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Modelling the impact of prescribed global warming on runoff from headwater catchments of the Irrawaddy River and their implications for the water level regime of Loktak Lake, northeast India

C. R. Singh[1], J. R. Thompson[1], J. R. French[1], D. G. Kingston[1,*], and A. W. Mackay[1]

[1]UCL Department of Geography, University College London, Gower Street, London, WC1E 6BT, UK
[*]now at: Department of Geography, University of Otago, P.O. Box 56, Dunedin, New Zealand

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Abstract. Climate change is likely to have major implications for wetland ecosystems, which will include altered water level regimes due to modifications in local and catchment hydrology. However, substantial uncertainty exists in the precise impacts of climate change on wetlands due in part to uncertainty in GCM projections. This paper explores the impacts of climate change upon river discharge within three sub-catchments of Loktak Lake, an internationally important wetland in northeast India. This is achieved by running pattern-scaled GCM output through distributed hydrological models (developed using MIKE SHE) of each sub-catchment. The impacts of climate change upon water levels within Loktak Lake are subsequently investigated using a water balance model. Two groups of climate change scenarios are investigated. Group 1 uses results from seven different GCMs for an increase in global mean temperature of 2 °C, the purported threshold of "dangerous" climate change, whilst Group 2 is based on results from the HadCM3 GCM for increases in global mean temperature between 1 °C and 6 °C. Results from the Group 1 scenarios show varying responses between the three sub-catchments. The majority of scenario-sub-catchment combinations (13 out of 21) indicate increases in discharge which vary from <1% to 42% although, in some cases, discharge decreases by as much as 20%. Six of the GCMs suggest overall increases in river flow to Loktak Lake (2–27%) whilst the other results in a modest (6%) decline. In contrast, the Group 2 scenarios lead to an almost linear increase in total river flow to Loktak Lake with increasing temperature (up to 27% for 6 °C), although two sub-catchments experience reductions in mean discharge for the smallest temperature increases. In all but one Group 1 scenario, and all the Group 2 scenarios, Loktak Lake water levels are higher, regularly reaching the top of a downstream hydropower barrage that impounds the lake and necessitating the release of water for barrage structural stability. Although elevated water levels may permit enhanced abstraction for irrigation and domestic uses, future increases in hydropower generation are limited by existing infrastructure. The higher water levels are likely to exacerbate existing ecological deterioration within the lake as well as enhancing problems of flooding of lakeside communities.

1 Introduction

Wetland ecosystems, including rivers, lakes, floodplains and marshes, provide many services that contribute to human well-being and poverty alleviation (Millennium Ecosystem Assessment, 2005). However, they are increasingly subject to intense pressure from multiple human activities such as water diversion, pollution, over-exploitation of natural resources, and reclamation. Even flagship wetlands recognised as internationally important are subject to these pressures and resulting ecosystem change. For example, as of September 2010, 1897 wetlands, covering an area of nearly 185.5 million hectares, are listed as internationally important under the Ramsar Convention (Ramsar Bureau, 2010). 51 of these sites are on Ramsar's Montreux Record, which lists those internationally important wetlands where changes in ecological character have occurred, are occurring or are

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Correspondence to: J. R. Thompson
(j.thompson@geog.ucl.ac.uk)

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Table 1. Sub-catchments of Loktak Lake.

Sub-catchment	Area (km^2)	Forested area (km^2)	Elevation range (m a.m.s.l.)
1. Thoubal	963	684	800–2430
2. Iril	1271	902	800–2300
3a. Nambul	178	114	800–2204
3b. Western[b]	851	545	800–2000
4. Imphal	354	251	800–2583
5. Khuga	504	358	800–1960
6. Sekmai[a]	301	99	800–1600
7. Heirok[a]	405	134	800–1467
8. Kongba	120	61	800–1500

[a] Flows from these two catchments are now diverted away from Loktak Lake; [b] The Western sub-catchment is comprised of over 20 small streams and rivulets including the Nambul.

likely to occur. Two of India's 25 Ramsar sites, including Loktak Lake which is the focus of this paper, are on this record of threatened wetlands. This situation reflects a wider trend for wetlands across the world. For example, the United States Environmental Protection Agency reported that the extent of wetlands in the lower 48 states of the United States was shrinking at a rate of over 24 000 hectares annually, mainly due to developmental pressures and agricultural reclamation (USEPA, 2001). Similarly, over the middle-late 20th Century, European countries including France, Germany, Italy and Greece lost between 57% and 66% of their wetlands (CEC, 1995), whilst Davis and Froend (1999) suggested that 70% of wetlands in the coastal plains of south-western Australia have been lost since British settlement (1829). Much of these losses are the result of infilling or drainage to create land for agricultural use or urban development.

The pressures on wetlands from human activities are likely to grow in the future as demand for water and other resources increases (e.g. Hollis, 1998; Ramsar Bureau, 2002a). Resulting ecological changes within wetlands may be exacerbated by the impacts of climate change with implications for wetland conservation, restoration and the wise use of wetland resources (Poff et al., 2002; Erwin, 2009). Projected intensification of the hydrological cycle associated with rising global temperatures (IPCC, 2007) will have large implications for wetlands which by their very nature are sensitive to changes in local and catchment-wide hydrometeorological conditions (Baker et al., 2009). The most pronounced impacts of climate change upon wetlands will be modifications to hydrological regimes. These will include alterations to the temporal and spatial patterns of water levels and changes in the roles of hydrological extremes of droughts and floods. Other impacts may include changes to wetland biogeochemistry, sediment loading, fire incidence and wave energy (e.g. Ramsar Bureau, 2002b). The nature and magnitude of climate change impacts will vary between wetland types and locations. For many freshwater wetlands the most important projected impacts of climate change are associated with changes in the amount, state and seasonal distribution of precipitation, higher evaporation due to warmer temperatures and the combined effects of these changes upon runoff (e.g. Hartig et al., 1997; Mortsch, 1998; Conly and van der Kamp, 2001). Many freshwater wetlands are particularly vulnerable to climate change induced modifications to hydrological regimes due to the delicate balance between precipitation and evaporation (Clair, 1998; Thompson et al., 2009). For example, the surface areas of both Lake Chad, West Africa (Talling and Lamoalle, 1998) and Qinghai Lake, China (Bates et al., 2008) have declined following reduced catchment precipitation and in turn smaller inflows from contributory rivers. Modified hydrological regimes will have knock-on implications for wetland flora and fauna, which often have very sensitive water level preferences (e.g. Mortsch, 1998; Wheeler et al., 2004). Changes to wetland floral and faunal diversity may impact the conservation significance of some sites (e.g. Keddy, 2000; Burkett and Kusler, 2000; Herron et al., 2002; Bates et al., 2008; Matthews and Quesne, 2009). Similarly, hydrological changes will influence biological, biogeochemical, and hydrological functions within wetland ecosystems, thereby affecting the socio-economic benefits that are valued by humans (Cox and Campbell, 1997).

Acknowledging the threats to wetland environments associated with climate change, the Ramsar Bureau (2002b) identified the urgent need to assess potential impacts in order to develop mitigation strategies. However, lack of regionally specific wetland data and regional climate change scenarios, let alone catchment level climate change scenarios, make it difficult to predict the impacts of climate change on many wetlands. Projections of the regional distribution of precipitation patterns are characterised by a high level of uncertainty and this is often magnified when the information is used to drive impacts models. In addition, in many less developed regions, data required to develop hydrological models for climate impacts studies are sparse. As a result, Matthews and Quesne (2009) stated that assessments of the impacts of climate change on freshwater ecosystems are characterised by medium to high levels of uncertainty. This paper investigates the uncertainty associated with the impacts of climate on water resources within a headwater catchment of the Irrawaddy River Basin and their implications for the hydrological regime of Loktak Lake, an internationally important lacustrine wetland. This is achieved using two groups of scenarios, the first employing results from a number of GCMs for the same increase in global mean temperature and the second focussing on results from one GCM for a range of higher temperatures.

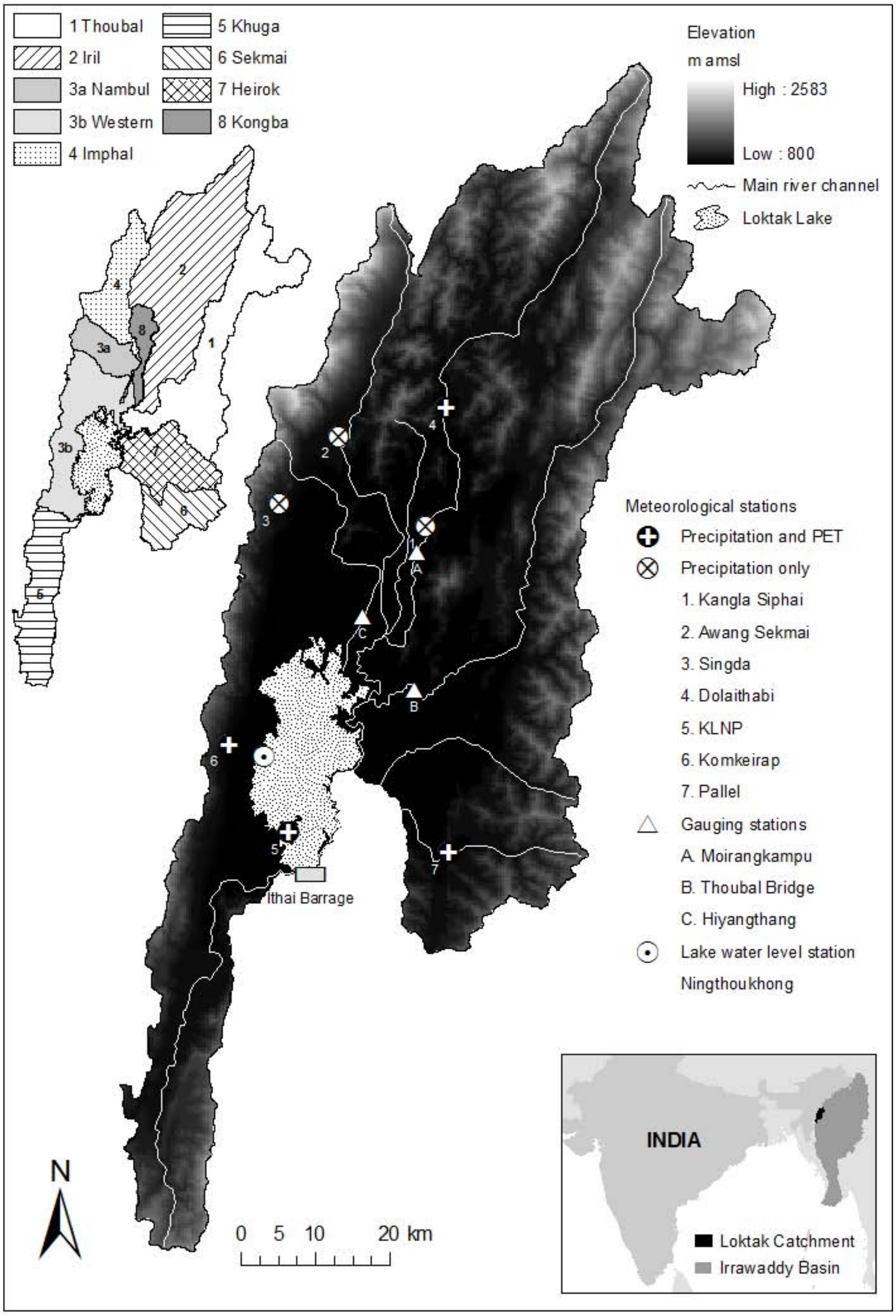

Fig. 1. Loktak Lake, its sub-catchments and location of hydrometeorological stations (Irrawaddy Basin outline from GRDC grdc.bafg.de).

2 Loktak Lake

Loktak Lake (area 287 km^2) is the largest freshwater wetland in northeast India (WAPCOS, 1993; LDA and WISA 1997; WISA 2005). The lake, which is located within the state of Manipur, has a total catchment area of 4947 km^2 which is divided into eight primary sub-catchments (Fig. 1, Table 1). Two of these (the Heirok and Sekmai), however, have been isolated from the lake by diversion schemes so that the present catchment area is 4241 km^2. The Manipur River, which drains from the lake, is a tributary of the much larger Irrawaddy Basin (total area 413 710 km^2). Loktak Lake is located within a central valley covering 28% of the catchment. The valley is surrounded by mountainous ranges characterised by steep slopes with incised drainage. Catchment elevation varies from 800 m above mean sea level (m a.m.s.l.) in the valley bottom to over 2500 m a.m.s.l. Catchment geology comprises young rock formations uplifted by the

Tertiary Orogeny of the Himalayas from the shallow bed of the Tethys Sea (Chakraborti et al., 2008). Rock types are primarily Tertiary and Cretaceous sedimentary formations, in particular limestones, with minor metamorphic and igneous intrusions (NBSS and LUP, 2001). The valley bottom is covered in alluvium composed of clays and mud derived from the weathering of the underlying argillaceous rocks and deposited by the rivers and streams as they flow from the hills into areas of lower gradient (PWD, 1967).

The valley is characterised by a tropical to semi-tropical climate whilst at higher altitudes the climate is semi-temperate to temperate (WAPCOS, 1993). The south-western monsoon of the Indian sub-continent drives the climate over the lake and its catchment. A rainy season starts with the onset of the monsoon in June and continues until September. Data from seven rain gauges (Fig. 1) operated by the Loktak Development Authority (LDA) between June 1999 and May 2003 shows that the wettest month is August (average 255 mm) followed by July (229 mm). June and September receive on average 225 mm and 181 mm respectively. These four monsoon months account for 63% of the annual average catchment precipitation of 1409 mm. The south-eastern part of the catchment (Pallel rain gauge) receives the lowest annual average precipitation of 1194 mm while the north-west (Sindga) receives the highest annual average precipitation of 1647 mm. The dry winter extends from October to February with the driest months being December and January (4 mm and 10 mm mean precipitation respectively). The pre-monsoon summer (March to May) is characterised by scattered showers. As the monsoon approaches, the intensity and frequency of precipitation increases (mean monthly precipitation for March, April and May are 45 mm, 99 mm and 147 mm, respectively). The mean annual temperature for June 1999–May 2003 derived from four meteorological stations within the catchment (Fig. 1) was 20.5 °C. Mean summer temperatures for the same period were 24.0 °C with the highest temperate of 35.5 °C recorded in June 1999 at Keibul Lamjao National Park (KLNP). In winter mean catchment temperature was 14.0 °C. The lowest temperature (−1.5 °C) was recorded at Pallel in January 2000. The four meteorological stations providing temperature data are located at elevations between 800 and 850 m a.m.s.l. However, temperatures at the higher parts of the catchment can be expected to be lower, especially in winter. Mean annual potential evapotranspiration (PET) (June 1999–May 2003) for the catchment evaluated by the LDA using the Penman-Monteith method was 1063 mm with monthly minimum and maximum of 37 mm and 144 mm in December and May respectively. The intense monsoon precipitation combined with steep slopes result in flashy runoff responses from the catchment. River flows are highly seasonal with the peak flow period coinciding with the wettest month of August. Dry season flows are less than 5% of those experienced during the monsoon.

Approximately 64% (3150 km^2) of the total catchment area is forested with the major types historically comprising tropical semi-evergreen, subtropical pine, and montane wet temperate forests (FSI, 2003). However, over 83% (2620 km^2) of this forested area has been subject to varying degrees of deforestation by local communities. Dense, relatively pristine, forests are now limited to the highest altitudes. Agricultural activities as well as human settlements are concentrated in the valley, although there is some agriculture in hilly areas through shifting cultivation (known locally as *jhum*). Paddy cultivation in the valley provides 65% of total rice production of Manipur and as a result the valley is known as the "Rice Bowl of Manipur". Pulses, tobacco, potato, chillies and other vegetables are important crops grown for local consumption while sugarcane and citrus fruits are the main cash crops.

Loktak Lake is oval in shape and varies in depth between 0.5 and 4.5 m (WAPCOS, 1993; LDA and WISA, 1998; Trisal and Manihar, 2004). Seasonal variations in lake water levels reflect the seasonality in precipitation and in turn river flows. The most striking characteristic of the lake is the occurrence of floating heterogeneous masses of soil, vegetation and organic matter at various stages of decomposition, known locally as *phumdis* (e.g. WAPCOS, 1988; Singh, 1992; LDA, 1996; Singh and Shyamananda, 1994; LDA and WISA, 2003). The KLNP is located in the south of the lake and is the only floating wildlife sanctuary in the world (Trisal and Manihar, 2004). It is the sole natural habitat of the world's most endangered ungulate species, the brow-antlered deer (*Cervus eldi eldi*) or *Sangai* (Khan et al., 1992; Prasad and Chhabra, 2001; Dey, 2002; Angom, 2005). The lake supports a human population of 279 935 (Trisal and Manihar, 2004) living on it and around its margins through the provision of water, fish and aquatic vegetation (LDA and WISA, 2003; Trisal and Manihar, 2004). Lake vegetation is harvested for use as food, fodder, fibre, fuel, material for handicrafts and for medicinal purposes. Historically the lake provided breeding and nursery habitat for migratory fish which form a major component of the diet of local people. Periodic inundation of the lake margin and floodplains within the central valley and the resulting deposition of nutrient-rich sediment has benefited the productive agricultural sector.

Due to its rich biodiversity and its socio-economic importance, Loktak Lake was designated as a wetland of internationally importance under the Ramsar Convention in 1990 (Singh and Shyamananda, 1994; LDA, 1996). It was also included on a list of priority wetlands identified by the Government of India for intensive conservation and management (Trisal and Manihar, 2004; MoEF, 2007). However, developmental activities with an emphasis on water resources, particularly the Loktak Multipurpose Project for generating 105 MW of hydro-electric power, have resulted in major modifications to the lake's hydrological regime. The largest impacts have been associated with the construction of the Ithai Barrage immediately downstream of the lake to impound water for hydropower generation. The barrage, which was commissioned in 1983, has raised mean water levels and reduced the magnitude of seasonal fluctuations. In addition, the lake is under stress from other anthropogenic pressures. Deforestation within the catchment, agricultural pollution leading to nutrient enrichment and the prolific growth of *phumdis* as well as encroachment around the lake margin have all increased in recent years (Hay, 1998; LDA and WISA, 1998; James, 2000; ERM, 2000). Water resource schemes have also been proposed within both the Khuga and Iril sub-catchments. Climate change represents an additional source of potential hydrological changes which, to date, have not been investigated.

3 Hydrological modelling of the Loktak Lake catchment

Hydrological models of sub-catchments draining to Loktak Lake were developed using MIKE SHE, a deterministic, fully distributed and physically based modelling system (DHI, 2005; Graham and Butts, 2005) developed from the Système Hydrologique Européen (SHE) (Abbott et al., 1986 a, b). It has been widely used to study a variety of water resource and environmental problems under diverse climatologically and hydrological regimes (Refsgaard and Storm, 1995). MIKE SHE is a comprehensive system for modelling all the major processes that occur in the land phase of the hydrological cycle. It describes a given catchment with a level of detail sufficiently fine to be able to claim a physically-based process description. The distributed nature of MIKE SHE allows the spatial distribution of catchment parameters, climate variables and hydrological response through an orthogonal grid network and columns of horizontal layers at each grid square in the horizontal and vertical, respectively. Channel flow is simulated using the one-dimensional hydraulic modelling system, MIKE 11. Dynamic coupling of MIKE SHE and MIKE 11 includes river-aquifer exchange, overland flow from MIKE SHE grid squares to MIKE 11 river branches and the inundation of MIKE SHE grid squares from MIKE 11 (Thompson et al., 2004).

Gauged daily discharge data at the outlet of two of the largest sub-catchments, the Iril (1271 km^2) and Thoubal (963 km^2) were available for the relatively short period June 1999–May 2003. These data were collected under a project jointly implemented by Wetlands International – South Asia (WISA) and the LDA with financial support from the Ministry of Environment and Forest (MoEF), Government of India and India Canada Environment Facility (ICEF). Data collection ceased at the end of this project, restricting the length of the records. Daily discharge data for the same period are also available for the Nambul (178 km^2), the largest stream within the Western sub-catchment. This sub-catchment is comprised of over 20 streams and rivulets, which have similar catchment characteristics but, with the exception of the Nambul, are ungauged. Discharge data for the remaining sub-catchments are not available. Given this paucity of data, the approach to model calibration and validation was to initially calibrate a model of one of the major sub-catchments for which discharge data were available, in this case the Thoubal, and then to apply the same calibrated parameter values to models developed for the other two gauged sub-catchments, the Iril and Nambul. This form of validation exercise was considered appropriate given the similar geology, soils and vegetation cover within the three catchments. It makes the best use of the available data since the short duration of the discharge records prevents the application of a more traditional split-sample approach (e.g. Klemes, 1986; Xu, 1999). Discharges for the ungauged sub-catchments (excluding the Heirok and Sekmai due to their diversion away from Loktak Lake) were subsequently estimated by weighting the simulated discharges by catchment area. An alternative approach would have been to develop MIKE SHE models for these sub-catchments (e.g. Pradhan et al., 2008) but some data required in the models were not available for these areas.

Catchment land use was spatially distributed using a 1:50 000 scale digital land cover map produced by the Department of Forest and Environment, Government of Manipur using Indian Remote Sensing Satellite (IRS) 1C 2001 imagery. Seven land cover classes are represented: forest, degraded forest, *jhum*, agriculture, settlements, water bodies and *phumdis*. The vegetation properties of each land use class required by MIKE SHE (leaf area index, LAI and root depth, RD) were taken from Jain et al. (1992) and WISA (2005). In the absence of detailed hydrogeological information and given the focus of representing catchment outflows rather than detailed groundwater level fluctuations, a single uniform saturated zone layer up to 100 m thick was specified and its saturated hydraulic conductivity varied during model calibration of the Thoubal sub-catchment. A uniform two-layer unsaturated zone was specified. An initial infiltration rate of $1.4 \times 10^{-6}\,\text{m}\,\text{s}^{-1}$ was specified based on catchment soil type and values from the literature (PWD, 1967; Brouwer et al., 1988). It was subsequently varied during model calibration.

Within each MIKE SHE model, a 600 m × 600 m grid was employed. This grid size was selected as a balance between facilitating a detailed representation of catchment characteristics such as topography and logistically appropriate computational times (e.g. McMichael et al., 2006). A series of experimental runs were undertaken varying grid sizes between 300 m × 300 m and 1000 m × 1000 m. Following the results of Vásquez et al. (2002) there was little change in model performance with change in grid size over this range. Catchment topography was provided from NASA Shuttle Radar Topographic Mission (SRTM, Farr et al., 2007) digital elevation data which have a resolution of 90 m at the equator. These data are widely used in the derivation of digital elevation models (DEMs) since they cover over 80% of the globe, including large portions of the tropics and other areas

Table 2. Calibrated MIKE SHE parameters values.

Model	Parameter	Calibrated value
MIKE SHE	Vertical hydraulic conductivity	$2 \times 10^{-7}\,\mathrm{ms}^{-1}$
	Horizontal hydraulic conductivity	$1 \times 10^{-7}\,\mathrm{ms}^{-1}$
	Overland flow resistance (Manning's M)	$27\,\mathrm{m}^{1/3}\,\mathrm{s}^{-1}$
	Unsaturated zone infiltration rate	$2 \times 10^{-8}\,\mathrm{ms}^{-1}$
MIKE 11	Bed resistance of the stream channel (Manning's n)	$0.04\,\mathrm{s}\,\mathrm{m}^{-1/3}$

of the developing world where other sources of high resolution topographic data are relatively scarce (e.g. Jarvis et al., 2004; Gorokhovich and Voustianiouk, 2006). Hypsometric curves for the three catchments derived using the original SRTM data and the same data resampled to the MIKE SHE model grid size were very similar suggested that the resampled dataset retains a good representation of catchment topographic characteristics.

MIKE 11 branches were abstracted from 1:50 000 scale 1980 Survey of India topographic maps and an IRS-1D 2002 image. River cross sections were defined based on field surveys undertaken by the LDA. All MIKE 11 branches were defined as coupled to MIKE SHE. River-aquifer exchange was evaluated using the Reduced Contact (a) formulation (DHI, 2005) in which conductance is a function of the hydraulic conductivity of both the aquifer and riverbed materials. A uniform value for the latter (the leakage coefficient) of $3 \times 10^{-7}\ 1\,\mathrm{s}^{-1}$ was applied throughout the river network. Similarly, a uniform Manning's n resistance was employed for the river channels and this was varied during model calibration for the Thoubal sub-catchment.

Daily precipitation was provided by the seven rain gauges operated by the LDA with their spatial coverage specified using Thiessen polygons. Similarly, Thiessen polygons were used to specify the spatial coverage of daily PET calculated using the Penmen-Monteith method and employing data from four LDA meteorological stations.

Refsgaard and Storm (1995) suggested that the number of parameters subject to adjustment during calibration of a distributed hydrological model such as MIKE SHE should be as small as possible. Al-Khudhairy et al. (1999) and Thompson et al. (2004) for example limited calibration parameters for MIKE SHE/MIKE 11 models of UK wetlands to hydraulic conductivity in the saturated zone, the Manning's roughness coefficient for overland as well as channel flow, the channel leakage coefficient and the drainage time constant used in the representation of sub-grid scale surface drainage. In the current study the calibration parameters were horizontal and vertical hydraulic conductivity of the saturated zone, unsaturated zone infiltration rate, overland flow resistance (Manning's M), and flow resistance within the stream channels (Manning's n). Initial values of these calibration parameters were taken from the literature. Calibration of the Thoubal model was based on a graphical comparison of observed and simulated discharge at the sub-catchment outlet (the Thoubal Bridge gauging station) with calibration terms being modified iteratively. Widely used statistical measures of model performance were evaluated for each model run and were used to refine the final calibration; the Nash–Sutcliffe coefficient ($R2$, Nash and Sutcliffe, 1970; Garrick et al., 1978: Xiong and Gou, 1999; Andersen et al., 2001; Yang et al., 2001) and the correlation coefficient (r) (Weglarczyk, 1998; Yang et al., 2001, 2002). The percentage difference in the observed and simulated mean daily flow was also calculated. The final values of the calibration parameters are shown in Table 2.

Figure 2a shows the observed and simulated discharge for the Thoubal sub-catchment for the period June 1999–May 2003. It demonstrates that the model is generally successful in reproducing the observed daily flows despite the very flashy nature of the sub-catchment's response to precipitation. Good sequencing of peak flows is achieved although there is a tendency for the model to slightly underestimate the magnitude of the largest peaks during the monsoon period. During the last two dry seasons simulated baseflow exceeds the observed, although a good representation of flows during this time of year is achieved in the first two years of the simulation period. Overall, the frequency distribution of simulated river discharge in the Thoubal sub-catchment closely approximates that of the observed discharge record as indicated by the similar flow duration curves, although the slight overestimation of baseflows is evident (Fig. 2a). Figure 3a demonstrates that the model provides a good representation of mean monthly discharge albeit with the slight underestimation of peak flows and marginally higher baseflows. Table 3, which presents the values of the statistical measures of model performance, confirms the ability of the model. Using the classification scheme of Henriksen et al. (2008) the performance of the model is classed as "excellent".

When the values of the calibration parameters shown in Table 2 were specified within the Iril and Nambul MIKE SHE models, the simulated discharges and their frequency

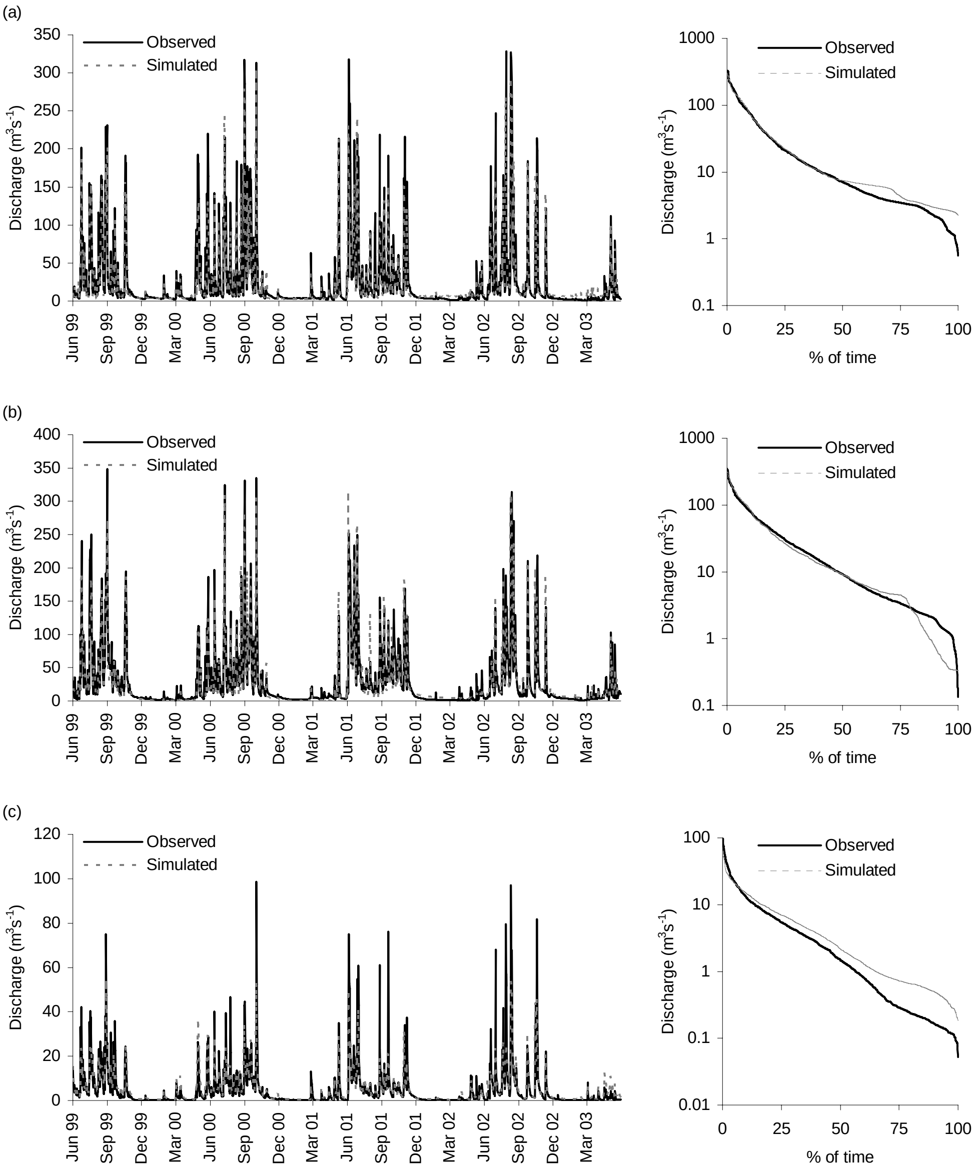

Fig. 2. Comparison (daily flows and flow duration curves) of observed and simulated discharge for the three modelled sub-catchments (June 1999–May 2003) **(a)** Thoubal, **(b)** Iril, **(c)** Nambul.

distribution at the sub-catchment outlets (Moirang Kampu and Hiyang Thang gauging stations, respectively) closely matched the observed records (Fig. 2b, c). Model performance was particularly good for high flows, although lower flows were underestimated (overestimated) in the Iril (Nambul) sub-catchments. A very close fit to observed mean monthly discharge was obtained for the Iril sub-catchment (Fig. 3b). In the Nambul sub-catchment the model's mean monthly discharge closely approximated the observed, although flows were overestimated between March and May (Fig. 3b). The statistical measures of model performance (Table 3) are classified as either "excellent" or "very good", suggesting a robust validation.

As previously noted, discharge records for the remaining ungauged sub-catchments that still contribute to Loktak Lake were derived by weighting simulated discharge for the closest sub-catchment for which a MIKE SHE model was developed by catchment area (Table 4).

4 Simulation of climate change on the Loktak Lake catchment

The study adopts the climate impact assessment approach used by Parry and Carter (1998), which translates specific changes in climatic inputs into changes in hydrological regime. This approach has been widely used to assess

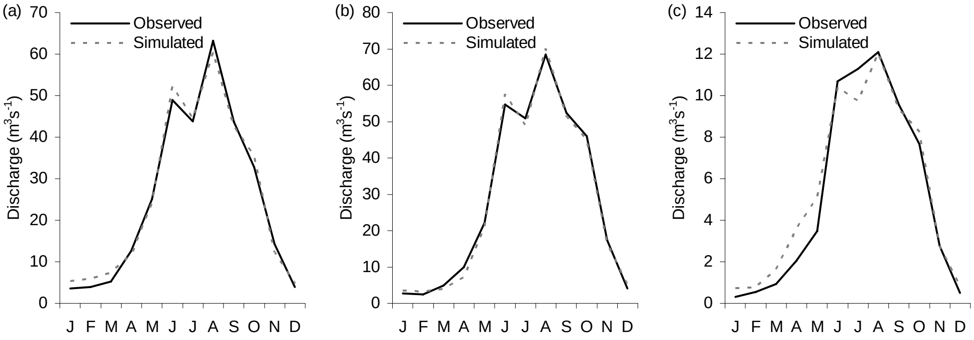

Fig. 3. Observed and simulated mean monthly discharge for the three modelled sub-catchments (June 1999–May 2003) **(a)** Thoubal, **(b)** Iril, **(c)** Nambul.

Table 3. Statistical measures of model performance.

Model	MDFo[a] (m^{3}s^{-1})	MDFs[b] (m^{3}s^{-1})	Dv[c] (%)	$R2$	r
Thoubal River	25.2	25.7	2.0 ∗∗∗∗∗	0.85 ∗∗∗∗∗	0.94
Iril River	28.1	27.9	0.7 ∗∗∗∗∗	0.84 ∗∗∗∗	0.93
Nambul River	5.2	5.5	5.4 ∗∗∗∗	0.82 ∗∗∗∗	0.91
Performance indicator[d]	Excellent ∗∗∗∗∗	Very good ∗∗∗∗	Fair ∗∗∗	Poor ∗∗	Very poor ∗
Dv	< 5%	5–10 %	10–20 %	20–40%	> 40%
$R2$	> 0.85	0.65–0.85	0.50–0.65	0.20–0.50	< 0.20

[a] Observed mean daily flow; [b] Simulated mean daily flow; [c] Deviation in simulated mean daily flow from observed mean daily flow; [d] Based on Henriksen et al. (2008).

Table 4. Simulated mean daily flows of ungauged sub-catchments.

Sub-catchment	Nearest gauging station	Area factor	Mean daily discharge (m^{3}s^{-1})
Imphal	Iril	0.28	7.8
Khuga	Nambul	2.83	15.4
Kongba	Iril	0.09	2.5
Western[a]	Nambul	4.78	26.1

[a] Excludes the Nambul sub-catchment.

climate change impacts on river and wetland hydrological regimes (e.g. Chiew et al., 1995; Fowler and Kilsby, 2007; Thompson et al., 2009) and is adopted by the other papers in this special issue. It involves the following stages (Arnell and Reynard, 1996): (i) define, calibrate and validate a model of the hydrological system using current climate data; (ii) define climate change scenarios and perturb the original input climate data accordingly; and (iii) run the hydrological model with these perturbed climate data and compare results with those simulated under current ("baseline") conditions. Land cover, and hence the model parameters used to represent it such as LAI and RD, are assumed to remain unchanged as a result of climate change. The calibrated models of the Loktak Lake sub-catchments described above provided the first stage in this process and the baseline conditions against which the results of climate change simulations described below were compared.

Two groups of climate change scenarios were investigated. Group 1 was designed to investigate uncertainty between different General Circulation Models (GCMs) for the same 2 °C rise in global mean temperature, the hypothesised threshold for "dangerous" climate change (Todd et al., 2010). Scenarios were generated based on results from seven different GCMs namely CCCMA CGCM31, CSIRO Mk30, UKMO HadCM3, UKMO HadGEM1, IPSL CM4, MPI ECHAM5 and NCAR CCSM30. These GCMs have been selected from the CMIP-3 database (Meehl et al., 2007) as exemplar GCMs representing different future representations of key global climate system features. The scenarios of Group 2 were generated for a prescribed warming of global mean temperature of 1, 2, 3, 4, 5 and 6 °C using the UKMO HadCM3 GCM.

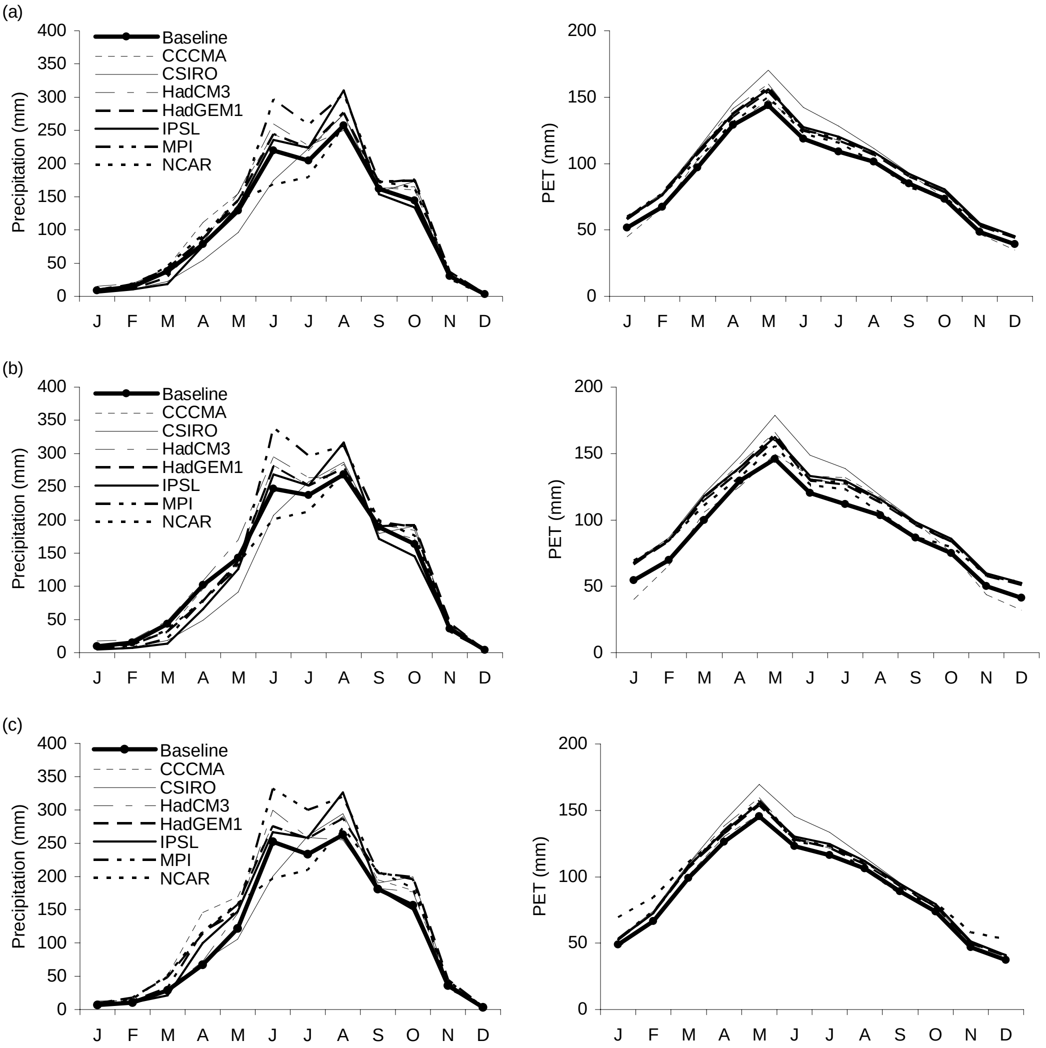

Fig. 4. Precipitation and PET in modelled sub-catchments for the Group 1 scenarios **(a)** Thoubal, **(b)** Iril, **(c)** Nambul (note different y-axis scales for precipitation and PET).

Initially, baseline (1974–2003) monthly mean, maximum and minimum temperature and precipitation totals were obtained for the 17 0.5° × 0.5° grid cells covering the Loktak catchment from the CRU TS 3.0 data set (Mitchell and Jones, 2005). The temperature data were used to evaluate monthly Hargreaves PET for each grid cell. This PET method was employed as results from some GCMs did not provide sufficient data to calculate Penman-Monteith PET. The Hargreaves method is recommended by the FAO in such situations (Allen et al., 1998; Kingston et al., 2009). Subsequently, mean monthly precipitation and PET for each modelled sub-catchment were calculated for the baseline period using those grid cells covering the geographical extent of the sub-catchment. Different combinations of grid cells were therefore used for the three modelled sub-catchments. The ClimGen pattern-scaling technique described by Todd et al. (2010) was used to define monthly mean, maximum and minimum temperature and precipitation totals for each sub-catchment for a future thirty year period for each climate change scenario. These data were used to calculate monthly Hargreaves PET and, in turn, mean monthly precipitation and evapotranspiration over the thirty year scenario period. The differences between mean monthly precipitation and evapotranspiration for the baseline period and each scenario, when expressed as a percent, defined delta factors by which the original station data employed within the calibrated models were modified (see Thompson et al., 2009). These perturbed meteorological inputs were subsequently used within the three MIKE SHE models of Loktak Lake sub-catchments and the resulting discharges used to re-evaluate discharges for ungauged sub-catchments using the method described above. This approach differs from

Table 5. Changes in meteorological precipitation and PET due to the climate change scenarios.

Group	Parameter	Scenario	Thoubal		Iril		Nambul	
			(mm)	% change	(mm)	% change	(mm)	% change
1	Precipitation	Baseline	1290.9	–	1458.0	–	1360.6	–
		CCCMA	1435.0	11	1512.4	4	1634.0	20
		CSIRO	1228.9	–5	1337.1	–8	1412.8	4
		HadCM3	1412.4	9	1604.9	10	1491.5	10
		HadGEM1	1432.1	11	1505.7	3	1620.6	19
		IPSL	1335.1	3	1409.5	–3	1507.1	11
		MPI	1507.9	17	1609.1	10	1707.8	26
		NCAR	1282.2	–1	1370.9	–6	1469.5	8
	PET	Baseline	1064.2	–	1088.7	–	1078.8	–
		CCCMA	1095.6	3	1118.1	3	1087.2	1
		CSIRO	1217.2	14	1301.3	20	1206.3	12
		HadCM3	1171.7	10	1248.6	15	1161.8	8
		HadGEM1	1144.1	8	1218.3	12	1135.0	5
		IPSL	1166.0	10	1245.8	14	1154.6	7
		MPI	1160.1	9	1237.7	14	1149.6	7
		NCAR	1115.8	5	1184.2	9	1106.9	3
2	Precipitation	Baseline	1290.9	–	1458.0	–	1360.6	–
		1 °C	1343.3	4	1523.2	4	1420.7	4
		2 °C	1412.4	9	1604.9	10	1491.5	10
		3 °C	1480.3	15	1674.4	15	1562.7	15
		4 °C	1552.4	20	1761.2	21	1633.3	20
		5 °C	1613.3	25	1808.3	24	1698.6	25
		6 °C	1682.8	30	1907.4	31	1762.5	30
	PET	Baseline	1064.2		1088.7		1078.8	
		1 °C	1137.9	7	1213.4	11	1127.7	5
		2 °C	1171.7	10	1248.6	15	1161.8	8
		3 °C	1205.6	13	1282.7	18	1194.8	11
		4 °C	1237.5	16	1316.9	21	1228.1	14
		5 °C	1269.7	19	1350.0	24	1261.0	17
		6 °C	1301.6	22	1382.6	27	1293.1	20

that employed by others (e.g. Kingston and Taylor, 2010; Thorne, 2010), where hydrological models were calibrated to monthly mean flows using CRU TS 3.0 meteorological inputs disaggregated to a daily resolution using a weather generator (see Todd et al., 2010). The alternative approach was required given the short discharge records which necessitated calibration to daily discharge. In addition, the flashy discharge response to precipitation exhibited by the steep catchments would not be reproduced using weather generator-derived daily meteorological inputs which, although having the same coefficient of variation as the station records, would not display the same day-to-day sequencing.

4.1 Results

Table 5 presents the mean annual precipitation and PET for the baseline period and each of the climate change scenarios for the three sub-catchments for which MIKE SHE models were developed. The percentage changes in both parameters between each scenario and the baseline are also indicated.

Changes in annual precipitation for the scenarios of Group 1 (different GCMs with a 2 °C increase in the global mean temperature) vary between GCMs and sub-catchments. In the Thoubal sub-catchment annual precipitation increases between 3% and 17% for the CCCMA, IPSL,

Table 6. Changes in the mean daily discharge of the three modelled sub-catchments and total annual river inflow to Loktak Lake due to the climate change scenarios.

Group	Scenario	Thoubal		Iril		Nambul		Total river inflow	
		(m^3s^{-1})	% change	(m^3s^{-1})	% change	(m^3s^{-1})	% change	(10^6m^3)	% change
1	Baseline	25.7		27.9		5.5		3498.8	
	CCCMA	25.8	0	29.2	5	7.6	38	4175.1	19
	CSIRO	20.6	–20	23.7	–15	5.9	7	3295.8	–6
	HadCM3	25.4	–1	28.3	1	5.9	7	3638.9	4
	HadGEM1	25.5	–1	29.5	6	7.3	33	4077.5	17
	IPSL	23.0	–11	26.1	–6	6.5	18	3634.6	4
	MPI	28.3	10	32.8	18	7.8	42	4458.4	27
	NCAR	22.1	–14	25.4	–9	6.4	16	3558.3	2
2	Baseline	25.7		27.9		5.5		3498.8	
	1 °C	23.9	–7	27.2	–3	5.7	4	3501.0	0
	2 °C	25.4	–1	28.3	1	5.9	7	3638.9	4
	3 °C	26.7	4	30.1	8	6.1	11	3820.5	9
	4 °C	28.4	11	31.7	14	6.4	16	4001.0	14
	5 °C	30.2	18	33.9	22	6.6	20	4216.7	21
	6 °C	31.8	24	35.4	27	7.0	27	4452.7	27

MPI, HadGEM1 and HadCM3 GCMs whereas it decreases by 1% and 5% for the NCAR and CSIRO GCMs, respectively. Similar variations are evident within the Iril sub-catchment although the IPSL GCM, which in the Thoubal sub-catchment was associated with the smallest (3%) increase in annual precipitation, produces a decrease of 3%. In contrast, for the Nambul sub-catchment annual precipitation increases for all the GCMs although this increase does vary between 4% and 26%. It is lowest for the CSIRO and NCAR GCMs. Figure 4 shows that for these two GCMs, precipitation declines in the early part of the monsoon period (in particular June). Although the peak August precipitation is very similar (NCAR) or greater (CSIRO) to the baseline, and towards the end of the rainy period (September and October) it is generally wetter, the early monsoon declines in precipitation account for the overall reduction in mean annual precipitation. The most noticeable change for the GCMs associated with larger annual precipitation totals is the increase in early monsoon (June) precipitation. In some cases (e.g. HadCM3 for the Iril and Nambul sub-catchments) June precipitation exceeds that of August, historically the wetter month, which also increases. Precipitation in the late monsoon period (September and October) is also higher. In contrast to the variability in precipitation change, Table 5 shows that for all Group 1 scenarios mean annual PET increases with the largest absolute increases occurring between April and August (Fig. 4). The range of increases in annual PET is smaller (1–20%) than the changes in precipitation. CSIRO followed by HadCM3 produced the largest increases in PET in all three sub-catchments whilst the smallest increases are associated with the CCCMA and NCAR GCMs.

For the Group 2 scenarios (changes in global mean temperature of between 1 °C and 6 °C using HadCM3) there is an almost linear increase in mean annual precipitation with each 1 °C increase in temperature (Table 5). Changes are consistent over the three sub-catchments. Figure 5 shows that increasing annual precipitation is largely the result of higher precipitation in the early monsoon period. Beyond an increase of 1 °C there is a switch in peak precipitation from August to June whilst more precipitation occurs in months leading up to this new wettest month. Although August precipitation falls slightly below the baseline for all the scenarios, later months, in particular October, are also progressively wetter with increasing temperature. Mean annual PET for all three sub-catchments increases linearly with increasing temperature (Table 5). The Iril sub-catchment, which under baseline conditions has the largest annual PET, experiences the largest increases. Each month experiences higher PET with the largest absolute increases occurring between March and May (Fig. 5).

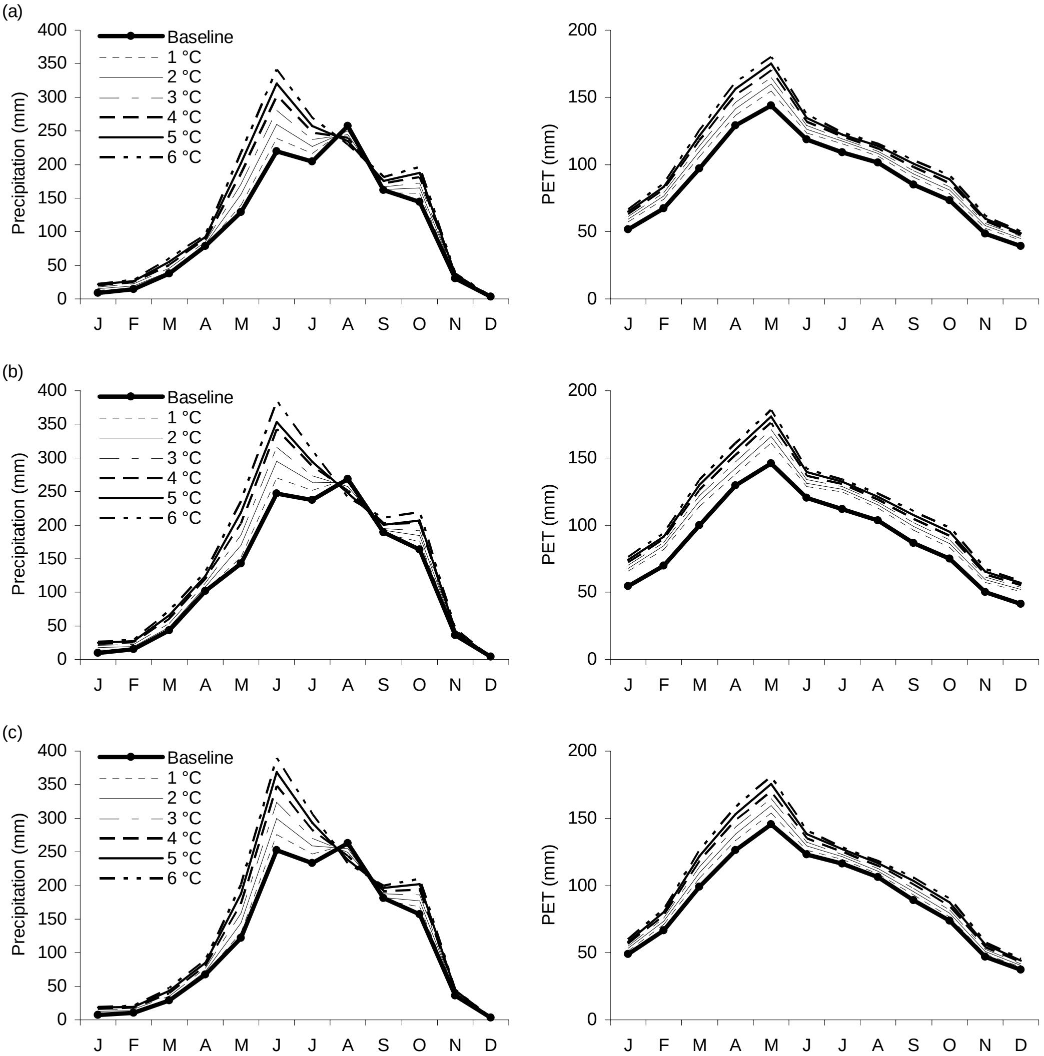

Fig. 5. Precipitation and PET in modelled sub-catchments for the Group 2 scenarios **(a)** Thoubal, **(b)** Iril, **(c)** Nambul (note different y-axis scales for precipitation and PET).

Figure 6a–c summarises the impacts of the Group 1 scenarios on simulated discharge for each of the three modelled sub-catchments. Within the Nambul (Fig. 6c) increases in mean discharge are indicated for all scenarios with magnitudes varying from 7% (CSIRO and HadCM3) to 42% (MPI) (Table 6). The relative magnitude of these changes generally follows those shown for precipitation. The earlier onset of monsoon precipitation for many of the GCMs results in higher discharge immediately before and during the monsoon period. Where this does not occur, most noticeably for the CSIRO GCM which shows a reduction in early monsoon precipitation, discharges increases towards the end of the monsoon period. Similar temporal changes in the distribution of river flows are shown for the Iril catchment although pre-monsoon discharges are lower than under baseline conditions (Fig. 6b). The magnitudes of increases in mean discharge are consistently smaller compared to the Nambul whilst the CSIRO, ISPL and NCAR GCMs, which over the Iril produced declines in annual precipitation of 8%, 3% and 6% (Table 5), result in 15%, 6% and 9% reductions in mean discharge respectively. In the Thoubal sub-catchment (Fig. 6a) increases in mean discharge occur for the CCCMA and MPI GCMs although for the former this increase is very small (0.39%) (Table 6). Increases in discharge for these scenarios are concentrated in the monsoon period with dry season flows being lower than those under baseline conditions. Those scenarios showing relatively small decreases in mean discharge for the Thoubal (HadCM3 and HadGEM1) still result in high discharge in some monsoon months. Discharges during this time of year are lower for the NCAR and, in particular, the CSIRO GCMs which are associated with the largest declines in mean discharge (−14% and −20% respectively, Table 6).

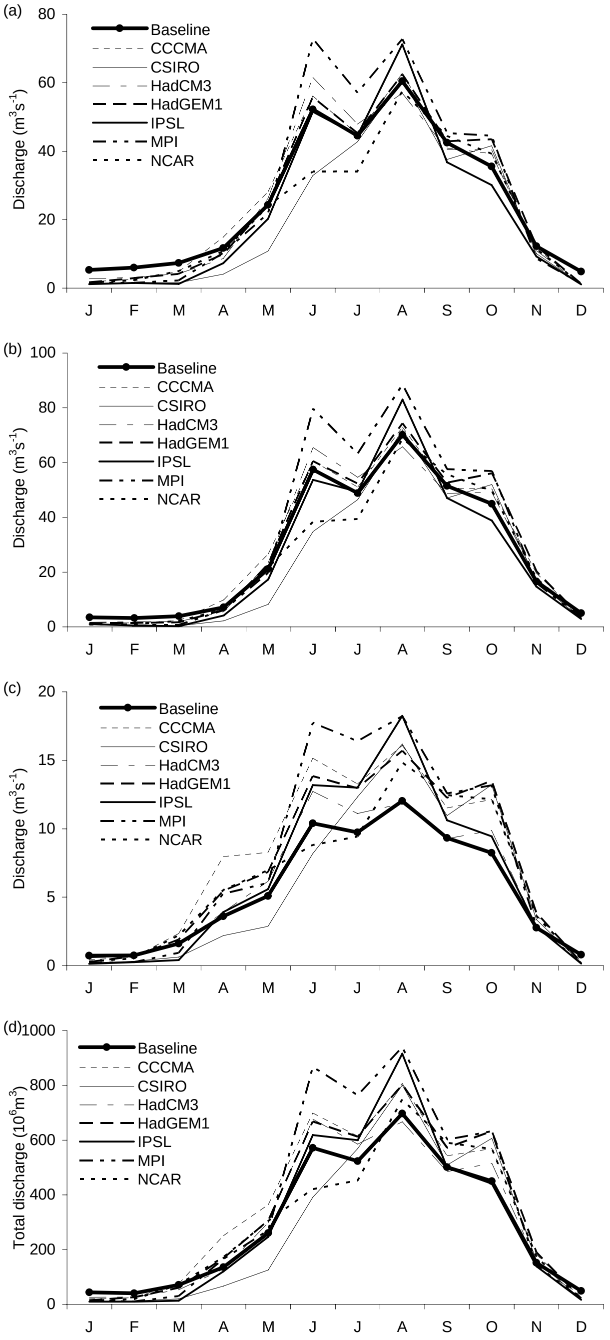

Fig. 6. Mean monthly discharge for the Group 1 scenarios **(a)** Thoubal, **(b)** Iril, **(c)** Nambul, **(d)** total river inflow to Loktak Lake.

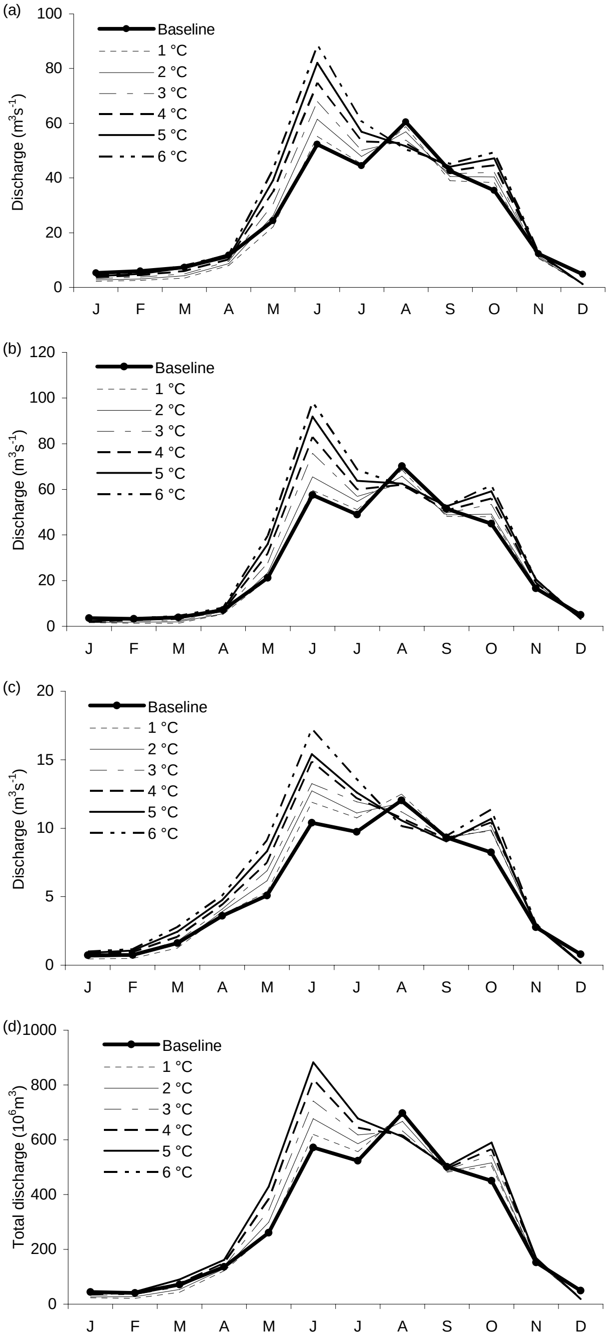

Fig. 7. Mean monthly discharge for the Group 2 scenarios **(a)** Thoubal, **(b)** Iril, **(c)** Nambul, **(d)** total river inflow to Loktak Lake.

Figure 6d shows the mean monthly total river inflow to Loktak Lake associated with each of the Group 1 scenarios. These are based on the combined discharge from the three modelled sub-catchments and flows from those ungauged sub-catchments discharging into the lake evaluated by weighting MIKE SHE modelled discharges by catchment area. The corresponding mean total annual discharges are shown in Table 6. The CSIRO GCM results in an overall decline in annual river flow to the lake with the noticeable reduction in early monsoon flows and higher flows in August. However, the magnitude of this decline is only 6% despite the larger reductions in flow reported above for the Iril and Thoubal sub-catchments (15% and 20% respectively). This is a result of the increases in discharge from Nambul which, as shown in Table 4, is employed in the evaluation of discharge from the Khuga and Western sub-catchment, the two largest ungauged sub-catchments (combined area 1355 km^2). In contrast, results from the Iril are used for the relatively small Imphal and Kongba sub-catchments (combined area 474 km^2) whilst the location of the Thoubal on the eastern side of Loktak Lake catchment means that results from this sub-catchment are not used in evaluating any ungauged flows. For the same reasons the HadCM3, IPSL and NCAR GCMs, which also result in reductions in flow from the Thoubal and, in the case of IPSL and NCAR, the Iril produce relatively small (2–4%) overall increases in river flow to the lake. The remaining GCMs, which increase mean discharge in all three modelled sub-catchments (except HadGEM1 which results in very small declines in discharge in the Thoubal), produce much larger (up to 27% for the MPI) increases in total river contributions to Loktak Lake.

A more consistent pattern of changes in discharge results from the Group 2 scenarios (Fig. 7). The progressively higher precipitation associated with rising global mean temperature leads to increases in mean discharge (of up to 24%, 27% and 27% for the 6 °C scenario in the Thoubal, Iril and Nambul sub-catchments respectively, Table 6), although for the Thoubal mean discharge initially declines for the 1 °C and 2 °C scenarios and for the Iril for the 1 °C scenario. The shift in the wettest month from August to June, increases in July precipitation and small declines in August precipitation are responsible for a change in the temporal distribution of river flow. Beyond the 1 °C scenario (2 °C for the Iril) peak flows shift from August to June and increase with the progressively warmer scenarios. After this peak, discharges are relatively constant until October which, as previously noted, experiences enhanced precipitation compared to the baseline. Discharges in August, which were the highest for the baseline period, are lower than baseline for all the scenarios in all three sub-catchments with the exception of 1 °C for the Nambul. Dry season flows in the Iril sub-catchment are relatively unchanged, in the Nambul they increase slightly (except for the 1 °C scenario) whilst in the Thoubal they are lower. Changes in total annual discharge to Loktak Lake increase almost linearly with increasing global mean temperature. Declines in flow in the Thoubal sub-catchment for the 1 °C and 2 °C scenarios (and for the Iril for the 1 °C scenario) are cancelled out by the increases in the Nambul and the subsequent evaluation of ungauged flows using results for these two sub-catchments. The 1 °C scenario produces a small (<0.1%) increase in total river inflow and this rises to 27.3% for the 6 °C scenario.

5 Implications of climate change for Loktak Lake

The implications of changes in river flow due to the two groups of climate change scenarios upon the water level regime of Loktak Lake were investigated using a monthly water balance model initially developed for the period June 1999–May 2003 under baseline conditions. Equation (1) summarises the water balance of the lake. Given the clays underlying the lake groundwater exchanges were assumed to be small and were excluded.

$$\begin{aligned} V_t = V_{t-1} + (P_t \times A_{t\text{-}1}) + R_t - (E_t \times (A_{t-1} - \mathrm{AP})) \\ -(\mathrm{ET}_t \times \mathrm{AP}) - \mathrm{AbsI}_t - \mathrm{AbsD}_t - \mathrm{AbsH}_t - O_t - S_t \end{aligned} \qquad (1)$$

Where:

- V is the volume of water in Loktak Lake with the initial water level in May 1999 calculated from observed water level at Ningthoukhong and a volume-level relationship developed by the LDA.
- t indicates present month.
- t-1 indicates previous month.
- P is the direct precipitation onto the lake based on rain gauge records from the KLNP meteorological station.
- A is the area of Loktak Lake calculated from a volume-area relationship developed by the LDA.
- R is the discharge from the catchment evaluated using the MIKE SHE models for the gauged sub-catchments with ungauged catchment flows estimated by weighting MIKE SHE results by catchment area as discussed above.
- E is pan open water evaporation from the KLNP meteorological station.
- AP is the area of *phumdis* (135 km^2, Trisal and Manihar, 2004).
- ET is evapotranspiration at KNLP provided by the LDA and based on the Penman-Monteith method.
- AbsI is abstraction for an irrigation scheme along the Manipur River based on records from the Public Works Department (PWD, 1967) and Irrigation and Flood Control Department (IFCD, 1987). Abstractions are only possible when lake level exceeds the minimum drawdown level (MDL) of 766.2 m a.m.s.l. (equivalent to 94.6×10^6 m^3).
- AbsD is abstraction for domestic consumption by communities around the lake and in Imphal based on estimates from IFCD (1987), Government of India (1999) and Government of Manipur (2000).
- AbsH is flow through the turbines of the hydroelectric power station associated with the Ithai Barrage. Monthly volumes were provided by records from the National Hydroelectric Power Corporation (NHPC) and are subject to the same water level restrictions as irrigation abstractions.

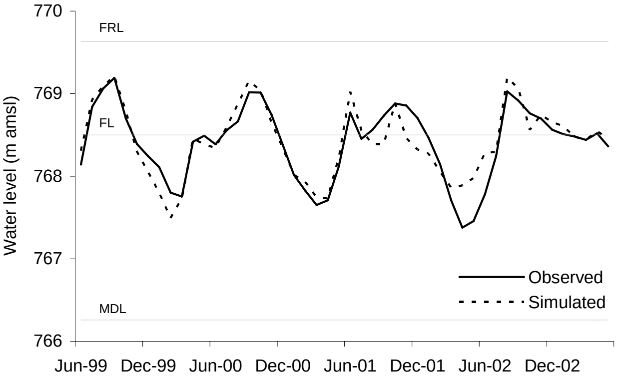

Fig. 8. Observed and simulated mean monthly Loktak Lake water levels (June 1999–May 2003) under baseline conditions (FRL: full reservoir level, FL: flood level, MDL: minimum drawdown level).

– *O* is outflow from the lake provided by releases from the Ithai Barrage and based on records from the NHPC.

– *S* are releases from the Ithai Barrage when lake water levels exceed the height of top of the barrage gates, the full reservoir level (FRL, 769.63 m a.m.s.l., equivalent to 841×10^6 m^3). These releases are made in order to ensure the structural stability of the barrage. Water levels are evaluated using the LDA's volume-level relationship and volumes of water in excess of the FRL are assumed to be released in one month.

Simulated lake volumes for each month were converted to lake levels using the LDA's volume-level relationship. Figure 8 shows the simulated lake level for the period June 1999–May 2003 derived using this approach together with observed levels from the staff gauge at Ningthoukhong. It demonstrates generally good agreement between observed and simulated levels which, on average, differ by only 0.02 m (observed mean: 768.41 m a.m.s.l., simulated mean 768.43 m a.m.s.l.). Statistical comparisons of observed and simulated lake water levels yield values of the correlation coefficient (r) and Nash–Sutcliffe coefficient ($R2$) of 0.81 and 0.80, respectively. These results add confidence in the approach used to evaluate discharges from the ungauged sub-catchments. Lake water levels during the first half of the simulation period are particularly well reproduced, although the subsequent dry season drawdown in 2002 is underestimated. The average annual inputs (based on the three complete years within the simulation period that coincide with the hydrological year) from river flow and precipitation are 3839×10^6 m^3 with the former accounting for 91% of the total. The largest outflows are barrage releases (on average 68% of the 3826×10^6 m^3 total) followed by hydropower abstraction (22%). Evaporation, evapotranspiration, domestic and irrigation abstractions account for small proportions (4%, 4%, 1% and 1%, respectively) of the total outflow. At no point were abstractions compromised by levels falling below the minimum drawdown level. Hydropower abstractions were at, or very close to, the maximum rated capacity of the power station in all months of the simulation period. Observed and simulated water levels did not reach the full reservoir level (769.63 m a.m.s.l.) under baseline conditions so that no barrage safety releases were simulated. Seasonal variations in lake level reflect seasonality in catchment precipitation and in turn river flow with peak levels occurring in September following gains throughout the monsoon period. Ithai Barrage releases are limited to these periods of high river inflow and at other times barrage gates are closed to maximise water supplies for hydropower generation, abstractions for which are largely responsible for the steady drawdown from October to April.

The water balance model was used to simulate the impacts of each of the climate change scenarios. For each scenario the same initial water level as the baseline simulation was employed. Revised river discharges were provided by the results of the MIKE SHE models and subsequent calculation of flows from ungauged sub-catchments. New precipitation, evaporation and evapotranspiration time series were evaluated using the delta factor approach detailed above, and the area of *phumdis* was assumed to remain unchanged. The same abstractions for irrigation, domestic consumption and hydropower generation employed in the simulation of baseline conditions were employed although they were subject to the minimum water level thresholds. Similarly, the recorded volumes of barrage releases were retained with additional releases being calculated if water levels exceeded the full reservoir level.

Figure 9a shows the simulated lake water levels resulting from the Group 1 scenarios. For nearly all of these scenarios lake water levels are higher throughout the year when compared to the baseline. The largest increases are associated with the CCCMA, HadGEM1 and MPI GCMs which induced the largest increases in annual discharge in the Iril and Nambul sub-catchments and the only increases (CCCMA and MPI) and smallest decline (HadGEM1) in Thoubal discharge. Mean lake levels under these scenarios increase by 0.78 m, 0.74 m and 0.64 m respectively compared to the baseline mean of 768.43 m a.m.s.l. Water levels are higher than those of the baseline in every month of the 48-month simulation period for the CCCMA and MPI GCMs whilst for HadGEM1 water level are only lower than baseline in the first month. Similarly, levels are also higher in every month except the first January for the HadCM3 GCM although the mean difference is smaller (0.47 m). The IPSL and NCAR GCMs increase mean lake water level by 0.25 m and 0.11 m respectively with water levels being higher than the baseline in 35 and 28 months (73% and 58% of the simulation period), respectively. Lower water levels compared to the baseline are concentrated in the dry seasons. As Fig. 9a shows, in all of these scenarios water levels exceed the full reservoir

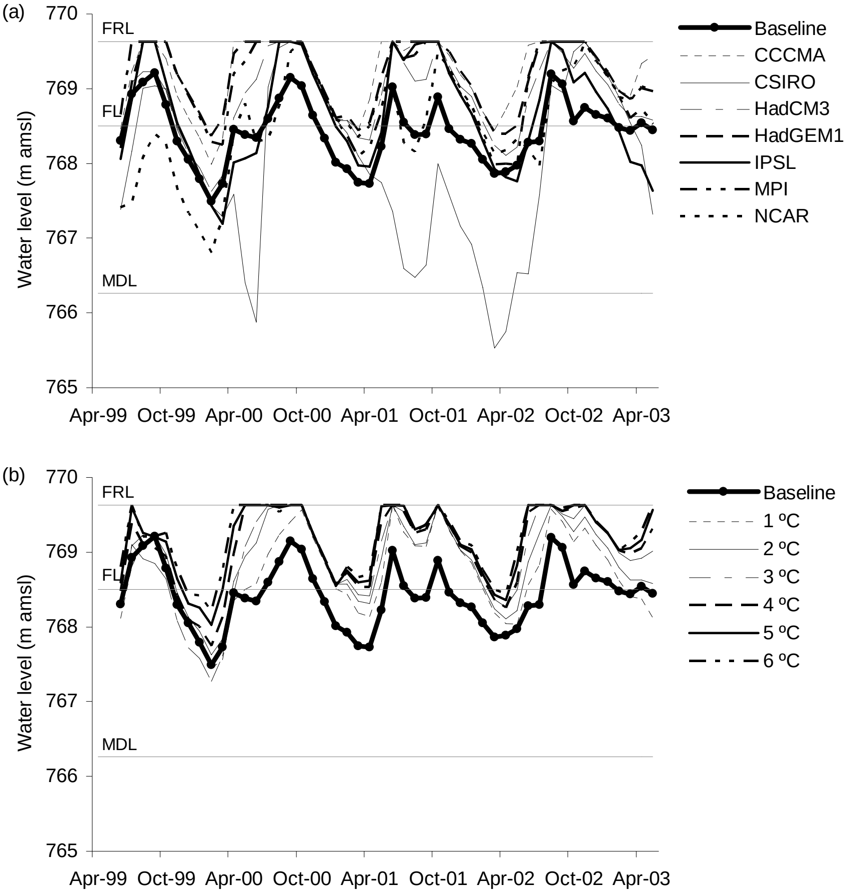

Fig. 9. Simulated mean monthly Loktak Lake water levels under baseline conditions (June 1999–May 2003) **(a)** Group 1 scenarios, **(b)** Group 2 scenarios (FRL: full reservoir level, FL: flood level, MDL: minimum drawdown level).

level (FRL) at some point necessitating additional releases to ensure the barrage is not overtopped. The number of months when these releases are required varies from 16, 15 and 13 for those scenarios resulting in the largest increases in lake water levels (CCCMA, MPI and HadGEM1, respectively) to six for both HadCM3 and IPSL and only one for NCAR which produces the smallest gains in water levels. Results for the CSIRO GCM also indicate that additional barrage releases would be necessary in three months. However, given the overall reduction in river flow to the lake the predominant trend is for lower water levels which on average are 0.47 m below those of the baseline scenario. Dry season lake level drawdowns are noticeably enhanced and in three months abstractions for irrigation and hydropower generation would be prevented. In contrast, for the other six scenarios sufficient water is available for these abstractions throughout the simulation period.

Simulated water levels within Loktak Lake for the Group 2 scenarios are shown in Fig. 9b. Increases in precipitation and especially river flow result in mean lake water levels which are higher than the baseline for all the scenarios. The difference in mean lake water levels from the baseline rises consistently with increasing global mean temperature from 0.30 m for the 1 °C scenario to 0.78 m for the 6 °C scenario. Months when water levels simulated for the Group 2 scenarios are lower than those of the baseline are largely restricted to the first 11 months of the simulation period and in particular the drawdown of 1999–2000 which under baseline conditions was the largest of the simulation period. Enhanced lake evaporation and *phumdi* evapotranspiration at this time of year, when river inflows and precipitation are small, results in lower water levels in at least one month for all of the scenarios and up to 10 months for the 3 °C scenario. In subsequent dry seasons, with the exception of March–May 2003 for the 1 °C scenario, water levels exceed those of the baseline due to enhanced river inflows during the preceding monsoon. Higher water levels during the monsoon period results in the need to release water from the barrage for all the scenarios. The number of months when these releases are necessary increases consistently with rising global mean temperature from two for the 1 °C scenario to 15 for the 6 °C scenario.

6 Discussion

Since the construction of the Ithai Barrage, water level management has focussed on maximising hydropower. As previously noted this has been responsible for changing the hydrological regime of Loktak Lake. Mean lake water levels have increased by approximately 1.1 m (767.3 m a.m.s.l. before the barrage, 768.4 m a.m.s.l. after barrage construction) whilst the magnitude of seasonal fluctuations has declined from approximately 3.1 m (May low water: 765.6 m a.m.s.l.; September high water: 768.7 m a.m.s.l.) to 1.1 m (March: 767.9 m a.m.s.l.; September: 769.0 m a.m.s.l.) (pre-barrage data from WAPCOS, 1993). In common with other wetlands where water levels have been maintained at higher and less variable levels (e.g. Beilfuss and Barzen, 1994; Ni et al., 2006; Baker et al., 2009), major ecological changes have resulted. These include the deterioration of the *phumdis* which are a special characteristic of the lake. During the dry season under pre-barrage conditions these floating islands would make contact with the lake bed from which they would derive nutrients for plant growth which maintains the accumulation of organic matter (Santosh and Bidan, 2002; Trisal and Manihar, 2004). Comparison of *phumdis* thickness and water level depth derived from a bathymetric map shows that this grounding no longer occurs throughout much of Loktak Lake including within the KLNP (Singh, 2010). As a result the thickness of *phumdis* is declining, with surfaces becoming unstable reducing the availability of suitable habitat for wildlife including the endangered brow-antlered deer (Trisal and Manihar, 2004; Angom, 2005). In addition, as shown in Fig. 8, water levels regularly exceed the flood level (FL) of 768.5 m a.m.s.l. specified in the original designs for the Loktak Multipurpose Project (PWD, 1967). This results in the inundation of lakeside villages and agricultural land impacting local rural livelihoods.

Results of the climate change scenarios suggest that unless water level management policies change, ecological modifications within the lake are likely to be exacerbated whilst flooding of lakeside communities will be more of a problem. There is some uncertainty in the magnitude and direction of change in river flows within the three modelled sub-catchments associated with the Group 1 scenarios (the same change in global mean temperature for different GCMs). As advocated by Kingston and Taylor (2010), uncertainty between GCMs could be addressed by the development of reliability ratings for GCMs through comparisons with observed climate (e.g. Perkins et al., 2007; Maxino et al., 2008; Ghosh and Mujumdar, 2009) or probabilistic climate change scenarios (Manning et al., 2009). Despite this uncertainty all but the CSIRO GCM result in increased total river inflow to Loktak Lake. As a result, lake water levels are predominantly higher than the baseline especially during the monsoon period. The Group 1 CSIRO scenario does, in contrast, result in a decline in mean water levels. However, levels in some monsoon months are still higher or similar to baseline conditions and in common with the remainder of the Group 1 scenarios additional releases will be necessary to maintain the safety of the Ithai Barrage. These releases will be required for all the Group 2 scenarios as total river inflow and mean lake water levels increase with rising global mean temperature, although there is some uncertainty in the response of individual sub-catchments for the smallest temperature changes.

The volumes of the releases from the Ithai Barrage calculated by the water balance model can be safely accommodated by the discharge capacity from the barrage when its five sluice gates are fully open (PWD, 1967). However, the ability of the barrage to make larger releases to restore pre-barrage water level regimes (e.g. WAPCOS, 1993) and reduce the incidence of lakeside inundation is not known. Current abstractions from the lake are possible under the climate change scenarios with the exception of three months for the Group 1 CSIRO scenario. However, the higher lake water levels for most of the Group 1 and all of the Group 2 scenarios will only result in very modest increases in hydropower generation since even under baseline conditions the existing infrastructure is operating close to maximum capacity.

It is important to recognise that there are other sources of uncertainty over the future water level regime and ecological conditions of Loktak Lake. For example, water resource development schemes which have been proposed within the Khuga and Iril might reduce inflows to the lake from these sub-catchments. These might, at least partially, counteract the enhanced inflows suggested by most of the climate change scenarios. As plans for such developments are refined their inclusion within the hydrological models developed in this paper would permit the quantification of their impacts. Changes in precipitation may have implications for sediment delivery to the lake, which could also be influenced by land use change such as deforestation within the catchment. Enhanced sedimentation within the lake, reported for other lakes in the Himalayan region (Jain et al., 2002; Rai et al., 2007), would modify the volume-level-area relationship employed within the lake water balance model. Assessment of these impacts would require the quantification of sedimentation rate and its spatial distribution within the lake, both of which are at present unknown.

7 Conclusions

This paper has demonstrated the sensitivity of future river discharge, and in turn water levels within Loktak Lake, northeast India, to different GCMs and changes in global mean temperature. Some uncertainty is evident in the response of different sub-catchments to the Group 1 scenarios (2 °C increase in global mean temperature for seven different GCMs). The majority of scenario–sub-catchment combinations (13 of the total 21) result in increases in mean discharge. Changes in discharge vary between declines of 20% and increases of 42%. All but one (CSIRO) of the seven scenarios increase total annual river flow into Loktak Lake (range between −6% and +27%). In contrast, all of the Group 2 scenarios (1 °C to 6 °C increase in global mean temperature for the same GCM, HadCM3) lead to almost linear increases in total river flow to the lake with rising temperature (>0.1% for 1 °C, 27% for 6 °C) although two subcatchments experience reductions in mean discharge for the smallest temperature increases.

With the exception of the CSIRO Group 1 scenario, results suggest predominantly higher water levels within Loktak Lake, especially during the monsoon period. This will further enhance the trend towards elevated water levels resulting from the Ithai Barrage and the focus on hydropower generation. Under these conditions existing abstractions of water for irrigation and domestic consumption could be maintained whilst they are only prevented in three months for the CSIRO scenario. Additional abstractions for these uses may be possible for the scenarios indicating higher water levels although the potential for further hydropower generation is limited by existing infrastructure. Higher lake water levels are, however, likely to lead to further habitat degradation within the internationally important Loktak Lake ecosystem as well as inundation of rural communities. The additional barrage releases that will be necessary under all the scenarios (including CSIRO which increases some monsoon lake water levels) to maintain the stability of the barrage can be released using existing infrastructure. Larger releases will, however, be required if a more ecological sensitive water level regime is to be restored in order to reverse habitat degradation and prevent undesirable flooding. Further research in this area is needed to inform management responses required to mitigate the impacts of climate change upon Loktak Lake.

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