data-driven decisions.

5 CONCLUSIONS

Loktak Lake has been under pressure due to various anthropogenic influences such as construction of hydroelectric project and pollution. For effective planning for the conservation and restoration of the lake, precise assessment of discharge from the catchment area of the lake is vital. This study focused on simulating discharge from the three sub-catchments namely Nambul, Iril and Thoubal. The hydrological models of the three sub-catchments were developed using coupled MIKE SHE-MIKE 11 model. Daily discharge of the sub-catchment is simulated for June 1999 to May 2003. Based on statistical evaluation, the hydrological models show satisfactory results in simulating river discharge. Consequently, the model can also be used to simulate discharges for ungauged sub-catchments considering similar physical characteristics. The study concluded that coupled MIKE SHE-MIKE 11 model is effective in capturing the runoff generation processes and offers acceptable accuracy, making it a suitable model for reconstructing the hydrology of the Loktak Lake catchment.

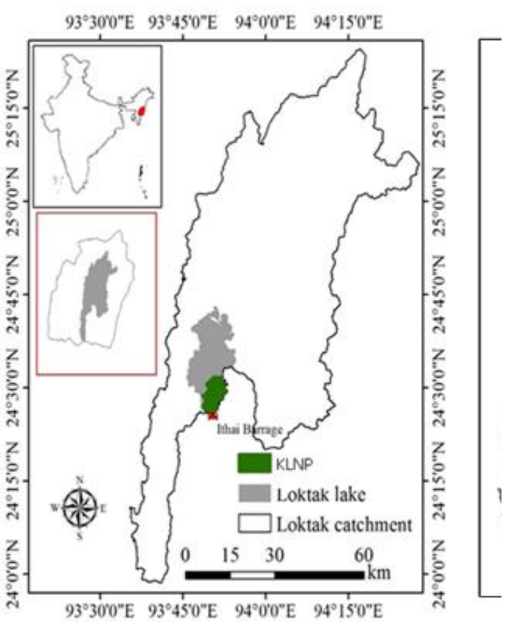

Figure 1: Location of Loktak Lake and its nine sub-catchments

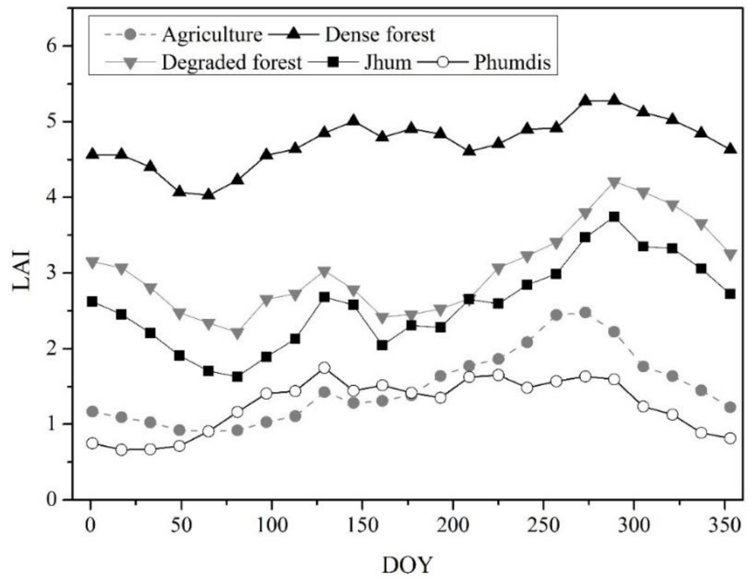

Figure 2: Sixteen days average LAI for different land use obtained from MODIS

Table 1**:** List of data and its sources used in the study

Data	Sources
Digital Elevation Model (DEM)	STRM
Land Use Land Cover (LULC)	Forest Department, Government of Manipur
Soil cover	NBSS & LUP
Precipitation	IMD (1991 –1999); LDA (1999 – 2003)
Evapotranspiration	LDA
Water level	LDA
River discharge and cross sections	LDA
LAI	MOD15 product

Table 2: Final calibrated parameters of coupled MIKE SHE **-** MIKE 11 model

Model	Parameter	Final calibrated value
MIKE SHE	Hydraulic conductivity for unsaturated zone (ms^{-1})	3×10^{-7}
	Horizontal hydraulic conductivity for saturated zone (ms^{-1})	1×10^{-7}
	Vertical hydraulic conductivity for saturated zone (ms^{-1})	1×10^{-7}
	Manning's coefficient for overland flow ($s\ m^{-1/3}$)	0.05
MIKE 11	Manning's coefficient for channel resistance ($s\ m^{-1/3)}$	0.04

The accuracy of developed models was assessed using statistical metrics namely coefficient of determination (R^2), Root mean square error (RMSE) and Nash–Sutcliffe Coefficient (NSE) as shown below:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y_{obs}}\right)^2}\right]$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{n}}$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y_{sim}}\right)^2}\right]$$

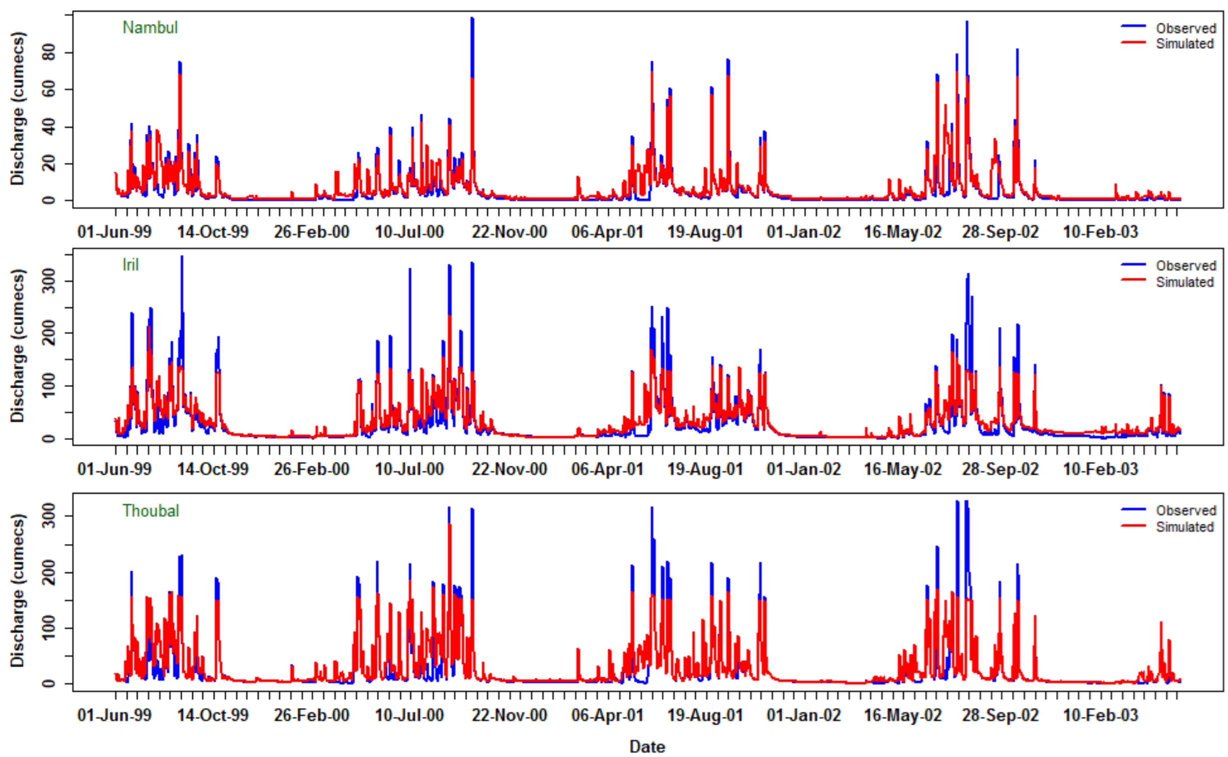

Figure 3: Model simulated daily discharge and observed discharge of Nambul, Iril and Thoubal rivers

Table-3: Model performance for daily river flows during calibration (June 1999 – May 2001) and validation (June 2001 – May 2003) periods

Loktak sub-catchment	1999 to 2001			2001 to 2003		
	R^2	RMSE	NSE	R^2	RMSE	NSE
Nambul	0.702	3.322	0.803	0.791	3.826	0.816
Iril	0.811	14.932	0.864	0.861	13.822	0.869
Thoubal	0.803	13.628	0.864	0.812	15.758	0.839

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