Developing a management plan for Loktak Lake considering Keibul Lamjao National Park and hydropower demand using a data driven modeling approach

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Monthly water balance of Loktak Lake has been developed using catchment discharge obtained from a combination of hydrological models, MIKE SHE and SWAT, abbreviated as hybrid SHE-SWAT. A management plan has been proposed considering the variation of lake water level without compromising hydropower generation. The management plan aims to restore ecological balance of Keibul Lamjao National Park prioritizing Sangai deer. This will also prevent inundation of surrounding area without compromising hydropower generation.

Keywords: Hybrid SHE-SWAT, Sangai deer, water balance model.

LOKTAK Lake has been listed under Ramsar designated wetland which includes wetlands of international importance. This lake has also been listed under 'Montreaux Record', a record of Ramsar site, where changes in ecological character have occurred, are occurring or are likely to occur[1]. The characteristic feature of this lake is the occurrence of vegetative floating masses, locally known as *phumdis*. The survival of these *phumdis* depends on the typical ecological phenomenon of sinking during lean season, gathering nutrients from the ground and staying afloat during rainy season[2]. A contiguous 40 km² area of *phumdis*, named as Keibul Lamjao National Park (KLNP) by Government of India (GoI) is the only floating wildlife sanctuary in the world[3]. This national park is the only natural home of the endemic and endangered species of Manipur's brow-antlered deer (*Rucervus eldii*) popularly known as Sangai. Sangai is the state animal of Manipur and the population trend of this deer species is decreasing[4,5]. The Loktak Hydroelectric project commissioned in 1983 by GoI, has an installed capacity of 105 MW. As part of the project, Ithai barrage was constructed to impound water in Loktak Lake to harness hydropower and irrigation facilities[6]. Higher water level regulated throughout the year affects natural habitat of KLNP and Sangai deer. This also leads to flooding of lakeside villages and agricultural areas[6,7].

Water balance analysis has been done by many researchers[8–11]. But, specific to Loktak Lake, only Singh *et al.*[7,12] have developed hydrological models of Loktak Lake sub-catchments namely, Nambul, Iril and Thoubal using MIKE SHE (Systeme Hydrologique European) for 1999 to 2003. They calculated run-off of the remaining five ungauged sub-catchments, namely Khuga, Western, Imphal Kongba and Iril based on area, and proposed four options for lake management. As an extension, we have developed hydrological models for all nine sub-catchments using a combination of MIKE SHE and soil and water assessment tool (SWAT) models, abbreviated as hybrid SHE-SWAT. Thereafter, water balance of the lake was developed considering discharge from all nine sub-catchments. A lake management plan was proposed using simulated water level for the time period 2015 to 2016. The plan aims to restore ecological condition of KLNP and Sangai deer without compromising hydropower generation. This will also prevent flooding of lakeside villages and agricultural areas.

Loktak Lake is situated in Manipur, Northeast India (Figure 1). KLNP is located between 24°27′N and 24°31′N and 93°31′E and 93°55′E at the south-western corner of Loktak Lake. The lake covers an area of 287 km² (ref. 13) and covers a total catchment area of
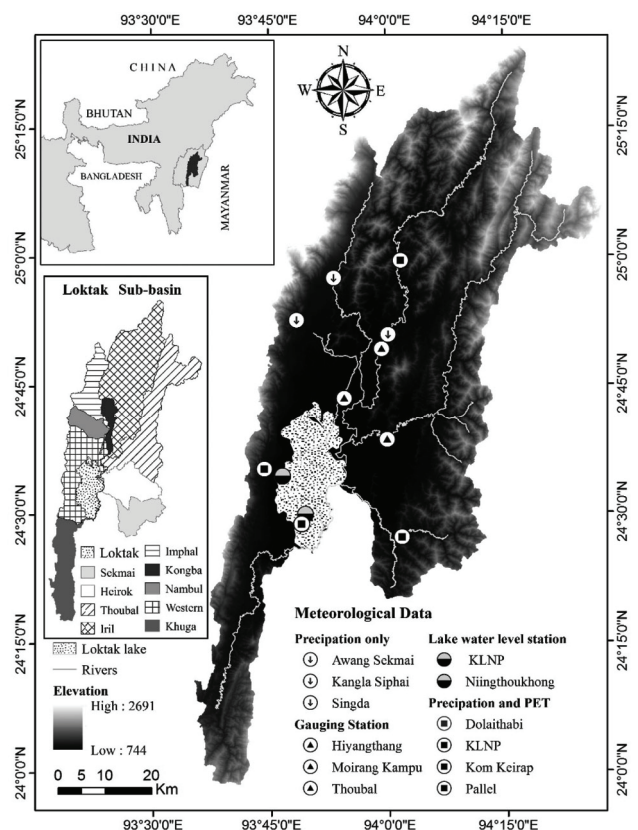
Figure 1. Location of Loktak Lake, its sub-catchments and hydrometeorological stations.

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about 5040 km[2]. Soil of the catchment area consists of clay and silt[14]. Field study indicated that soil ranges from moderate to slightly acidic. The catchment area receives an average annual rainfall of 1392 mm with 150 rainy days[15,16]. The temperature ranges between 11°C and 25°C, pan-evaporation varies from 19 to 130 mm, relative humidity ranges from 51% to 81%, and wind speed ranges from 2 to 5 km/h annual average[15]. The elevation ranges from 744 to 2691 m amsl.

Hydrologically, Loktak Lake is dependent on nine sub-catchments namely, Khuga, Western, Nambul, Imphal, Kongba, Iril, Thoubal, Heirok and Sekmai. However, a barrage has been constructed at the outlet of Sekmai and Heirok sub-catchments for irrigation. This barrage functions during lean season (September to March). Hydro-meteorological data were measured for a limited time period (June 1999 to May 2003).

The distinctive influence of the monsoon during the rainy and lean seasons was visible in Loktak Lake before the construction of Ithai barrage. Figure 2 shows the monthly water level of the lake during 1963 to 1966. Sangai deer in KLNP, has rutting period from late January to March which requires grounding of KLNP[17]. The Sangai deer are able to move unhindered during this critical time when the maximum area of KLNP is grounded. On an average, pre-Ithai barrage water level during December to March for 1963–1966 was estimated to be 767.6, 767.2, 766.6 and 766.2 m amsl respectively[13]. The corresponding percentage of KLNP grounded at these water levels was 11%, 31%, 66% and 88% respectively[17,18].

The general framework of the methodology is shown in Figure 3. We describe now the MIKE SHE and hybrid SHE-SWAT model set-up followed by monthly water balance development.

MIKE SHE is a physically based, deterministic and fully distributed modeling system based on SHE model[19]. It simulates the major processes of the hydrological cycle and 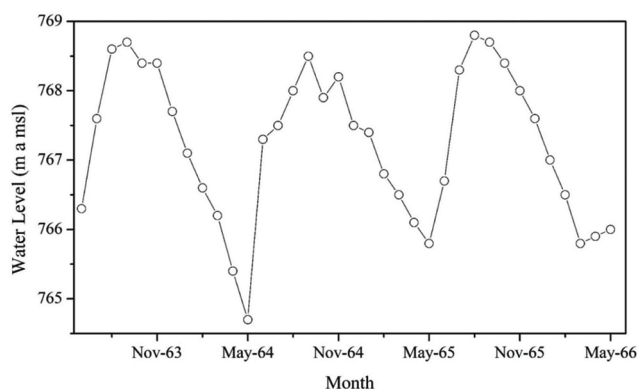comprises process models for precipitation, evapotranspiration, channel flow, overland flow, unsaturated flow and saturated flow along with their interactions[20].

A grid size of 500×500 m and reasonable computational times were maintained throughout the simulation. DEM, precipitation and potential evapotranspiration (PET) were obtained from different sources as shown in Table 1. The spatial coverage of daily precipitation from seven stations and PET from four stations was specified using Theissen polygons for simulation of 1999–2003. For 2015–2016 simulation, a single time series rainfall was used. Digital land use (2003, 2016) was spatially distributed. The leaf area index (LAI) value was available with a time difference of eight days. Root depth was derived from literature[18,21–24]. For river and lakes, MIKE 11 HD model was developed for each sub-catchment, and was linked to the respective MIKE SHE model. Zero was specified as initial water depth on the ground surface. Considering the shallow groundwater depth and the data unavailability, the two layers of unsaturated zone (UZ) with uniform soil type were used. The average groundwater level of the valley was specified as 1.79 m (below ground level)[25]. Zero-flux boundary condition was specified as the outer boundary defined by each model domain. The hydrodynamic modeling of corresponding rivers in each sub-catchment was done through coupled MIKE SHE-MIKE 11. For MIKE 11HD model, cross-sections were synthesized at various locations within the river network using MIKE 11 GIS platform considering limited availability of surveyed cross-section of rivers obtained from LDA.
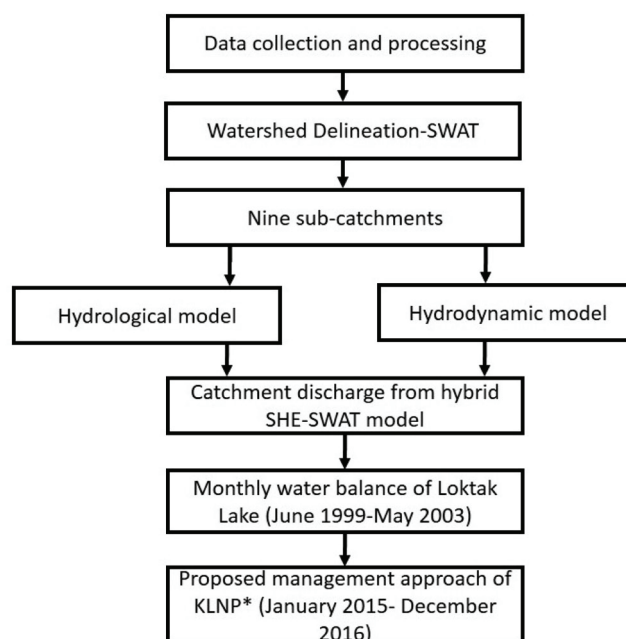

Figure 2. Mean monthly water level of Loktak Lake at Ningthoukhong station (June 1963 to May 1966).

Figure 3. Flowchart of the methodology (*Keibul Lamjao National Park).

Table 1. Input data and its source

Data	Sources
DEM	Earth Resources Observation and Science (Shuttle Rader Topography Mission)
Land cover map	Forest Department, Government of Manipur (GoM)
Soil cover map	NBSS and Land use Planning
Precipitation	India Meteorological Department (June 1991–May 1999, June 2003 to December 2016); Loktak Development Authority (June 1999–May 2003)
Evapotranspiration	Loktak Development Authority (LDA)
River discharge and water level	LDA
River cross sections	LDA
Leaf area index	MODIS
Lake area-volume-water level relationship	LDA
Irrigation volume	Public Works Department (1967); Irrigation and Flood Control Department (IFCD) (2000, 2016), GoM
Domestic consumption	IFCD (1987), GoI (1999), GoM (2000), GoI (2011), GoM (2012, 2014), IFCD (2016)

Table 2. Calibrated parameter values of coupled MIKE SHE-MIKE 11 model

Model	Parameter	Calibrated value
MIKE 11	Manning's coefficient for channel flow (s m$^{-1/3}$)	0.04
MIKE SHE	Manning's coefficient for overland flow (s m$^{-1/3}$)	0.05
	Saturated hydraulic conductivity for unsaturated zone (K_s) (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}

SWAT is a physically based model with spatially explicit parameterization[26]. The model divides the basin into sub-basins which are further divided into hydrological response units (HRUs), land use, vegetation and soil characteristics[27,28]. The hydrological cycle simulated by SWAT is based on the water balance equation. A combination of MIKE SHE and SWAT were employed for developing hydrological models. SWAT was used to model hydrological models of hilly regions while MIKE SHE was used to model valley regions of each sub-catchments considering differences in hydrological processes. Henceforth, hybrid MIKE SHE-SWAT will be abbreviated as hybrid SHE-SWAT.

SWAT was used to model hilly regions of each sub-catchments with relatively higher elevation and more topographical slope. Model inputs include DEM, land use, soil and rainfall which were procured from different sources (Table 1). The remaining valley regions of each sub-catchment were modelled using MIKE SHE. MIKE 11HD was coupled to model hydrodynamics. The same input data except model domain as explained before were employed in each MIKE SHE valley models. Final calibrated values obtained were specified in each MIKE SHE models. Discharge obtained from each SWAT models was integrated as input data in each coupled MIKE SHE-MIKE 11 models.

Calibration and validation were based on comparison of observed discharge available for Nambul, Iril and Thoubal sub-catchments during June 1999 to May 2003. Models were developed from June 1991 to May 2003, of which the period from June 1991 to May 1999 (eight years) was used for model stabilization. The effective simulation period was divided into two: September 1999 to May 2001 for calibration and June 2001 to May 2003 for validation. Table 2 shows the final calibrated values for coupled MIKE SHE-MIKE 11 models for Nambul, Iril and Thoubal. Values were found to be the same probably due to similar physiography of sub-catchments. Manning's roughness coefficient for overland flow and vertical hydraulic conductivity for the unsaturated zone were the two most sensitive parameters. SWAT is designed to calculate the sediment and agricultural chemical yields, the impact of land use and management on water in ungauged watershed[29]. No specific calibration was used considering unavailability of observed data in hilly regions, except replacing deep recharge with zero. The model is computationally efficient, process-based and capable of continuous simulation over long-time periods. The SWAT model has also been employed on various Indian catchments of varied sizes and found to performed well without much calibration[30]. This successful application also verifies the capability of SWAT as a model suited for ungauged catchments. Table 3 shows the performance of the three validated hydrological models using hybrid SHE-SWAT suggesting robust validation and applicability for ungauged sub-catchments. Consequently, hydrological models of the remaining six ungauged sub-catchments were developed using hybrid SHE-SWAT. Considering similar land use, mean catchment elevation and soil characteristics, final calibrated

Table 3. Statistical analysis of hydrological models using hybrid SHE-SWAT for daily flows

	Model calibration (September 1999–May 2001)				Model validation (June 2001–May 2003)			
Sub-catchment	NSE*	R^2**	RMSE	F_{Bal} (%)***	NSE*	R^2**	RMSE	F_{Bal} (%)***
Nambul	0.86	0.85	2.3	08.0	0.83	0.79	03.5	04.0
Iril	0.95	0.94	7.5	12.3	0.94	0.93	09.3	13.4
Thoubal	0.92	0.90	9.2	13.7	0.89	0.87	13.1	15.1

*Nash–Sutcliffe efficiency; **Coefficient of determination; ***Mean discharge simulating error.
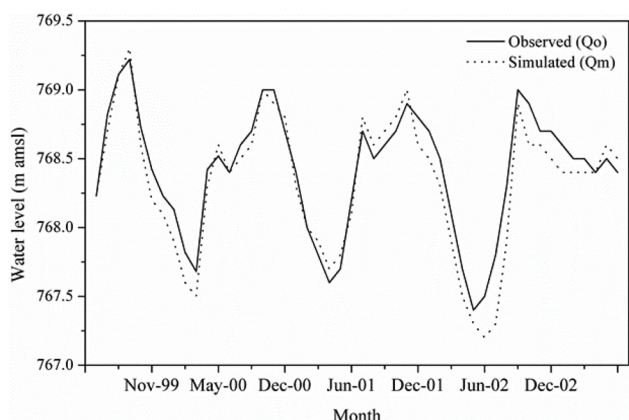
Figure 4. Observed verses simulated mean monthly Loktak water levels (June 1999–May 2003).
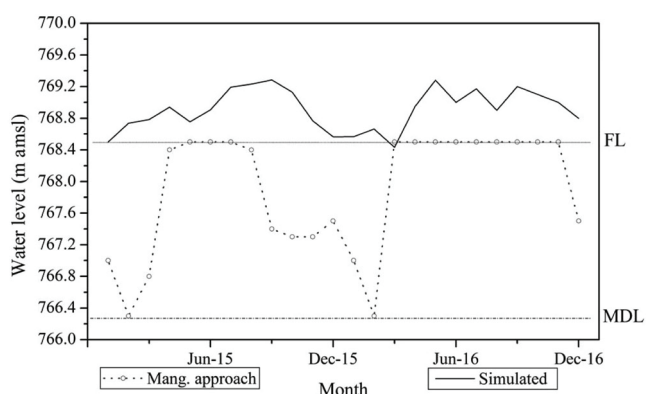
Figure 5. Current versus management approach monthly water levels of Loktak Lake (January 2015–December 2016) (FL, Flood level; MDL, Minimum drawdown level).

values were transferred to ungauged sub-catchments while modeling[31].

The water balance model of Loktak Lake was simulated for two different time periods: June 1999–May 2003 and January 2015–December 2016. Water balance equation of the lake was derived from Singh *et al.*[12]. The lake is fed by direct precipitation and runoff from sub-catchments that drain into the lake while abstractions are associated with evapotranspiration from phumdis, evaporation from open water surface, water for hydropower generation, irrigation, domestic consumption and releases

through the Ithai Barrage. As the underlying soil consists of heavy, impermeable clays, groundwater exchanges are assumed to be small and excluded from the water balance equation[14,32]. All parameter values were obtained from different sources as shown in Table 1. Discharge from Heirok and Sekmai sub-catchments were considered only during April to October months.

$$V_t = V_{t-1} + (R_t \times A_{t-1}) + D_t - (ET_t \times AP) \\ - (E_t \times (A_{t-1} - AP)) - H_t - I_t - DM_t - IB_t - O_t, \quad (1)$$

where V is the lake volume; t specifies the current month; $t - 1$ specifies the previous month; A the lake area; R the direct rainfall onto the lake; D the discharge from all sub-catchments (Heirok and Sekmai sub-catchments were considered during April to October), E the pan open water evaporation; ET the evapotranspiration; AP the area of Phumdis; H the abstraction for hydropower; I the abstraction for irrigation; DM the domestic consumption; IB the outflow through Ithai barrage; and O is the outflow when the water level reached full reservoir level.

Figure 4 shows the comparison of observed and simulated mean monthly Loktak water level during June 1999 to May 2003. Simulated water level was evaluated using statistical indicators, and shows Nash-Sutcliffe efficiency (NSE) of 0.86 and coefficient of determination (R^2) of 0.91. The mean annual inputs are 3720.753×10^6 m^3; accounted by discharge from catchment which contributed the largest fraction (91%) and the remainder was contributed by direct precipitation onto the lake area. The mean annual outputs were 3723×10^6 m^3; the largest fraction was accounted by releases through the Ithai barrage (69%). Abstractions for hydropower generation, evaporation from the lake surface, evapotranspiration from the area of *phumdis*, and domestic consumption accounted for 22%, 2%, 5%, 1% and 1% respectively. The term 'O' was omitted as the lake level did not reach the full reservoir level (FRL). The mean lake water level has increased by 1.2 m (767.2 m amsl during pre-Ithai barrage during June 1963–May 1966 and 768.4 m amsl during post-Ithai barrage during June 1999 to May 2003). During pre-Ithai barrage, the distinctive influence of the monsoon during the rainy and the lean seasons were visible. The magnitude of seasonal fluctuations of lake water level decreased from about 3.1 m (May low water:
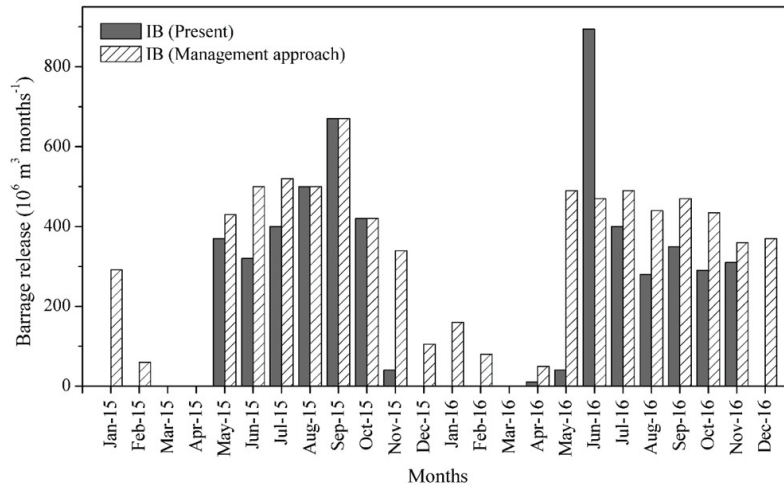
Figure 6. Present versus management approach Ithai barrage release.

765.5 m; September high water: 768.6 m) to 1.1 m (March low water: 767.85 m; September high water: 768.96 m).

Hydrological models of each sub-catchments during January 2015–December 2016 were developed using the final calibrated values. Simulated water balance of the lake (2015–2016) is shown in Figure 5. Water balance components were analysed. It was found that the mean annual inputs were 4012×10^6 m³, with discharge from sub-catchments and direct rainfall onto the lake accounting for 88% and 12% respectively. The mean annual outputs were 4023×10^6 m³, with release through the Ithai barrage being the largest fraction accounted (66%). The abstractions for evapotranspiration, evaporation, hydropower generation, irrigation and domestic consumption accounts for 2%, 5%, 21%, 5% and 1% respectively. Analysing outputs used in water balance equation for the two scenarios: evapotranspiration decreased due to decreasing ecological condition of *phumdis*, evaporation increased.

The management approach was designed by simulating mean monthly water balance of the Loktak Lake without compromising abstraction of water level demand for hydropower generation. The management approach of KLNP considered the variation of water level suitable for Sangai deer and prevention of inundation of surrounding areas. Figure 5 shows the comparison of present and management approach water levels of the lake. Existing withdrawals for Loktak lift irrigation (LLI) and Imphal barrage project (IBP) were estimated to be 32.4×10^6 m³ during each month from October to March[23,33,34]. LLI has potential to irrigate 400,00 ha as estimated by IFCD[33], in which the total water requirement for both LLI and IBP would be 61.3×10^6 m³. Additional withdrawals were specified for irrigation in management approach. Barrage releases were specified when the water level reached above the flood level (FL). Releases were specified even

during the lean season after maintaining minimum drawdown level. Existing management approach for monthly releases of Ithai barrage for the whole simulation is shown in Figure 6. Monthly releases were set considering the carrying capacity in downstream to avoid flooding. Throughout the simulation, the fraction of KLNP to be grounded during December to March is 15%, 29%, 85% and 29% respectively. This will help in absorption of nutrients from the ground. Grounding of KLNP will improve the habitat of Sangai deer due to less hindrance during their rutting season. In addition, the approach will also prevent inundation of nearby villages and agricultural areas without compromising hydropower.

Monthly water balance for the Loktak Lake was simulated for two different time periods: June 1999–May 2003 and January 2015–December 2016. The water balance equation incorporated catchment discharge obtained from hydrological models developed using hybrid SHE-SWAT. The equation also included outflows associated with abstractions for hydropower generation, irrigation, and releases through the Ithai barrage. Comparison of observed and simulated water levels demonstrated that the developed monthly water balance is able to capture the hydrological characteristics of Loktak wetland successfully. There is a high possibility that the maintenance of high water level throughout the year is affecting the natural habitat of KLNP and contributing to flooding of surrounding agricultural areas and villages. Thereby, a management approach has been framed which will be suitable for KLNP prioritizing habitat of Sangai deer. The approach suggested that it is possible to fulfil irrigation requirement and release of water during lean seasons through the Ithai barrage to achieve water level needed for grounding of KLNP suitable for Sangai deer, while at the same time maintaining the minimum drawdown level for hydropower generation. It will also prevent inundation of surrounding agricultural areas and villages. As

incorporated in the management approach, there will be provision for increase in irrigation which will benefit agriculture. However, enhanced agricultural abstractions may lead to decrease of water supply downstream and increase of pesticides content in water. This will enhance nutrient enrichment, which has already been reported by LDA[15]. However, this can be managed with organic farming. Thus, it demonstrates that the lake water level can be maintained considering habitat for KLNP and Sangai deer without compromising hydropower generation.

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