HYDROLOGICAL AND HYDRAULIC MODELLING FOR THE RESTORATION AND MANAGEMENT OF LOKTAK LAKE, NORTHEAST INDIA

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UCL

Thesis submitted for the degree of Doctor of Philosophy

Declaration

Chabungbam Rajagopal Singh confirm that the work presented in this thesis is my own. Where information had been derived from other sources, I confirm that this had been indicated in the thesis.

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17 December 2010

Abstract

Loktak Lake is an internationally important wetland in northeast India that provides valuable goods and services to local communities as well as supporting high biodiversity. Over the last three decades ecological modifications have occurred, most notably due to the construction and operation of the Ithai Barrage. The focus on maximising hydropower generation increased mean lake water levels and reduced their annual variability. This thesis synthesises hydrometeorological and related data for the lake and its catchment. Data are employed in coupled hydrological / hydraulic catchment models (MIKE SHE / MIKE 11) of three gauged sub-catchments, which are calibrated / validated using observed discharges. Results are used to estimate ungauged sub-catchment flows. Catchment model results are combined with meteorological data and current abstractions within a water balance model which successfully simulates observed lake water levels. A series of barrage operation options are developed using the water balance model which prioritise the requirements of major stakeholders (hydropower, agriculture, and the lake ecosystem). A final option is developed, which shows that it is possible to balance the demands of these stakeholders. The implications of climate change are assessed by forcing meteorological inputs to the catchment and water balance models based upon a number of climate scenarios. In the majority of these scenarios, river inflows increase resulting in higher lake water levels that could further exacerbate ecological degradation of the lake as well as enhancing flooding of lakeside communities. The elevated water levels may permit additional irrigation abstractions however existing infrastructure limits increases in hydropower generation. The sustainability of the barrage operation options in the face of climate change is assessed. Results suggest that climate change is likely to limit the ability of barrage management to satisfy hydropower and agricultural demands whilst at the same time establishing a more ecologically appropriate lake water level regime.

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Acronyms and abbreviations:

BO	Barrage operation
CCG1	Climate change scenario Group 1 (seven GCMs for 2°C rise in global mean temperature)
CCG2	Climate change scenario Group 2 (HadCM3 GCM with 1-6°C rise in global mean temperature)
CCGn_{T}-BOx	
CCGn_{H}-BOx	Where, CCGn is climate change scenarios (n=1 denotes Climate Change Group 1; n=2 denotes Climate Change Group 2) BOx is the barrage operation options (x=1 denotes prioritization to hydropower demand; x=2 denotes prioritization to agriculture demand; x=3 denotes prioritization to ecological demand; x=4 denotes integrated option) T denotes the employment of Thornthwaite method for computing evapotranspiration. H denotes the employment of Hargreaves method for computing evapotranspiration.
FL	Flood level
FRL	Full reservoir level

GCM	Global climate model
IFCD	Irrigation and Flood Control Department
KLNP	Keibul Lamjao National Park
LDA	Loktak Development Authority
LHEP	Loktak Hydro Electric Project
LLI	Loktak Lift Irrigation Project
MA	Millennium Ecosystem Assessment
MDL	Minimum drawdown level
NHPC	National Hydro-Electric Power Corporation
WISA	Wetlands International – South Asia

Acknowledgements

I offer my respect and regards to all those who supported me in any respect during the completion of this thesis. I would like to make a special reference to the Ted Hollis Scholarship in Wetland Hydrology and Conservation through which this thesis was funded. Thanks are also due to the staff of Loktak Development Authority and Wetlands International – South Asia, without their corporation I could not have gotten the relevant data.

I am heartily thankful to my supervisors, Dr. Julian Thompson, Prof. Jon French and Dr. Anson Mackay who had encouraged, supervised and supported me right from the preliminary to the concluding level of this thesis.

I would also like to thank my father, mother, brother and my father-in-law who always had prayed and encouraged me throughout the thesis.

Lastly, I would like to thank my wife, Sangeeta who had always supported me and stood by my side throughout the good and bad times.

Chapter 1 - Wetland Ecosystems

1.1. Introduction

This chapter examines the issues relating to hydrology and ecology and their interrelationship within wetland ecosystems. It focuses on understanding the term ‘wetlands’, their extent and distribution, classifications, the values and benefits they provide. It also discusses the hydro-ecological characteristic of wetland ecosystem and their management issues.

Wetlands are areas where water is the primary factor controlling the environment and associated plants and animal life (Ramsar, 2006). They are transition zones between open water and dry land. They provide many services that contribute to human well-being and poverty alleviation (Millennium Ecosystem Assessment, 2005). Wetlands have always influenced human beings and are vital life-supporting systems for many communities throughout the world. Keddy (2000) observed that early civilizations first arose along the edges of rivers in the fertile soil of floodplains. For example, the lower Mesopotamia Plain was the home to some of the earliest known civilizations and was founded on the sustainable use of the region’s water resources including the uses of marshes for agricultural purposes (Maltby, 2009). Since early civilization, many cultures have learned to live in harmony with wetlands and have benefited economically from surrounding wetlands (Nicholas, 1998). Many major cities of the world, such as Chicago in the United States and London in United Kingdom, stand on sites that were once part wetlands.

The term ‘wetland’ came gradually into common scientific usage only in the second half of the twentieth century (William, 1995). Before that, wetlands were referred to by many common terms such as swamp, marsh, bog, fen, mire, and moor. These terms are still being used but only to specify certain types of wetlands. Cowardin et al. (1985) stated that marshes, swamps, and bogs have been well-known terms for centuries, but only relatively recently have attempts been made to group these landscape units under the single term wetlands. There is no single, indisputable, ecologically sound definition for wetlands, primarily because of the diversity of wetlands and because the demarcation between dry and wet environments lies along a continuum (Cowardin et al., 1985). Institutes and governments agencies dealing with wetlands have also developed their own definitions for scientific and management purposes. Dugan (1993) found over 50 different definitions and classifications of ‘wetland’ which are currently in use. A synthesis of some wetland definitions used by various organizations across the globe is given in Table 1.1. The broadest and most flexible definition is that of the ‘Convention on Wetlands of International Importance’, also popularly know as the ‘Ramsar Convention’. Under the Article 1.1 of the Convention, wetlands are defined as:

*‘‘areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters’’ (*Ramsar, 2006, Page 7).

The figure of not exceeding six metres for marine wetlands under this definition is thought to come from the maximum depth to which sea ducks can dive whilst feeding (Ramsar, 2006). Lakes and rivers are understood to be covered by this definition of wetlands in their entirety, regardless of their depth. In addition, a wide variety of human-made wetlands such as fish and shrimp ponds, farm ponds, irrigated agricultural land, salt pans, reservoirs, gravel pits, sewage farm and canals are covered under this definition.

The Ramsar Convention is an intergovernmental treaty whose mission is ‘the conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world’ (Ramsar, 2006). The convention provides a framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. As of June 2010, 160 nations have joined the Convention as Contracting Parties and henceforth their definition is the most widely used and recognized. Their definition embraces a huge range of habitats (Figure 1.1) including high altitude lakes, floodplains, and mangroves. The Ramsar Convention advocates the philosophy of “wise use” of wetland, which is defined as "the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development" (Ramsar, 2007c).

Table 1.1. Examples of wetland definitions

Organization	**Definition**
US Fish and Wildlife Service	‘Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. For purposes of this classification wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year’ (Cowardin et al., 1979).
U.S. Army Corps of Engineers (Corps) and the U.S. Environmental Protection Agency (EPA)	‘Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas’.
Federal Policy on Wetland Conservation – Implementation Guide for Federal Land Managers, Wildlife Conservation Branch, Canadian Wildlife Service, Environment Canada. 1996	A wetland is land where the water table is at, near or above the surface or which is saturated for a long enough period to promote such features as wet-altered soils and water tolerant vegetation. Wetlands include organic wetlands or “peatlands,” and mineral wetlands or mineral soil areas that are influenced by excess water but produce little or no peat.
Coastal Commission, California Code of Regulations	‘...land where the water table is at near, or above the land surface long enough to promote the formation of hydric soils or to support the growth of hydrophytes, and shall also include types of wetlands where vegetation is lacking and soil is poorly developed or absent as a result of frequent drastic fluctuations of surface water levels, wave action, water flow, turbidity or high concentration of salts or other substances in the substrate. Such wetlands can be recognized by the presence of surface water or saturated substrate at some during each year and their location within, or adjacent to vegetated wetland or deepwater habitats’ (14 CCR 13577).
Ramsar Convention Bureau	‘areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters’ (Ramsar, 2006).

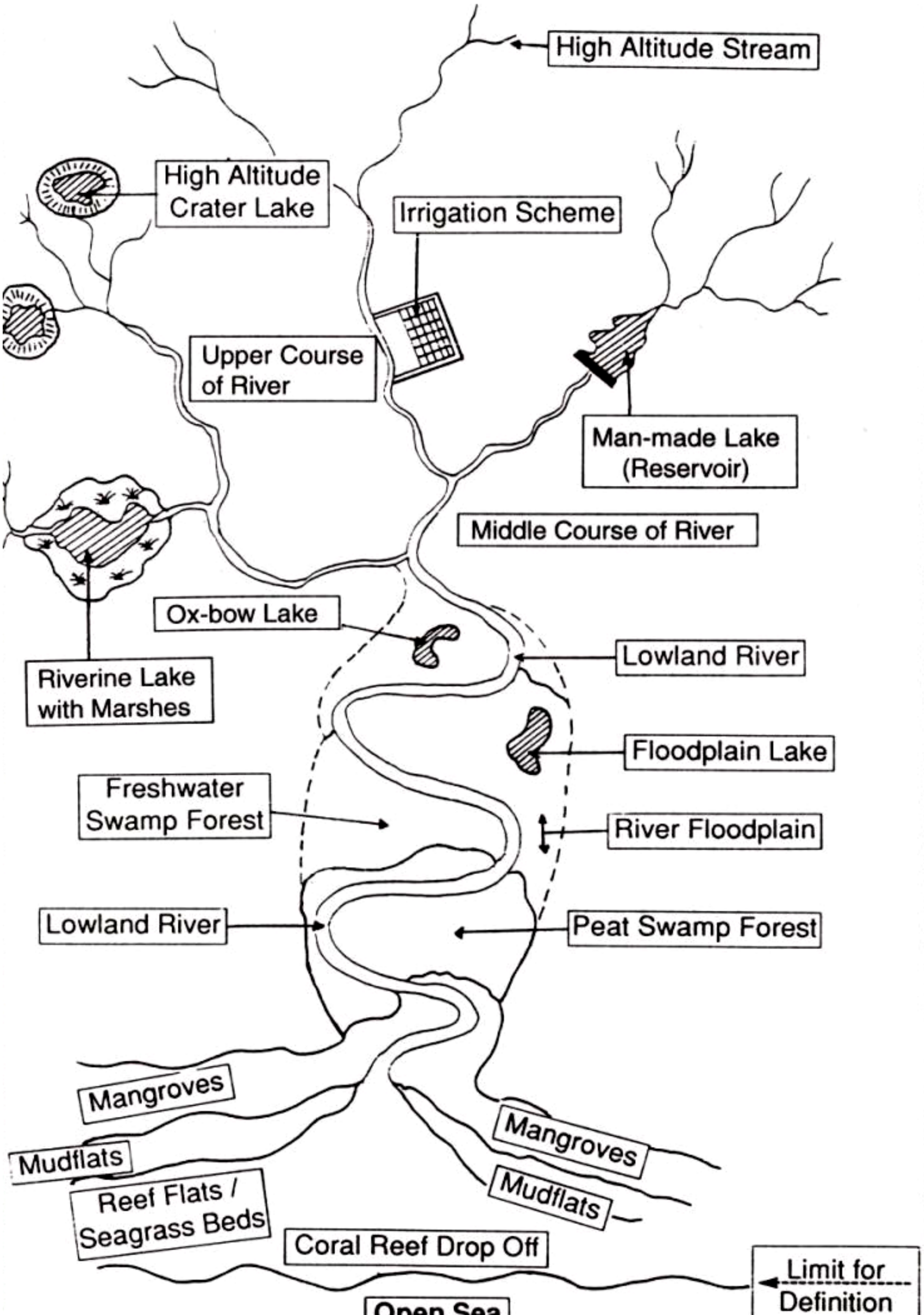


Figure 1.1. Types of wetlands included in the Ramsar definition. Source: Davis and Claridge (1993)

1.2. Extent and distribution of wetlands

Wetlands are found in almost all the continents and in every climate, from the tropics to the tundra (Mitsch and Gossenlink, 2000). However, the exact extent of wetlands is uncertain because of difficulties in identifying and classifying wetlands on a global scale. The global extent of wetlands has been estimated as 5.3×10^6 km^2 (Matthews and Fung, 1987) and 8.6×10^6 km^2 (Mitchell, 1990), but these figures are uncertain. Estimates of the global extent of wetlands differ significantly among different studies (Finlayson et al., 1999; Lehner and Doll, 2004; Finlayson and D'Cruz, 2005; Fernandez-Prieto et al., 2006) and are highly dependent on the definition of wetlands used and on the methods for delineating wetlands. Table 1.2 presents the two best available estimates of wetland distribution: the Global Review of Wetland Resources and Priorities for Wetland Inventory (GRoWI) (Finlayson et al., 1999) and the WWF / Kassel University Global Lakes and Wetlands Database (Lehner and Doll, 2004).

Table 1.2. Estimates of Global Wetland Area (with percentage area in parentheses) for each of the six geopolitical regions used by Ramsar Convention on Wetlands

Region	**1999 Global Review of Wetland Resources (Finlayson et al., 1999)** (10^4 km^2) (%)	**2004 Global Lakes and Wetlands Database (Lehner and Doll, 2004)** (10^4 km^2)(%)
Africa	125 (10)	131 (14)
Asia	204 (16)	286 (32)
Europe	258 (20)	26 (3)
Neotropics	415 (32)	159 (17)
North America	242 (19)	287 (31)
Oceania	36 (3)	28 (3)
Total area	**1280**	**917**

Source: Rebelo et al. (2009)

According to GRoWI, the overall wetland area was estimated to be 1280×10^4 km^2, an area 33% larger than the United States and 50% larger than Brazil. This estimate adopted the wetland definition of the Ramsar Convention Bureau, which includes inland and coastal wetlands near-shore marine areas, and human-made wetlands such as reservoirs and rice paddies. However, this estimate is known to under-represent many wetland types (Rebelo et al., 2009), especially for the Neotropics and for certain wetlands such as intermittently flooded inland wetlands, peatlands, artificial wetlands, seagrasses, and coastal flats where data were incomplete or not readily accessible (Millennium Ecosystem Assessment, 2005). The separate assessment carried out by Lehner and Doll (2004) (Table 1.2) estimated the global wetland area to 917×10^4 km^2 which differs substantially to the earlier estimate put forward by Finlayson et al., (1999), particularly in relation to area of wetlands in Europe and the Neotropics. Figure 1.2 shows a global map of the distribution of large lakes, reservoirs, and wetlands based on data in the Global Lakes and Wetlands Database.

1.3. Wetland classification

Wetlands have been difficult natural systems to classify because the term is imprecise, there have been confusing concepts of what constitutes a wetland, and there have been differing criteria used in their classification (Semeniuk and Semeniuk, 1995). For instance, some wetlands have been classified solely on their vegetation structure or floristics (e.g. salt marshes, and meadows), some according to their vegetation combined with associated soil/substrate and water types (e.g. peatlands, bogs, fens), and some on their hydrological characteristic including permanence of water (U.S.EPA, 2002; Ramsar, 2007d). The primary objective of wetland classification is to impose boundaries on wetland ecosystems for the purposes of inventory, evaluation, and management (Cowardin et al., 1985) and to reduce variability within classes caused by differences in natural condition related to factors such as geology, hydrology, and climate (U.S.EPA, 2002). Cowardin et al. (1985) further added that the type of classification system chosen depends on the particular scientific, management, or regulatory application of interest.

As previously stated, the Ramsar Convention has adopted a broad and flexible wetland definition which complicates the process of classification. As per Recommendation 4.7 and amended by Resolutions VI.5 and VII.11 of the Conference of the Contracting Parties to Ramsar Convention, wetlands are divided into 42 types, grouped under three categories: marine and coastal, inland, and human-made wetlands (Table 1.3, Ramsar, 2006). This classification is one of the most widely used schemes. Some countries base their national classification system on Ramsar classification with slight modifications to suit their regional requirement. An example is the wetland classification system in Australia adopted by the Australian and New Zealand Environment and Conservation Council (ANZECC) in 1994 which was based on the Ramsar classification system with the notable addition of non-tidal freshwater forested wetlands and rock pools. The present PhD research was carried on a permanent inland freshwater water lake in northeast India, which falls under Category O of the Ramsar classification system.

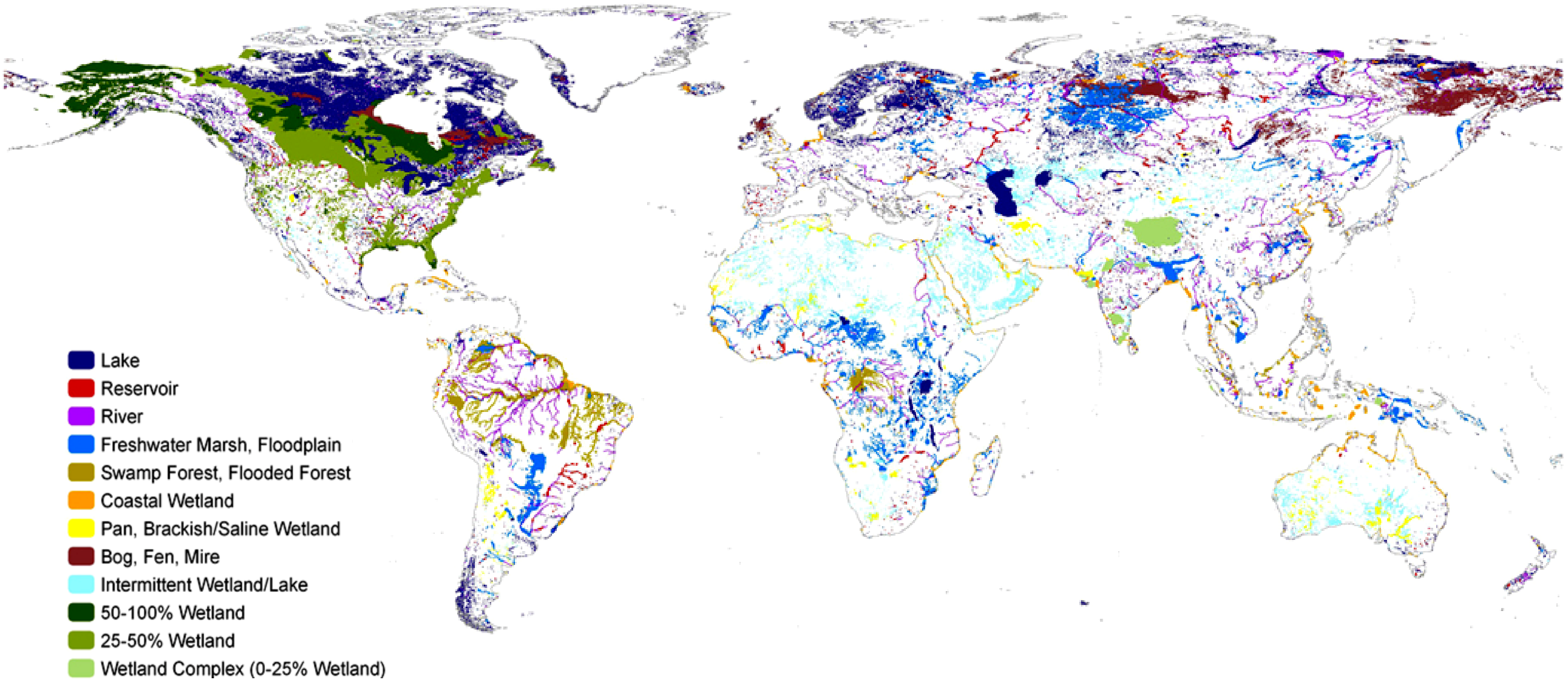


Figure 1.2: Global distribution of lakes and wetlands. Source: Lehner and Doll (2004)

Table 1.3. Ramsar Wetland Classification system

Marine/Coastal Wetlands	
A	Permanent shallow marine waters in most cases less than six metres deep at low tide; includes sea bays and straits.
B	Marine subtidal aquatic beds; includes kelp beds, sea-grass beds, tropical marine meadows.
C	Coral reefs.
D	Rocky marine shores; includes rocky offshore islands, sea cliffs.
E	Sand, shingle or pebble shores; includes sand bars, spits and sandy islets; includes dune systems and humid dune slacks.
F	Estuarine waters; permanent water of estuaries and estuarine systems of deltas.
G	Intertidal mud, sand or salt flats.
H	Intertidal marshes; includes salt marshes, salt meadows, saltings, raised salt marshes; includes tidal brackish and freshwater marshes.
I	Intertidal forested wetlands; includes mangrove swamps, nipah swamps and tidal freshwater swamp forests.
J	Coastal brackish/saline lagoons; brackish to saline lagoons with at least one relatively narrow connection to the sea.
K	Coastal freshwater lagoons; includes freshwater delta lagoons.
Zk(a)	Karst and other subterranean hydrological systems, marine/coastal.
Inland Wetlands	
L	Permanent inland deltas.
M	Permanent rivers/streams/creeks; includes waterfalls.
N	Seasonal/intermittent/irregular rivers/streams/creeks.
O	Permanent freshwater lakes (over 8 ha); includes large oxbow lakes.
P	Seasonal/intermittent freshwater lakes (over 8 ha); includes floodplain lakes.
Q	Permanent saline/brackish/alkaline lakes.
R	Seasonal/intermittent saline/brackish/alkaline lakes and flats.
Sp	Permanent saline/brackish/alkaline marshes/pools.
Ss	Seasonal/intermittent saline/brackish/alkaline marshes/pools.
Tp	Permanent freshwater marshes/pools; ponds (below 8 ha), marshes and swamps on inorganic soils; with emergent vegetation water-logged for at least most of the growing season.
Ts	Seasonal/intermittent freshwater marshes/pools on inorganic soils; includes sloughs, potholes, seasonally flooded meadows, sedge marshes.
U	Non-forested peatlands; includes shrub or open bogs, swamps, fens.
Va	Alpine wetlands; includes alpine meadows, temporary waters from snowmelt.
Vt	Tundra wetlands; includes tundra pools, temporary waters from snowmelt.
W	Shrub-dominated wetlands; shrub swamps, shrub-dominated freshwater marshes, shrub carr, alder thicket on inorganic soils.
Xf	Freshwater, tree-dominated wetlands; includes freshwater swamp forests, seasonally flooded forests, wooded swamps on inorganic soils.
Xp	Forested peatlands; peatswamp forests.
Y	Freshwater springs; oases.
Zg	Geothermal wetlands.
Zk(b)	Karst and other subterranean hydrological systems, inland.
Human-made wetlands	
1	Aquaculture (e.g., fish/shrimp) ponds
2	Ponds; includes farm ponds, stock ponds, small tanks; (generally below 8 ha).
3	Irrigated land; includes irrigation channels and rice fields.
4	Seasonally flooded agricultural land (including intensively managed or grazed wet meadow or pasture).
5	Salt exploitation sites; salt pans, salines, etc.
6	Water storage areas; reservoirs/barrages/dams/impoundments (generally over 8 ha).
7	Excavations; gravel/brick/clay pits; borrow pits, mining pools.
8	Wastewater treatment areas; sewage farms, settling ponds, oxidation basins, etc.
9	Canals and drainage channels, ditches.
Zk(c)	Karst and other subterranean hydrological systems, human-made

Source: Ramsar (2006)

These types of wetlands are important component of the aquatic ecosystem and are characterized by high levels of biodiversity (Roy and Nandi, 2008). Permanent inland freshwater water lakes are generally situated within a topographic depression and are greatly influenced by both physiographic and climatic conditions.

1.4. Wetland values and benefits

Wetlands are vital life support systems for many communities throughout the world (Thompson and Hollis, 1999) and have provided humans with essential resources throughout their entire evolution history (Barker and Maltby, 2009). Many past human civilizations for 6000 years had been concentrated around river valleys and many wetlands systems including lakes, for example the Babylonians, Egyptians and the Aztec (Mitsch and Gossenlink, 2000). The multiple roles of wetland ecosystems and their value to humanity have been increasingly understood and documented in recent years (Barbier et al., 1997; Millennium Ecosystem Assessment, 2005). The recent rise in awareness of the importance of wetlands has much to do with an enhanced appreciation of their many positive, ecological and environmental functions and the values that society places on those functions (Williams, 1990; Boavida, 1999). Wetland ecosystems, including rivers, lakes, marshes, rice fields, and coastal areas, provide many services that contribute to human well-being and poverty alleviation (Millennium Ecosystem Assessment, 2005). People living on and around the wetlands across the world, especially in Asia and Africa, are highly dependent on the wetland resources for their livelihood. For example; Chilika Lagoon, situated in eastern coast of India, supports 177,000 people through direct fisheries and its associated industries and marketing operations (WISA, 2004). Wetlands are also considered as the cradles for biological diversity, providing water and primary productivity upon which countless species of plants and animals depend for their survival (Ramsar, 2006). Mitsch and Gossenlink (2000) refer to wetlands as biological supermarkets' because of the extensive food chain and rich biodiversity that they support.

According to the Millennium Ecosystem Assessment (MA) (2005), the wide range of goods and services that wetlands provide can be broadly classified as *provisioning*, *regulating* and *cultural*, which are directly affecting people, and *supporting* which are needed to maintain the other services. All the services and goods derived from wetlands, which are also known as ecosystem services (Ehrlich and Wilson, 1991) are summarized in Table 1.4. MA (2005) further stated that fish supply and water availability are the two most important services affecting human-well being. According to their estimation, capture fisheries in coastal waters accounts for $34 billion annually. Inland fisheries are of immense importance especially to developing countries as they are sometime the primary source of animal protein to rural communities. For example, the fishery from Tonle Sap and its associated floodplains provides about 60-80% of the total animal protein for the people of Cambodia (Millennium Ecosystem Assessment, 2005). Dugan (1990) found that around 66% of all fish consumed by humans are dependent upon wetlands at some stage of their life.

Wetland ecosystems are the primary resources from which water and all its benefits for humans are derived, and they are a major and critical component of the hydrological cycle which keeps human population supplied with water (Ramsar, 2007a, b, c; McCartney and Acreman, 2009). The principal supply of renewable fresh water for human use comes from an array of inland wetlands, including lakes, rivers, swamps, and shallow groundwater aquifers. Inland wetlands serve 12 times as many people downstream through river corridors as they do through locally derived runoff (Millennium Ecosystem Assessment, 2005). For many communities in developing countries, wetlands remain the major source of water for domestic and irrigational purposes (Masiyandima et al., 2004; MaCartney and van Koppen, 2004). Groundwater is often recharged by wetlands (Ramsar, 2006; McCartney and Acreman, 2009) and plays an important role in water supply, with an estimated 1.5–3 billion people dependent on it as a source of drinking water (Millennium Ecosystem Assessment, 2005). Inland wetlands provide a wide array of hydrological services, notably flood reduction, water purification and regulation of river flows (Evans et al., 1996; Boavida, 1999; Acreman, 2000; Ghosh and Sen, 2000; Dordio et al., 2008; Chen et al., 2008; Kadlec, 2009). In addition, wetlands have significant aesthetic, education and cultural values and also provide tremendous scope for recreation and tourism (Thompson and Hollis, 1997; Ramsar, 2006; Barker and Maltby, 2009). Some wetlands play a major part in supporting the rural economies though their tourism activities. For example, in the United States some 35–45 million people take part in recreational fishing (inland and saltwater) spending a total of $24–37 billion each year on their hobby (Millennium Ecosystem Assessment, 2005).

Table 1.4. Ecosystem services provided by or derived from wetlands

Services	Comments and examples
Provisioning	
Food	production of fish, wild game, fruits, and grains
Fresh water*	storage and retention of water for domestic, industrial, and agricultural use
Fiber and fuel	production of logs, fuelwood, peat, fodder
Biochemical	extraction of medicines and other materials from biota
Genetic materials	genes for resistance to plant pathogens, ornamental species, and so on
Regulating	
Climate regulation	source of and sink for greenhouse gases; influence local and regional temperature, precipitation, and other climatic processes
Water regulation (hydrological flows)	groundwater recharge/discharge
Water purification and waste treatment	retention, recovery, and removal of excess nutrients and other pollutants
Erosion regulation	Retention of soils and sediments
Natural hazard regulation	flood control, storm protection
Pollination	habitat for pollinators
Cultural	
Spiritual and inspirational	source of inspiration; many religions attach spiritual and religious values to aspects of wetland ecosystems
Recreational	opportunities for recreational activities
Aesthetic	many people find beauty or aesthetic value in aspects of wetland ecosystems
Educational	opportunities for formal and informal education and training
Supporting	
Soil formation	Sediment retention and accumulation of organic matter
Nutrient cycling	storage, recycling, processing, and acquisition of nutrients

* *While fresh water was treated as a provisioning service within the MA, it is also regarded as a regulating service by various sectors*

Source: Millennium Ecosystem Assessment (2005)

Table 1.5 highlights examples of hydrological-ecological relationships at different river flow conditions that support the ecological characteristic of wetlands and services they provide. Hydrological regime is generally the most important factor determining the establishment and maintenance of specific types of wetland and wetland processes (Gilman, 1994; James, 2000; Keddy, 2000; Ramsar, 2007b). Different hydrological conditions, as shown in Table 1.5, affect numerous abiotic factors, including nutrient availability, flushing of pollutants including organic materials and woody debris, soil anerobiosis, creating suitable chemical conditions, including dissolved oxygen etc that determine wetland biota. In addition, wetlands also play a synergistic role in the global water cycle.

Table 1.5. Examples of hydrological-ecological relationships at different flows that support ecological character of wetlands and their services.

Flow component	Ecological role
Low (base) flows Normal level:	Provide adequate habitat space for aquatic organisms
	Maintain suitable chemical conditions, including dissolved oxygen
	Maintain water table levels in floodplain and plant soil moisture
	Provide drinking water for terrestrial animals
	Keep fish and amphibian eggs suspended
	Enable passage of fish to feeding and spawning areas
	Support hyporheic organisms (living in saturated sediments)
Low (base) flows Drought level:	Enable recruitment of certain floodplain plants
	Purge invasive, introduced species from aquatic and riparian communities
	Concentrate prey into limited areas to the benefit of predators
Higher flows (small flood pulses)	Shape physical character of river channel, including availability and heterogeneity of different biotopes(such as riffles, pools) and microhabitats
	Restore normal water quality after prolonged low flows, flushing away waste products, pollutants, and proliferations of nuisance algae
	Maintain suitable salinity conditions in estuaries
	Prevent encroachment of riparian vegetation into the channel
	Aerate eggs in spawning gravels, prevent siltation of cobble interstices
	Determine size of river bed substrata (sand, gravel, cobble, boulder)
Large floods	Provide fish migration and spawning cues
	Provide new feeding opportunities for fish and waterbirds
	Recharge floodplain water table
	Maintain diversity in floodplain forest types through prolonged inundation
	Control distribution and abundance of plants on floodplain
	Trigger new phases of life cycles (such as insects)
	Enable fish to spawn on floodplain, provide nursery area for juvenile fish
	Deposit nutrients on floodplain
	Maintain balance of species in aquatic and riparian communities
	Create sites for recruitment of colonizing plants
	Shape physical character and habitats of river channels and floodplain
	Deposit substrata (gravel, cobble) in spawning areas
	Flush organic materials (food) and woody debris (habitat structures) into channel
	Purge invasive, introduced species from aquatic and riparian communities
	Disburse seeds and fruits of riparian plants
	Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes)
	Provide plant seedlings with prolonged access to soil moisture
	Drive floodplain productivity

Source: Millennium Ecosystem Assessment (2005)

1.5. Wetland hydrology

This section examines the characteristics and dynamics of wetland hydrology. Barker and Maltby (2009) argued that understanding hydrology (including the rate and balance of water inputs and loss, together with net water storage) is pre-requisite to understanding and effective management of wetland ecosystems. Mitsch and

Gossenlink (2000) argued that the hydrology of wetland ecosystem creates the unique physiochemical conditions that make it different from both well-drained terrestrial systems and deepwater aquatic systems. Hydrology controls the abiotic and biotic characteristics of wetlands (William, 1995; Russo, 2008, Baker et al., 2009). Figure 1.3 shows how the hydrology of a wetland can directly influence its physiochemical environment (chemical and physical properties), such as nutrient availability, and pH.

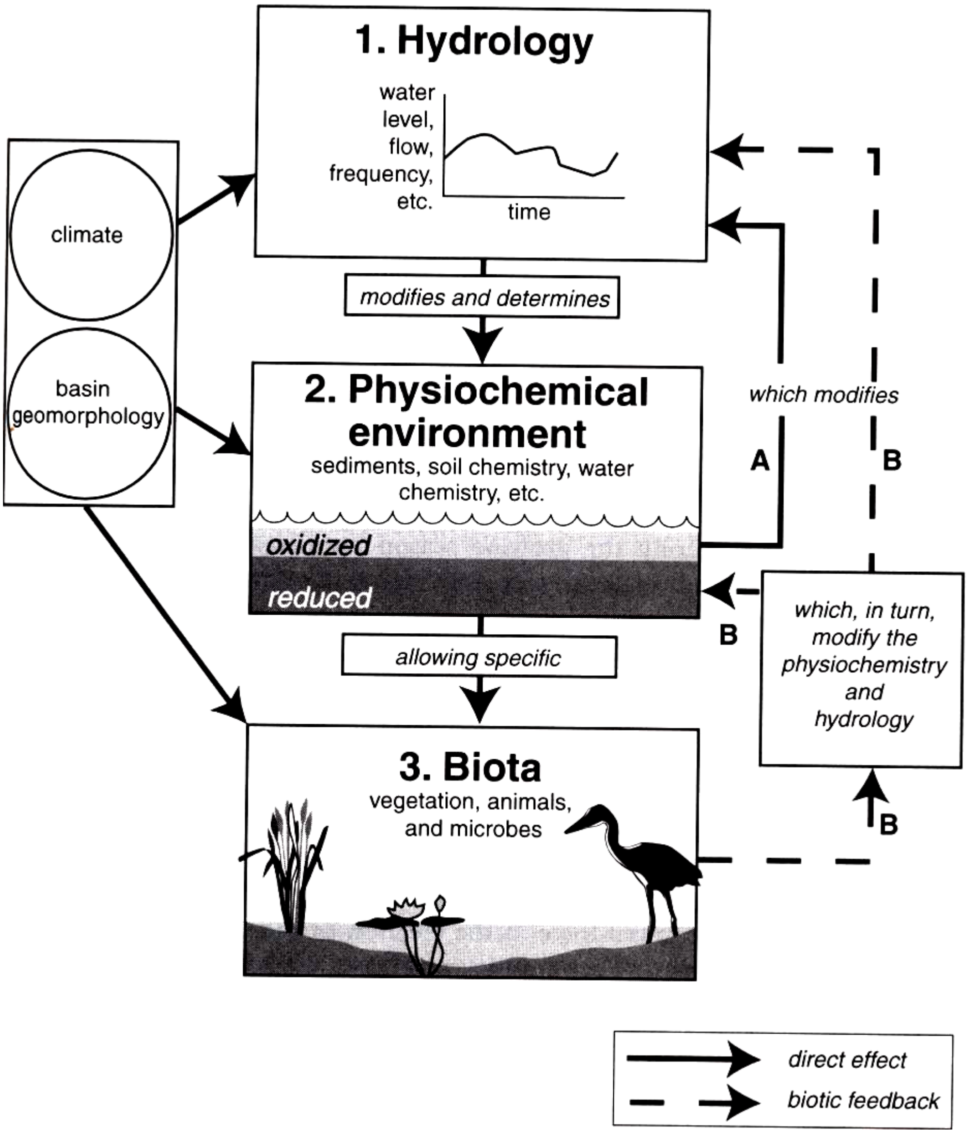


Figure 1.3. Conceptual diagram illustrating the effects of hydrology on wetland function and the biotic feedbacks that effect wetland hydrology. Pathways A and B are feedbacks to the hydrology and physiochemistry of the wetland. Source: Mitsch and Gosselink (2000)

Hydrological processes are also associated with the transport of sediment, nutrients, and even toxic materials, thereby further influencing the physiochemical environment. Climate and geomorphology are two important factors influencing the hydrology within a wetland (Mitsch and Gosselink, 2000). Cool climates have less water loss via evapotranspiration, whereas wet climates have excess precipitation. Flat or gentle slope terrains have more wetlands than compared to steep terrains. In addition to climate and geomorphology, it is very important to understand that inland freshwater wetlands do not function in isolation. Rather, their hydrology is commonly linked to a larger catchment and understanding of the interactions with hydrological processes operating at the broader catchment scale is essential (Hollis and Thompson, 1998; Baker et al., 2009). Wetlands are an integral part of the catchment and are highly dependent upon the upstream conditions within their catchment for their input of water, energy and nutrients. It is possible for activities taking place within one part of a river basin to impact wetlands which are far downstream from the sources of disturbance (Thompson and Hollis, 1997).

Many engineering approaches to water resources development, such as dams and diversion, often cause significant damages to wetlands (Thompson and Hollis, 1995; Manley and Wright, 1996; Kingsford et al., 2006; Walker 2006). In most cases, activities, such as construction of dams and abstraction of water for human uses, taking place in the upper reaches of a river basin are often felt in the lowlands. For example, the diversion of water from the Banganga and Gambhir rivers for irrigation and other human uses had severely impacted the Keoladeo National Park, a wetland of international importance in western India (Vijayan, 1991). The inter-relationship between wetlands and their catchments at a broader scale is particularly important with respect to understanding the human-induced impacts on wetlands. Considering the important roles that wetlands can play in river management, the integration of wetland conservation and wise use into river basin management, is essential in order to maximise and sustain the benefits they together provide to human populations (White and Fennessy, 2005; Hattermann et al., 2006; Ramsar, 2007a,c).

1.5.1. Wetland water balance

Water may flow in several ways into, through and out of wetland (Baker et al., 2009). Precipitation, surface water inflow and outflow, groundwater exchange, and evapotranspiration are the major components which influences the hydrology of most wetlands (USEPA, 1993). The sum total effect of all the hydrological factors or in other words, the balance of inflows and outflows of water through a wetland defines the water balance or water budget, which is commonly used tool to consider the hydrology of any ecosystem (Gasca-Tucker and Acreman, 2000; Bonnet et al., 2008; Baker et al., 2009). The generalized water balance for inland freshwater wetland as shown in Figure 1.4 can be represented by the equation:

$$\Delta V/\Delta t = P_n + S_i + G_i - ET - S_o - G_o - Abs \qquad (1.1)$$

where,

$\Delta V/\Delta t$	is change in volume of water storage in wetland per unit time, t
P	is precipitation
S_i	is surface inflows
G_i	is groundwater inflows
ET	is evapotranspiration
S_o	is surface outflows
G_o	is groundwater outflows
Abs	is Anthropogenic abstractions

Each of the terms in Equation 1.1 can be expressed in terms of depth per unit time (e.g. m month^{-1}, m yr^{-1}) or in term of volume per unit time (e.g. m month^{-1}, m^3 yr^{-1}).

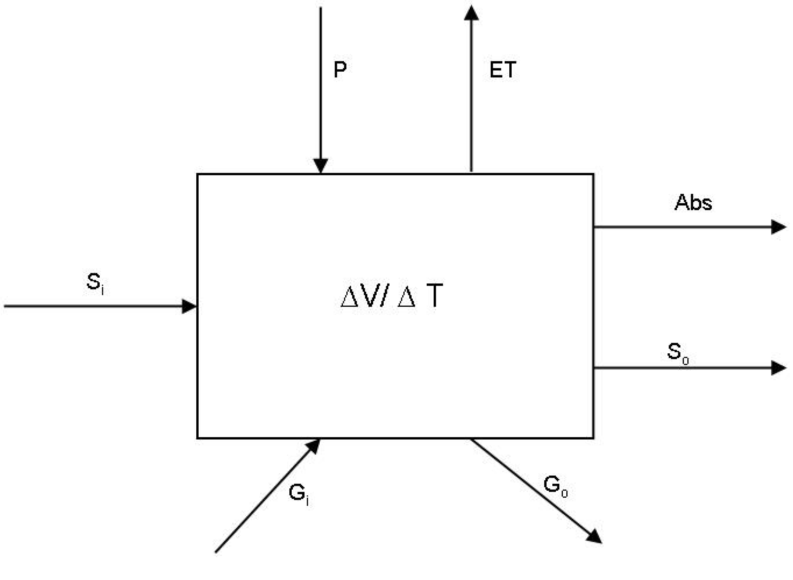


Figure 1.4. Concept diagram of a water balance. Source: Mitsch and Gosselink (2000)

Gilman (1994) and Hollis and Thompson (1998) argued that effective management of a wetland depends on a thorough understanding of the way in which the components of the water budget interact to provide a stable, though seasonally varying, template against which wetland plant communities can develop. Gilman (1994) further stated that changes in any of these variables, either through natural processes or those induced by human activities, have the potential to affect the functioning of a wetland**.** The wetland water balance can provide insights into the key processes determining the functioning of the system as a whole (Krause and. Bronstert, 2008). However, water-balance calculations are typically associated with large errors due to errors in the calculation of the terms in the water balance (Dooge 1972, McGuinness and Bordne 1972). Accordingly, it is important to understand the processes described by the terms and the factors that regulate them in wetlands to minimize these errors.

Precipitation: The contribution of precipitation in the estimation of water balance can be sub-divided into two categories. The first is precipitation falling directly into the open water of wetland and the other, falling through the vegetation cover (Duever, 1988; Gilman, 1994; Mitsch and Gosselink, 2000). The precipitation falling directly into open water areas can be estimated as a product of the depth of precipitation and the open surface water area and contributes directly to the storage capacity of the wetland. The contribution of open water precipitation varies according to size and type of wetland. For example, the open water area in Pevensey Levels in East Sussex, UK, when water levels are bank-full is only 0.5% of the wetland area (Gasca-Tucker, 2005), in contrast the Chilika Lagoon in India, which has an open water area of 1100 km^2 during monsoon (WISA, 2000) is capable of receiving large volume of water through direct precipitation. When the precipitation falls over a vegetation cover, some proportion is retained as interception by the overlaying vegetation canopy. Interception depends on several factors, including the total amount of precipitation, the intensity of precipitation, and the character of vegetation, including the stage of vegetation development and the type of vegetation.

Evapotranspiration: Evapotranspiration is defined as the water that vaporizes from water or soil in a wetland (evaporation), together with moisture that passes through the plants to the atmosphere (transpiration). It is a major component of the wetland water balance (Campbell and Williamson, 1997). Jacobs et al., (2002) reported that in the southeastern United States, evapotranspiration represents a significant component of the water balance in wetland systems and, in some years, exceeds the annual rainfall. Rushton (1996) found that annual evapotranspiration of 1.6 m was approximately equal to the rainfall for a freshwater marsh in southwest Florida. Similarly Hollis and Thompson (1998) reported that in the Bells Creek catchment of the North Kent Marshes, Southeast England the annual evapotranspiration accounts between 63% to 87% (mean 73%) of the outflows for the catchment area.

It is vital to understand whether the presence of wetland vegetation increases or decreases the amount of water loss as compared to that from an open body of water. Gilman (1994) reported that conflicting results have been obtained by various studies. Most found that evapotranspiration from a plant community could at times exceed evaporation from open water, but others found the converse. Smid (1975) reported that evapotranspiration from a dense reed stand in Czechoslovakia was 86% higher than evaporation from open water. In contrast, Heimburg (1984) found evapotranspiration from a forested pond cypress dome of north-central Florida was approximately 80% of the pan evaporation during the dry season and as low as 60% of pan evaporation during the wet season.

Surface Flow (inflow and outflow): Surface inflow is one of the major inputs of water in many wetland water balances (Gilman, 1994). Wetlands can receive surface flow in the form of overland flow and channelized stream flow (Williams, 1990; Thompson and Hollis, 1995; Hollis and Thompson, 1998; James, 2000) and also through seasonal or episodic pulses of flood flow from adjacent streams and rivers (Finlayson et al., 1989; Junk et al., 1989; Middleton, 1999) when they are at bankfull. Otherwise these channels may not be connected hydrologically with the wetland. The percentage of precipitation that becomes surface flow depends on a number of variables amongst which climate is the most important. Mitsch and Gosselink (2000) reported that in a humid cool region such as the Pacific Northwest, western British Columbia, and northeastern Canadian provinces 60 to 80 percent of precipitation is converted to runoff, whereas in the arid southwestern United States less than 10 percent of precipitation becomes runoff. Riparian wetlands or the wetlands that occur along the adjacent floodplains of a river or stream have very a special form of hydrological connectivity with the main river channel. Seasonally, these wetlands are flooded by flood water from the river channel when the river floods. For example, the Sudd in Sudan, the largest wetland in tropical Africa, is seasonal inundated by the flood wave passed down by the White Nile (Sutcliffe and Parks, 1996). The characteristic of such flooding pattern such as their frequency, duration and magnitude, are controlled by the regime of the river (Baker et al., 2009).

Groundwater flow: One frequently stated myth used as a justification for wetland preservation is that wetlands are groundwater recharge areas (Carter and Novitzki, 1988). This statement is true for some wetlands but invalid for many others. The relative importance of groundwater processes on the water balance varies with wetland type, and regional factors such as climate, hydrogeology, and physiography (WRP, 1993). Some wetlands, such as potholes in higher ground, may serve as important groundwater recharge areas. Others, especially those in low-lying areas such as freshwater marshes, may be the receptors for significant amounts of groundwater discharge. Wetlands fed by groundwater are found globally, for example fens in Europe (Boeye and Verheyen, 1992), swamps and marshes in the Americas (Fretwell et al., 1996) and ground water dependent playas in Australia (Bryant, 1999). The key variable to the inter-relationship between wetlands and groundwater are (a) aquifer type (e.g. alluvial gravel aquifer, sandstone or limestone), (b) the piezometric surface, and (c) the degree of connectivity between the wetland and the groundwater body (Gilvear and Bradley, 2009). The latter variable is the most important one as it describes the way in which the base of a wetland which may be covered by a layer of fine sediment or compressed organic deposits, effectively acts as a semi-impermeable layer restricting water seepage. If the wetland is on a clay substrate, groundwater-surface water interactions are likely to be lower than if the substrate is permeable.

1.5.2. Wetland water level regime or hydroperiod

Wetlands experience natural water level fluctuations that are closely associated with its morphopology and basin hydrological regime (Stockdale, 1991; Coops amd Hosper, 2002; Leira and Cantonati, 2008). A wetland water level regime or hydroperiod is the seasonal pattern of the water level of a wetland and is a hydrological signature of each wetland type (Mitsch and Gosselink, 2000; Hollis, 1994). Azous & Homer (1997) define hydroperiod as “the seasonal occurrence of flooding and/or soil saturation, encompassing the depth, frequency, duration, and seasonal pattern of inundation”.

Wetland hydroperiod integrates all aspects of the water balance (William, 1995) and reflects the pattern of inflows and outflows, the critical relationships between water depth, flooded area and water volume in the wetland (Hollis, 1994).

Water-level fluctuations are dominant forces controlling the functioning of many wetland ecosystems (Wilcox & Meeker, 1991; Poff et al., 1997). The amplitude and frequency of water level fluctuations control the characteristics of wetlands (Keddy, 2000; Steven and Toner 2004; Coops and Havens, 2005). Figure 1.5 demonstrates the seasonal water level fluctuations within 12 different wetland types. Hellsten et al., (1996) and Hawk et al., (1999) added that the hydrological regime modifies or determines the structure and functioning of wetlands by controlling the composition of the plant communities and thereby the animal communities. Jackson (2006) stated that in such ecosystems, the hydroperiod is important ecologically because most aquatic organisms live within the water column, and their life histories must be synchronized to the inundation periods of the wetland. For example, Junk (1983) reported that water level in the swamps of the Amazon basin fluctuated more than 10 m within one year and this large water level fluctuation determines the development of floral and faunal colonization within the floodplains.

Permanent changes in water level can also occur due to many factors, including drainage of the wetland, damming of its outlet, or climate change. More permanent water-level changes of any magnitude may result in significant changes in the growth dynamics of flora and fauna of a wetland and in extreme cases will result in its conversion into some other kind of ecosystem. For example, Shay et al., (1999) examined historical change in the emergent vegetation of the Delta Marsh, at the south end of Lake Manitoba, Canada, and concluded that the reduced amplitude of interannual water-level fluctuations due to the construction of water level control structures to reduce flooding had resulted in the replacement of *Phragmites australis*, which had been the dominant emergent species, by *Typha spp*. Water-level changes can have both direct and indirect effects on the establishment, growth and survival of wetland plants (Van der Valk, 2005). Indirect effects include increased sediment and nutrient inputs during wet years and increased grazing and fire during dry years.

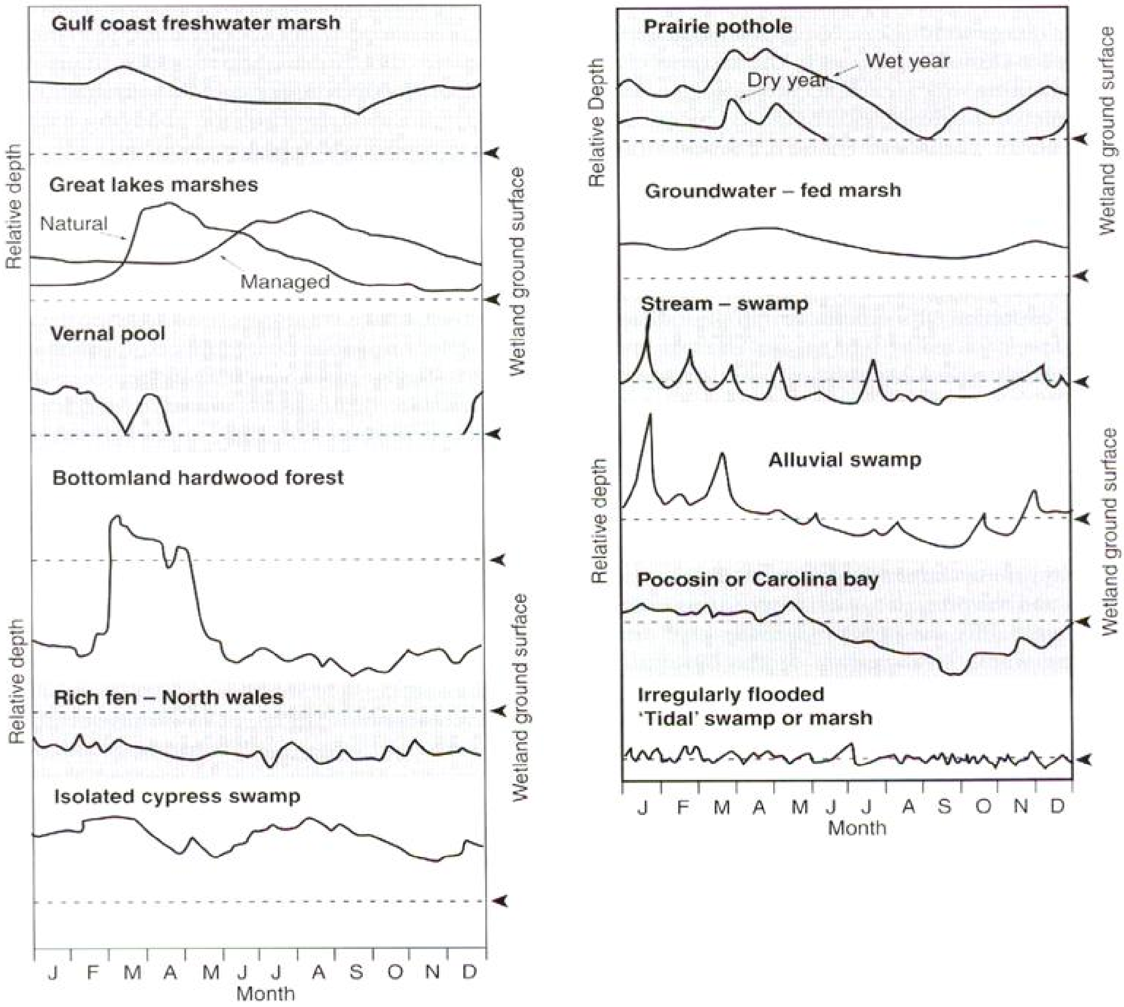


Figure 1.5. Water level regimes or hydroperiod of different wetland types. Source: Baker et al. (2009)

Morphometric parameters such as depth, area, basin shape, and volume clearly affect the water balance and hydroperiod (Brooks and Hayashi, 2002). Hollis and Thompson (1998) argued that the knowledge of the relationships between water level, area of inundation and volume of water is essential for the understanding of how hydrological inputs and outputs impact upon ecologically vital elements such as the level of saturation in the root zone, water depth for diving ducks, and the area of inundation for rice cultivation. This relationship has been employed in many hydrological models (Thompson and Hollis, 1995; Hayashi and van der Kamp, 2000; Brooks and Hayashi, 2002; Gasca-Tucker, 2005) of wetlands to transform water volumes into ecologically significant depths and areas. As the water level in a wetland increases, the surface water area of the wetland increases inundating the peripheral areas and subsequently the volume increases. The level-area-volume relationship developed by Gasca-Tucker (2005) for a sub-catchment of the Sussex Wildlife Trust's Reserve, UK (Figure 1.6) shows that with increase in water level within the ditches, the area of inundation of the adjacent land as well as the water volume increases. He evaluated the extent and the depth of inundation using this relationship in combination with a Digital Elevation Model (DEM).

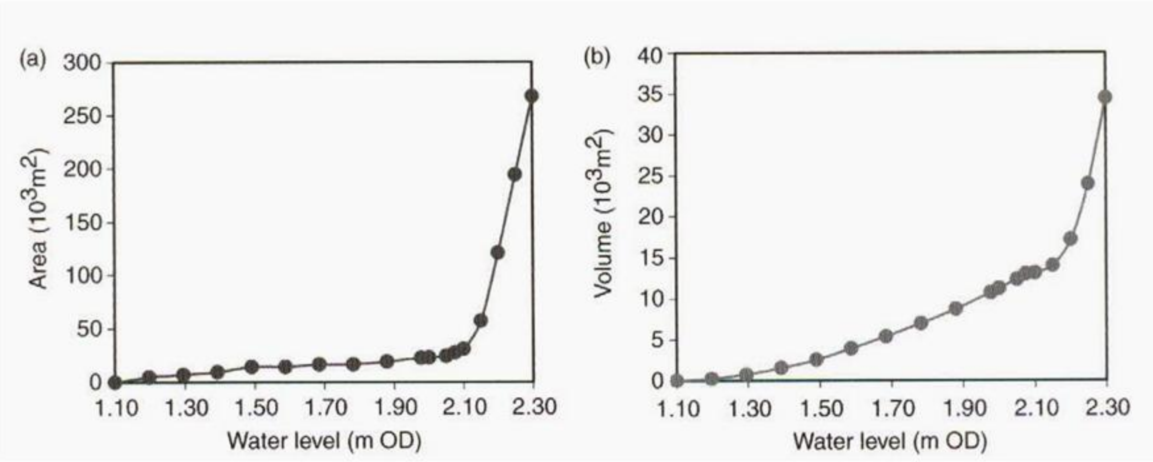


Figure 1.6. Level-area-volume relationship for a sub-catchment of the Sussex Wildlife Trust's Reserve, UK (a) Level–area relationship (b) Level–volume relationship
Source: Gasca-Tucker (2005)

1.6. Wetland vegetation

Wetland plants are defined as those species normally found growing in wetlands, either in or on the water, or where soils are flooded or saturated long enough for anaerobic conditions to develop in the root zone (Cronk and Fennessy, 2001). A history of definitions of wetland plants is given in Table 1.6. They are found wherever there are wetlands and they are often the most conspicuous component of the ecosystem. Wetland plants have multiple roles in the functioning of wetlands. They have a major effect on the physical (e.g. temperature, light penetration, soil characteristics) and chemical environment of the wetlands (e.g. dissolved oxygen, nutrient availability). Like all photosynthetic organisms, they are crucial in fixing the energy that powers all other components of the system. They are the drivers of ecosystem productivity and biogeochemical cycles, in part because they occupy a critical interface between the sediments and the overlaying water column (Carpenter and Lodge, 1986). They also play a key role in preventing erosion and maintaining the water quality of wetlands by filtering out nutrients and sediments. In addition, wetted vegetation provides food, shelter and breeding habitat for both aquatic and terrestrial fauna. Wetland plants are also important from the point of research and management of wetlands. For example, wetland plants are routinely used to help identify or delineate jurisdictional boundaries of wetlands in the US and elsewhere (US Army Crops of Engineering, 1987). Wetlands are dynamic environment that can experience natural fluctuations in both water level and water quality. As a consequence some wetland plants are able to tolerate both flooding and short periods of drought within a single year (Roberts et al., 2000).

Table 1.6. A history of the definition of wetland plants

Wetlands definition	**Author**
"Any plant growing in a soil that is at least periodically deficient in oxygen as a result of excessive water content''	Daubenmire, 1968
"Any plants growing in water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content''	Cowardin et al., 1979
"Any macrophyte that grows in water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content', plants typically found in wet habitats''	U.S. Army Corps of Engineering, 1987
"Large plants (macrophytes) that grow in permanent water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content. This term includes both aquatic plants and wetland plants''	Sipple, 1988
"…an individual plants adapted for life in water or periodically flooded and / or saturated soils…(which) may represent the entire population of a species or only a subset of individuals so adapted…"	Tiner, 1988
"Any macrophytes that grows in water or on a substrate periodically deficient in oxygen as a result of excessive water content, plants typically found in wetlands and other aquatic habitats''	Federal Interagency Committee for Wetland Delineation, 1989

Source: Adapted from Cronk and Fennessy (2001)

Cronk and Fennessy (2001), following Sculthrope (1967), classified wetland plants under the following four categories (Figure 1.7a):

Emergent: Emergent wetland plants are rooted in the soil with basal portions that typically grow beneath the surface of water, but whose leaves, stems, and reproductive organs are aerial (Figure 1.7b). Among all types of wetland plants, emergents are

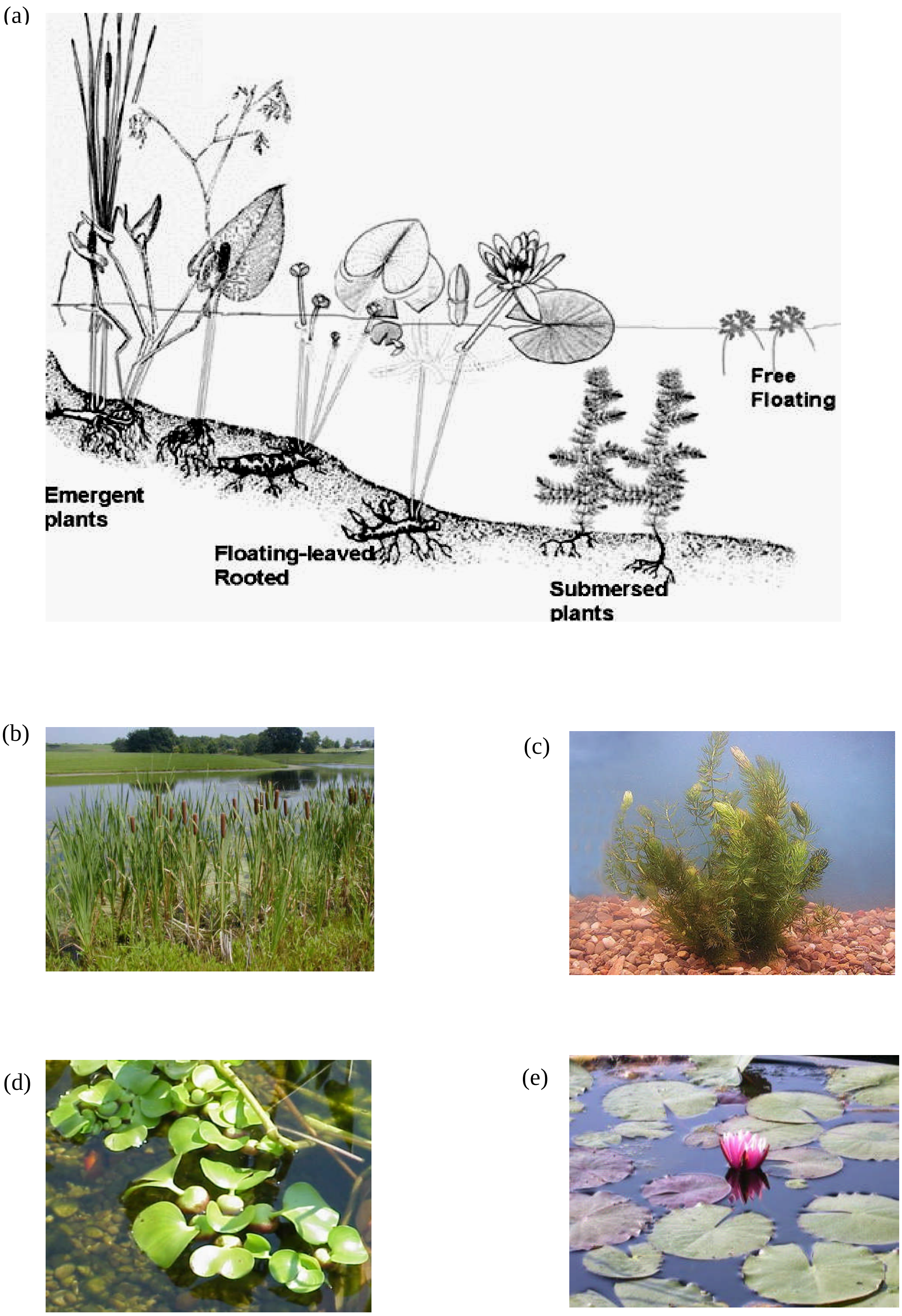


Figure 1.7. (a) Schematic diagram showing different types of wetland plants; (b) Emergent species (Typha latifoloa). Source: www.mobot.org;, (c) Submerged specie (Echinodorus Red Flame). Source: www.hardypondplants.com; (d) Floating species (Eichhonia crassipes). Source: www.uky.edu; (e) Floating leaved species (Nymphaea odorata). Source: www.mellowmarshfarm.com

perhaps the most similar to terrestrial species, relying on the aerial (above the water) reproduction and on the soil as their exclusive source of nutrients. Most of the plants in this group are herbaceous. Some of the most common emergent species are from the *Poaceae* (grasses e.g *Phragmites australis*), *Cyperaceace* (sedges, e.g. *Carex, Cyperus*), *Juncaceae* (rushes), *Typhaceae* (cattail)

Submerged: This group of plants typically spends their entire life cycle beneath the surface of water except for the flowering periods in some species (Figure 1.7c). They are found in both coastal and freshwater wetland habitats. Cook (1996) reported that all photosynthetic tissues in submerged species are normally underwater. These plants lack the external protective tissues required by land plants to limit water loss. The main function of the roots of submerged plant species is anchorage, rather than absorption of nutrients and water from the substrate. Examples of families in which all or nearly all of the species are submerged include the *Callitrichaceae* (water starwort), *Potamagetonaceae* (pondweeds) and *Hydrocharitaceae* (frogbit).

Floating: The leaves and stems of floating plants float on the water's surface (Figure 1.7d). If roots are present, they float free in the water and are not anchored in the sediments. These species float and move around on the surface of water depending on wind and water current. There are several types of small free floating plants. The most common is the fern-like *Azolla* spp. which can cover areas of still water like a green lawn. *Eichhornia crassipes* (water hyacinth) and *Elodea canadensis* (Canadian pondweed) (Sculthrope 1967; Gopal 1987) are examples of such species which are spread around the globe.

Floating-leaved: The leaves of floating-leaved species float on the water surface while their roots are anchored in the substrate (Figure 1.7e). Most floating leaved species have circular, oval, or cordate leaves with entire margins that reduce tearing, and a tough leathery texture. Some of the examples of floating-leaved plants are yellow water lily (*Nuphar lutea*), fringed water lily (*Nymphoides peltata*) and white lily (*Nymphaea alba*). Some species, such as *Ranunculus flabellaris*, have underwater leaves in addition to the floating leaves.

The distribution of wetland plants depends on the distribution and types of wetland ecosystem. Some wetland species, like *Phragmites australis* and *Eichhornia crassi,* have extensive geographical distributions that range over several continents. However, some species are endemic to a small area or certain wetland types. For example, *Sagittaria sanfordii* has been found only in the Great Valley of Carlifornia. The position of the water table in wetland soils undoubtedly exerts a major influence upon the distribution and performance of plants species and the composition of vegetation (Wheeler, 1999). Vegetation zonation can be often found along a water level gradient, such as around the margins of lakes. Mitsch and Gossenlink (2000) describe hydrology to be two-edged sword in term of its effect on species composition and diversity. It acts as a limit or a stimulus to species richness, depending on the hydroperiod and physical energies. Flowing water can be thought of as a stimulus to diversity, probably due to its ability to renew minerals and reduce anaerobic conditions.

1.7. Hydro-ecology of wetland ecosystem

This section examines the inter-relationship between the hydrological and ecological components of wetland ecosystem, which is the key focus of this thesis.

Traditional water management depends on information derived from hydrological science. But in the recent past, a new holistic approach to water management has been adopted which integrates the interdependency of hydrological and ecological processes. Plate (1994) highlighted the importance of understanding the influence of biotic factors on the hydrological cycle and the reciprocal effects of hydrological factors on biology for effective management of water resources. According to Nuttle (2002), this approach provides a holistic vision of water's role in the environment. Figure 1.8 shows the integration of hydrology and ecosystem sciences in water management. This new approach has been termed '*hydroecology'* or '*ecohydrology*'. The terms '*hydroecology*' and '*ecohydrology'* (including the subdiscipline of ecohydraulics) both imply research at the interface between the hydrological and biological (ecological) sciences (Hannah et al., 2004). Nuttle (2002) stated that these two terms are used interchangeably. Dunbar and Acreman (2001) also seem to have considered ecohydrology and hydroecology as largely the same entity. However, in practice this rubric has not been applied, as many ecologists refer to *ecohydrology* (e.g. Zalewski, 2000) and hydrologists refer to *hydroecology* (e.g. Dunbar and Acreman, 2001). Some of the key publications which have set the stage for the concepts and methods in applied hydro – ecology include Junk et al. (1989); Poff and Ward (1990); Jacobsen et al. (1997); Poff et al. (1997); Hildrew (1998); and Puckridge et al. (1998).

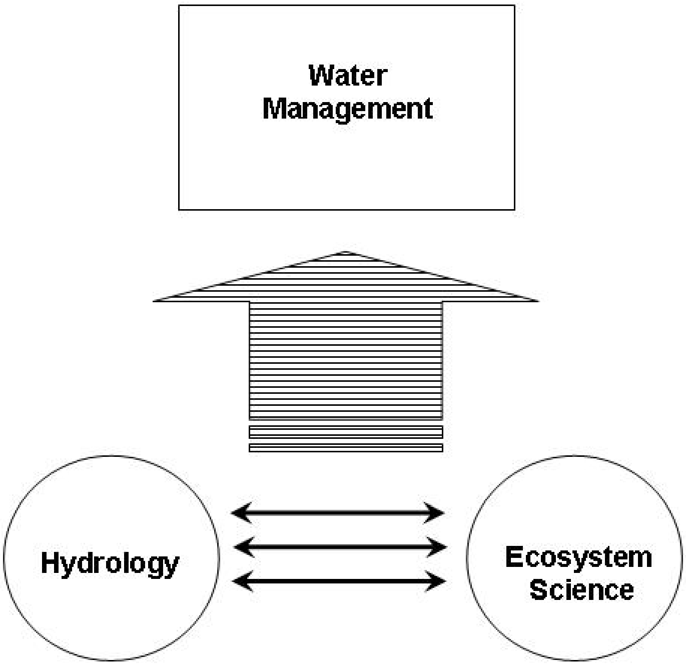


Figure 1.8. The integration of hydrology and ecosystem science in water management Source: Nuttle (2002)

Dunbar and Acreman (2001, page1) defined hydroecology as ‘the linking of knowledge from hydrological, hydraulic, geomorphological and biological/ecological sciences to predict the response of freshwater biota and ecosystems to variation of abiotic factors over a range of spatial and temporal scales’. According to Wassen and Grootjans (1996) it is application driven with an aim to better understand the hydrological factors determining the natural development of wet ecosystems, especially in regard of their functional value for nature protection and restoration. It is an approach which occupies the interface between the disciplines of ecology and hydrology (Nuttle, 2002) and wetland ecosystems are analysed in a landscape-ecological context. In the Netherlands, hydroecology first moved from the analysis of landscapes and wetland ecosystems to water and wetland management and is presently shifting to the field of restoration ecology where more attention is given to, for instance, experimental research on plant adaptations (Wheeler et al., 1985; Roelofs 1991, Dunbar and Acreman, 2001, Hickley et al., 2004).

Wassen and Grootjans (1996) stated that hydroecological research usually does not claim to unravel all hydrological and ecological mechanisms responsible for the observed changes in the species composition of damaged or restored wetlands, but may contribute to the understanding of how to properly manage these ecosystems. Research on wetlands had played a central role in the development of hydroecology in Europe and the United Kingdom (Baird and Wilby, 1999). Hydrological and ecological processes are intimately connected in wetlands, and their interaction has consequences for the functions they serve on larger scales. For example, in the extensive wetland regions found at high latitudes in the Northern Hemisphere, the interaction of hydrology and ecological processes involved in soil diagenesis influences stream flow, water quality, and geomorphology in the local drainage basin and the carbon cycle and climate on a global scale. Any changes in the wetland ecosystem due to over-abstraction of water from wetlands and the catchments in which they occur, and pollution of the water which feeds them, can all lead to significant changes in wetland ecosystems, particularly to their structure and functioning, which further can lead to significant alteration in the flow pattern and chemical and micorobiological signature. This then impacts on their floral and faunal diversity. Wetlands, especially inland freshwater lakes, require sufficient water of adequate quality, at the right time and in the right pattern to maintain a desired level of ecological health and functioning (Ramsar, 2007).

1.7.1. Impacts of water regime on wetland vegetation

In wetland ecosystems, the land-water interface zone covers a large area extending from the hydrosoils that are at least periodically saturated through to the littoral areas to depths that have sufficient light to support larger aquatic plants. According to Wetzel (1999) this land-water interface is critical as it is always the most productive region per unit area along the gradient from land to open water. He further reported that the emergent macrophyte zone is the most productive region. Emergent plants have a number of structural and physiological characteristics that not only tolerate the hostile anaerobic sediments but also take advantage of the relatively abundant nutrients and water conditions of this habitat. The primary productivity rates of different types of wetland vegetation are summarized in Table 1.7. Emergent macrophytes have a maximum production rate of 5000 $gdrym^2year^{-1}$ and produce maximum seasonal biomass of 2500 $gdrym^2$. It has long been accepted that the water requirement of wetland ecosystems are reflected by the requirements of wetland vegetation.

Table 1.7. Average (and ranges) of rate of primary production of different types of wetland vegetation

Type	Seasonal maximum biomass (g dry m^2)[a]	Rate of production (g dry m^2 $year^{-1}$)[b]
Emergent macrophytes	2500 (<2 – 9900)	5000 (3000 – 10300)
Temperate	-	3800 (3000 – 4500)
Tropical	-	7500 (6500 – 10300)
Floating	(630 – 1500)	(1500 – 4400)
Floating-leaved	140 (25 – 340)	300 (110 – 560)
Submerged	220 (15 – 500)	1300 (100 – 2000)
Temperate	-	600 (100 – 700)
Tropical	-	1700 (1200 – 2000)

[a] – Approximate only

[b] – Rates of turnover vary greatly. Most aquatic plants are herbaceous perennials and often exhibit multiple cohorts (1.5 to 3 temperate to 10 per year in tropical regions) or continuously growth with seasonal variations.

Source: Wetzel (1999)

The distribution, growth and reproduction of wetland vegetation, in turn, have a strong relationship to the depth, duration and amplitude of the seasonal flooding it experiences (Orme, 1990; Mitsch and Gosselink; 2000, Keddy, 2000) and changes in water balance and water quality have resulted in habitat destruction (Acreman and McCartney, 2009). A variety of floral and faunal species intolerant of ecological changes are bound to suffer stress (Bruce, 1995) and eventually extinction. For example, the change in the hydrological regime of Peace River, Alberta, Canada by the construction of Bennett Dam had led to the conversion of many productive wetlands within the Peace-Athabasca Delta into woody vegetation (Rosenberg and Barton, 1986; Rosenberg et al., 1995). Similar changes in wetland vegetation as a consequence of altered hydrological regimes by construction of dams were reported in the Colorada River in Arizona, US (Turner and Karpiscak, 1980), the Volta River in Ghana (Petr, 1986) and the Platte River in Nebraska, UK (Johnson, 1994). Van der Valk (2005) reported that in the North American prairie wetlands, water level oscillations determine the type of vegetation change that will occur during a wet-dry cycle. Altered water regimes demonstrate the importance of water levels, as each species is adapted to a specific water level range and changes in the water regime may cause a shift in community composition and structure (Wheeler, 1999). Numerous studies have been carried out to examine the relationship between wetland plant species and water levels (e.g. Reid and Brooks, 2000; Environment Agency, 2004; Van der Valk, 2005; Battalagia and Collins, 2005; Centre of Ecological Management, 2006; Paillisso, 2006). However, Wheeler (1999) stated that while it is possible to find broad trends in water level-plant distributions in wetlands, the range of conditions occupied by particular species or communities can be wide and may be inconsistent between, or even within sites. There is also some evidence that groups of species may show clearer relationships to water level behaviour than individual species. Many studies aimed at understanding the response of aquatic ecosystem to changes in hydrological have been carried out (e.g. Ertsen et al., 1998; Hardy, 1998; Bartell et al., 1999 and Bobba et al., 2000).

Richter et al. (1996) argued that effective management of aquatic ecosystem requires that existing hydrological regimes be characterized using biologically-relevant hydrological parameters, and that the degree to which human-altered regimes differ from natural or preferred conditions be related to the status and trends of the biota. They also suggested a series of hydrological statistics or ‘indicators of hydrological alteration’ that can be used to describe the hydrology of, and to assess hydrological alterations to, aquatic ecosystem. Their hydrological statistics are based on five fundamental characteristics of hydrological regimes:

i) magnitude – the water condition (e.g. level or volume at any given time);
ii) timing – when specific water conditions (especially highs or lows) normally occur;
iii) frequency – how often over some time interval do specific water conditions occur;
iv) duration – how long does a specific water condition last; and
v) rate of change – how quickly do water levels go up or down.

Table 1.8 shows five groups of hydrological statistical parameters as proposed by Richter et al. (1996) that can be used to describe the water regimes of wetlands. Specific parameters chosen need to have a known impact on the establishment, growth, and survival of the plant species or communities. Van der Valk (2005) reported that duration of flooding has most commonly been used to explain the distribution of plant species at any given time in prairie wetlands. In many wetlands, including inland freshwater lakes, the inflowing water provides a major mechanism for the import of chemical elements (Wheeler, 1999). This helps to determine the availability of essential plants nutrients as well as regulating other components of the chemical environment of the rooting zone, such as pH. Variation in the chemical composition of the water sources helps to control species distribution and vegetation composition in wetlands. Water quality can therefore be of equal ecological importance to water quantity.

Table 1.8. Groups of hydrological statistics and some example hydrological parameters that can be used to describe the water regimes of wetlands

Groups	Regime Characteristics	Hydrological parameters
Magnitude	Magnitude, timing	Mean monthly water level
Magnitude and duration of extreme events	Magnitude, duration	Mean annual or interannual maximum or minimum water level
Timing of extreme water conditions	Timing	Mean julian date of annual or interannual maximum or minimum water level
Frequency and duration of	Magnitude, frequency duration	Mean duration of annual or high and low water interannual high or low water levels
Rate and frequency of change of water conditions	Frequency, rate of change	Mean slope during periods when water levels are increasing or decreasing

Source: Adapted from Richer et al. (1996)

1.7.2. Impacts of vegetation on water regime of wetland ecosystem

Although wetland plant growth and survival are governed by the quantity and quality of the water within wetlands, they on the other hand also have a substantial influence on the hydrological processes within wetlands. As discussed previously, the evaporation losses from wetlands, including lakes, are greatly modified by transpiration from emergent and floating-leaved aquatic plants. Some plant species, for example *Eichhornia crassipes*, enhance water losses by 32-51 %, whereas some species such as *Nymphaea* (lotus) retards losses by 5-18 % (Wetzel, 1999). The evapotranspiration rates of aquatic plants generally increases with increasing wind velocity and decreasing relative humidity (Gessener, 1959; Rao, 1988). The rate of photosynthesis also has a direct impact on the rate of evapotranspiration. In most situations, the transport of water from wetland to atmosphere is greatly increased by presence of dense stand of actively growing vegetation, as compared with evaporation rates from open water (Table 1.9). Such high rates of evapotranspiration plays a significantly role to the overall water balance of wetland and can also result in an increase in the concentration of nutrients and other soluble materials.

Some wetland plants are also capable of reducing suspended solids, biochemical oxygen demand (BOD), nitrogen, phosphorous, and some metals (Cronk and Fennessy, 2001), and are thereby capable of altering the biochemistry of the wetland water. Wetland plants such as *Typha latifolia* and *Phragmites australis* (Ye et al., 1997a, b) play an important role in metal removal via filtration, adsorption, and cation exchange, and through plant-induced chemical changes in the rhizosphere (Dunbabin and Bowmer, 1992; Wright and Otte, 1999; Allen et al., 2002; Yang and Ye, 2009). Some wetland plants can release enough oxygen into the root zone to support aerobic microbial activity (Reddy et al., 1989b; Bodelier et al., 1996; Armstrong et al., 1990).

Table 1.9. Representative rates of evapotranspiration (E_t) by aquatic plants and comparison with rates of evaporation from open water (E_o)

Species	**mm day^{-1}**	E_t / E_o
Emergent:		
Typha domingensis Pers.	2.7 – 4.7	1.3
Typha latifolia L.	4 – 12	1.41 – 1.84
Carex lurida Wallend.	4.0 – 6.3	1.33
Panicum regidulum Nees	5.5 – 7.5	1.58
Rice (*Oryza sativa* L.)	6 – 13	-
Myriophyllum aquaticum (Vellozo) Vercourt	0.2 – 1.0	-
Juncus effuses L.	3.8 – 8.0	1.52
Sedge-grass marsh (*carex*, *Calamagrostis*, *Glyceria*), Czeh. Republic	2.2 – 4.5	-
Lakeshore marsh (*Sagittaria, Pondederis, Panicum, Hibiscus* dominating), Florida	0.5 – 1.0	0.35 – 1.2
Carex-dominated marsh, Ontaria subarctic	2.6 – 3.1	0.74 – 1.02
Floodplain forest, Florida	5.57	-
Reed (*Phragmites*) swamp, Czeh Republic	1.4 – 6.9	1.03
Floating-leaved rooted:		
Nymphaea lotus (l.) Willd.	2.5 – 6.0	0.82 – 1.35
Floating (not rooted):		
Eichhornia crassipes (Mart.) Solms.	3.8 – 10.5	1.30 – 1.96
Salvinia molesta D.S. Mitchell	2.1 – 6.8	0.96- - 1.39
Pistia stratiotes L.	19.9	1.07
Azolla caroliniana Willd.	7.1	0.95

Source: Adapted from Wetzel (1999)

The presence of thick dense wetland vegetation, especially emergent species like *Phragmites australia*, can also have a great impact on water movement within wetland thereby impacting the distribution of sediment, nutrients and other chemical elements. The presence of thick vegetations within the wetlands can reducing flow velocity thereby accelerating sedimentation process (Dawson, 1981). Sanchez-Carrillo et al.,

(2001) reported high rate of accretion (1.61-3.87 cm yr^{-1}) in Las Tablas de Daimiel National Park in Central Spian due to the presence of thick bed of *Phragmites australis* (reed) and *Cladium mariscus* (sawgrass). In addition, Mistch and Gosselink (1993) and Sanchez-Carrillo et al. (2001) reported these emergent macrophytes are source of most of the organic matter that accumulates in the wetlands. Similar finding were also observed by Buttler and Malanson (1995) in ponds in Montana, US and by Reddy et al. (1993) in the Everglades.

1.8. Threats to wetlands

Wetland habitats are one of the most impacted and degraded ecological systems worldwide (Williams, 1990; Thorsell et al., 1997; Millennium Ecosystem Assessment, 2005; Whigham, 2009). The current over-use of freshwater resources and projected future increases creates serious threats, not only to the continued maintenance and functioning of wetland ecosystems and their biological diversity, but also to the essence of human well-being (Millennium Ecosystem Assessment, 2005). The abuse of wetlands, their unwise use, reduces their ability to perform useful functions such as water retention and flood control, to supply services and, in many cases, valuable products. Replacing these goods and services, where it is possible, incurs heavy financial and environmental costs (Gosselink and Maltby, 1990). Conversion of swamps, marshes, lakes and floodplains for commercial development, drainage schemes, extraction of minerals and peat, overfishing, tourism, siltation, pesticide discharges from intensive agriculture, toxic pollutants from industrial waste, and the construction of dams and dikes, often in an attempt at flood protection, are major threats to wetlands everywhere (Williams 1990; Mitsch and Gosselink, 2000; Mitsch, 2005). Even flagship wetlands recognised as internationally important are subject to these pressures and resulting ecosystem change. For example, as of June 2010, 1890 wetlands, covering an area of over 185 million hectares, are listed as internationally important under the Ramsar Convention (Ramsar Bureau, 2010). 50 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 likely to occur. Two of India’s 25 Ramsar sites, including Loktak Lake, which is the focus of this thesis, are on this record of threatened wetlands. This situation reflects the wider trend for wetlands in general across the world. For example, the US Environmental Protection Agency (2001) 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. Similarly, CEC (1995) estimated that over the middle-late 20th Century European countries including France, Germany, Italy and Greece lost between 57% and 66% of their wetlands, 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.

According to Millennium Ecosystem Assessment (2005), the primary direct drivers of degradation and loss of inland wetlands include infrastructure development, land conversion, water withdrawal, pollution, overharvesting and overexploitation, and the introduction of invasive alien species. Clearing and drainage, often for agricultural expansion, and increased withdrawal of freshwater are the main reasons for the loss and degradation of inland wetlands such as swamps, marshes, rivers, and associated floodplain water bodies (Mitsch, 2005). By 1985, an estimated 56–65% of inland and coastal marshes (including small lakes and ponds) had been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America, and 2% in Africa (Millennium Ecosystem Assessment, 2005). The extensive use of water for irrigation (some 70% of water use globally is for irrigation) and excessive nutrient loading associated with the use of nitrogen and phosphorus in fertilizers have resulted in a decline in the delivery of services such as freshwater and some fish species. Millennium Ecosystem Assessment (2005) identified population growth and increasing economic development as the main primary indirect drivers for wetland loss and degradation

In developing countries, especially in South Asia, inland wetland ecosystems are of immense importance in providing economic and ecological security to a large population living in and around the wetlands (WISA, 2004). The local communities have developed unique techniques for harnessing these resources without altering their ecological balance (Trisal and Manihar, 2002). However, with the phenomenal increase in human populations and rapid development in the region, wetlands have been drained, filled and reclaimed for more economic gains particularly to meet the food and housing demands for ever increasing population (Thompson and Hollis, 1997). The inland wetland ecosystems depend on the maintenance of the natural water regime for maintaining their biodiversity, functions and values (Keddy, 2000; Gopal, 2009). The impacts on these wetlands can be caused both by human activities within them and, because of the interconnectedness of the hydrological cycle, by the activities that take place within the wider catchment. Human modification of the hydrological regime, by removing water (including groundwater) or altering fluxes, can have detrimental consequences for the integrity of ecosystems. Water is being abstracted, stored and diverted for public supply, agriculture, industry and hydropower (Williams, 1990; Pinder and Witherick, 1990; ERM, 2003; Trisal and Manihar, 2004; WISA, 2005). Rapid and unsustainable development of wetlands, and the river basins in which they sit, has led to the disruption of natural hydrological cycles (Keddy, 1990; Trisal and Manihar, 2002; McCartney and Acreman, 2009). In many cases this has resulted in disruption of frequency and severity of flooding, drought and pollution (Novikova et al., 1998; McCartney and Acreman, 2009). For example, Hughes et al., (1994) reported that removal of forests for agricultural purposes in the upper reaches of the catchments of Ganges, Brahmaputra and Indus had resulted in alteration of the hydrological regimes of these rivers causing severe flooding to their floodplain in the lower reaches. Modification of the hydrological regime of Mekong Delta by the construction of hydro-electricity and irrigation projects was reported by Scott (1991). The degradation and loss of wetlands and their biodiversity imposes major economic and social losses and costs to the human populations of these river basins.

In the future, demands on water resources will continue to increase. We have witnessed in the past that water resources and wetlands have been managed by separate sectoral agencies, with very different objectives and modes of operation (Singh et al., 2010). The management of floodplain wetlands of the River Yamuna in Delhi, India provides a classic example of such sectoral conflicts. The jurisdiction and management responsibility for the wetlands lies within the Government of Delhi while flows within the Yamuna River, which provides water to these wetlands, are regulated by the Ministry of Water Resources, Government of India. As a result of this sectoral conflict, the wetlands are not allocated enough water at the right time in order to become inundated (WISA, 2005b). As a result, there have been regular conflicts over water resource use and river basin management. Regrettably, in these circumstances wetlands have not always been given the priority they deserve based on the important functions they perform in contributing to the maintenance of healthy and productive river systems. In addition, many policies are more driven by economic gains rather than environmental concerns (WISA, 2005a). As a consequence of these factors, there has been relatively little consideration of water allocation decisions for wetlands, which has been one of the major causes for their degradation.

Global climate change will have 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 (Ramsar Bureau, 2002). 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).

Wetlands plants are threatened by the same forces that threaten wetland ecosystems generally, including human activities such as wetland draining or filling, hydrological alterations, chronic degradation due to nonpoint source pollution, and the invasion of exotic species. Declines in wetland area have led to decreases in wetland plants species, which are home to a disproportionately large number of rare plant species. Niering (1988) and Murdock (1994) estimated that nearly one third of the threatened and endangered plants species in the U.S. depend on wetlands for their survival.

1.9. Wetland management

The concept of wetland management has had different meanings at different times to different disciplines and in different parts of the world (Mitsch and Gossenlink, 2000). Until the middle 20th century, wetland management usually meant wetland drainage to many policy makers, except for a few resource managers who maintained wetlands for hunting, fishing, and waterfowl/wildlife protection. Today, with the increase in understanding the values and functions of the wetlands, the management of wetlands means setting several objectives, depending on the priorities of the wetland managers (Ramsar 2003). Objectives can, for examples, be managing and zoning floodplain wetlands to minimize human encroachment and maximizing floodwater retention; protection coastal wetlands for storm protection and sanctuaries and subsidies for estuarine fauna. Boavida (1999) noted that in the recent past, intensive research has been carried out taking the objective of the full ecological role of wetlands. Maltby (2009) advocated a more holistic interdisciplinary approach to wetland management which places wetland centrally in the implementation process integrating water, land and living resources management (Figure 1.9). As the focus is shifted away from the wetlands, the model (Figure 1.9) demonstrates the linkages between the society and natural environment and environmental management for the conservation and sustainable use of wetland ecosystems. The linkages are in accordance to the roles of wetlands in the water cycle, ecosystem functioning, spatial linkages and policies which feed into the management of water resources, conservation and the use of wetland resources, connectivity and vulnerability in the larger landscape and the social significance and the economic values that wetland can provide. Maltby (2009) further elaborated that the application of this holistic approach can only be made by interdisciplinary collaboration between and within the natural and social science.

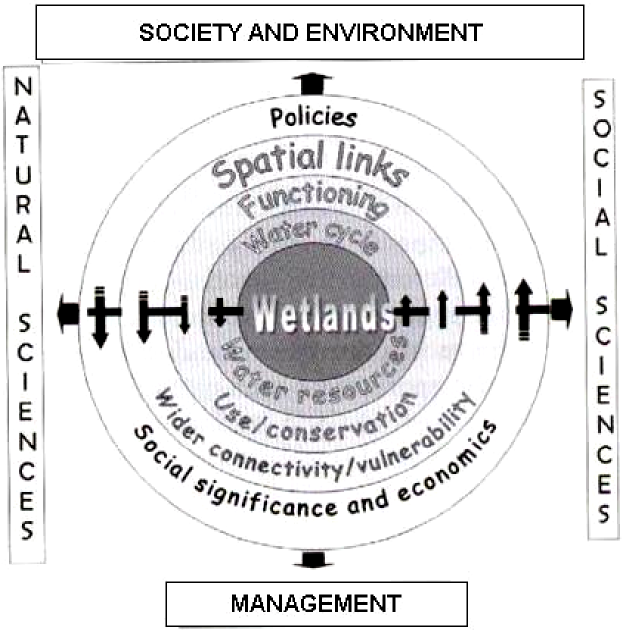


Figure 1.9. Structure for new paradigm for wetland conservation. Source: Maltby (2009)

Efforts have been made by various countries across the world to conserve wetlands to harness their goods and services. Many countries including the United States, Canada and Uganda have dedicated wetland policies (Matlby, 2009). The United States has a policy of 'no net loss' of wetlands with a goal to halt the decline in the overall number of wetland areas in the country (Womach, 2005). However, the solutions involve much more than addressing individual sites or specific ecosystems. Many wetland ecosystems are shared by many countries – there are over 300 transboundary river systems (for example, the Mekong River shared by Tibet, China, Burma, Laos, Thailand, Cambodia and Vietnam; and the Ganges River shared by India and Bangladesh) – and it is at this international level that action must be forthcoming if conservation efforts are not to be compromised for these transboundary wetland ecosystems. Key to this will be actions that focus on bringing conservation and management requirements more in line with development activities, and vice versa, so that the two can focus on mutually obtainable goals.

There has been growing number of international efforts by governments and non-government organizations such as Wetlands International, WWF and IUCN. The oldest of these efforts and perhaps the most important one is the Ramsar Convention (Williams, 1990). The Ramsar Convention advocates a cross-sectoral approach that emphasizes securing wetland ecosystems and their services in the context of achieving sustainable development and improving human well-being. It has developed the principles of "wise use" and the maintenance of "ecological character" of wetlands (Ramsar 2007d). Ecological character is the combination of the ecosystem components, processes and benefits/services that characterise the wetland at a given point of time (Ramsar, 2005a). The Water Framework Directive (Directive 2000/60/EC), which is the most substantial piece of European water legislation, though not a primary emphasis, recognizes the need and importance of wetland conservation notably Article 1: Establishment of a wetland protection framework; Article 4a: An emphasis on ecological quality as well as water quality; Article 5: The characterization of wetlands in the context of their river basin; Article 8: The assessment of water moving in and out of wetlands in terms of flow rates, chemicals quality and ecological potential; and Article 13: The development of river basin management plans.

Wetlands are water providers (McCartney and Acreman, 2009) and purifying water (Dordio, et al., 2008; Weber and Legge, 2008), but at the same time they are also water users (Ramsar, 2006). Ramsar (2006) advocated the message of 'No water, no wetland' and argued that wetland ecosystems need water, in the right amount, at the right time, and of the right quality and hence the integration of wetland into river basin management (Thompson and Hollis, 1997). Ramsar (2005b) further emphasized the development of effective monitoring and survey programme for assessing whether or not a wetland has undergone a change in its ecological character (Ramsar, 2005a).

1.10. Summary

Wetland ecosystems, including rivers, lakes, floodplains and marshes, provide many services including the provision of food and water, flood control, water regulation and purification, recreational and tourism benefits that contribute to human well-being and poverty alleviation as well as supporting large biodiversity. Many of the ecosystem services provided by wetlands are controlled by hydrological processes within wetlands. However, wetlands are increasingly subject to intense pressure from multiple human activities such as water diversion, pollution, over-exploitation of natural resources, and reclamation. As discussed in Section 1.5, hydrology controls the biotic and the abiotic characteristics of wetlands so that even small modification to a wetland's hydrological regime may have implication for the valuable ecosystem services that it provides. Increases in human populations and developmental activities are significant factors driving wetland degradation as demands for food, water and land increase. This process frequently occurs when particular goods and services provided by a wetland are favoured over others. In many cases, this form of trade-off results in the provision of the favoured services being increased at the expense of others and the implications for other ecosystem services or the integrity of the overall ecosystem have frequently been compromised. Failure to adequately understand and evaluate the trade-offs between different ecosystem services provided by wetlands can lead to use and user conflicts, sub-optimal allocation of resources and, in many cases, resource degradation. The projected intensification of the hydrological cycle associated with rising global temperatures may impose additional constraints upon the management of water and consequently on wetland ecosystem and their ability to provide goods and services.

The present study focuses on Loktak Lake, an internationally important wetland in northeast India. It uses hydrological modelling to simulate the lake water balance. This includes the application of distributed physically based hydrological models to evaluate catchment inflows. Subsequently, a framework for trade-off between the major ecosystem services which the lake provides is developed. Finally, the sustainability of the framework developed is assessed in the face of the projected climate change.

Chapter 2 - Loktak Lake

2.1. Introduction

The chapter presents a synthesis of the hydro-ecological characteristics of Loktak Lake, a wetland of international importance in northeast India and the study site of the present research work. The later part of the chapter outlines the aim, objectives and the research design of this thesis.

Loktak Lake (Figure 2.1) is the largest freshwater wetland in the northeastern region of India (WAPCOS, 1993; LDA and WISA 1997). It is located between longitudes 93° 46' and 93° 55' E and latitudes 24° 25' and 24° 42' N, in the state of Manipur, (Figure 2.2). The lake is oval in shape, spreading over an area of 287 km^2 (WAPCOS, 1993; Singh and Shyamananda, 1994; LDA, 1996; LDA and WISA, 1998; Trisal and Manihar, 2004). The depth of the lake varies between 0.5 to 4.6 m with an average depth of 2.7 m (WAPCOS, 1988; LDA and WISA, 1998; Trisal and Manihar, 2004).

Figure 2.1. An overview of Loktak Lake. Source: WISA

The characteristic feature of Loktak Lake is the presence of floating heterogeneous masses of soil, vegetation and organic matter at various stages of decomposition, locally known as *phumdis* (WAPCOS, 1988; Singh and Shyamananda, 1994; LDA, 1996; LDA and WISA, 2003; Trisal and Manihar, 2004). They can be found in various shapes, sizes

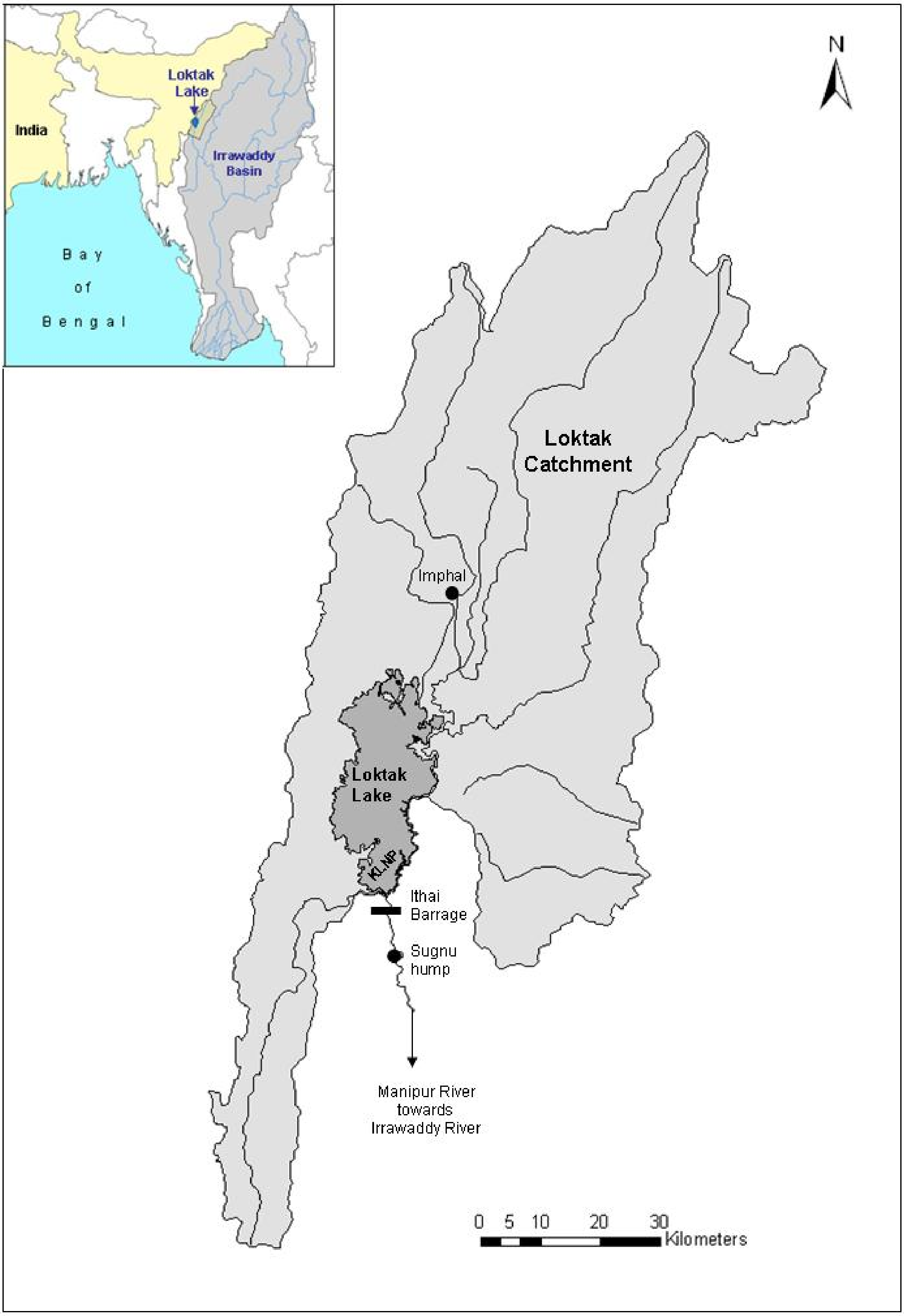


Figure 2.2. Location of Loktak Lake in northeastern India.

and thicknesses and occupy nearly 74 % (LDA and WISA, 2003) of the lake area. In the southern portion of lake there is a continuous mass of *phumdis* spreading over an area of 40 km^2, which was declared as the Keibul Lamjao National Park (KLNP) by the Government of India in 1977 (Prasad and Chhabra, 2001; Dey, 2002; Trisal and Manihar, 2004; Angom, 2005). KLNP is the only floating wildlife sanctuary in the world (Trisal and Manihar, 2004) and the only natural habitat of the most endangered ungulate species, the brow-antlered deer (*Cervus eldi eldi*) (Figure 2.3), locally known as the *Sangai* (Khan et al., 1992; LDA, 1996; Prasad and Chhabra, 2001; Dey, 2002; Trisal and Manihar, 2004; Angom, 2005).

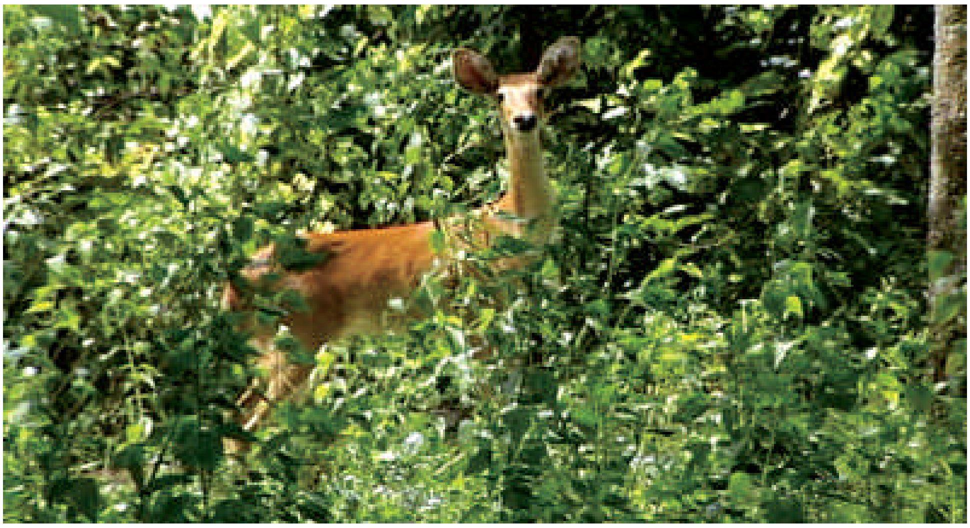


Figure 2.3. Sangai (Cervus eldi eldi) in Keibul Lamjao National Park. Source: Trisal and Manihar, 2004

Trisal and Manihar (2004) stated that Loktak Lake, historically, was flooded by the Manipur River from its lateral flows as well as backflow from the natural rocky barrier of Sugnu hump (Figure 2.2) south of the lake. During this period, people living on and around the lake had been wisely using the lake and its resources for agricultural and fisheries purposes (WISA, 2005). Lake vegetation was harvested for use as food, fodder, fibre, fuel, handicrafts and medicinal purposes. The periodic inundation bringing nutrient rich sediments ensured highly productive agriculture and thus served as the lifeline of the region. The lake also provided good navigational benefits to the people living on and around the lake (Figure 2.4). Migratory fish from Irrawaddy River used to breed in the lake. These fish form a staple diet for the people living in the area. The lake, with its enchanting beauty amidst lush green hills and floating *phumdis* of different geometrical shapes, also makes it a unique destination for ecotourism (WISA, 2005).

Based on its rich biodiversity and socioeconomic importance, Loktak Lake was designated by the Government of India as a Wetland of International Importance under the Ramsar Convention in 1990 (Singh, 1992; Singh and Shyamananda, 1994; LDA, 1996; LDA and WISA, 2003; Trisal and Manihar, 2004; MoEF, 2007). It was also included in the list of priority wetlands identified by Government of India for intensive conservation and management purposes (MoEF, 2000; Trisal and Manihar, 2004).

Figure 2.4. Loktak Lake used for navigational purposes. (Source: LDA)

2.2. Lake catchment

The catchment of Loktak includes drainage sub-basins of the Manipur River and its associated tributaries up to Ithai Barrage (Figure 2.2). The catchment covers an area of 4947 km^2 and constitutes 22% of the total geographic area of the state.

2.2.1. Sub-catchments

Based on the drainage features, the catchment area of Loktak Lake can be sub-divided into eight sub-catchments namely Heirok, Imphal, Iril, Khuga, Kongba, Sekmai, Thoubal and the Western sub-catchment (Figure 2.5). Two of these (the Heirok and Sekmai), however, have been isolated from the lake by diversions schemes so that the present catchment area is 4241 km^2. The Western sub-catchment comprises over 20 streams and rivulets, which directly drain into the lake. Iril is the largest sub-catchment with an area of 1271 km^2 (Table 2.1) while Kongba the smallest (120 km^2), excluding the small catchments under the western sub-catchment.

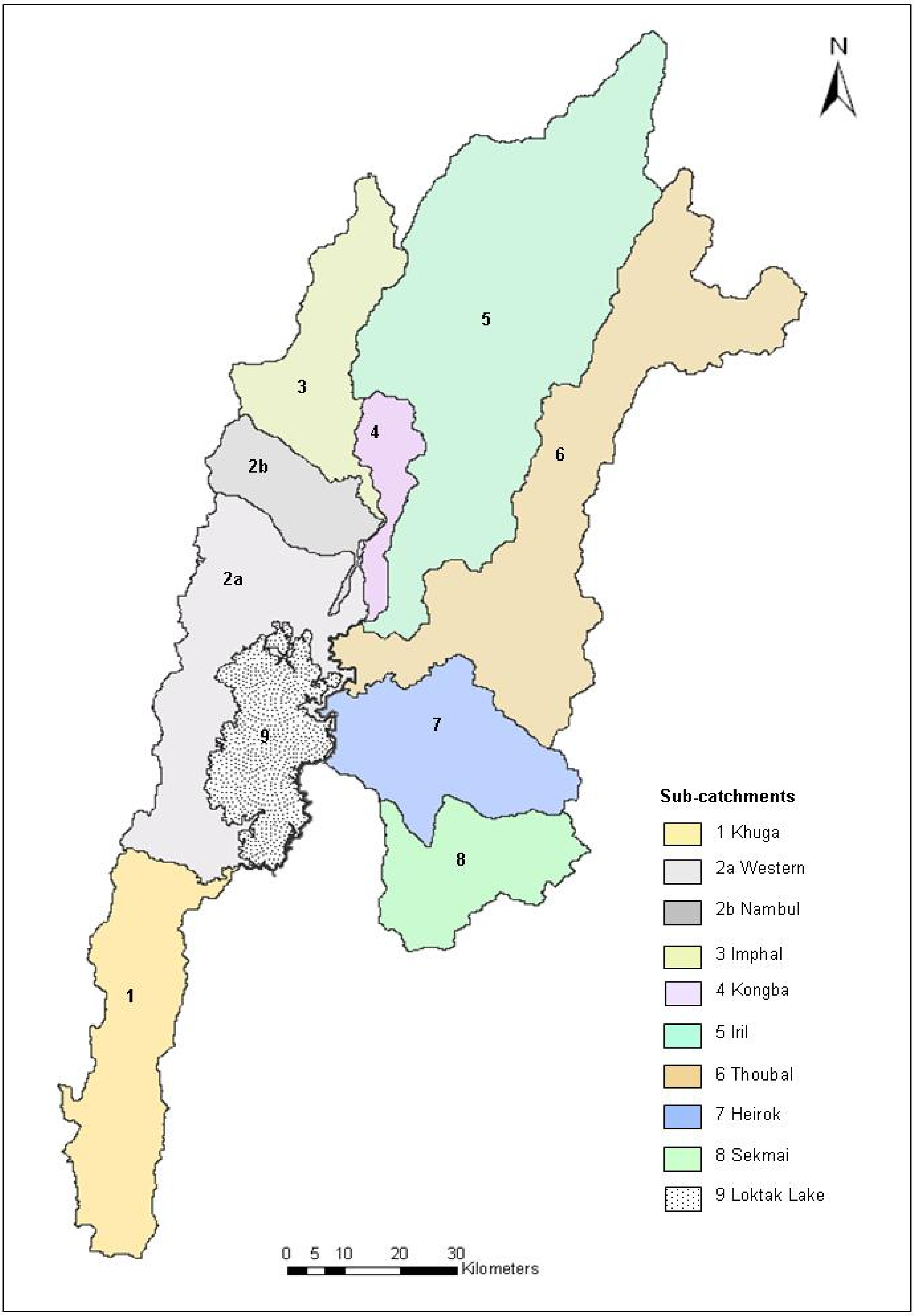


Figure 2.5. Map of Loktak Lake sub-catchments. *Source: LDA*

2.2.2. Topography

The Loktak catchment comprises a central valley, elongated and tapered towards the south, and surrounded by hilly ranges. The overall catchment can be divided into two broad divisions, the hills accounting for 72% of the area and a valley region for the remaining 28%. The hilly ranges are an outcrop of the Himalayas and are aligned north to south in parallel ridges. The area is also drained from north to south parallel with these ranges. Due to the lack of other forms of data the topography of the catchment for the use in this thesis was extracted from NASA Shuttle Radar Topographic Mission (SRTM, Farr et al., 2007) elevation data which has 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 developing world where other sources of topographic data are scare (e.g. Jarvis et al., 2004; Gorokhovich and Voustianiouk, 2006). The topographic map of Loktak catchment derived using ArcGIS from the SRTM data is shown in Figure 2.6.

The elevation of the eastern ranges varies between 800–2430 m above mean sea level (m amsl), whereas the western ranges between 800–2582 m amsl. The central valley has a mean elevation of 800 m amsl with a very gentle slope towards the south interrupted by isolated small hillocks in places. Slopes in both eastern and western ranges are quite steep. In the eastern ranges 59% of its area has slopes >35%, while 40% of the western ranges has slope >35%. The elevation ranges as well the percentage of area over the critical slope of 35% of all the eight sub- catchments are summarised in Table 2.1.

Table 2.1. Sub-catchments of Loktak Lake

Sub-catchment	**Area (km^2)**	**Elevation range (m amsl)**	**Area under steep slopes (> 35%)**
1. Thoubal	963	800 – 2430	61%
2. Iril	1271	800 – 2300	62%
3 Western catchment	1029	800 – 2204	32%
4. Imphal	354	800 – 2582	37%
5. Khuga	504	800 – 1960	51%
6. Sekmai[a]	301	800 – 1600	-NA-
7. Heirok[a]	405	800 – 1467	62%
8. Kongba	120	800 – 1500	-NA-

Source: WISA (2005)

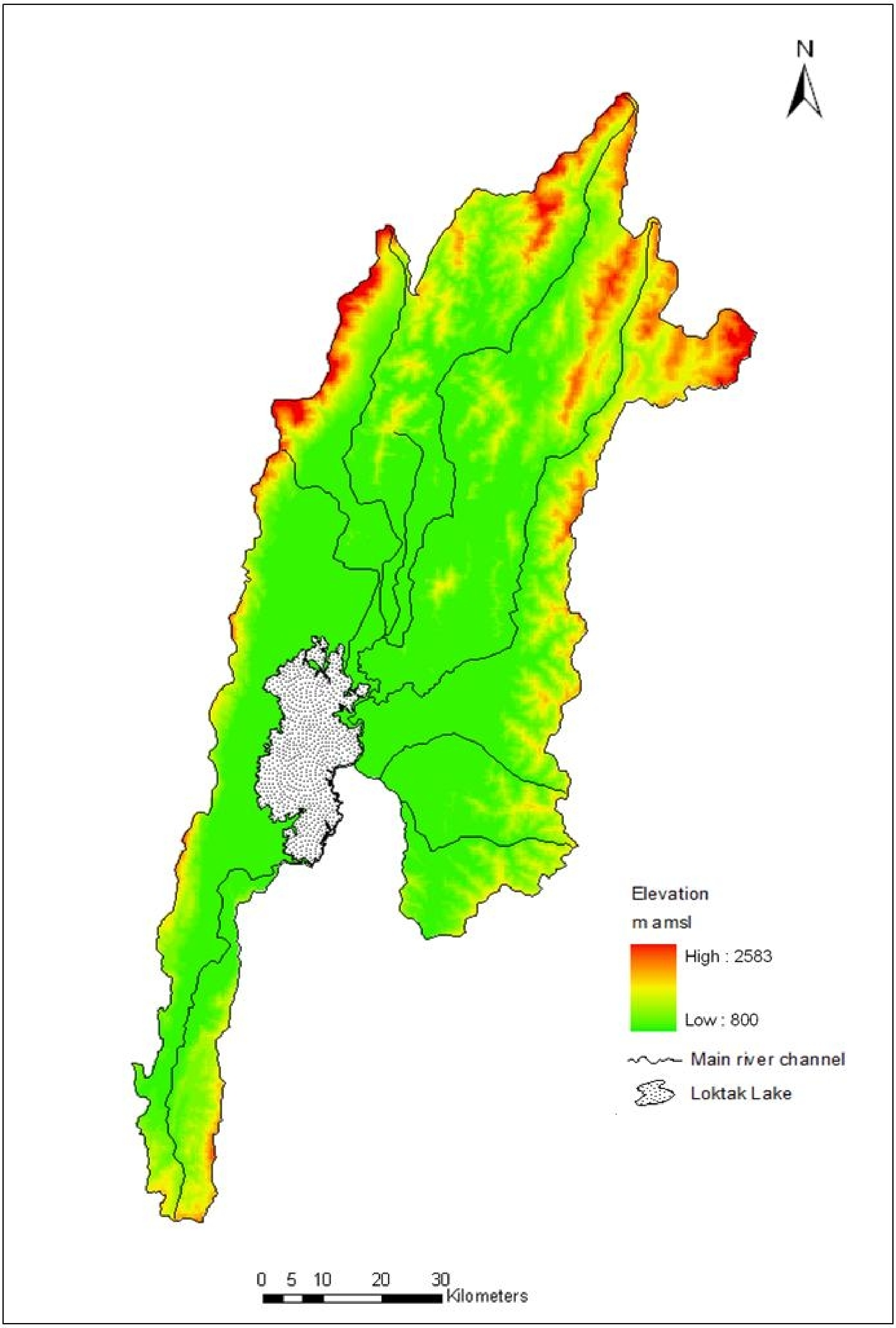


Figure 2.6. Topographic map of Loktak catchment

2.2.3. Geology

The catchment is comprised of geologically young rock formations that were uplifted by the Tertiary Orogeny of the Himalayas from the shallow bed of the Tethys Sea (Chakraborti et al., 2008). The rocks vary from upper Cretaceous to the present alluvium (Environment and Forests Depatment, 2007). The general geological succession of Loktak catchment is given in Table 2.2. The oldest formations are the Disang Series (Eocene) which is overlain by the Oligocene Barail Formation.

The original structure of Manipur valley is that of an anticeinorium (a large fold, convex upward, on which many folds are superimposed) whose crest has been eroded away (PWD, 1967). The rocks are dominantly Tertiary and Cretaceous sediments with minor igneous and metamorphic rocks (Soibam 1998). The hills adjoining the valley on either side are exposed fissile and finely laminated shales of the Disang Series and further away in the west and east, they are succeeded by Barail Series (NBSS and LUP, 2001). The Disang shales formed in this area are intercalated by siltstone and fine sandstone of light to brownish grey. They are characterized by intense folding and faulting. The Barail groups occupying the western portion of the hills are light brownish to grey, fine to medium grained sandstone inter-bedded with shales. Chakraborti et al. (2008) reported the general tectonic trend of rock formations in the area is NNE-SSW, but varies between N–S and NE–SW, and locally NNW–SSE. The detail of the rock formation found at various depths as investigated by Public Works Department (PWD) (1967) is given in Table 2.3. The valley area of the state is filled up by unconsolidated alluvium. It mainly consists of clays and mud derived from the weathering of the underlying argillaceous rocks and sediments carried by streams.

Table 2.2. Geological succession of Loktak catchment

Geologic period	**Formation**	**Details**
Recent	Alluvium	Sand, silts, muds and clays
Oligocene	Barail	Flaggy sandstone, coarse bedded with shales
Eocene	Disang	Dark grey to green splintery shales intercalated with fine grained sandstone, occasionally carbonaceous shale present

Source: PWD (1967)

2.2.4. Soil

The soils in the Loktak catchment are dominantly alluvium with patches of red ferrogenous soil on steep hill slopes in the western part of the catchment (WAPCOS, 1993; NBSS and LUP, 2001). The old alluvial soil brought down by rivers is spread all across the valley area. This old alluvial soils are of considerable thickness, compact and less permeable with a grey to pale brown colour (Environment and Forests Department, 2007). They are acidic to neutral and are poorly drained. Soils on the hill slopes are deep under thick vegetation cover but are otherwise very thin and subjected to high erosion resulting in the formation of sheets and gullies and barren rock slopes. The hill soils are rich in nitrogen and phosphate and are acidic in nature. Clays and loams are the dominant and sub-dominant soil texture found in the area covering 62.6% and 37.4% respectively (NBSS and LUP, 2001). In some parts of the valley, high clay content prevents farming.

Table 2.3. Type of rock formation in Loktak catchment

Depth (m)		**Formation**
From	To	
0	44	Brownish clayey material with whitish silty material
44	49	Greyish sandy and silty material
49	58	Pieces of siltstone
58	61	Greyish sandy and silty material
61	76	Fine grained sandy and silty material
76	77	Siltstone and clayey material
77	81	Greyish sandy and silty material
81	83	Greyish white silty material
83	84	Fresh siltstone
84	90	Greyish white siltstone – vertical and horizontal joints present with strains
90	92	Greyish white silty material
92	95	Fresh siltstone

Source: PWD (1967)

2.2.5. Landuse

Figure 2.7 shows the landuse map derived from superficial classification of remotely sensed imagery provided by Forest Department, Government of Manipur. The landuse of the basin can broadly be divided into forest, agricultural areas, settlement and wetlands (water bodies and *phumdis).* The forest can further be sub-classified into dense forest, degraded forest and *jhum*. *Jhum* areas are those where shifting cultivation takes place. They are normally forested areas which are burned and cleared by the local people to be able to use for agricultural purposes (Trisal and Manihar, 2004).

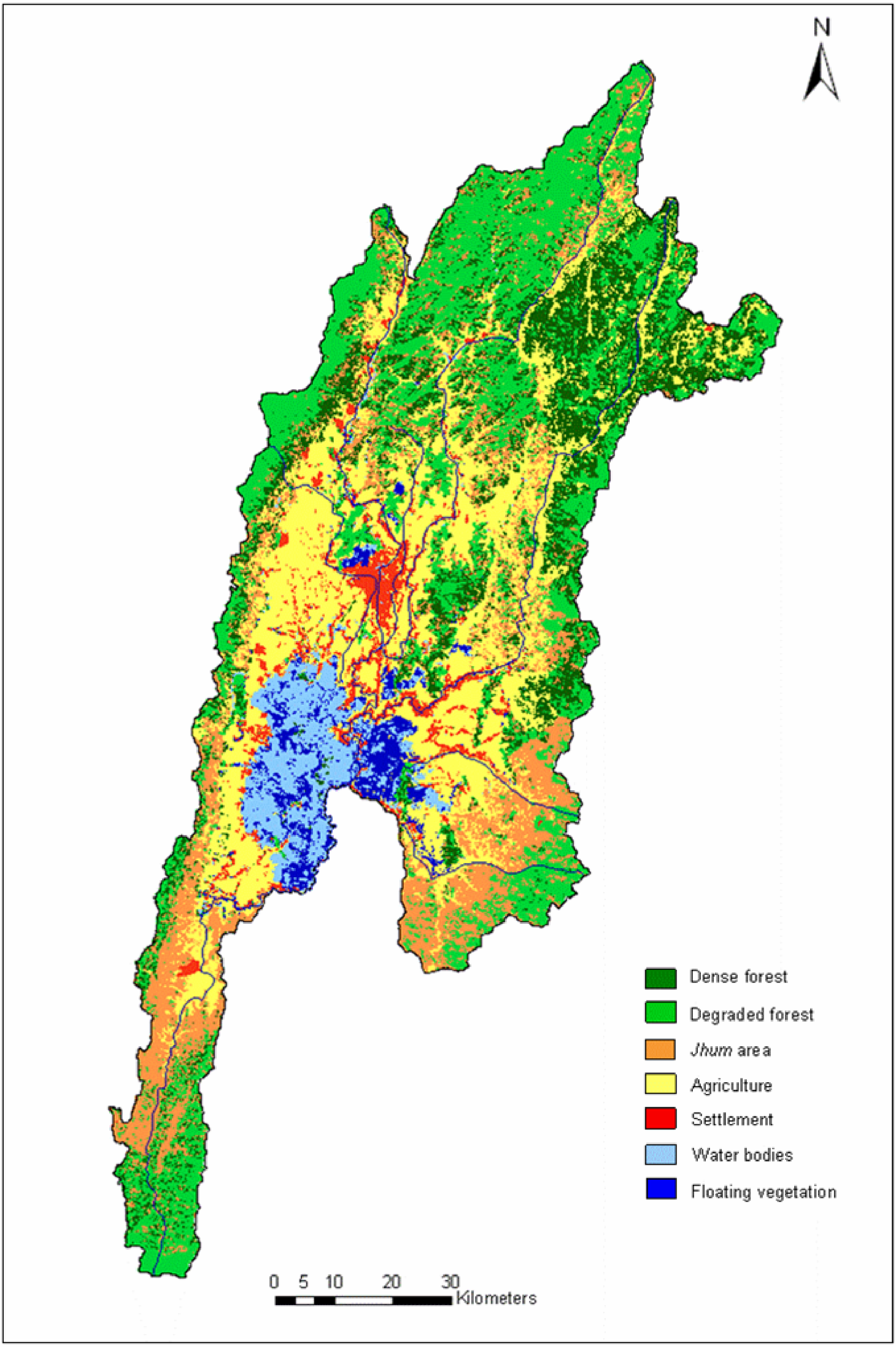


Figure 2.7. Landuse map of Loktak catchment based in data provided by Forest Department, Government of Manipur

Forest: Forest constitutes 64% (3148 km^2) of the total catchment (WISA, 2005). Of these forested areas, the degraded forest accounts for 61%, the active *jhum* area 25% (Figure 2.8) and dense forest 14%. The major forest types occurring in the basin are tropical semi-evergreen, subtropical pine, and montane wet temperate forests (FSI, 2003). Vegetation is particularly sparse in the steep slopes (>35%) (NBSS and LUP, 2001). The degradation of the catchment area can be attributed to the practice of *jhum* by local people. WISA and LDA (2005) reported that shifting cultivation yields approximately twenty times more soil loss per unit area than dense forests. Currently, 616 km^2 of area is under shifting cultivation in the Loktak catchment. The area under shifting cultivation is highest in the Thoubal watershed covering an area of 260 km^2 (27% of the sub-catchment area). Cairns (1998) observed that in the Loktak catchment, the shifting cycle, which until a few decades was more than twenty years, has been reduced to less than five years due to rapid growth of population and declining land availability. Srivastava (1999) stated that destruction of forests and associated loss of biodiversity, severe erosion, degradation and poverty is associated with the spread and intensification of shifting cultivation. He further estimated that in the northeastern region of India, the soil erosion due to shifting cultivation varies between 5–200 t ha^{-1} yr^{-1}. This is responsible for the sedimentation of streams, rivers and associated wetlands in the region. In addition, the traditional land tenure systems in the hill communities has restricted the adoption of soil and moisture conservation measures, leading to further degradation of the *jhum* lands.

Figure 2.8. Jhum areas in Western sub-catchment. Source: Trisal and Manihar (2004)

Agriculture*:* Agricultural areas constitute 15% of the catchment area (WISA, 2005). Rice is the major crop grown in the catchment and is cultivated in 54% of the entire agricultural area. The agricultural activities are more focused in the valley, though there is some limited agriculture in the hilly region through shifting cultivation. The paddy cultivation in the valley area of the catchment accounts for 65% of overall production of the entire state and hence the valley is known as the 'Rice Bowl of Manipur' (Trisal and Manihar, 2004). Pulses, tobacco, potato, chilies and vegetables are other important crops grown in the valley. Sugarcane and citrus fruits are the main cash crop and are exported to other parts of the country. Due to the ever increasing population pressure, multiple cropping patterns have been adopted in the past two decades. The area sowed more than once increased at an annual rate of 6.2% between 1990 and 2000. The use of fertilizer has also increased many fold during the same period, which has resulted in the pollution of the water bodies, especially Loktak Lake.

Settlements: The Loktak catchment is the source of life for the people of Manipur and hence 66% of the population is concentrated in this region (Trisal and Manihar, 2004). The central valley region contains 30 towns and 1429 villages and accounts for 71% of the entire population of the catchment. Imphal is the biggest town in the region and the administrative capital of the state of Manipur. There are 53 settlements (10 towns and 43 villages) on and around Loktak Lake. In 2001 these settlements had a population of 200,000, accounting for 13% of the population in the catchment (Directorate of Economics and Statistics, 2002).

Wetlands (water bodies and *phumdis*): Wetlands, locally called *pats*, covered an area of 385 km^2 in 2002 (Trisal and Manihar, 2004). Loktak Lake is the largest and the most important wetland, with an area of 287 km^2. These wetlands account for approximately 13% of the entire water available in the catchment and hence play important roles in the management of the surface water resource. The wetlands absorb floodwater during the monsoon, which is used for agriculture during dry seasons. These wetlands, especially Loktak Lake, play a vital role in the socio-economy by provision of water, food, fodder, fuel, timber and other wetland products. They also support a large biodiversity of floral and faunal species. In addition, these wetlands have a very high cultural value.

2.3. Catchment climatology

Climate in the Indian sub-continent is dominated by the monsoon. The monsoon can be defined as strong winds which blow from cold to warm region and change directions with seasons. The monsoon wind blows from sea toward land in summer and land toward the sea during winter. In India, the summer monsoon breaks during the months of June to September (Kumar et al., 1999) and blows from the southwest. The southwest monsoon can be sub-divided into two branches – (1) blowing from the Arabian Sea and (2) blowing from the Bay of Bengal. Both these branches carry high amount of moisture and often cause torrential rainstorms. The monsoon first strikes the Indian mainland (Malabar Coast of Kerala, southern India) by the first week of June. By July, the entire country experiences the rainfall. The monsoon is very important for the Indian economy as agriculture, which contributes 20% of the GDP and employs 600 million farmers, depends on the monsoon rainfall. In addition, the rains also replenish the rivers, lakes, wetlands and groundwater, and also help to reduce the high summer temperature.

The Loktak catchment has a tropical to semi-tropical climate in the valley and semi-temperate to temperate in the higher altitudes (WAPCOS, 1993). It has distinct summer, rainy and winter seasons. The rainy season starts with the onset of monsoon in the Indian sub-continent and arrives in the catchment area by June and continues until September. This is then followed by winter from the month of October until February.

2.3.1. Rainfall

The rainfall data available for Loktak catchment are very limited as no thorough long-term monitoring of rainfall has been carried out. However, for the current study, data collected from seven rain gauges operated by the Loktak Development Authority (LDA) (Figures 2.9 and 2.10) during the period June 1999–May 2003 were used. These data were collected under a project ‘Sustainable Development and Water Resources Management of Loktak Lake’ (SDWRML) 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.

Table 2.4 presents the mean monthly and mean annual rainfall recorded in all seven rain gauges. The Pallel rain gauge, located in the south-eastern part of the catchment receives the lowest annual mean rainfall of 1195 mm while the Singda rain gauge in the north-west receives the highest annual mean rainfall of 1648 mm. Figures 2.11 and 2.12 show the daily and the mean monthly rainfall for all seven rain gauges. Rainfall are highest during the monsoon months across all the stations with August being the wettest month with rainfall recorded as high as 310 mm and 306 mm at Singda and Dolaithabi, respectively.

Table 2.4. Mean monthly rainfall (mm) for seven rain gauges in the Loktak catchment

	Dolaithabi	Awang Sekmai	Singda	KLNP	Komkeirap	Pallel	Kangla Siphai
January	3	6	14	11	12	11	12
February	10	9	19	24	19	21	12
March	24	20	62	68	50	47	42
April	59	50	151	154	103	85	92
May	108	121	150	199	173	143	135
June	266	260	267	211	179	162	231
July	213	281	249	238	220	195	207
August	306	239	310	244	219	224	243
September	187	193	188	216	183	137	163
October	172	175	196	150	188	137	124
November	29	46	36	37	30	29	33
December	2	3	4	8	6	4	4
Annual	**1379**	**1404**	**1648**	**1560**	**1382**	**1195**	**1299**

Figure 2.9. Meteorological station at Komkeirap. Source: LDA

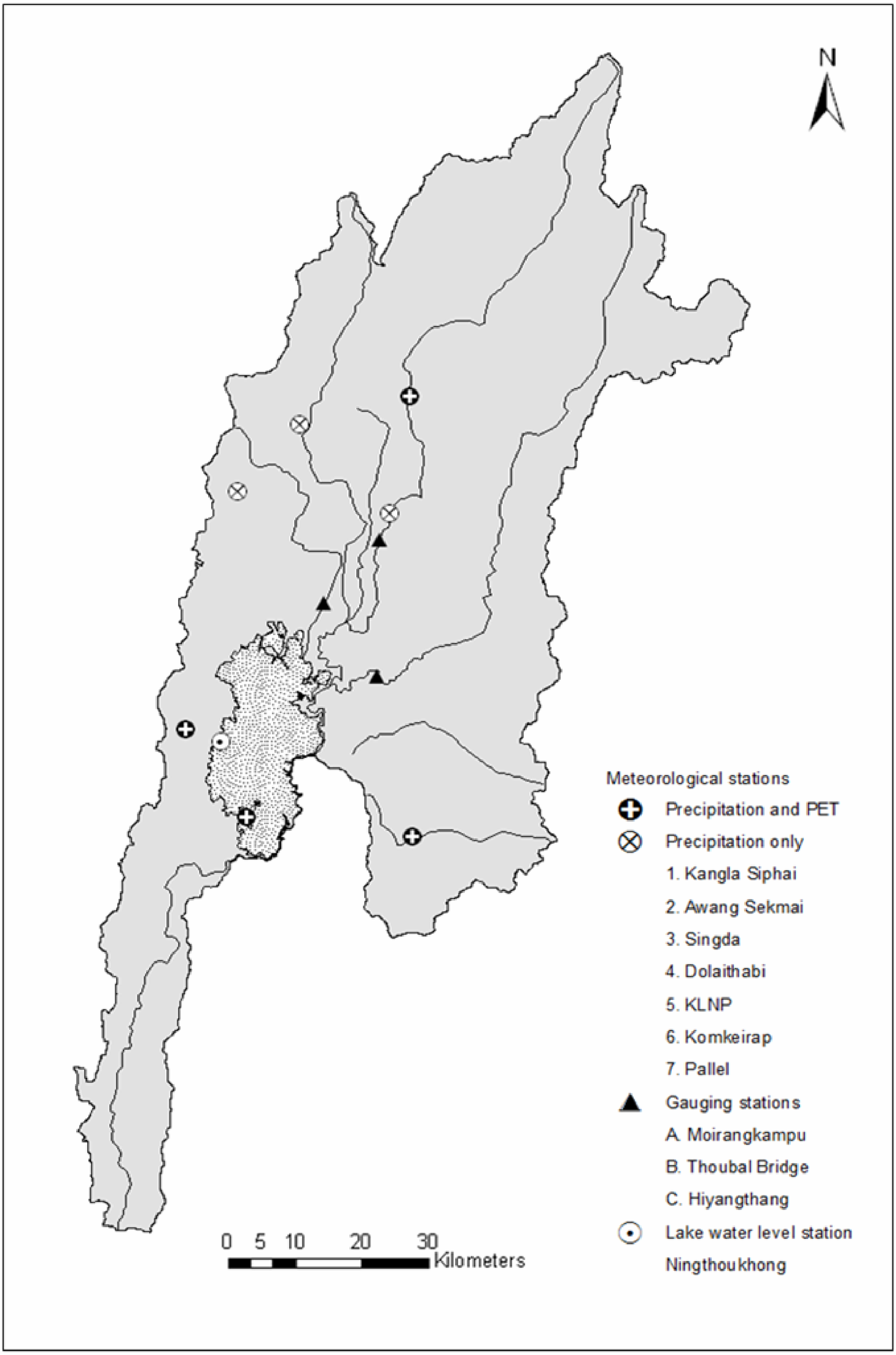


Figure 2.10. Hydro-meteorological stations within Loktak catchment. Source: LDA

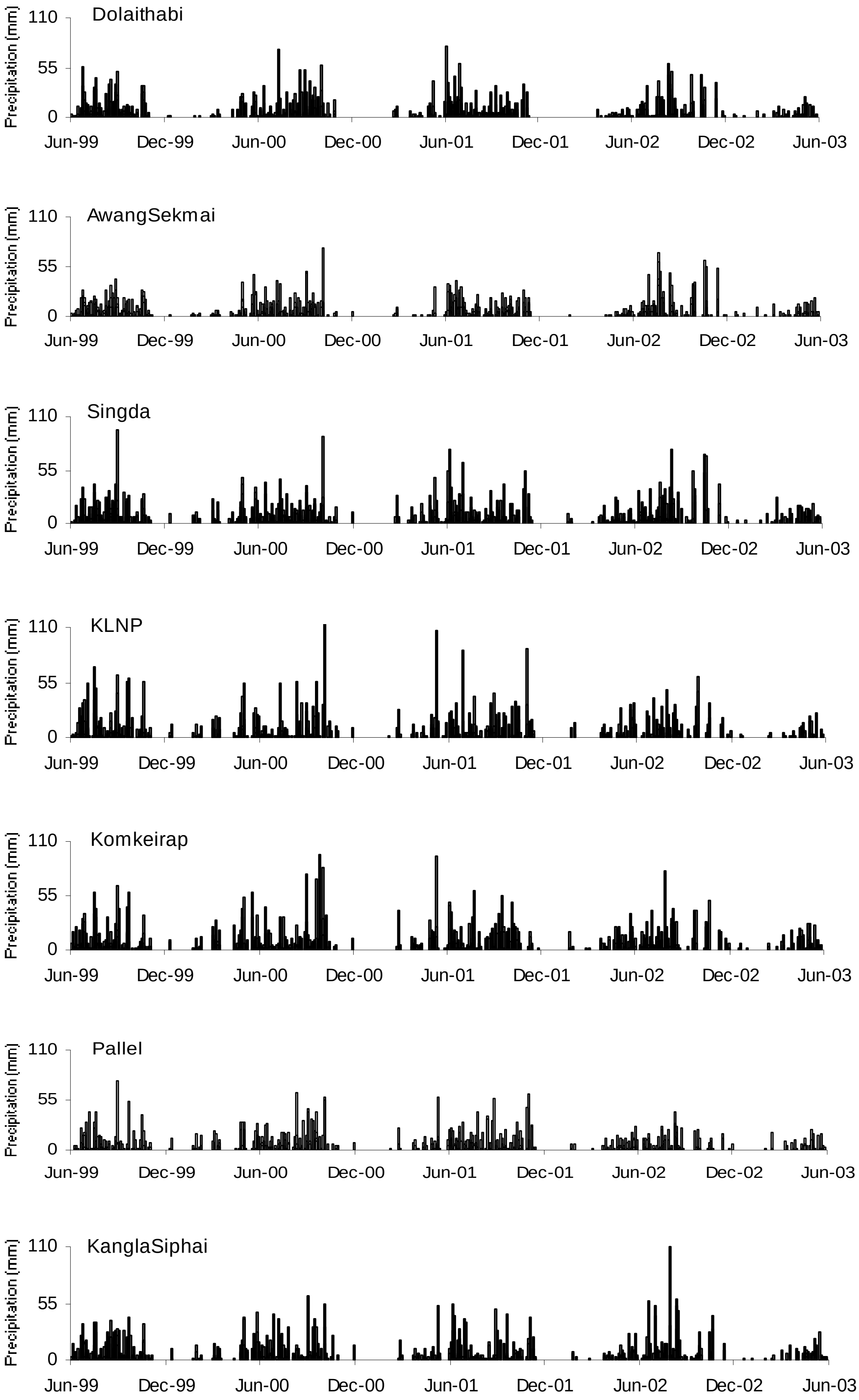


Figure 2.11. Daily rainfall at different stations within the Loktak catchment (June 1999–May 2003)

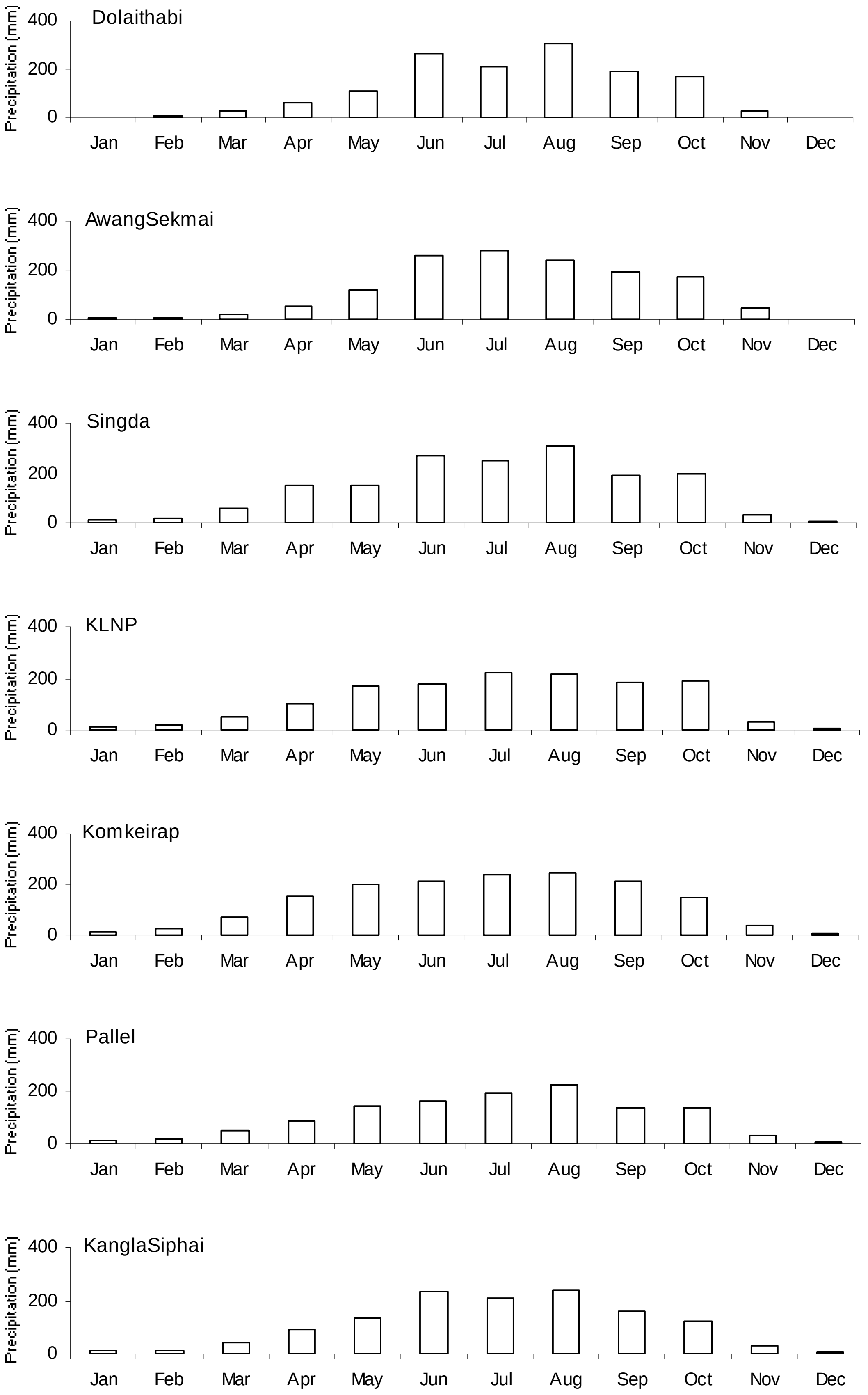


Figure 2.12. Mean monthly rainfall at different rain gauges within the catchment

On average, the four monsoon months (June–September) account for 63% of the annual rainfall. The dry winter extends from October to February with the driest months being December (2 mm and 3 mm recorded at Dolaithabi and Awang Sekmai, respectively). The pre-monsoon summer (March to May) is characterised by scattered showers. As the monsoon approaches, the intensity and frequency of rainfall increases across all the stations (Table 2.4).

Figure 2.13 shows the annual rainfall recorded in all seven gauges between 2000–2002. During this period, the annual rainfall across all stations is similar except for Dolaithabi and Pallel, which show slight decrease during 2002. Dolaithabi recorded an annual rainfall totally of 1415 mm and 1502 mm in 2001 and 2002 respectively, which decreased to 1109 mm during 2003. In Pallel rainfall decreases to 946 mm in 2003 from 1415 mm in 2000 and 1367 mm in 2002. The annual rainfall varies between 1392–1699 mm (average 1484 mm) across the stations during 2000, between 1165–1596 mm (average 1440 mm) during 2001 and between 947–1632 mm (1297 mm) during 2002.

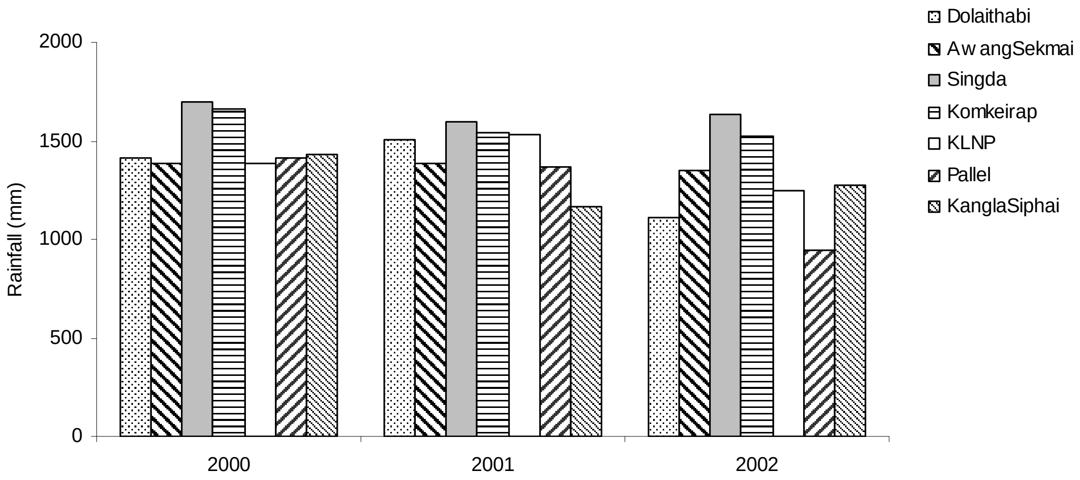


Figure 2.13. Annual rainfall in all seven rain gauges (2000-2002)

Double-mass analysis of the rainfall data collected at all the seven stations was carried out to check the consistency of the data. Figure 2.14 plots cumulative rainfall at each station against the cumulative mean rainfall at the other six stations. The constant slope provided by the double mass analysis (Wilson, 1990; Gasca-Tucker, 2005) suggests that the data are consistent and of good quality. The area of influence associated with each rain gauge within the catchment was estimated by application of Thiessen polygons, which weights the fractions of a catchment area represented by each rain gauge by

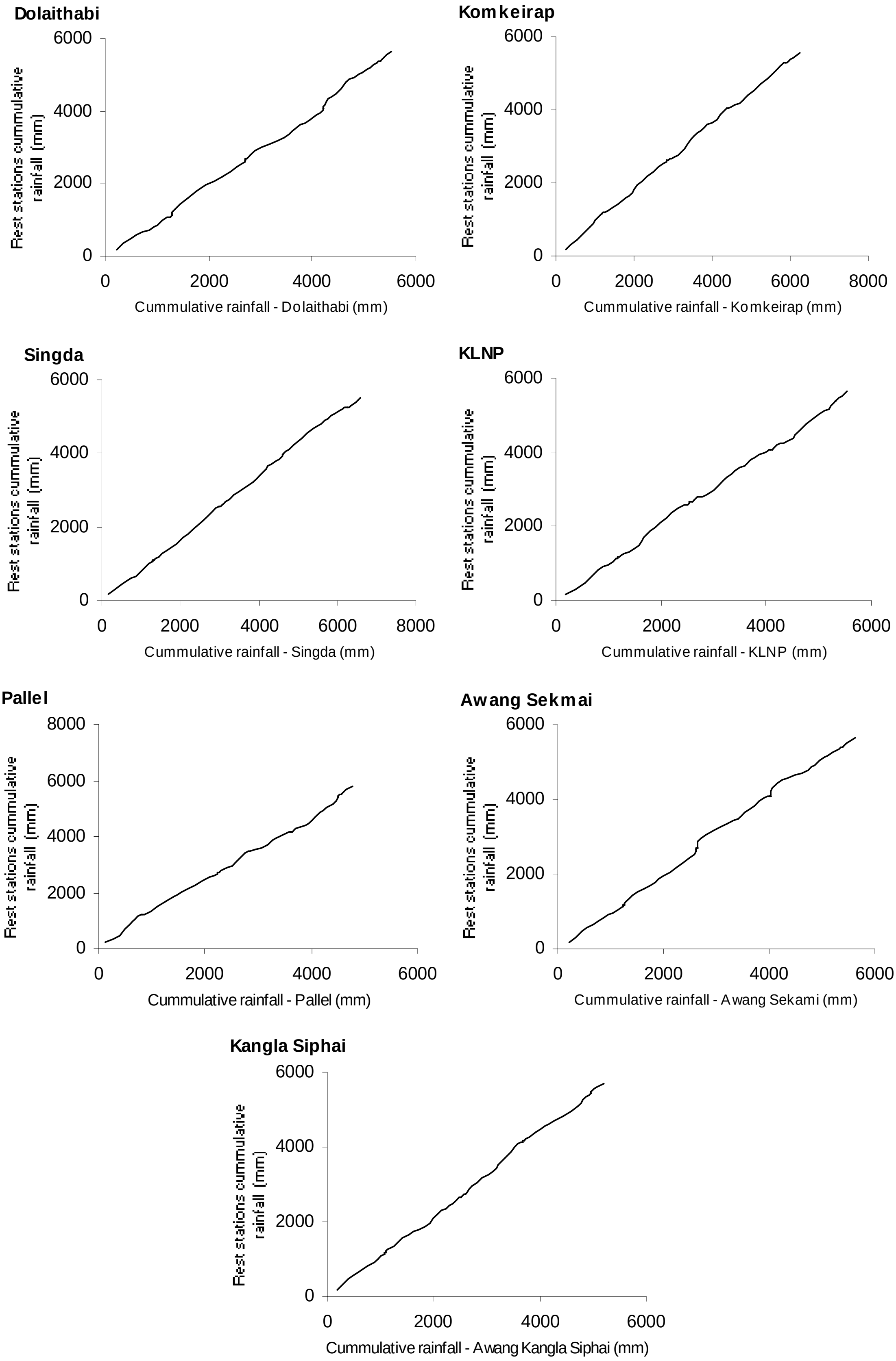


Figure 2.14. Double-mass analysis (daily data June 1999–May 2003) of each rain gauge to the cumulative pattern recorded in other six other gauges

dividing the area into polygons by lines that are equidistant between pairs of stations (Shaw, 1993; Fiedler, 2003). Figure 2.15 shows the Thiessen polygons whilst Table 2.5 provides the representative area associated with each at the seven rain gauges. The Dolaithai gauging station has the maximum influence area (33%) while Singda and Awang Sekmai gauging station the minimum (6% each).

Table 2.5. Representative areas of each rain gauge within Loktak catchment

Raingauge	Representative area (km^2)	% area of the catchment
Dolaithabi	1633	33
Awang Sekmai	297	6
Singda	297	6
KLNP	792	16
Komkeirap	346	7
Pallel	742	15
Kangla Siphai	841	17

2.3.2. Temperature, evaporation and evapotranspiration

Temperature: The availability of temperature data for the Loktak catchment is limited to just four years (June 1999–May 2003) during which LDA established their own meteorological stations. There are four meteorological stations (Figure 2.10) spread across the Loktak catchment. There is also a meteorological station at Imphal airport, which has been monitoring temperature from the late 1980s. However, due to sensitivity in data sharing procedures amongst Government departments, these data could not be procured.

Figure 2.16 shows the daily maximum and minimum temperatures recorded at the four meteorological stations. The highest daily temperate of 35.5ºC was recorded in June 1999 at Keibul Lamjao National Park (KLNP) while the lowest temperature (-1.5ºC) was recorded at Pallel in January 2000. Figure 2.17 shows the monthly temperature recorded in all four meteorological stations during June 1999–May 2003. The monthly variation in temperature across all stations within the catchment is similar with high summer temperature (maximum between 25.75–26.90^{o}C either in June or July) and low winter temperature (minimum between 10.87–13.28^{o}C either in December or January. During this period, the variation in average annual temperature recorded across all these stations was very small. In 2000, the average annual temperature were between 19.20–20.62^{o}C (average 19.92^{o}C), 20.14–21.44^{o}C (average 20.80^{o}C) in 2001 and between 20.35–21.44^{o}C (average 20.80^{o}C) during 2002.

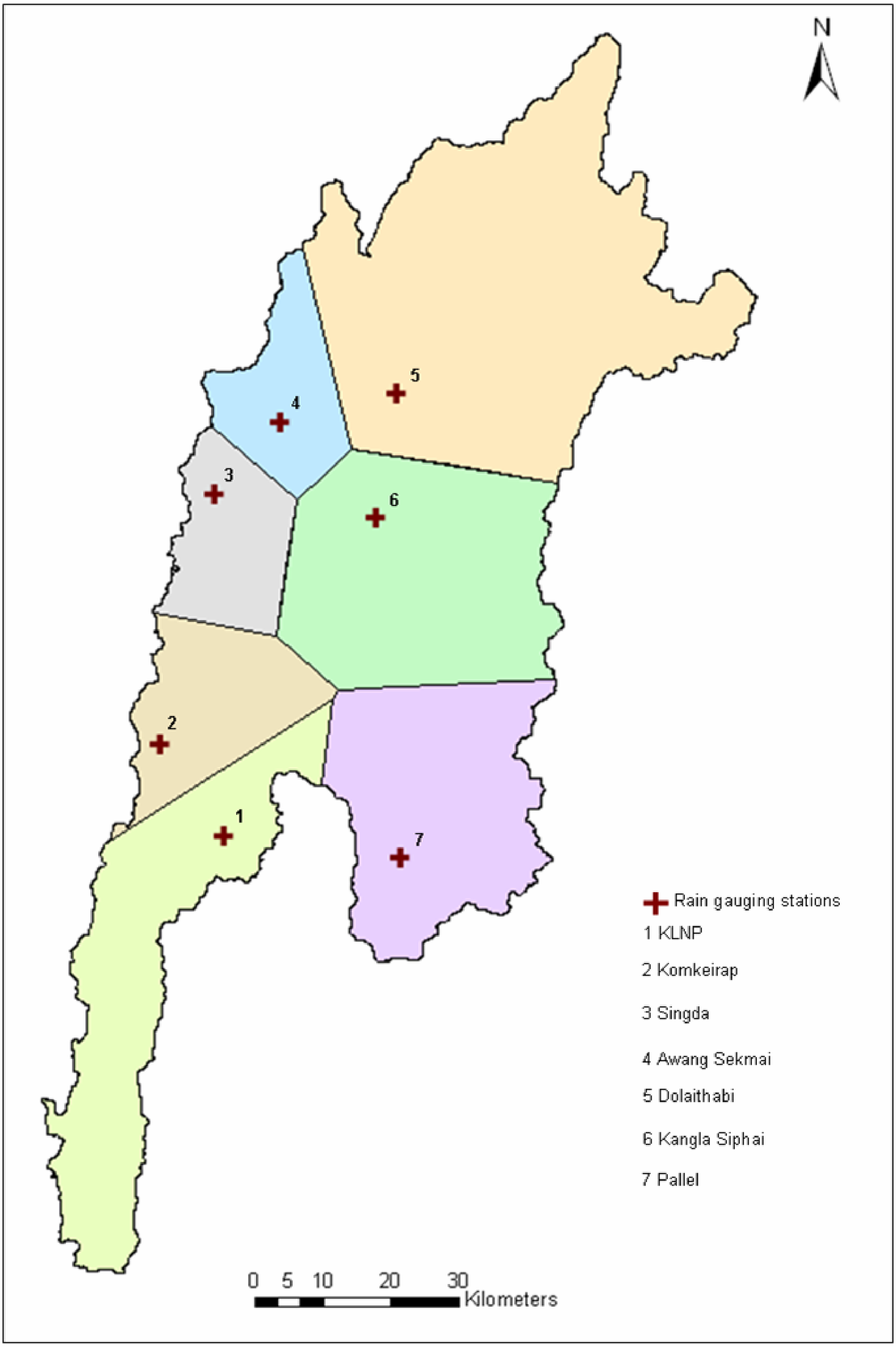


Figure 2.15. Thiessen polygons for rain gauges within the Loktak catchment

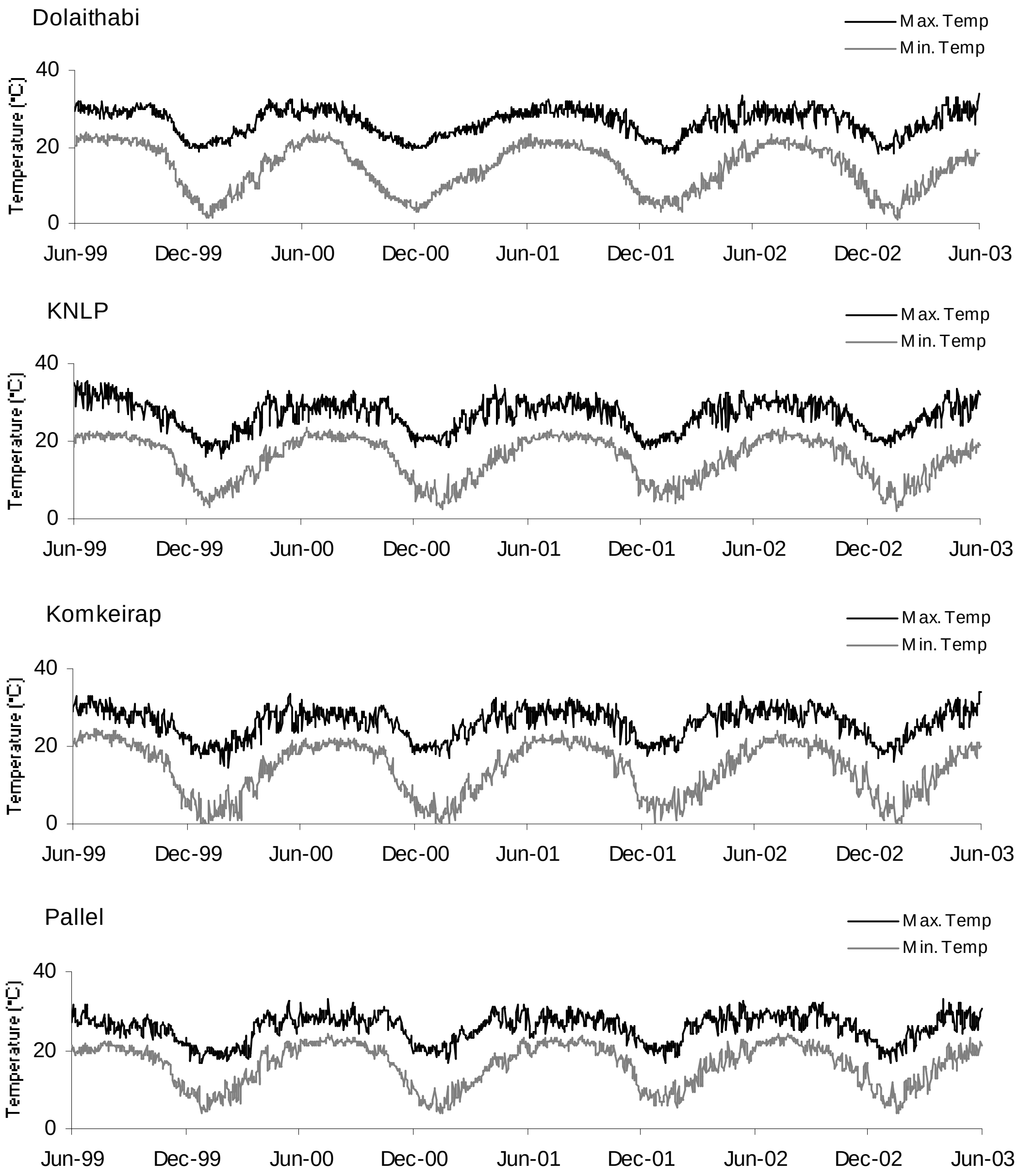


Figure 2.16. Daily maximum and minimum temperature for meteorological stations (June 1999–May 2003)

On average, July is the hottest month with a mean monthly temperature ranging across the stations of between 24.8°C and 25.9°C (average 25.4°C). January is the coldest month with mean monthly temperature varying between 11.75–13.73°C (average 13.1°C) (Figure 2.18). Since the four meteorological stations providing temperature data are located in the valley area of the catchment at an elevation of approximately 800 m amsl, the spatial variation in the temperature is very small (maximum average annual temperature of 21.0°C at KLNP and minimum of 20.1°C at Pallel). However, the temperatures at the higher parts of the catchment can be expected to be lower, especially during winter.

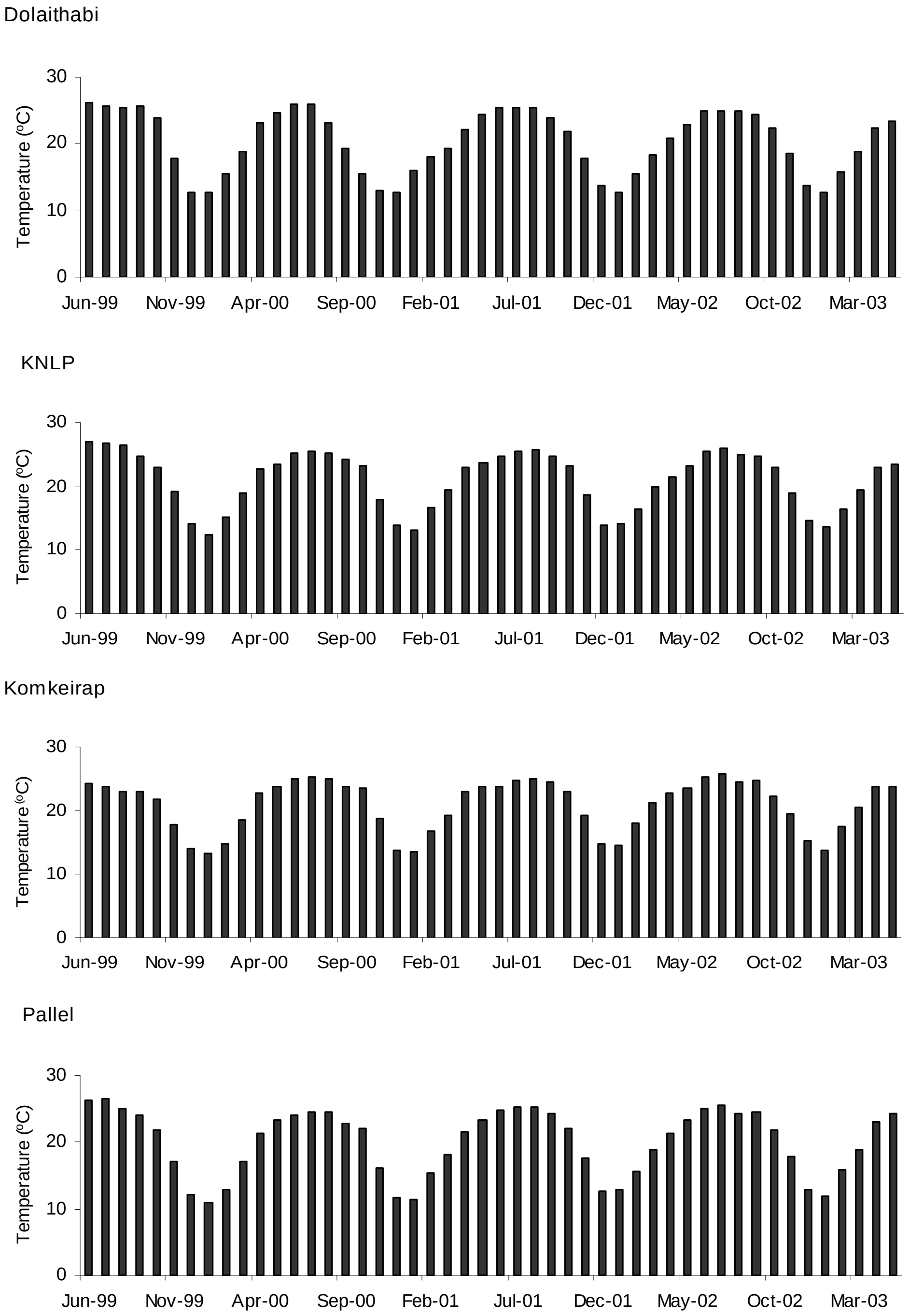


Figure 2.17. Monthly temperature in all four meteorological stations within the catchment (June 1999–May 2003)

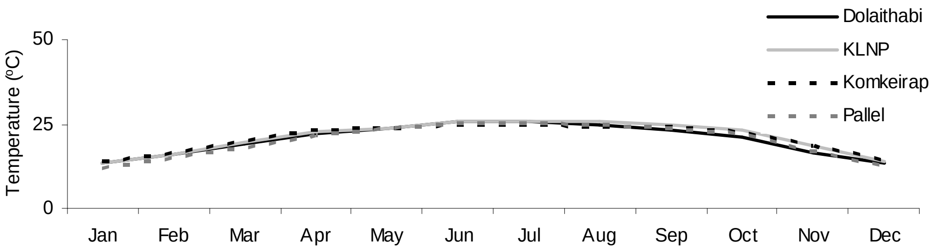


Figure 2.18. Mean monthly temperature for meteorological stations (June 1999–May 2003)

Double–mass analysis of the temperature data collected from the four meteorological stations was carried out. Daily cumulative temperature of each station was plotted against the cumulative mean temperature at other three meteorological stations. The constant slopes of the relationships shown in Figure 2.19 confirm a good quality and consistency of the temperature data collected by LDA at all four stations. The area of influence of each meteorological station within the catchment was estimated by the application of Thiessen polygon method. Figure 2.20 shows the Thiessen polygon indicating the representative area of each of the four meteorological stations and Table 2.6 provides the representative areas associated with each station. The Dolaithabi meteorological station covers the largest part of the catchment (43%, 2127 km^2) while KLNP meteorological station the smallest (14%, 693 km^2).

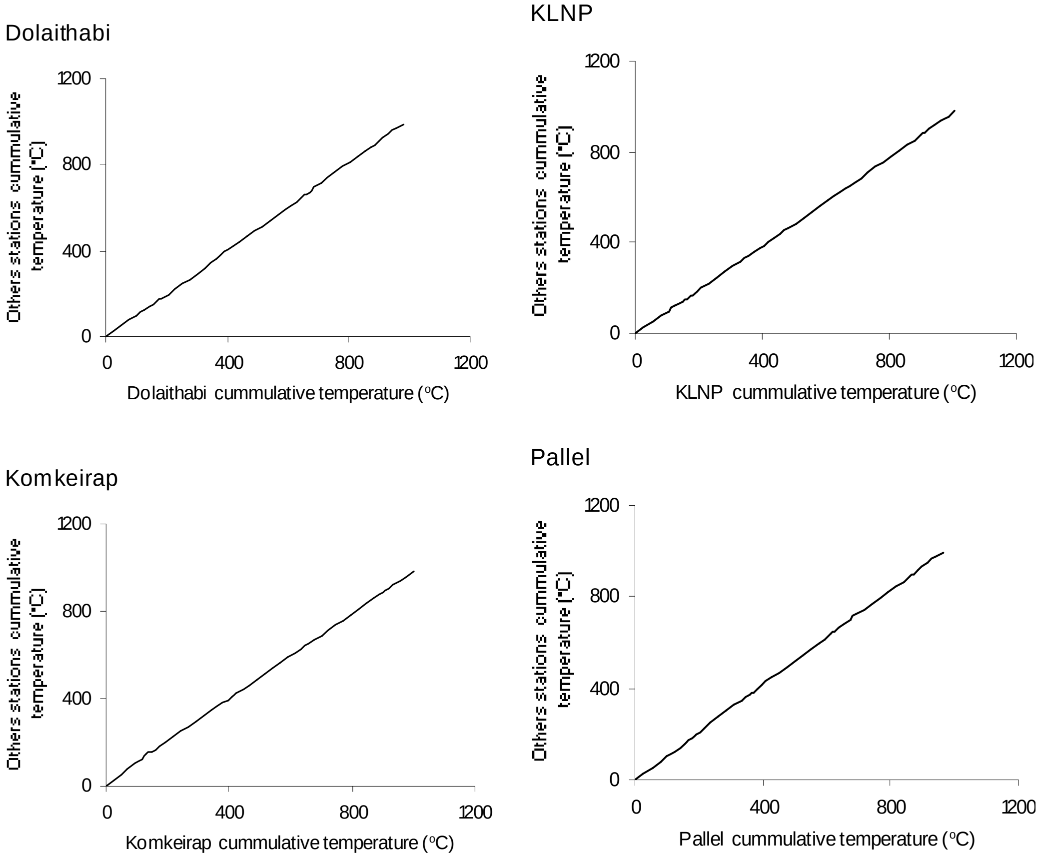


Figure 2.19. Double-mass analysis (June 1999–May 2003) of each meteorological station against the cumulative pattern recorded in other three other stations.

Table 2.6 Details of meteorological stations indicating their representative areas within Loktak catchment

Meteorological station	Representative area (km^2)	% area of the catchment
Dolaithabi	2127	43
Komkeirap	1187	24
KLNP	693	14
Singda	940	19

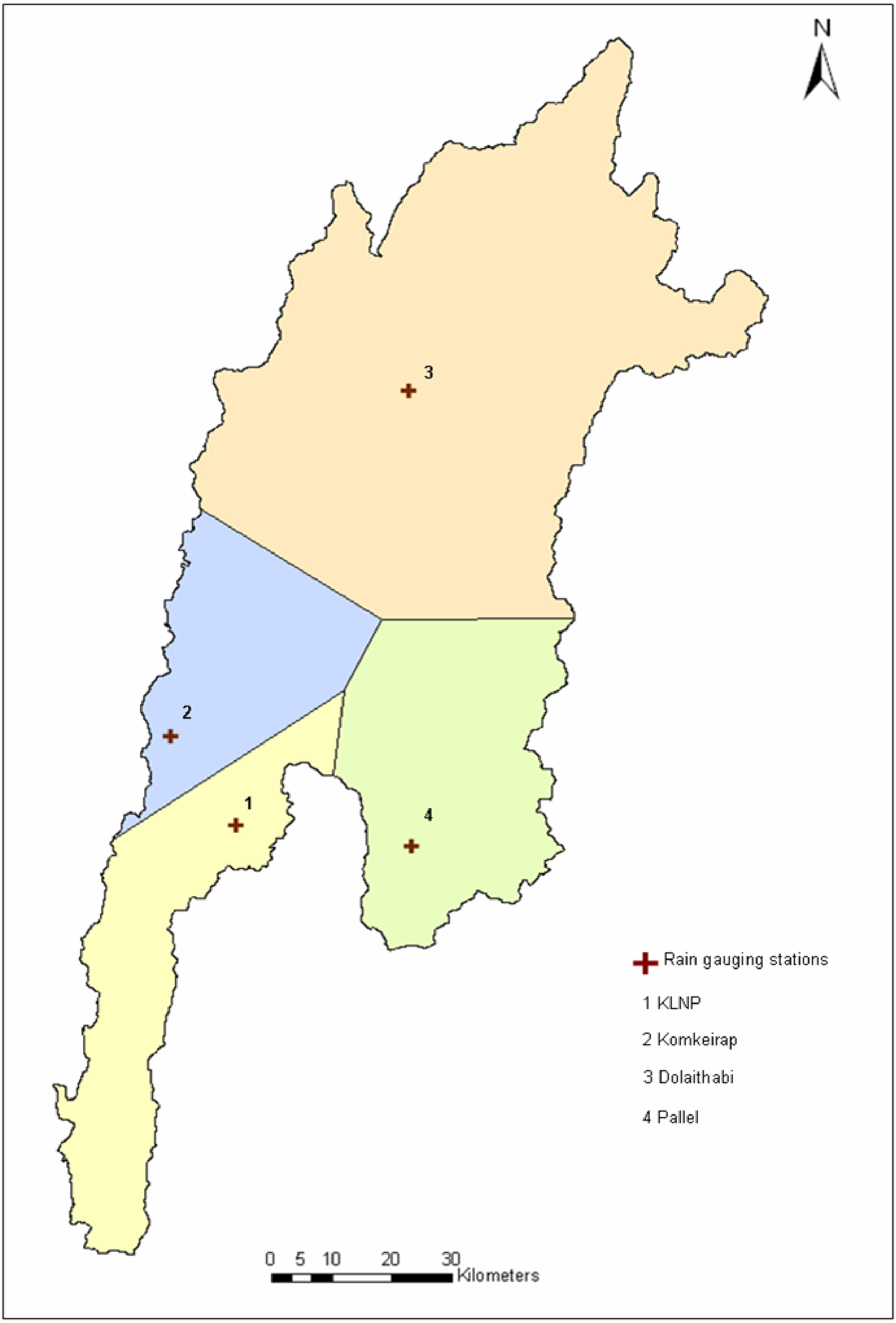


Figure 2.20. Thiessen polygons for meteorological stations within Loktak catchment providing temperature, evaporation and evapotranspiration data

Evaporation and evapotranspiration: Similar to temperature, evaporation and evapotranspiration data are also limited to June 1999–May 2003 and are available from the four meteorological stations (Figure 2.10). For the purpose of the present research, the processed daily evaporation and evapotranspiration data for these stations were procured from LDA. However, it has been reported that the LDA employed Class A Pans to collect the pan evaporation, which were then multiplied by a pan coefficient of 0.7. Potential evapotranspiration were estimated using the Penman-Monteith method. Figure 2.21 shows daily Class A Pan evaporation during June 1999–May 2003. The variation in daily evaporation within the catchment area is quite high with a maximum of 8.6 mm day^{-1} recorded in Komkeirap during April 2000 while a minimum of 0.8 mm day^{-1} in KLNP during December 2001. The variation in the monthly evaporation (Figure 2.22) shows a similar pattern to that of temperature in all the stations with high summer evaporation and low winter evaporation.

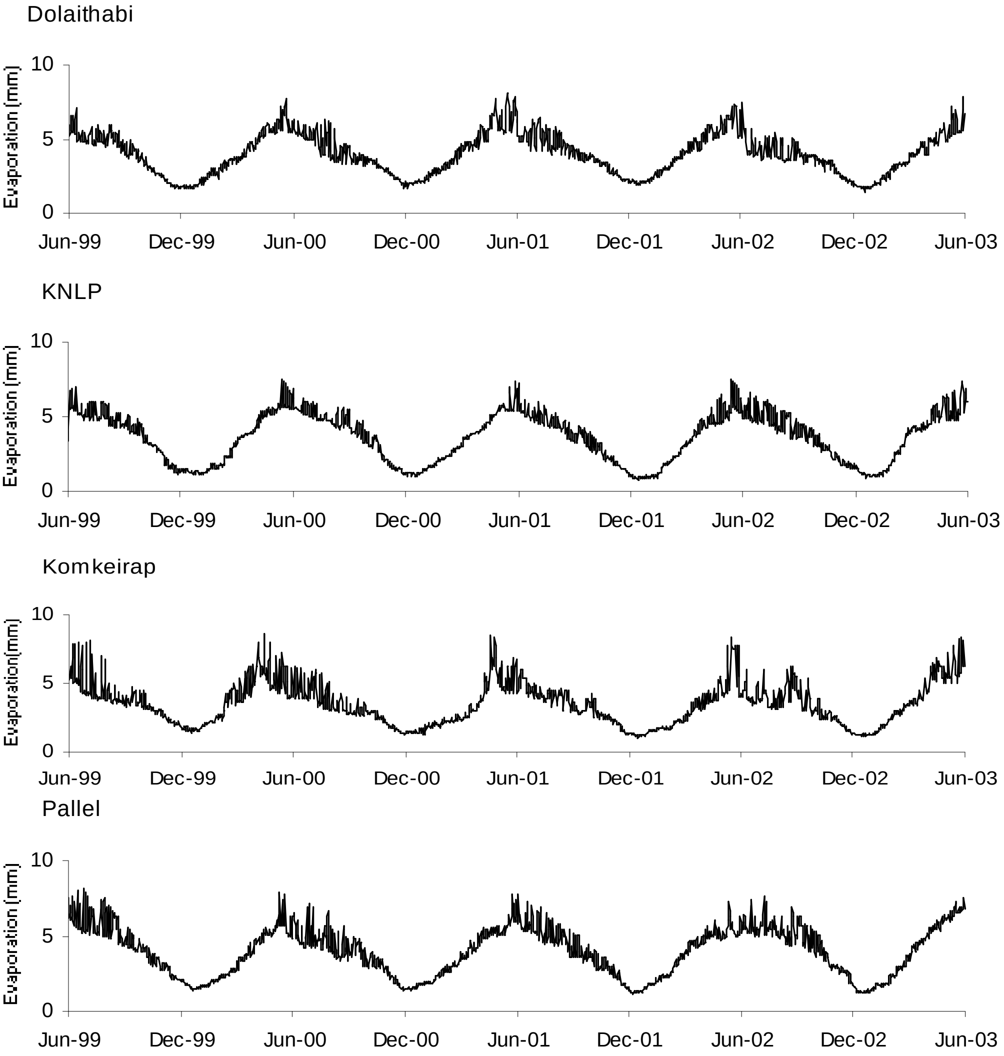


Figure 2.21. Daily Class A evaporation at four meteorological stations within the Loktak catchment (June 1999–May 2003)

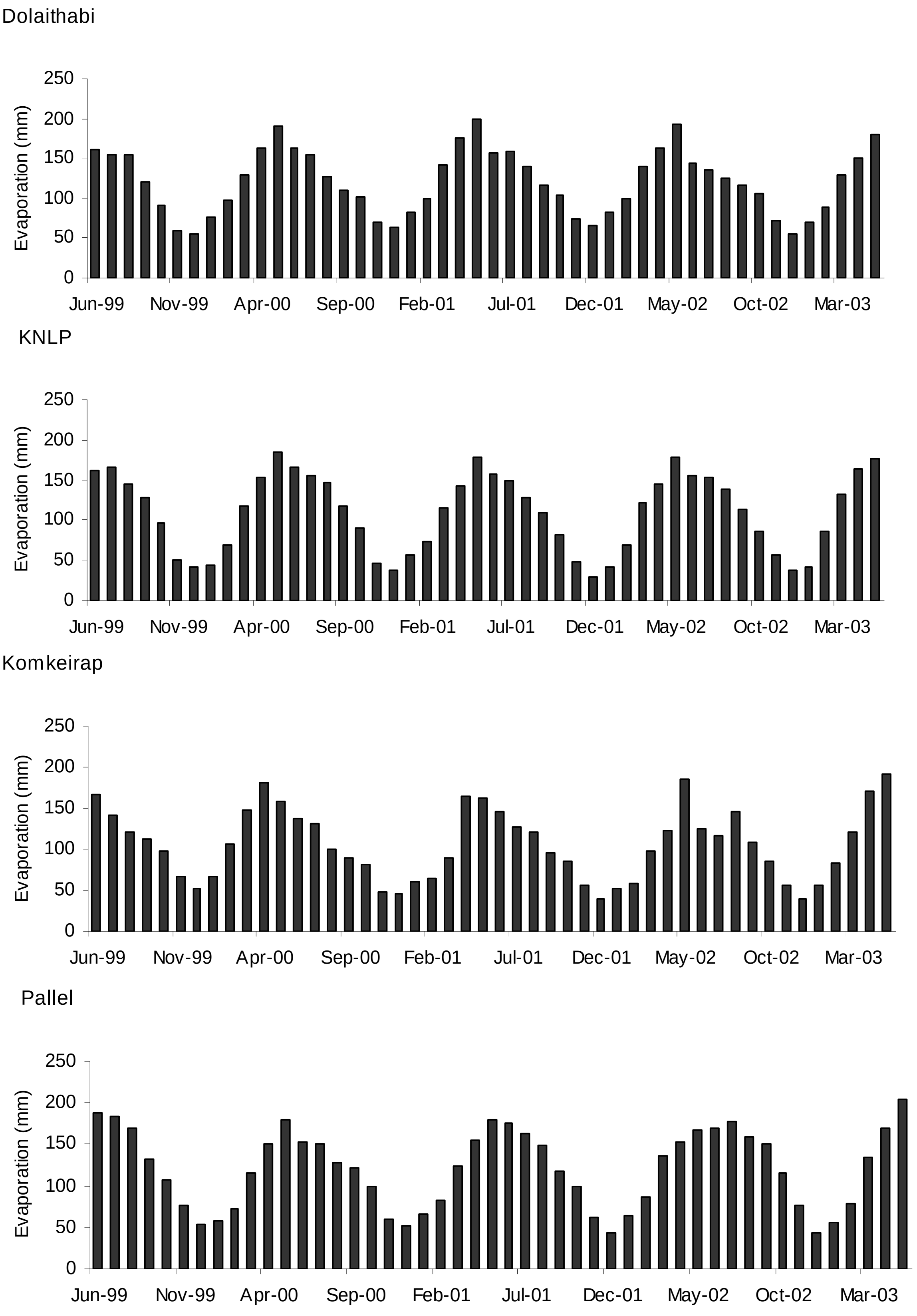


Figure 2.22. Monthly Class A evaporation in all four meteorological stations within the Loktak catchment (June 1999–May 2003)

On average, May has the maximum evaporation rate (between 130.7-152.5 mm month^{-1}) while December the minimum (between 29.0-47.8 mm month^{-1}) (Figure 2.23). The Dolaithabi station recorded the maximum mean annual evaporation of 1453 mm followed by Pallel (1452 mm), KLNP (1323 mm) and the lowest at Komkeirap (1270 mm). The variation in annual evaporation recorded across all these stations is very small (Figure 2.24). In 2000, the annual evaporation was between 1291-1447 mm (average 1352 mm), 1212-1517 mm (average 1355 mm) in 2001 and between 1193-1496 mm (average 1355 mm) during 2002.

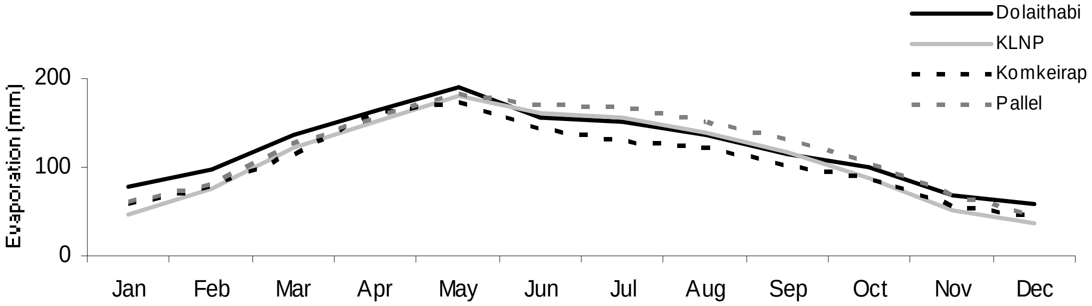


Figure 2.23. Mean monthly Class A evaporation at four meteorological stations within the Loktak catchment (June 1999–May 2003)

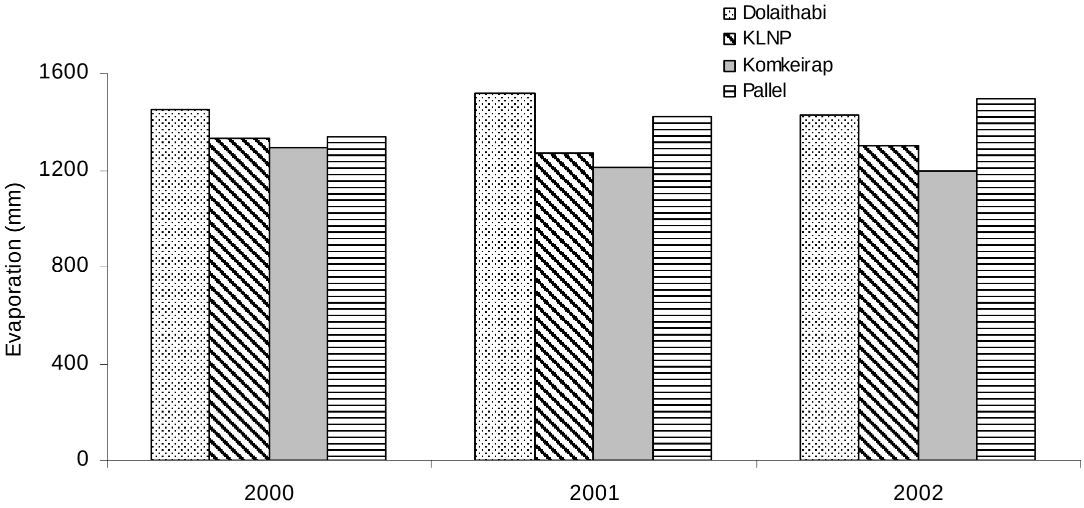


Figure 2.24. Annual Class A evaporation at all four meteorological stations within the Loktak catchment (2000–2002)

Double-mass analysis of the evaporation data from the four meteorological stations was carried out. The constant slope of the relationships shown in Figure 2.25 confirms the quality and consistency of the evaporation data estimated by the LDA.

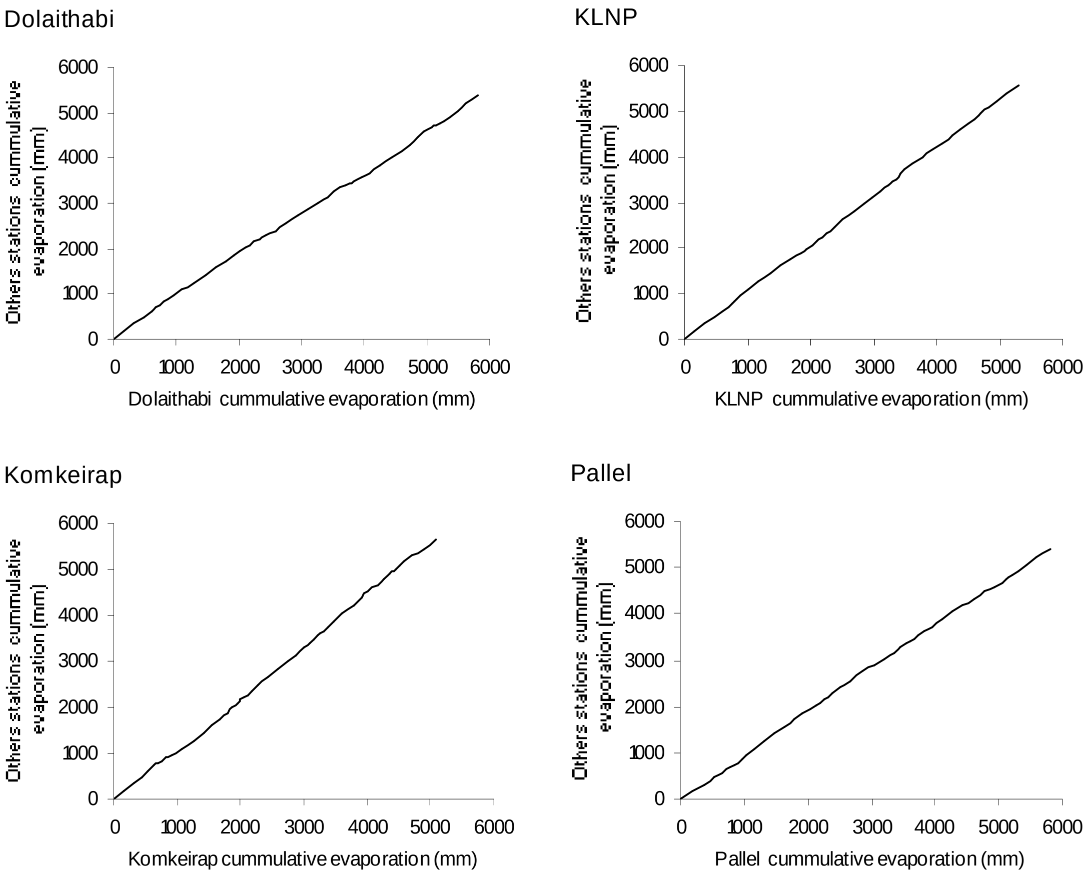


Figure 2.25. Double-mass analysis (daily data June 1999–May 2003) of each meteorological station against the cumulative pattern recorded in the other three other stations.

Figure 2.26 shows the daily Penman-Monteith evapotranspiration as estimated at the four meteorological stations. The variation in the monthly evapotranspiration at across each station closely follows the pattern of temperature and evaporation with high summer evapotranspiration and low winter evapotranspiration (Figure 2.27). On average, May has the maximum evapotranspiration across all the four stations (between 139.5-153.5 mm month-1) while December the minimum (between 29.0-47.8 mm month-1) (Figure 2.28). The variation in the annual evapotranspiration across all the stations varies between 1033-1158 mm (mean 1081 mm) in 2000, 967-1214 mm (average 1084 mm) in 2001 and between 955-1197 mm (average 1084 mm) during 2002 (Figure 2.29) indicating very small annual variation in the evapotranspiration during the study period. The constant slope of the double-mass curve analysis (Figure 2.30) confirms a good and consistency quality of the evapotranspiration data estimated.

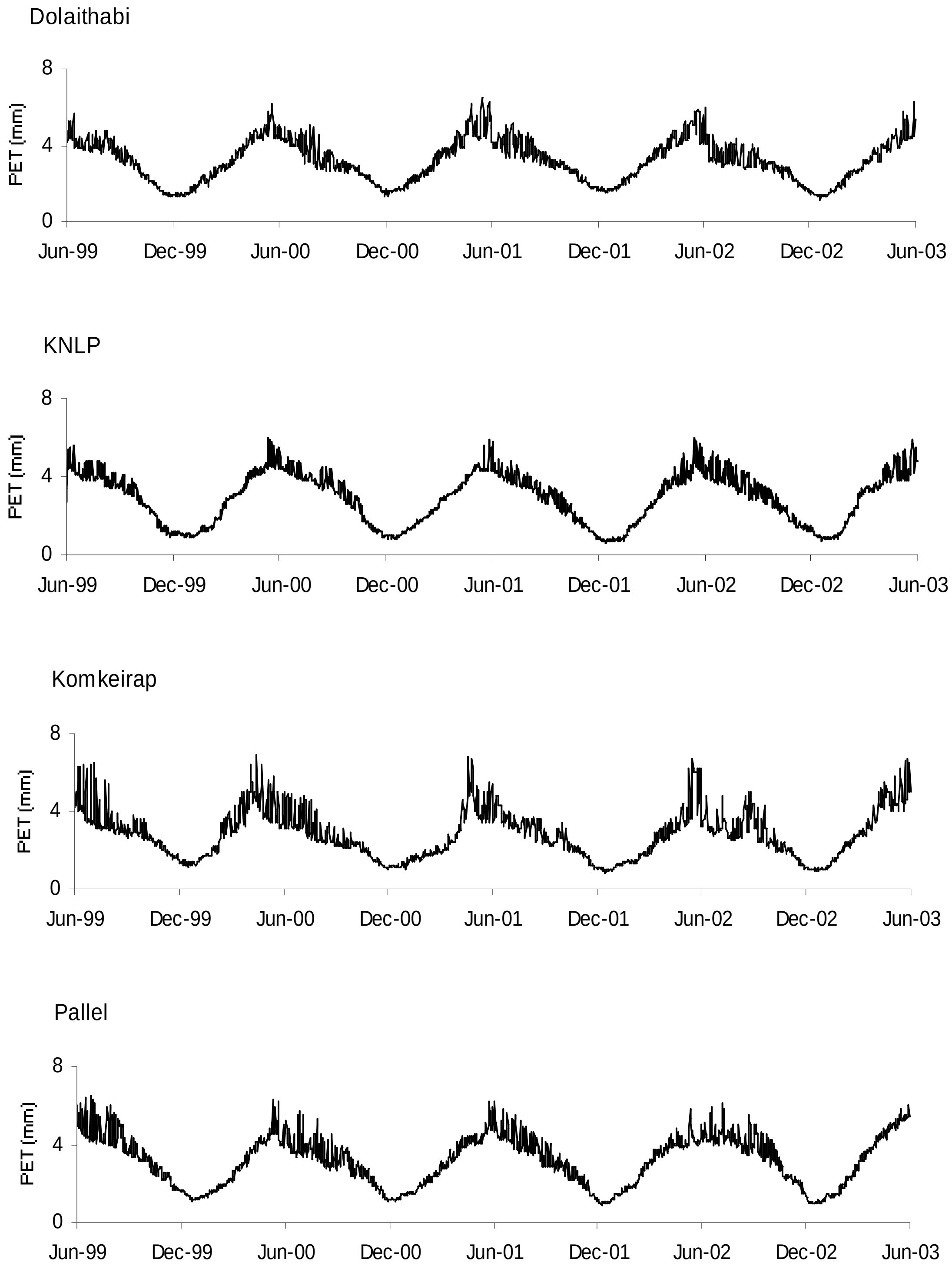


Figure 2.26. Daily Penman - Montieth evapotranspiration at the four meteorological stations within Loktak Lake catchment (June 1999–May 2003)

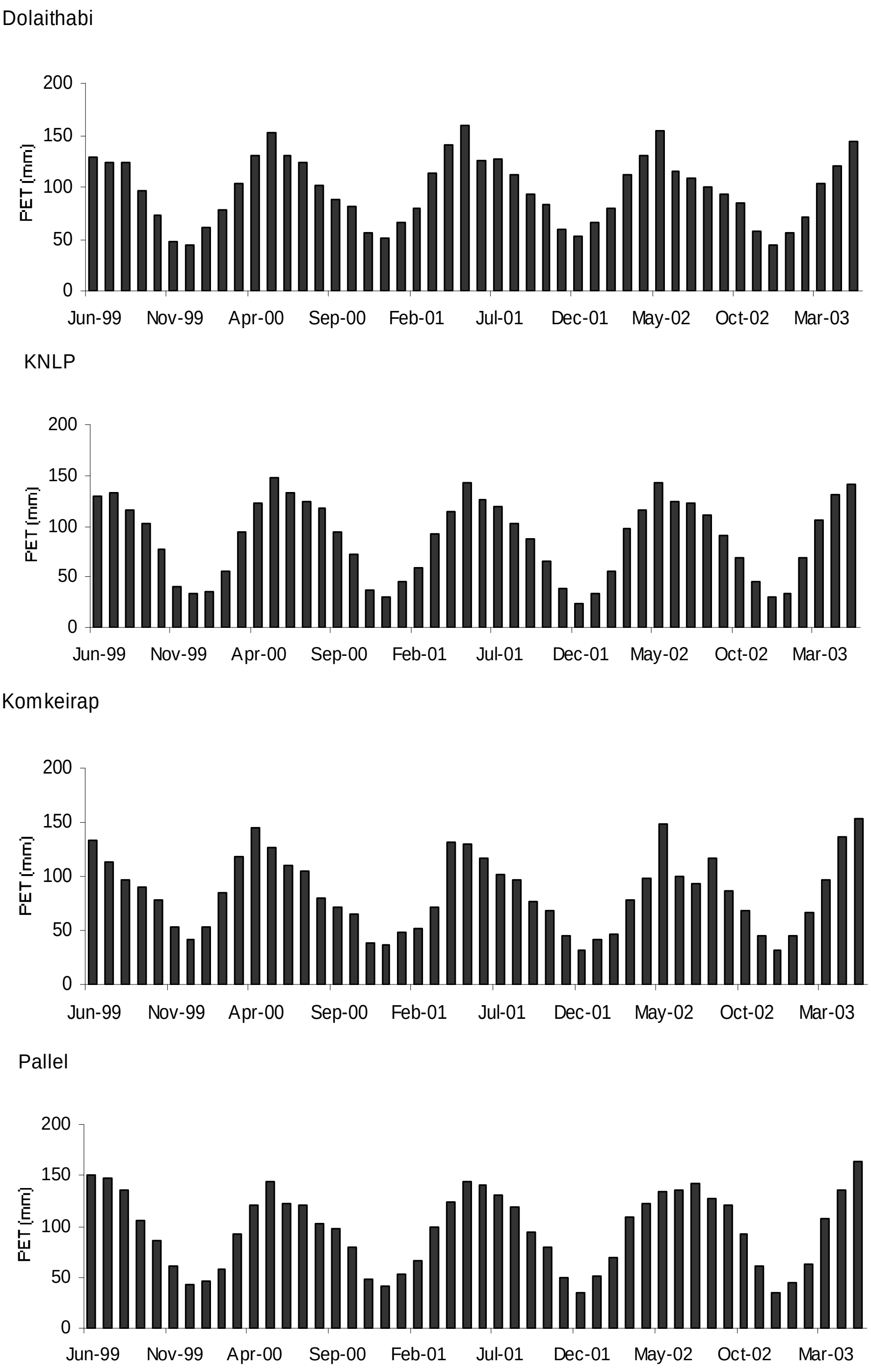


Figure 2.27. Monthly evapotranspiration at the four meteorological stations within the Loktak catchment (June 1999–May 2003)

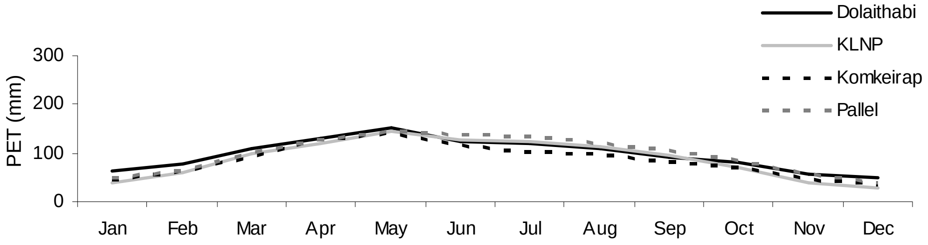


Figure 2.28. Mean monthly evapotranspiration at the four meteorological stations within the Loktak catchment (June 1999–May 2003)

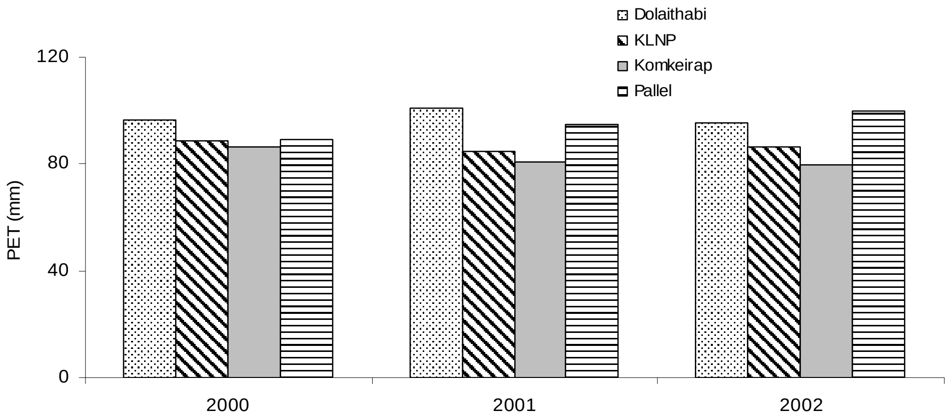


Figure 2.29. Annual evapotranspiration at all four meteorological stations (2000-2002)

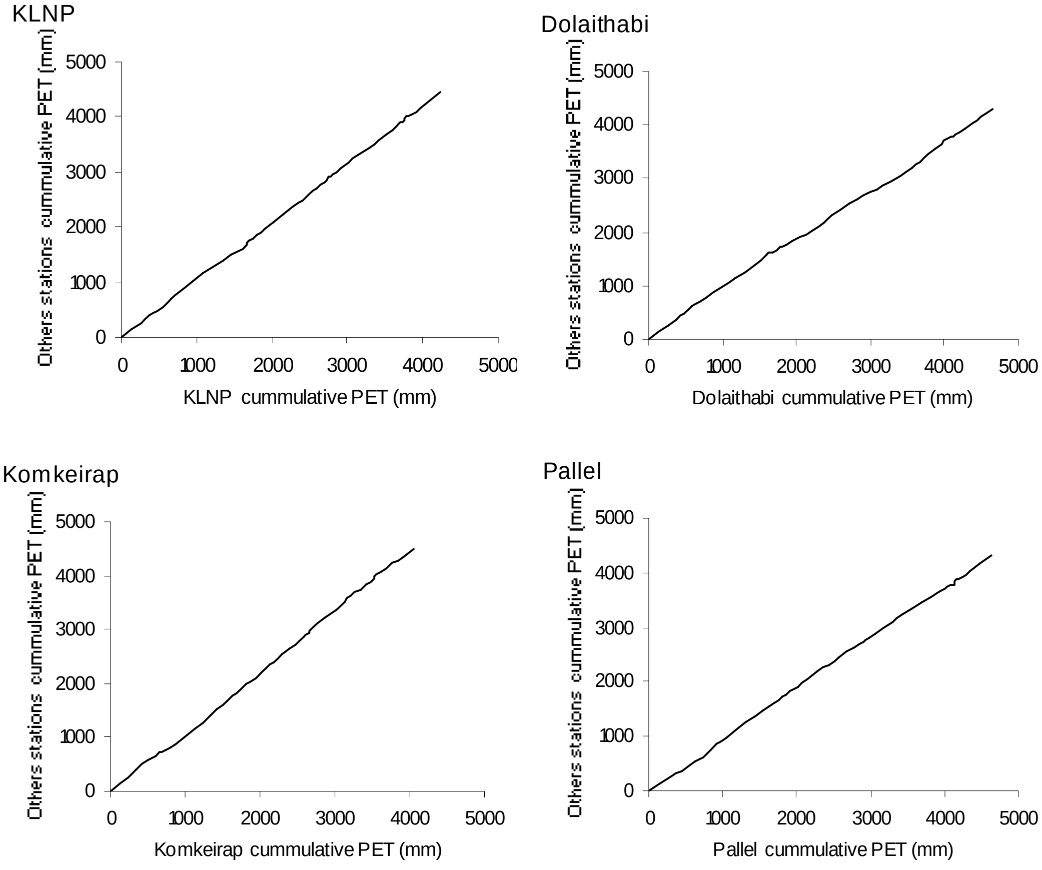


Figure 2.30. Double-mass analysis (daily data June 1999–May 2003) of each meteorological station against the cumulative pattern recorded in the other three other stations.

2.4. Catchment river runoff

Historically, Loktak Lake was primarily fed by seven main rivers namely the Imphal, Iril, Thoubal, Kongba, Heirok, Sekmai and Khuga rivers and over 20 smaller rivers and rivulets from the Western sub–catchment including Nambul River (Figure 2.31). However, in the last two decades, Heirok and Sekmai rivers have been isolated from the lake by various diversions schemes implemented by state government. The rivers and rivulets from the Western sub-catchment flows directly into the Loktak Lake, while the other five rivers (Imphal, Kongba, Iril, Thoubal and Khuga) joins together to form the Manipur River, which is then connected to the lake. The Imphal River rises in the northern part of the catchment and flows southwards towards Imphal city. The Kongba and Iril rivers join the Imphal River on its left bank about 10 km south of Imphal. Further downstream, the Thoubal River joins from the left bank and thereafter, it is known as Manipur River, which flows parallel to the lake. Further downstream, the Khuga River joins the Manipur River on its right bank.

Despite several piecemeal studies carried out on these rivers, no systematic monitoring of discharge has been undertaken. The Ministry of Irrigation and Power through the National Hydro-electric Power Corporation (NHPC) carried out preliminary investigation of the hydrological regimes for the construction of Ithai Barrage. Based on their report, they developed an empirical equation predicting runoff between 1923–1964. Using this equation, they estimated the average annual runoff of Manipur River at site of the Ithai Barrage to be $3774 \times 10^6 m^3$. However, this was a one-off study carried out specifically for the conceptualization and construction of Ithai Barrage. No further data beyond this are available.

Through the project previously mentioned in Section 2.3.1, LDA and WISA established daily discharge monitoring stations on the Iril River (Moriang Kampu), Thoubal River (Thoubal Bridge) and Nambul River (Hiyangthang). The locations of the discharge monitoring stations are shown in Figure 2.10. Stage boards were set-up by the LDA at natural cross-sections of these rivers and the water-levels were read manually on daily basis. The cross-sections of the rivers were surveyed once every year to record changes in the river cross-section, if any. However, the data are limited to the period of June 1999–May 2003, and monitoring of river discharge was discontinued with the completion of the project. Figure 2.32 shows the stream gauging station at Moirang Kampu for measuring discharge in Iril River.

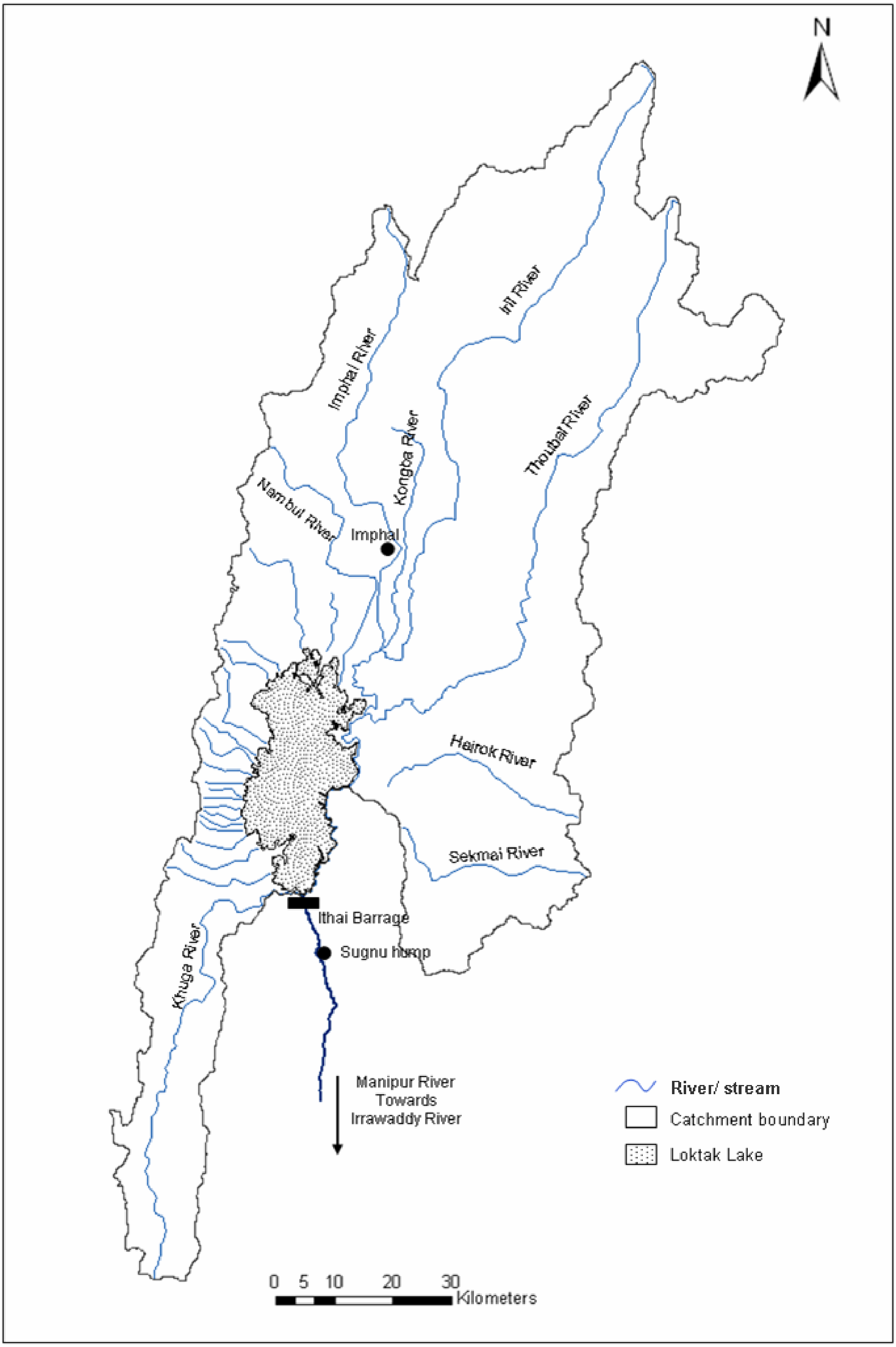


Figure 2.31. Drainage map of the Loktak Lake catchment

Figure 2.32. Stream gauging station at location on the Iril River (Source: LDA)

Iril River: The Iril sub-catchment lies in the north eastern part of the Loktak catchment (Figure 2.5) and drains an area of 1271 km^2. The mean daily discharge of the river at Moirang Kampu is 28.13 m^{3}s^{-1}. Figures 2.33 (a), 2.34 (a) and 2.35 (a) show the mean daily, average mean monthly and the flow duration curve of the Iril River for the period June 1999–May 2003. They show a very distinctive flow regime with high flows during the monsoon months (June–September) and minimal flow during the dry period of the year (December–March). The maximum daily discharge of 348.13 m^{3}s^{-1} was recorded during August 1999, while a minimum of just 0.13 m^{3}s^{-1} was recorded during April 2002. The average monthly discharge during the monsoon months (June–September) is 56.60 m^{3}s^{-1} with the highest during the month of August (68.40 m^{3}s^{-1}) followed by June (54.63 m^{3}s^{-1}), September (52.42 m^{3}s^{-1}) and July (50.95 m^{3}s^{-1}). However, during the dry months (December–March) the average monthly flows reduces drastically to just 3.92 m^{3}s^{-1} with the minimum (3.22 m^{3}s^{-1}) during the month of February owing to reduced rainfall in the catchment area. The flow-duration curve (Figure 2.35 a), shows that the discharge in Iril River exceeded 9.24 m^{3}s^{-1} for 50% of the time. Very high flows (above 200 m^{3}s^{-1}) are observed only 1.8% of the time which are mainly during the monsoon months. The graph also reveals the perennial characteristic of the river with some flow being maintained all throughout the year. The high flows (Q5) was estimated to be 121.92 m^{3}s^{-1}, while the low flow (Q95) was estimated at 1.31 m^{3}s^{-1}.

Thoubal River: The Thoubal sub-catchment lies on the eastern Part of the Loktak catchment (Figure 2.5) and drains a large area of 963 km^2. Figures 2.33 (b), 2.34 (b) and 2.35 (b) show the mean daily, average mean monthly and the flow duration curve of Thoubal River for the period June 1999–May 2003. The mean daily discharge is 25.18 m^{3}s^{-1}. Similar to the Iril River, the Thoubal River also shows a very distinctive flow regime with high flows during the monsoon months (June–September) and minimal flow during the dry period of the year (December–March). The maximum daily discharge of 328.02 m^{3}s^{-1} was recorded during July 2002 while a minimum of just 0.56 m^{3}s^{-1} was recorded during March 2003. The average monthly discharge during the monsoon months has been estimated to be 49.87 m^{3}s^{-1} with the highest during the month of August (63.21 m^{3}s^{-1}) followed by June (48.87 m^{3}s^{-1}), July (43.75 m^{3}s^{-1}) and September (43.64 m^{3}s^{-1}). However during the dry months (December–March) the average monthly flows reduces drastically to just 4.16 m^{3}s^{-1} with the minimum (3.44 m^{3}s^{-1}) during the month of January. The flow-duration curve (Figure 2.35 b), shows that for 50% of the time, the flow in the river is above 7.09 m^{3}s^{-1}. The Q5 and Q95 discharges were estimated to be 122.26 m^{3}s^{-1} and 1.51 m^{3}s^{-1}, respectively. The flow duration curve also reveals the perennial nature of Thoubal River, which is again similar to Iril River with some flow being maintained all throughout the year.

Nambul River: The Nambul sub-catchment with an area of 178 km^2 lies in the western side of Loktak catchment and is a part of the Western sub–catchment. As shown in Figures 2.33 (c), 2.34 (c) and 2.35 (c), Nambul River is a relatively small river compared to Iril and Thoubal Rivers. The average mean annual discharge is estimated as 5.17 m^{3}s^{-1}. Although the discharge may be relatively small, the flow pattern follows a similar pattern to that of Iril and Thoubal rivers. A maximum daily discharge of as high as 98.53 m^{3}s^{-1} and minimum of approximately 0.05 m^{3}s^{-1} was observed during the study period. The mean discharge during the monsoon months (June–September) is 10.90 m^{3}s^{-1} the highest occurring in the month of August (12.09 m^{3}s^{-1}) followed by July (11.28 m^{3}s^{-1}), June (10.68 m^{3}s^{-1}) and September (9.64 m^{3}s^{-1}). During the dry months (December–March) the average monthly flows reduce to just 0.57 m^{3}s^{-1} with the minimum (0.30 m^{3}s^{-1}) during the month of January. The flow-duration curve (Figure 2.35c) shows that for 50% of the year, the flow in the river is above 1.49 m^{3}s^{-1}. The Q5 discharge was estimated to be 22.30 m^{3}s^{-1}, while the Q95 was estimated at 0.13 m^{3}s^{-1}. The graph also reveals the perennial characteristic of the river with some flow being maintained all throughout the year. The normalized flow duration curves as shown in Figure 2.36 demonstrates the similarity in the discharge characteristics of these three rivers during the study period, although there are some difference, most notably in the Nambul, for low flows.

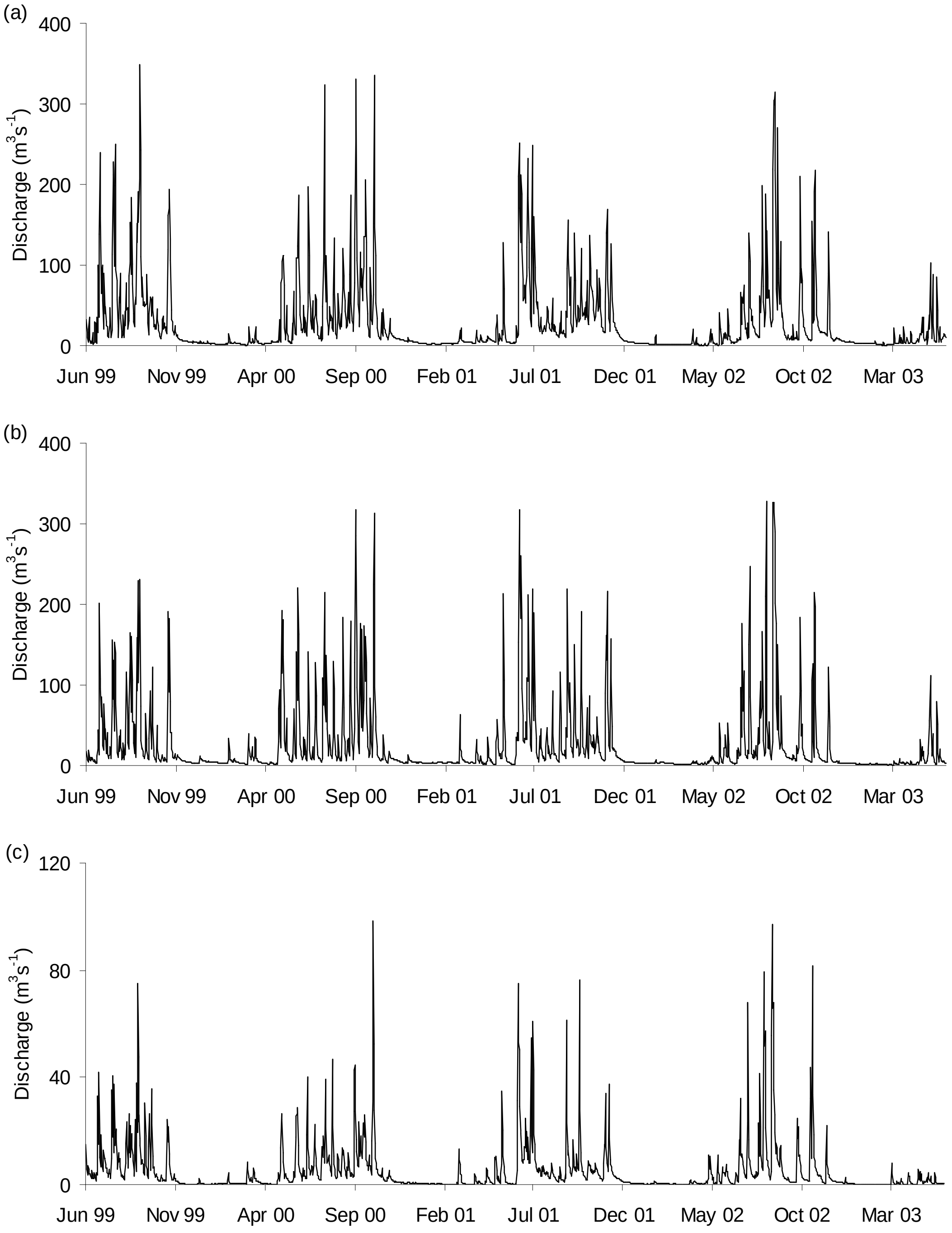


Figure 2.33. Daily discharge (June 1999–May 2003) – (a) Iril River; (b) Thoubal River; (c) Nambul River

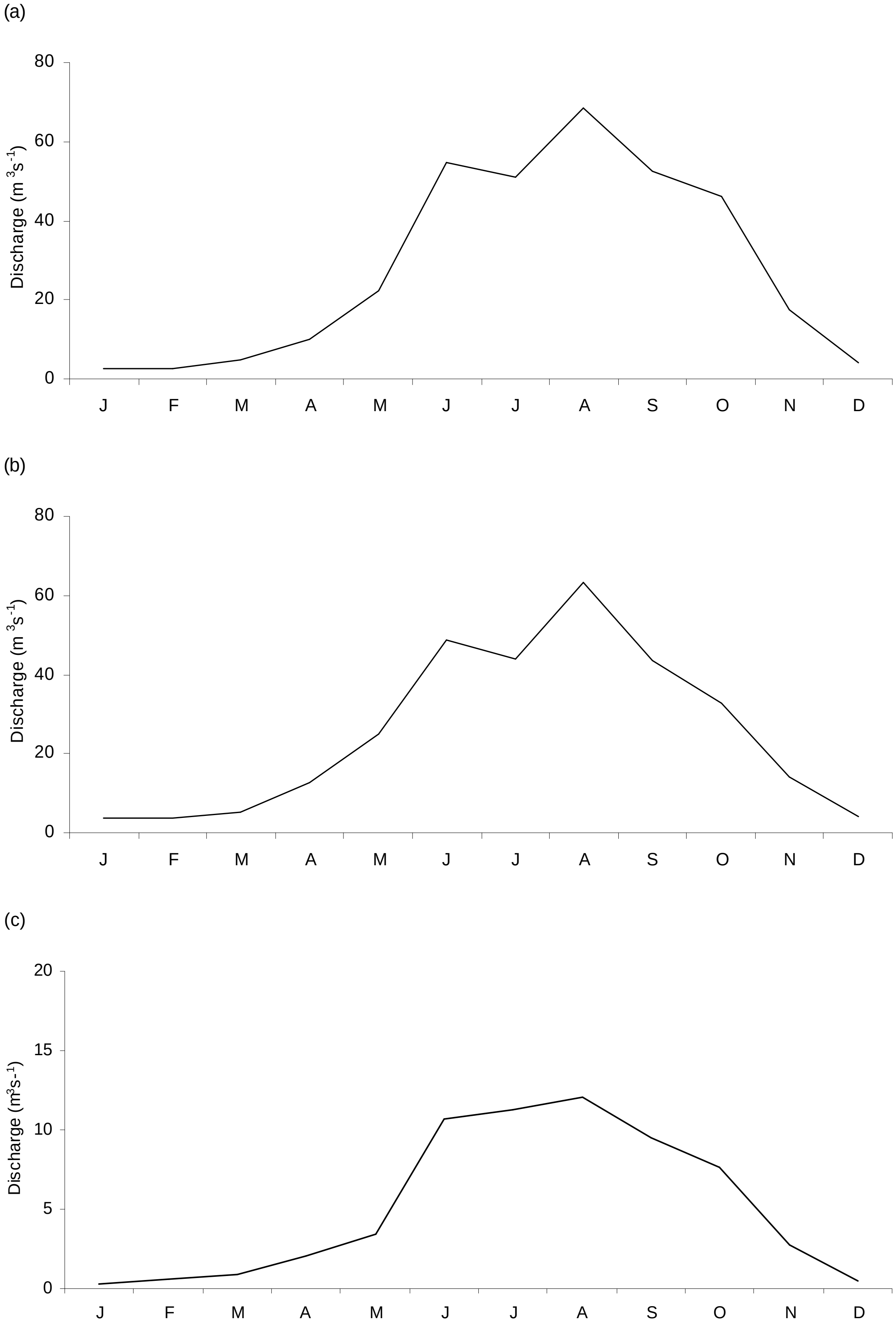


Figure 2.34. Mean monthly discharge (June 1999–May 2003) – (a) Iril River; (b) Thoubal River; (c) Nambul River (note different y-axis scales for Nambul River)

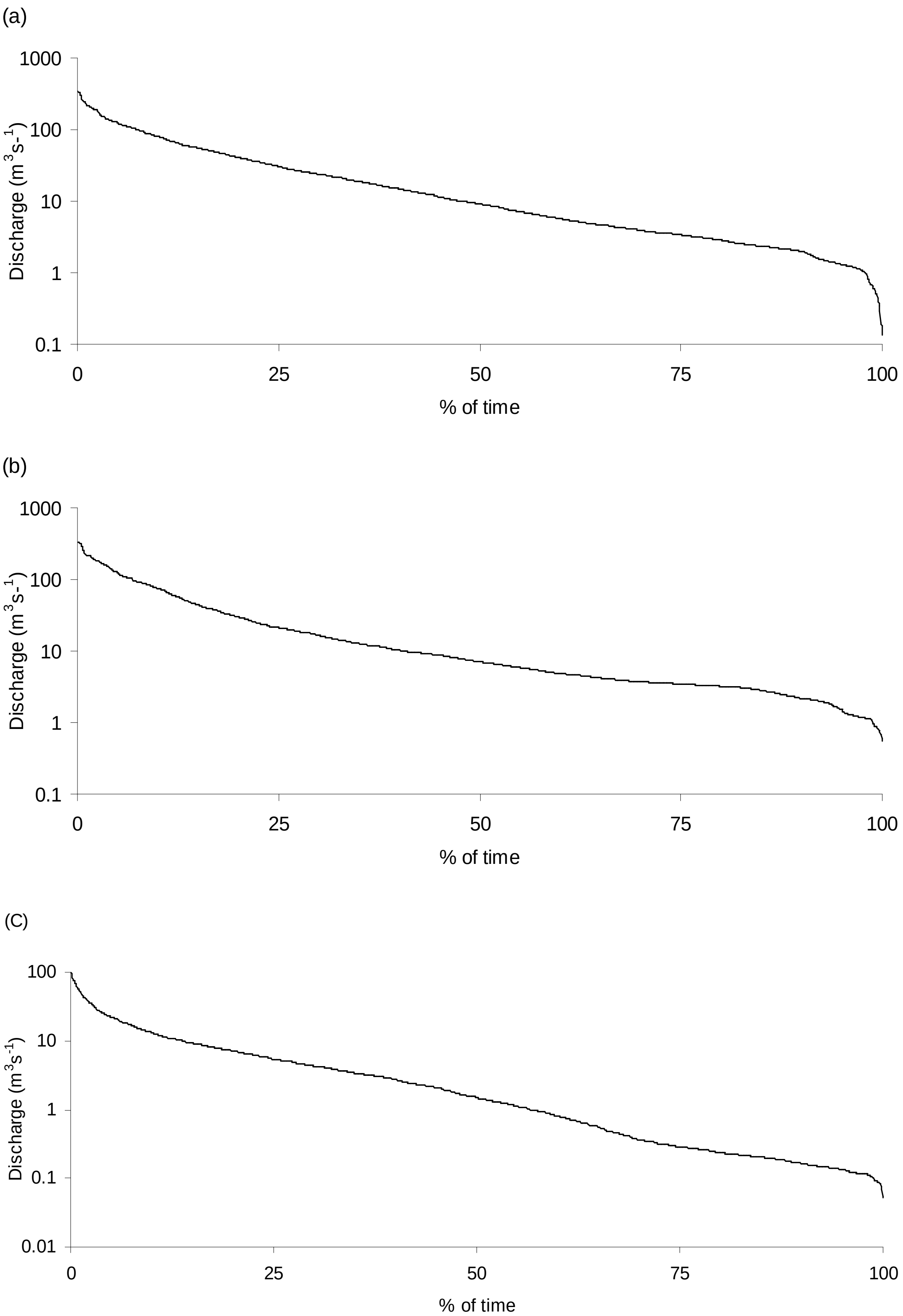


Figure 2.35. Flow duration curve (June 1999–May 2003) – (a) Iril River; (b) Thoubal River; (c) Nambul River (note different y-axis scales for Nambul River)

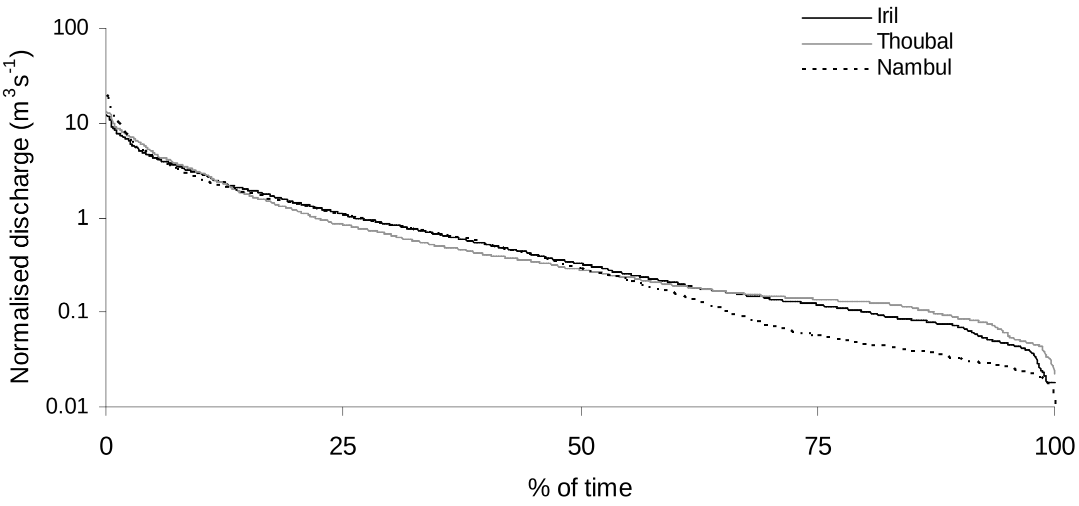


Figure 2.36. Normalised flow duration curve (June 1999–May 2003)

2.5. Loktak Lake hydrology

This section presents the historical as well as the present hydrological regime of Loktak Lake. It highlights the modifications that have taken place in the hydrological regime of the lake as a consequence of the construction of Ithai Barrage for abstraction of lake water resources for hydropower generation and irrigation.

Loktak Lake has been the subject of study since 1950s with the primary objective being flood control and optimal use of water resources for accelerated economic development in the region (Maudgal, 2000). The Ministry of Irrigation and Power, Government of India (GoI) through National Hydro-electric Power Co-operation (NHPC) constructed the Ithai Barrage (Figure 2.37) to impound water in Loktak Lake and harness its potential for hydropower generation and agricultural purposes (PWD, 1967). The project was commissioned in June 1983 and has an installed capacity of 105 MW with three units of 35 MW each. The Loktak Lift Irrigation (LLI) facilities were also provided for a Culturable Command Area (CCA) of 24,000 ha. The maximum water withdrawn from the lake was estimated at 58.8m^3s^{-1} (42m^3s^{-1} for power generation and 16.8m^3s^{-1} for irrigation).

The commissioning of the Ithai Barrage has brought about drastic changes in the hydrological regime of Loktak Lake. These alterations have been the root cause of the degradation of the lake ecosystem, thereby posing a direct threat to the rich biodiversity it harbours as well as to the large human population that directly depends on the lake resources for their survival. Therefore, in order to enhance the hydrological regime of the lake, it is necessary to understand the hydrological conditions of the lake before the construction of the barrage so that a comparative assessment can be carried out to evaluate the changes brought about by the construction of the barrage. In addition, such an investigation can also provide a bench mark against which to judge the extent to which the natural hydrological regime can be restored.

Figure 2.37. Ithai Barrage looking downstream

2.5.1. Pre–Ithai Barrage hydrological conditions

In the pre-Ithai period, Loktak Lake was mainly fed by inflows from the rivers and rivulets, flowing in from the Western sub-catchment. PWD (1967) estimated that the annual inflow of water into the lake from the rivers of the Western sub-catchment and direct rainfall on the lake surface was $1172.00 \times 10^6 m^3$. Nambul is the biggest river flowing from the Western sub-catchment with an average annual flow of $156.00 \times 10^6 m^3$. They also reported that the influence of the Manipur River on the lake was very limited as the two water bodies were only connected via the Khordak link channel, (Figure 2.38) which has a very limited water carrying capacity. The Khordak channel had a bi-directional flow regime. When water levels in the lake were higher than that in Manipur River, the direction of the flow in the link channel was from the lake towards the Manipur River and vice versa. The average inflow of water into the lake from the river system was estimated to be $119.09 \times 10^6 m^3$ while the average

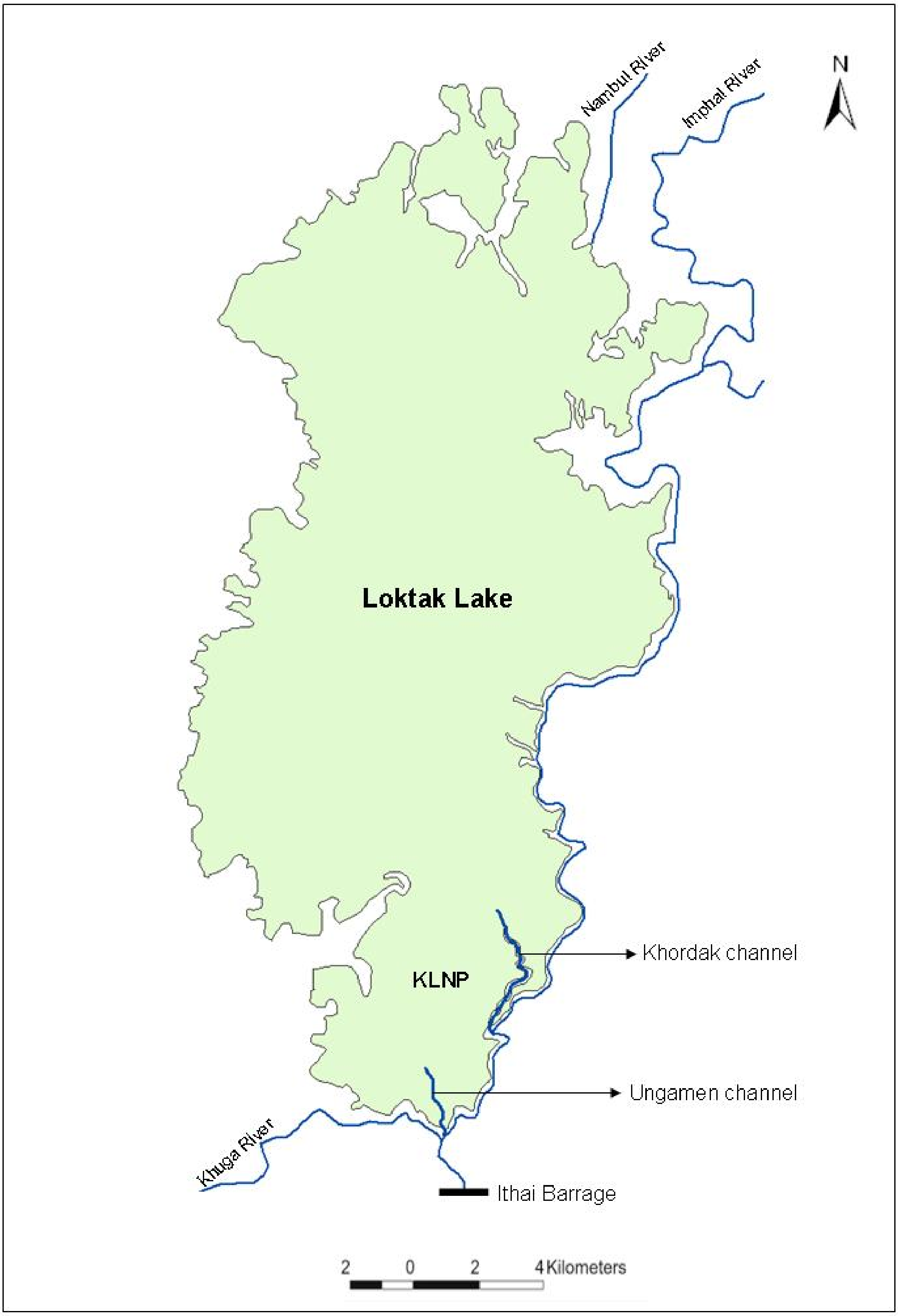


Figure 2.38. Map showing Khordak and Ungamen channels

outflow of water from the lake into the river system was estimated to be much higher at 380.23 × $10^6 m^3$ (WAPCOS, 1993). The mean annual net discharge at Khordak was therefore 261.14 × $10^6 m^3$ from the lake into the river (Table 2.7).

Figure 2.39 shows monthly discharge in the Khordak channel during June 1957–May 1959. Positive values indicate flow into the lake and negative values are associated with flows from the lake towards the Manipur River. In 17 out of 24 months, the outflow from the lake exceeds the inflow into the lake from the Manipur River. Maximum inflow to the lake of 50.29 × $10^6 m^3$ was observed during July 1957 while a maximum outflow of 80.69 × $10^6 m^3$ was observed during December 1957.

Table 2.7. Mean monthly discharge in the Khordak channel (June 1957–May 1959)

Months	**Inflow** (Mm^3)	**Outflow** (Mm^3)	**Net discharge** (Mm^3)
January	0.00	60.32	-60.32
February	0.00	41.64	-41.64
March	0.00	41.11	-41.11
April	0.00	33.15	-33.15
May	22.90	19.93	2.97
June	9.00	4.88	4.11
July	44.21	6.60	37.61
August	17.90	19.36	-1.46
September	9.17	37.20	-28.03
October	15.92	23.78	-7.87
November	0.00	46.57	-46.57
December	0.00	45.68	-45.68
Total	119.09	380.23	-261.14

* (+) net discharge means inflow of water into the lake
(-) net discharge means outflow of water from the lake

Source: PWD (1967)

Figure 2.40 shows the monthly water level of the lake at Ningthoukhong during June 1963–May 1966 using data collected by PWD (1967) and WAPCOS (1993). The lake level shows the distinctive influence of the monsoon with high water level during the rainy season and low water level during the drier months. The mean lake level was 767.26 m amsl with a maximum of 768.89 m amsl observed during August 1968 and minimum of 764.88 m amsl during the May 1964. On average September has the highest water levels (mean 768.65 m amsl) closely followed by August 768.49 m amsl while the minimum water level (765.55 m amsl) occurred during May (Figure 2.41).

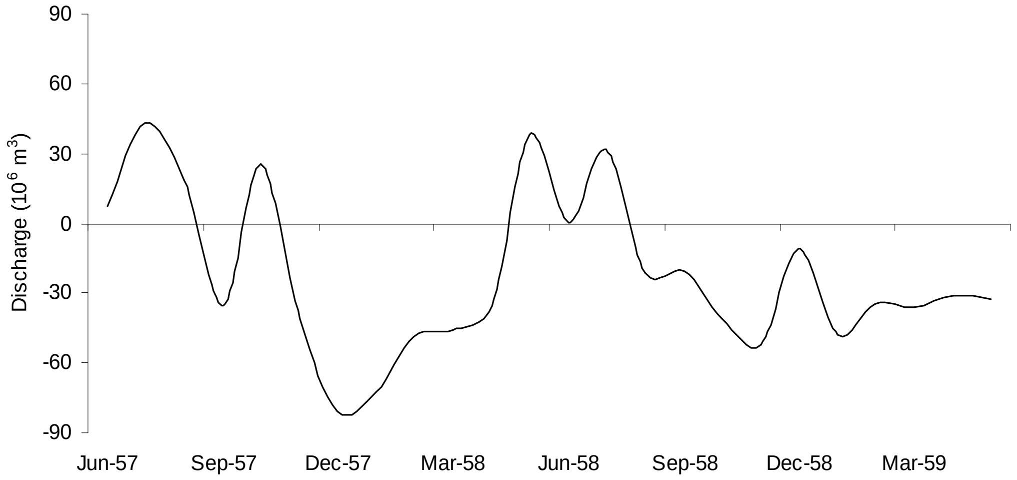


Figure 2.39. Discharge in Khordak link channel (June 1957–May 1959). Note: (+) net discharge indicates inflow of water into the lake; (-) net discharge indicates outflow of water from the lake

Figure 2.40. Mean monthly water level at Ningthoukhong (June 1963–May 1966)

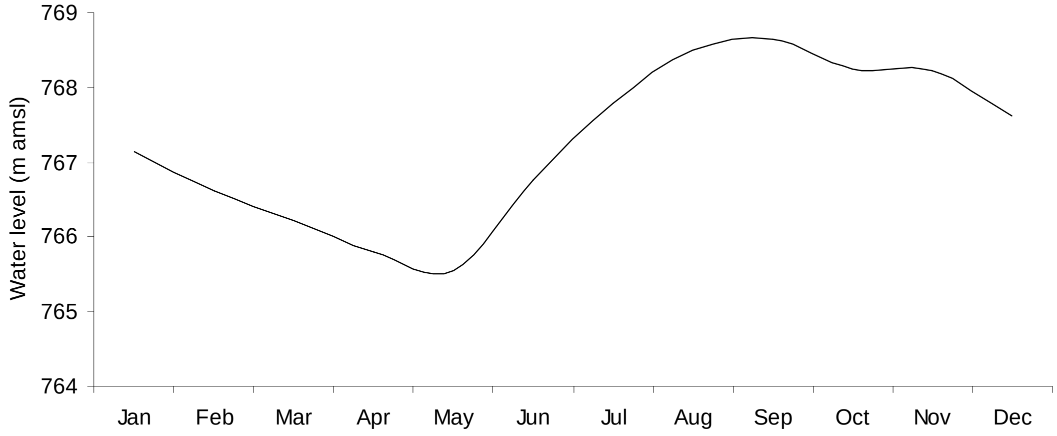


Figure 2.41. Average mean water level at Ningthoukhong (June 1963–May 1966)

During monsoon months the lake would fill up due to inflows provided by runoff from the western sub-catchments and the Manipur River via the Khordak channel. Lake level reach its highest in August. As soon as the monsoon receded, the water level in Manipur River would drop and the flow in the Khordak channel would reverse. The water in the lake would then start to be flushed out into the Manipur River. At the same time, owing to the receding monsoon, inflows from the western sub-catchment into the lake would reduce. Draining of the lake would continue until May when levels reached their lowest. From June with the commencement of the monsoon, the lake level starts to gradually rise again. The annual fluctuation in the water level of the lake was estimated to be 3.1 m (September high of 768.65 m amsl; May low of 765.55 m amsl).

2.5.2. Post–Ithai Barrage hydrological conditions

The Ithai Barrage was constructed in order to impound water from the Manipur River and its tributaries into Loktak Lake for generation of hydropower under the Loktak Hydro Electric Project (LHEP). The barrage was constructed near the village of Ithai, hence its name. The barrage has a total length of 68.6 m with a Full Reservoir Level (FRL, the highest level which the barrage can safely store water without compromising its structural safety) of 769.63 m amsl and Flood Level (FL, level beyond which flooding in the peripheral area of the lake take place) of 768.50 m amsl (PWD, 1967). The Minimum Drawdown Level (MDL) for abstraction of water from the lake for hydropower generation is fixed at 766.23 m amsl. If the lake level drops below this level, abstraction of water from the lake is not possible. There are five gates in the barrage which, when fully opened, have a discharge capacity of 850 m^3s^{-1}. After the construction of barrage there have been drastic modifications in the lake’s hydrological regime. The influence of Manipur River on Loktak Lake has increased. In addition to the inflow from Khordak channel, there is another channel, the Ungamen channel (Figure 2.38) which has cut in order to divert the backflow from Ithai Barrage into the lake. By this time, Loktak Lake has become more or less a continuous body of water until Ithai barrage via these two channels.

Figures 2.42 and 2.43 show the daily discharge in Khordak and Ungamen channels during the period January 2000–December 2002. The two link channels serve more as inflow channels rather than outflow. In 991 days of the 1096 day monitoring period (i.e. 90% of the duration), flows in the Khordak channel were towards the lake. The days duration during which the flows in Khordak channel were towards the Manipur River (10% of the duration) occurs mainly during the monsoon months (23 September–22 October 2000, 7 October–15 November 2001, 22 August–5 September 2002). Similarly, the Ungamen channel also acts as inflow for 86% (938 days of the 1096 day monitoring period). The days during which, the Ungamen channel acts as outflow channel were mainly during the monsoon months, however, unlike Khordak channel, it does not have continuously outflow days. Throughout the monsoon months it has intermediate days of inflows and outflows (Figure 2.43). Figure 2.44 shows the mean monthly discharge in Khordak and Ungamen channels. Khordak channel shows inflow into Loktak Lake for 11 months of the year with maximum inflow during July ($14.75 \times 10^6 m^3$). October is the only month during which the Khordak channel serves as an outflow channel draining $4.39 \times 10^6 m^3$ of water from the lake into the Manipur River. Similarly, the Ungamen channel also shows inflow during 11 months of the year with a maximum inflow in June ($39.95 \times 10^6 m^3$). September is the only month during which the Ungamen channel serves as an outflow channel draining on average $14.20 \times 10^6 m^3$ of water out from the lake into the Manipur River. Owing to its proximity to Ithai Barrage, flows within the Ungamen channel are much larger compared to the Khordak channel (Figure 2.44).

As a consequence of the changes to the inflow-outflow pattern from the lake following the construction of Ithai Barrage, the water level regime within the lake has also undergone considerable alteration. Figure 2.45a shows the daily lake water level as recorded at Ningthoukhong by the LDA during June 1999–May 2003. The mean water level in the lake is 768.37 m amsl with a maximum water level of 769.44 m amsl in August 1999 and a minimum of 767.15 m amsl in May 2002.

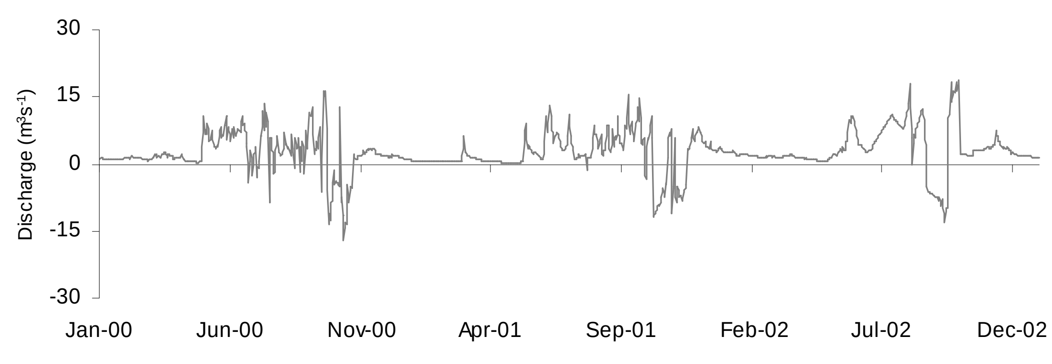


Figure 2.42. Daily discharge in Khordak channel (2000–2002). Note: (+) net discharge means inflow of water into the lake; (-) net discharge means outflow of water from the lake

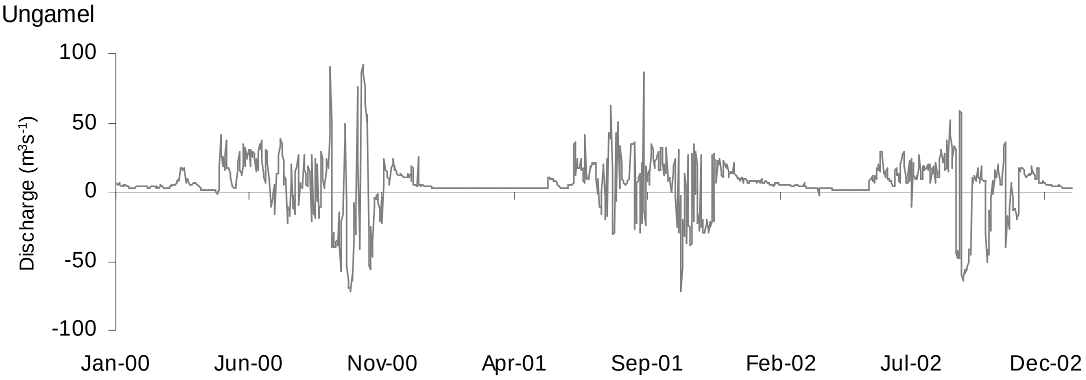


Figure 2.43. Daily discharge in Ungamen channel (2000–2002) Note: (+) net discharge means inflow of water into the lake; (-) net discharge means outflow of water from the lake

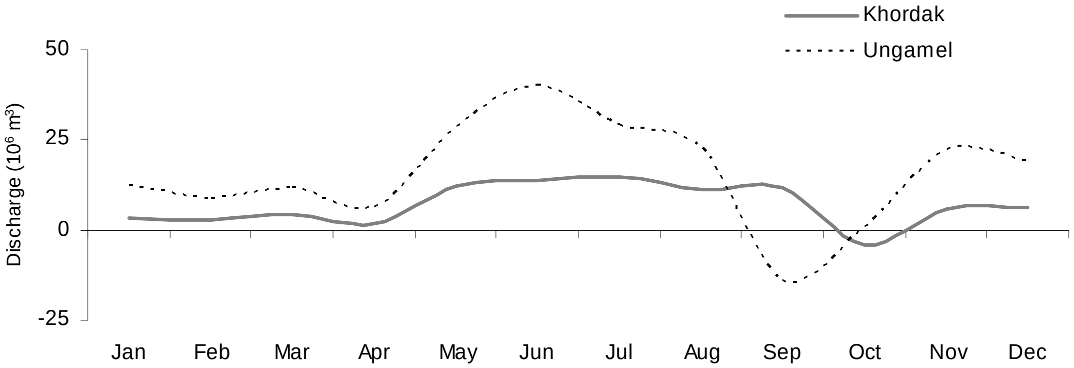


Figure 2.44. Mean monthly discharge in Khordak and Ungamen channels (2000–2002). Note: (+) net discharge means inflow of water into the lake; (-) net discharge means outflow of water from the lake

Throughout the four years represented in Figure 2.45, the water level in the lake has not dropped below the MDL for a single day, signifying the storage of sufficient water for abstraction of hydropower generation as well as irrigation. In addition, the water level never reached the FRL, hence there was no threat to the structural stability of the barrage. However, the water level was maintained above the FL for 46% of the study period (i.e. 676 days of the 1460 day study period). This indicates the severity of the flooding caused due to the construction of the barrage in the surrounding areas of Loktak Lake. Figure 2.46 shows the flood prone areas in the periphery of the Loktak Lake .The flooding can mainly be attributed to the operation of the barrage gates by NHPC with an interest to store as much water as possible to maximise hydropower generation. Figure 2.45b present the mean monthly water level of the lake during June 1999–May 2003. On average, September has the highest water level (768.98 m amsl) followed by October (768.89 m a msl), August (768.78 m amsl) and November (768.75 m amsl) (Figure 2.45b). These levels are all above the FL. The dry month of December also has an average water level above the FL (768.55 m amsl). This high water level when there is least inflow from the catchment can be attributed to the closing of the barrage gates during the monsoon months. The minimum water level of 767.58 m amsl was observed during the month of April. Following the construction of the barrage the annual fluctuation in the water level of the lake is approximately 1.4 m (April low of 767.58 m amsl; September high of 768.98 m amsl), compared to 3.1 m (September high of 768.65 m amsl; May low of 765.55 m amsl) before the construction of the barrage.

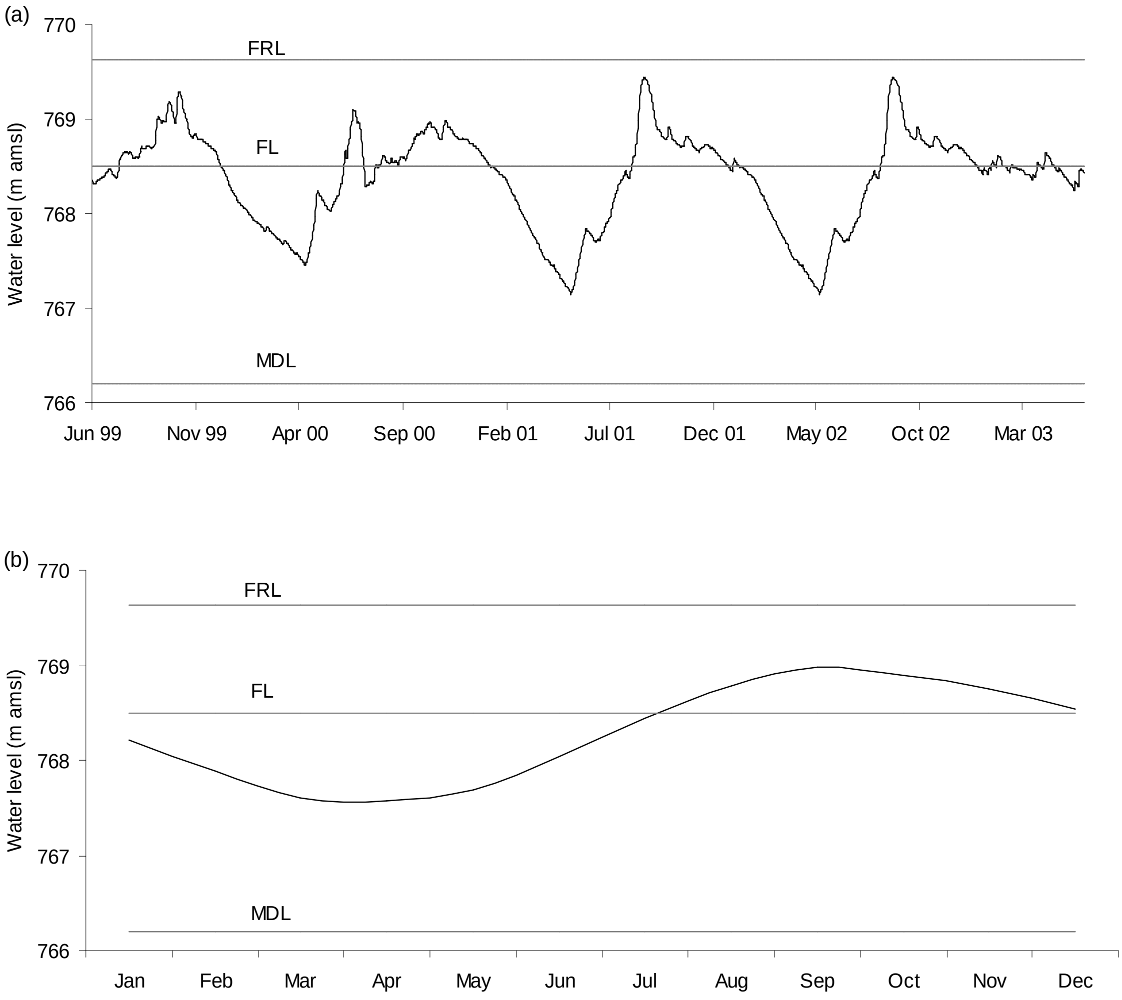


Figure 2.45. Water level at Ningthoukhong during June 1999–May 2003 – (a) Daily water level (b) Average mean monthly water level (FRL: full reservoir level, FL: flood level, MDL: minimum drawdown level)

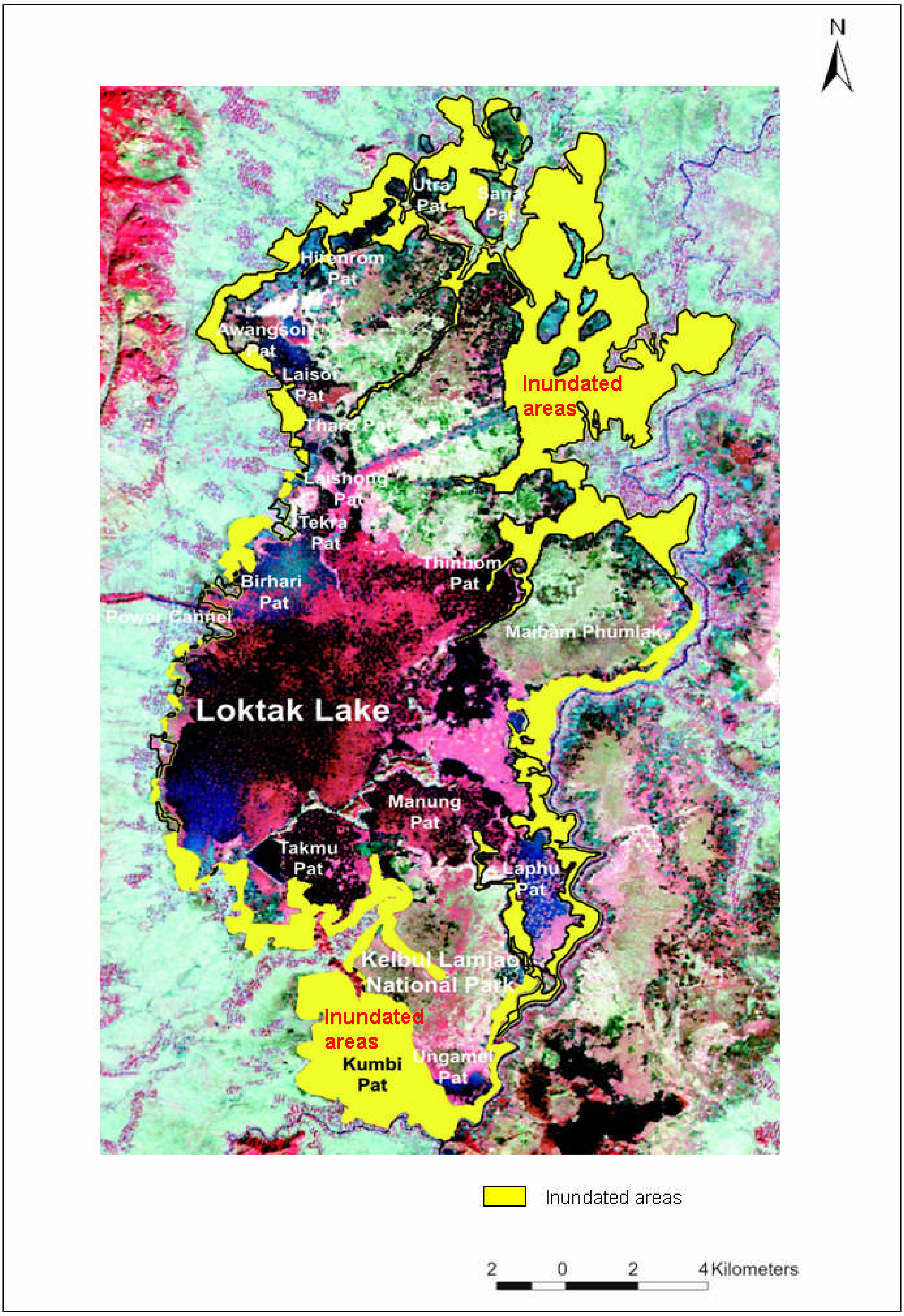


Figure 2.46. Flood prone areas around Loktak Lake. Source: LDA

Figure 2.47 summarizes the changes in the hydrological regimes of Loktak Lake brought about by the construction of Ithai Barrage. Figure 2.47a and 2.47b represents the high and low water level periods before the construction of the Barrage. As previously discussed, September had the highest mean monthly water level of 768.65 m amsl while May the lowest (765.55 m amsl).

Figure 2.47 also indicates the rise and fall of the *phumdis* as water levels change. It shows that the *phumdis*, especially in the KLNP, are grounded during the low water level period, allowing the *phumdis* to replenish their nutrients from sediment on the lake bed. In pre-Ithai conditions (Figures 2.47a and 2.47b), during September (the wettest month) inflow to the lake comes from Western sub-catchment, while outflow is via Khordak channel into Manipur River due to the high lake level. However, during May (dry month) there is a reverse in flow direction in Khordak channel from Manipur River towards Loktak Lake.

After construction of Ithai Barrage, the highest mean monthly water level increased by 0.33 m (from 768.65 m amsl to 768.98 m amsl) (Figures 2.47a and 2.47c), leading to increased flooding in the areas surrounding of the lake. However, a more critical change is observed during the low water level period, which witnessed an increase in the minimum mean monthly water level of 2.03 m (from 765.55 m amsl to 767.58 m amsl) (Figures 2.47b and 2.47d). This increase in lake water level during the low water level season means that the *phumdis* remain afloat throughout the year, depriving them of nutrient uptake from the lake bed. This high water level regime has been attributed as one of the main reasons for the degradation of *phumdis* in Loktak Lake (Singh, 2002; Meitei, 2002; Trisal and Manihar, 2004; Angom, 2005). Changes in the flow direction in the Khordak channel are also observed during September. The Ungamen channel shows outflows of water from the lake during September but for the rest of the year, it provides large inflow from Manipur River into the lake.

2.5.3. Elevation–area–volume relationship of Loktak Lake

The bathymetric map of Loktak Lake established in 2001 and procured from the LDA is shown in Figure 2.48. The map shows lake bathymetry at 0.5 m contours between 764–769.0 m amsl. The LDA tabulated the lake volume and area at lake water level of 766.2 m amsl, 766.5 m amsl and thereafter at an interval of 0.5 m upto the level of 769.0 m

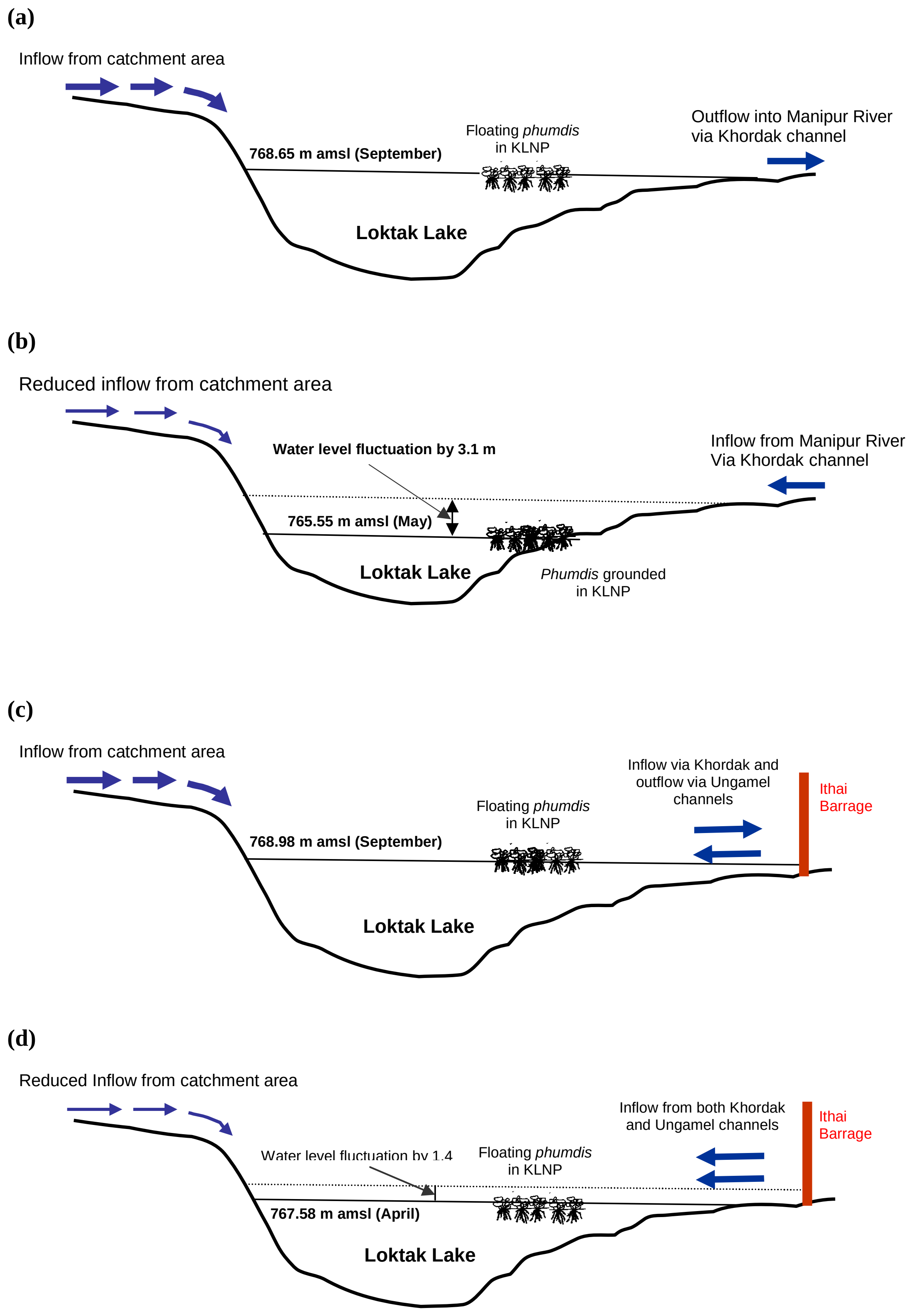


Figure 2.47. Schematic diagram of the changes in the hydrological regime of Loktak lake after the construction of Ithai Barrage. (a) Pre-Ithai high water level – September (b) Pre-Ithai low water level – May (c) Post-Ithai high water level – September (d) Post-Ithai low water level – April.

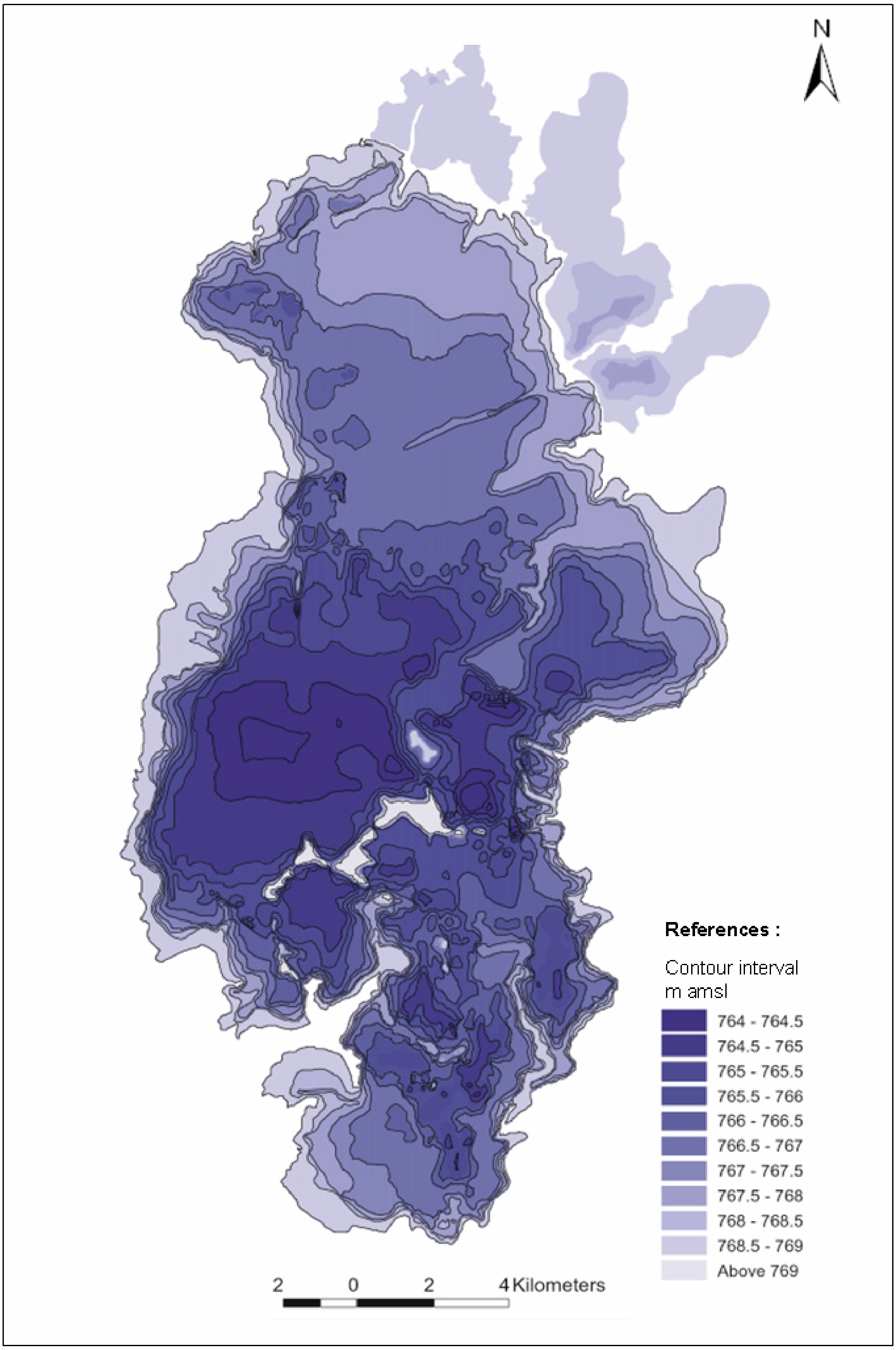


Figure 2.48. Bathymetric map of Loktak Lake Source: LDA

amsl. These data are shown in Figure 2.49. It estimated that at 766.20 m amsl (MDL), the lake has a water surface area of 100.78 km^2 and a volume of 94.60 × $10^6 m^3$. At 768.50 m amsl (FL), the lake has an area of 255.10 km^2 and corresponding volume of 524.60 × $10^6 m^3$. However, the relationship estimated by LDA was limited only to a maximum elevation of 769.00 m amsl, just above the FL. As discussed in Section 2.5.2 the water levels rose above 769.00 m amsl on a number of occasions during the study period. The critical information missing from the elevation-area-volume relationship provided by LDA is the volume that the Ithai Barrage can hold at its FRL (769.63 m amsl) and the corresponding water surface area. The elevation–area–volume relationship was therefore extrapolated to the FRL. Using the topographic map of the Loktak Lake catchment developed using the SRTM dataset (Section 2.2.2), the 800 m contour was first extracted. This 800 m contour was then combined with the contour data from the bathymetric map (764.0–769.0 m amsl at 0.5 m intervals) within ArcGIS to develop a digital elevation model (DEM) of the Loktak Lake up to a maximum elevation of 800 m. This DEM is shown in Figure 2.50. Using this DEM, the corresponding volume and water surface areas of the elevations between 769.00 m amsl and 769.63 m amsl (FRL) at an interval of 0.1 m were derived using the ArcGIS area-volume procedure (Table 2.8). The corresponding volume and water surface area of the lake at FRL were estimated to be 841 x $10^6 m^3$ and 334 km^2, respectively.

The extrapolated volumes and areas of the lake corresponding to lake water levels between 769.10–769.63 m amsl (Table 2.8) were combined with those for lake water levels between 766.2.0–769.0 m amsl provided by the LDA as demonstrated in Figure 2.49. The elevation-area-volume relationship of the Loktak Lake was derived using Curve Expert 1.3 (Figure 2.49). The volume-elevation relation can be described using the Harris model given in Equation 2.1 and the volume-area relationship can be described by a 3rd degree polynomial given in Equation 2.2.

$$\text{Lake level} = (0.0013 - 2.0117 \times 10^{-7} (\text{lake volume})^{0.05500})^{-1} \tag{2.1}$$

$$\text{Lake area} = 60756031 + 545149.4(\text{lake volume}) - 311.082(\text{lake volume})^2 + 0.05877(\text{lake volume})^3 \tag{2.2}$$

Table 2.8. Area and volume of the lake extracted from the digital elevation model

Elevation	Area (km^2)	Volume (10^6m^3)
769.10	318	664
769.20	324	697
769.30	329	730
769.40	334	765
769.50	338	799
769.60	341	834
769.63	334	841

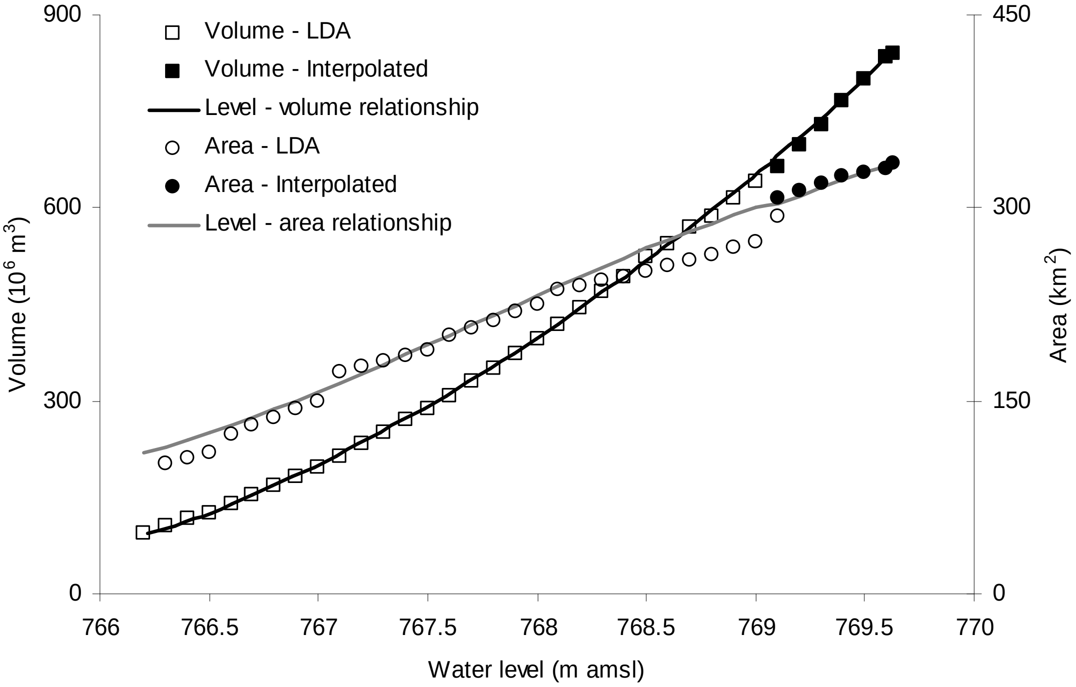


Figure 2.49. Elevation-area-volume relationship of Loktak Lake

2.5.4. Post-Ithai water level management in Loktak Lake

The various stakeholders of Loktak Lake in regards to water use in the post-Ithai period are (i) the Loktak Hydro-Electric Project (LHEP) which is the responsibility of the NHPC, a Government of India enterprise. The main objective of the project is to generate 105 MW of electricity by withdrawal of 1324 x 10^6 m^3 of water annually from Loktak Lake. In order to operate the scheme it is envisaged that the lake level be maintained between 768.5m above msl (the Flood Level, FL) and 766.2m above msl (the minimum drawdown level, MDL). (ii) The Irrigation and Flood Control Department (IFCD), State Government of Manipur, has a stake on the lake for the provision of water for two of its major irrigation schemes, the Imphal Barrage Project and the Loktak Lift Irrigation Project. (iii) the Public Health Engineering Department

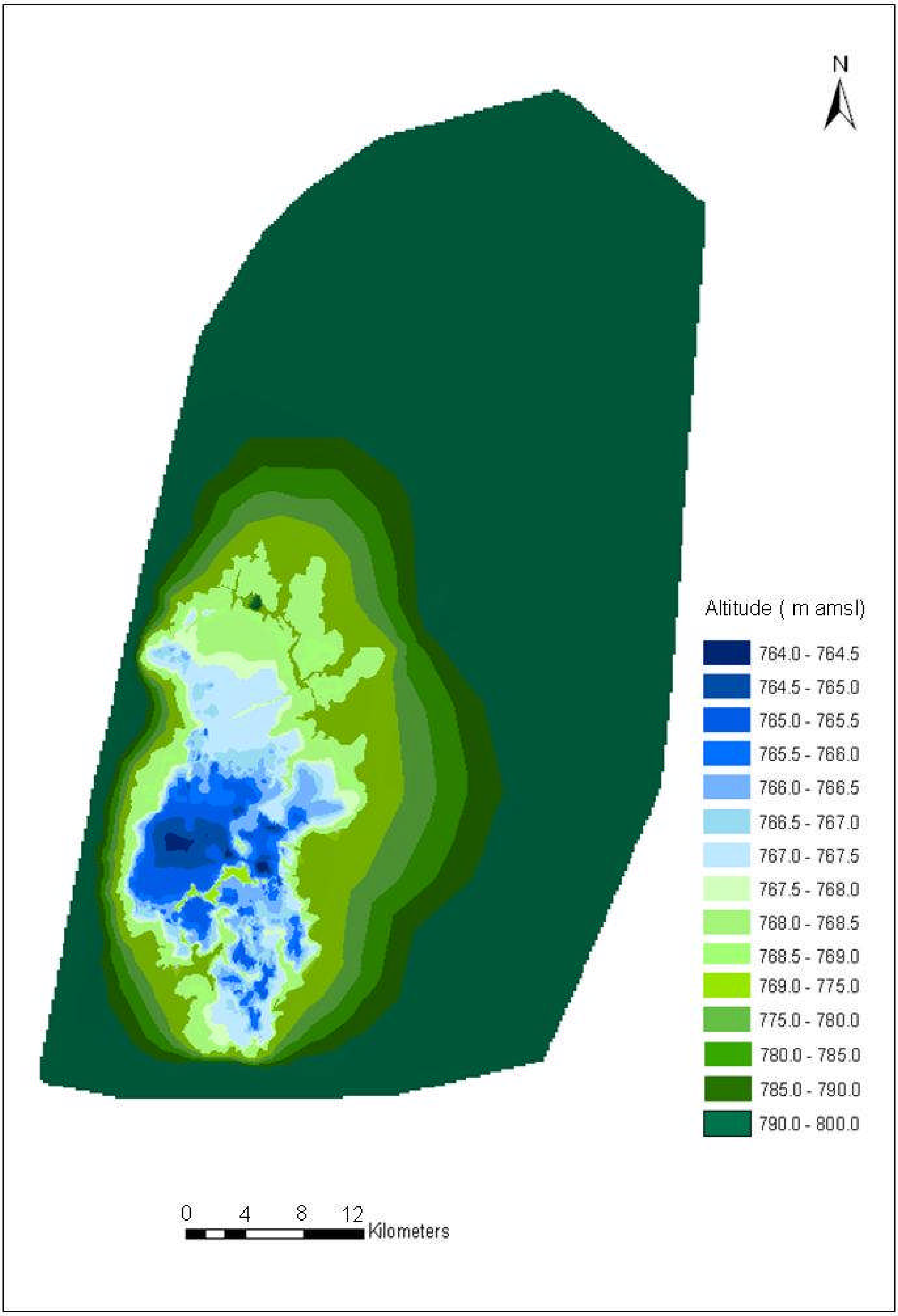


Figure 2.50. Digital elevation model of Loktak Lake and its catchment up to elevation of 800 m amsl.

(PHED), State Government of Manipur, depends on the Loktak Lake for the supply of drinking water to rural communities on and around the lake as well as the urban communities in Imphal city and the surrounding smaller towns. (iv) the Wild Life Department, State Government of Manipur, are responsible for the maintenance of the Keibul Lamjao National Park (KLNP) and a demand lower water level regime for the lake which will enable a healthy growth of the phumdis in KLNP. (v) the Fisheries Department, State Government of Manipur, requires a large open water area free from phumdis and other aquatic vegetations within the lake with desired water quality for capture fisheries. (vi) the Tourism Department, State Government of Manipur, consider Loktak Lake as a tourism hot spot and promotes tourism activities including construction of tourist complexes within the lake with facilities for boating. (vii) Local communities living on and around the lake directly depend upon the lake for fisheries and other resources which are all mediated through maintenance of appropriate water levels in the lake. They also utilize the lake as a mean for local transportation. However, the flooding in the lake periphery due to the maintenance of the high lake water level to satisfy hydropower demands are damaging lives and properties including agricultural fields.

In the post-Ithai period, the LHEP is the only stakeholder for which the lake water levels are operated to meet their demands (Maudgal, 2000). The NHPC intake channel carries a discharge of 58.8 m^3s^{-1} and the entire hydrological regime of Loktak Lake is maintained to cater to this demand. As discussed previously, even during the monsoon the lake level is maintain high to store the maximum amount of water for hydropower generation at the expense of flooding in the peripheral areas of the lake as well as the ecological condition. There are no instances of operating the barrage to lower the lake level in advance to provide space to attenuate subsequent flood peaks. The regulation of the hydrological regime of the lake is solely dictated by hydropower generation requirements. There is no consideration for the ecological water requirement and no appropriate water use allocation plan had been prepared so far, which aims to consider all the water users within the basin.

2.5.5. Water quality

According to criteria of designated best use developed by the Central Pollution Control Board (CPCB), MoEF, Government of India, the water quality of Loktak Lake, in general, falls within class C to E. These categories signifies that the lake water is not fit for direct drinking without treatment but can be used for irrigation and ecological purposes. A comparative analysis of water quality of different parts of the lake indicates significant levels of pollution in the northern and southern sectors. The pollution in the northern sector can mainly be attributed to the high amount of pollutants brought down by the Nambul River. A large population of 0.28 million people living within the Nambul catchment generates 72.23 million tones per day of solid waste and 31,207 m^3 of sewage. All these waste directly or indirectly find their way into the northern sector of the lake. The water quality in the sector is further deteriorated by runoff from the surrounding agricultural fields which use large volume of fertilizer.

The lake bed has a gentle slope in the southward direction. Therefore, all the pollutants from the northern sector are slowly transported to the southern sector. Here it accumulates due to the poor flushing by the closure of Ithai Barrage. The situation is further compounded by the high nutrient loading from the large population living on and around the lake. Microbiological analysis of lake water samples indicates pollution due to human waste and other organic matter (Trisal and Manihar, 2004). In KLNP, the values of standard plate count for bacteria were found to be as high as 58,000 ml^{-1}. The pH values recorded were as low as 4.5 at the surface and 4.1 at the bottom indicating acidic conditions in the core zone area of KLNP. The free CO_2 concentration ranges between 2.4 mgl^{-1} to 53.7 mgl^{-1} at the surface and 7.1 mgl^{-1} to 64.2 mgl^{-1} at the bottom. Higher value of free carbon dioxide and low values of DO show relatively high respiration and decomposition over photosynthesis by phytoplankton and aquatic vegetation.

2.6. *Phumdis*

Loktak Lake is covered with thick vegetation comprising emergent, submerged and floating types. The characteristic features of these types of vegetation are previously discussed in Section 1.6. The plant species in Loktak Lake, in general, are inter-mixed forming large associations in different geographical locations. A fully formed *phumdis* is about 1-2 m thick, compact and sturdy enough to support the weight of thatched houses built on it by the fishermen as temporary shelter (Devi et al., 2002)

(Figure 2.51). Of the total thickness of the *phumdi*, one-fifth lies above the water surface while the remaining four-fifth remains submerged (Trisal and Manihar, 2002).

Newly formed or young *phumdis* are generally made up of aquatic floating plants with the attachment of silts at the roots (Singh, 2002). A mature *phumdis* can be divided structurally into four distinct vertical zones (LDA and WISA, 2002; Singh, 2002; Figure 2.52). The uppermost zone is called the vegetative zone, which floats above the water surface. LDA and WISA (2002) have reported that overall 132 plant species have been identified in Loktak Lake of which 60 species are common to *phumdis* in all portions of the lake. List macrophytes which form the phumdis are given in Annexure–1. Amongst them *Zizania*, *Phragmites*, *Capillipedium*, *Echinochloa*, *Impatiens*, *Saccharum*, *Hedychium*, and *Alpinia* are the most common. The zone below the vegetative zone is the root zone. This is the zone where only roots of the vegetation are found. The next zone is the mat zone, which is the thickest of all the zones. Singh (2002) reported the mat zone is as thick as 65 cm. The zone is a layer of densely interwoven live, dead, decaying roots with some litter accumulation on the surface. The lower most layer is called the peat zone. This layer is made up of decomposed peat, still intact enough to cling to the overlying roots.

Figure 2.51. Hut built on top of phumdis. Source: LDA

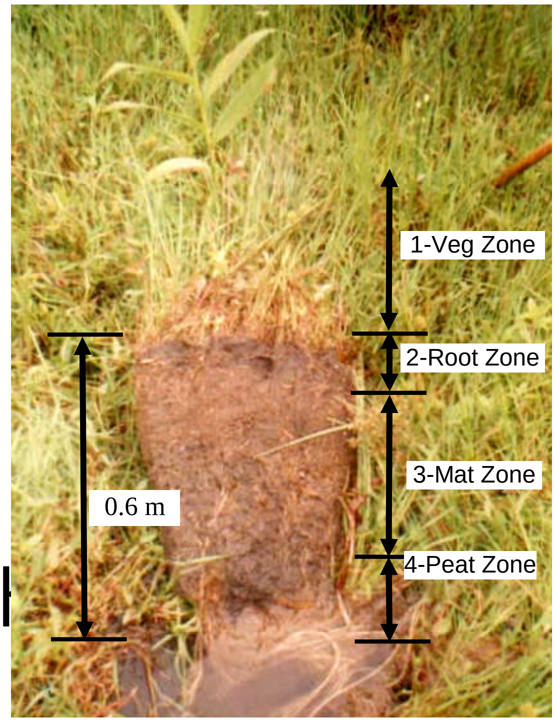


Figure 2.52. Cross-sectional profile of phumdis. Source: LDA and WISA

2.6.1. Distribution and extent of *phumdis*

Phumdis, in general, are found in all parts of Loktak Lake. Figures 2.53 and 2.54 presents the extent of distribution of *phumdis* in 1989 and 2002. The LDA used remote sensing imagery and estimated that the area covered by *phumdis* in the lake has increased from 116.4 km^2 to 134.6 km^2 between 1989 and 2002. This increase can be attributed to the enhancement of aquaculture activities using *phumdis*. In the recent past due to the anthropogenic influence, another type of *phumdi* called *athaphums* has been created which are extensively used for aquaculture activities within the lake. This type of *phumdis* are very thick on the edges but almost hollow inside and are covered with various plant species. This type of *phumdi* does not occur by itself in nature but are made by the local fishermen using the thick naturally occurring *phumdis*. LDA and WISA (2004) reported that the number of athaphums has increased from 217 in 1989 to 2642 in 2002, covering an area of 11.18 km^2 of the open water area of the lake (Figure 2.55).

Figure 2.56 shows *phumdis* thickness in various parts of the lake, based on data collected in 2001 and 2002 by the LDA under a survey project called HYDREC. During the survey, the lake was divided into transects running across the lake and *phumdis* thickness and water depth manually measured for every 50 m along the transect. In the

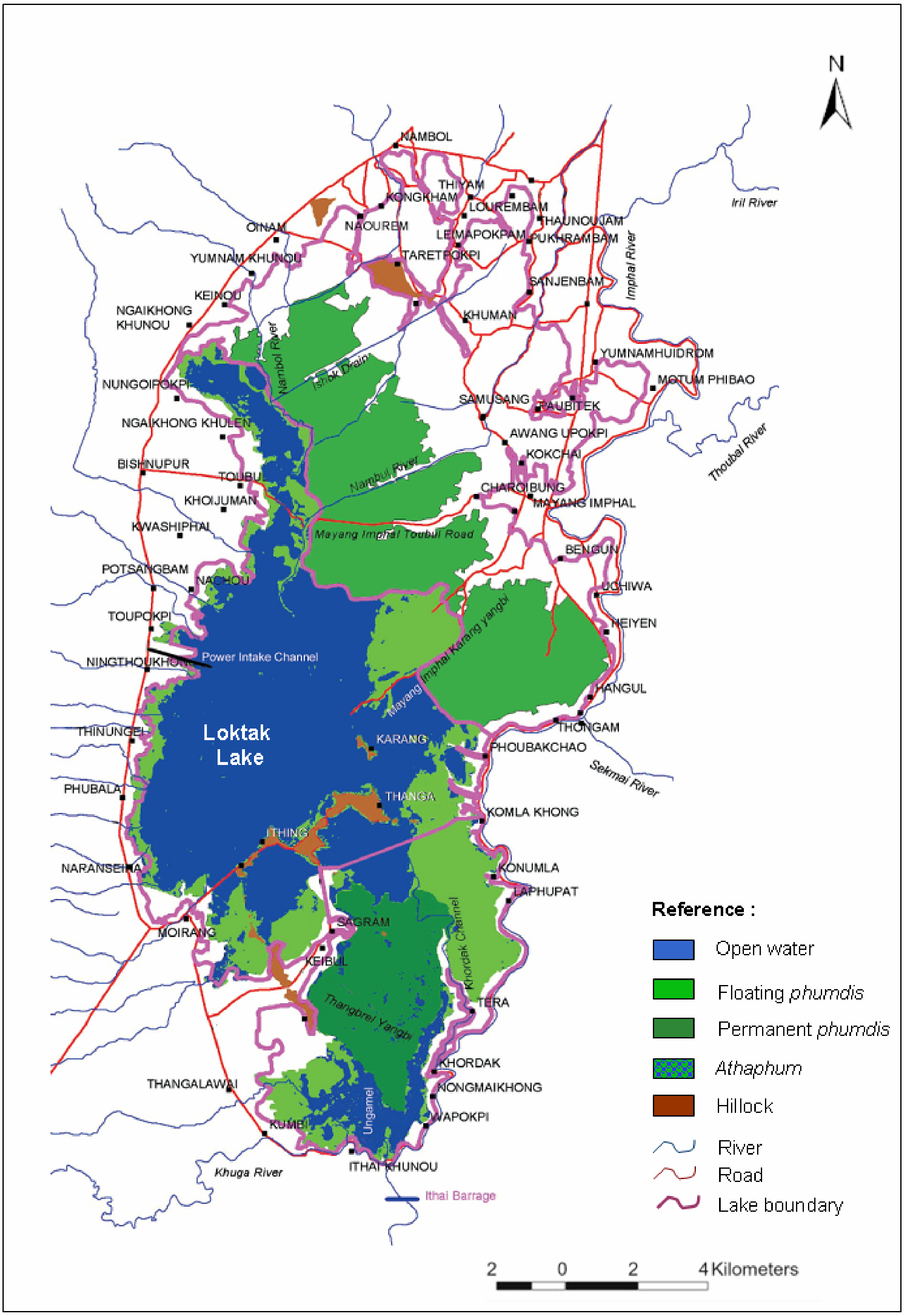


Figure 2.53. Phumdis distribution in 1989. Source: Trisal and Manihar (2004)

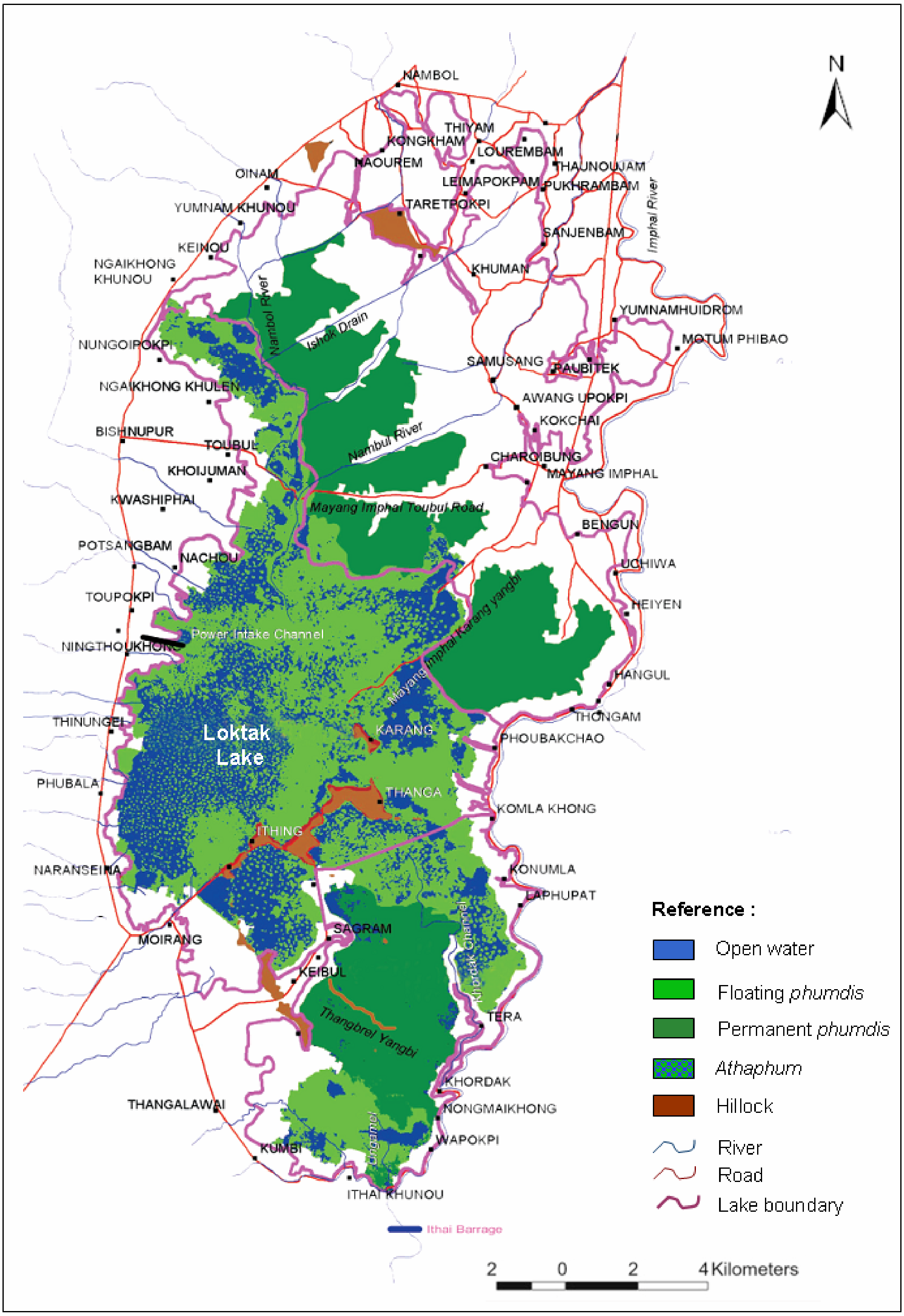
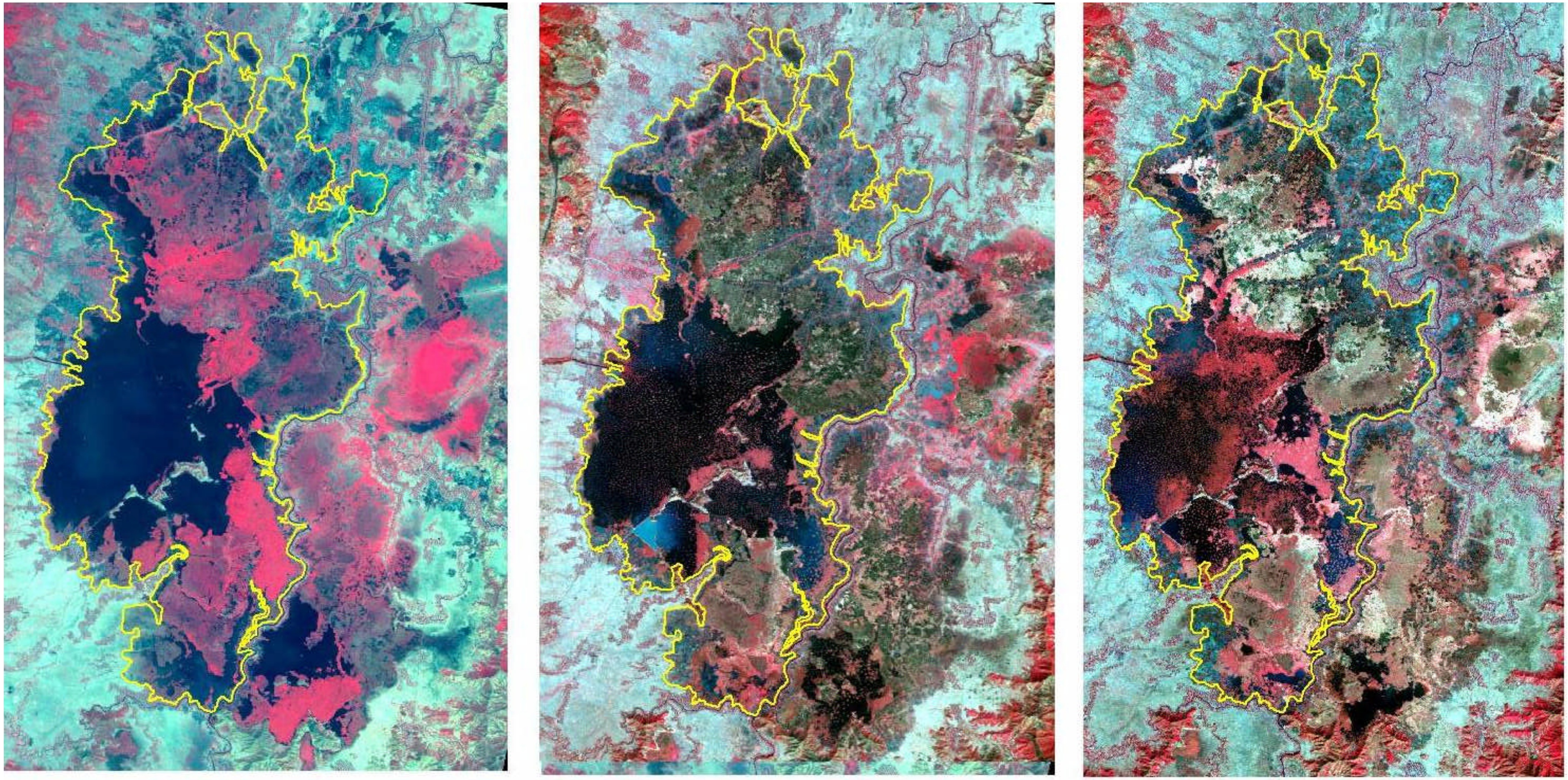


Figure 2.54. Phumdis distribution in 2002. Source: Trisal and Manihar (2004)



1989

No of Attaphum = 217
Area covered by Attaphum = 92 ha

1999

No of Athaphums = 2,286
Area covered by Athaphums = 967 ha

2002

No of Athaphums = 2,642
Area covered by Athaphums = 1,118 ha

Figure 2.55: Athaphums proliferation in Loktak Lake (1989, 1999 and 2002). Source: Trisal and Manihar (2004)

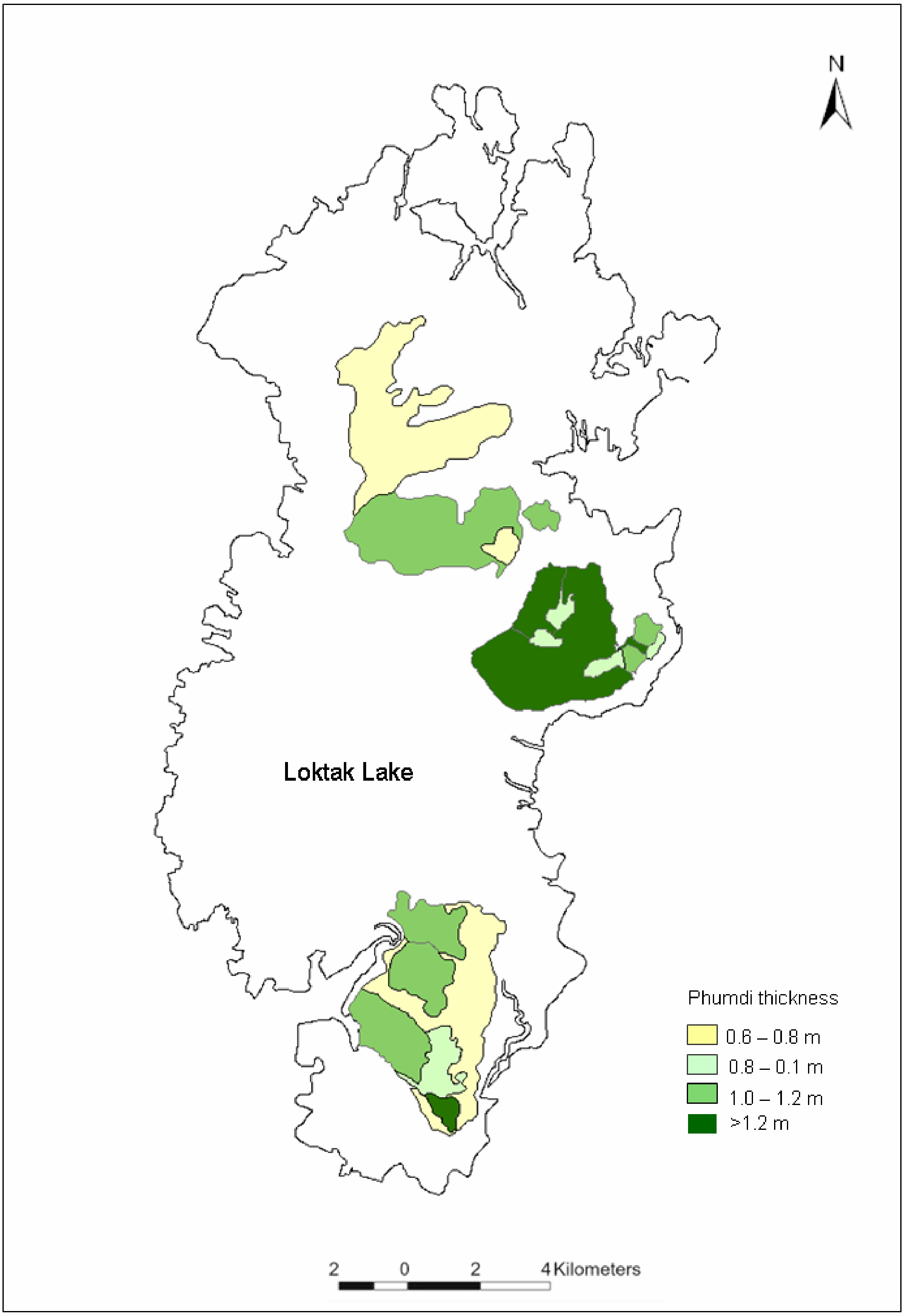


Figure 2.56. Thickness of phumdis in Loktak Lake in 2002. Source: LDA

southern and the northwest portion of the lake, the *phumdis* were generally over 1 m thick. *Phumdis* of such thickness were also found in some parts of the northern sector of the lake. Owing to their thickness and weight, these *phumdis* are fixed to an area and cannot be easily moved by wind. The thick *phumdis,* which are referred as 'permanent *phumdis'* in Figures 2.53 and 2.54 are shown to remain in the same area during 1989 and 2002. On the other hand, the thinner *phumdis* are much lighter and are relatively easily moved by the wind as well as water currents within the lake. The thinner *phumdis* which are referred as 'floating *phumdis'* in Figures 2.53 and 2.54 are not fixed in the same area during 1989 and 2002. Figure 2.57 shows the extent of *phumdis* which are grounded at the lowest mean monthly water level (April – 767.58 m amsl) of the current water level regime (June 1999–May 2003). It is estimated to ground just 14.7 km^2 of *phumdis* in the entire lake area, while in KLNP an area of just 2.1 km^2. This inability to ground the *phumdis*, as discussed earlier in Section 2.5.2, is one of the main reasons for the deteriorating condition of the *phumdis* in Loktak Lake.

2.6.2. Keibul Lamjao National Park

KLNP is located in the southeastern part of Loktak Lake between longitude 24°27' to 24°31' N and latitude 93°53' to 93°55' E (Trisal and Manihar, 2005, **Figure 2.2**). The Park is the only natural habitat in the world for the rare and the endangered Brow-antlered deer (*Cervus eldi eldi*) locally called the Sangai (Angom, 2005). The Government of Manipur had declared the *Sangai* as the state animal and being the flagship species it is central to all the wildlife management programmes in the state. The park is also the habitat for 81 species of birds, 25 species of reptiles and 22 species of mammals (Singh, 1992). In addition the park also supports 132 plants species including *Zizania latifolia, Phragmitis karka, Echinochloa stagnina and Saccharum munja Cyperus sp.*

Prior to 1891, the *Sangai* was preserved by order of the royal family of Manipur. However, the poaching of *Sangai* continued and by 1951, the Government of Manipur declared the *Sangai* extinct. However, a detailed survey conducted by IUCN in 1953 identified a few survivors in a small pocket of *phumdis*. In response, the Government of Manipur designated the southern portion of the lake covering an area of 52 km^2 as a sanctuary. The notification declaring the area as a national park was issued in 1975 followed by final notification in the year 1977. The declaration of Keibul Lamjao as a

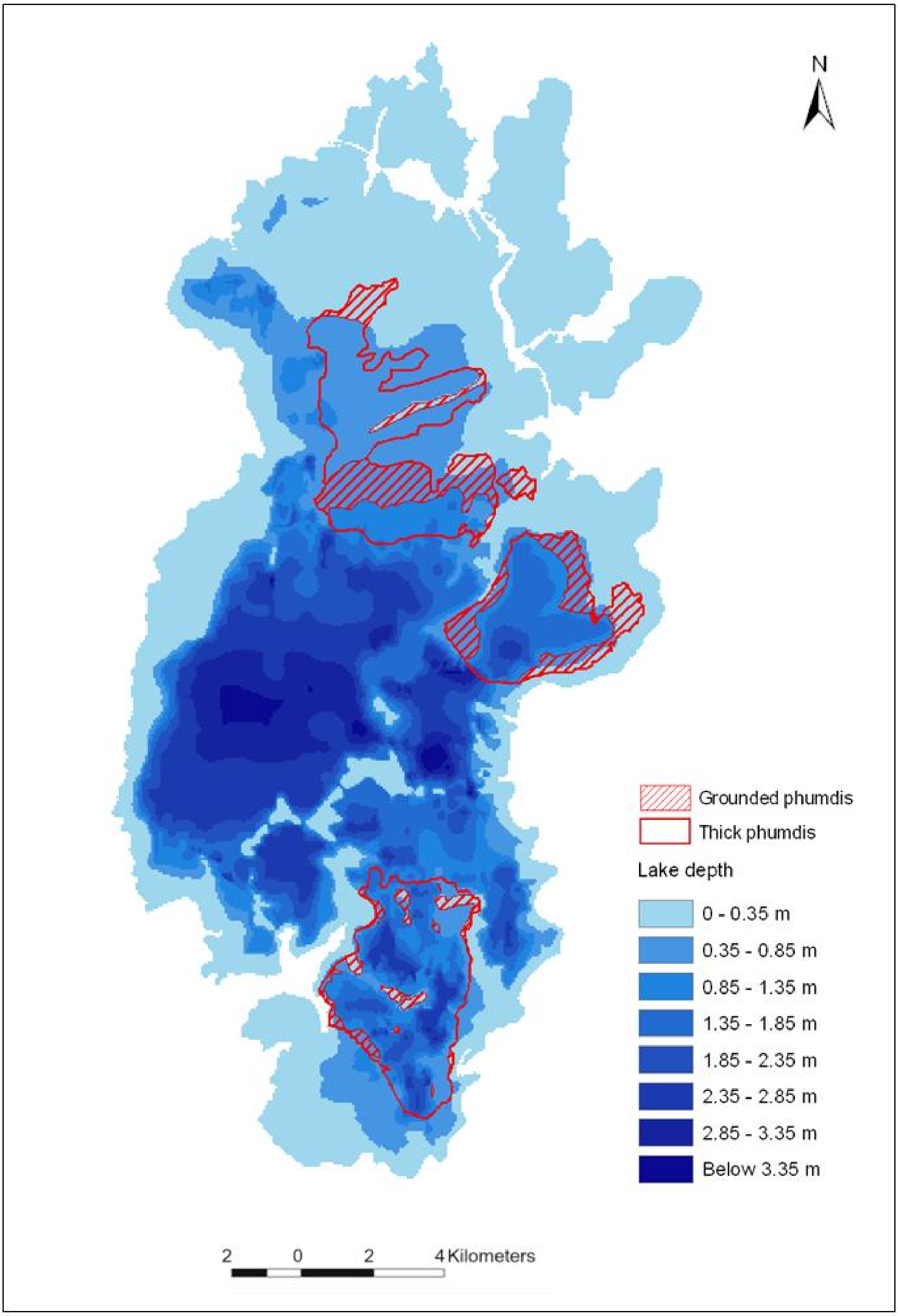


Figure 2.57. Map showing grounded phumdis at the lowest mean monthly water level (April – 767.58 m amsl) during June 1999–May 2003

National Park has helped in the conservation of the *Sangai* and the population increased from 14 in 1975 to 162 in 2000. The population of other wildlife species, such as hog deer (*Axis porcinus*) and wild boar (*Sus scrofa*), was estimated in 2000 to be 244 and 26 respectively (Trisal and Manihar, 2004).

In the currently designated park area, the western portion constituting two very thick blocks of *phumdis* forms the main habitat of the *Sangai*. This area is occupied by thick vegetation mainly comprising emergent species such as *Oryza rufipogon* (wild paddy species), *Capillipedium sp.* and *Dactyloctenium aegypticum,* which are used as food and shelter by the deer. The eastern portion of the Park is mainly covered by thinner *phumdis* intermixed with dense growth of plant such as *Zizania* and *Phragmites*. The northern portion has deeper water and is covered with thinner *phumdis*. This portion of the park is being used for protection of migratory and resident waterbirds.

The deteriorating condition of Loktak Lake, particularly the construction of Ithai Barrage, as discussed in Section 2.5.2, has seriously affected the park habitat. The constant and high water level maintain throughout the year to facilitate hydropower generation without allowing *phumdis* to settle down at the bottom has seriously impacted the growth and the thickness of *phumdis* in the park area (Singh, 1994; Prasad and Chhabra, 2001; Trisal and Manihar, 2004).

2.6.3. Role of *phumdis in* Loktak ecosystem

Phumdis play an important role in governing the hydro–ecological processes and functions of the lake ecosystem (Trisal and Manihar, 2002). The *phumdis* in the northern portion of the lake play a critical role in providing a biological sink for the pollutants and nutrients (Kosygin, 2002) brought in by Nambul River. They are therefore important in the maintenance of water quality within the lake. WISA and LDA (2005) stated that 50% of the mineral nutrients present in the wetland system are locked within the macrophytic tissues, thus helping to reduce the nutrient concentration within water, thereby suppressing algal growth. They also harbour a rich biodiversity (Singh, 1992). The *phumdis* also plays a critical role in the socio–economy of the people living on and around Loktak Lake by provided food in terms of rich fishery resources and edible plants recourses including *Nulembo* (Figure 2.58) *and Alpinia galangal* (Figure 2.59). It has been estimated that *athaphum* fishing yields 590 tonnes of fish annually contributing around 39% of the total fish yield from the lake (Figure 2.60).

They also provide fodder, fuel, construction materials and medicines. A list of some plant species which have socio – economic importance are provided in Table 2.9. *Phumdis* can also be utilized as compost, bio-fertilizers and several other products, which can provide economic benefits to the people as well as regenerate the health of lake ecosystem. *Phumdis* also provide temporary settlements for a large number of fishermen during the winter season. As of 2001, there were 733 *phum* huts providing shelter to 1977 fishermen. *Phumdis* plays a critical role in the maintenance of the lake hydrological regime. The *phumdis*–hydrology inter-relationships within the lake are discussed in the following section.

Figure 2.58. Nelumbo in Loktak Lake (Source: LDA)

Figure 2.59. Alpinia galangal, locally known as Pullei are used as vegetable (Source: LDA)

Figure 2.60. Fishery resource from Loktak Lake (Source: LDA)

Table 2.9. List of plant species found in phumdis which are of socio-economic values

Uses	**Plant species**
Food	*Nelumbo, Euryle, Nympheae, Alpinia, Hedychium, Zizania and Polygonum,*
Fodder	*Echinocloa, Capillipedium, Zizania, Alternanthera* and *Brachiaria*
Fuel	*Coix, Phragmites* and *Saccharum*
Construction	*Arundo, Phragmites, Zizania* and *Saccharum*
Medicinal	*Fuirena,Polygonum, Impatiens*, and *Malaxis, Fuirena umbellata, Polygonum, Arundo donax, Eichhornia crassipes, Hedychium coronarium, Mikania cordata*
Handicraft	*Cyperus* and *Scirpus*

Source: Trisal and Manihar (2004)

2.6.4. *Phumdi* – hydrology inter-relationships

Influence of *phumdis* on lake hydrology*:* *Phumdis* and associated flora are capable of exerting a biotic control on the hydrological regime of Loktak Lake (Trisal and Manihar, 2002). A large amount of water is lost from the lake through evapotraspiration from the *phumdis*. It is estimated that 142 x $10^6 m^3$ of water is lost annually from Loktak Lake through evapotranspiration from *phumdis*, although this is less than the amount of water lost through evaporation from the open lake water area (162 x $10^6 m^3$). Thus, *phumdis* help in reducing water losses from the lake. The presence of *phumdis* in the channels within the lake and in the mouths of the rivers and streams has the effect of choking flows. This leads to prolonged stagnation and impoundment of water in the upper courses of the rivers and in some pockets within the lake, especially the north. These impoundments are one of the major factors in the flooding of peripheral areas around the lake (Meitei, 2002). The Nambul River is one such river which causes severe flooding each year due to this phenomenon. The stagnation of these river and streams due to blockage from the *phumdis* allows the large amount of sediment they carry from their degraded catchments to settle in the wetland promoting further growth of *phumdis*. A similar phenomenon was reported by Sanchez-Carrillo et al. (2001) in Las Tablas de Daimiel National Park in Central Spain.

Prior to the construction of Ithai Barrage, *athamphum* fishing activities earlier were a seasonal activity concentrated during high water level season. The post-Ithai water level regime of more constant high water levels throughout the year established conditions which make it a permanent activity throughout the year. As a result *phumdis*, especially the *athaphums*, have proliferated all throughout the lake. The presence of *athaphums* across the lake interferes with the movement and circulation pattern of the water and sediments (Trisal and Manihar, 2002). WISA (2005) estimated that 336,325 tonnes of silt are deposited annually leading to a loss of 25% in the water holding capacity in the last three decades. This enhanced sedimentation can partly be attributed to the interference of the flow pattern within the lake due to the proliferation of these *phumdis*. The *athaphums* also interfere with the navigational benefits that the lake provides to the local communities.

Hydrological control on the growth and proliferation of *phumdis* within the lake: As discussed in Section 1.5, the hydrological regime of a wetland plays a major role in the dynamics of growth, spread and movement of floral and fauna diversity within the system. Loktak Lake is no exception to this inter-relationship. Meitei (2002) stated that the distribution, abundance and role of *phumdis* are mainly governed by the hydrological regime of the lake. *Phumdis* floats on the water surface and rise with the rising water level during the monsoon seasons and fall with the receding water level during the dry season. As discussed in Section 2.5.2, this seasonal floating and grounding cycle of the *phumdis* is critical to their growth and existence as it enables them to derive nutrients from the nutrient rich sediments on the lake bed during their grounding period (Santosh and Bidan, 2002; Trisal and Manihar, 2002). As noted in Section 2.5.1, prior to the construction of Ithai Barrage mean monthly lake water level fluctuated by 3.1 m and the water level dropped as low as 765.5 m amsl during May.

This enabled the *phumdis* to ground for a certain period of time each year (during the lean season – December to March) in order to obtain nutrients from the lake bed. However, the scenario drastically changed after the construction of the Ithai Barrage. The hydrological regime of the lake has been modified into a more or less constant water level. The fluctuation of the water level between the monsoon and dry season has reduced to just 1.2 m with the lowest water at 767.9 m amsl. This new water regime does not allow the grounding of the *phumdis*.. The high water levels also wash away sediments and humus that are attached to the roots of the *phumdis* plants, which are responsible for interlocking the roots and the plants together. This have resulted in the disintegration and decay of the *phumdis* (Angom, 2005), a phenomenon which is very common to the *phumdis* in the KLNP area. Another change in the hydrological conditions which affects the *phumdis* in KLNP area is the backflow from the Ungamen and Khordak link channels. Owing to the proximity to Ithai Barrage, the backflow from these two channels has a relatively high velocity and the water carries a large amount of sediment (Meitei, 2002). Deposition of sediment on the *phumdis* in the KLNP area is causing them to sink thereby further deteriorating the *phumdis*. This deteriorating condition of the KLNP *phumdis* has serious implications for the survival of these unique floating islands and the high biodiversity they harbour, including the *Sangai* deer.

Due to the impoundment of water within the lake by the construction of barrage, proper flushing of the pollutants and the sediments downstream seldom takes place and as a result the water quality in the lake is also deteriorating. As noted in Section 2.5.5, a study carried out by LDA and WISA under the SDWRML project reported pH level dropping to as low as 4.1 in some pockets in the core area of KLNP, which added to further degradation of the *phumdis* in KLNP.

2.7. Problems and issues

The key issue facing Loktak Lake are the changes in its hydrological regime brought about by the construction of Ithai Barrage for the commissioning of the Loktak Hydro Electric Project in 1983. As discussed in Section 2.5.2, this alteration in the hydrological regime from a natural wetland with fluctuating water levels into a reservoir with more or less constant water level underlies all the major problems the lake is currently subjected to. One particular concern is the deteriorating condition of the *phumdis*, the presence of which makes the lake unique and underpins the lake’s ability to sustain a large biodiversity. The existence of the KLNP, the only natural habitat of the highly endangered *Cervus eldi eldi* is threatened due to thinning and deteriorating of the *phumdis* in the core areas of the habitat. The ability of the *phumdis* to provide socio-economic goods in term of food, fodder, fuel, construction materials and medicinal plants to the local communities is also being threatened.

One of the primary objectives of the barrage was to control flooding in the peripheral areas of Loktak Lake. Instead, it has aggravated the flooding frequency and intensity in the region (Maudgal, 2004). Flooding in the peripheral agricultural and settlement areas has become a regular annual phenomenon. The lake water level should ideally be maintained below the flood level of 768.5 m amsl. However, it has been observed to persist at a higher level (up to 769.19 m amsl during September 1999), causing severe flooding. Choking of the mouths of streams and rivers flowing into the lake due to the presence of the *phumdis* is one of the main factors contributing to this flooding. The interference in the flow regime within the lake due to the construction of the barrage as well as *athaphum* proliferation has also aggravated sedimentation leading to large loss in the water holding capacity of the lake.

The poor flushing pattern due to both the construction of Ithai Barrage and proliferation of *athaphums*, has led to the deterioration of water quality within the lake. The lake receives high amounts of pollutants from pesticides and chemical fertilizers used on the agricultural land around the lake, municipal wastes brought by rivers, soil nutrients from the denuded catchment area and domestic sewage from settlements on and around the lake. The fisheries production and species diversity are also in the decline due to the blockade of the migratory route of fishes from the Chindwin-Irrawaddy river system of Myanmar by the construction of Ithai Barrage. This issue is further aggravated by over-exploitation through indiscriminate methods of fishing (*athaphum* fishing).

In addition, the lack of baseline data, sectoral approaches of different government agencies leading to conflicting interests (e.g. Department of Fisheries with Irrigation and Flood Control Department), lack of an institutional framework and policy mechanism and lack of awareness about the values and functions of wetlands have further complicated the problems of Loktak Lake. Climate change is also likely to have implications to the hydrological regime of Loktak Lake and compound these issues, however no thorough study in this regards has been carried out so far.

2.8. Outline of the PhD

2.8.1. Aim

The main aim of this thesis is to develop a framework for restoring an ecologically-driven hydrological regime for Loktak Lake through the operation of the Ithai Barrage, while satisfying the water demands from other stakeholders. The impact of climate change on the hydrological regime of Loktak Lake and the sustainability of the newly formulated barrage operation plans will also be assessed.

2.8.2. Objectives

The research has the following five principal objectives:

(i) To develop catchment hydrological models of the main catchments draining into Loktak Lake to establish their contribution to the lake.

(ii) To develop a water balance model of Loktak Lake capable of simulating observed lake water levels which includes the principal hydrometeorological inputs and outputs as well as abstractions.

(iii) To develop multiple options for allocating water of Loktak Lake to major stakeholders including an option designed to balance human stakeholders with ecological requirements of the lake.

(iv) To assess the impact of climate change on the catchment and lake hydrological regime.

(v) To assess the implications of climate change on the long-term sustainability of the formulated water allocation options including the balanced human:ecological requirement option.

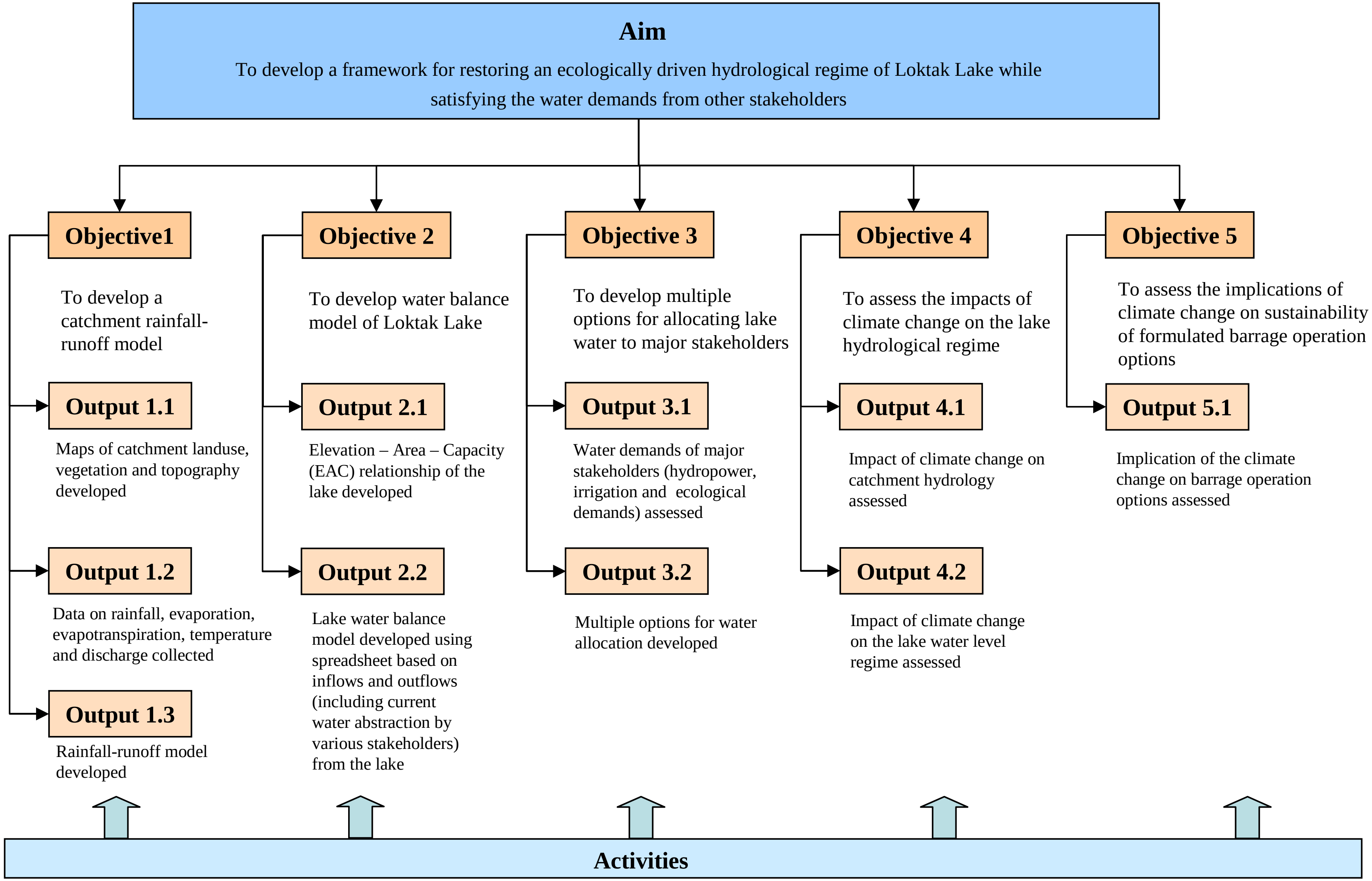
2.8.3. Research design

To address the problems confronted by Loktak Lake, it is essential to recognize the interconnectivity of the wetland with its catchments. An Integrated Water Resource Management (IWRM) approach (UNESCO, 2003) is adopted during the course of the research to provide a broad understanding and assessment of the hydrological regimes at the catchment level. Hydrological and ecological data collected under the project SDWRML (Section 2.3.1), jointly implemented by the LDA and WISA in which the author played a central role are used. Other relevant data including landuse, vegetation and *phumdis* extent and depth were collected from various government agencies including the State Departments of Remote Sensing, Forests and Environment, and

Irrigation and Flood Control as well as other international sources. A concept diagram summarizing the aim and objectives of the study is present in Figure 2.61.

Catchment hydrological models are developed using data from three gauged sub-catchments to provide daily discharges. Results are extrapolated to the ungauged sub-catchments to estimate the inflow of water from the catchment area into the lake. This catchment modelling is discussed in Chapter 3. A water balance model of the lake is developed to simulate the lake water level with special focus on the seasonal fluctuations in water levels. Due to data availability, the water balance model is developed on a monthly time-scale. The water balance modelling is described in Chapter 4. Based on a hydro-ecological assessment, multiple options for operation of the Ithai Barrage are developed in Chapter 5. The water balance model developed in Chapter 4 is used in the formulation of the barrage operation scenarios to assess the impacts on lake water levels.

The implication of climate change on Loktak catchment hydrology is assessed in Chapter 6 by running pattern-scaled GCM output through the catchment hydrological models developed for each sub-catchment and in turn the ungauged parts of the catchment. Impacts of climate change upon water levels within Loktak Lake are subsequently investigated using the 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 one GCM for increases in global mean temperature between 1ºC and 6ºC. Under the same two groups of climate change scenarios, the sustainability of the formulated water allocation options is assessed using the water balance model in Chapter 7. Chapter 8 highlights the principal findings of the research and discusses the future research which is required for the effective conservation and management of Loktak Lake.



Aim

To develop a framework for restoring an ecologically driven hydrological regime of Loktak Lake while satisfying the water demands from other stakeholders

Objective1

To develop a catchment rainfall-runoff model

Output 1.1

Maps of catchment landuse, vegetation and topography developed

Output 1.2

Data on rainfall, evaporation, evapotranspiration, temperature and discharge collected

Output 1.3

Rainfall-runoff model developed

Objective 2

To develop water balance model of Loktak Lake

Output 2.1

Elevation – Area – Capacity (EAC) relationship of the lake developed

Output 2.2

Lake water balance model developed using spreadsheet based on inflows and outflows (including current water abstraction by various stakeholders) from the lake

Objective 3

To develop multiple options for allocating lake water to major stakeholders

Output 3.1

Water demands of major stakeholders (hydropower, irrigation and ecological demands) assessed

Output 3.2

Multiple options for water allocation developed

Objective 4

To assess the impacts of climate change on the lake hydrological regime

Output 4.1

Impact of climate change on catchment hydrology assessed

Output 4.2

Impact of climate change on the lake water level regime assessed

Objective 5

To assess the implications of climate change on sustainability of formulated barrage operation options

Output 5.1

Implication of the climate change on barrage operation options assessed

Activities

Figure 2.61. Research design – aim and objectives

Chapter 3 - Hydrological modelling of the Loktak Lake catchment

3.1. Introduction

This chapter introduces the types of hydrological models that can be used for simulating catchment run-off. It also discusses the modelling system, MIKE SHE, which is employed in this study to simulate runoff from the Loktak sub-catchments. The main part of this chapter then details the modelling process for the Loktak Lake sub-catchments including model development, calibration and validation. The method used to estimate flows from ungauged sub-catchments is also presented.

According to Watts (1996), any conceptual representation of a real world system is a model. Models provide a simplified explanation of complex systems, allowing the modeller to understand the system in a better and systematic manner. They enable modellers to develop new theories and ask ‘What if?’ questions. Ward and Robinson (2000) argued that hydrologists have long regarded the development of models which accurately represent drainage basin hydrology as an important test of their understanding of hydrological processes (for example Refsgaard et al., 1992; Jain et al., 1992; Thompson and Hollis, 1995; Christianens and Feyen, 2001; Thompson et al., 2004; McMichael et al. , 2006). Watts (1996) further noted that these models are also used for predicting the behaviour of the system (for example Lorup et al., 1998; Al-Khudhary et al., 1999; Karvon et al., 1999; Gunnar and Mey, 2007).

Brooks et al. (1991) argued that hydrological models simplify actual hydrological systems, predict hydrological responses and provide improved understanding of the function and interaction of various inputs, outputs and hydrological events. However, Ward and Robinson (2000) observed that many hydrological models are rarely applicable with equal success to another drainage basin than the one for which the model was developed. Most hydrological models are developed for a specific purpose rather than the more fundamental purpose of scientific investigation of hydrological functions. In addition, models differ as they are developed to accommodate a wide range of hydrological data availability. As a result there are numerous drainage basin models. Some of the models are simple black box models which may give reasonably correct results for a chosen hydrological variable, such as runoff or infiltration. The quality of data used and the model structure are more important ingredients for success than model complexity (Ward and Robinson, 2000). The spatial scale of the model may also vary from few centimetres (for example, Hoogmoed and Bouma, 1980 developed a model for predicting infiltration into cracked clay soil) to many hundreds of kilometres (for example Collischonn et al. 2008 developed a hydrological model for the Amazon Basin using TRMM rainfall estimates).

The advancement in hydrological modelling in the past four decades has led to a dramatic increase in the understanding of hydrological systems and hence in the scope of hydrological applications. Hydrological modelling forms the basis for modern hydrology (Watts, 1996). It has been considered as a powerful technique of hydrological system investigation for both research hydrologists and the practising water resources engineers involved in planning and development of integrated approaches for management of water resources. However it must be noted that each model has its own strengths and weaknesses and the choice of model type depends greatly on the system to be modelled or the hydrological problem it is intended to address.

3.2. Classification and comparison of hydrological models

Many attempts have been made to classify hydrological models depending on different criteria or perspectives (for example Woolhiser, 1973; Fleming, 1975; Singh, 1995; Refsgaard, 1996). In general, hydrological models can be classified according to system representation, hydrological processes representation and spatial discretisation.

3.2.1. System representation

Based on the system representation, hydrological models can be classified as deterministic and stochastic. If all the variables of the model are free of any distribution in probability then the model is said to be deterministic (Visser, 1972). Deterministic models are based on cause-effect relationships (Yevjevieh, 1987) and simulate by describing the behaviour of catchment processes in terms of mathematical relations, outlining the interactions of various phases of the hydrological cycle (Viessman and Lewis, 1995). Examples of deterministic models include the Soil and Water Assessment Tool (SWAT, Arnold et al., 1993; Luzio et al., 2002; Olivera et al., 2006), TOPMODEL (Beven and Kirkby, 1979; Holko and Lepistö, 1997), HBV (Lindström et al., 1997; Zhang and Lindström, 1997) and MIKE SHE (Refsgaard and Storm, 1995; Butts et al., 2005). Stochastic models, on the other hand, are based on the principle that relationships often cannot be expressed in simple or complex cause-effect mathematical forms (Yevjevich 1974). Stochastic models are partly driven by some random process which expresses the part of reality that is not covered by the model (i.e. the parts which are uncertain). A stochastic model has at least one component of random character (Abbott and Refsgaard, 1996). In a deterministic model, two identical set of inputs will produce the same output with the initial and boundary conditions being the same (Zhang, 2007) while in stochastic models, identical inputs will generally result in different outputs if run through the model under identical conditions (Abbott and Refsgaard, 1996).

3.2.2. Hydrological processes

Based on the mathematical formulations for process mechanisms, hydrological models can be classified as empirical, conceptual and physically-based (Zhang, 2007). Empirical models represent the relationship between the system output and input without any considerations of process mechanisms. This relationship can be based on empirical knowledge (for example the unit hydrograph method, Sherman, 1932), or derived from statistical analysis (for example Constrained Linear Systems (CLS) model, Todini and Wallis, 1977), or data-based hydroinformatic approaches (for example the Artificial Neural Network (ANN) approach, Minns and Hall, 1966). Empirical models are limited to the range of available data, offering little capability of predicting ungauged basins and effects of changing conditions in a catchment (Zhang, 2007).

Conceptual models are the most common class of hydrological models in general use and are important hydrological tools that can capture dominant catchment dynamics while remaining parsimonious and computationally efficient (Kavetski et al., 2006). The important feature of conceptual models is that their parameters are not directly measurable and must be inferred (‘calibrated’) from the observed data (e.g. Beven and Binley, 1992). Processes perceived to be dominant in watersheds are developed using prior information available for the watershed (Zhang, 2007). Such processes are represented by a number of interrelated reservoirs, and described by continuity equations of water balance in combination with functions relating storage and time lag functions accounting for routing effects. A classic example of a conceptual model is the O’Donnell model (Shaw, 1994), which simulates total discharge using inputs of rainfall and evaporation through a mechanism of four storages (surface storage, channel storage, soil moisture storage and groundwater storage) whose content varies with time. Other examples of conceptual model are given in Table 3.1. In recent years, conceptual models have been used as a component of more larger and comprehensive models. For example, a linear reservoir approach is often used to represent the groundwater system in conceptual rainfall-runoff models (for example MIKE SHE includes an option to use the linear reservoir method to estimate the flow in the saturated zone).

Table 3.1. Notable Conceptual Hydrological Models

Model name	**Country**	**Authority**	**Purpose**
BILIK	France	Sogreah, Grenoble	General forecasting
CBM	Australia	Commonwealth Bureau of Meteorology	Forecast flood flows
CLS	Italy	Pavia Univ. AND ibm Pisa	Flood Forecasting
CREC	France	Chatou	Forecasting Discharges
GIRARD 1	France	ORSTOM, Paris	Multipurpose
HBV	Sweden	Swedish Meteorological and Hydrological Institute, Sweden	Flood forecasting and water resources evaluation
HEC	USA	US Army Corps of Engineers Davies, California	Flood and low flow forecasting
HMC	USSR	Hydromet. Centre, Moscow	Short-term forecast of floods
HYREUN	South Africa	Hydrological Research Unit, Univ. of Witwatersrand	Flood Hydrograph simulation
HYRROM	UK	Institute of Hydrology, UK	Forecast flows, infilling missing flow data, and water resources assessment
Mero	Israel	TAHAL Eng. Co.	Cyprus water planning
NWSH	USA	Nat. Weather Service Maryland	Flood and low flow forecasting
SRFCH	USA	Nat. Weather Service Sacramento R. Forecast Center	Flood and low flow forecasting
SSARR	USA	US Army Corps of Engineers Portland, Oregon	Flood and low flow forecasting
TANK 2	Japan	Yodo R. Dams Control Hirakate City	Discharge for water resources projects
UBC	Canada	University Of British Columbia	Flow forecasting with snowmelt

Source: Modified from Shaw (1994)

Physically-based models are based on measured mathematical-physics using equations of the real world motion and quantum mechanics, hydrodynamics and thermodynamics (Beven, 2001). The watershed to be described is usually represented by an assembly of spatially discrete grid cells with the belief that processes occurring in these grids can be represented by small-scale physics (Zhang, 2007). Physically-based models are either fully-distributed or semi-distributed and are capable of simulating almost all the hydrological processes within a watershed with multiple outputs, for example overland flow, the groundwater table dynamics , evaporation flux and discharge simultaneously.

The spatial distribution capability of such models enables the estimation of hydrological variables at different location within the watershed. Some of the commonly used physically-based models are MIKE SHE (Refsgaard and Storm, 1995, Butts et al., 2005; Graham and Butts, 2005), SHETRAN (Ewen et al., 2000), IHDM (Beven et al., 1987) and THALES (Grayson et al., 1992).

3.2.3. Spatial discretisation

Based on their spatial discretisation, hydrological models can be classified as either lumped or distributed models (Zhang, 2007). Lumped models ignore spatial variability (Viessman and Lewis, 1995) and treat the entire catchment as one uniform hydrological entity, thus representing average values of variables and parameters for the entire catchment. The mode of operation for lumped hydrological models can be characterized as a bookkeeping system that is continuously accounting for the moisture contents in the storages (Refsgaard, 1996). An example of a lumped model is the prediction of the time distribution of surface run-off for different storm events over a homogenous drainage basin using the unit hydrograph. Other examples of lumped models include the Stanford Watershed Model (Crawford and Linsley, 1966), HYRROM (Blackie and Eles, 1985), HBV (Bergström, 1995) and NAM (Nielsen and Hansen, 1973). A detailed discussion of different types of lumped model is given by Fleming (1975) and Singh (1995).

Distributed hydrological models take account of spatial variations in variables and parameters (Refsgaard, 1996) by segregating the watershed into a finite number of spatial units (Zhang, 2007). In principle, parameters, inputs and outputs for a distributed hydrological model all vary with time. Distributed models can either be semi-distributed or fully-distributed. The distribution function component of this type of model is an attempt to make allowance for the fact that not all parts of the catchment responds exactly in a similar way (Beven, 2001). For example, the volume of runoff generated varies with slope within the same catchment. In distributed models, the flow of water is directly calculated from the governing continuum (partial differential) equations, such as for instance the Saint Venant equations for overland and channel flow and Richards's equations for unsaturated zone flow (Refsgaard, 1996). However the computational and parametrical demands of such models are quite complex (Beven, 2001). Typical example of distributed model is Thales (Grayson et al., 1992a, b).

Modelling a catchment involves a decision of fundamental philosophy as to whether the model should be ‘‘lumped’’ or ‘‘distributed’’, and whether it should be ‘‘deterministic’’ or ‘‘stochastic’’ (Beven, 2001). Grayson et al. (1993) stated that in the past, management of water resources have been concentrated on reservoir analysis, flood forecasting and control of industrial and urban point source pollution. But with rapid expansion in the scope of hydrological applications, increased pressure on natural resources and the growing awareness of environmental issues, the focus has shifted towards integrated management of catchments. In order to meet these challenges, in recent years there has been increasing emphasis on the development of physically-based distributed models (Ward and Robinson, 2000).

Refsgaard (1996) noted that distributed physically-based hydrological models give a detailed and potentially more correct description of hydrological processes in the catchment than other model types. It is also possible to reach a high level of understanding of catchment hydrology using a fully-distributed model, which separately describes each small sub-area of the catchment through physically consistent formulations and parameters related to measured catchment properties (Karvonen et al, 1999). Grayson et al. (1993) added that by explicitly representing topography and utilizing a distributed parameter structure, this type of model can represent the spatial variability of catchment features such as soils, vegetation and rainfall. Furthermore, by solving equations based on an understanding of the small scale processes, the parameters used in such models have a physical meaning and can, in principle, be measured in the field.

According to Das et al. (2008), spatially-distributed hydrological models have been increasingly applied to account for spatial variability of the main forcing variables (e.g. precipitation), physiographic characteristics of a catchment (e.g. topography, soil, land use) and detailed process calculation within a catchment (Liang et al., 1994; Beldring et al., 2003). Such models have been widely used for undertaking impact assessment studies (Refsgaard and Sorensen, 1997; Christensen and Lettenmaier, 2007; Zhang et al., 2008; Thompson et al., 2009), investigating the influence of spatial variability of catchment physiographic-climatic characteristics (Liang et al., 2004), wetland management (Refsgaard and Sorensen, 1994; Thompson et al., 2004), estimation of internal fluxes and state variables at high spatial resolution (Beldring et al., 2003), and prediction in interior locations of a catchment (Brath et al., 2004; Reed et al., 2004). Examples of this type of models are MIKE SHE (Refsgaard and Storm, 1995, Butts et al., 2005) and IHDM-model (Beven et al., 1987). According to Graham and Butts (2005), the need for fully integrated surface and groundwater models, like MIKE SHE, has been highlighted by several recent studies (e.g. Camp Dresser & McKee Inc., 2001; Kaiser-Hill, 2001; West Consultants Inc. et al., 2001; Kimley-Horn & Assoc. Inc. et al., 2002; Middlemis, 2004, Thompson, 2004; Thompson et al., 2004 and 2009). MIKE SHE is considered to be one of the most complex hydrological model which is capable of thoroughly representing the complexity of rainfall-runoff processes within a catchment. MIKE SHE is also capable of incorporating the influence of landuse on rainfall-runoff response of the catchment and predicting multiple flow pathways. As such it is one of the most comprehensive hydrological models (Refsgaard and Sørensen, 1997; Beven, 2002).

The current study employs the physically-based spatially-distributed approach of the MIKE SHE modelling system to simulate runoff from gauged Loktak sub-catchments. MIKE SHE is discussed in detail in the following section.

3.3. The MIKE SHE modelling system

MIKE SHE is a deterministic, fully distributed and physically based modelling system (Jain et al., 1992; Christianens and Feyen, 2001; Thompson et al., 2004; Graham and Butts, 2005; McMichael et al., 2006). It is based on the Systeme Hydrologique Europeen (SHE) model (Abbott et al., 1986a, b), which integrated the unsaturated and saturated zone together with the overland flow into a complete dynamic system with interaction among the various components (Xevi et al., 1997). The original system had a relatively simple river model but this has been coupled to MIKE 11, a one-dimensional hydraulic model (Havnø et al., 1995; Thompson et al., 2004). It allows components to be used independently and customized to local needs (DHI, 2004).

According to Butts et al. (2005), MIKE SHE is a comprehensive system for modelling all the major processes that occur in the land phase of the hydrological cycle. MIKE SHE 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 column of horizontal layers at each grid square in the horizontal and vertical, respectively (Graham and Butts, 2005). The river network is assumed to run along the boundaries of the grid squares (Thompson et al., 2004, Xevi et al., 1997). The model comprises the finite difference representation and solution of the theoretical partial differential equations of mass and energy balance. MIKE SHE has been applied to small (<10 km^2) catchments (e.g. Thompson et al., 2004) to major international rivers such as Senegal (Andersen et al., 2001 and 2002). The modular structure of the model enables data exchange between components as well as the addition of new components. The flexible operating structure of MIKE SHE allows the use of as many or as few components of the model, based on availability of data and the aim of the study (Oogathoo, 2006).

3.3.1. MIKE SHE process representation

The MIKE SHE Water Movement (WM) module has a modular structure comprising six process-oriented components which describe the major physical process of the land phase of the hydrological cycle: interception/ evapotranspiration (ET), overland/channel flow (OC), unsaturated zone (UZ), saturated zone (SZ), snow melt (SM) and exchange between aquifers and rivers (EX) (Refsgaard et al., 1995; Christianens and Feyen, 2001; Thompson et al., 2004) (Figure 3.1). Each of these processes can be represented at different levels of spatial distribution and complexity, according to the goals of the study, the availability of data and the modeller’s choices, (Butts et al. 2004). Figure 3.2 shows the hydrological processes that can be simulated within MIKE SHE. It specifies the numerical engines for computation of each hydrological process. The processes which are relevant to the current study are discussed below.

Precipitation: Precipitation is the major input data in simulation of catchment runoff using the MIKE SHE model. These data are provided as precipitation rate comprising both a distribution and a value. The distribution can either be uniform, station-based or fully distributed (DHI, 2005). If the data is station-based then Thiessen polygons or a similar distribution method is used to spatially distribute the precipitation data within the catchment. The precipitation data for a station located within each polygon is assigned to each grid cell within that polygon.

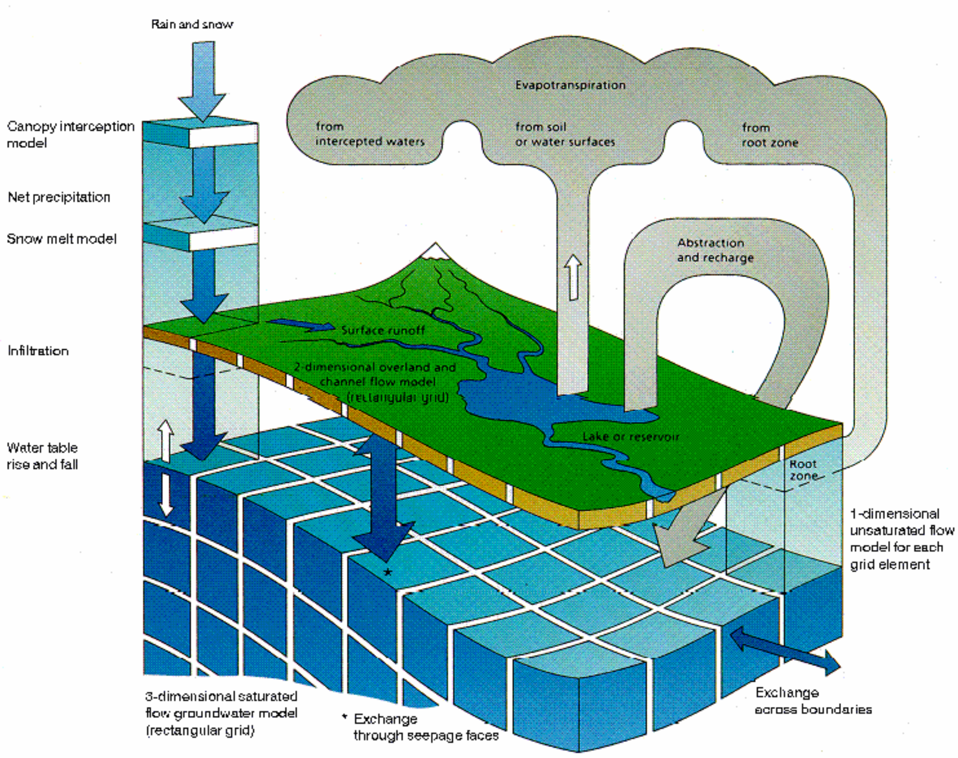


Figure 3.1. Hydrological processes simulated by MIKE SHE. Source: Refsgaard and Storm (1995)

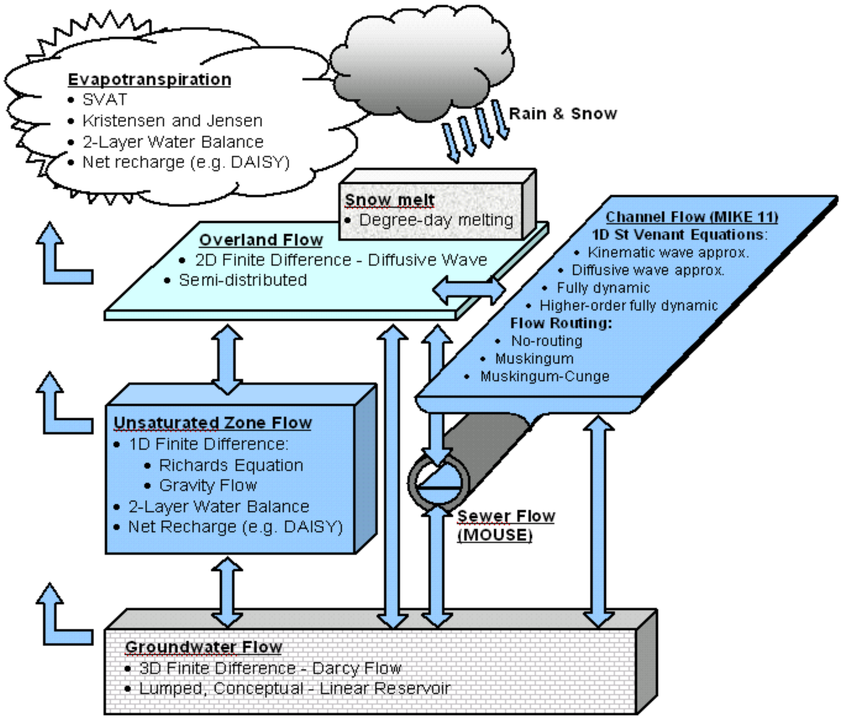


Figure 3.2. Schematic view of the hydrological processes in MIKE SHE, including the available numerical engines for each process. Source: Graham and Butts (2005)

Evapotranspiration: In MIKE SHE, evapotranspiration (ET) is referred to as the sum of direct evaporation from open water surfaces and transpiration from sub-surface water whether directly or via plants (Graham and Butts, 2005). In order to represent this hydrological process MIKE SHE uses both meteorological and vegetation data. The primary MIKE SHE's evapotranspiration model is based on empirically derived equations that follow the work of Kristensen and Jensen (1975). In this approach, the actual ET and soil moisture status in the root zone is estimated from potential evaporation, maximum root depth and leaf area index (LAI) for the plants (DHI, 2005). In addition to this method, MIKE SHE also includes a simplified ET model for a two-layer UZ/ET model. This module calculates the actual evapotranspiration as well as the amount of water that recharges the saturated zone. The simplified ET module divides the unsaturated zone into two separate zones (a root zone, from which ET can be extracted, and a zone below the root zone, where ET does not occur). The ET is computed from the intercepted water (based on LAI), ponded water and via transpiration from the root zone. This method requires similar input data to that of Kristensen and Jensen approach but differs by not including the flow dynamics.

Unsaturated zone (UZ): The unsaturated zone is usually heterogeneous and characterised by cyclic fluctuations in soil moisture, as soil moisture is replenished by rainfall and removed by evapotranspiration and recharge to the groundwater (Graham and Butts, 2005; DHI, 2005). Flow in the unsaturated zone is assumed to be vertical (Oogathoo, 2006), since gravity dominates infiltration. As a result unsaturated flow in MIKE SHE is estimated only vertically. The model calculates soil moisture and water table dynamics in the lower part of the soil profile by an iterative coupling process between unsaturated and saturated zones. There are three methods in MIKE SHE to simulate unsaturated flow and moisture content: (a) Richards Equation, (b) Gravity Flow and, (c) Two–Layer Water Balance methods. Richards Equation uses soil profiles that can have different soils at different depths and is most accurate when the unsaturated flow is dynamic (Graham and Butts, 2005) and is of particular interest to the study. Gravity flow also uses soil profiles that can have different soils at different depths but is more suitable for varying recharge of groundwater based on actual precipitation and evapotranspiration. The two-layer water balance method uses a uniform soil for the entire depth and is more suitable when the water table is shallow. It is computationally efficient making it particularly useful when soil moisture dynamics are not the focus of the study and instead features such as river discharge are of particular interest. It estimates the amount of water that recharges the saturated zone and the actual evapotranspiration. The two-layer water balance model method divides the entire unsaturated zone into two layers (first layer extending from the ground surface to the ET extinction depth and second layer extending from the bottom of the first layer to the water table) representing average conditions in the unsaturated zone, rather than then detailed descretization of the soil profile. This module assumes that if sufficient water is available in the root zone, then there is enough water available for evapotranspiration. This module includes interception, ponding, infiltration, evapotranspiration and groundwater recharge.

Saturated zone: The saturated zone component interacts with all other components of the MIKE SHE modelling system (overland flow, unsaturated flow, channel flow and evapotranspiration). There are two methods for determining the flow in the saturated zone: (a) 3-Dimensional (3-D) finite difference method and, (b) the linear reservoir method. In the 3-D finite difference method a spatial and temporal variation of hydraulic head in the saturated zone are described by 3-D Darcy mathematical equation and is solved numerically by an iterative implicit finite difference technique. The estimation of saturated zone flow using the 3-D finite difference method involves defining the geological model, vertical numerical discretization and defining initial and boundary conditions. The initial conditions are defined as a property of the numerical layer, while the boundary is defined independent of the sub-surface numerical layers. Whereas, in the linear reservoir method, the entire groundwater catchment is sub-divided into smaller sub-catchments. The water from these linear reservoirs is subsequently added to the river as lateral flow.

Overland: Overland flow comprises water that flows over the ground surface to stream channels (Ward and Robinson, 2000). It occurs when net rainfall rate exceeds infiltration capacity of the soil (DHI, 2005). The exact route and quantity of overland flow is determined by topography and flow resistance, as well as the losses due to evaporation and infiltration along the flow path. Overland flow is important for irrigating crops, replenishing pasture and sustaining critical environmental processes such as fish breeding. The amount of overland flow and its direction is calculated by MIKE SHE’s Overland Flow Module, using the diffusive wave approximation of the 2-

D Saint–Venant equations (Finite Difference method) or a semi-distributed approach based on the Mannings equation (Simplified Overland Flow Routing method).

Channel flow: In MIKE SHE, the channel flow is computed using MIKE 11, a one dimensional hydraulic modelling system. It uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries (DHI, 2009). The modelling system is capable of representing a wide range of hydraulic structures including weirs, gates, bridges and culverts that are commonly found within wetland environments (Thompson et al., 2004).

Exchange between aquifers and rivers / MIKE SHE – MIKE 11 coupling: The coupling between MIKE SHE and MIKE 11 is made via river links, which are located on the edges that separate adjacent grid cells (DHI, 2005). Coupling of MIKE SHE and MIKE 11 follows three basic set-up steps: (a) establishment of a stand-alone MIKE 11 HD hydraulic model (b) establishment of a MIKE SHE model including the overland flow component as well as the saturated zone and unsaturated zone components and (c) coupling of MIKE SHE and MIKE 11 by defining branches where the MIKE 11 HD model interact with MIKE SHE. The MIKE SHE – MIKE 11 coupling is crucial for a correct description of the dynamics of river-aquifer interaction (Refsgaard et al., 1994). The coupling of these two systems also enables the simulation of inundation from MIKE 11 river model onto MIKE SHE grid squares.

By default, the entire MIKE 11 model is included in the hydraulic model, but MIKE SHE only exchanges water with those reaches which are specified as being coupled. In these coupled reaches, during the simulation, water levels from the MIKE 11 H-points (points along the river network within the model domain for which water levels are estimated within the model) are transferred to adjacent MIKE SHE river links. MIKE SHE then estimates the overland flow to each river links from adjoining grid cells. The river-aquifer exchange flow is then estimated as a conductance multiplied by the head difference between the river and the grid cell. The conductance between the river links and the grid cell depend on conductivity of either the aquifer material, river bed material or both depending upon the aquifer exchange option which is specified. The exchange flow is then fed back to the corresponding MIKE 11 H-points as lateral inflows or outflow.

3.3.2. Application of MIKE SHE modelling system

MIKE SHE has been widely used to study a variety of water resources and environmental problems under diverse climatological and hydrological regimes (for example Refsgaard and Storm, 1995; Butts et al., 2005; Thompson et al., 2008; Zhang, 2008). It has been used in many countries around the world by organizations ranging from universities and research centres to consulting engineering companies. Refsgaard et al. (1992) and Jain et al. (1992) demonstrated the successful application of MIKE SHE modelling system in reproducing the rainfall-runoff process and presented a physically reasonable representation of the intermediate hydrological processes for the characteristic monsoon environment in six sub-catchments of the Naramda Basin in western India. According to Graham and Butts (2005), MIKE SHE has been extensively used in the analysis, planning and management of a wide range of water resources and ecological problems including basin management and planning, wetland management and restoration and impact of climate change on water resources. Table 3.2 presents some key areas where MIKE SHE has been applied along with some references.

Table 3.2. Some key areas of MIKE application and their references (modified from Graham and Butts, 2005)

Application areas	References
Wetlands	Refsgaard and Sorensen (1994), Refsgaard et al. (1994 and 1998), Al-Khudhairy and Thompson (1997), Yan et al (1999), Jacobsen et al. (1999), Thompson et al. (2004), Thompson et al. (2008)
River basin management and modelling	Refsgaard et al. (1992, 1998, 2003), Jain et al. (1992), Refsgaard et al. (1992), Refsgaard and Sørensen (1994), Sandholt et al. (1999), Andersen et al. (2001), Jensen et al. (2002), Henriksen et al. (2003), Vazquez. (2003), Christensen (2004), Graham and Butts (2005)
Integrated surface water and groundwater	Sørensen et al. (1996), Refsgaard et al. (1998), Olesen et al. (2000), Graham and Refsgaard (2001), Kaiser-Hill (2001)
Groundwater modelling	Refsgaard et al. (1998), Christiaens and Feyen (2001, 2002), Madsen and Kristensen (2002), Sonnenborg et al. (2003)
Soil studies	Lørup and Styzcen (1996), Nielsen et al. (1996), Storm et al. (1987), Morgan et al. (1999, 1998), Christiaens and Feyen (2001)
Agriculture	Styczen and Storm (1993a,b,c), Thorsen et al. (1998, 2001), Hansen et al. (2001), Refsgaard et al. (1999), Boegh et al. (2004)
Irrigation	Carr et al. (1993), Lohani et al. (1993), Singh et al. (1997, 1999a,b), Jayatilaka et al. (1998)
Remote sensing	Sandholt et al. (1999, 2003), Andersen et al. (2002a, b), Butts et al. (2004a,b), Boegh et al. (2004)
Landuse use change	Refsgaard and Sørensen (1994, 1997), Refsgaard and Knudsen (1996), Lørup et al. (1998), Zhang et al. (2008)
Flood studies	Butts et al. (2005)
Model parameter estimation, calibration and validation	Xevi et al. (1997), Refsgaard (1997a,b, 2001a,b), Refsgaard et al. (1998), Madsen and Kristensen (2002), Madsen (2003), Vazquez (2003), Mertens et al. (2004), McMichael et al. (2006)

3.4. Modelling the Loktak Lake catchment using MIKE SHE

For the purpose of modelling the catchment of Loktak Lake has been sub-divided into six sub-catchments namely the Thoubal, Iril, Imphal, Kongba, Khuga and Western sub-catchment. The Heirok and Sekmai sub-catchments have been excluded as they no longer contribute water to the lake following their diversion (Section 2.2). Out of these sub-catchments, the Thoubal and Iril are gauged while the Imphal, Kongba and Khuga are ungauged. The Nambul River, which is the largest river in the Western sub-catchment, is gauged while the rest of smaller rivers/rivulets are ungauged. Therefore MIKE SHE models were developed for these sub-catchments, the Thoubal, Iril and Nambul. The modelling of the sub-catchment was undertaken using the hydrometeorological data available for the four year (June 1999–May 2003) period reviewed in Chapter 2. Given the paucity of data, the approach to model calibration and validation was to initially calibrate the model of the Thoubal sub-catchment with available observed discharge data and then to apply the same calibrated parameter values to models developed for the Iril and Nambul sub-catchments as validation (Figure 3.3). This form of validation exercise was considered appropriate given the similar geology, soils and vegetation cover within the three sub-catchments in addition to similar flow regime with high monsoon and low dry season flows, discussed previously in Section 2.4. 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; Henriksen et al., 2003). Discharges for the ungauged sub-catchments were subsequently estimated by weighting the simulated discharges by catchment area (see Section 3.5)

3.4.1. MIKE SHE model set-up

The MIKE SHE model set-up process for modelling the Loktak Lake sub-catchments is discussed in a stepwise manner following the vertical structuring of the model components provided by MIKE SHE (Figure 3.4), which ensures the model is ready to be run when the data for last component of the model in the vertical set-up is specified.

Simulation specification: Simulation specification is a step during which different modules within the MIKE SHE model are selected. The Water Management module comprising of Overland Flow, Rivers and Lakes, Unsaturated Flow, Evapotranspiration and Saturated Flow models, was selected for modelling Loktak sub-catchments.

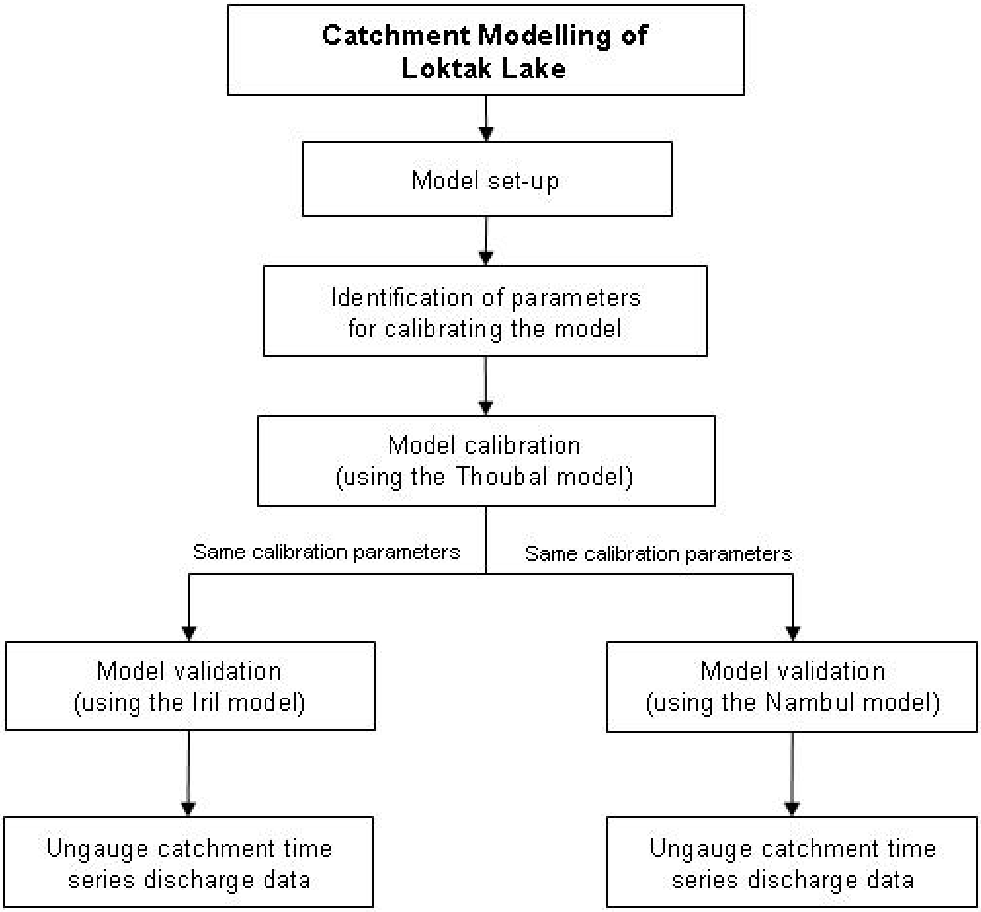


Figure 3.3. Schematic diagram of the MIKE SHE modelling process of Loktak Lake sub-catchments.

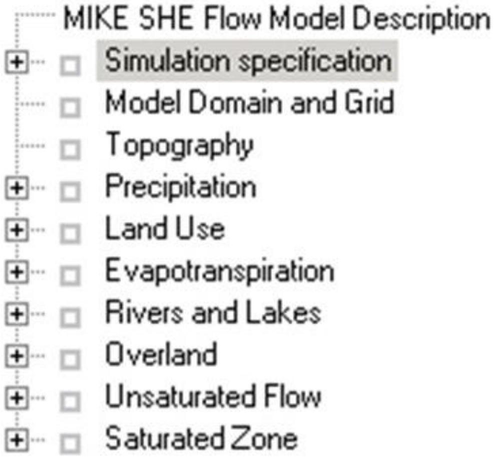


Figure 3.4. Vertical structuring of model components in MIKE SHE modelling system

Due to limitation in the availability of data as discussed in Chapter 2, all three sub-catchment models (Thoubal, Iril and Nambul) were run for a period of 52 months (March 1999–May 2003). The effective simulation period was however only 48 months (4 years) from June 1999–May 2003. The first three months (March–May 1999) were used as an initial model stabilization period. The period between June 1999–May 2003 was chosen as there is continuous hydrometeorological data available (Sections 2.3 and 2.4). A series of initial experiments were carried out to assess the performance of the model against the simulation time. Based on these experiments, the following time steps were chosen for efficient simulation of the Thoubal sub-catchment models:

a. Initial time step - 6 hour
b. Maximum allowed UZ, OL,ET time step - 6 hours
c. Maximum allowed SZ time step - 24 hours
d. MIKE11 time step - 360 minutes

The parameters for precipitation dependent time control step are:

a. Maximum precipitation per time step - 100mm
b. Maximum infiltration amount per time step - 10mm

Grid size: Vásquez et al. (2002) found little change in a number of model performance measures when MIKE SHE was applied over a range of grid cell sizes (300–1200 m) in a large catchment, while McMichael (2006) emphasised that the selection of model grid size should enable accurate representation of catchment attributes without placing excessive demands on computer run time. A grid size of 600 m × 600 m was adopted for the MIKE SHE modelling of Loktak sub-catchments. Trial runs were undertaken using grid sizes of 300 m × 300 m and 1000 m × 1000 m. In the case of 300 m × 300 m, although the catchment area, in particular topography, was described in more detail, the computational time for the Thoubal model was considered excessive (approximately six hours on a Pentium Duo-core, 3 Ghz, 2 MB RAM PC) given the requirement to undertake multiple runs during calibration. In the case of the 1000 × 1000 m^2 grid, whilst the computational time was reduced (approximately 1 hour), the resolution was considered too coarse to represent the variable topography given the rugged nature of the terrain in the study sub-catchments. The 600 × 600 m^2 grid size represents a compromise between detailed representation of sub-catchment areas and computation time (approximately two hours for Thoubal sub-catchment). Table 3.3 shows the number of grid cells for each sub-catchment modelled.

Table 3.3. Number of grid cells in each sub-catchment to be modelled

Sub-catchment	Catchment area (km^2)	Number of grid cells
Thoubal	963	2745
Iril	1271	3612
Nambul	178	583

Topography: Topographical data of the Loktak catchment (Section 2.2.2, Figure 2.6) derived from NASA Shuttle Radar Topographic Mission (SRTM, Farr et al., 2007) digital elevation data which had a grid size of 200 m × 200 m was resampled to the 600 m × 600 m model grid size. The resampling process was carried out using the nearest neighbour assignment technique which determine the location of the closest cell center on the input raster and assign the value of that cell to the cell on the output raster. The resampled topographic data was extracted to ASCII raster format and subsequently converted to DHI's dfs2 format, which is used for gridded data. Figure 3.5 shows the hypsometric curves of Loktak catchment derived from the original and the resampled topographic data. The curves demonstrate that the resampled topographic data represents similar topographic characteristic of the Loktak catchment area to the original topographic data despite the reduction in resolution. Figures 3.6, 3.7 and 3.8 show the topographic data of the Thoubal, Iril and Nambul sub-catchments. The elevation of Thoubal sub-catchment lies between 800–2430 m amsl while for Iril sub-catchment it varies between 800–2300 m amsl and Nambul sub-catchment between 800–2204 m amsl.

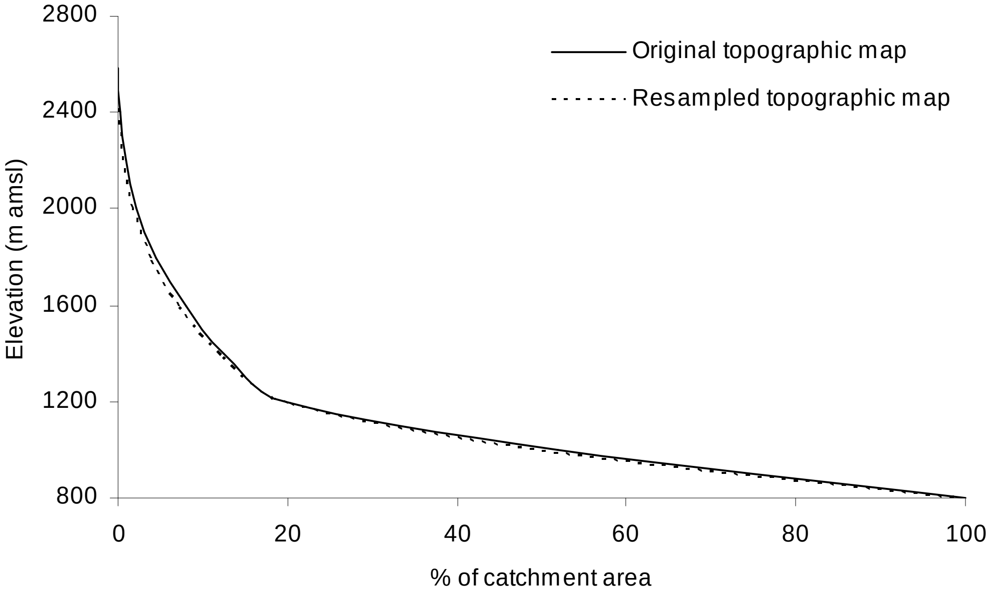


Figure 3.5. Hypsometric curves for Loktak catchment

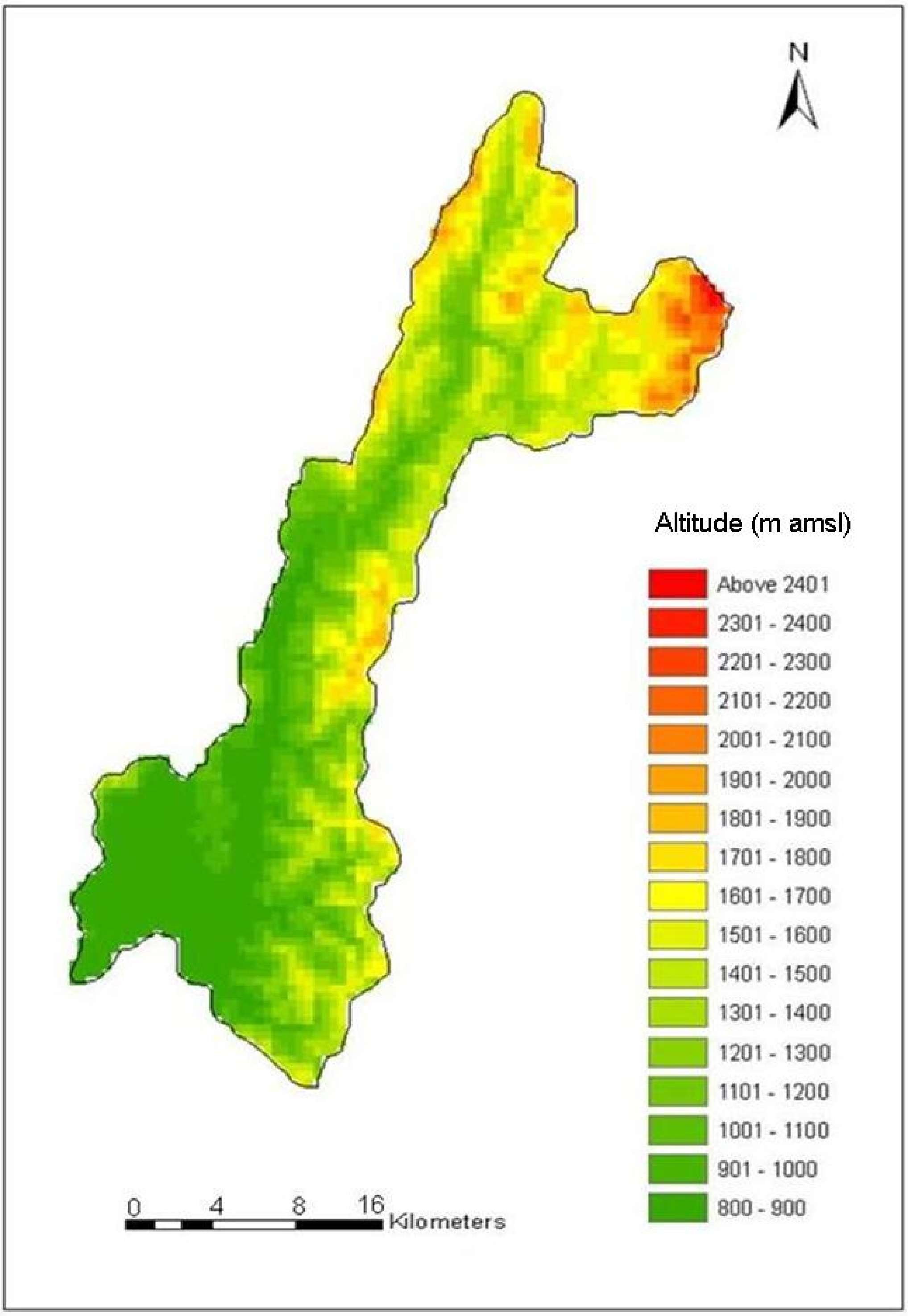


Figure 3.6. Resampled (600 m × 600 m) topographic map of the Thoubal sub-catchment

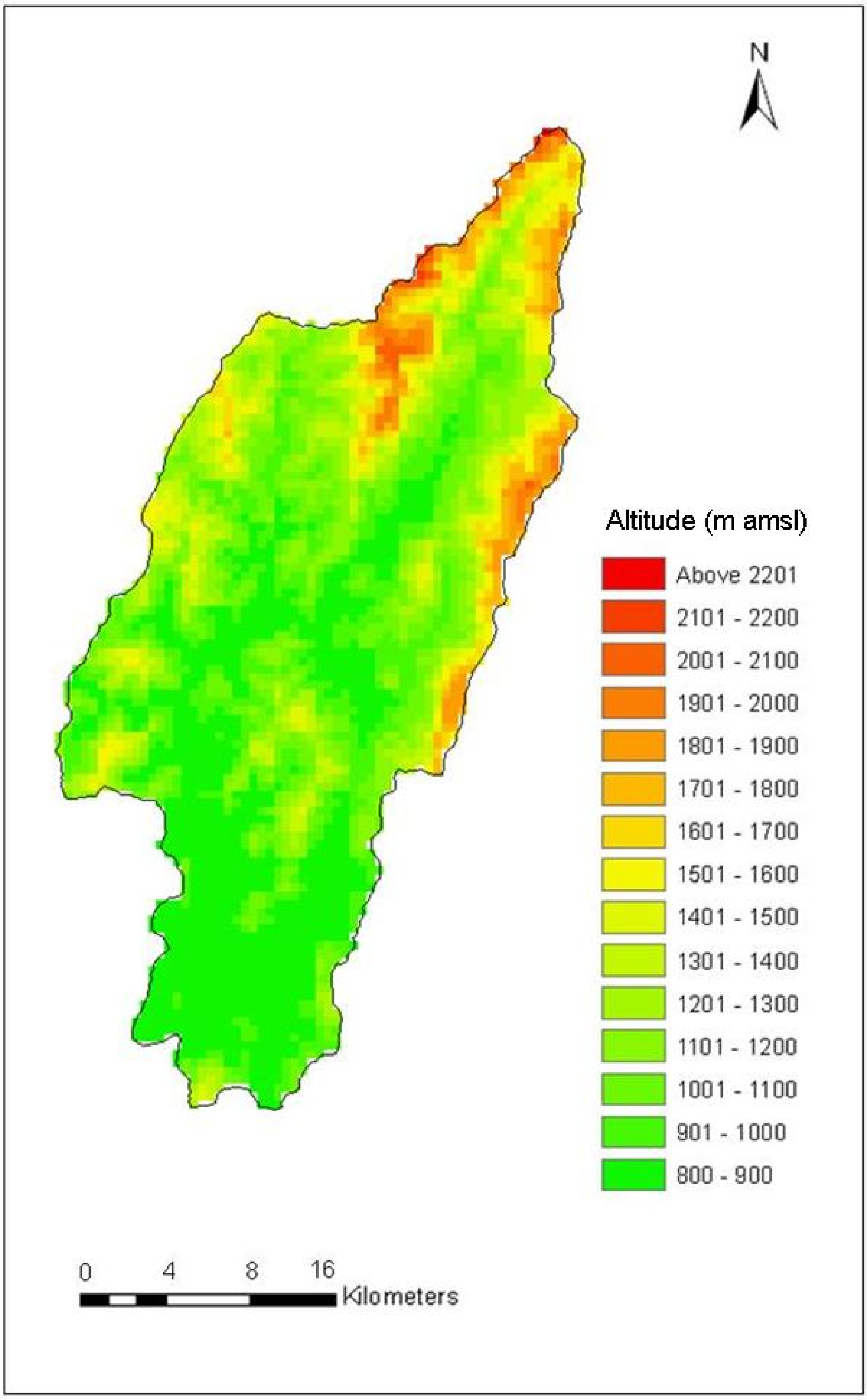


Figure 3.7. Resampled (600 m × 600 m) topographic map of the Iril sub-catchment

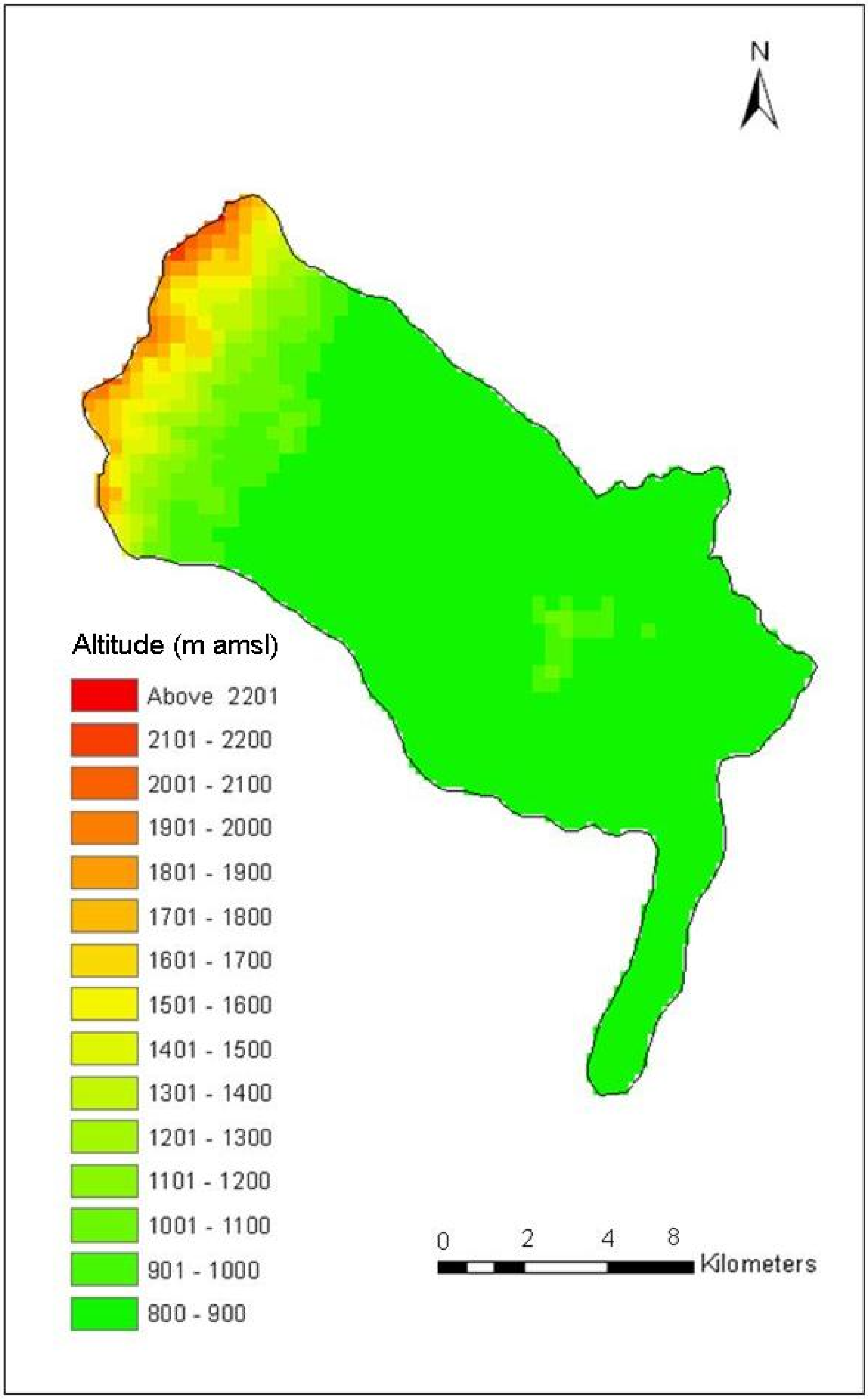


Figure 3.8. Resampled (600 m × 600 m) topographic map of the Nambul sub-catchment

Precipitation: Precipitation data from the seven rain gauges (discussed in Section 2.3.1), were used as input data for the three MIKE SHE models. Daily precipitation data for the period May 1999–June 2003 in DHI's dfs0 format for the seven stations were specified within the MIKE SHE models. Thiessen polygons established in Section 2.3.1 (Figure 2.15) were employed to spatially distribute the rainfall throughout the modelled sub-catchments. Figure 3.9 shows which rain gauge stations influence the rainfall pattern in each of the modelled catchments. The Thoubal sub-catchment is influenced by the Kangla Siphai, Dolaithabi and Pallel rain gauges; the Iril sub-catchment by the Dolaithabi, Kangla Siphai and Awang Sekmai rain gauges; and the Nambul sub-catchment by the Singda, Dolaithabi and Awang Sekmai rain gauges.

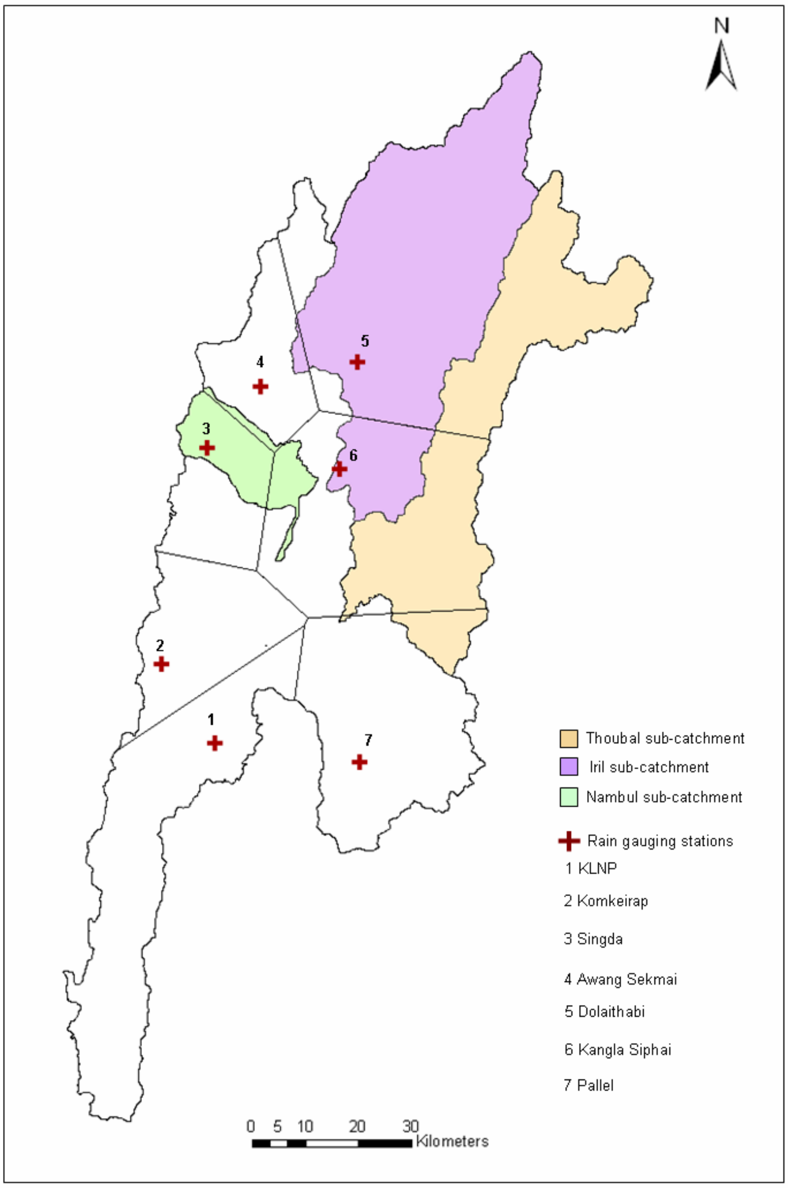


Figure 3.9. Thiessen polygons for precipitation and modelled sub-catchments

Landuse: The landuse map discussed in Section 2.2.5 (Figure 2.7) was used as input data for defining the landuse characteristics of each model domain. Similar to the topographic data, the landuse map was also resampled to the 600 m × 600 m model grid size. The original data were polygons (shapefile) describing the distribution of the different land cover classes, when resampling to a grid using ArcGIS, it assigns the most dominant land cover to that grid since it can not interpolate to a non-integer values. Table 3.4 demonstrates that the areas covered by the different landuse categories for the three modelled sub-catchments provided by the original and the resampled landuse maps are similar. The changes in the areas under different landuse categories for the Thoubal sub-catchment varies between 0.3 km^2 (floating vegetation) to 9.8 km^2 (degraded forest). The largest change of 9.8 km^2 in the area covered by degraded forest represents only a 3% change when compared to the total area covered by degraded forest (324.9 km^2) in the Thoubal sub-catchment. The largest absolute change in Iril sub-catchment is associated with *jhum* area (13.5 km^2), which represents a 5% change when compared to the total area under *jhum* in this sub-catchment. For the Nambul sub-catchment, the largest absolute change is associated with dense forest (1.5 km^2), which represent 16% change when compared to its total dense forest area within the sub-catchment. However, this land cover (dense forest) constitutes only 4.4% of the total catchment area (173.8 km^2), so the impact of this change is likely to be small. The resampled landuse maps were then converted to dfs2 format and specified within the MIKE SHE models as shown in Figures 3.10.

Table 3.4. Comparison of the original and the processed land use map

Landuse	**Thoubal**		**Iril**		**Nambul**	
	Original km^2 (%)	Resampled km^2 (%)	Original km^2 (%)	Resampled km^2 (%)	Original km^2 (%)	Resampled km^2 (%)
Dense Forest	95.3 (9.9)	92.7 (9.7)	143.1 (11.3)	133.8 (10.6)	9.2 (5.2)	7.7 (4.4)
Degraded Forest	324.9 (33.7)	315.1 (33.0)	597.6 (47.0)	584.1 (46.2)	38.6 (21.7)	38.9 (22.4)
Jhum Area	260.3 (27.0)	265.6 (27.8)	248.6 (19.6)	262.1 (20.7)	13.7 (7.7)	14.5 (8.3)
Agriculture	259.0 (26.9)	260.1 (27.2)	268.9 (21.2)	271.9 (21.5)	83.2 (46.7)	80.2 (46.1)
Settlement	17.3 (18.0)	15.8 (15.8)	9.3 (0.7)	7.8 (0.6)	24.9 (14.0)	24.7 (14.2)
Water bodies	2.2 (0.2)	2.1 (0.2)	2.9 (0.2)	3.3 (0.3)	3.2 (1.8)	2.8 (1.6)
Floating vegetations	4 (0.4)	3.7 (0.4)	0.6 (0.0)	0.7 (0.1)	5.2 (2.9)	5 (2.9)
Total	**963**	**955.1**	**1271**	**1263.7**	**178**	**173.8**

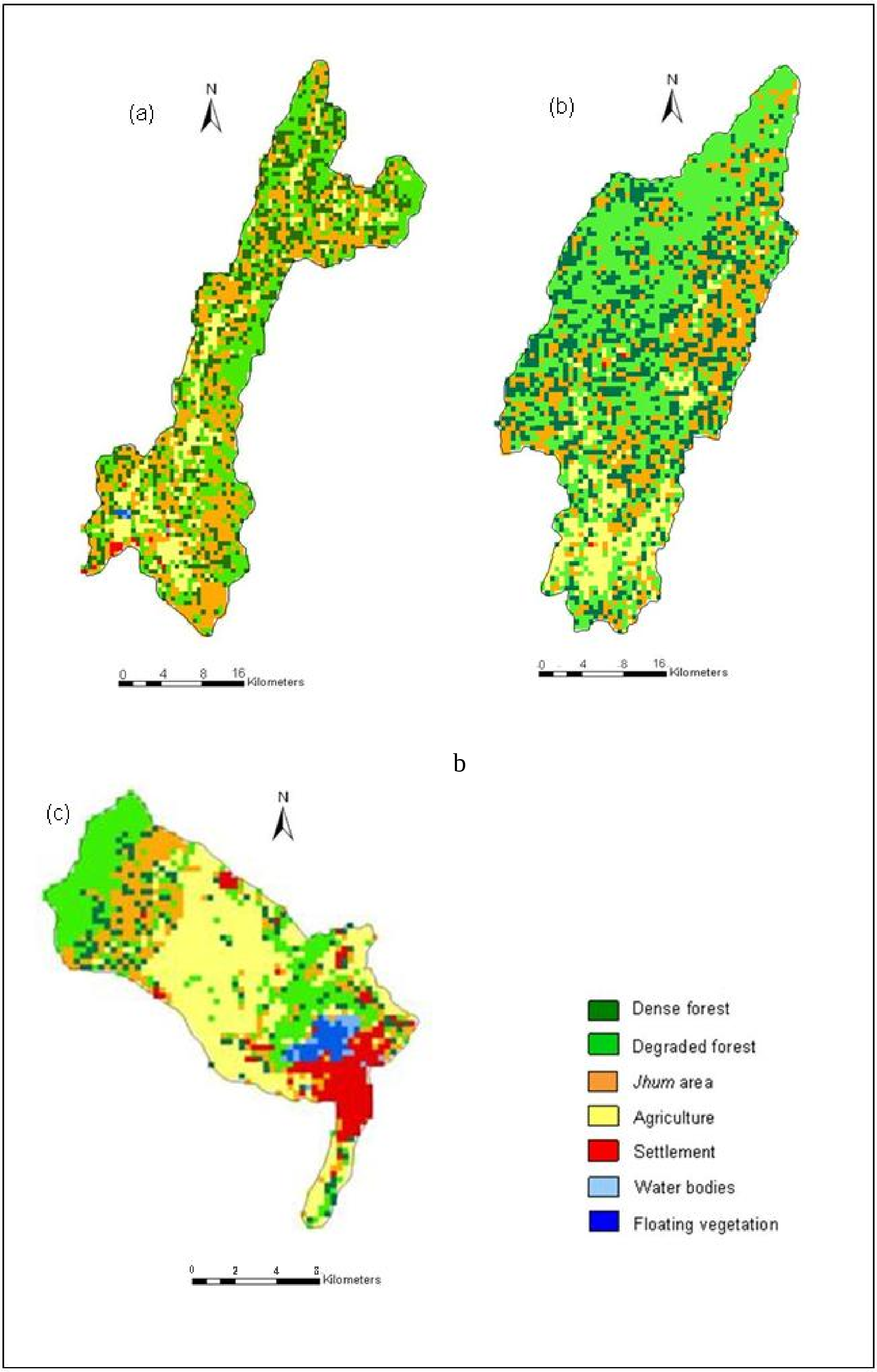


Figure 3.7. Resampled (600 m × 600 m) landuse maps (a)Thoubal sub-catchment, (b) Iril sub-catchment (c) Nambul sub-catchment

A vegetation property file was used to define the leaf area index (LAI) and root depth for dense forest, degraded forest, *jhum* areas, agriculture and *phumdis*. The areas under the settlement and water bodies were specified LAI and root depth values of zero throughout the simulation period. These LAI and root depth estimates were obtained from literature (Jain et al., 1992; FSI, 2003; WISA, 2005) and are shown in Figures 3.11 and 3.12. The LAI for dense forest, degraded forest and agriculture varies throughout the year. They have low LAI values during the dry months and gradually rise and attend their maximum values during the monsoon season as the seasonal growth pattern of the vegetations under this landuse categories are govern by the monsoon rainfall. The LAI values for *phumdis* also varies throughout the year, however this variation is main due to anthropogenic factors. After the monsoon season, the *phumdis* are harvest and in many cases burned by the local communities due to which the LAI values during these months were reduced. The *jhum* areas were specified a constant value of LAI throughout the year. The root depths for the dense forest, degraded forest, *jhum* area and the *phumdis* are keep constant throughout the year, while the root depth for the agriculture land cover varies slightly depending on the type of vegetation grown in the catchment area.

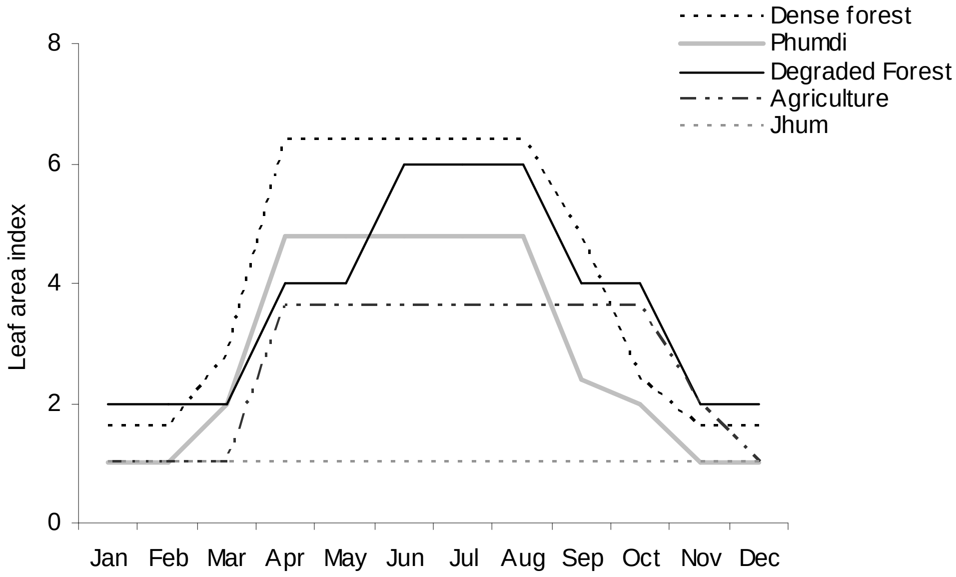


Figure 3.11. Leaf area index employed in the MIKE SHE modelling of Loktak sub-catchments

Evapotranspiration: Similar to precipitation, evapotranspiration is also time-varying as well as spatially distributed data. Evapotranspiration (PET) data procured from LDA for four meteorological stations (Section 2.3.2) were used as input data for the three MIKE SHE models. Daily evapotranspiration data for the period May 1999–June 2003 in DHI’s dfs0 format for the four stations were specified to the MIKE SHE models. The Thiessen polygons established in Section 2.3.2 (Figure 2.20) were employed to spatially distribute the PET throughout the modelled sub-catchments. Figure 3.13 demonstrates that the Iril sub-catchment is influenced by only the Dolaithabi station, while the Thoubal sub-catchment is influenced the Dolaithabi and Pallel stations. The Nambul sub-catchment is mainly influenced by the Dolaithabi station with a very small portion of the sub-catchment falling under the influence zone of the Komkeirap station.

River and Lakes: In this part of the modelling process, a stand alone MIKE 11 HD model of each sub-catchment was first developed, which was then linked to the MIKE SHE model. A shape file featuring the main river channel and its tributaries for each of the three rivers was initially specified in the MIKE 11 model. The river network, which was employed in the simulation of the MIKE 11 HD model, was then obtained by digitizing the main river channel and its major tributaries in the River Network Editor. The point which was used to define the branches of the rivers while digitizing becomes the H-point, the points where water level was estimated within the model. A balance was made during digitizing process between representation of the river network and the maximum number of H-points (250) that can be specific for efficient running of the model. One H-point was specified at the location of the stream gauging station in the sub-catchment and the river model extended a consistent distance (between sub-catchment river models) downstream from the gauging station. The main river channel and the branches (major tributaries) were digitized separately and then linked by branch connecting in the Network Editor. Figures 3.14, 3.15 and 3.16 shows the river network employed in the MIKE 11 HD model for the Thoubal, Iril and Nambul rivers. Chainages were provided for each ends of the main river channel as well as the branches. The chainage value of zero was provided for the most upstream point. The total length of the river network along with the number of branches within each MIKE 11 HD model of the three modelled Loktak sub-catchments are provided in Table 3.5. The boundary of the model was being specified as coupled using the conductivity of the

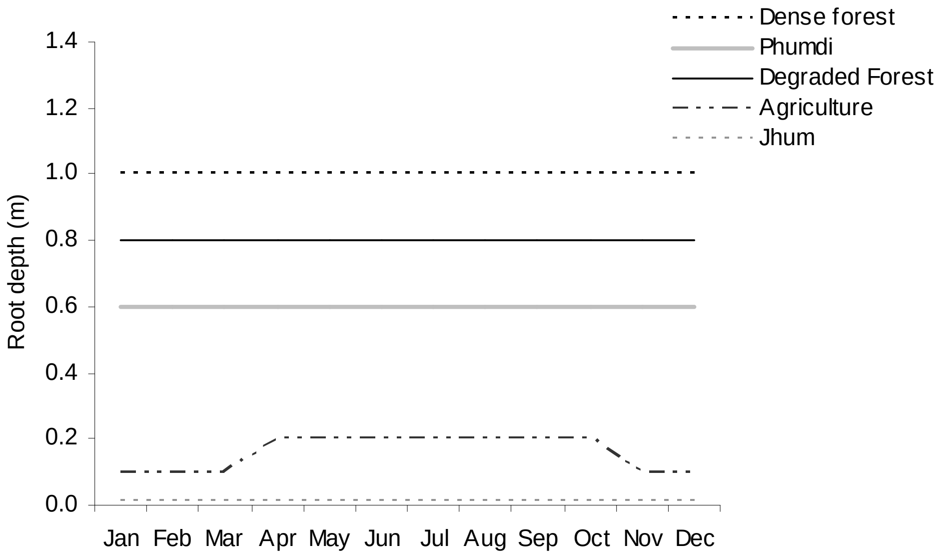


Figure 3.12. Root depth employed in the MIKE SHE modelling of the Loktak sub-catchments

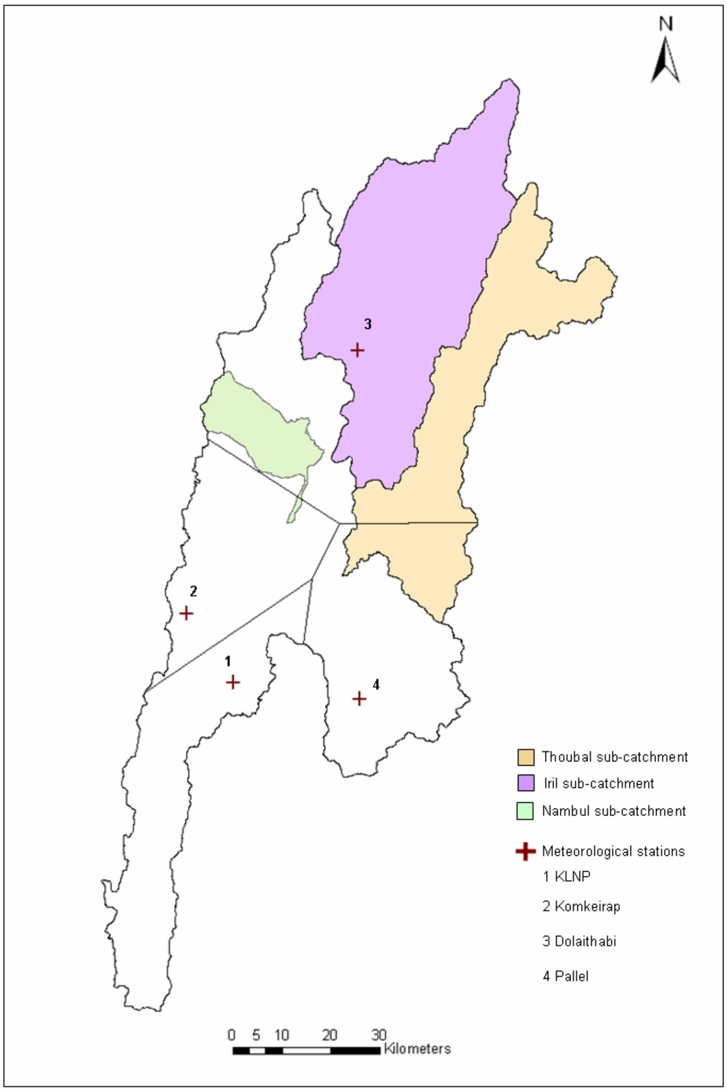


Figure 3.13. Thiessen polygons for evapotranspiration and modelled sub-catchments

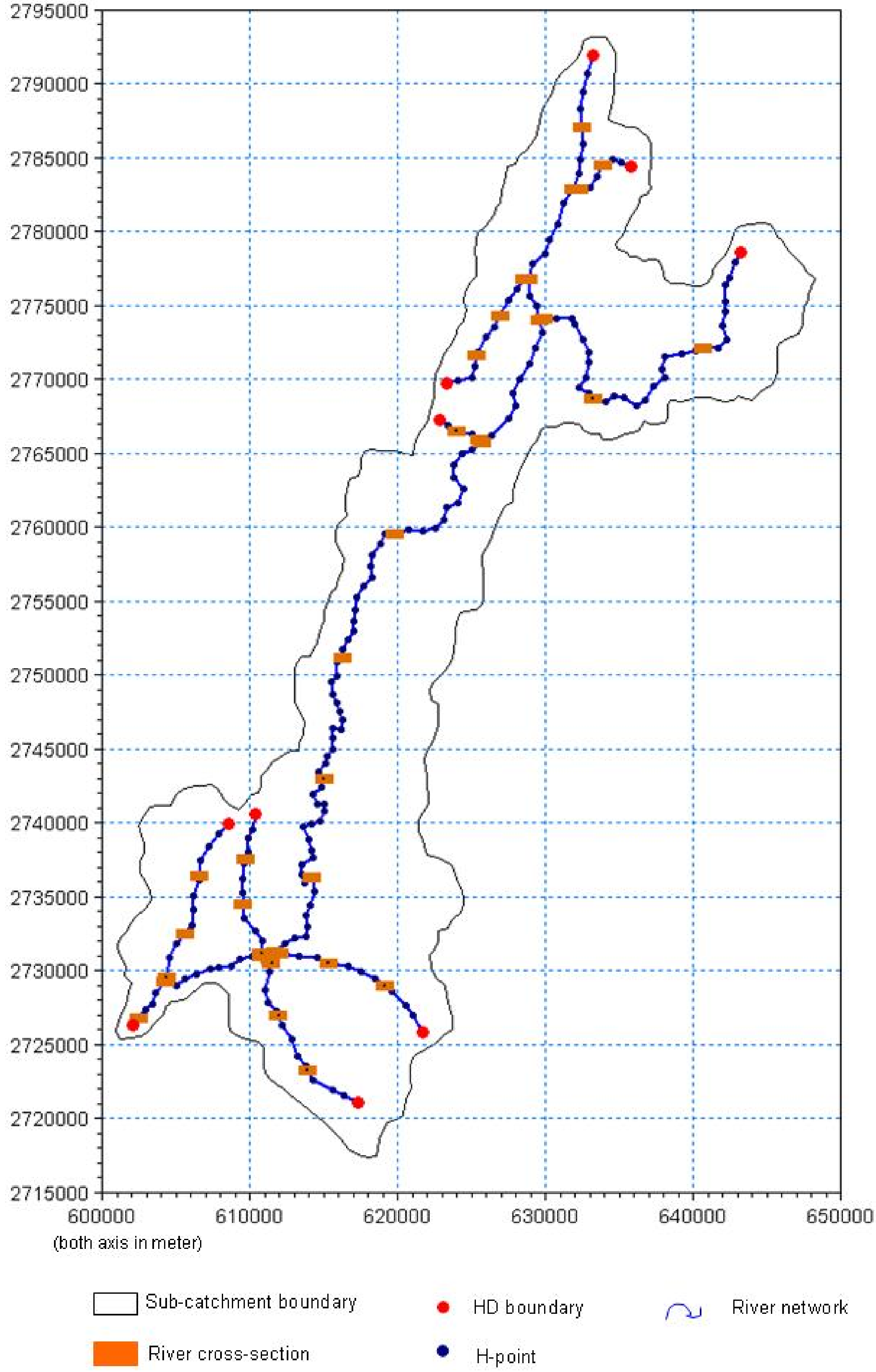


Figure 3.14. MIKE 11 model of the Thoubal River

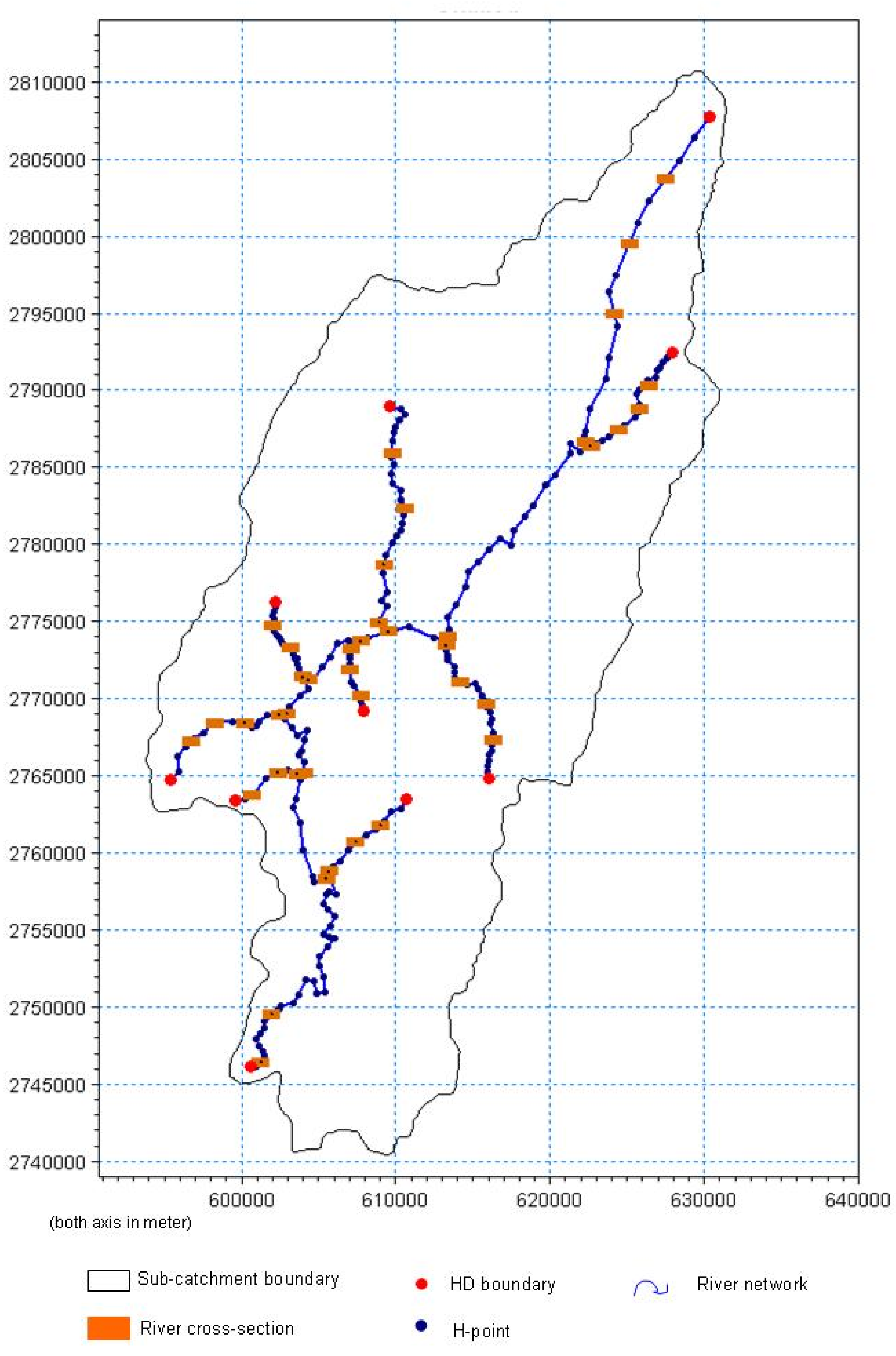


Figure 3.15. MIKE 11 model of the Iril River

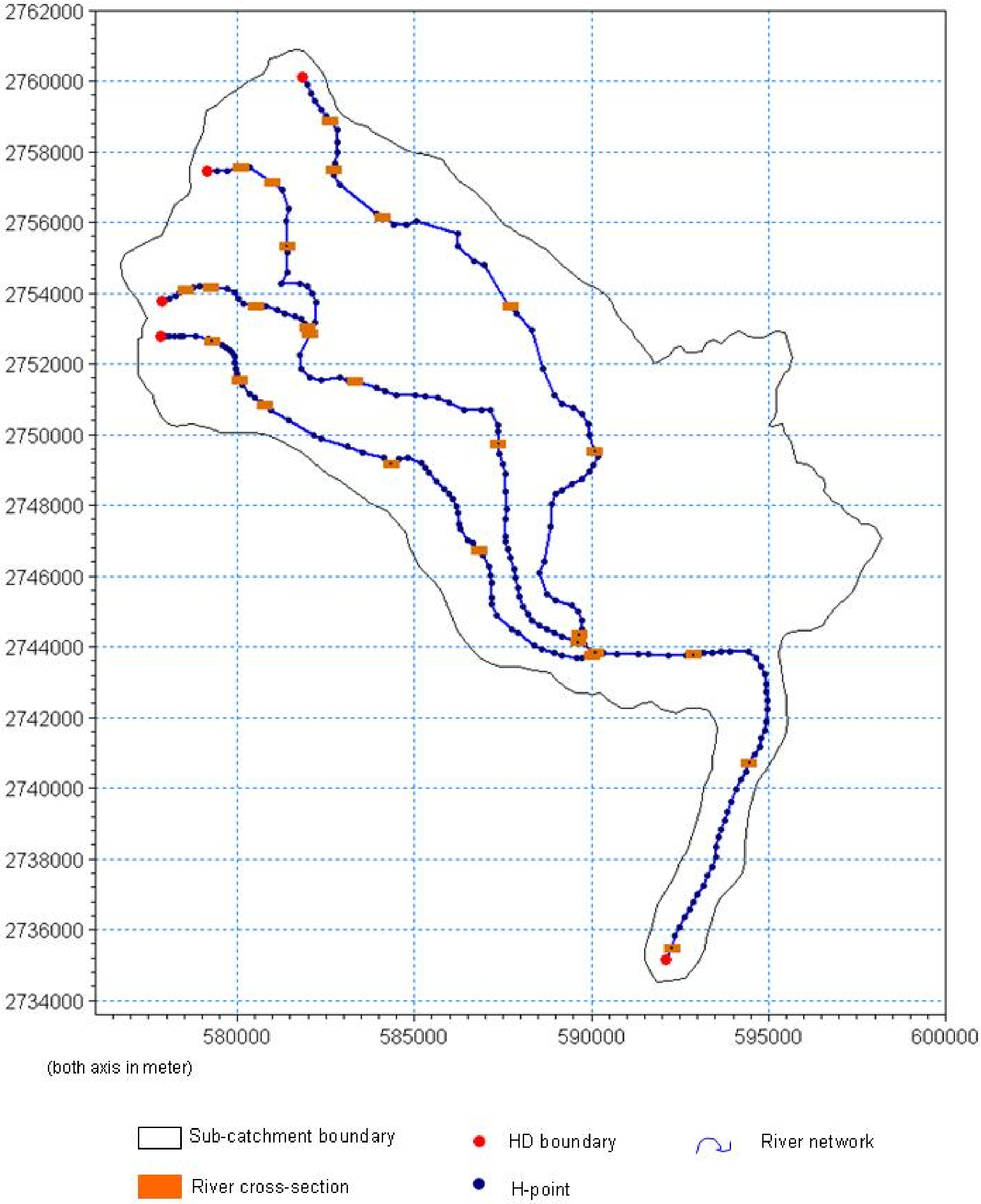


Figure 3.16. MIKE 11 model of the Nambul River

river bed material [Reduced contact (b)] and a leakage coefficient of 3×10^{-7} was applied throughout the river network owing to the clay lining of the river bed.

Table 3.5. Details of the river networks for Thoubal, Iril and Nambul MIKE 11 HD models

	Thoubal River	**Iril River**	**Nambul River**
Branches	9	9	4
Total length of the river network (km)	174	158	79
H-point	207	238	239
Total cross-sections	34	37	27
Surveyed	6	6	3
Synthetic	28	31	23
Upstream open boundary (m^3s^{-1})	0	0	0
Elevation of downstream head boundary (m amsl)	789.66	788.6	794.25

MIKE 11 HD models require a reasonably high number of river cross-sections along the main channel as well the branches to ensure the river elevations are representative of the surface topographic features. Due to limited availability of surveyed cross-section for all the three modelled sub-catchments synthetic cross-sections at various locations within the river network were developed. The widths and the depths of the synthetic cross-section were interpolated proportional to the distances between the available surveyed cross-sections and the location of the synthetic cross-sections. The number of cross-sections (surveyed and synthetic) for the Thoubal, Iril and Nambul rivers models is given in Table 3.5. As an example Figures 3.17 shows the cross-sections specified in the MIKE 11 HD model along the main river channel of Thoubal River. The locations of these cross-sections along the river network were then specified based on the chainage of the river network specified earlier. The locations of all the cross sections within the three MIKE 11 river models are shown in Figure 3.14, 3.15 and 3.16. The depths of the cross-sections were specified as depth relative to the top of the stream bank, whose elevations were extracted from the topographic grid specified within MIKE SHE. Figures 3.18, 3.19 and 3.20 present the longitudinal profile of the Thoubal, Iril and Nambul rivers respectively. All demonstrate a steep slope in the hilly areas and relatively flat profile on the valley.

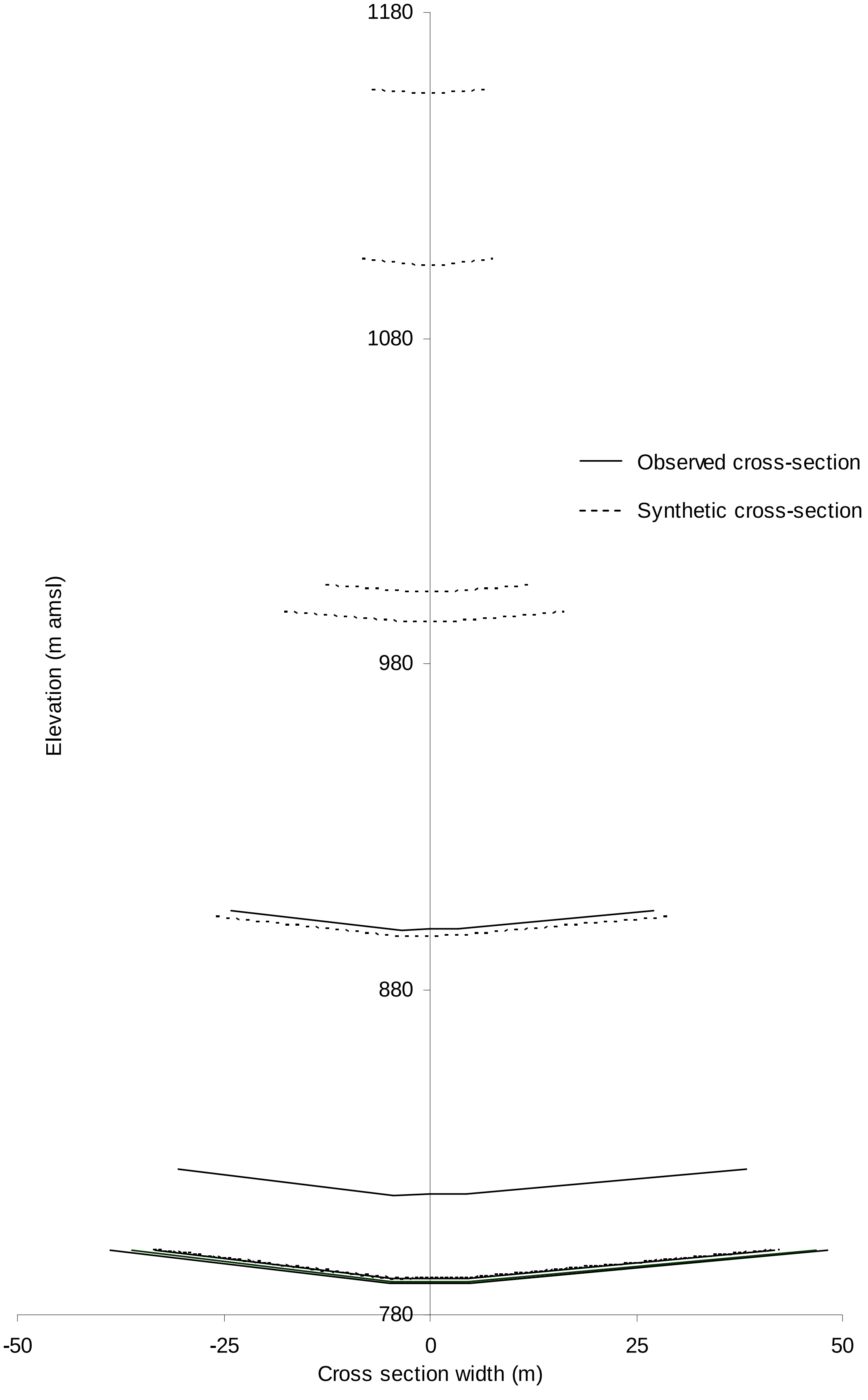
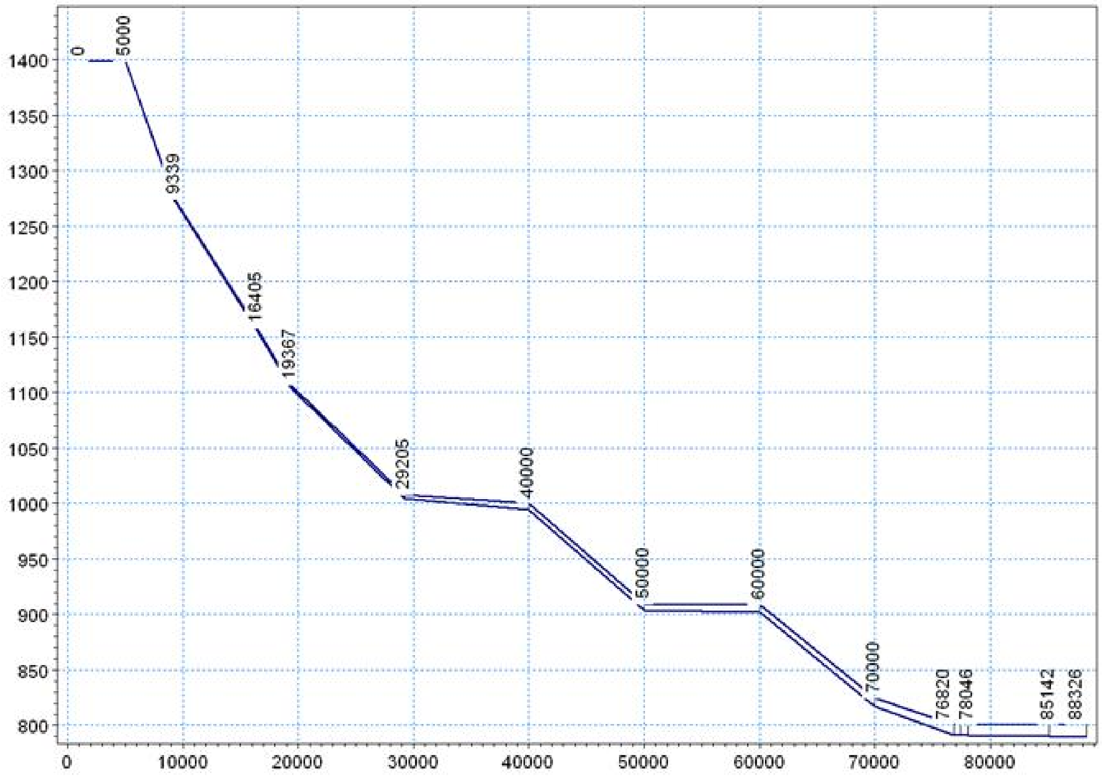


Figure 3.17. Cross-section details of the Thoubal River

A uniform Mannings's coefficient (n) for channel resistance of 0.035 was applied throughout the river network. This value is taken from the literature (Chow, 1959) based on the type of channel which is characteristically an earthen channel with stones and cobbles. Zero flow boundaries were applied to the upstream open ends of the main stream and each tributaries. The downstream open end of main channel was assigned a fix water-level boundary with a consistent depth (between the three sub-catchments) just above the river bed to ensure water flowing within the models is discharged with no drying out effect. The numbers of MIKE 11 H-points along the river network where water are transferred to adjacent MIKE SHE river links are provided in Table 3.5.



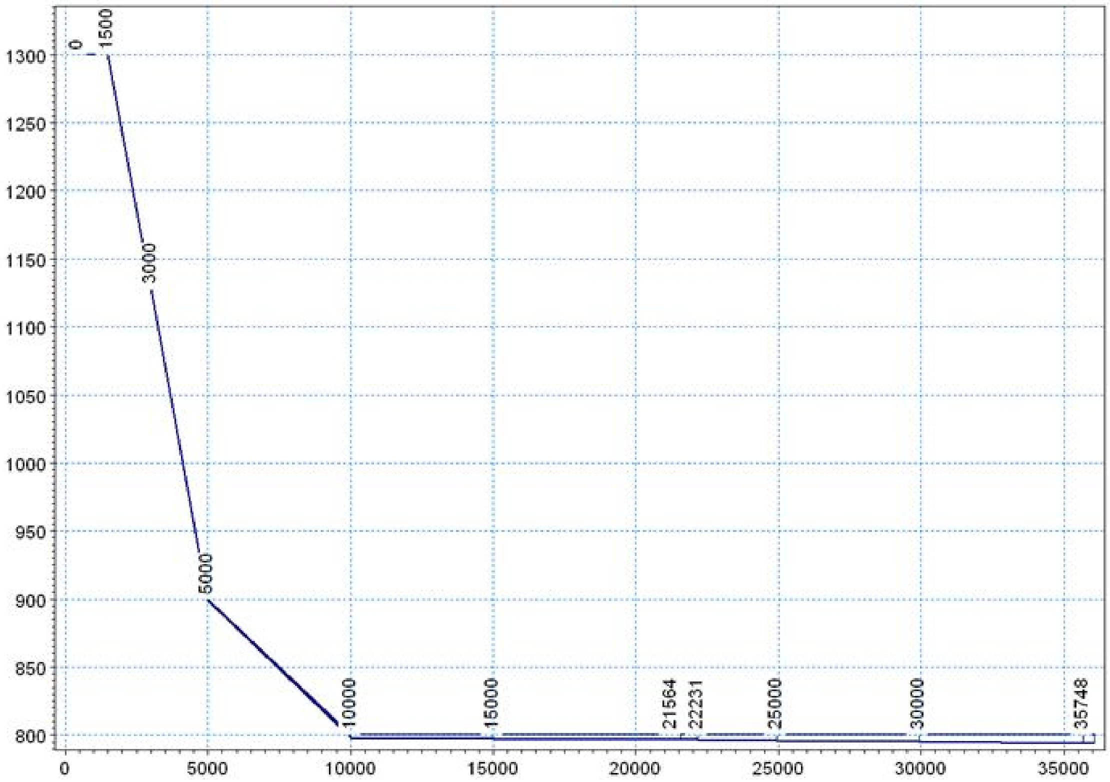
(Both axis in meter)

Figure 3.18. Longitudinal section of Thoubal River

Overland flow: The overland flow for the Thoubal, Iril and Nambul MIKE SHE model was estimated in the Overland Flow Module using the finite different method. The initial water depth on the ground surface was specified as zero. The detention storage was specified with a value of 0.01mm enabling more water to flow as overland flow. The topographic details which determine the route of the overland flow was provided by the processed topographic data specified within the MIKE SHE models. Initially a uniform Manning M value of 10 $m^{1/3}\ s^{-1}$ was specified into the model which was later modified during the calibration process.

(Both axis in meter)

Figure 3.19. Longitudinal section of Iril River



(Both axis in meter)

Figure 3.20. Longitudinal section of Nambul River

Unsaturated flow: As discussed in Section 2.2.4, soil in the Loktak sub-catchments is dominantly clayey rich alluvium, which is considerably thick, compact and relatively impermeable (1×10^{-8} ms^{-1}, Environment and Forests Department, 2007). The clay content in the soil is high comprising 62.6% of the soil texture (NBSS and LUP, 2001). The soil was represented as a single layer in which the same hydraulic parameter was employed throughout the model domain. A similar approach was adopted by Thompson et al. (2004). Therefore, the two-layer water balance method, which uses a uniform soil, was employed to estimate the unsaturated flow in all three Loktak sub-catchment MIKE SHE models. An infiltration rate of 1.4×10^{-7} ms^{-1} was initially assigned based on literature (PWD, 1967; Brouwer et al., 1988), and was modified during the calibration process. The soil water content at saturation, field capacity and field wilting point were specified as 0.4, 0.3 and 0.2 respectively. These values are taken from literature (Brouwer et al., 1985; Jain et al., 1992; IAEA, 2008).

Saturated Zone: In the absence of detailed hydrogeological information and given the focus of representing sub-catchment outflow rather than detailed groundwater level fluctuations, a single uniform saturated zone layer up to a depth of 100 m thick was specified and the saturated flow estimated employing the 3-D finite difference method. An initial hydraulic conductivity of 1×10^{-8} ms^{-1} was specified for both vertical and horizontal conductivity. These two parameters were later used as calibration terms. An outer boundary defined by the model domain was specified with a zero flux (no-flow) boundary condition.

3.4.2. Model calibration

Refsgaard and Storm (1995) suggested that the number of parameters subjected 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). The initial values of the calibration parameters given in Table 3.6, were obtained from the literature (Chow, 1959; PWD, 1967; Bear, 1972; Brouwer et al., 1988

Table 3.6. Initial and final calibrated values

Model	**Parameter**	**Initial value**	**Final calibration value**
MIKE SHE	Hydraulic conductivity (Vertical)	1e-008 ms^{-1}	2e-007 ms^{-1}
	Hydraulic conductivity (Horizontal)	1e-008 ms^{-1}	1e-007 ms^{-1}
	Overland flow resistance (Manning's M)	10 m$^{1/3}$ s^{-1}	27 m$^{1/3}$ s^{-1}
	Unsaturated zone infiltration rate	1.4e-007 ms^{-1}	2e-008 ms^{-1}
MIKE 11	Bed resistance of the stream channel (Manning's n)	0.035 s m$^{-1/3}$	0.04 s m-$^{1/3}$

As discussed in the pervious section, initially the Thoubal sub-catchment model was calibrated and the values of calibration terms were then applied to the Iril and Nambul models for validation. Calibration of the Thoubal sub-catchment model was carried out through a manual iterative procedure. The performance of each model run was assessed based on a graphical comparison of observed and simulated discharge at the sub-catchment outlet (the Thoubal Bridge gauging station) and widely used statistical measures of model performance 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; Thompson et al., 2004; Krause et al., 2005; Das et al., 2008) and the correlation coefficient (R) (Weglarczyk, 1998; Yang et al., 2001, 2002). Similar to pervious modelling experiences (e.g. Jain et al., 1992; Thompson et al., 2004), the Thoubal model was most sensitive to changes in hydraulic conductivity (both vertical and horizontal). Therefore, the initial calibration model runs were carried out by modifying the hydraulic conductivity and subsequent fine tuning was undertaken by modifying overland flow resistance, unsaturated zone infiltration rate and bed resistance of the stream channel. The final values of the calibration parameters are shown in Table 3.6.The percentage difference in the observed and simulated mean daily flow (D*v*) was also estimated.

Figure 3.21 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 the magnitude of the largest peaks during the monsoon period was slightly underestimated. The average of 20 largest peak discharges was simulated to be 4% lower than the observed (observed: 267.72 m^3s^{-1}; simulated: 257.34 m^3s^{-1}).

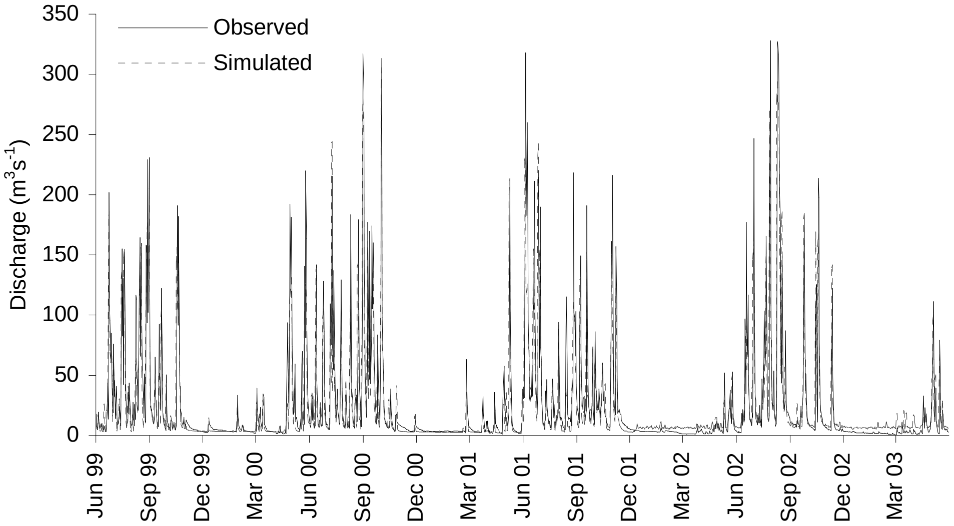


Figure 3.21. Comparison of daily flows of observed and simulated discharge for Thoubal sub-catchment (June 1999–May 2003)

During the last two dry seasons, simulated baseflow exceeds the observed, although a good representation of flows during this time of year was 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 overestimation of baseflow is evident (Figure 3.22). The low flow (Q95) was simulated to be higher by 1.18 m^3s^{-1} (observed: 1.51 m^3s^{-1}; simulated: 2.69 m^3s^{-1}). Figure 3.23 demonstrates that the model provides a good representation of mean monthly discharge albeit with the slight underestimation of peak flows and marginally higher baseflows. The highest mean monthly discharge was observed during August, which the model tends to simulate slightly lower by 2.72 m^3s^{-1} (observed: 62.21 m^3s^{-1}; simulated: 60.49 m^3s^{-1}) while the lowest observed during January was simulated slightly higher by 1.29 m^3s^{-1} (observed: 3.54 m^3s^{-1}; simulated: 5.34 m^3s^{-1}).

Table 3.7, summarizes the values of statistical measures model performance and confirms the ability of the model with R2 and R estimated as high as 0.86 and 0.95 respectively. The deviation in simulated mean daily flow from observed mean daily flow was estimated to be just 2%. Using the classification scheme of Henriksen et al. (2008) the performance of the model is classed as “excellent” (Table 3.7).

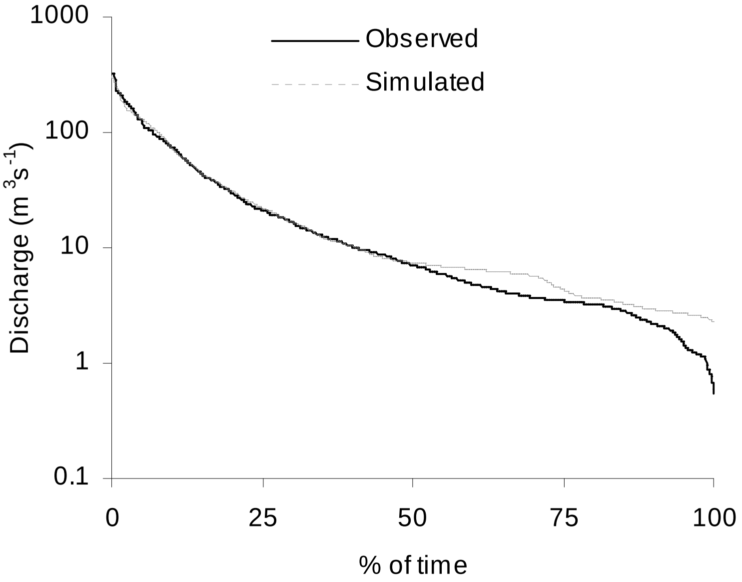


Figure 3.22. Comparison of flow duration curve of observed and simulated discharge for Thoubal sub-catchment (June 1999–May 2003)

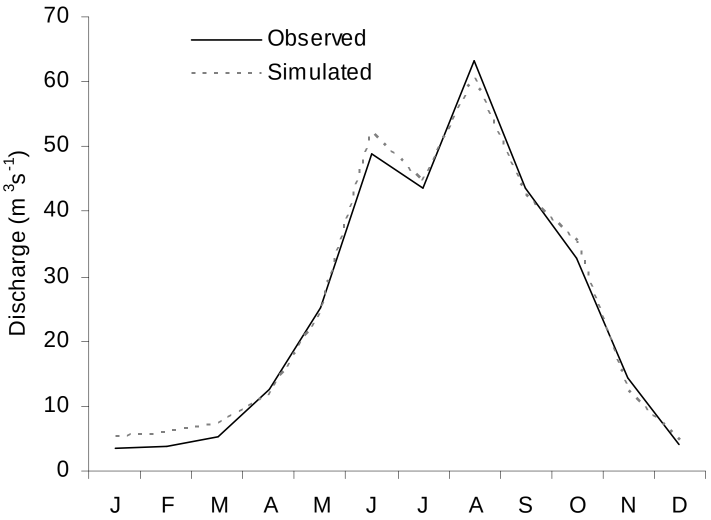


Figure 3.23. Comparison of mean monthly flow of observed and simulated discharge for Thoubal sub-catchment (June 1999–May 2003)

Table 3.7. Statistical measures of model performance of calibration

Model	**MDFo[a] (m^{3}s^{-1})**	**MDFs[b] (m^{3}s^{-1})**	**D*v*[c] (%)**	**R2**	**R**
Thoubal sub-catchment	25.2	25.7	2.0 ☆☆☆☆☆	0.86 ☆☆☆☆☆	0.95
Performance indicator[d]	**Excellent** ☆☆☆☆☆	**Very good** ☆☆☆☆	**Fair** ☆☆☆	**Poor** ☆☆	**Very poor** ☆
D*v*	< 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).

3.4.3. Model validation

The validation of the model was carried out by specifying the final calibrated parameters of the Thoubal MIKE SHE model provided in Table 3.6, within the Iril and Nambul MIKE SHE models. The basis for validating the model was by graphical comparison of observed and simulated discharges at the sub-catchment outlets (Moirang Kampu and Hiyangthang gauging stations, respectively) as well as the statistical measures of model performance discussed in the previous section.

Figure 3.24 shows the observed and simulated discharge for the Iril sub-catchment for the period June 1999–May 2003. It demonstrates a good agreement between the simulated and observed daily flows. Similar to the Thoubal model, the Iril model also provides a good sequencing of peak flows although there is slight overestimation in the magnitude of the largest peaks during the monsoon period. The average of 20 largest peak discharges was simulated to be 1% higher by the model (observed: 266.96 m^3s^{-1}; simulated: 270.34 m^3s^{-1}). The Iril model performance is particularly good for high flows, although lower flows are slightly underestimated (Figure 3.25). Figures 3.26 demonstrate that the model provides a good representation of mean monthly discharge. The model marginally overestimates the peak monthly discharge in August, by 1.73 m^3s^{-1} (observed: 68.40 m^3s^{-1}; simulated: 70.13 m^3s^{-1}) as well as the lowest discharge in January by 0.86 m^3s^{-1} (observed: 2.67 m^3s^{-1}; simulated: 3.53 m^3s^{-1}). The Nash-Scutcliffe coefficient (R2) for the Iril sub-catchment is 0.84 while the correlation coefficient (R) is 0.93 (Table 3.8). The deviation in simulated mean daily flow from observed mean daily flow is very small (0.7%). Based on the model performance scheme of Henriksen et al. (2008), the performance of the Iril model can be classified as "excellent".

Figure 3.27 shows the observed and simulated discharge for the Nambul sub-catchment for the period June 1999–May 2003. It again demonstrates a good agreement between the simulated and observed daily flows. Good sequencing of peak flows is achieved. The flow duration curve (Figure 3.28) demonstrates the MIKE SHE model the sub-catchment perform well for high flows, although lower flows are slightly overestimated. The low flows (Q95) was simulated to be higher by 0.24 m^3s^{-1} (observed: 0.13 m^3s^{-1}; simulated: 0.37 m^3s^{-1}).

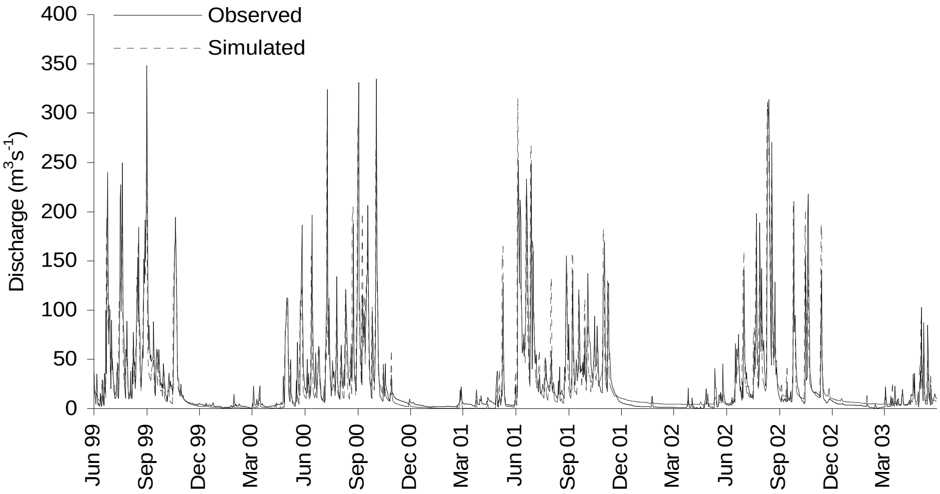


Figure 3.24. Comparison of daily flows of observed and simulated discharge for Iril sub-catchment (June 1999–May 2003)

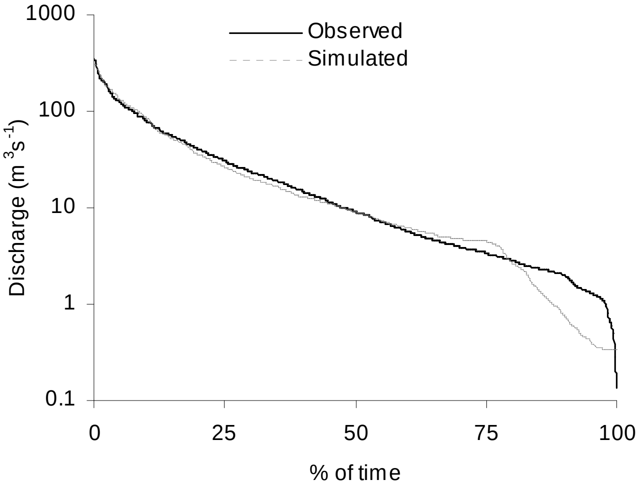


Figure 3.25. Comparison of flow duration curve of observed and simulated discharge for Iril sub-catchment (June 1999–May 2003)

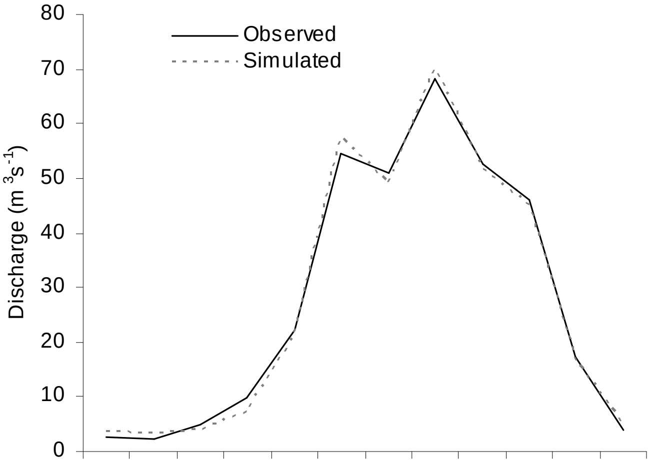


Figure 3.26. Comparison of mean monthly flow of observed and simulated discharge for Iril sub-catchment (June 1999–May 2003)

Table 3.8. Statistical measures of model performance for validation

Model	MDFo[a] (m^3s^{-1})	MDFs[b] (m^3s^{-1})	D*v*[c] (%)	R2	R
Iril sub-catchment	28.1	27.9	0.7 ☆☆☆☆☆	0.84 ☆☆☆☆	0.93
Nambul sub-catchment	5.2	5.5	5.4 ☆☆☆☆	0.82 ☆☆☆☆	0.91

Performance indicator[d]	**Excellent** ☆☆☆☆☆	**Very good** ☆☆☆☆	**Fair** ☆☆☆	**Poor** ☆☆	**Very poor** ☆
D*v*	< 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).

Figures 3.29 demonstrate that the model provides a good representation of mean monthly discharge albeit slightly overestimating the low flows during January–May. The lowest mean monthly discharge is observed during January, which the model overestimates by 0.44 m^3s^{-1} (observed: 0.30 m^3s^{-1}; simulated: 0.74 m^3s^{-1}) while the highest observed discharge during August is simulated very well (observed: 12.09 m^3s^{-1}; simulated: 12.04 m^3s^{-1}). The Nash-Scutcliffe coefficient (R2) is 0.82 while the correlation coefficient (R) is 0.91. The deviation in simulated mean daily flow from observed mean daily flow is estimated to be 5.4% (Table 3.8).According to the statistical measures of model performance (Table 3.8) Nambul MIKE SHE model can be classified as either “very good”.

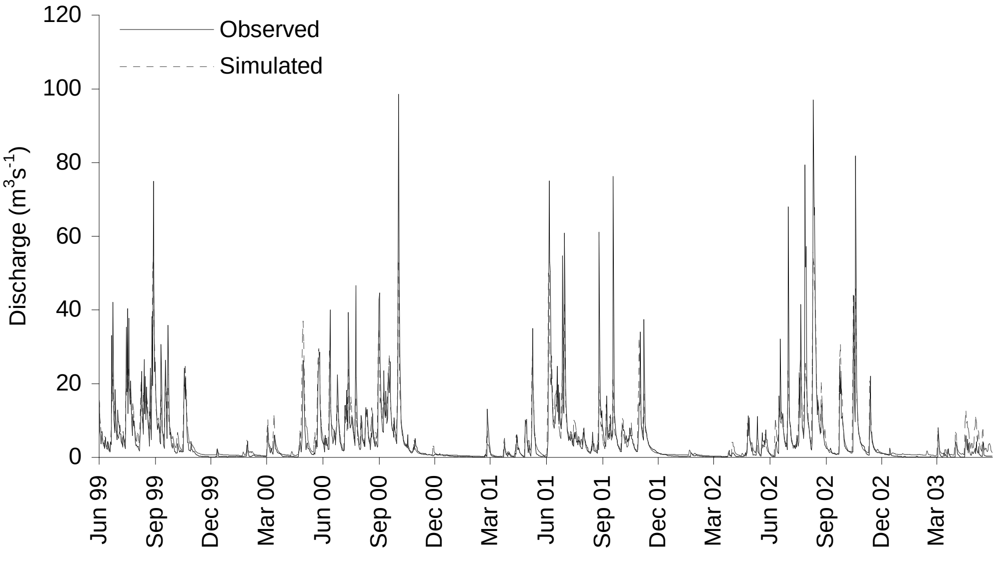


Figure 3.27. Comparison of daily flows of observed and simulated discharge for Nambul sub-catchment (June 1999–May 2003)

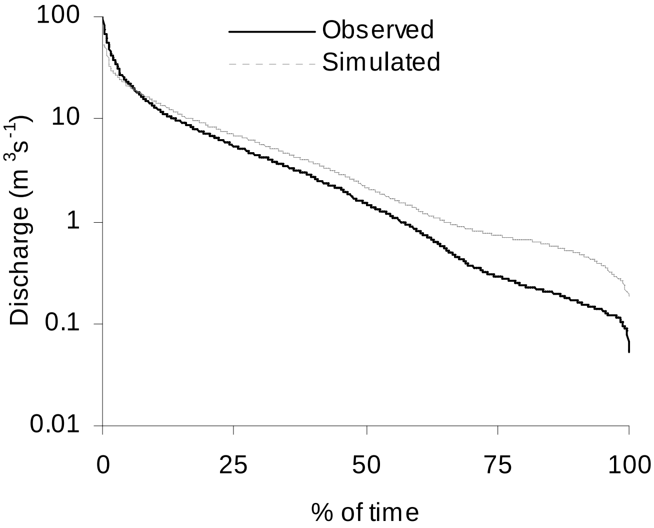


Figure 3.28. Comparison of flow duration curve of observed and simulated discharge for Nambul sub-catchment (June 1999–May 2003)

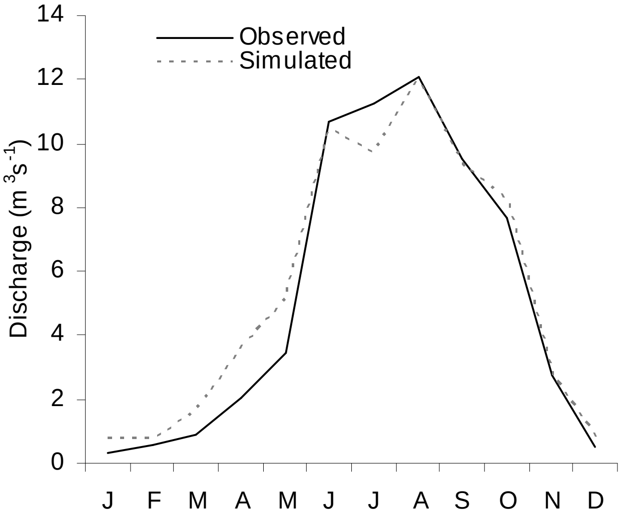


Figure 3.29. Comparison of mean monthly flow of observed and simulated discharge for Nambul sub-catchment (June 1999–May 2003)

3.5. Estimation of runoff for ungauged sub-catchments

The incomplete spatial coverage of the data employed within the models of the three gauged sub-catchment for the ungauged sub-catchments restricted the extension of modelling approaches to the ungauged sub-catchments. For example, no information on the channel networks were available within the ungauged sub-catchments, In addition, the Western sub-catchment comprises of more than 20 streams and rivulets which would require individual models potentially with much smaller grid sizes than those employed for the models of the gauged catchments. Therefore, an alternative weighting by area method was employed to estimate the discharges for the ungauged catchments.

The discharge from ungauged sub-catchments (Imphal, Kongba, Khuga and Western sub-catchment excluding Nambul) were estimated by weighting the simulated discharge by catchment area of the nearest MIKE SHE modelled sub-catchments (Thoubal, Iril and Nambul). The area ratio, which is defined as the ratio of the catchment area of the ungauged catchment to the nearest gauged catchment, were estimated for all ungauged sub-catchments. Table 3.9 provides the area ratio of all four ungauged sub-catchments which currently provide water to Loktak Lake. As discussed in Section 2.2.1, the Heirok and Sekmai are excluded due to the diversion of the water away from the lake. This area ratio was then multiplied by daily simulated discharge of the nearest modelled sub-catchment to compute the daily discharge from the ungauged sub-catchments.

As demonstrated in Table 3.9, the daily discharge of Imphal and Kongba sub-catchments are estimated by multiplying the area ratio by the daily simulated discharge of the Iril sub-catchment, while for the Khuga and Western sub-catchments the area ratio to the Nambul sub-catchment is used. The Thoubal sub-catchment, due to its position on the far east of the catchment and so relatively remote from other sub-catchments are not used in the estimation of discharge from any of the ungauged sub-catchment. Figure 3.30 shows the daily discharge of the Imphal, Kongba, Khuga and Western sub-catchments for the period June 1999–May 2003. Owing to its catchment area, the Western sub-catchment has the highest mean daily discharge (26.1 m^3s^{-1}), while the Khuga sub-catchment the lowest (2.5 m^3s^{-1}; Table 3.9).

In order to assess the validity of the weighting by area method employed for estimating the runoff from the ungauged sub-catchments mean daily discharges for the Nambul sub-catchment computed using both the Nambul MIKE SHE model and the weighting by area method using the simulated discharge of calibrated Thoubal model were compared. Using the Nambul MIKE SHE model, the mean daily discharge was estimated to be 5.5 m^3s^{-1} while employing the weighting by area method it was 5.1 m^3s^{-1}. This small difference (0.4 m^3s^{-1}) in the two estimates adds confidence on the approach adopted to estimate discharges from ungauged sub-catchments.

Table 3.9. Area ratio of the gauged and un-gauged sub-catchments

Ungauged sub-catchment	**Area (km^2)**	**Nearest gauged sub-catchment**	**Area (km^2)**	**Area Ratio**	**Mean daily discharge (m^3s^{-1})**
Imphal	354	Iril	1271	0.28	7.8
Kongba	120	Iril	1271	0.09	2.5
Khuga	504	Nambul	178	2.83	15.4
Western	851	Nambul	178	4.78	26.1

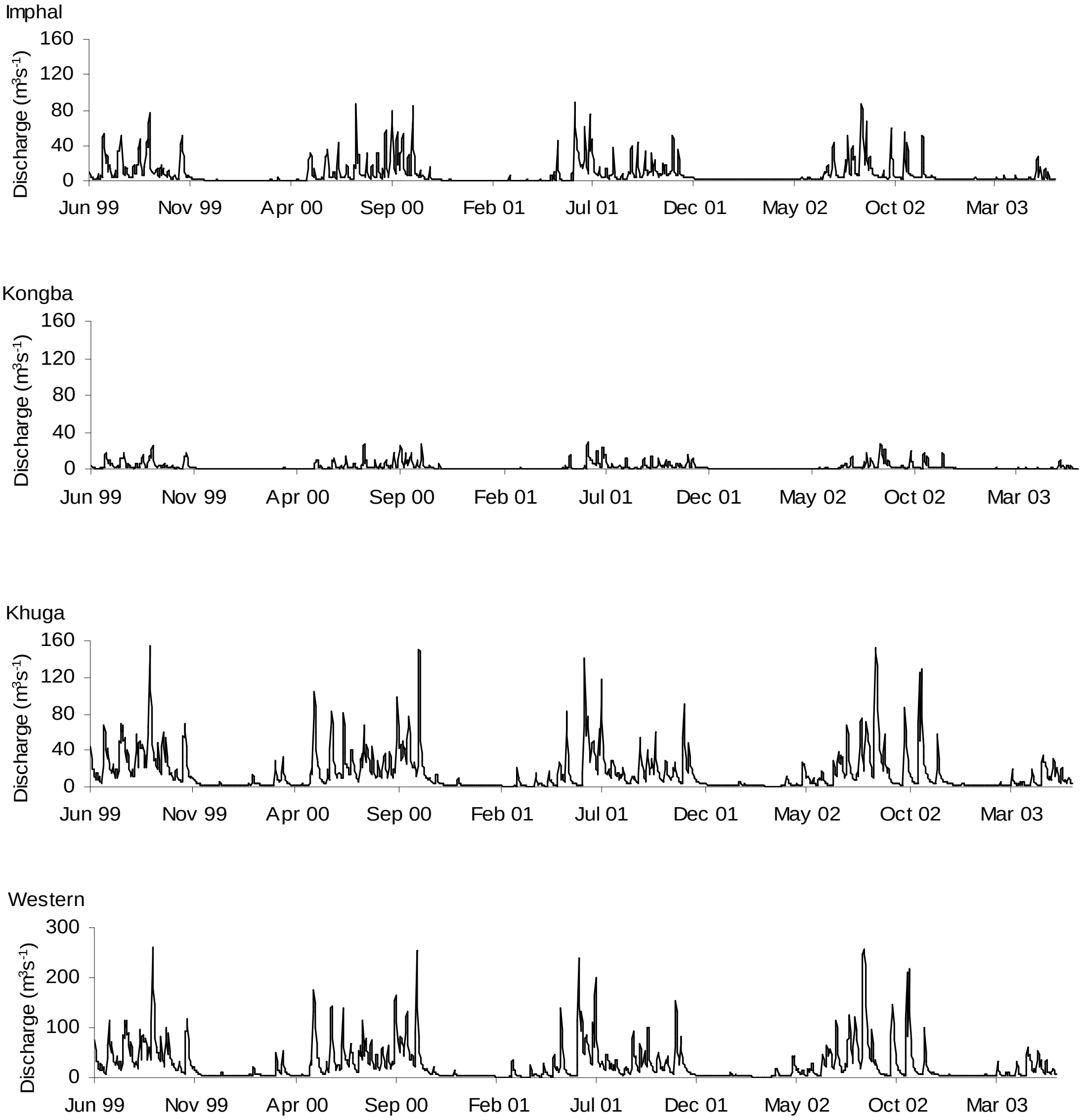


*Figure 3.30. Daily discharge in ungauged sub-catchments of Loktak Lake (June 1999–May 2003). * Note the different y-axis.*

Figure 3.31 presents the mean monthly discharge of the four ungauged sub-catchments. It shows a similar discharge pattern with high monsoon discharges and low dry season flows across all the four sub-catchments. The peak flow is observed during August for all the sub-catchments.

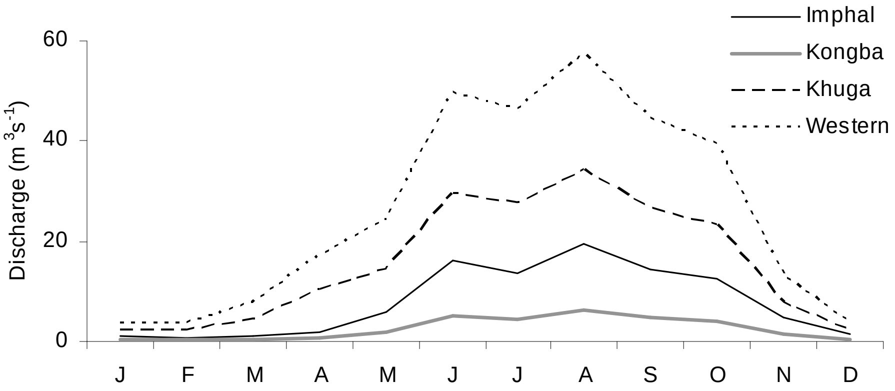


Figure 3.31. Mean monthly discharge in ungauged sub-catchments of Loktak Lake (June 1999–May 2003

3.6. Summary

This chapter has shown that the catchment models simulated using the MIKE SHE modelling system successfully reproduce observed discharges for three sub-catchments draining to Loktak Lake (Thoubal, Iril and Nambul). The performance of the three models can be classified as either “excellent” or “very good”. The application of calibration parameter values from one sub-catchment model (Thoubal) to the models of the other sub-catchments and the results of good model performance suggest a robust calibration. Based on these simulated discharges, the runoff from the ungauged sub-catchments (Kongba, Imphal, Khuga and the Western sub-catchment) have subsequently been estimated. These newly generated runoff data for the seven sub-catchments are further employed in the development of the water balance model of the Loktak Lake, which is discussed in the following chapter.

Chapter 4 -Water Balance Model of Loktak Lake

4.1. Introduction

The chapter presents the water balance model developed for Loktak Lake and its validation. The components of the lake's water balance and their significance for the hydrology of the lake are discussed.

4.2. Water balance model

The water balance of Loktak Lake can be defined as the balance of different inflows and outflows of water to and from the lake. Inflows into the lake are provided by direct precipitation onto the lake surface and runoff from the sub-catchments that drain into the lake. Outflows of water occur through evapotranspiration from the *phumdis*, evaporation from the open water surface of the lake, barrage releases and abstractions for agriculture, domestic consumption and hydropower generation. Given the heavy, impermeable clays underlying the lake, groundwater exchanges were assumed to be small and have been excluded from the model. Due to constraints on the availability of data for some water balance components, the model was developed on a monthly basis for the period June 1999–May 2003. Equation 4.1 summaries the water balance of Loktak Lake.

$$V_t = V_{t-1} + (P_t \times A_{t-1}) + R_t - (ET_t \times AP) - (E_t \times (A_{t-1} - AP)) - AbsI_t - AbsD_t - AbsH_t - O_t \qquad (4.1)$$

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 the volume-level relationship developed in Section 2.5.3.
t	indicates current month.
t-1	indicates previous month.
P	is the direct precipitation onto the lake based on rain gauge records from the KLNP meteorological station which is located close to the edge of the lake.
A	is the area of Loktak Lake calculated from the volume-area relationship developed in Section 2.5.3.
R	is the discharge from the sub-catchments 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 in Chapter 3.

ET	is evapotranspiration provided by the LDA (Penman-Monteith method).
E	is open water pan evaporation from the KLNP meteorological station.
AP	is the area of *phumdis* (135 km^2, Trisal and Manihar, 2004).
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). These abstractions are only possible when lake level exceed the minimum drawdown level (MDL) of 766.26 m amsl (equivalent to $94.6 \times 10^6 m^3$) and are therefore not abstracted when simulated water levels are below this threshold.
AbsD	is abstraction for domestic consumption by rural communities on and around the lake and urban communities (including Imphal city) from estimates from IFCD (1987), Government of India (1999) and Government of Manipur (2002).
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 agriculture abstractions.
O	is outflow from the lake provided by releases from the Ithai Barrage and based on records from the NHPC.

4.2.1. Model results

Figure 4.1 presents the simulated monthly water volume of the lake estimated using Equation 4.1 during June 1999–May 2003. The simulated monthly lake volumes are converted to corresponding lake levels using the volume-level relationship described in Section 2.5.3. Figure 4.2 shows the simulated lake water level from the water balance model. The simulated lake water level neither exceeded the FRL nor goes below the MDL throughout the simulation period signifying the structural safety of the barrage as well as availability of adequate water in the lake to meet the demands from various stakeholders. However, the simulated water level exceeded the FL for 19 of the 48 months simulation period indicating severe flooding to the surrounding areas of the lake.

The monthly simulated and the observed lake level at Ningthoukhong by LDA for the period June 1999–May 2003 as shown in Figure 4.2 demonstrate a good agreement between the observed and simulated lake levels, which on average differ by only 0.02 m (observed mean: 768.35 m amsl, simulated mean 768.37 m amsl). The monthly mean water levels, observed and simulated, for the study period is shown in Figure 4.3. It also demonstrates a good agreement between the mean monthly observed and the simulated water level, although, the model tends to over-estimate water level in the lake during March–August with the largest over-estimate of 0.22 m. During September–February it tends to under-estimate with the largest by 0.14 m during November (Table 4.1). Statistical comparisons of observed and simulated lake water levels yield values of the correlation coefficient (R; Weglarczyk, 1998; Yang et al., 2001, 2002) of 0.81 (Figure 4.4) and Nash–Sutcliffe coefficient (R2; Nash and Sutcliffe, 1970; Garrick et al., 1978: Xiong and Gou, 1999; Andersen et al., 2001; Yang et al., 2001) 0.80 respectively. The good agreement between observed and the simulated lake levels is further evident in Figure 4.4. According to the criteria used for statistical measures of model performance as described in Section 3.4.2, performance of the water balance model can be considered to be very good. These results add confidence in the approach used to evaluate discharges from the ungauged sub-catchments contributing to Loktak Lake because of the fact that, despite using no calibration factor, the water balance model is able to simulate water levels, which are very similar to the observed water levels.

Table 4.1. Observed mean monthly water level and simulated mean monthly water level

Month	Observed water level (m amsl)	Modelled water level (m amsl)	Difference (m)
January	768.27	768.17	0.10
February	768.06	767.99	0.07
March	767.89	767.94	-0.06
April	768.01	768.15	-0.15
May	768.11	768.26	-0.15
June	768.27	768.49	-0.22
July	768.52	768.59	-0.07
August	768.83	768.88	-0.06
September	768.96	768.95	0.01
October	768.84	768.82	0.02
November	768.67	768.54	0.14
December	768.47	768.34	0.13

The lake surface area (A) varies throughout the year depending on the volume of water. The lake surface area for a given month is estimated based on the volume of water it holds during the previous month. For each step of the model, the lake surface area is estimated employing a 3rd order polynomial fit derived using the volume-area relationship previously developed in Section 2.5.3.

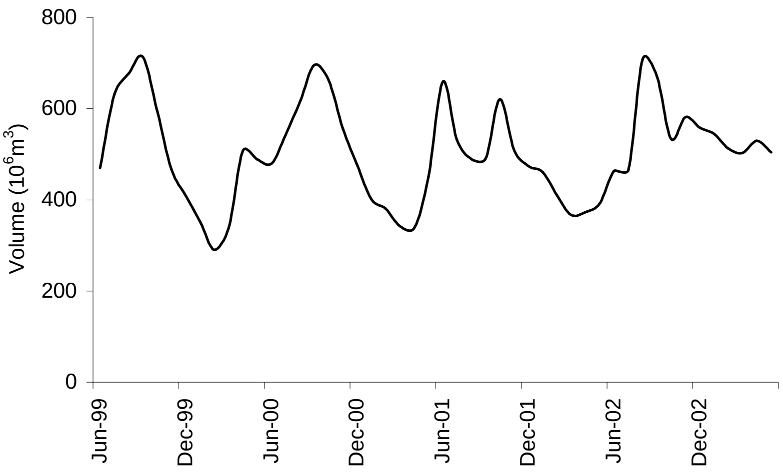


Figure 4.1. Simulated water volume of Loktak Lake (June 1999–May 2003)

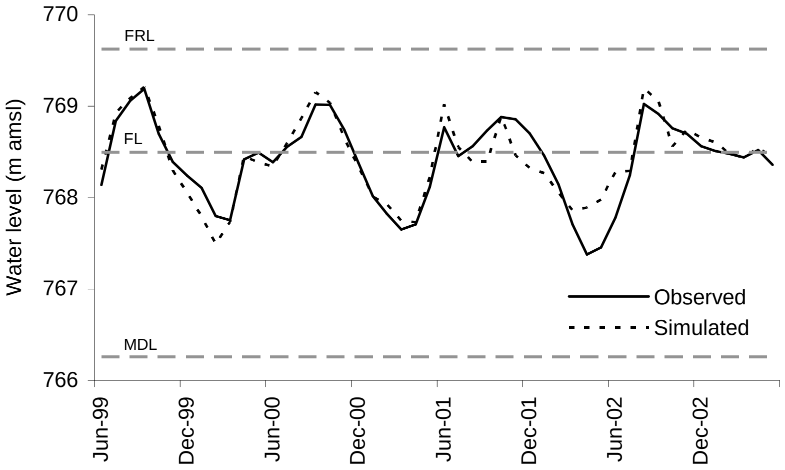


Figure 4.2. Observed water level Vs simulated water level (June 1999–May 2003)

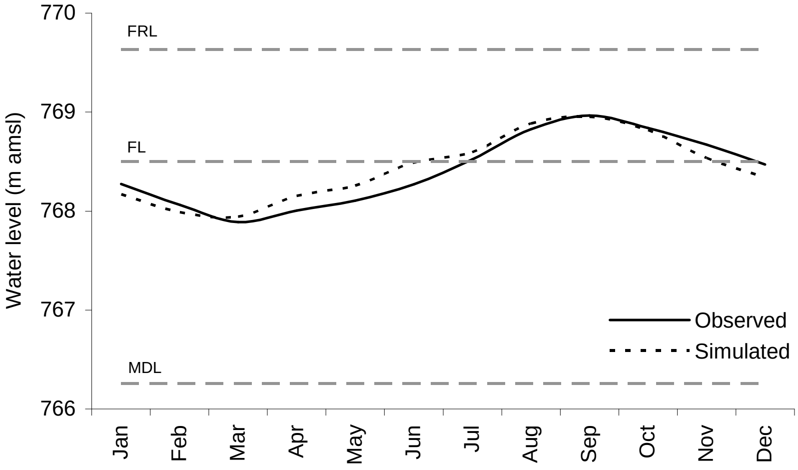


Figure 4.3. Mean monthly observed water level and simulated water level

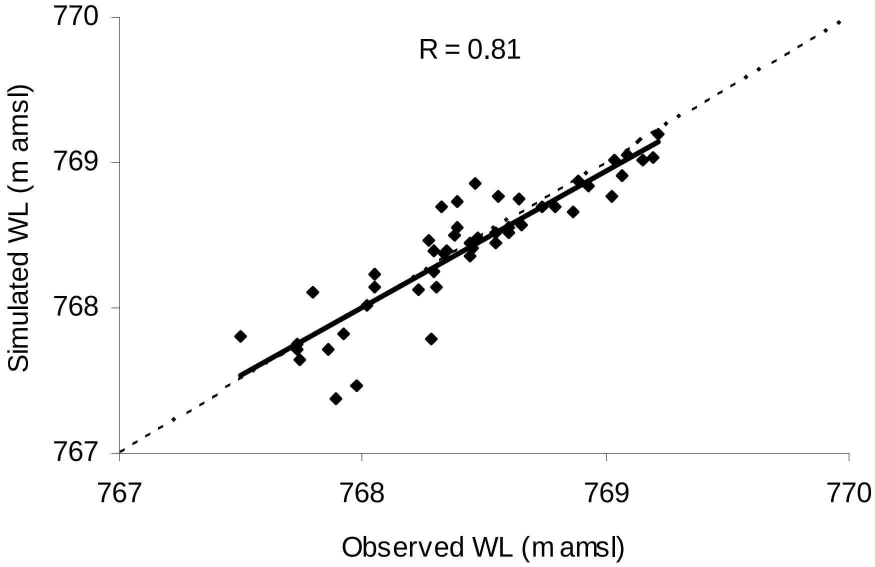


Figure 4.4. Correlation between observed and simulated water levels

The mean surface area, during the modelled period, was computed to be 262 km^2, but this varies between a low of 194 km^2 in February 2000 to a high of 313 km^2 in September 1999. In the absence of more than one estimate of *phumdis* area (AP) available for the study period, the *phumdis* area within the lake, as discussed in Section 4.2, has been kept constant at 135 km^2 throughout the simulation period. The open water area of the lake was estimated by subtracting the *phumdis* area from the lake surface area of the particular month. The mean open water area during the simulation period was 128 km^2 with the lowest open water area of 60 km^2 in February 2000 and highest of 179 km^2 in September 1999. The lake surface area and the open water lake area during the simulation period are shown in Figure 4.5.

Figure 4.6 a shows the mean monthly lake area simulated by the water balance model during June 1999–May 2003. Figure 4.6 b-g shows the mean monthly inundated area of the lake estimated using ArcGIS and the elevation-volume-level relationship (Section 2.5.3) for two months intervals. The lake area is the lowest during the months of March (227 km^2, Figure 4.6 c) and gradually increases with the arrival of the monsoon. It attends it maximum during September (297 km^2 Figure 4.6 f)) during which the water surface area of the lake extends below it original lake boundary. The lake area then decreases gradual during the dry seasons.

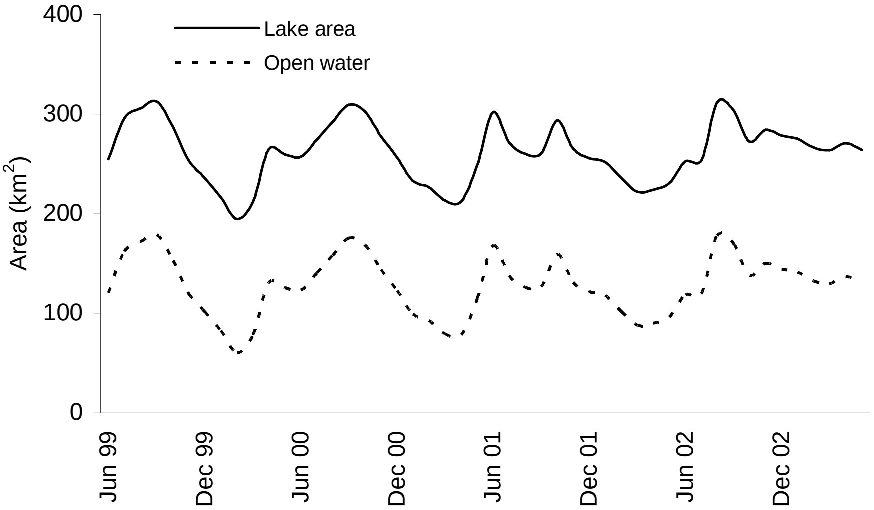


Figure 4.5. Lake areas (June 1999–May 2003)

4.3. Water balance components

4.3.1. Inflows

As discussed in Section 4.2, the inflows into the lake are from the direct precipitation on the lake surface area and the runoff from the sub-catchments of Loktak Lake. Each of these water balance components are discussed in this section.

Direct precipitation (P): The contribution of water inflow into the lake during the modelled period through direct precipitation is estimated by multiplying the depth of rainfall (m) and the lake area (discussed in Section 4.2.1). As noted in Section 4.2, the precipitation recorded at KLNP meteorological station, is used for this computation. The monthly inflow of water into the lake through precipitation during the period June 1999–May 2003 is shown in Figure 4.7. The maximum monthly inflow of $91 \times 10^6 m^3$ was simulated during the month of July 1999, while the lowest ($0 \times 10^6 m^3$) was simulated during the months of December 2000 and 2001, January 2002 and 2003 and February 2002. Table 4.2 summarizes the mean monthly inflow into the lake through direct precipitation as well as runoff from the sub-catchments. The maximum mean monthly inflow into the lake through direct precipitation was simulated during the month of August ($60.12 \times 10^6 m^3$) followed by July ($57.80 \times 10^6 m^3$), while the minimum of $1.52 \times 10^6 m^3$ during December. The mean annual inflow contributed by direct precipitation has been estimated to be $360.12 \times 10^6 m^3$ with 74% during the rainy months between June and October (Table 4.2).

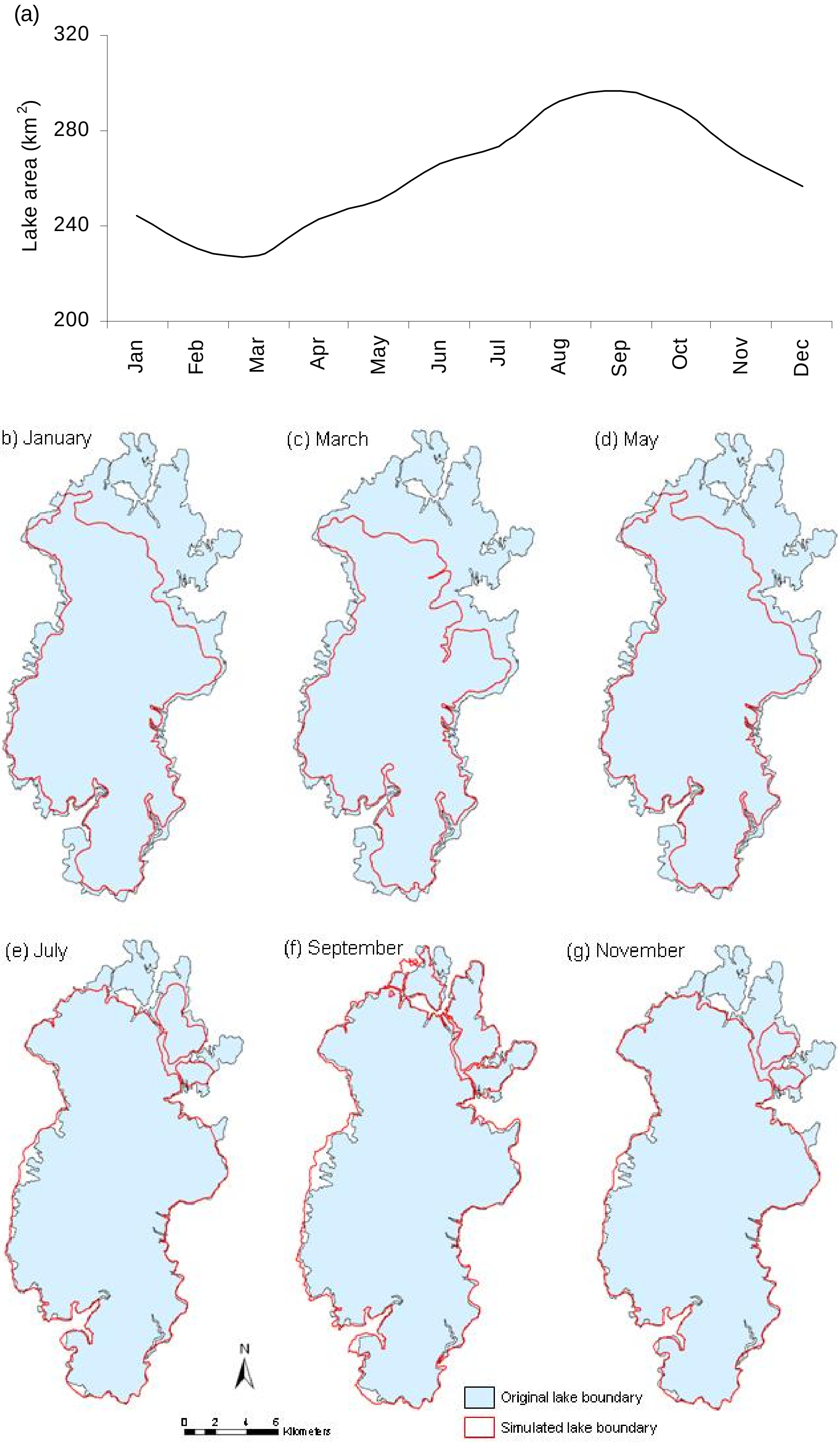


Figure 4.6. Mean monthly lake areas during June 1999–May 2003

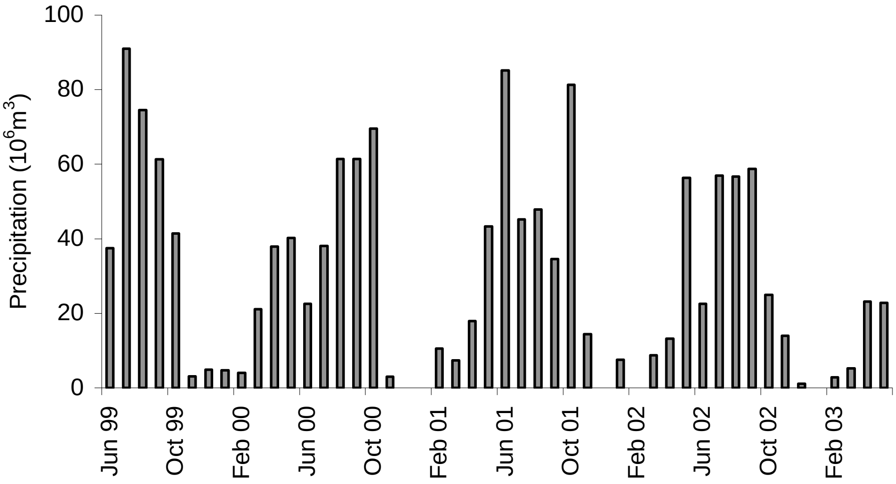


Figure 4.7. Monthly precipitation on lake surface area (June 1999–May 2003)

Runoff from the sub-catchments (R): The contribution of water from the sub-catchments draining into Loktak Lake is estimated as sum of discharge from all the sub-catchments simulated by MIKE SHE models and use of these results to estimate flows from the ungauged sub-catchments. As stated in Section 2.2.1, Loktak has a total catchment area of 4241 km^2, which is divided into six primary sub-catchments, namely the Thoubal, Iril, Imphal, Kongba, Khuga, and Western sub-catchment, with the Heirok and Sekmai sub-catchment being diverted away from the lake by diversions schemes. The total monthly runoff from the entire catchment area into the lake during the period June 1999–May 2003 is shown is Figure 4.8. The maximum runoff of 1124 × 10^6m^3 was simulated during the June 2001 while the minimum of 19 × 10^6m^3 was during January 2001.

Table 4.2. Mean monthly inflow into the lake (June 1999–May 2003)

Months	**Precipitation (10^6m^3)**	**Runoff (10^6m^3)**	**Total inflow (10^6m^3)**
January	3.06	44.29	47.35
February	4.36	41.16	45.52
March	10.63	71.36	81.99
April	23.05	136.18	159.23
May	40.68	260.41	301.09
June	41.92	571.50	613.42
July	57.80	523.11	580.91
August	60.12	697.02	757.14
September	54.03	501.18	555.21
October	54.28	450.06	504.34
November	8.67	152.72	161.39
December	1.52	49.77	51.29
Total	360.12	3498.76	3858.88
% contribution	9.33	90.67	-

On average, 66% of the inflow into the lake through runoff from the sub-catchments was during the four monsoon month (June–September, Table 4.2). The maximum mean monthly runoff was during the month August ($697.02 \times 10^6 m^3$) while the minimum during February ($41.16 \times 10^6 m^3$).

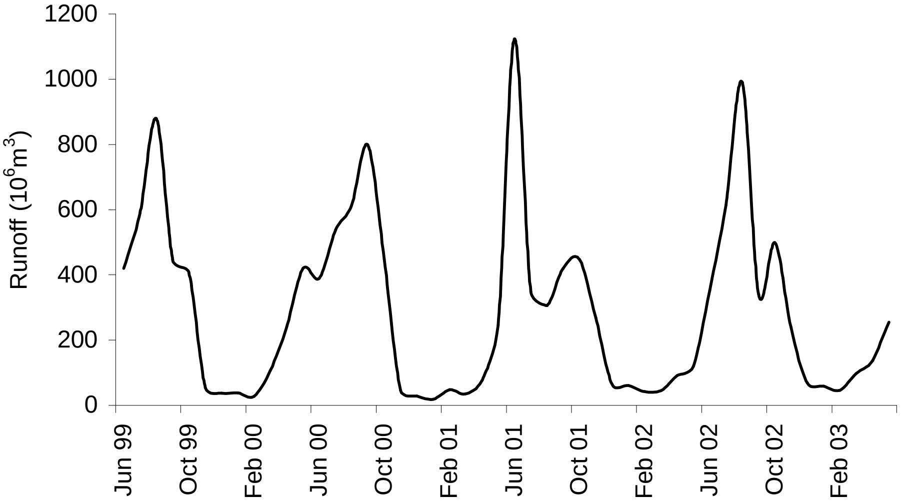


Figure 4.8. Monthly runoff from the sub-catchments of Loktak Lake (June 1999–May 2003)

4.3.2. Outflows

As discussed in Section 4.2, the outflows of water from the lake are through evapotranspiration from *phumdis*, evaporation from lake open water area, barrage releases and abstractions for domestic, agriculture and hydropower generation purposes. Each of these terms in the water balance are discussed in the following sections.

Evapotranspiration (ET): As shown in Equation 4.1, the total monthly water loss from the lake through evapotranspiration is estimated by multiplying the evapotranspiration rate by the area of *phumdis*. The evapotranspiration rate from the *phumdis* for the simulation period was provided by LDA using the Penman-Monteith method. As previously noted in Section 4.2, *phumdis* area is kept constant at 135 km^2 throughout the simulation period. Figure 4.9 shows monthly evapotranspiration from the *phumdis* during the period June 1999–May 2003. It follows a very similar pattern in each year during the simulation period with high evapotranspiration during summer and monsoon months and low evapotranspiration during the winter months. The maximum water loss of $19.26 \times 10^6 m^3$ was simulated during the month of May 2000 while a minimum of $3.89 \times 10^6 m^3$ during the month of December 2001.

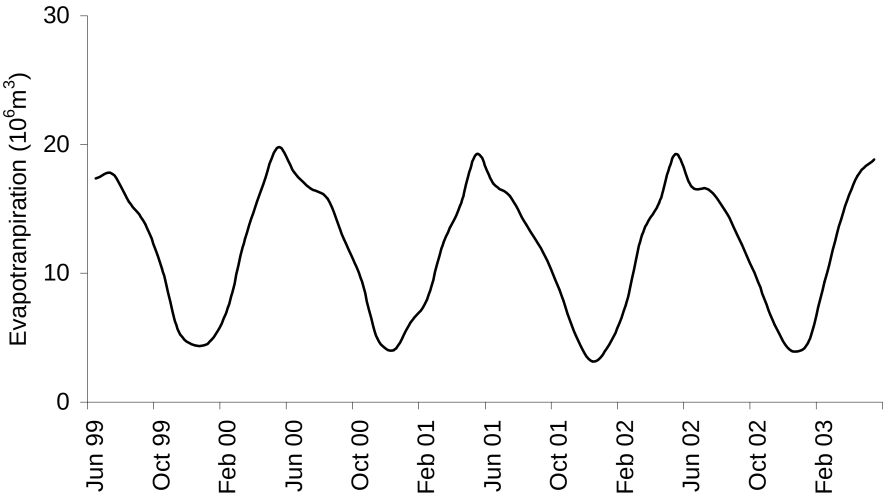


Figure 4.9. Monthly evapotranspiration from phumdis (June 1999–May 2003)

Table 4.3 summarizes componentwise mean monthly outflows from the lake. The maximum average monthly evapotranspiration loss was during the month of May (19 × 10^6m^3) followed by June and July (both 17 × 10^6m^3) while the minimum loss in December (4 × 10^6m^3) and January (5 × 10^6m^3). The mean annual water loss from the lake through evapotranspiration from the *phumdis* was simulated as 141.81 × 10^6m^3. However, the monthly variation in evapotranspiration, unlike runoff and precipitation, does not follow the monsoonal pattern, instead it follows the monthly temperature pattern recorded in KLNP.

Table 4.3. Total average monthly outflow from the lake (June 1999–May 2003)

Months	**ET**[a] (10^6m^3)	**E**[b] (10^6m^3)	**Agriculture** (10^6m^3)	**Domestic** (10^6m^3)	**HEP**[c] (10^6m^3)	**Barrage release** (10^6m^3)	**Total Outflow** (10^6m^3)
January	5.00	5.72	8.00	3.41	65.15	0.00	87.28
February	8.04	8.41	8.00	3.08	59.09	0.00	86.62
March	13.05	11.94	8.00	3.41	56.48	0.00	92.88
April	16.17	14.26	8.00	3.30	68.08	0.00	109.81
May	19.28	19.63	0.00	3.41	67.80	169.09	279.21
June	17.22	16.17	0.00	3.30	67.29	399.90	503.88
July	16.70	20.51	0.00	3.41	71.66	443.38	555.67
August	15.01	19.61	0.00	3.41	73.88	565.60	677.52
September	12.57	18.64	0.00	3.30	78.40	422.66	535.57
October	9.49	14.46	0.00	3.41	80.41	436.45	544.22
November	5.39	7.73	8.00	3.30	77.21	134.34	235.97
December	3.89	5.00	8.00	3.41	79.56	0.00	99.85
Total	141.81	162.08	48	40.15	845.01	2571.42	3808.48
% contribution	3.72	4.26	1.26	1.05	22.19	67.52	

[a] Evapotranspiration
[b] Evaporation
[c] Hydroelectric power abstraction

Open water evaporation (E): With the maximum temperature reaching as high as 34°C during the summer months, water loss due to open water evaporation is important in the water balance of Loktak Lake. The evaporation rate is based on the data provided by LDA for the KLNP meteorological station discussed in Section 2.3.2. The total monthly water loss from the lake due to evaporation is estimated by multiplying the evaporation rate by the lake open water surface area, discussed in Section 4.2.2.

Figure 4.10 shows the monthly water loss from the lake due to evaporation from open water area during the period June 1999–May 2003. Similar to evapotranspiration, it also follows the temperature pattern recorded in KLNP with high evaporation during summer and monsoon months and low during the winter months. The mean annual evaporation loss from open water in the lake was 162.08 × 10^6m^3. The maximum mean monthly evaporation loss was simulated in July (20.51 × 10^6m^3) followed by May (both 19.28 × 10^6m^3), while the minimum loss was simulated in December (5.00 × 10^6m^3) and January (5.72 × 10^6 m^3, Table 4.3).

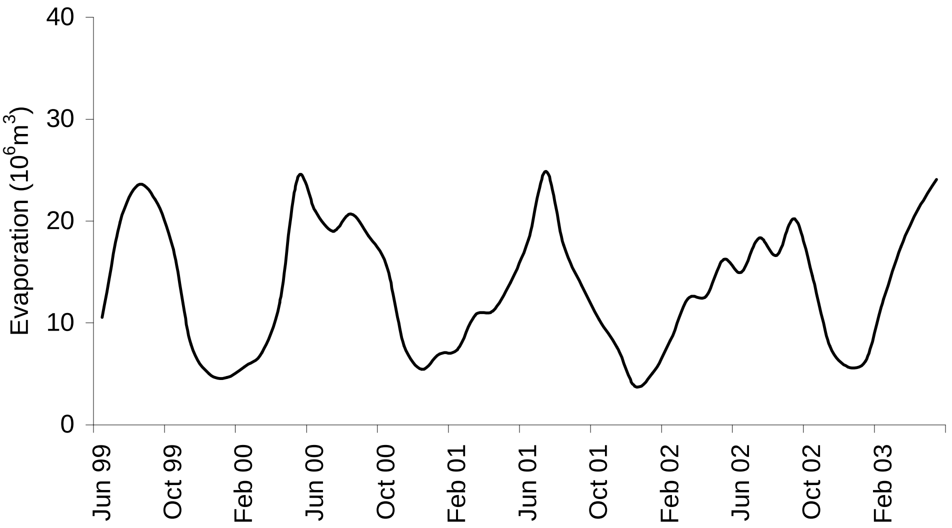


Figure 4.10. Monthly evaporation on lake open water area (June 1999–May 2003)

Agriculture abstraction (AbsI): As noted in Equation 4.1, the abstraction of water for irrigation schemes along the Manipur River is based on records from the Public Works Department (PWD, 1967) and Irrigation and Flood Control Department (IFCD, 1987). There are two irrigation schemes, the Imphal Barrage Irrigation Scheme and the Loktak Lift Irrigation (LLI) Scheme (discussed in Section 2.5). The former scheme is currently operational and diverts 8 × 10^6m^3 monthly during the dry months November–April for irrigating a command area of 60 km^2. The latter scheme (LLI), which has the potential to lift 16.8 m^{3}s^{-1} of water from Loktak Lake to provide irrigation to 243 km^2 is currently non-functional and is not included in the current water balance modelling. These abstractions are only possible when lake level exceeds the minimum drawdown level (MDL) of 766.2 m amsl (equivalent to lake volume of 94.6 x 10^{6}m^3). Figure 4.11 present the monthly water abstraction of water for agriculture purposes during the simulation period. The repetition of regular pattern each year shows that the current abstractions of water through the Imphal Barrage Irrigation Scheme are possible throughout the simulation period and not compromised by the lake levels.

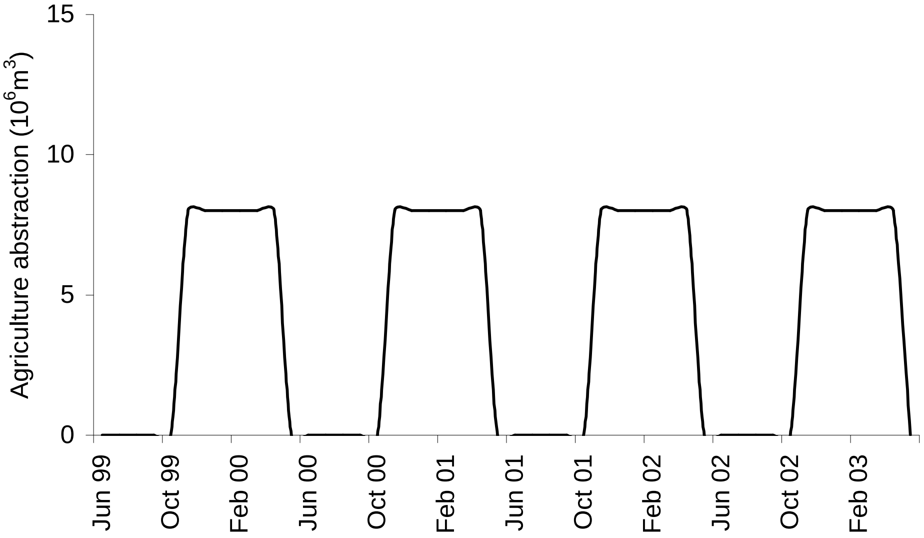


Figure 4.11. Monthly agricultural abstraction (June 1999–May 2003)

Domestic abstraction (AbsD): Abstraction for domestic uses are withdrawn from the rivers draining into the lake as well as from the lake by communities in the urban areas (Imphal city and surrounding towns within the catchment) and the rural communities on and around the lake. Total water abstracted for domestic supply was estimated to be 0.11 × 10^{6}m^{3}d^{-1} (Imphal city – 0.08303 × 10^6 m^{3}d^{-1}, other towns within the Loktak catchment – 0.01897 × 10^6 m^{3}d^{-1} and rural communities on and around the lake – 0.008 × 10^6 m^{3}d^{-1}) (IFCD, 1987; Government of India, 1999; Government of Manipur, 2002). The total daily water abstracted for domestic purposes is estimated by multiplying the abstraction rate with the number of days in a particular month. Monthly abstraction varies between 3.08 × 10^{6}m^3 and 3.41 × 10^{6}m^3 depending the number of days in a month. These abstractions are not controlled by the lake levels and were withdrawn continuously all throughout the simulation period. Annually, $40.15 \times 10^6 m^3$ of water was abstracted for domestic purposes, which was the smallest contributor to the water balance of the lake (Table 4.3).

Hydropower abstraction (AbsH): The Ithai Barrage was primarily constructed to impound water in Loktak Lake, which can then be withdrawn for generation of up to 105 MW of hydropower under the Loktak Hydro Electric Project (LHEP). The power channel at Ningthoukhong through which the water for hydropower generation is withdrawn has a capacity of $42\ m^3s^{-1}$ and the strategy of LHEP is to impound as much water as possible within Loktak Lake to enable them to withdraw the maximum generating capacity throughout the year. However, the exact amount of water withdrawn on a monthly basis varies depending on the water level within the lake and the capacity of the installed turbines. The monthly volume of water abstracted from the lake during the simulation period was procured from records provided by NHPC. Figure 4.12 shows the monthly water withdrawn for hydropower generation during the period June 1999–May 2003. The abstraction for hydropower are generally high during the monsoon and post-monsoon months (June–December) every year due to the fact that more water (sub-catchments runoff) is being stored in the lake by the operation of the Ithai Barrage. The maximum volume of $87 \times 10^6 m^3$ was abstracted in October 2002, while a minimum of $48 \times 10^6 m^3$ in March 2001 (Figure 4.12). The mean annual water abstraction for hydropower generation during the four year study period was $845.01 \times 10^6 m^3$. The maximum mean monthly withdrawal of $80.41 \times 10^6 m^3$ was simulated during the months of October while minimum mean monthly withdrawal of $56.48 \times 10^6 m^3$ was simulated during March (Table 4.3). December, the driest month of the year, shows a large withdrawal (low $72.41 \times 10^6 m^3$ in December 2002; high $86.77 \times 10^6 m^3$ in December 2000; mean $79.56 \times 10^6 m^3$).

Barrage releases (O): As discussed in Section 2.5.2, one of the main purposes of Ithai Barrage was to divert water from the Manipur River and its tributaries into Loktak Lake, its operation is governed with the principle of diverting the maximum amount of water for the purpose of hydropower generation. The barrage gates are generally opened to release water downstream only in extreme circumstances of flooding. It has been observed that the water levels in the lake during some months are maintained above

769m amsl. The data for monthly barrage releases used in the current simulation of the water balance model of the lake were procured from NHPC and LDA. Figure 4.13 shows the monthly release of water from Ithai Barrage between June 1999 and May 2003. It clearly shows that water was released only during the months between May–November, with the four monsoon months (June–September) accounting for 71% of the releases. For the rest of the year (December–April), the barrage gates remained closed. The maximum monthly release of 891.21 × 10^6m^3 was during June 2001. The mean annual water released from Ithai barrage was estimated to be 2751.42 × 10^6m^3 (Table 4.3). The largest mean monthly barrage releases was during the month of August (565.60 × 10^6m^3) followed by July (443.38 × 10^6m^3).

Figure 4.12. Monthly hydropower abstraction (June 1999–May 2003)

4.3.3. Comparison of contributions by different water balance components

Tables 4.2 and 4.3 summarize the mean annual total inflow and outflow to and from Loktak Lake through the components of the water balance. The total mean annual inflow into the lake (sum of direct precipitation and runoff from the sub-catchments) has been estimated to be 3498.76 × 10^6m^3 with 64.96% of the inflows taking place during the monsoon months (June–September). Runoff from the sub-catchments contributes 90.67% of the total inflow while direct precipitation accounts for the remaining 9.33%. The total mean annual outflow from the lake was estimated to be 3809 × 10^6m^3 with 59.67% of the outflow taking place during the monsoon months. Barrage releases accounts for 67.52% of the total outflow from the lake followed by hydropower abstraction (22.19%), evaporation (4.26%), evapotranspiration (3.72%), agriculture (1.26%) and domestic abstraction (1.05%).

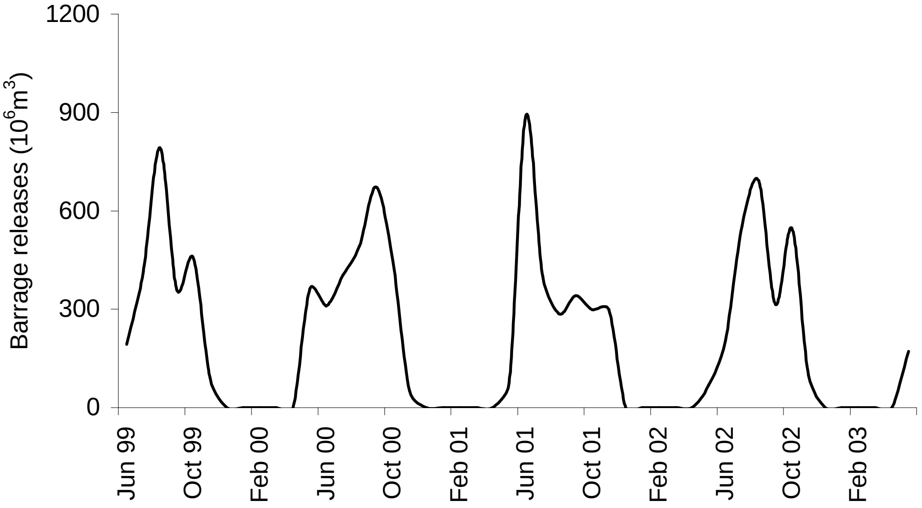


Figure 4.13. Monthly barrage releases (June 1999–May 2003)

Figure 4.14 shows the monthly water balance between the total inflow and the outflow from Loktak Lake during the period June 1999–May 2004. The monthly balance signifies the amount of water flowing in and out of the lake, on a monthly basis. A positive net volume indicates inflow into the lake exceeds outflow and negative volumes indicate the utilization of water from the lake storage. In 20 of the 48 months of the simulation period, the inflow exceeds the outflow from the lake, while during the remaining 28 months, the outflow exceeds the inflow. The maximum positive monthly water balance of 242 × 10^6m^3 was simulated in August 2002, which can be largely attributed to the high amount of runoff (990 × 10^6m^3) owing to high monsoonal rainfall over the catchment area. The maximum negative monthly water balance of (136 × 10^6m^3) was simulated in October 2002, which can be attributed to a large outflow via barrage releases (545 × 10^6m^3) and hydropower abstraction (87 × 10^6m^3).

Figure 4.15 summarises the monthly discharges of all the water balance components of the Loktak Lake. The graph clearly demonstrates the runoff from the sub-catchments of Loktak Lake and the barrage releases are the major contributors (90.67% of the total inflow and 67.52% of the total outflow) to the water balance of the lake and hence play a significant role in the maintenance of the water level regime and thereby on the water availability within the lake. The runoff, in turn is governed by the amount of precipitation over the catchment area. Therefore, alteration in the precipitation pattern can have serious implication on the lake hydrology.

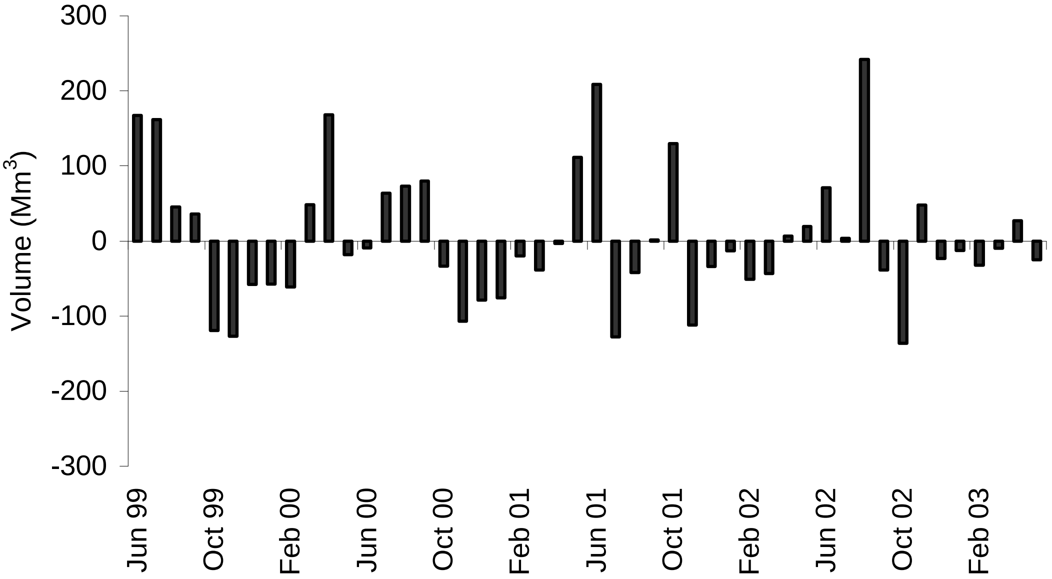


Figure 4.14. Monthly water balance of the total inflows and total outflows to and from the lake (June 1999–May 2003)

4.4. Summary

This chapter demonstrates that the water balance model developed is able to reproduce a water level regime similar to the observed water level regime of the lake. The water balance model is classified as ‘very good’, which also add confidence to the modelling approach of the sub-catchments using MIKE SHE modelling system and the subsequent evaluation of the discharges from the ungauged sub-catchments. This water balance model will further be employed in the formulation of multiple options for operation of Ithai Barrage and also in the assessment of the implication of climate change on the lake water level regime as well as the sustainability of the multiple barrage operation options which are discussed in Chapters 5, 6 and 7.

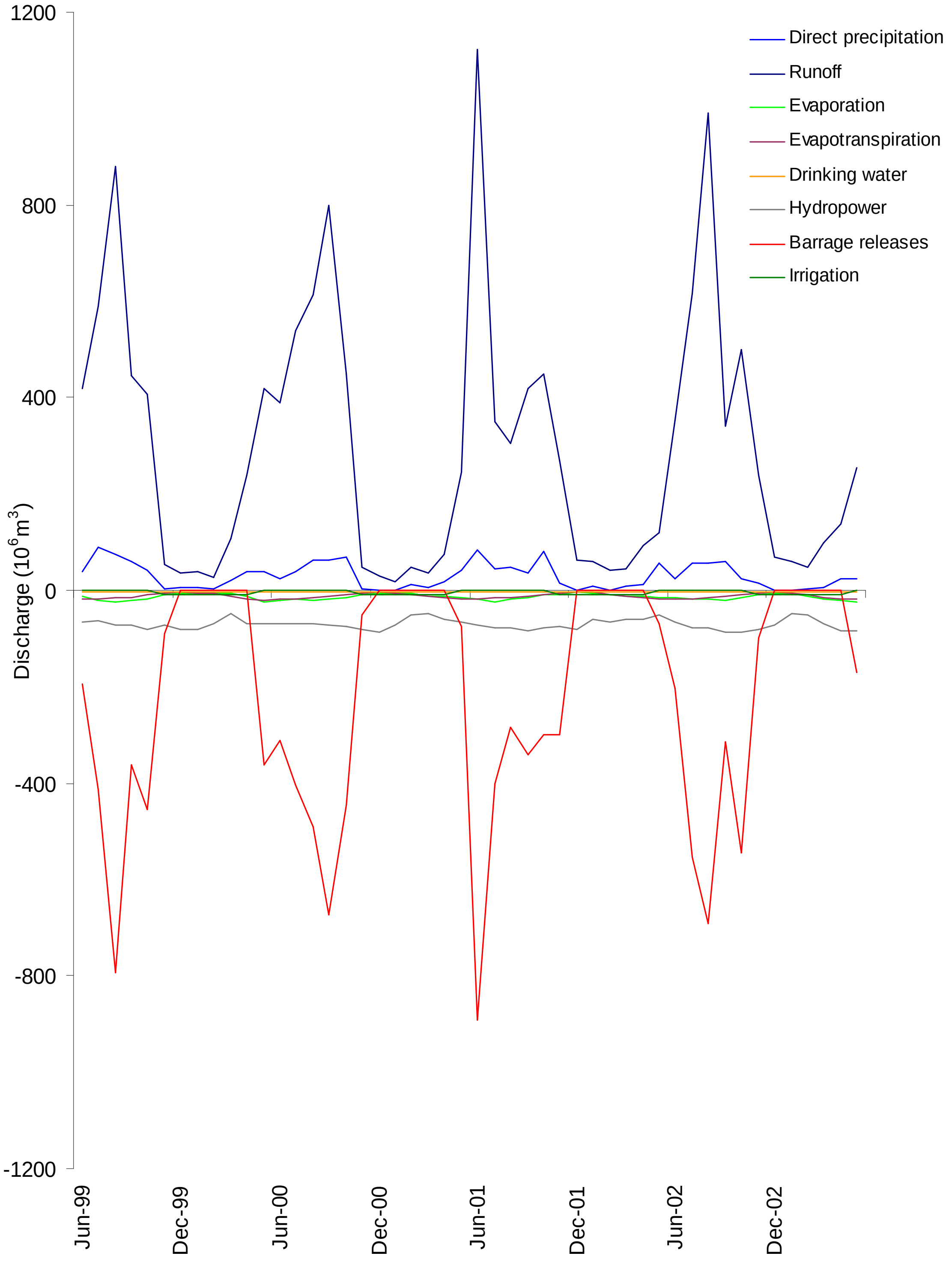


Figure 4.15. Discharges of all the water balance components

Chapter 5 - Ithai Barrage operation options

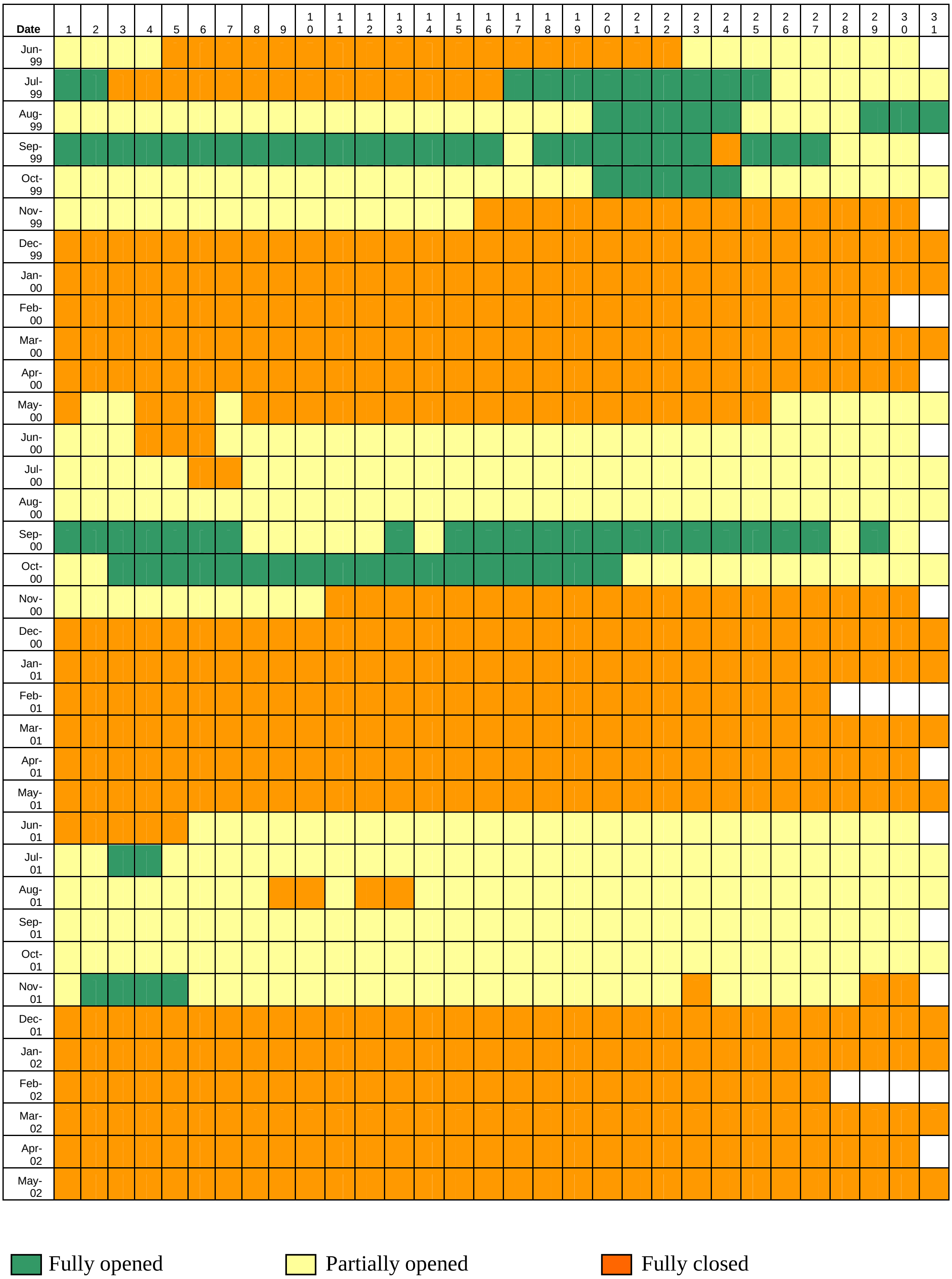
5.1. Introduction

This chapter provides a synthesis of the current operation regime of Ithai Barrage and the demands of the lake's water resources by various stakeholders. The later part of the chapter focuses on the development of multiple options for allocating the water of Loktak Lake to major stakeholders including an option designed to balance human stakeholders with ecological requirements of the lake.

5.2. Current barrage operation regime

As discussed in Section 2.7, operation of the Ithai Barrage is central to the management of water resources in Loktak Lake. Water level regime in the lake is more-or-less dictated by demands for the hydropower generation, and there are no specific allocations of water for other sectors (Hays, 1988). Although the flood level (FL) of the barrage was fixed at 768.5m amsl (lake volume of 524×10^6 m^3), it has been recorded that during the monsoon the water level rises above the FL, causing severe flooding in the peripheral areas of the lake. As discussed in Section 2.5.2, an area of 63.5 km^2 in the surrounding areas of the lake prone is to flooding (Trisal and Manihar, 2004). WISA (2003) estimated that areas inundated due to flooding would have otherwise yielded crops worth approximately 4 million US$ per annum.

WISA (2005) reported that the barrage gates were operated on an adhoc basis and only when the water level exceeded the flood level in order to release the excess water rather than operating the gates prior to flooding in order to attenuate subsequent flood peaks. Data on daily barrage operation schedule was procured from LDA for three year (June 1999–May 2002). The daily operation schedule is presented in Figure 5.1. During the 1096 days of record, it was seen that the barrage was fully opened only for 95 days and partially opened for 378 days. According to the data provided by LDA, "fully opened" implies the opening of all five barrage gates to their maximum capacity. "Partially" opened indicates the opening of 1–5 gates to various capacities. However, LDA noted that most of the time only one gate is opened between 0.5 m to 3.0 m. For the remaining 623 days (57% of the period), the barrage gates were kept fully closed to enhance the lake level.



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Jul-99	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨
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Sep-99	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	🟩	🟨	🟨	🟨	
Oct-99	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Nov-99	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
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Feb-00	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧		
Mar-00	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Apr-00	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
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Jun-00	🟨	🟨	🟨	🟧	🟧	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	
Jul-00	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Aug-00	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
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Oct-00	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Nov-00	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
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Feb-01	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧				
Mar-01	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
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Jun-01	🟧	🟧	🟧	🟧	🟧	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	
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Oct-01	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Nov-01	🟨	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟨	🟨	🟨	🟨	🟨	🟧	🟧	
Dec-01	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Jan-02	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Feb-02	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧				
Mar-02	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Apr-02	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	
May-02	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

🟩 Fully opened 🟨 Partially opened 🟧 Fully closed

Figure 5.1. Operation schedule of Ithai Barrage (June 1999–May 2002). Source: LDA

Maudgal (2000) reported that no appropriate water use/allocation plan that considers all water users within the basin had been prepared. At present no consideration has been given to the ecological water requirements of the lake ecosystem. This has resulted in the sharp deterioration in the ecological health of the lake as discussed in Section 2.7. Construction of Ithai Barrage has blocked the migratory pathway of riverine fish, which used to migrate from the Chindwin–Irrawaddy system, thereby drastically reducing the population and diversity of the fishery in the lake. Prior to construction of the barrage, migratory riverine fishes constituted around 40% of capture fisheries of the lake (Trisal and Manihar, 2004). The barrage and its current operating regime has also contributed to the deterioration of the water quality within the lake as it does not allow proper flushing of pollutants entering into the lake. However, the largest impact as a consequence of the current barrage operating regime which caters only to the demand of hydropower requirements has been on the *phumdis*, especially in the KLNP area. The reduction in the stability of the *phumdis* in this area represents a direct threat to the survival of the highly endangered *Cervus eldi eldi* and other wild animals living in the park.

In order to formulate an effective water allocation plan for Loktak Lake, it is pre-requisite to understand the demands from various stakeholders on the water resources of the lake. The following section addresses the demands from various stakeholders.

5.3. Water demand from Loktak Lake

In addition to hydropower, the other major stakeholders of the lake's water resources are agriculture and domestic uses for people living on and around the lake. For the present study, the ecological water requirements are also considered to be one of the demands of the lake water resources. A major aim of this chapter is therefore to incorporate the ecological requirements into the operating plan of the barrage through the re-establishment of a more ecologically sensitive water level regime for the lake. The various stakeholders and their water demands, which will be considered in the formulation of the barrage operation plan, are discussed below.

5.3.1. Hydropower

As discussed in Section 2.5, the Loktak Hydro Electric Project (LHEP; Figure 5.2) was designed to withdraw 42 m^3s^{-1} of water from Loktak Lake through a conductor system,

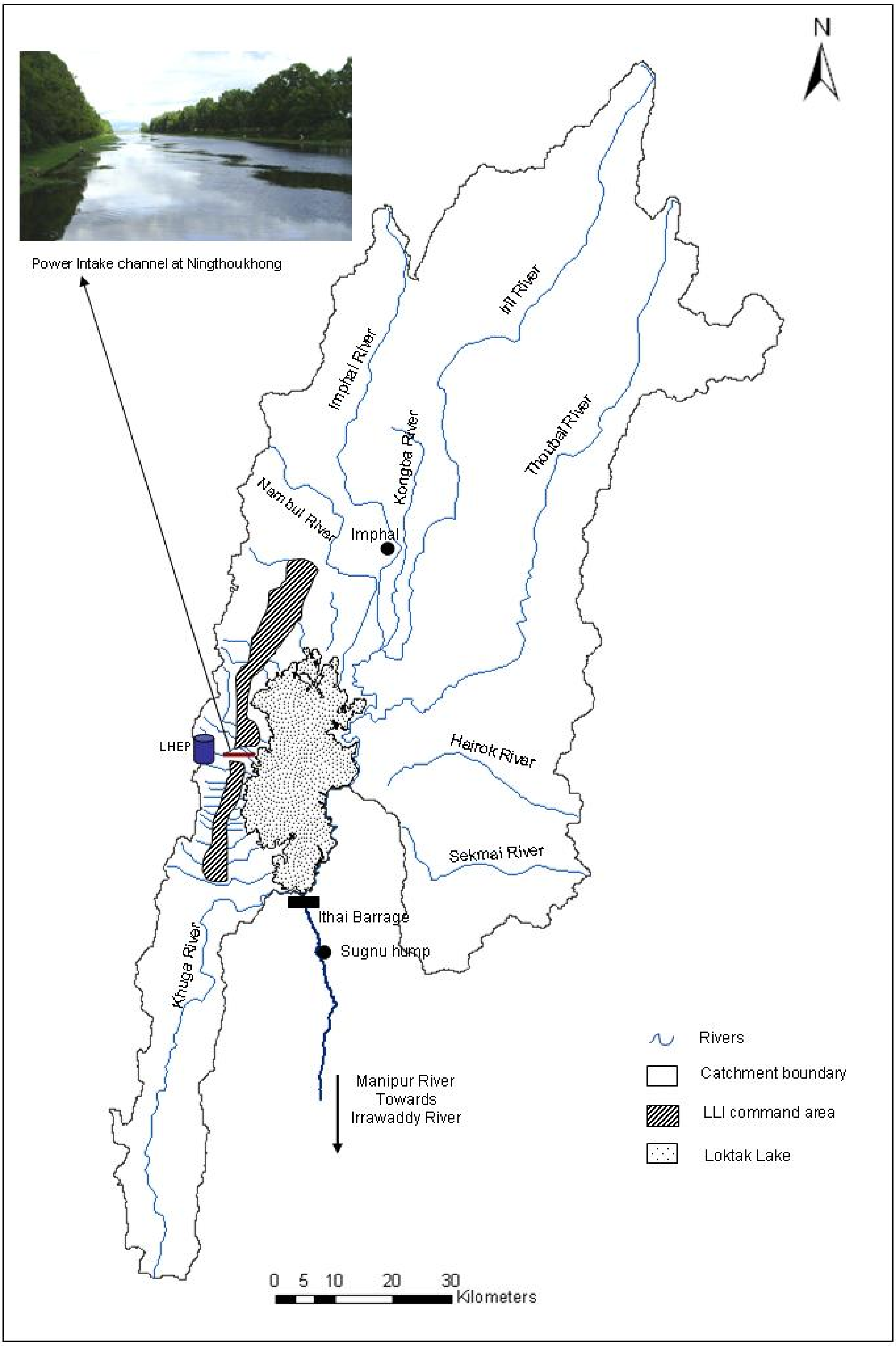

Figure 5.2. Location map of Loktak Hydro Electric Project (LHEP) and Loktak Lift Irrigation Project (LLI)

comprising a 3.49 km long open power channel at Ningthoukhong (WAPCOS, 1993). The powerhouse is installed with three turbines, however, it was envisaged that only two turbines will be operational at any given time while the third provides a standby in case one should fail. The optimal condition for generating the hydropower is to regulate Loktak water levels so that they are around 768.5 m amsl to ensure adequate water is available in the lake for withdrawal. Although the design capacity of the conductor system is to withdraw 42 m^3s^{-1} of water from the lake, the "desired" amount of water required for the power plant to operate two turbines simultaneously to generate its optimum capacity of 70 MW (35 MW + 35 MW) has been estimated to be just 28.4 m^3s^{-1} (14.2 m^3s^{-1} each turbine). Additional withdrawal of water beyond the "desired" capacity will not yield extra hydropower generation unless the third turbine is also in operation.

The "desired" monthly water required for optimal hydropower generation is estimated by multiplying the capacity of the two turbines (28.4 m^3s^{-1}) and the number of seconds in the month. Figure 5.3 shows the actual monthly water abstracted for hydropower generation during the period July 1999–May 2003 (baseline option) compared to the "desired" demand. In 19 of the 48 months, the water withdrawn for hydropower generation was above the desired monthly demand and in 29 months the withdrawal was below its desired amount. The actual water abstracted from the lake for hydropower generation fluctuates during the study period depending on the availability of water within the lake with high abstractions during June–December and lower abstraction during January–May, while the "desired" demands are at a constant rate throughout the study period as demonstrated in Figure 5.3. As noted in Section 4.3.3, a maximum of $87 \times 10^6 m^3$ was withdrawn in October 2002 while a minimum of $48 \times 10^6 m^3$ was withdrawn during March 2001. On average, the annual water abstracted for hydropower generation was estimated to be $845 \times 10^6 m^3$ compared to the "desired" capacity of $896 \times 10^6 m^3$. To enable production of adequate hydropower during the dry season, NHPC tries to store as much water as possible in the lake by closing the barrage gates during the monsoon season resulting in flooding in the surrounding areas of the lake.

Information on the amount of water abstracted for hydropower generation is sensitive due to data sharing issues between the NHPC and the Manipur State Government agencies. However, under the SDWRML project (discussed in Section 2.3.1), LDA was able to procure information on the amount of water abstracted for hydropower generation as well as the amount of power generated from NHPC during the year 1985-1990 and 1998-2003. These data (Table 5.1) clearly demonstrate the increase in the annual water abstraction for hydropower generation and corresponding power generated from the late 1980s to the early 2000s. During 1985-1990 the average annual water abstracted was 597 × 10^6m^3 which dramatically increased to 827 × 10^6m^3 (39%) during 1998-2003. Subsequently, the average annual power generation also increased by 34% (from an annual average of 398 Million Units in 1985-1990 to 531 Million Units in 1998-2003). The State of Manipur receives on average 35% of the total power generated by LHEP and the rest is sold to the neighbouring states of Nagaland, Assam and Tripura (Figure 2.2) to generate revenues.

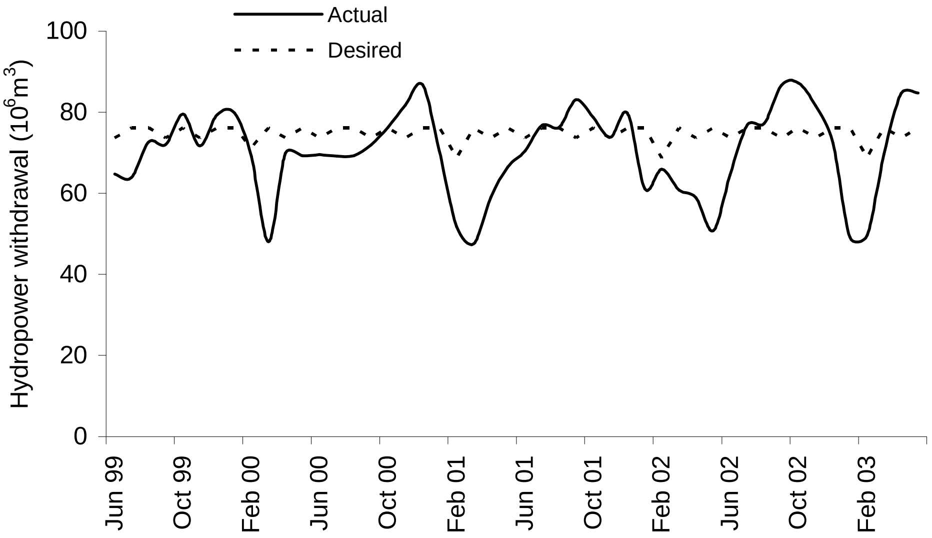

Figure 5.3. Monthly hydropower withdrawal (June 1999–May 2003)

Table 5.1. Annual water withdrawal from the lake for hydropower generation

Year	Power Generated (MU)	Water abstracted (10^6m^3)
1985-86	427	626
1986-87	380	544
1987-88	405	-
1988-89	338	559
1989-90	438	660
1998-99	472	755
1999-00	551	840
2000-01	553	820
2001-02	556	836
2002-03	524	884

Source: LDA and NHPC

Despite the steep rise in the hydropower generated and hence the water abstraction from the lake, it is still below the “desired” demand. Therefore, while formulating barrage operating options, the “desired” water requirement of 28.4 m^3s^{-1} (annual average $896 \times 10^6 m^3$) will be considered as the water demand from the hydropower sector.

5.3.2. Agriculture

Owing to the availability of water, agricultural activities in the lake basin are mainly driven by the monsoon. As a result, cultivation is only done during the months June–October. Most of the agricultural land is uncultivated for the rest for the year. To ensure availability of water throughout the year to enable multiple cropping, there are two irrigation schemes within the lake basin, the Imphal Barrage Project and the Loktak Lift Irrigation (LLI) project. The LLI project, as discussed in Section 4.3.2, is currently non-functional due to lack of financial commitment from the State Government for the repair and maintenance of the irrigation canals.

The Imphal Barrage Project diverts a small amount of water ($8 \times 10^6 m^3$ monthly) from the Imphal River during October–March to irrigate an area of 60 km^2 mainly for paddy cultivation and a few winter crops including gram and mustard. This project is currently operational. The LLI project was initiated to lift 16.8 m^3s^{-1} of water from the lake to irrigate an area of 243 km^2 on the western side of the lake between the Nambul River in the north and Khuga River in the south (Figure 5.2). The scheme was designed to operate only during the dry period from November–February to enable two crops of rice and a third winter crop comprising wheat, gram and mustard to be grown. In the future, if the scheme is made operational it will abstract $43.5 \times 10^6 m^3$ each month between November and February ($174 \times 10^6 m^3$ annually) from the lake.

The critical aspect in supplying water for LLI project from the Loktak Lake is the timing of the supply. The LLI project, if made operational, will be withdrawing $43.5 \times 10^6 m^3$ of water each month during the dry season, which will substantially reduce the abstractable amount of water available within the lake, hence in direct conflict with that associated with hydropower power generation. However, it might have benefits for achieving water level for the *phumdis* by lowering the water level in the lake thereby enabling the *phumdis* to be grounded to the bed of the lake. The monthly water demand for the LLI project is estimated by multiplying the demand rate, as discussed above, with the number of seconds in a particular month. Figure 5.4 presents the monthly water demands from both the irrigation schemes for the period June 1999–May 2003. The irrigation sector is estimated to demand a total of 222 × $10^6 m^3$ (LLI + Imphal Barrage Project) between November and March each year.

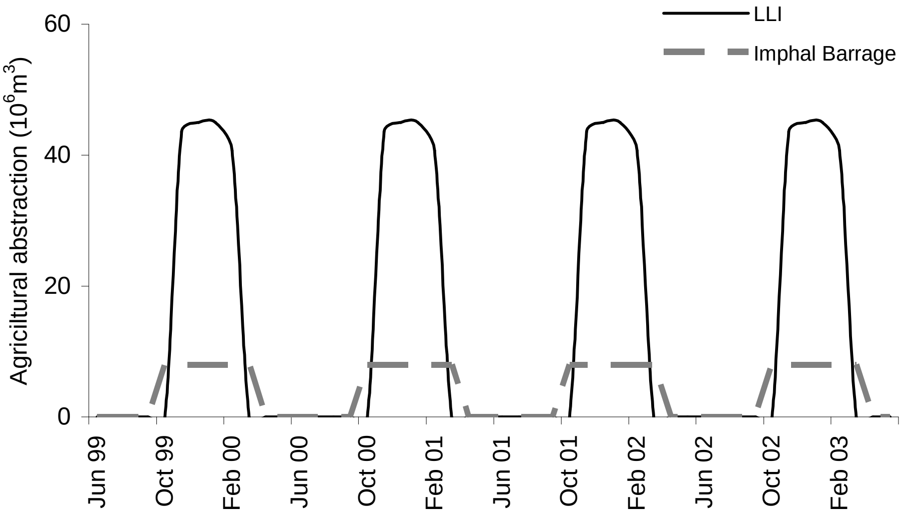

Figure 5.4. Monthly water withdrawal by Imphal Barrage Project and Loktak Lift Irrigation Project (June1999–May 2003)

5.3.3. Domestic water supply

As noted in Section 4.3.3, domestic water supply demands are associated with the provision of drinking water for rural communities residing on and around Loktak Lake and the urban communities in Imphal city and the surrounding smaller towns. Both these abstractions are made continuously throughout the year and are not controlled by the operation of Ithai Barrage. Hence, the demands for domestic supply (40.15 × $10^6 m^3$ annually) will be treated as an outflow from the lake and are always satisfied, irrespective of the lake water level going below the minimum drawdown level (MDL), as long as the lake is not completely dried up.

5.3.4. Environmental water allocation

Consideration of the water regime is a fundamental component of wetland management (McCosker, 1998) as every structural and functional characteristic of a wetland is directly or indirectly determined by the hydrological regime (Hammer 1992; Gilman 1994; Ramsar 2007; Grootjans and Diggelen, 2009). As discussed in Section 1.5, disturbance to hydrological processes is the greatest threat to wetland conservation and has caused most wetland degradation (Martin and André 1993; Davis and Froend, 1999;

Riis and Hawes 2003; Van Der Valk, 2005). For example, in Cameroon, a dam constructed in 1978 to divert water for irrigation greatly restricted the seasonal flooding downstream thereby severely degrading the floodplain wetlands along the Logone River and disrupting the traditional livelihood. However in 1988, IUCN – The World Conservation Union initiated the Waza Logone rehabilitation scheme and released water downstream through newly constructed openings in the main river levee thereby restoring approximately 60% of the affected floodplain (IUCN, 2000). The restored hydrological regimes and the flooding pattern dramatically improved the living conditions for the people and their environment, without affecting the irrigation scheme. Braund (2000) stated that the ongoing Waza Logone rehabilitation scheme proves that water allocation for irrigation as well as for ecosystem restoration can exist side by side and benefit the local people.

Ramsar (2006) advocated allocation of adequate water to wetlands to sustain the functioning of the ecosystems, respecting their natural dynamics for the benefit of future generations. Ramsar (2007) further defines the water allocation to a wetland ecosystem as "the water quantity and water quality required to maintain a particular ecological character of the water resource which will sustain selected wetland ecosystem functions and services". Schofield et al. (2003) stated that environmental water requirements can be achieved through an ecological approach using specific knowledge of water-regime requirements for a particular species, community or processes. Young (2004) added that this water regime can be expressed as the depth and time variations in depth of the water body. Roberts et al. (2000) noted that a vegetation–hydrology relationship can be established by treating a plant community as an entity, and linking it to water regime. He further suggested that community level information is a better integration of ecosystem processes and is also a means of reducing bulky amounts of information about species. It serves as a 'model' of species behaviour or response to any hydrological changes. Finlayson et al. (1989) adopted a similar approach to assess the seasonal changes in the macrophytic vegetation in Magela Creek floodplain, northern Australia. The ecological groups can be based on observations, assumptions, or measurements, and are typically a mixture of all three. Determining the volume of water required is a relatively straightforward exercise once the area of the wetland and required depth are established and the water budget inputs and outputs can be quantified (Arlington and Zalucki, 1998). Roberts et al. (2000) published guidelines for wetland water requirements for extensive floodplain complexes and there are several other studies on water level requirements for wetland vegetation (e.g. Wheeler et al., 2004; Vander Valk, 2005; Loomes et al., 2006; Paillisson et al., 2006; Leira and Cantonati, 2008).

The present study will consider *phumdi* as the floral community for which environmental water requirements are defined. Construction of the Ithai Barrage has brought about a drastic change to the water level regime of the lake thereby severely impacting the *phumdis*, especially in the KLNP area (Section 2.7). This phenomenon is in common with other wetlands where levels have been maintained at higher and less variable levels (e.g. Beilfuss and Barzen, 1994; Ni et al., 2006; Baker et al., 2009).

To ensure a healthy growth of the *phumdis*, it is necessary for them to ground on the lake bed for some part of the year. With the current management practise it is not possible to restore the lake water level regime back entirely to its pre-barrage condition. However, while formulating the barrage operation options, the water level in the lake will be restored to its original regimes (pre-barrage) for the months of December, January and February by lowering the water level in the lake to its original mean levels of 767.63 m, 767.15 m and 766.61 m amsl respectively. These three months are also the rutting season of the *Sangai* deer (Trisal and Manihar, 2004) and hence will help in providing a stable habitat if the *phumdis* in KLNP are in contact with the lake bed. The aim is to ground the fixed *phumdis* that occur in the lake as a large continuous mass (Section 2.6.1). These thick *phumdis* currently cover an area of 55.3 km^2 with 19.1 km^2 in the KLNP core area. The free floating *phumdis* are not considered.

5.4. Development of different options for barrage operation

The most vital element in allocating water to the above mentioned stakeholders is the lake water level, which determines the grounding of *phumdis*, as well as the extractable water available in the lake to satisfy the demands from the hydropower and agriculture. Currently, the water level regime of the lake is more-or-less dictated by demands for hydropower generation (Section 2.5.4) which, after releases through the barrage gates, accounts for the second largest output term in the lake's water balance (Section 4.3.3). There are no specific formal allocations of water for other sectors whilst, as previously noted (Section 2.5.4), the focus on hydropower generation through maintaining high water levels has impacted other ecosystem services. Elevated water levels have, in particular, impacted the unique ecological conditions within the lake which are associated with *phumdis*. The high water levels have resulted in the flooding of peripheral area around the lake which is more extensive than that which occurred before the barrage. Trisal and Manihar (2004) suggested that 63.5 km^2 are regularly inundated whilst WISA (2003) estimated that these flooded areas would have otherwise yielded crops worth approximately US$4 million per annum. The inundation of lakeside villages also impacts the rural poor through loss and damage to property and possessions and agricultural fields.

Maintaining high water levels in the lake during March–November to ensure availability of water to satisfy the demands from hydropower and irrigation sectors will not effect the ecological water requirement. However, potential conflict may arise during the dry months (December–February) where ecological requirements come into play demanding low water level in the lake, thereby reducing the lake volume. If the lake water level is lowered to satisfy the ecological demand and at the same time there is adequate extractable water available in the lake compared to demands from both of the hydropower and agriculture put together, then there is no conflict and all demands are likely to be simultaneously satisfied. However, conflict may arise when either the water level in the lake is not lowered during the dry periods to satisfy ecological requirements or when the extractable water available is less than the demands from the other two stakeholders. It is at this point where tradeoffs or prioritization will have to be made in order to determine which stakeholder's demands are given primacy.

There is no formal procedure or set of rules that can be followed while deciding the tradeoffs/prioritization. It is very location-specific, and basin or water development agencies throughout the world have their own set of priorities. In many cases, no single agency has overall responsibility for basin-level water management and prioritizing needs becomes a complex issue (Dourojeanni, 2001). As a result, water is managed in a fragmented and sectoral way (Agarwal et al., 2000) such that short-term needs tend to be prioritized. This is certainly the case for Loktak Lake, where management is currently being dictated by the demands of hydropower generation.

The present study focuses on the conflicts between three main stakeholders: ecological water demand, hydropower demand and agricultural demand. Accordingly three alternative barrage operation (BO) options are developed using the water balance model developed in Chapter 4, which give priority to each of these services. The same simulation period of June 1999–May 2003 is used and the impacts upon the other two services of each option explored. Subsequently a fourth option is developed which aims to establish a compromise by, as far as possible, satisfying the demands of these three ecosystem services. Impacts on hydropower and agriculture are assessed by comparing the demands for water from these two sectors with those which can be provided under a particular barrage operation option. In addition, the impacts on local communities around the periphery of the lake are assessed by evaluating the impacts due to flooding their agricultural field when lake water levels are above the flood level inundating the cropped areas.

5.4.1. Option 1 – prioritization of hydropower demand (BO1)

As discussed above, hydropower generation requires a flow of 28.4 m^3s^{-1}, to enable LHEP to operate the two turbines to generate optimum capacity of 70 MW. Hence, this option of barrage operation with prioritization of hydropower demands (hereafter referred to as BO1) will focus on providing water for hydropower generation at the rate of 28.4 m^3s^{-1} throughout the year. The only pre-requisite criterion for this option to be fulfilled is that at no point, the water level of the lake should go below the MDL of 766.2 m amsl.

The monthly water volume is estimated employing the water balance model developed in Chapter 4 and its corresponding water level is estimated using the volume–level relationship given in Section 2.5.3. The inflow into the lake through runoff from the sub-catchments and direct precipitation of the lake surface remains the same as to that of the baseline option (June 1999–May 2003; Section 4.3.1). The outflow components of the water balance also remain the same to that of the baseline scenario except the hydropower abstraction (AbsH) which is replaced with the water demand from the hydropower sector at the rate of 28.4 m^3s^{-1} (mean annually $896 \times 10^6 m^3$).

Figure 5.5 shows the new water level regime of the lake for BO1 and confirms the possibilities of allocating water at the desired rate of 28.4 m^3s^{-1} throughout the study period. In seven months of the 48 month study period, the lake water level was above the FL with the highest water level (679.21 m amsl) occurring in September 1999. However, under this option the intensity as well as the frequency of flooding reduces drastically compared to the current baseline condition, where the number of flooding months is as high as 19. The maximum area flooded during the month with highest water level (both September 1999 for BO1 and baseline condition) reduces by 7% during the BO1 regime when compared with the baseline condition (48 km^2 for BO1 from 55 km^2 for baseline condition). There is enough water left in the lake to satisfy the demand of the agricultural sector and hence no conflict of interest arises between these two stakeholders. However, the irrigation demand considered in this option is the same as the current baseline option with only the Imphal Barrage project in operation.

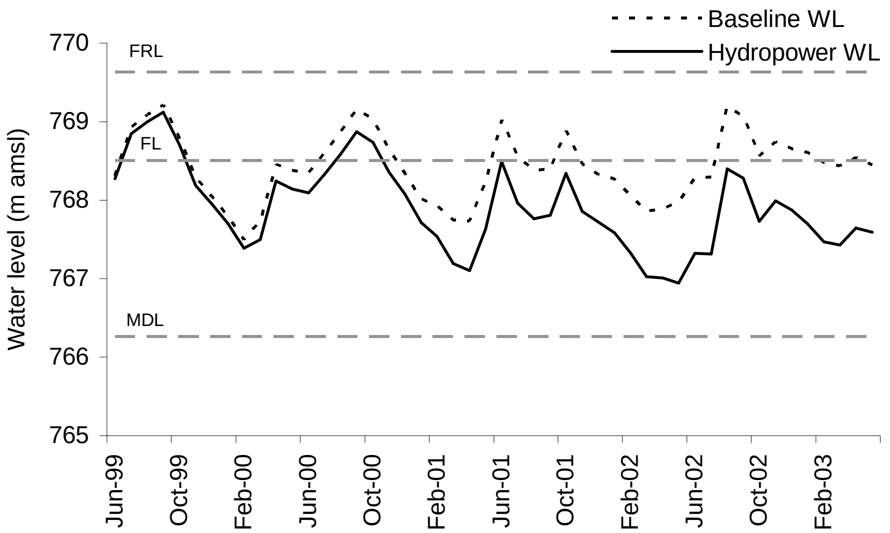

Figure 5.5. New hydrological regime satisfying hydropower demands (BO1)

Figure 5.6 highlights the mean monthly water levels of the lake during December, January and February. The BO1 water level regime results in a reduction in the water level during these three critical months compared to the current baseline condition. Reduction in the lake water level in December are 0.64 m, January 0.53 m and February 0.46 m. However, these reduction are not adequate to satisfy the desired ecological level (December - 767.63 m amsl; January - 767.15 m amsl; and February - 766.61 m amsl) to ground the *phumdis*. Hence, this option of operating the lake water level, prioritizing the hydropower does not simultaneously satisfy the ecological demands.

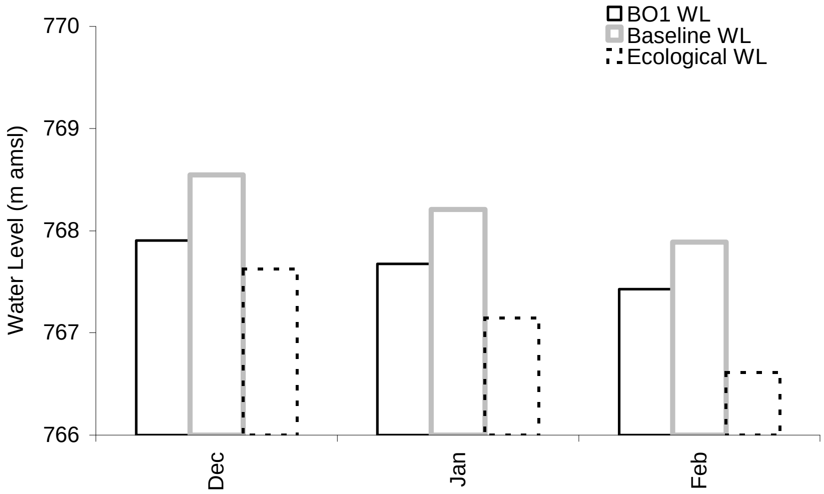

Figure 5.6. Mean monthly water level during December, January and February for BO1

5.4.2. Option 2 – prioritization of agricultural demand (BO2)

In the current baseline water level regime, the demand from the agricultural sector is only associated with the Imphal Barrage Project which demands an allocation of $8 \times 10^6 m^3$ during the months from October–March. As previously noted, the LLI has not been operating for the past eight years. However, in formulating the option which prioritizes agricultural demands (hereafter referred to as BO2), it is assumed that the LLI is fully operation and its demand of $16.8\ m^3s^{-1}$ for the months November–February are to be abstracted from the lake. As noted in Section 5.3.2, the irrigation sector (LLI + Imphal Barrage Project) demands a total of $222 \times 10^6 m^3$ during November–February each year from the lake. The only binding criterion to the allocation of water to these agricultural demands is that the lake water level should be above the MDL level of 766.2 m amsl.

In the same way as for BO1, the monthly lake water volume for BO2 is also estimated employing the water balance model and its corresponding water level using the volume–level relationship. All inflow and the outflow components of the water balance remain the same as the baseline option except for the agricultural abstractions. The agricultural abstractions in BO2 are replaced with the water demand from the agriculture sector (Imphal Barrage project and LLI project).

Figure 5.7 shows the new water level regime designed to satisfy the demands of agriculture. The frequency of flooding reduces considerably. Water level in the lake exceeds the FL for only five months of the 48 month study period compared to 19 months during the baseline condition. This new regime also reduces the lake level during December–February as demonstrated in Figure 5.8. On average, the water level in the lake, under this new regime, is maintained at 766.98 m amsl, 766.24 m amsl and 766.30 m amsl for the months of December, January and February respectively compared to the ecological requirements of 767.63 m amsl (December), 767.15 m amsl (January) and 766.61 m amsl (February). Table 5.2 shows the area of *phumdis* grounded (i.e. those areas where *phumdis* depth > water depth) under the BO2 water level regime. A total of 77%, 81% and 83% of the fixed *phumdis* within the lake are grounded to the bed of the lake during December, January and February, respectively. In the critical KLNP area, during the same months 51%, 76% and 76% of the *phumdis* are grounded.

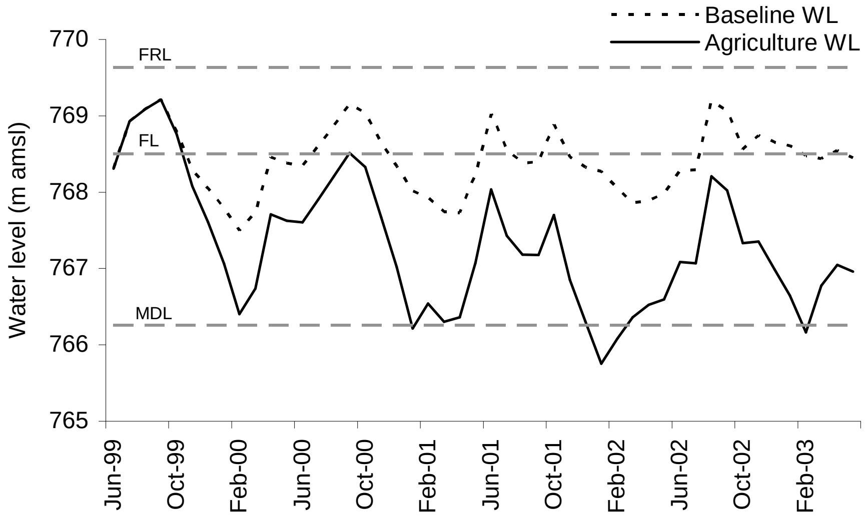

Figure 5.7. New hydrological regime satisfying agricultural demands (BO2)

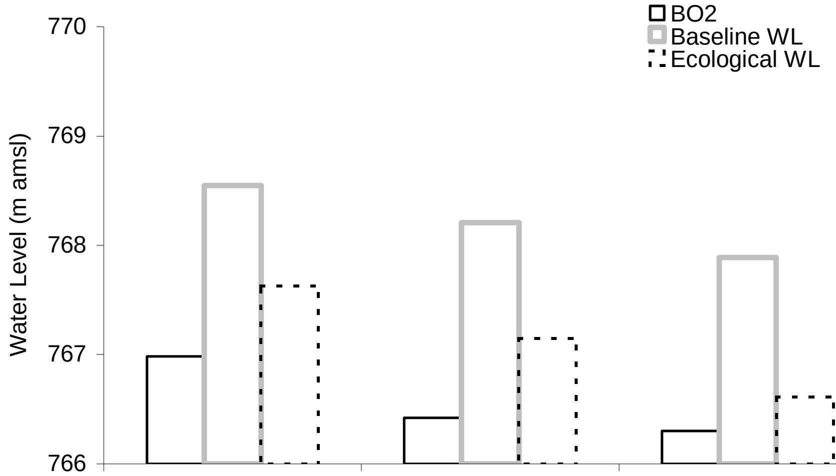

Figure 5.8. Mean monthly water level during December, January and February for BO2

Table 5.2. Phumdi area grounded under the BO2 water level regime

Year	Loktak Lake			KLNP		
	Total *phumdi* area (km^2)	*Phumdi* area grounded (km^2)	% grounded	Total *phumdi* area (km^2)	*Phumdi* area grounded (km^2)	% grounded
December	55.3	42.3	77	19.1	9.7	51
January	55.3	51.4	93	19.1	16.3	85
February	55.3	51.9	94	19.1	16.8	88

Figure 5.9 presents the distribution of water depth in February, the month with lowest mean water level for the BO2 water level regime. It also shows the extent of the thick phumdis and the area within the phumdis where the phumdis thickness > water depth. During this month the maximum area of *phumdis* able to be grounded by the new BO2 water level regime is 94% of the total thick *phumdis* in the Loktak Lake compared to the maximum of just 27% during the baseline condition and for the KLNP area, 88% compared to 11% during the baseline condition.

However, the main problem encountered in the operation of the lake water level regime with prioritization of agricultural demands is that levels fall below the MDL for four months (January 2001, January 2002, February 2002 and February 2003). As a result, it would not be possible to provide water to both agriculture and hydropower in the months that follow (February 2001, February 2002, March 2002 and March 2003). There is a huge combined demand of $100.43 \times 10^6\text{m}^3$, $114.52 \times 10^6\text{m}^3$, $68.85 \times 10^6\text{m}^3$ and $77.80 \times 10^6\text{m}^3$ during these four months from both the stakeholders. Hence this new regime conflicts with its own demands as well as with the hydropower demands. The inability of this regime to provide water for four months would not be acceptable to NHPC, who operate the LHEP. There will also be economic implication due to the inability of hydropower generation and crop failure during these four months.

5.4.3. Option 3 – prioritization of ecological demand (BO3)

As discussed above, the ecological demand requires the restoration of the water level in the lake during the months of December, January and February to the original (pre-barrage) condition. In the baseline option, average monthly lake water levels during December, January and February were 768.55 m, 768.21 m and 767.89 m amsl respectively. These are to be lowered to 767.63 m, 767.15 m and 766.61 m amsl.

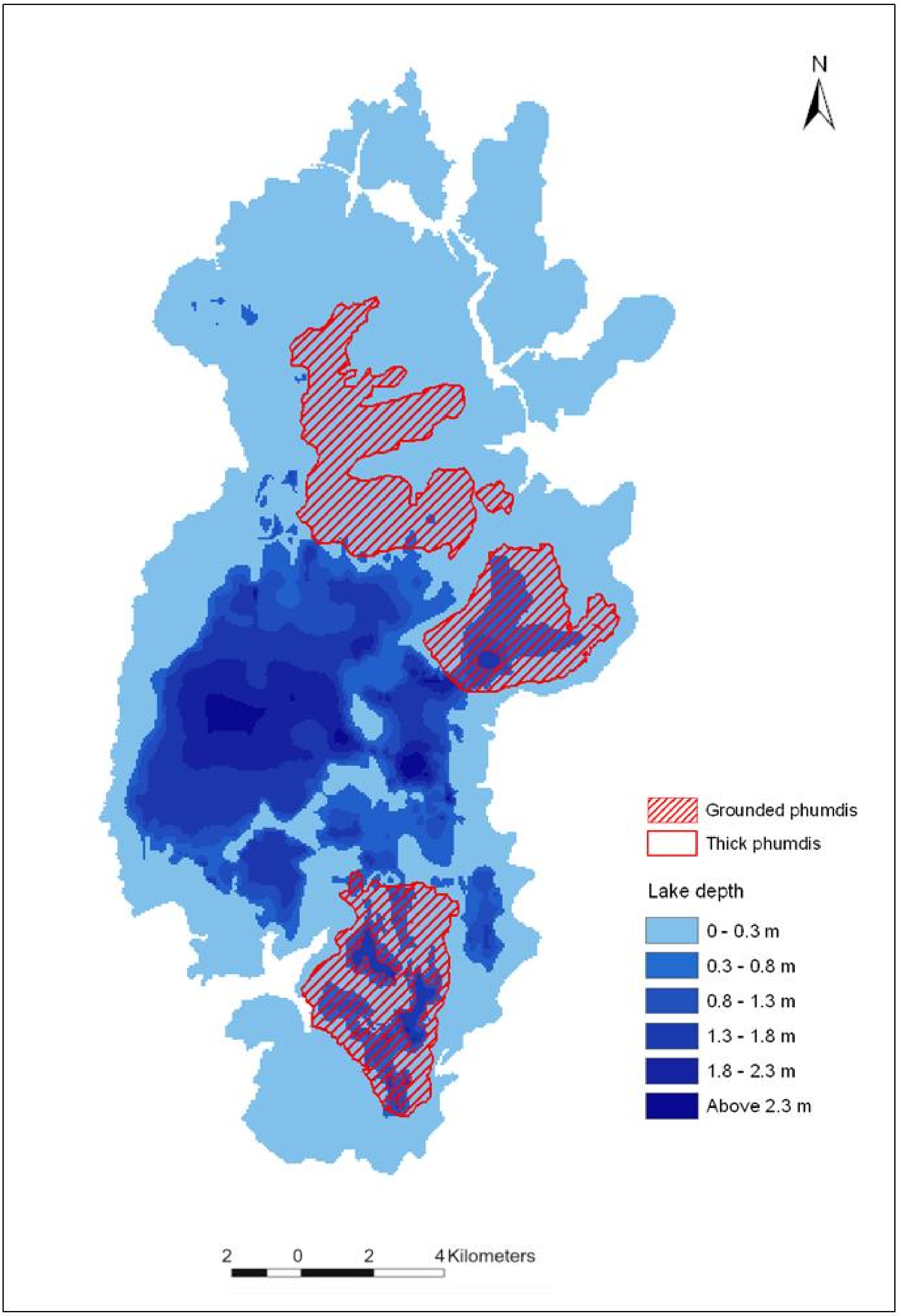

Figure 5.9. Grounding of phumdis during February under BO2 water level regime

The barrage operation option with prioritization of ecological demand (hereafter referred to as BO3) also employs the water balance model to estimate the monthly water volume and corresponding water level using the volume–level relationship discussed in Section 2.5.3. All inflow and outflow components of the water balance remain the same to that of the baseline condition. However, during December–February, the water balance model estimate the volumes of water required to lower the current water level to the desired water level using the level-volume relationship for each of the three months. These estimated volumes are then specified in the model as the additional releases for lowering the water level in order to satisfy the ecological requirements.

Figure 5.10 presents the new water regime designed to satisfy the ecological demands. The new BO3 water regime clearly shows the lowering of the water levels throughout the simulation period, except for the first five months. The mean monthly water levels during December, January and February are maintained at the desired level of 767.63 m, 767.15 m and 766.61 m amsl respectivrtly (Figure 5.11). As demonstrated in Table 5.3, under this new regime, 26%, 83% and 91% of the thick *phumdis* within the lake are in contact with the bed of the lake during December, January and February, respectively. In the critical KLNP area, during the same months 10%, 67% and 79% of the *phumdis* are grounded.

Figure 5.12 presents the extent of the grounded *phumdis* (i.e. *phumdis* depth > water depth) in the lake during February (the month with the lowest water level of the year) for the BO3 water level regime. The maximum area of *phumdis* able to be grounded by the new BO3 water level regime is 91% (during February) of the total thick *phumdis* in the Loktak Lake compared to the maximum of just 27% during the baseline condition and for the KLNP area, 79% compared to 11% during the baseline condition. Figure 5.13 presents the original as well as the additional releases of water through the Ithai Barrage during the study period. A maximum of $90 \times 10^6 m^3$ was released in December 1999 followed by $68 \times 10^6 m^3$ in February 2001. However, in comparison to the original releases, the additional releases are quite small and the present capacity of the gates provided in the Ithai Barrage for releasing water downstream ($2203 \times 10^6 m^3$), discussed in Section 2.5.2, is capable of accommodating these additional releases from the lake.

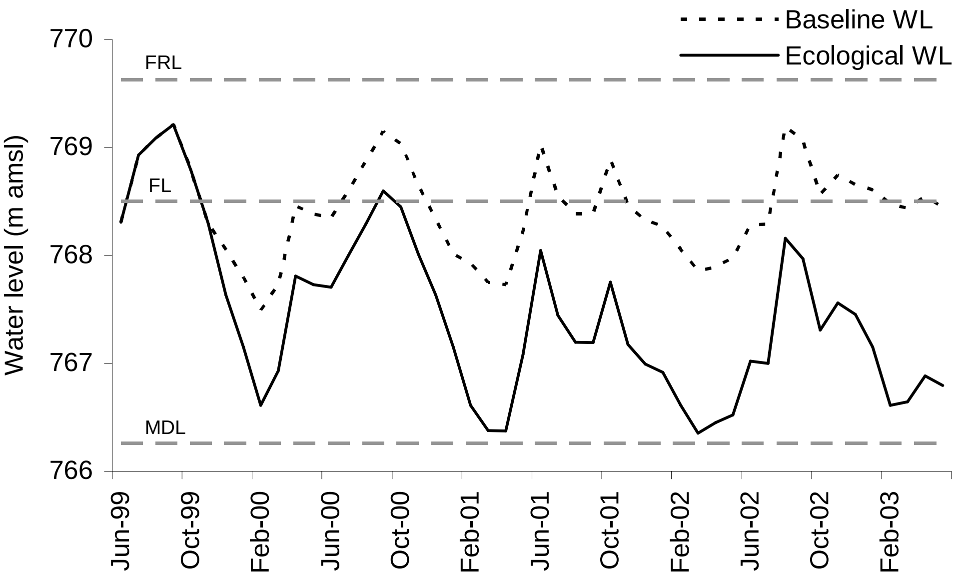

Figure 5.10. The new hydrological regime satisfying ecological demand (BO3)

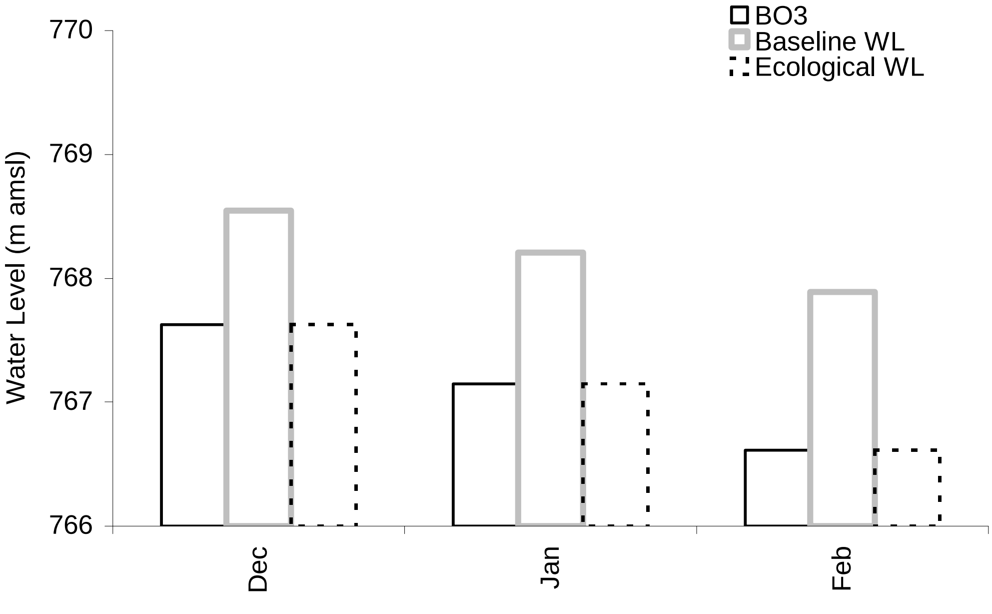

Figure 5.11. The mean monthly water level during December, January and February for BO3

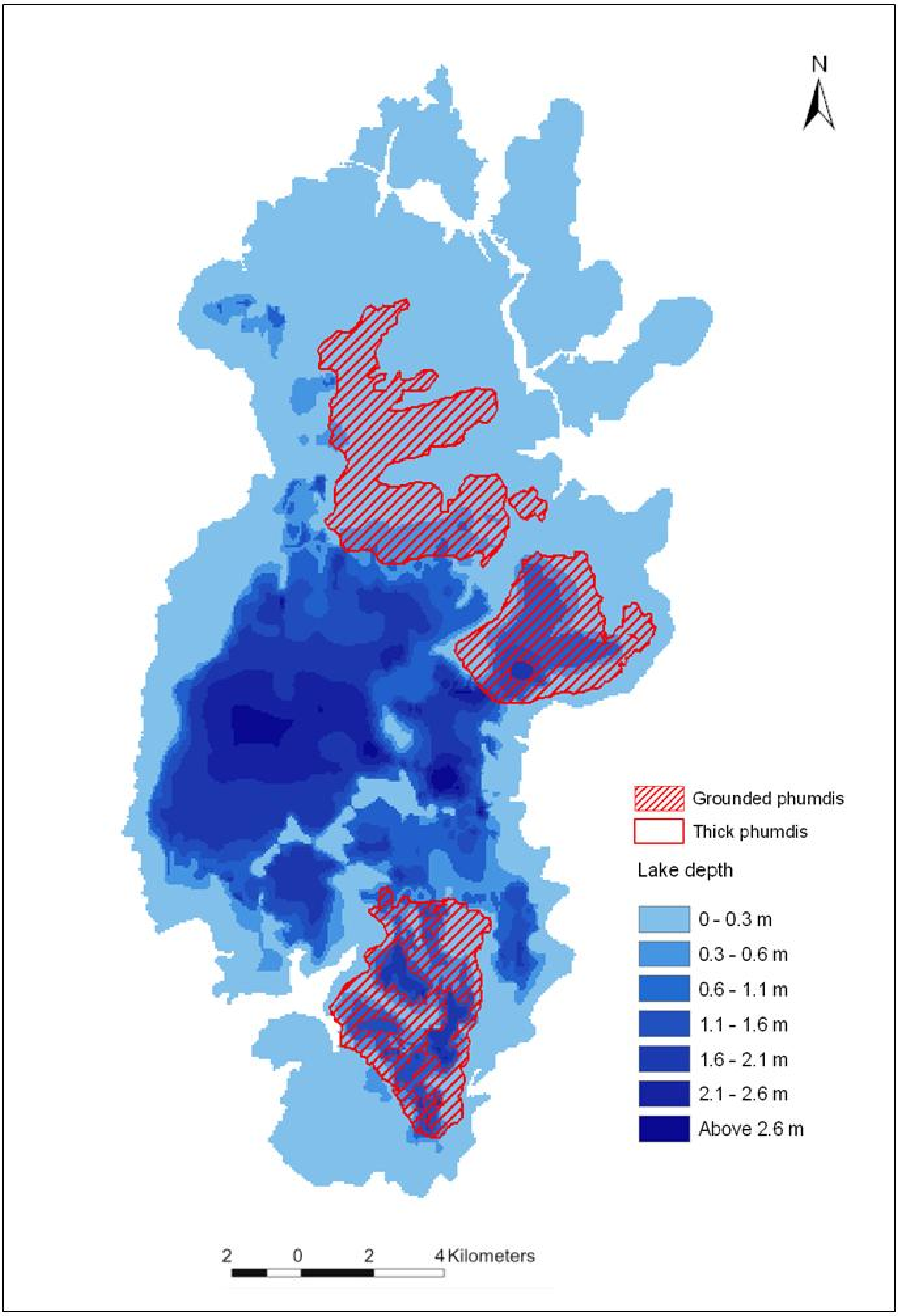

Figure 5.12. Grounding of phumdis during February under BO3 water level regime

Table 5.3. Phumdi area grounded under the BO3 water level regime

Year	Loktak Lake			KLNP		
	Total *phumdi* area (km^2)	*Phumdi* area grounded (km^2)	% grounded	Total *phumdi* area (km^2)	*Phumdi* area grounded (km^2)	% grounded
December	55.3	14.2	26	19.1	2.0	10
January	55.3	45.9	83	19.1	12.8	67
February	55.3	50.1	91	19.1	15.0	79

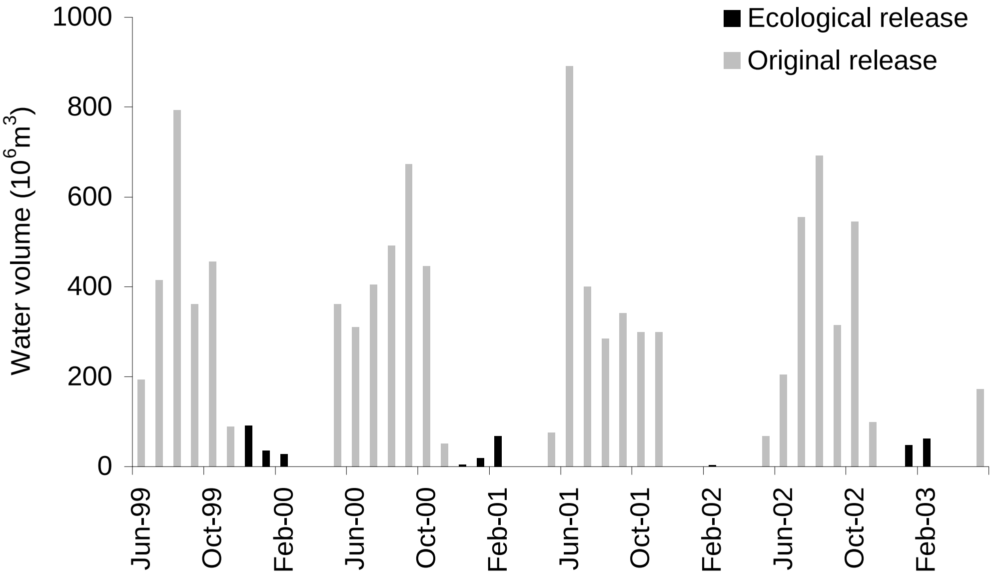

Figure 5.13. Additional water releases to satisfy ecological needs for BO3

This new ecologically driven water regime does not conflict with the current ongoing demands from the hydropower and agricultural sector (Figure 5.11), since despite the large volume of water released to lower the water level within the lake levels, are still above the MDL. There will therefore be no reduction to the amount of water allocated to LHEP and hence no reduction on the amount of power generated. Agricultural abstraction can also continue at the current rates. The flooding pattern under the new ecological regime is also much improved, with the water levels in the lake exceeding the FL for only five months of the 48 months study period compared to 19 of the 48 months during the baseline option.

5.4.4. Option 4 – integrated regime (BO4)

The integrated water level regime (hereafter referred to as BO4) attempts to satisfy the demands of all the major stakeholders discussed above – hydropower, agriculture and ecological needs. In addition, a new stakeholder, the communities around the lake who are currently flooded, is also incorporated into this option. In cases where there is a conflict of interest or insufficient water available in the lake compared to the total demands of all stakeholders, it is necessary to prioritize stakeholders whose demands are met first. In this study, the ecological heath of Loktak Lake is given prime importance so that the wetland is able to sustain the goods and services to the people of Manipur. Ecological demands are therefore given the first priority in case of any such conflicts. Such prioritization of ecological requirements is practised in many parts of the world. For example, in the Murray-Darling 2001 Program of the Natural Heritage Trust priorities were given to establishing environmental flows capable of sustaining natural processes and protecting the aquatic environment including wetlands (Ramsar 2007). Release of environmental flow from the newly constructed Naraj Barrage in a distributary of Mahanadi River upstream of Chilika Lagoon, a Ramsar Site in India, was given the top priority in the formulation of the barrage operation policy to release water for the ecological functioning of the Chilika ecosystem (CDA, 2004). Since the construction of the Ithai Barrage was designed to bring benefits to the people of Manipur (as discussed in Section 2.7), communities which are being affected by flooding are given the second priority. The third consideration is hydropower demand since the LHEP is the only hydropower plant in the entire region and one of the major sources of electricity for the state of Manipur. Agricultural demands will receive the last priority under this option.

The water balance model has been used to estimate the monthly water volume and the corresponding water level is estimated using the volume–level relationship. All the inflow components of the water balance are kept the same as in baseline option. All the outflow components except for hydropower and agriculture abstractions are also kept the same as in the baseline option. Hydropower abstraction is replaced with the hydropower demand discussed in Section 5.2.1, while the agriculture abstractions will be the total demand from both the LLI and the Imphal Barrage projects. Similar to the estimation of addition releases for BO2, the water balance model for BO3 also estimate the volumes of water required to lower the current water level to the desired ecological water level as well as flood level (FL) using the level-volume relationship. These estimated volumes are then specified in the model as the additional releases for lowering the water level to the desired ecological requirements as well as below the FL of 768.5 m amsl. Once the desired water level for the ecological system and if necessary to lower level below the FL is satisfied, the remaining water in the lake is abstracted for both hydropower and agriculture demands. These are prevented if the water level reaches the MDL of 766.2 m amsl.

Figure 5.14 shows the new integrated water level regime. It provides an option of restoring an ecological driven hydrological regime for Loktak Lake while avoiding flooding of the surrounding areas of the lake and satisfying the demands from hydropower and agricultural sectors. Seasonal water level fluctuations are also enhanced to 1.54 m (high of 767.94 m amsl during November; low of 766.39 m amsl during March; Figure 5.15) from 1.1 m in the baseline option.

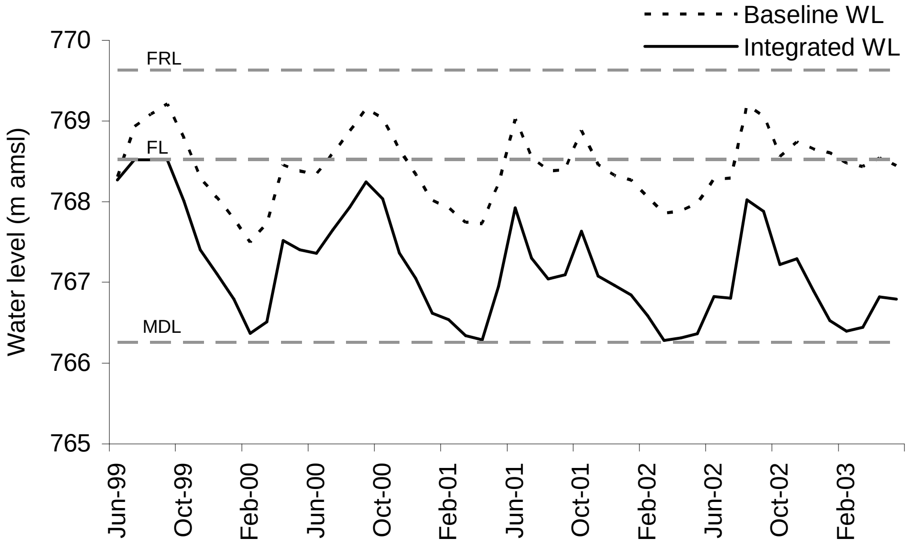

Figure 5.14. The new integrated water level regime (BO4)

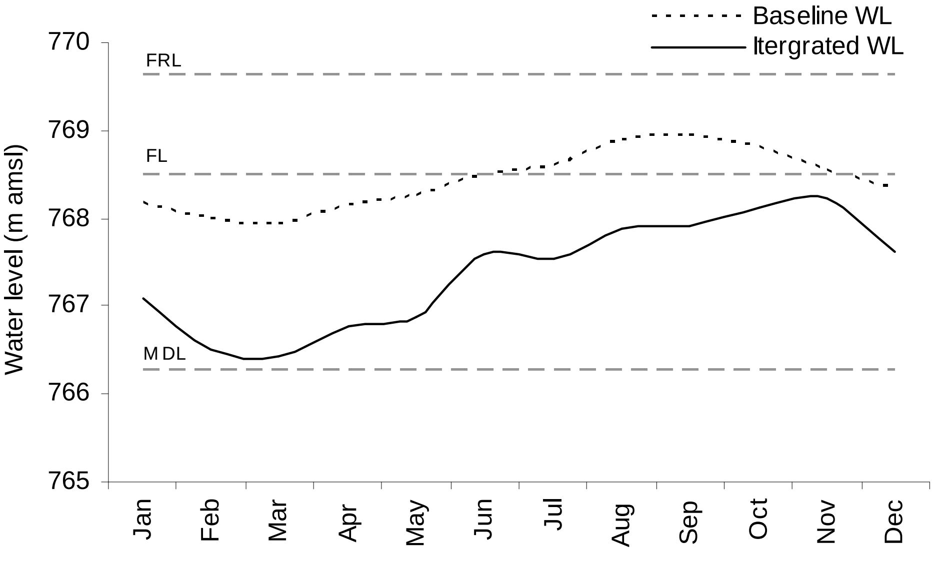

Figure 5.15. Average monthly water level during December, January and February for BO4

Figure 5.16 demonstrates that the water levels during December, January and February are lowered enough to meet the desired ecological requirements. Table 5.4 presents the percentage of *phumdis* which are grounded under the new BO4 water level regime in the lake as well as in KLNP during December, January and February. During the month with lowest mean monthly water level (February: 766.47 m amsl), 93% of the thick *phumdis* are grounded (i.e. *phumdis* depth > water depth) in the lake compared to 27% during the baseline condition. In the KLNP area, 85% of the *phumdis* are grounded compared to 11% for the baseline condition. Figure 5.17 shows the extent of grounded *phumdis* during February for the BO4 water level regime. The water level throughout the 48 months is below the FL and hence there will be no incidence of flooding in the surrounding areas. As shown in Figure 5.18, additional releases are required during only three months in the entire study period (July 1999 – 85.73 × 10^6m^3; August 1999 – 39.48 × 10^6m^3; September 1999 – 31.49 × 10^6m^3) in order to achieve the new BO4 water level regime. The current infrastructure of gates provided in the barrage is able to make the additional releases (Figure 5.18).

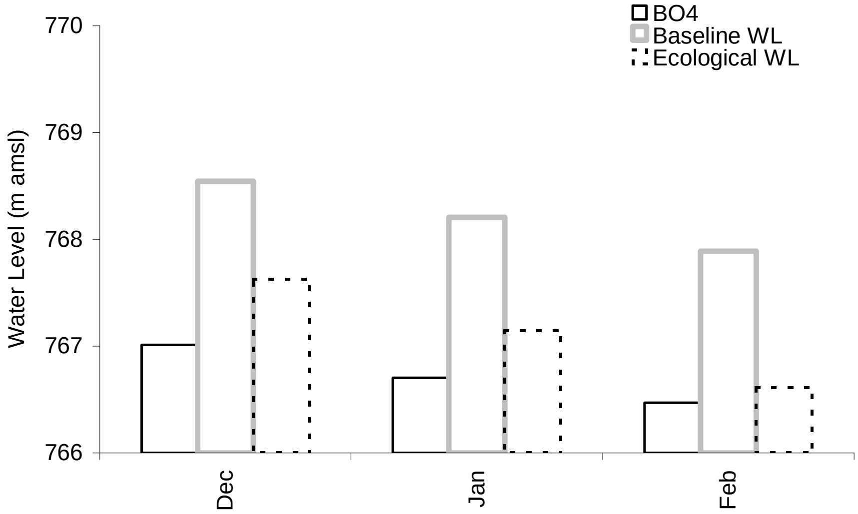

Figure 5.16. Mean monthly water level during December, January and February for BO4

Table 5.4. Phumdi area grounded under the BO4 water level regime

Year	Loktak Lake			KLNP		
	Total *phumdi* area (km^2)	*Phumdi* area grounded (km^2)	% grounded	Total *phumdi* area (km^2)	*Phumdi* area grounded (km^2)	% grounded
December	55.3	40.5	73	19.1	9.2	48
January	55.3	44.2	80	19.1	14.3	75
February	55.3	51.3	93	19.1	16.2	85

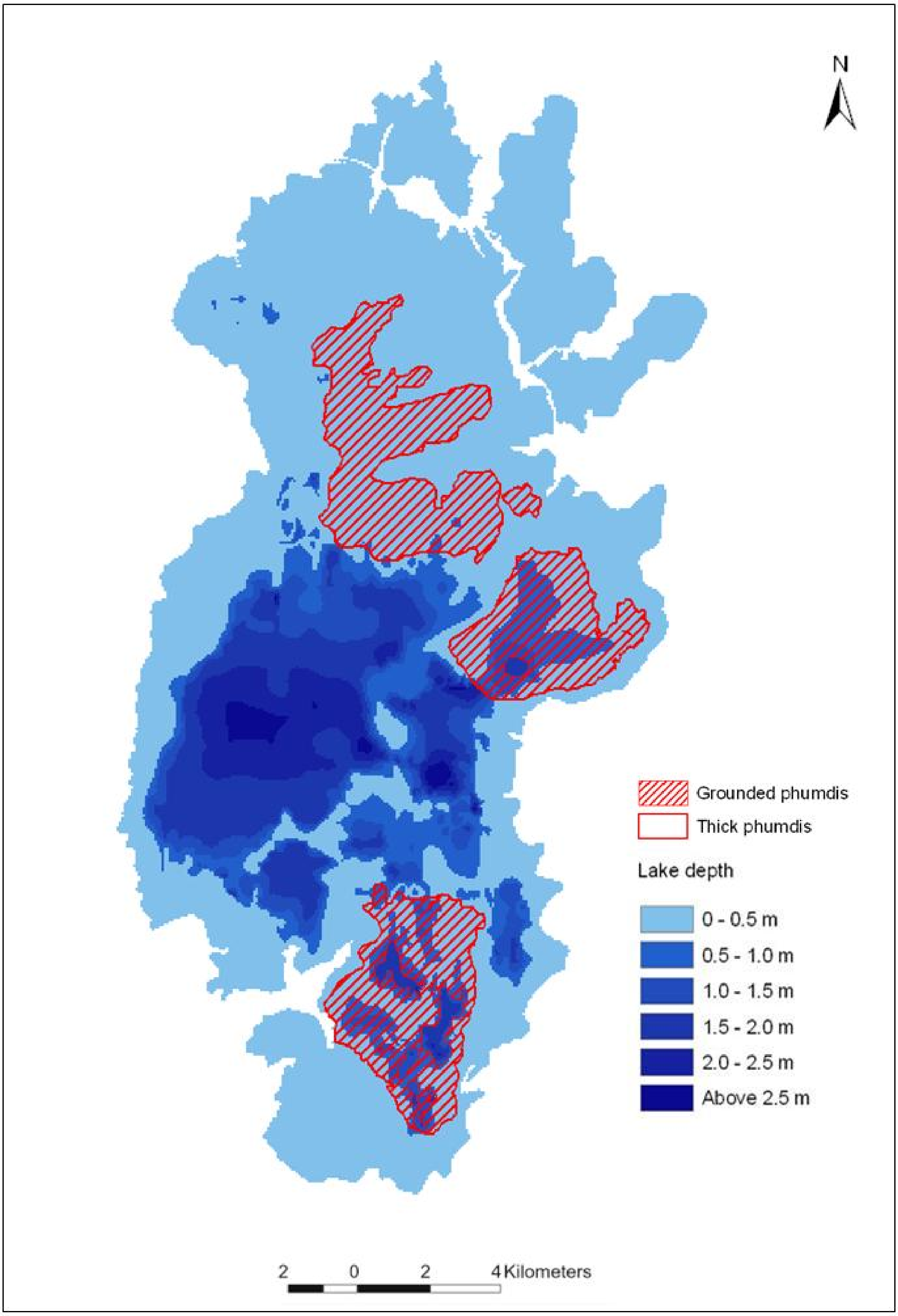

Figure 5.17. Grounding of phumdis during February under BO4 water level regime

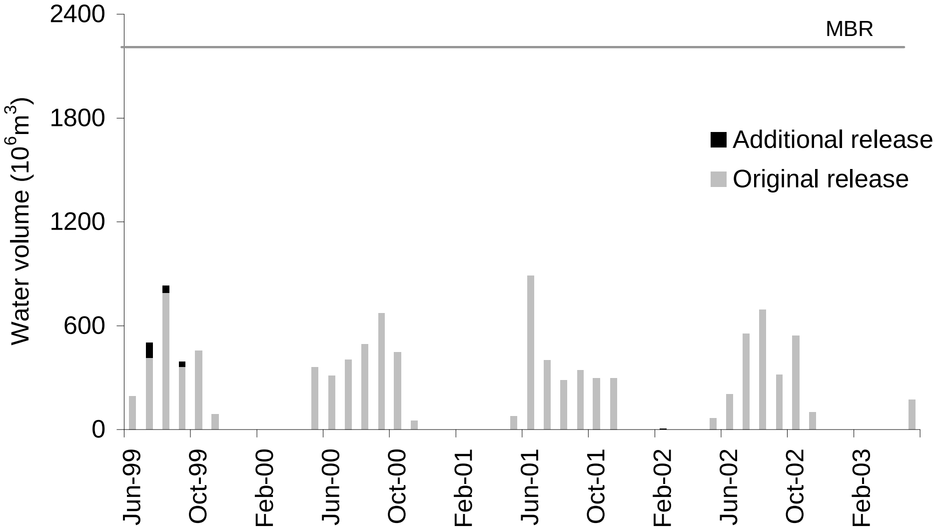

Figure 5.18. Monthly total barrage releases BO4 (MBR: maximum barrage release capacity)

The hydropower sector is able to receive the desired water demand for 43 months out of 48 months under the integrated regime (Table 5.5). Hydropower abstractions during the five months in which the desired demand could not be satisfied are still higher compared to the current baseline regime (Table 5.5). On an average annual basis, the new regime is able to provide 869.83 × 10^6m^3 of water for hydropower generation. This is less than the desired amount of 896 × 10^6m^3, but more than the current baseline hydropower abstraction of 845.01 × 10^6m^3.

The agricultural sector, being the last on the priority list of the four stakeholders considered under the integrated regime option, has the largest shortfall in water supply made. It is able to abstract 70 × 10^6m^3 annually under the new integrated regime, which is considerably less compared to the desired demand of 222 × 10^6m^3 (Table 5.5). However it is 46% higher than the current baseline regime where agriculture is only provided with 48 × 10^6m^3 annually. With the new BO4 water level regime, it will be able to provide irrigation to 96 km^2 of agricultural land in the valley areas of the Loktak catchment compared to 60 km^2 during the baseline condition. The new regime could not satisfy agriculture demands in 15 months (Table 5.5). During these 15 months there is less water available in Loktak Lake compared to its total demands from hydropower and agricultural sectors and hydropower demands are satisfied first.

Table 5.5. Water abstraction for hydropower and agricultural demands

Months	**Current hydropower abstraction** (10^6m^3)	**Desired hydropower abstraction** (10^6m^3)	**Integrated hydropower releases** (10^6m^3)	**Current agricultural abstraction** (10^6m^3)	**Desired agricultural abstraction** (10^6m3)	**Integrated agricultural releases** (10^6m^3)
Jun-99	64.76	73.61	**73.61**	0.00	0.00	**0.00**
Jul-99	63.85	76.07	**76.07**	0.00	0.00	**0.00**
Aug-99	72.72	76.07	**76.07**	0.00	0.00	**0.00**
Sep-99	72.01	73.61	**73.61**	0.00	0.00	**0.00**
Oct-99	79.50	76.07	**76.07**	0.00	8.00	**8.00**
Nov-99	71.70	73.61	**73.61**	8.00	51.55	**8.00**
Dec-99	79.37	76.07	**76.07**	8.00	53.00	**8.00**
Jan-00	79.86	76.07	**76.07**	8.00	53.00	**8.00**
Feb-00	69.10	71.16	**71.16**	8.00	48.64	**8.00**
Mar-00	48.07	76.07	**76.07**	8.00	8.00	**8.00**
Apr-00	69.88	73.61	**73.61**	8.00	0.00	**0.00**
May-00	69.23	76.07	**76.07**	0.00	0.00	**0.00**
Jun-00	69.53	73.61	**73.61**	0.00	0.00	**0.00**
Jul-00	69.15	76.07	**76.07**	0.00	0.00	**0.00**
Aug-00	69.22	76.07	**76.07**	0.00	0.00	**0.00**
Sep-00	71.93	73.61	**73.61**	0.00	0.00	**0.00**
Oct-00	76.28	76.07	**76.07**	0.00	8.00	**8.00**
Nov-00	81.77	73.61	**73.61**	8.00	51.55	**51.55**
Dec-00	86.77	76.07	**76.07**	8.00	53.00	**0.00**
Jan-01	70.46	76.07	**76.07**	8.00	53.00	**0.00**
Feb-01	51.79	68.71	**54.00**	8.00	48.64	**0.00**
Mar-01	47.51	76.07	**50.00**	8.00	8.00	**0.00**
Apr-01	58.95	73.61	**73.61**	8.00	0.00	**0.00**
May-01	66.51	76.07	**76.07**	0.00	0.00	**0.00**
Jun-01	70.45	73.61	**73.61**	0.00	0.00	**0.00**
Jul-01	76.76	76.07	**76.07**	0.00	0.00	**0.00**
Aug-01	76.34	76.07	**76.07**	0.00	0.00	**0.00**
Sep-01	83.04	73.61	**73.61**	0.00	0.00	**0.00**
Oct-01	78.67	76.07	**76.07**	0.00	8.00	**8.00**
Nov-01	73.75	73.61	**73.61**	8.00	51.55	**0.00**
Dec-01	79.68	76.07	**76.07**	8.00	53.00	**0.00**
Jan-02	61.08	76.07	**76.07**	8.00	53.00	**0.00**
Feb-02	65.88	68.71	**68.71**	8.00	48.64	**0.00**
Mar-02	60.85	76.07	**76.07**	8.00	8.00	**0.00**
Apr-02	58.87	73.61	**73.61**	8.00	0.00	**0.00**
May-02	50.77	76.07	**52.00**	0.00	0.00	**0.00**
Jun-02	64.42	73.61	**73.61**	0.00	0.00	**0.00**
Jul-02	76.87	76.07	**76.07**	0.00	0.00	**0.00**
Aug-02	77.26	76.07	**76.07**	0.00	0.00	**0.00**
Sep-02	86.64	73.61	**73.61**	0.00	0.00	**0.00**
Oct-02	87.18	76.07	**76.07**	0.00	8.00	**8.00**
Nov-02	81.60	73.61	**73.61**	8.00	51.55	**51.55**
Dec-02	72.41	76.07	**76.07**	8.00	53.00	**53.00**
Jan-03	49.20	76.07	**51.00**	8.00	53.00	**53.00**
Feb-03	49.60	68.71	**53.00**	8.00	48.64	**0.00**
Mar-03	69.50	76.07	**76.01**	8.00	8.00	**0.00**
Apr-03	84.62	73.61	**73.61**	8.00	0.00	**0.00**
May-03	84.69	76.07	**76.07**	0.00	0.00	**0.00**

Despite some compromises required from hydropower and agricultural water uses, the new integrated regime is able to satisfy 100% of the ecological demands with no incident of flooding in the surrounding areas and an increase in hydropower abstractions by 3% and agricultural abstractions by 46% compared to the baseline.

5.5. Summary

This chapter demonstrates the development of three operation options barrage which prioritise the requirements of the major stakeholders (BO1 – hydropower, BO2 – irrigation and BO3 – lake ecosystem). A fourth option (BO4) was also developed, which shows that it is possible to balance the demands of these stakeholders.

The BO1 water level regime is able to satisfy the agriculture demands as well as reduce flooding in the surrounding areas of the lake. However, it is unable to satisfy the ecological requirement, which is vital to the existence and functioning of the lake ecosystem. The water level regime under BO2 is the only regime where the water level goes below the threshold MDL, indicating inability to supply any water for hydropower for four months, which is not a viable option to the NHPC. The BO3, which prioritizes the ecological demands, is able to provide a water level regime which satisfies both the hydropower and agricultural demands and provides marked improvements in the flooding pattern. Flooding, although improved, still occurs in five months under this regime, which will still incur losses to the communities in the surrounding areas of the lake. The water level regime under BO4 is a viable option to all the stakeholders including the lakeshore communities as it is capable of satisfying both the low water level requirements for the ecological health of the lake and preventing floods in the lake shore communities as well as enhancing the hydropower and agriculture abstractions compared to the current baseline condition. Although the agricultural sector has a shortfall in the supply of water to meet it desire demands, the amount of water allocated for irrigation sector under the BO4 regime is higher (46%) compared to its current baseline allocation. However, climate change is likely to have implications for the catchment as well as the lake hydrology and hence the water level regime. The sustainability of these barrage operation options in the light of climate change is investigated in Chapter 7.

Chapter 6 - Impacts of global climate change on hydrological regime of Loktak Lake

6.1. Introduction

In India, several studies had shown an increasing trend in the surface temperature during the last century (Srivastava et al., 1992; Rupa Kumar et al., 1994; De and Mukhopadhyay, 1998; Singh and Sontakke, 2002; Singh et al., 2001). However, there is a large uncertainty in the impact of climate change on the Indian monsoon (Turner and Slingo, 2009) with some parts of the country projected to receive more rainfall while other less (Rupa Kumar et al., 1992; Mall et al., 2006; Gulati et al., 2009), thereby changing the pattern, frequency and the intensity of extreme rainfall events (floods and droughts, Mall and Kumar, 2009). Gupta et al. (2009) predicted a reduction in runoff from basins located in the eastern part of India including the lower part of the Ganges, while Asokan and Dutta (2008) predicted increases in runoff and flood events in the Mahanadi Basin, another major river of India draining into the Bay of Bengal. Such alterations in hydrological regime, as discussed in Section 1.5, will exacerbate attempts to restore and conserve wetland, especially inland freshwater wetlands, which by their nature are sensitive to slight alterations in the catchment hydro-meteorological conditions.

This chapter investigates the implications of global climate change on runoff from the sub-catchments draining to Loktak Lake and the water level regimes within the lake are examined. This study will be the first to asses the impacts of climate change on the hydrological regime of Loktak Lake.

6.2. Modelling the impact of climate change on catchment runoff

The current study adopts the climate impact assessment approach used by Parry and Carter (1998) which translate specific changes in climatic inputs into changes in hydrological regime. This approach has been widely used to assess climate change impacts on river and wetland hydrological regimes (e.g. Chiew et al., 1995; Viney and Sivapalan, 1996; Arnell, 1999 a and b; Limbrick et al., 2000; Kamga, 2001; Menzel and Burger, 2002; Sharma, 2003; Sharma et al., 2002; Kay et al. 2006; Fowler and Kilsby, 2007; Thompson et al., 2009). It involves the following stages (Arnell and Reynard, 1996): (i) define, calibrate and validate a model of a 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. The first stage of this process is provided by the calibrated MIKE SHE models of the Loktak Lake sub-catchments (Thoubal, Iril and Nambul) described in Chapter 3. These models provide the baseline condition against which the results of climate change simulations are compared.

Two groups of climate change scenarios were investigated. Group 1 was designed to investigate the implications of different Global Climate Models (GCMs) for a 2ºC rise in global mean temperature, the hypothesised threshold for 'dangerous' climate change (Mallon et al., 2007; Jones et al., 2009; 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 were selected from the CMIP-3 database (Meehl et al., 2007; Timbal et al., 2008; Lobell et al., 2008; Wild, 2008; Joly and Voldoire, 2009; Rauscher and Giorgi, 2009) as exemplar GCMs representing different future representations of key global climate system features. These GCMs were also selected for the Quantifying and Understanding the Earth System programme - global-scale impacts of climate change (QUEST–GSI) on water resources at the basin scale project. This research project, funded by Natural Environment Research Council (NERC), UK, aims to assess the impacts of climate change and future development on freshwater resources at the basin scale and quantify uncertainty in the predictions. Loktak Lake was one of the case studies selected for this project. The scenarios of Group 2 were generated for prescribed warming of global mean temperature of 1, 2, 3, 4, 5 and 6°C using the UKMO HadCM3 GCM. The UKMO HadCM3 GCM is one of the most widely used GCM to study impacts of climate change on water resources and environment (Arnell, 1999; Hulme et al., 1999; Johns et al., 2003; Fischer et al., 2005; Bartholy et al., 2009; Doll and Zhang, 2010; Kingston and Taylor, 2010; Thorne, 2010) and is also extensively used in India (Kumar et al., 2006; Asokan and Dutta, 2008; Turner and Slingo, 2009; Gupta at al., 2010).

Hereafter, the climate change scenario Group 1 will be referred to as CCG1 and Group 2 as CCG2. Figure 6.1 presents a schematic diagram detailing the stepwise process for modelling the impact of climate change on catchment runoff from the Loktak sub-catchments. Initially, monthly rainfall data for a past 30 year period (1974–

2003) was obtained from the CRU TS 3.0 dataset (Mitchell and Jones, 2005; Solymosi et al., 2007; Kingston and Taylor, 2010; Klotzbach et al., 2010) and for a future 30 years (2040-2069) generated using the ClimGen pattern-scaling technique described in Todd et al., (2010) for all CCG1 and CCG2 scenarios were procured. ClimGen is a spatial climate scenario generator that uses the pattern-scaling approach to generate spatial climate change information for a given global-average temperature change and given GCM (McKague et al., 2003; Abraha and Savage, 2006; Gosling et al., 2009). These data were obtained for the 17 0.5°×0.5° grid cells covering the Loktak catchment Both these datasets were provided by the QUEST-GSI project. The mean monthly rainfall for the past 30 years as well as the future 30 years was estimated for each grid cells. The difference in the average mean monthly rainfall between past and future 30 years were estimated as a % change, which defines delta factors by which the original daily rainfall data used in the calibration and validation of MIKE SHE models for the baseline period (June 1999–May 2003) were modified. The perturbation of the rainfall data is discussed in detail in Section 6.2.1.

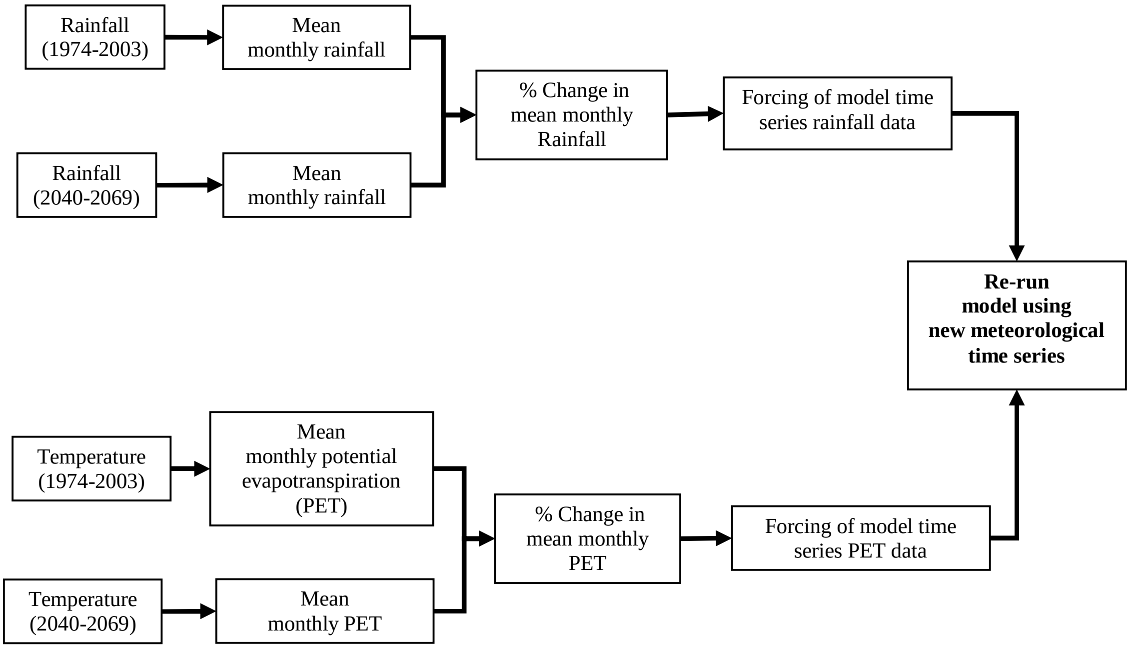

Figure 6.1. Schematic diagram of the climate change modelling process

Similarly, monthly temperature data (maximum, minimum and mean) for a past 30 year period (1974–2003) from the CRU TS 3.0 dataset and a future 30 year period (2040 2069) generated using the ClimGen pattern-scaling technique were procured for the same 17 0.5°×0.5° grid cells. These data were used to derive monthly and subsequently the mean monthly evapotranspiration (PET) of each grid cells for both the past and future 30 years. Similar to the rainfall data, the difference in the mean monthly PET between past and future 30 years were estimated as a % change (delta factor) for each grid cell by which the original daily PET data used earlier in MIKE SHE models for the baseline period were modified. The perturbation of the PET data is discussed in detail in Section 6.2.2.

These perturbed meteorological data (rainfall and PET) were subsequently used within the three MIKE SHE models of Loktak Lake sub-catchments (Thoubal, Iril and Nambul) to evaluate the modified runoff induced by the climate change scenarios. These simulated discharges were then employed to re-evaluate discharges for ungauged sub-catchments using the method described in Section 3.5.

6.2.1. Generation of perturbed rainfall data

The perturbed rainfall data was estimated following the procedure described in Figure 6.1. The grid cells which cover the influence area of each rain gauge within the Loktak catchment were computed by overlaying the layer of grid cells over the layer of Thiessen polygons of rain gauge stations described in Section 2.3.1 using ArcGIS. The grids covering the influence area of each station are shown in Table 6.1.

Table 6.1. Grid cells covering the influence area of each rain gauge stations

Rain gauging stations	**Grid cells**
KNLP	1,2,3,4,7
Komkeirap	6,7,9,11
Singda	9,11
Awang Sekmai	11,12,14
Dolaithabi	11,12,13,14,15,16,17
Kangla Siphai	7,8,9,10,12
Pallel	4,5,7,8

The delta factors for all CCG1 and CCG2 scenarios for each of the rain gauges were then estimated based on these grid cells. Figures 6.2 and 6.3 shows the average monthly % change (delta factor) in rainfall for all CCG1 and CCG2 scenarios. The CCG1 scenarios show a mixed pattern of changes in rainfall within the catchment. The CCCMA and HadGEM1 GCMs show an increase in the rainfall almost throughout the year except for slight decreases during January and December. The CCCMA GCM shows a maximum increase of 46.2 % in April at Awang Sekmai meteorological station while a maximum decrease of 4.2 % at KLNP in December. The HadGEM1 GCM

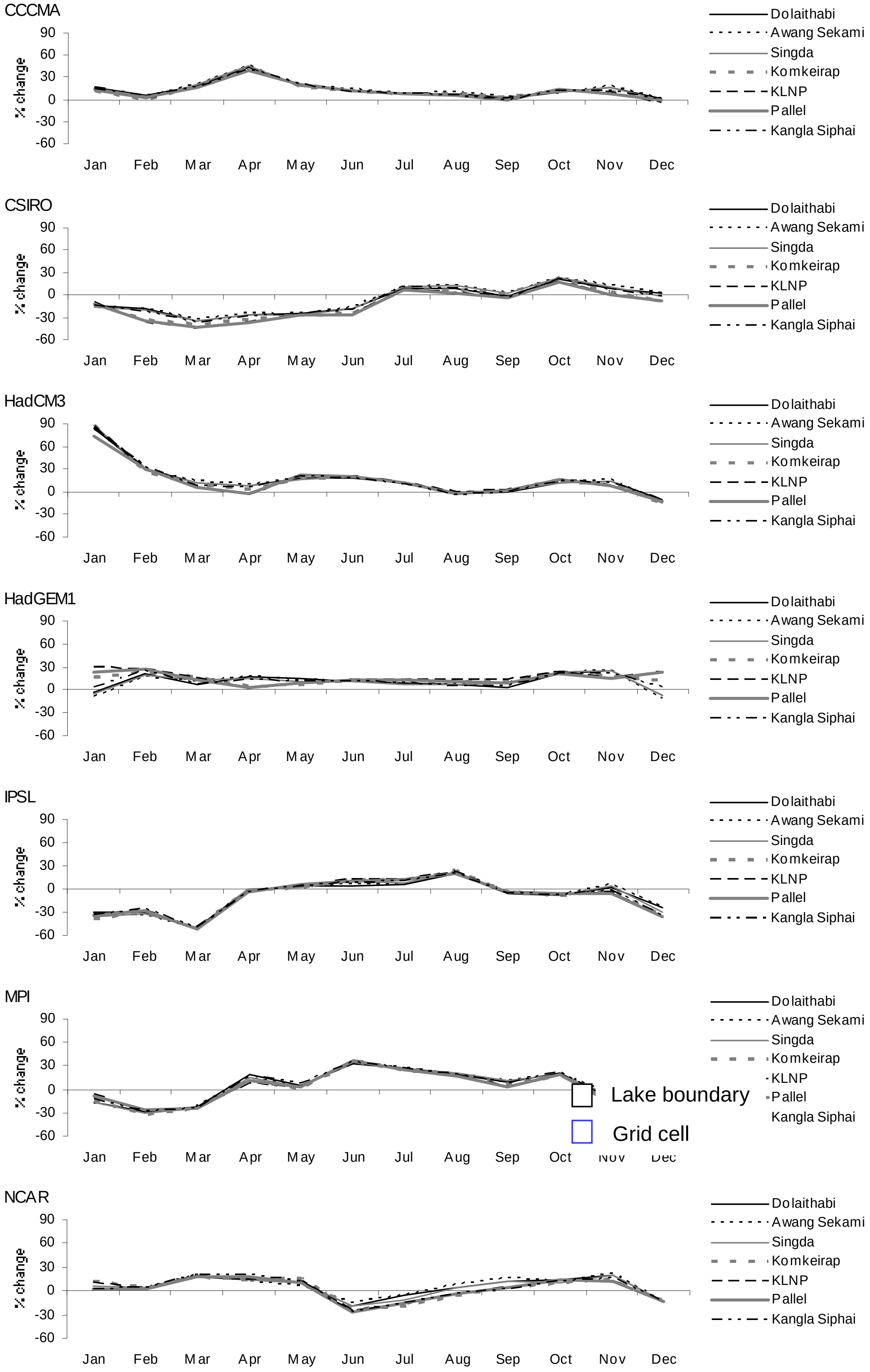

Figure 6.2. Mean monthly % change in rainfall for all rain gauging stations under CCG1 scenarios

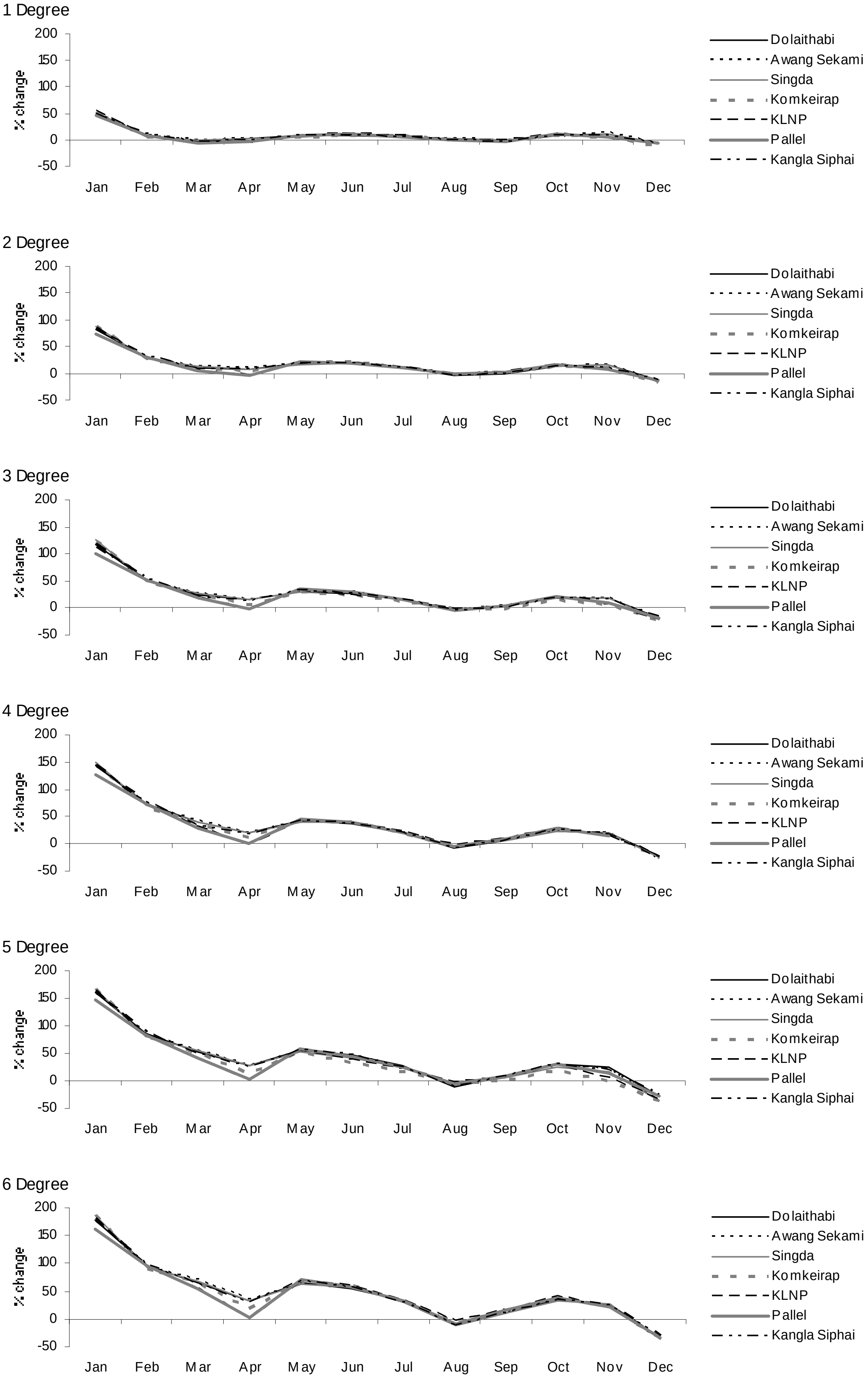

Figure 6.3. Mean monthly % change in rainfall for all rain gauge stations under CCG2 scenarios

produced a maximum increase of 29.9 % at KLNP in January, while a maximum decrease of 10.5 % at Awang Sekmai in December. The HadCM3 GCM also shows increasing rainfall at all the stations except for a small decrease during the months of April (only KLNP and Pallel stations), August and December. The maximum increase under HadCM3 GCM was for Singda (88.1 %) in January while a maximum decrease at KLNP (15.2 %) in December. The CSIRO GCM estimated a small increase for all stations during four months (July, August, October and November) while for the remaining 8 months, rainfall decreases. A maximum decrease of 44.85 % for the CSIRO GCM scenarios was at KLNP in March. The IPSL GCM scenario shows an increase in rainfall during May–August, while for the rest of the year it decreases at all seven rain gauges. The maximum increase of 21.0 % was at Pallel in August while a maximum decrease of 52.1 % was estimated for the Dolaithabi station in March. The MPI GCM shows an increase in rainfall during the months of April–October while rainfall decreases during September–March. The largest increase (37.1 %) was at Pallel in June while the largest decrease (31.5 %) was at Komkeirap during February. The NCAR GCM shows an increase in rainfall for all stations throughout the year except for June, July and December. The largest increase (20.1%) in November was at Singda while the largest decrease (26.9%) in June was Pallel. As stated in Section 2.3.1, rainfall during the four monsoon months accounts for 63% of total annual rainfall. Alteration in the rainfall pattern during these monsoon months is critical, and is likely to have significant implications on the runoff from the sub-catchments. The HadGEM1, CCCMA and MPI GCMs were the CCG1 scenarios, which show a consistent increase in rainfall across all stations during the monsoon months.

The CCG2 scenarios show a more consistent pattern of changes in rainfall within the catchment area. Rainfall was estimated to increase gradually with the increase in global temperature from 1°C to 6°C (Figure 6.3) for all stations throughout the year except for August and December where the rainfall decreases gradually with the rise in global mean temperature. A maximum increase of as high as 186.4 % was estimated at Sindga during January for the 6°C rise in global temperature. The maximum decrease of 40.0 %, again associated with the 6°C rise, was estimated during December at Awang Sekmai.

For each scenario, there are 12 delta factors estimated corresponding to each month. The observed daily rainfall data for all seven rain gauges, which was previously used in MIKE SHE models were then, multiply by the delta factor for the corresponding month to derive the perturbed daily rainfall data for all the stations.

The changes in the mean annual rainfall of each of the modelled sub-catchments of both CCG1 and CCG2 scenarios are shown in Table 6.2. Changes in annual rainfall for the CCG1 scenarios (different GCMs with a 2°C increase in the global mean temperature) vary between GCMs and sub-catchments. In the Thoubal sub-catchment annual rainfall increases between 3% and 17% for the CCCMA, IPSL, 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 rainfall, produces a decrease of 3%. In contrast, for the Nambul sub-catchment annual rainfall increases for all the GCMs although this increase does vary between 4% and 26%. It is lowest for the CSIRO and NCAR GCMs.

Table 6.2. Changes in rainfall for the modelled sub-catchments due to climate change

Group	**Parameter**	**Scenario**	**Thoubal (mm)**	**% change**	**Iril (mm)**	**% change**	**Nambul (mm)**	**% change**
CCG1	Rainfall	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
CCG2	Rainfall	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

Figure 6.4 shows that for these two GCMs, rainfall decline~~s~~ in the early part of the monsoon period (in particular June). Although the peak August rainfall is very similar (NCAR) or greater (CSIRO) to the baseline, towards the end of the rainy period (September and October) it is generally wetter. The early monsoon decline in rainfall account for the overall reduction in mean annual rainfall. The most noticeable change

for the GCMs associated with larger annual rainfall total is the increase in early monsoon (June) rainfall. In some cases (e.g. the HadCM3 for the Iril and Nambul sub-catchments) June rainfall exceeds that of August, historically the wetter month, which also increases. Rainfall in the late monsoon period (September and October) is also higher.

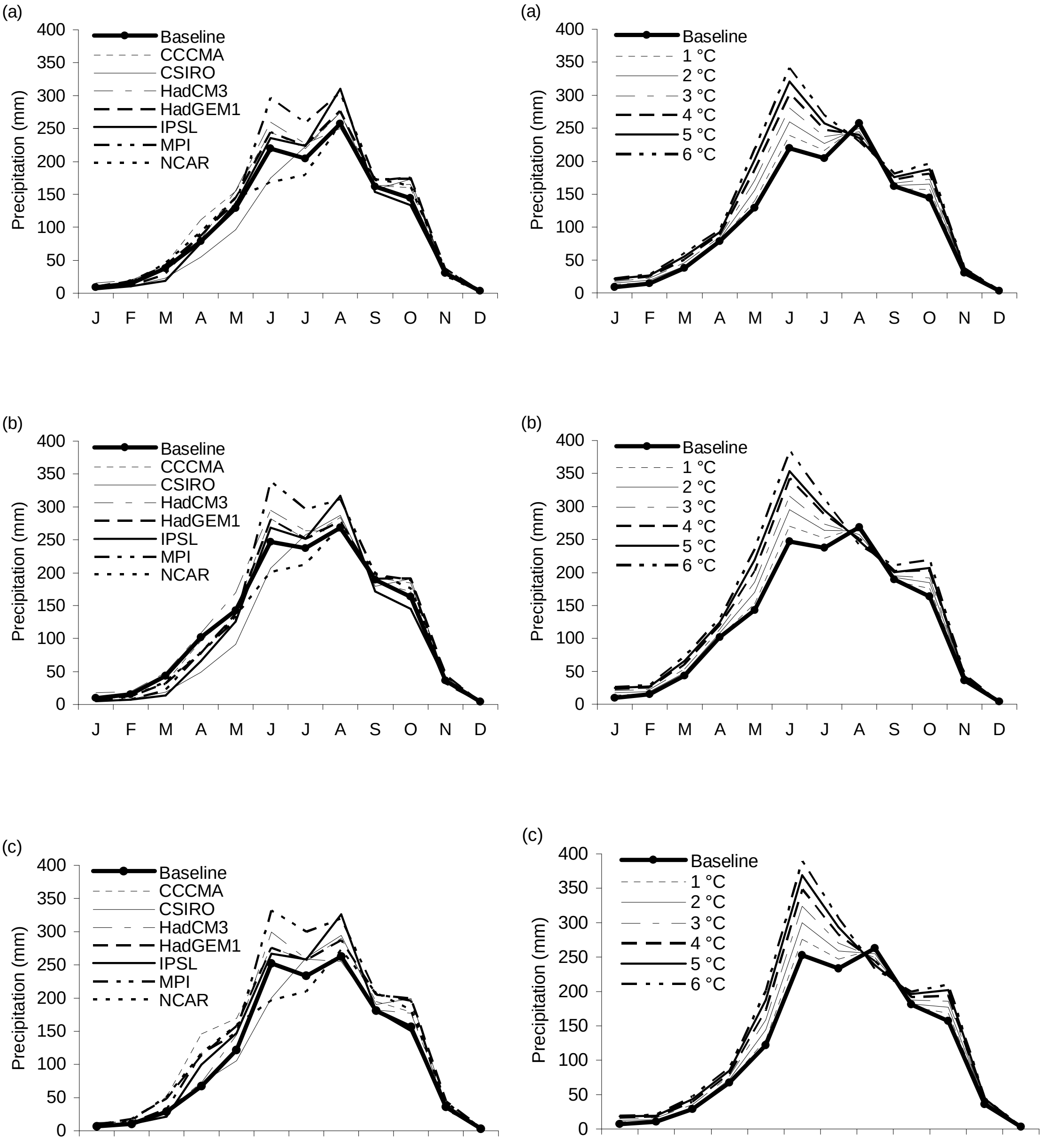

Figure 6.4. Perturbed mean monthly rainfall in modelled sub-catchments for the CCG1 and CCG2 scenarios (a) Thoubal, (b) Iril, (c) Nambul

For the CCG2 (changes in global mean temperature of between 1°C and 6°C using HadCM3) mean annual rainfall increases almost linearly with each 1°C increase in temperature (Table 6.2, Figure 6.5). Changes are consistent over the three sub-catchments. Figure 6.4 shows that increasing annual rainfall is largely due to the result of higher rainfall in the early monsoon period. Beyond an increase of 1°C there is a switch in peak rainfall from August to June whilst more rainfall occurs in months leading up to this new wettest month. Although August rainfall falls slightly below the baseline for all the scenarios, later months, in particular October, are also progressively wetter with increasing temperature.

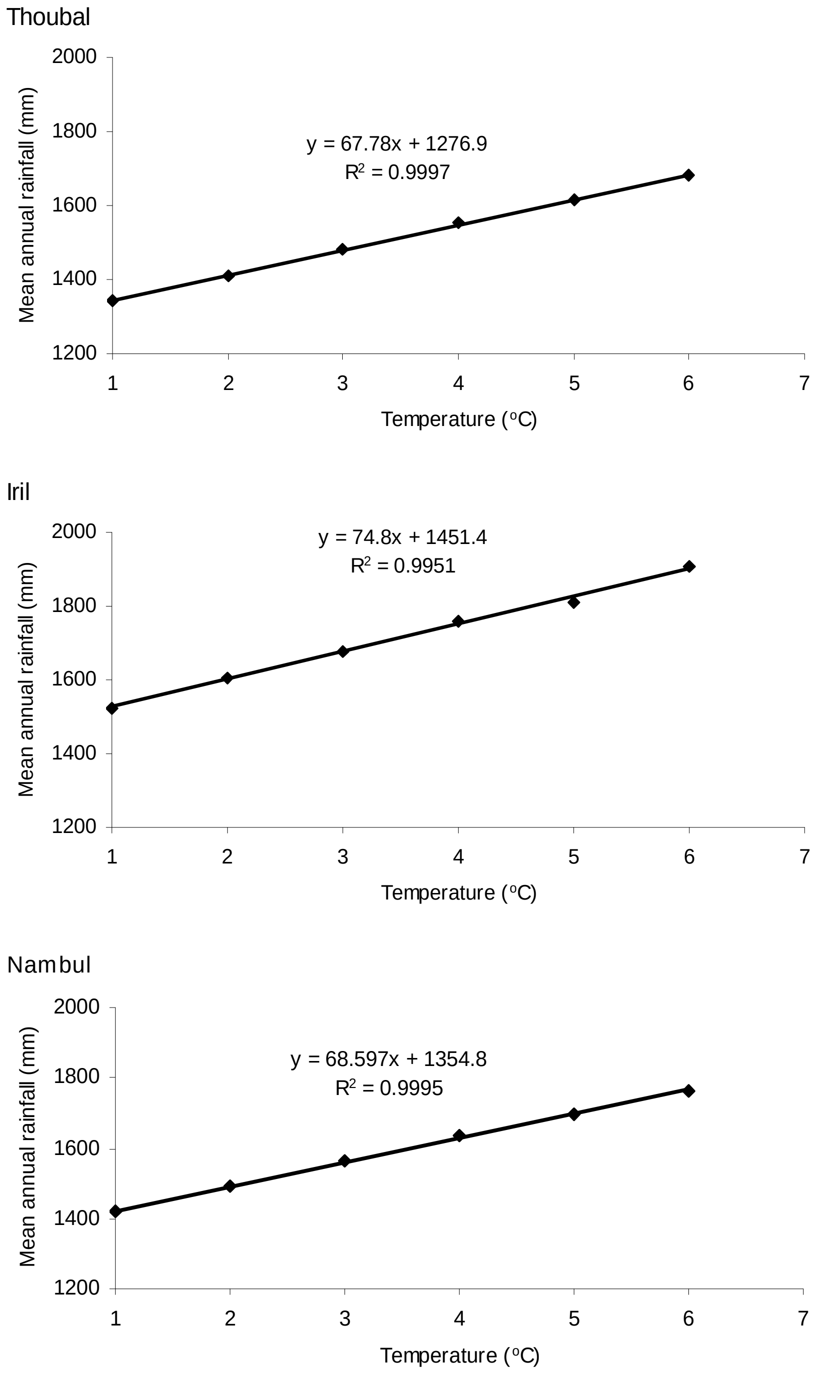

Figure 6.5. Relationship between perturbed mean annual rainfall and temperature

6.2.2. Generation of perturbed evapotranspiration data

The perturbed PET data, similar to the perturbed rainfall data, was estimated following the procedure described in Figure 6.1. Using the temperature data procured for the past and future 30 year period, as discussed above, the monthly PET were estimated for all 17 grid cells. In the absence of sufficient data for CSIRO and HadGEM1 GCMs, monthly PET could not be calculated using the Penman-Monteith method. Therefore, the Hargreaves method, recommended by the FAO in such situations (Allen et al., 1998; Kingston et al., 2009) as well as Thornthwaite method, one of the widely used methods in India (Kumar et. al, 1987; Leichenko et al., 2004; Roy et al., 2006, Bautista and Bautista, 2009) were employed.

Kingston et al. (2009) noted that employing different methods of estimating PET can produce marked difference in climate change signals. Similar variation was also demonstrated by Kingston and Taylor (2010) in Mitano Basin, southwestern Uganda, when PET was estimated using Hargreaves, Penman-Monteith and Priestley-Taylor methods. In order to assess the sensitivity of catchment runoff and subsequently on the Loktak Lake water level regime, to the choice of PET evaluation methods, the two above mentioned methods for PET estimation (Hargreaves and Thornthwaite methods) were used in the current study.

6.2.2.1. Perturbation of original PET data using the Hargreaves method

Using the temperature data, monthly PET for all the 17 grid cells for the past as well as future 30 year periods was estimated using Hargreaves equation (6.1, Choisnel et al., 1992).

$$PET_{H} = 0.0023 \times Ra \times (T_{mean} + 17.8) \times (T_{max} - T_{min})^{1/2} \qquad (6.1)$$

where:

Ra	is extraterrestrial radiation (calculated from latitude and time of year)
T_{mean}	is mean temperature
T_{min}	is minimum temperature
T_{max}	is maximum temperature

Subsequently, the mean monthly PET and the delta factor for each grid cell for all the CCG1 and CCG2 scenarios were computed. The grid cells, which cover the influence area of each meteorological station within the Loktak catchment, were established by overlaying the layer of grid cells over the layer of Thiessen polygons of meteorological stations as described in Section 2.3.2. The grids covering the influence area of each meteorological station are shown in Table 6.3.

The delta factors for all CCG1 and CCG2 climate change scenarios for each of the meteorological stations are estimated based on the grids falling in the influence area of each station as described in Table 6.3. Figures 6.6 and 6.7 shows the % change in PET for all CCG1 and CCG2 scenarios for all meteorological stations. The PET increases for all CCG1 scenarios across all stations. The maximum percentage increase of 18.9% is for the CSIRO GCM in June at the KLNP station while the minimum increase of just 0.3% is seen in October for the NCAR GCM at the Pallel station. The CCG2 scenarios show a consistent increase in PET with increase in temperature. The smallest increase of 1.8% at Dolaithabi is associated with a 1°C rise in global mean temperature while the largest increase of 29.7% is for the same station with a 6°C rise in temperature.

Table 6.3: Grid cells covering the influence area of each meteorological station

Rain gauging stations	Grid cells
KNLP	1,2,3,4,7
Komkeirap	6,7,9,11
Dolaithabi	9,10,11,12,13,14,15,16,17
Pallel	4,5,7,8,9,10

Similar to the estimating of the perturbed rainfall data, 12 delta factors corresponding to each month were estimated for each climate change scenarios. The observed daily PET data for all four meteorological stations were then multiplied by the delta factor for the corresponding month to derive the perturbed daily PET data for all the stations. Based on this station-wise perturbed PET data, the daily PET of each of the modelled sub-catchments for the period June 1999–May 2003 were re-evaluated following a similar methodology to that discussed in Section 3.4.1.

The changes in the mean annual PET of each of the modelled sub-catchments for both the CCG1 and CCG2 scenarios are shown in Table 6.4. All CCG1 scenarios show an increase in the mean annual PET with the largest absolute increases occurring between April and August (Figure 6.8). In the Thoubal sub-catchment annual PET increases between 3% and 14%, while in the Iril sub-catchment the increases vary between 3-20%. PET in the Nambul sub-catchment increases between 1 and 12%. The CSIRO

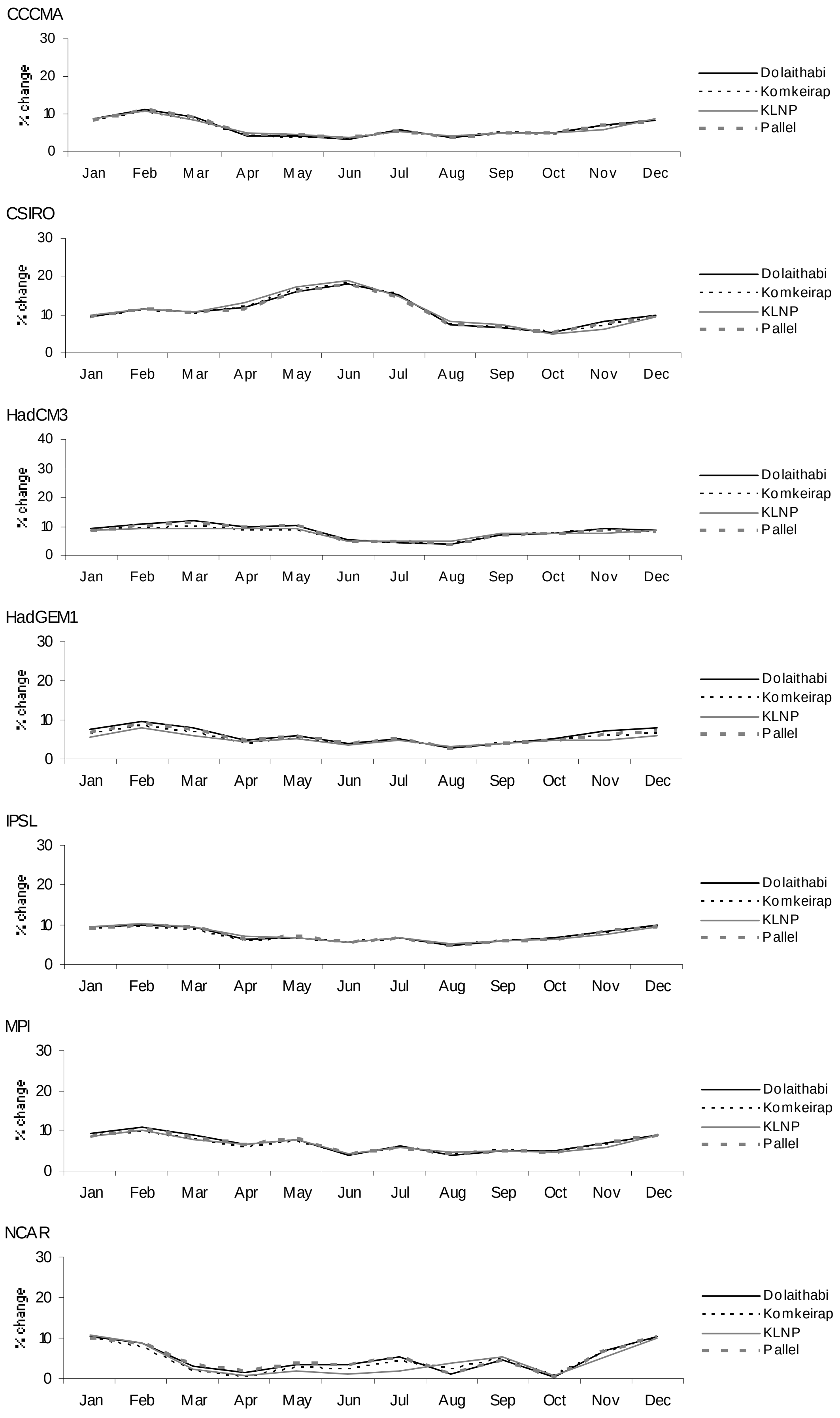

Figure 6.6. Mean monthly % change in PET for all meteorological stations under CCG1 scenarios estimated using Hargreaves method

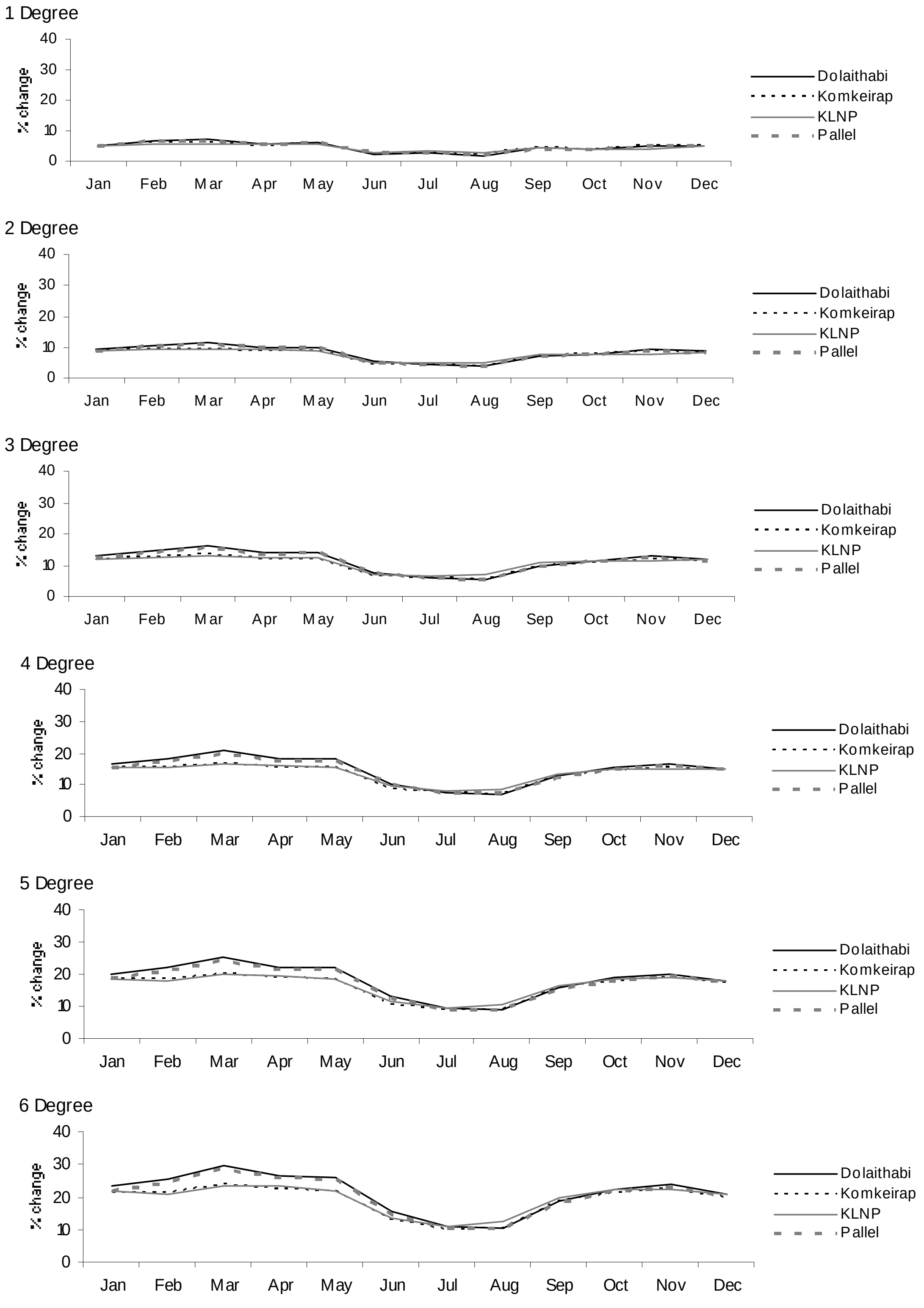

Figure 6.7. Mean monthly % change in PET for all meteorological stations under CCG2 scenarios estimated using Hargreaves method

GCM followed by the HadCM3 GCM 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 CCG2 scenarios, mean annual PET for all three sub-catchments increases almost linearly with increasing temperature (Table 6.4, Figure 6.9). The Iril sub-catchment, which under baseline condition has the largest annual PET, experiences the largest increases (11% increase in the annual PET with 1°C rise in temperature to 27% increases in annual PET with 6°C rise in temperature). Each month experiences higher PET with the largest absolute increases occurring between March and May (Figure 6.8).

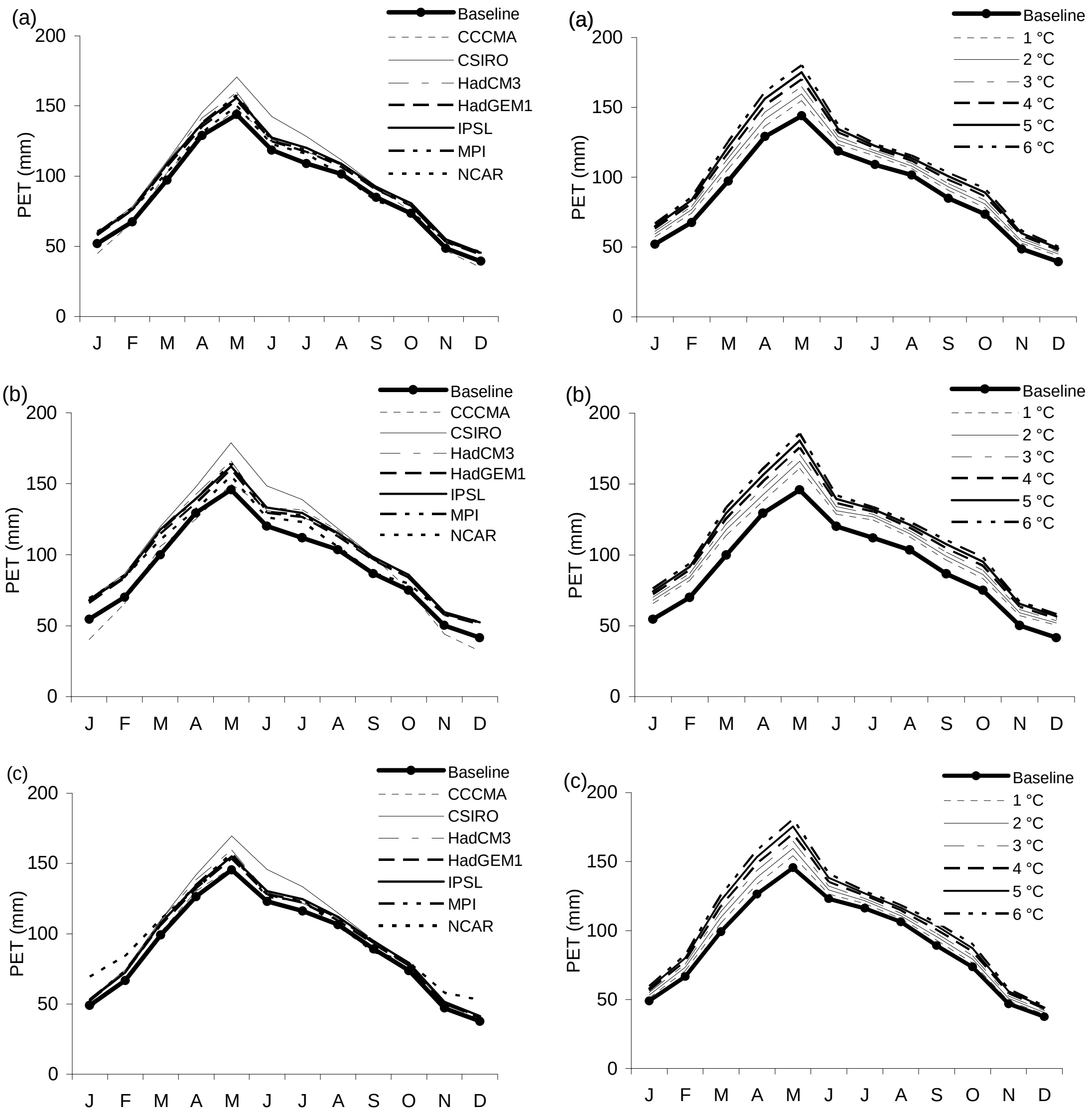

Figure 6.8. Perturbed mean monthly evapotranspiration using Hargreaves method in modelled sub-catchments for the CCG1 and CCG2 scenarios (a) Thoubal, (b) Iril, (c) Nambul

Table 6.4. Changes in PET for the modelled sub-catchments due to climate change scenarios perturbed using Hargreaves method

Group	Parameter	Scenario	Thoubal (mm)	% change	Iril (mm)	% change	Nambul (mm)	% change
CCG1	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
CCG2	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

6.2.2.2. Perturbation of original PET data using the Thornthwaite method

The process of perturbing PET data using the Thornthwaite method for all CCG1 and CCG2 scenarios is similar to that which employs the Hargreaves method. It uses the Thornthwaite method for estimating monthly PET (6.2; Thornthwaite, 1948; Thornthwaite and Mather, 1955).

$$\mathrm{PET}_{\mathrm{T}} = 16\,(10\,t/I)^{a} \qquad (6.2)$$

where:

t is mean monthly temperature (°C)

I is a heat index for a given area which is the sum of 12 monthly index values *i*.

i is $(T/5)^{1.514}$

a $0.675 \times 10^{-6} I^{3} - 0.771 \times 10^{-4} I^{2} + 0.1792 \times 10^{-1} I + 0.49239$

Figure 6.10 shows that for all the CCG1 scenarios, PET increases at all meteorological stations. However, the magnitude of increase varies across the GCMs and between stations. The maximum increase is estimated at the Komkeirap station in May for the CSIRO GCM while the minimum increase is at the Dolaithabi station in April for the NCAR GCM. All CCG2 scenarios show a gradual increase in PET with increase in global mean temperature from 1°C to 6°C for all stations (Figure 6.11). The smallest increase (2.0%) is associated with the 1°C rise in the global mean temperature at the Dolaithabi station in August while the largest increase (138.0%) is associated with the 6°C rise in temperature at KLNP in November.

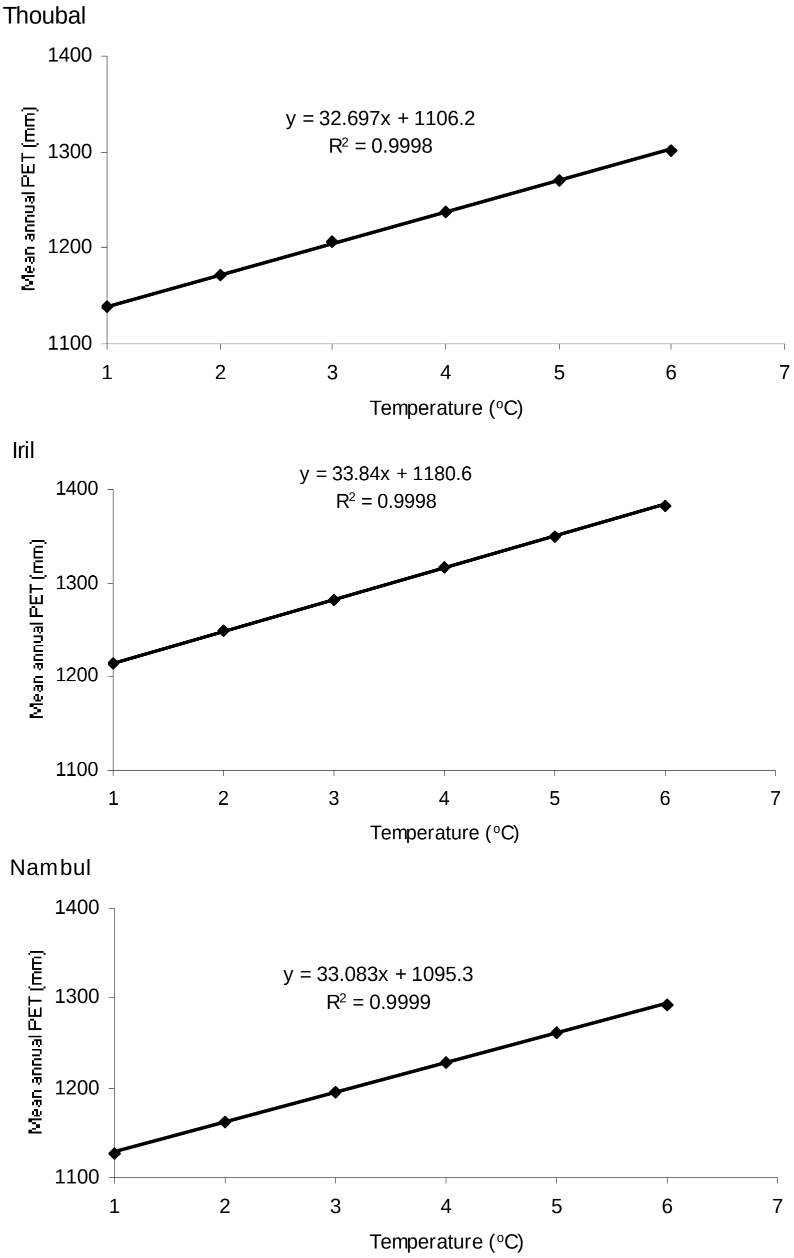

Figure 6.9. Relationship between perturbed mean annual PET using the Hargreaves method and temperature

The new perturbed daily PET data for all four meteorological stations for the CCG1 and CCG2 scenarios were estimated by multiplying the 12 delta factors corresponding to each month by the original PET data. Table 6.5 shows that mean annual PET for all the CCG1 scenarios increases across all meteorological stations. The range of increases in annual PET are between 11–26% with the HadCM3 GCM producing the largest increases in all sub-catchments and the smallest associated with the NCAR and HadGEM1 GCMs. Figure 6.12 shows the mean monthly for the three sub-catchments for CCG1 scenarios, which demonstrates that the largest increase in the PET occur

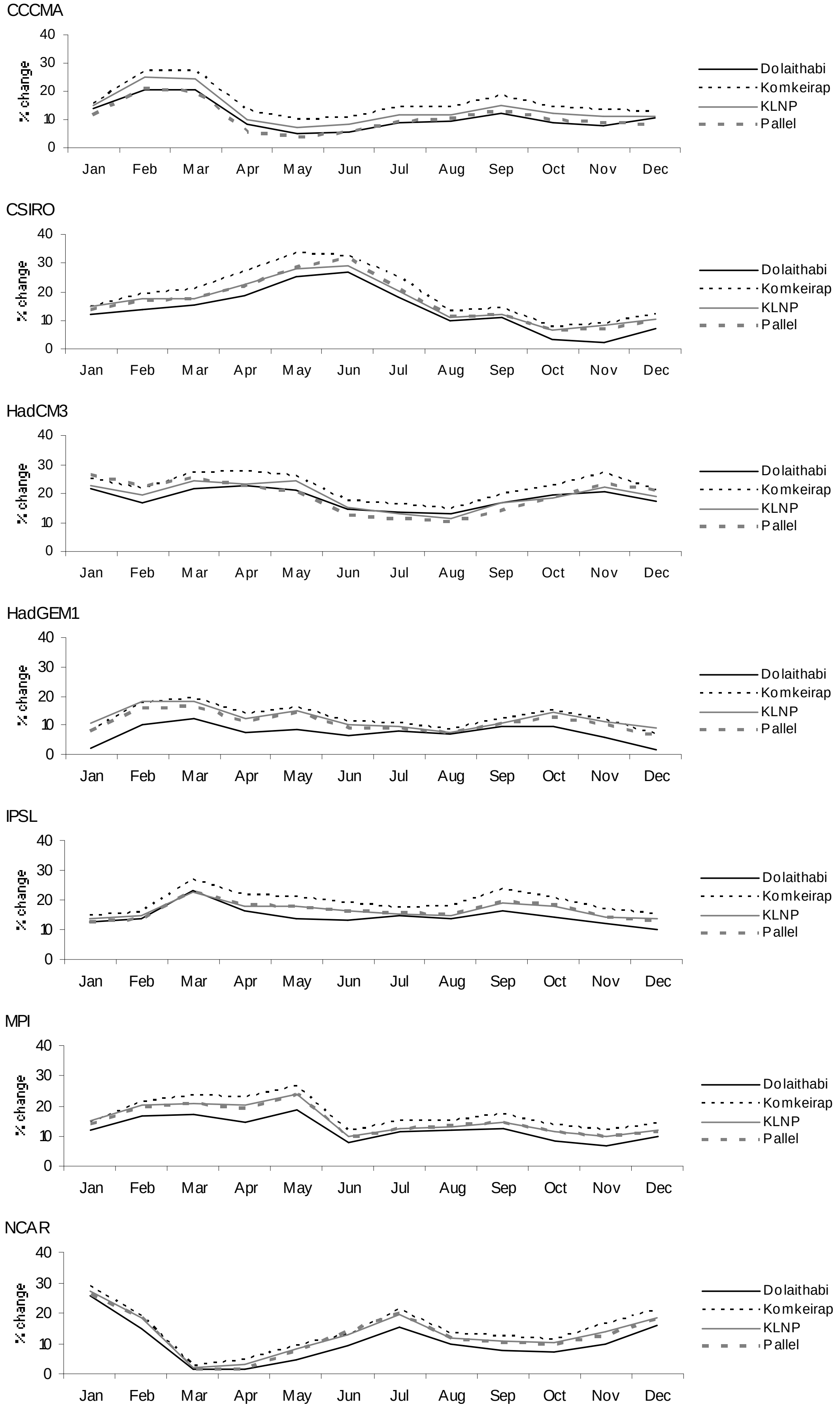

Figure 6.10. Mean monthly % change in PET for all meteorological stations under CCG1 scenarios estimated using the Thornthwaite method

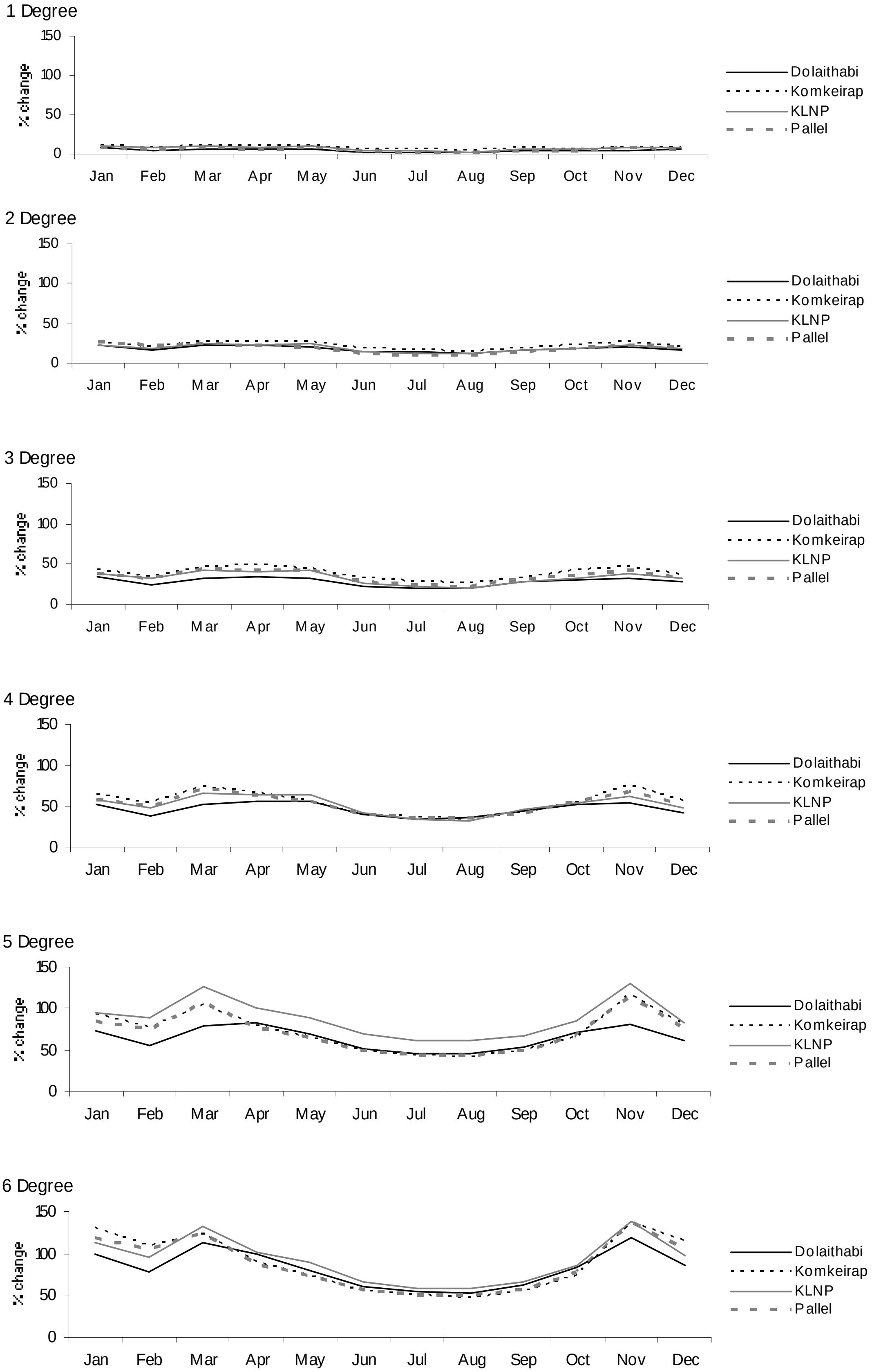

Figure 6.11. Mean monthly % change in PET for all meteorological stations under CCG2 scenarios estimated using the Thornthwaite method

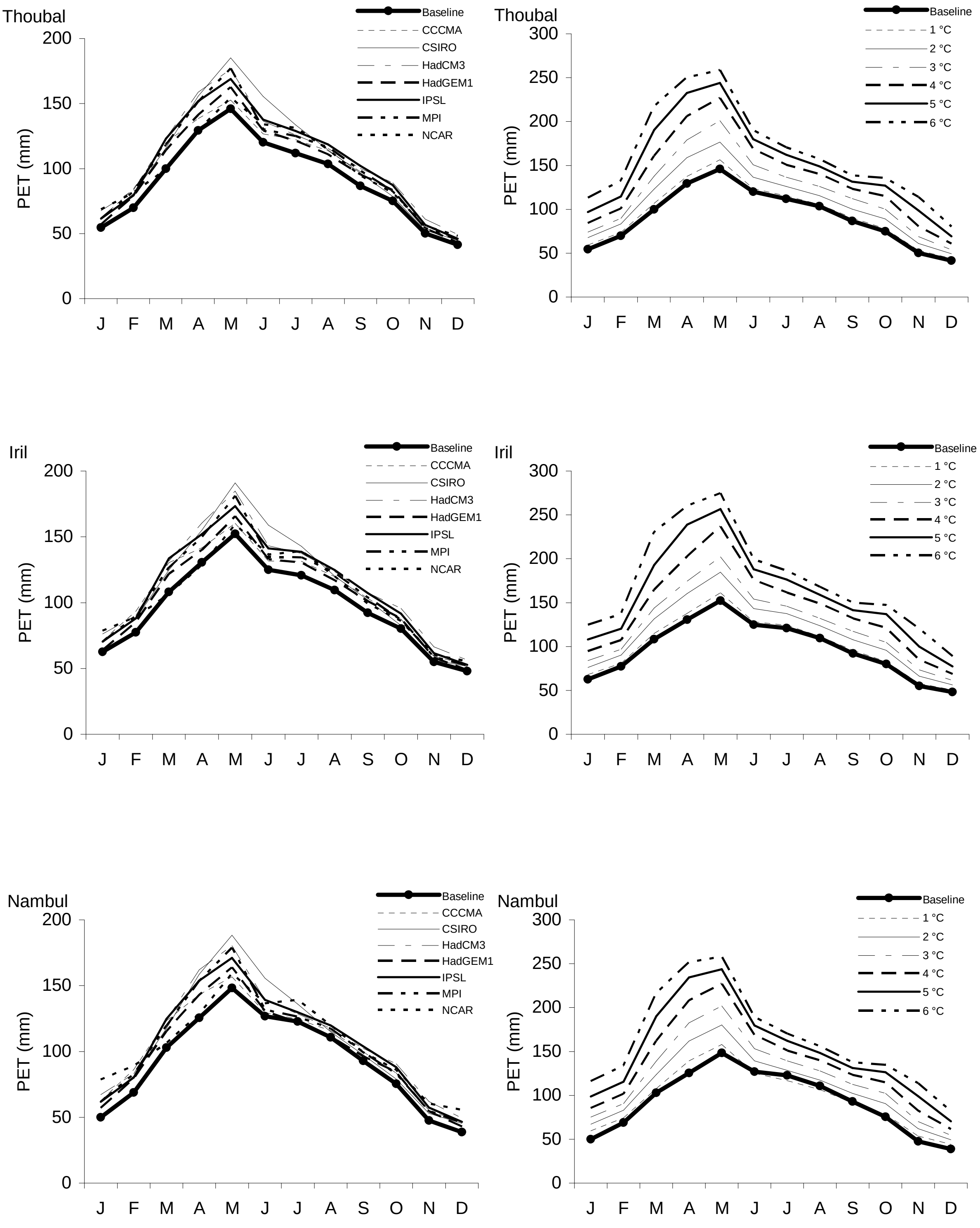

Figure 6.12. Perturbed mean monthly evapotranspiration using the Thornthwaite method in modelled sub-catchments for the CCG1 and CCG2 scenarios

between April and August. The CCG2 scenarios show an almost linear increase in the mean annual PET with increase in temperature from 1°C to 6°C (Figure 6.13). Each month experiences higher PET with the largest absolute increases occurring between March and May (Figure 6.12). These changes are consistent across the different sub-catchments (Table 6.5). The range of increase in the mean annual PET ranges between 7-84%, 11-92% and 7-82% for Thoubal, Iril and Nambul sub-catchments, respectively, with the smallest increases associated with the 1°C rise in global mean temperature and the largest increases associated with 6°C rise in temperature.

Table 6.5. Changes in PET for the modelled sub-catchments due to climate change scenarios perturbed using the Thornthwaite method

Group	**Scenario**	**Thoubal (mm)**	**% change**	**Iril (mm)**	**% change**	**Nambul (mm)**	**% change**
CCG1	Baseline	1064.2	-	1088.7	-	1078.8	-
	CCCMA	1199.4	13	1282.9	18	1227.1	14
	CSIRO	1275.0	20	1343.4	23	1289.2	20
	HadCM3	1287.1	21	1373.4	26	1306.0	21
	HadGEM1	1191.3	12	1252.9	15	1201.0	11
	IPSL	1262.4	19	1335.4	23	1276.6	18
	MPI	1243.8	17	1311.3	20	1255.9	16
	NCAR	1193.6	12	1259.1	16	1201.9	11
CCG2	Baseline	1064.2	-	1088.7	-	1078.8	-
	1°C	1144.0	7	1213.8	11	1155.2	7
	2°C	1287.1	21	1373.4	26	1306.0	21
	3°C	1430.4	34	1490.6	37	1448.7	34
	4°C	1618.2	52	1699.4	56	1627.0	51
	5°C	1796.3	69	1896.4	74	1800.3	67
	6°C	1959.2	84	2087.7	92	1960.9	82

6.2.3. Implication of climate change scenarios on catchment runoff

The changes in runoff from the modelled Loktak sub-catchments (Thoubal, Iril and Nambul) for all CCG1 and CCG2 scenarios were simulated by re-running the MIKE SHE models using the perturbed meteorological data. These simulated runoff were then employed to re-evaluate the modified discharges for the ungauged sub-catchments (Imphal, Kongba, Khuga and Western sub-catchment) using the method described in Section 3.5. Two different methods (Hargreaves and Thornthwaite) were employed to perturb the PET data in order to assess the sensitivity of catchment runoff to the PET evaluation method.

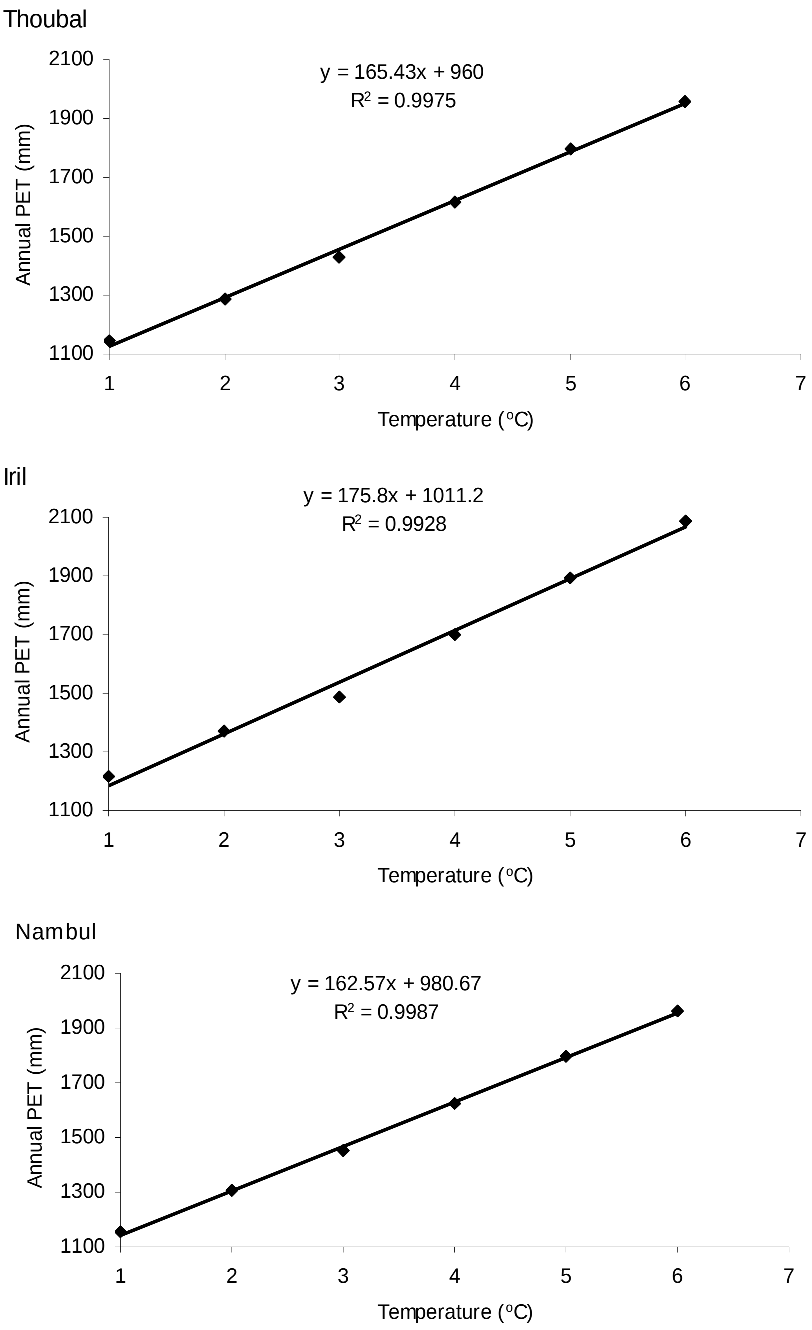

Figure 6.13. Relationship between perturbed PET using the Thornthwaite method and temperature

6.2.3.1. Simulation of catchment runoff using PET data perturbed using the Hargreaves method.

Figure 6.14 demonstrate that the simulated mean monthly discharges for Thoubal, Iril and Nambul sub-catchments for all the CCG1 scenarios for the period June 1999–May 2003 vary across GCMs and between sub-catchments. The largest increase in discharge (82% for Nambul, 53% for Iril and 45% for Thoubal) was estimated for the MPI GCM during June 2001. All GCMs except for the IPSL and CSIRO shows an increase in the simulated discharges during the monsoon months in all the three sub-catchments. During the dry months, all GCMs in all the three sub-catchment indicated a decrease in discharge throughout the simulation period. Figure 6.15 summarises the impacts of CCG1 scenarios on simulated discharge for each of the three modelled sub-catchments as well as the total river inflow into the Loktak Lake (i.e. the combined flow of the three modelled sub-catchments and the four ungauged sub-catchments). Within the Nambul (Figure 6.15c) increases in mean discharge are indicated for all scenarios with magnitudes varying from 7% (CSIRO and HadCM3) to 42% (MPI) (Table 6.6). The relative magnitude of these changes generally follows those shown for rainfall. The earlier onset of monsoon rainfall 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 rainfall, discharges increase towards the end of the monsoon period. Similar temporal changes in the distribution of river flows are shown for the Iril sub-catchment although pre-monsoon discharges are lower than under baseline conditions (Figure 6.15b). The magnitude of increases in mean discharge are consistently smaller compared to the Nambul whilst the CSIRO, ISPL and NCAR GCMs, which over the Iril produced decline in annual rainfall of 8%, 3% and 6% (Table 6.4), result in 15%, 6% and 9% (Table 6.6) reductions in mean discharge respectively. In the Thoubal sub-catchment (Figure 6.15a) increases in mean discharge occur for the CCCMA and MPI GCMs although for the former this increase is very small (0.39%) (Table 6.6). Increases in discharge for these scenarios are concentrated in the monsoon period with lower dry season flows than those under baseline conditions.

Those scenarios showing relatively small decreases in mean discharge for the Thoubal (HadCM3 and HadGEM1) still result in higher discharges 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 decline in mean discharge (-14% and -20% respectively, Table 6.6). Figure 6.16 presents the flow duration curve for all the GCMs and in all the three modelled sub-catchments. It demonstrates the similar trend of increase in larger flow and decrease of smaller flow for all modelled sub-catchments across all GCMs. The magnitude of the reduction in lower flow is quite large for all the CCG1 scenarios in all the three modelled sub-catchments. The Q95 for all CGMs in the Thoubal sub-catchment varies between 0.62-0.70 m^3s^{-1} compared to the baseline Q95 of 2.69 m^3s^{-1}, while in the Iril sub-catchment, the Q95 varies between 0.17-0.25 m^3s^{-1} compared to the baseline Q95 of 0.41 m^3s^{-1}. For the Nambul sub-catchment Q95 simulated by different GCMs of CCG1 scenarios varies between 0.06-0.07 m^3s^{-1} compared to the baseline Q95 of 0.37 m^3s^{-1} .

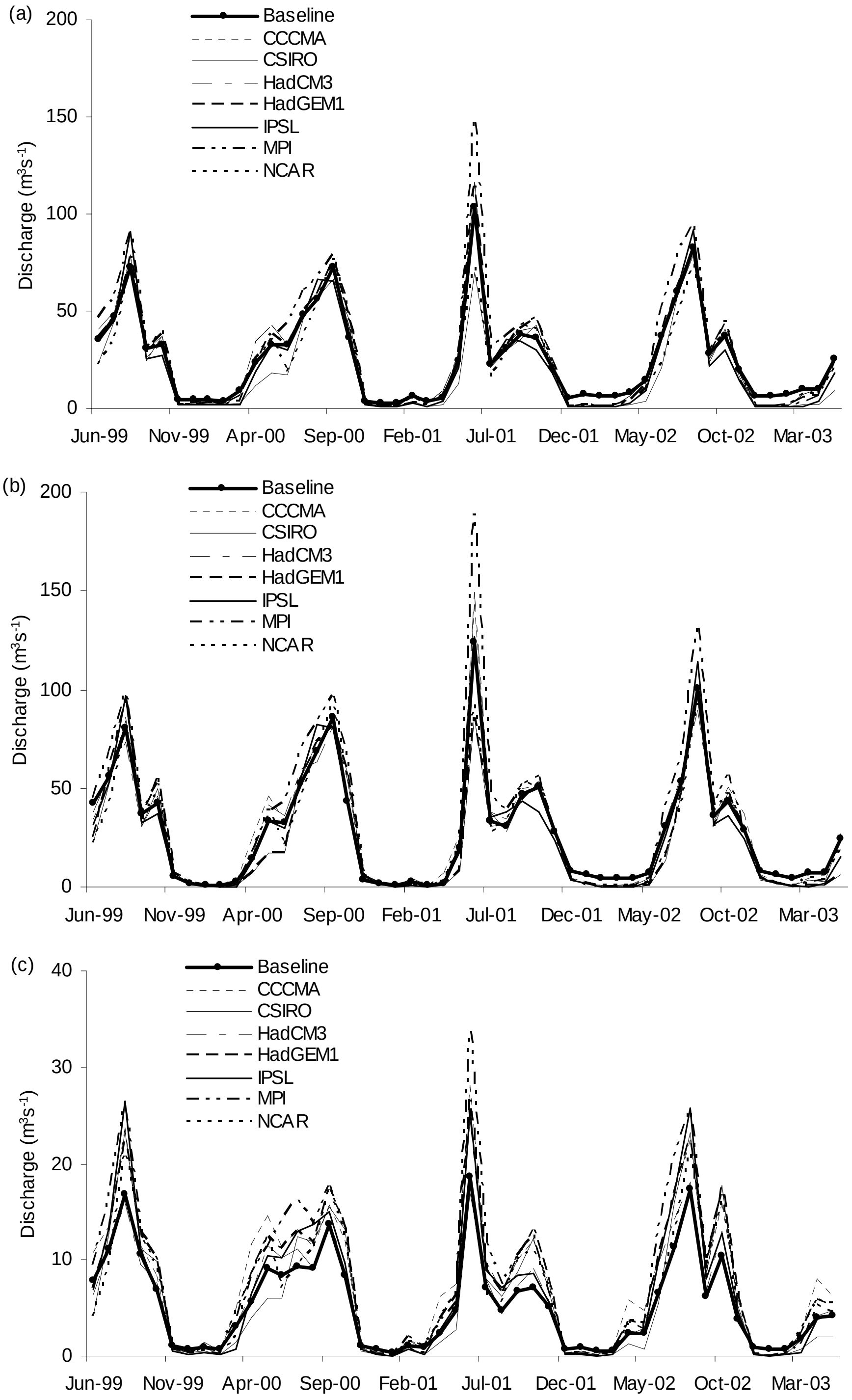

Figure 6.14. Perturbed monthly discharge in modelled sub-catchments for the CCG1 scenarios estimated using the Hargreaves method perturbed PET during June 1999-May 2003 (a) Thoubal, (b) Iril (c) Nambul

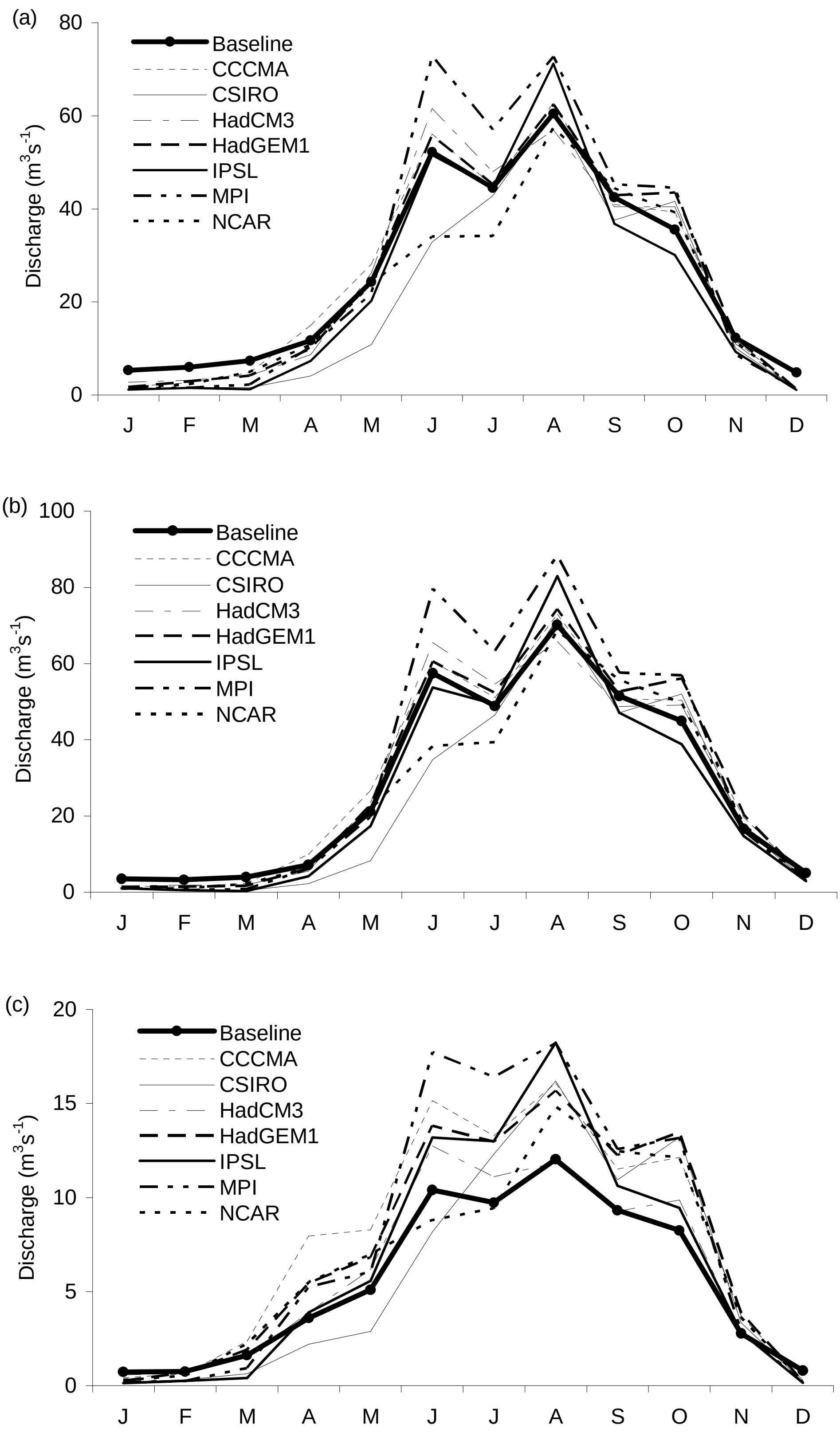

Figure 6.15. Mean monthly discharge for the CCG1 scenarios estimated using the Hargreaves method perturbed PET (a) Thoubal, (b) Iril, (c) Nambul

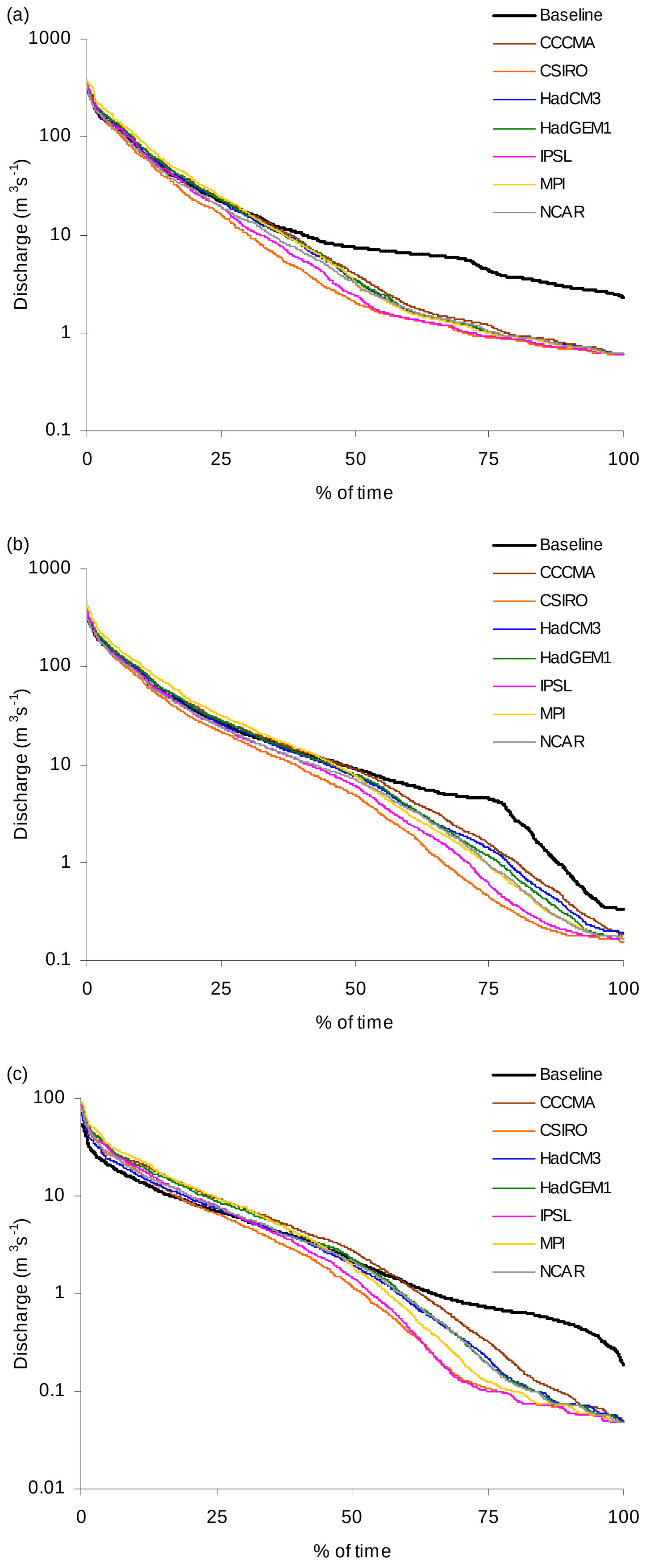

Figure 6.16. Flow duration curve for the CCG1 scenarios estimated using the Hargreaves method perturbed PET (a) Thoubal, (b) Iril, (c) Nambul

Table 6.6. 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 estimated using the Hargreaves method perturbed PET

Group	**Scenario**	**Thoubal**		**Iril**		**Nambul**		**Total River Inflow**	
		(m^3s^{-1})	**% change**	**(m^3s^{-1})**	**% change**	**(m^3s^{-1})**	**% change**	**(10^6m^3)**	**% change**
CCG1	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
CCG2	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

Figure 6.17 shows the mean monthly total river inflow to Loktak Lake associated with each of CCG1 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 sub-catchment area (Section 3.5). The corresponding mean total annual discharges are shown in Table 6.6. The CSIRO GCM results in an overall decline in annual river flow to the lake with a 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 (Table 6.6), which is employed in the evaluation of discharge from the Khuga and Western, 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 results in increase in 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.

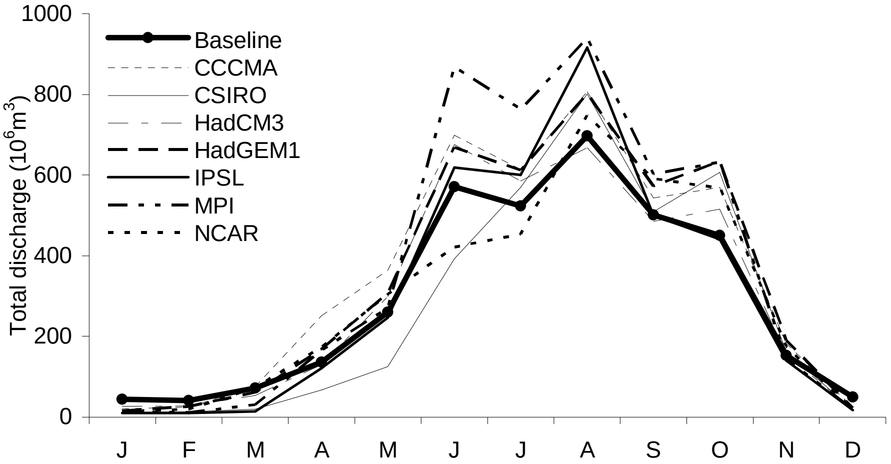

Figure 6.17. Mean monthly total river inflow into Loktak Lake for CCG1 scenarios estimated using the Hargreaves method perturbed PET

Figure 6.18 present the simulated monthly discharge of the modelled sub-catchments for all CCG2 scenarios for the period June 1999–May 2003. In contrast to CCG1 scenarios, the monthly discharge increase consistently with the increase in temperature from 1°C to 6°C. The largest increase in discharge (88% for Iril, 78% for Nambul and 63% for Thoubal) is associated with the 6°C rise in temperature during June 2001. The simulated discharge for all the scenarios are higher during the monsoon months and low during the dry period for all the three sub-catchments throughout the simulation period. Figure 6.19 presents the mean monthly discharge for all CCG2 scenarios for all the three modelled sub-catchments estimated using the Hargreaves method perturbed PET. This graph further demonstrates the consistent pattern of changes in discharge. The progressively higher rainfall associated with rising global mean temperature leads to increases in mean discharge (of up to 24%, 27% and 27% for the 6ºC scenario in the Thoubal, Iril and Nambul sub-catchments respectively, Table 6.6), although for the Thoubal, mean discharge initially decline for 1°C and 2°C scenarios and for the Iril the 1°C scenario.

The shift in the wettest month from August to June increases in July rainfall and small decline in August rainfall 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. 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. Similar to CCG1 scenarios, the flow duration curves (Figure 6.20) for the three modelled sub-catchments for CCG2 scenarios also indicates a similar trend of increase in larger flow and decrease of smaller flow across all GCMs. The magnitude of the decrease in lower flows, similar to CCG1, are quite large for all the CCG2 scenarios in all the three modelled sub-catchments when compared to the baseline low flows. The Q95 for all CGMs in the Thoubal sub-catchment varies between 0.67-0.71 m^3s^{-1} compared to the baseline Q95 of 2.69 m^3s^{-1}, in the Iril sub-catchment, the Q95 varies between 0.20-0.26 m^3s^{-1} compared to the baseline of 0.41 m^3s^{-1} and in the Nambul sub-catchment it varies between 0.06-0.07 m^3s^{-1} compared to the baseline Q95 of 0.37 m^3s^{-1}.

Figure 6.21 shows mean monthly total river inflow to Loktak Lake associated with each of CCG2 scenarios. Total annual discharge into the lake increases almost linearly with the increase in global mean temperature (Figure 6.22). Declines of flow in the Thoubal sub-catchment for the 1°C and 2°C scenarios (and 1°C scenario for Iril) are cancelled out by the increases in the Nambul and the subsequent evaluation of ungauged flows using results for this sub-catchment. 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.

6.2.3.2. Simulation of catchment runoff using PET data perturbed using the Thornthwaite method.

Figure 6.23 shows the modified monthly average discharge simulated for Thoubal, Iril and Nambul sub-catchments for all CCG1 scenarios. It shows a mixed response of the sub-catchments to the climate change scenarios with changes in the monthly discharge varying across GCMs and between sub-catchments. The largest increase in the discharge (71% for Nambul, 59% for Iril and 44% for Thoubal) is estimated for the MPI GCM during June 2001. All GCMs except for the IPSL and CSIRO shows an increase in the simulated discharges during the monsoon months in Thoubal and Iril sub-catchments. In the Nambul sub-catchment, all GCMs of CCG1 scenarios simulated higher monsoon discharges throughout the simulation period except for the 2nd year where the CSIRO GCM showed a slight decrease. During the dry season, the Thoubal sub-catchment simulated lower flows while the Iril and Nambul sub-catchments simulated similar discharges to the baseline condition.

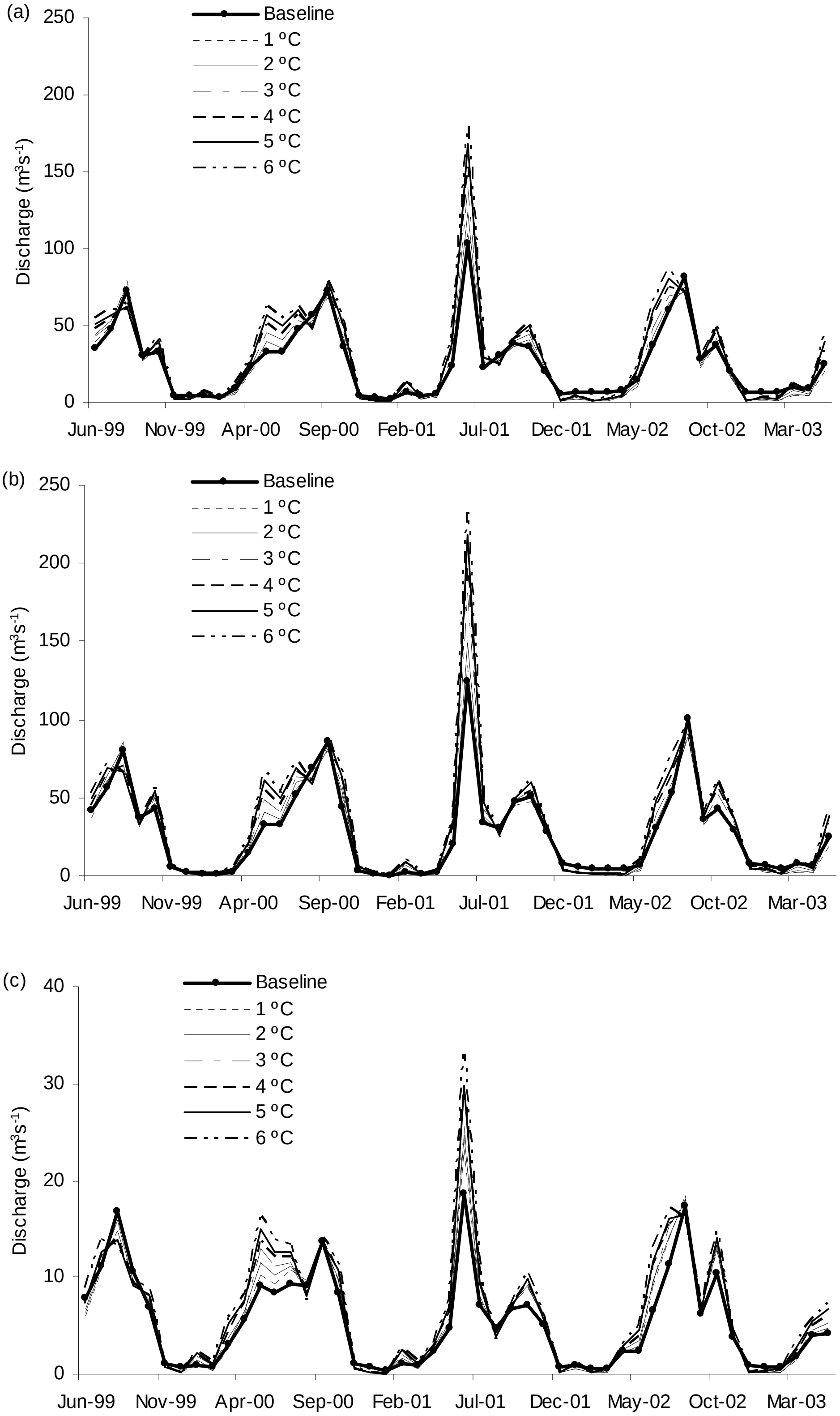

Figure 6.18. Perturbed monthly discharge in modelled sub-catchments for the CCG2 scenarios estimated using the Hargreaves method perturbed PET during June 1999-May 2003 (a) Thoubal, (b) Iril (c) Nambul

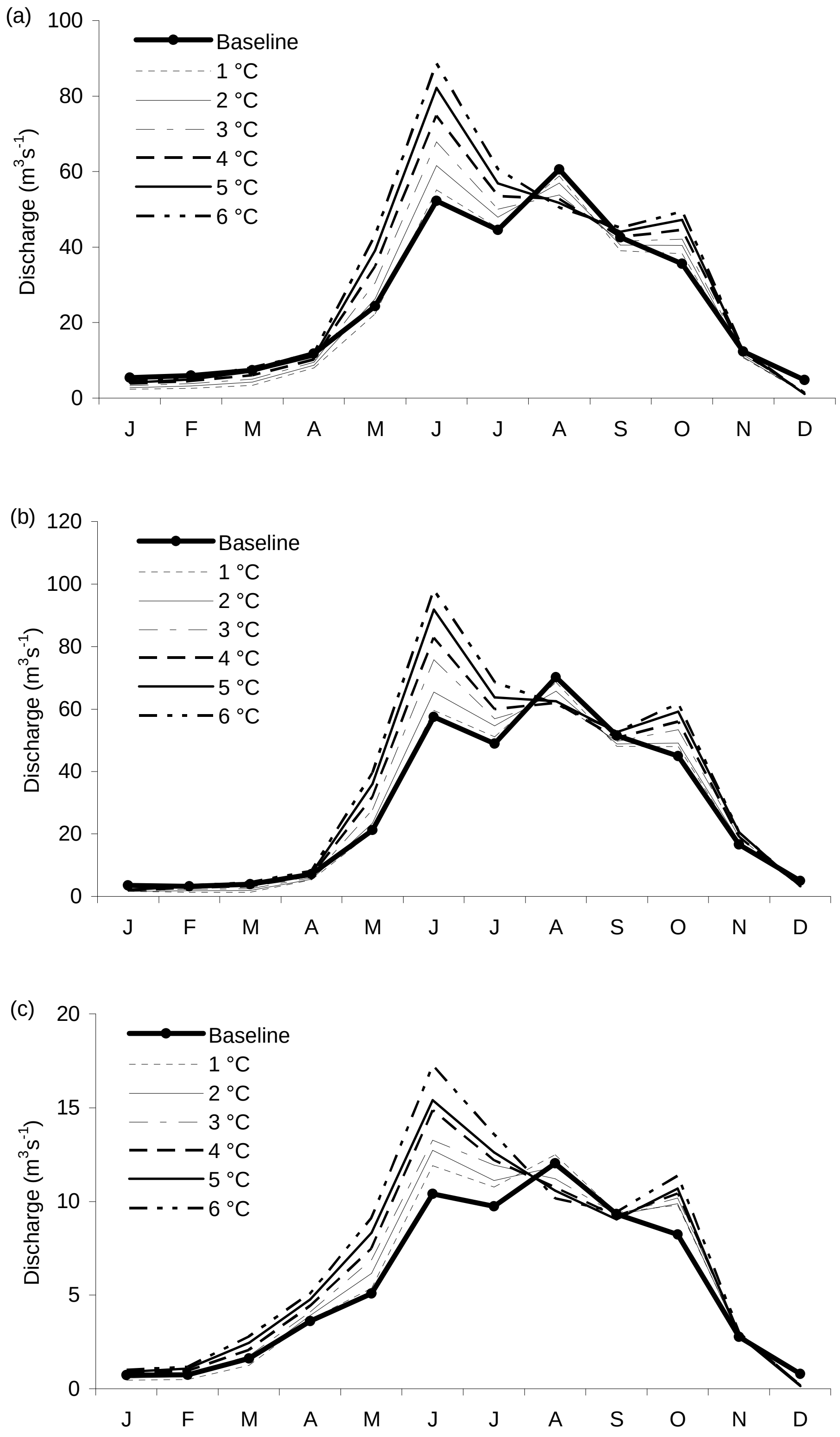

Figure 6.19. Mean monthly discharge for the CCG2 scenarios estimated using the Hargreaves method perturbed PET (a) Thoubal, (b) Iril, (c) Nambul

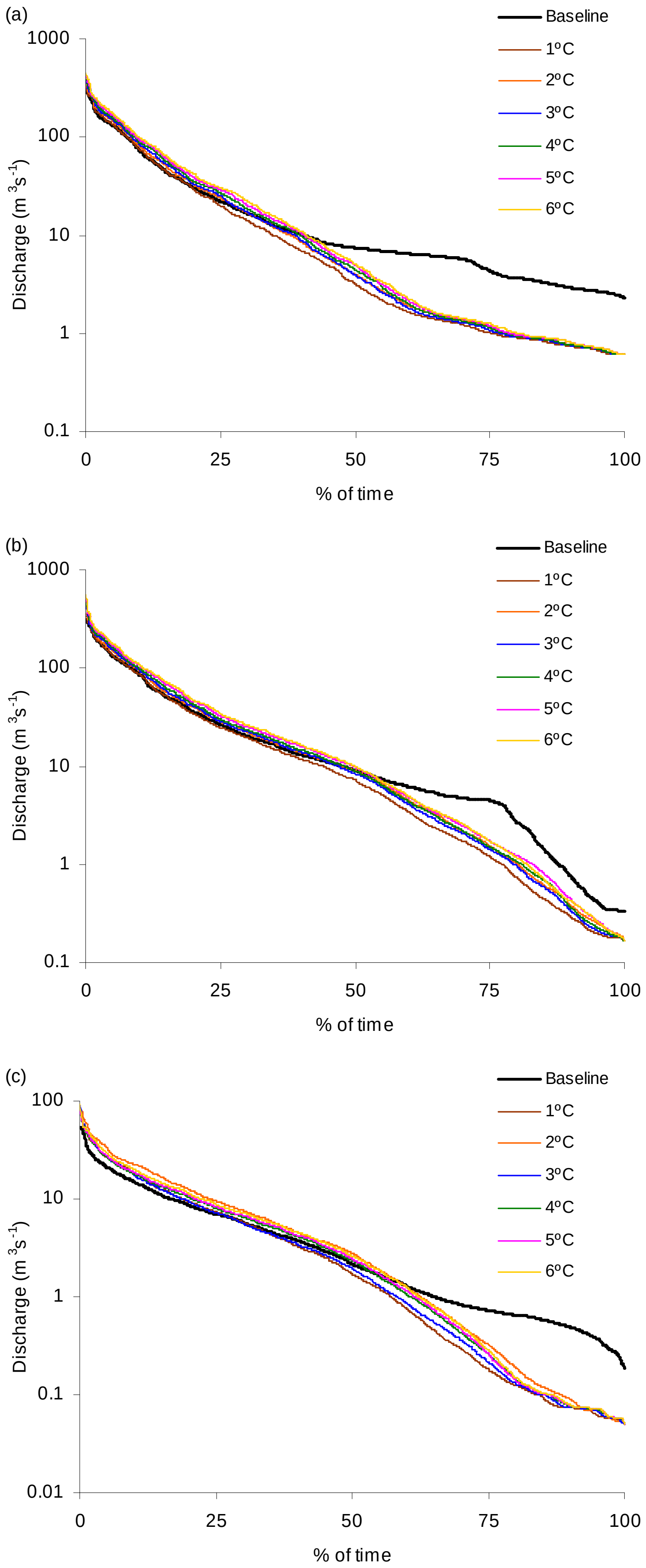

Figure 6.20. Flow duration curve for the CCG2 scenarios estimated using the Hargreaves method perturbed PET (a) Thoubal, (b) Iril, (c) Nambul

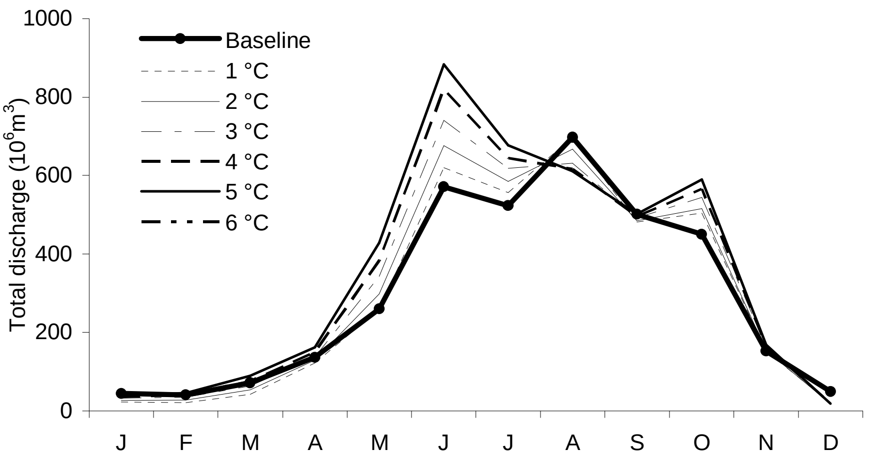

Figure 6.21. Mean monthly total river inflow into Loktak Lake for CCG2 scenarios estimated using the Hargreaves method perturbed PET

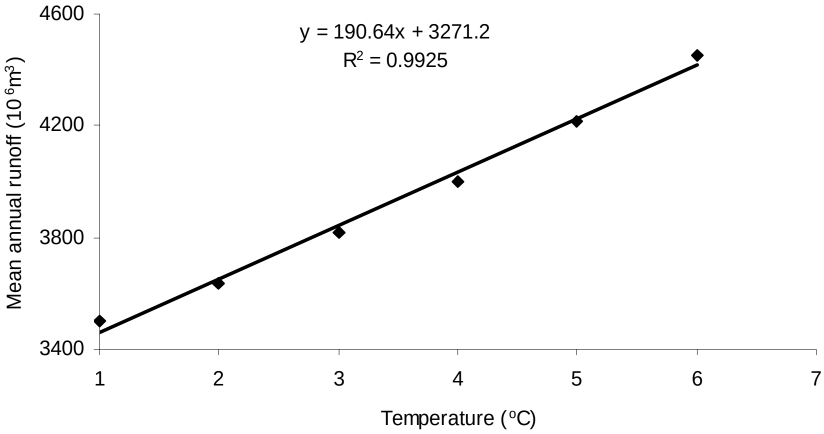

Figure 6.22. Relationship between temperature and total runoff from catchment area of Loktak Lake estimated using the Hargreaves method perturbed PET

The mean monthly discharge for all the modelled catchment for CCG1 scenarios are shown in Figure 6.24 and the corresponding mean total annual discharges are given in Table 6.7. Similar to the discharges simulated using the Hargreaves method to perturb PET, the CSIRO GCM results in an overall decline in annual river flow to the lake with the noticeable reduction in early monsoon flows. The Iril and Thoubal sub-catchments show a large reduction in flow (8% and 20% respectively, Table 6.7) for the CSIRO GCM, while the Nambul sub-catchment shows a large increase in the discharge (13%, Table 6.7). As a result of this increase in runoff from the Nambul sub-catchment (which is, as noted above, used for computation of discharge in the relatively large ungauged Khuga and Western sub-catchments) the magnitude of the decline in the total river inflow into the lake for the CSIRO GCM is estimated to be only 2%, despite the large

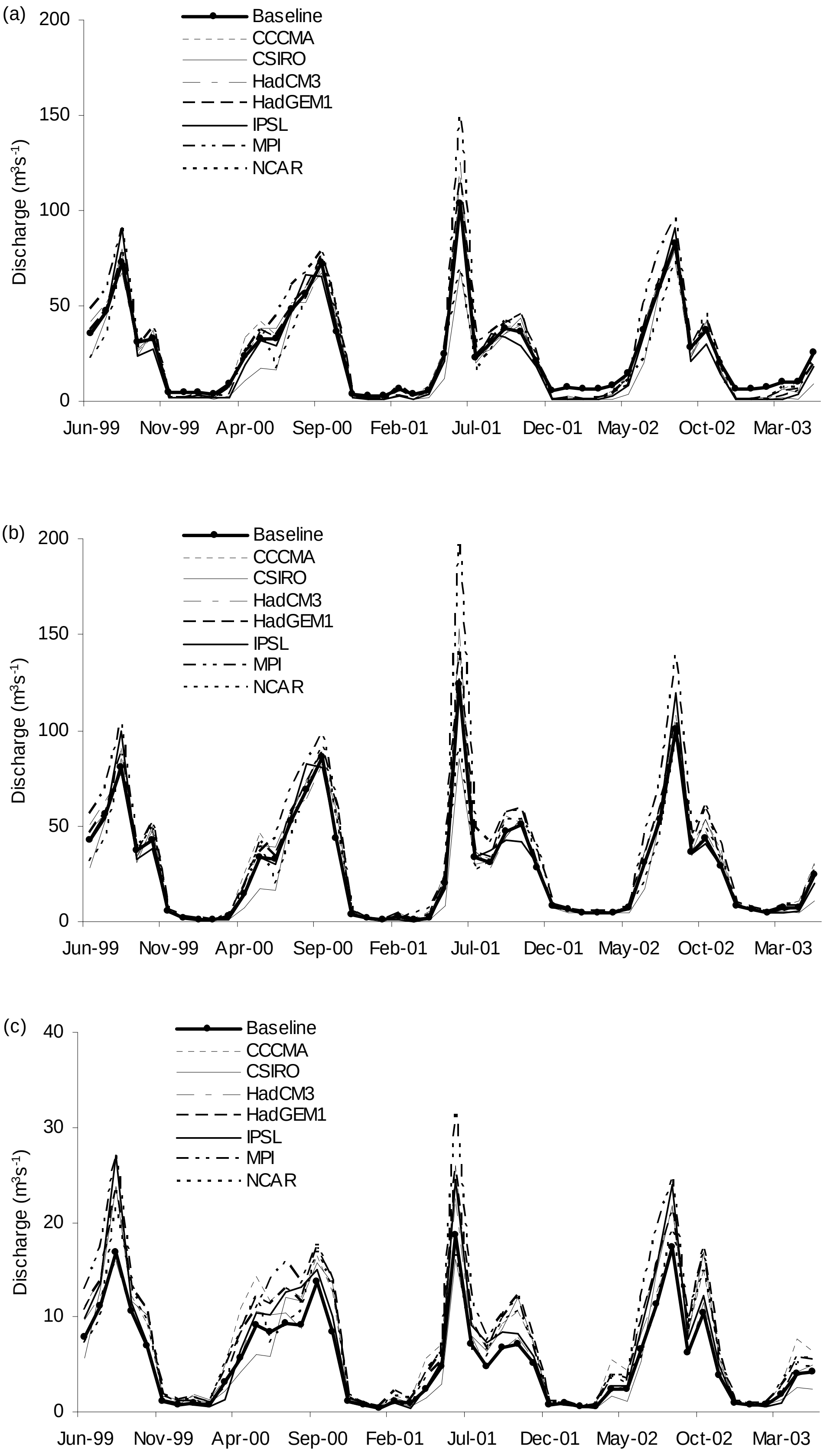

Figure 6.23. Perturbed monthly discharge in modelled sub-catchments for the CCG1 scenarios estimated using the Thornthwaite method perturbed PET during June 1999-May 2003 (a) Thoubal, (b) Iril (c) Nambul

reduction in Iril and Thoubal sub-catchments. For similar reasons the HadCM3, IPSL and NCAR GCMs, which also results in decline in flow from Thoubal, shows an overall increases in total river flow to the lake (5-7%, Table 6.7). The remaining GCMs, which increase mean discharge in all three modelled sub-catchments, produce much larger increases in total river contributions to Loktak Lake (HadGEM1 21%, CCCMA 22%, and MPI 32%).

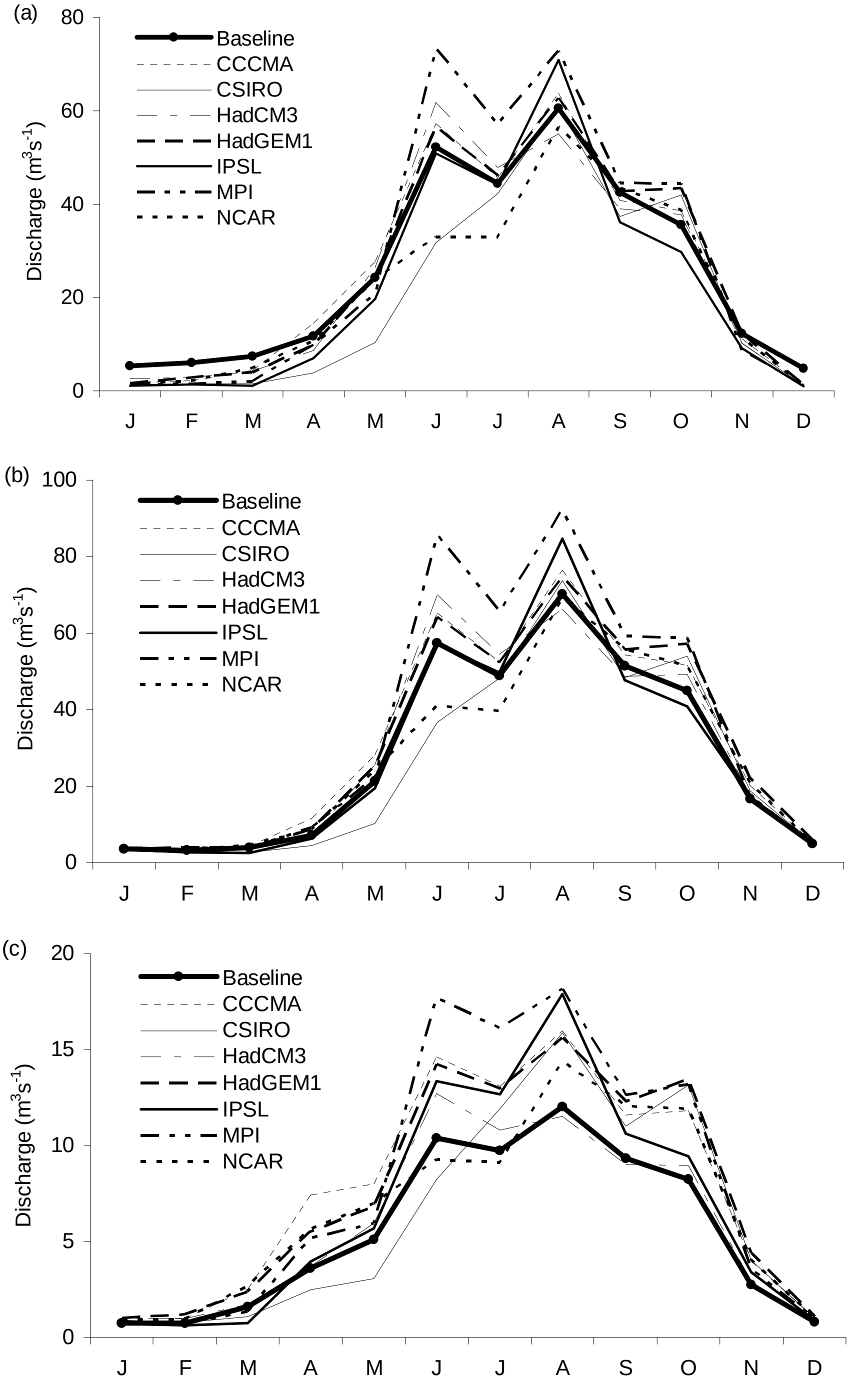

Figure 6.24. Mean monthly discharge for the CCG1 scenarios estimated using the Thornthwaite method perturbed PET (a) Thoubal, (b) Iril, (c) Nambul

Table 6.7. 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 estimated using the Thornthwaite method perturbed PET

Scenario	**Thoubal**		**Iril**		**Nambul**		**Total River Inflow**	
	(m^3s^{-1})	**% change**	**(m^3s^{-1})**	**% change**	**(m^3s^{-1})**	**% change**	**(10^6m^3)**	**% change**
CCG1								
Baseline	25.7	-	27.9	-	5.5	-	3498.8	-
CCCMA	25.8	1	31.5	13	7.7	41	4271.9	22
CSIRO	20.5	-20	25.8	-8	6.2	13	3437.6	-2
HadCM3	24.9	-3	29.7	6	5.9	8	3663.6	5
HadGEM1	25.7	0	31.6	13	7.6	40	4250.0	21
IPSL	22.8	-11	28.2	1	6.7	23	3758.4	7
MPI	28.2	10	35.7	28	8.1	48	4624.5	32
NCAR	21.8	-15	27.4	-2	6.6	21	3667.0	5
CCG2								
Baseline	25.7	-	27.9	-	5.5	-	3498.8	-
1°C	23.8	-8	29.3	5	5.8	6	3595.0	3
2°C	24.9	-3	29.7	6	5.9	7	3663.6	5
3°C	25.7	0	31.2	12	6.1	11	3815.8	9
4°C	26.4	3	31.6	13	6.2	13	3881.4	11
5°C	27.3	6	32.3	15	6.3	15	3975.9	14
6°C	28.3	10	33.1	19	6.5	18	4107.2	17

The maximum increase in discharge for all modelled sub-catchments is in August, which is also the month with the peak flow under the baseline condition (Figure 6.23). Figure 6.25 presents the flow duration curve for all the CCG1 scenarios. The low flows are simulated lower then the baseline for CCG1 scenarios in the Thoubal sub-catchment, while in the Iril and Nambul sub-catchments, the lows are almost similar to that of the baseline. The higher flows are simulated quite similar to the baseline for the Thoubal and Iril sub-catchment while in the Nambul sub-catchment, it tends to simulate slightly higher.

Figure 6.26 presents the mean monthly total river inflow to Loktak Lake associated with each of CCG1 scenarios estimated using the Thornthwaite method perturbed PET. The total inflows are simulated higher during the monsoon months for all GCMs although the CSIRO and NCAR CGMs shows slight decrease in the earlier part of the monsoon season. The mean total inflow into the lake from all the sub-catchment decreases by 2% for the CSIRO GCM while for the rest of the GCMs of CCG2 scenarios, the mean total river inflow increases between 5% (both HadCM3 and NCAR GCMs) and 32% (MPI GCM).

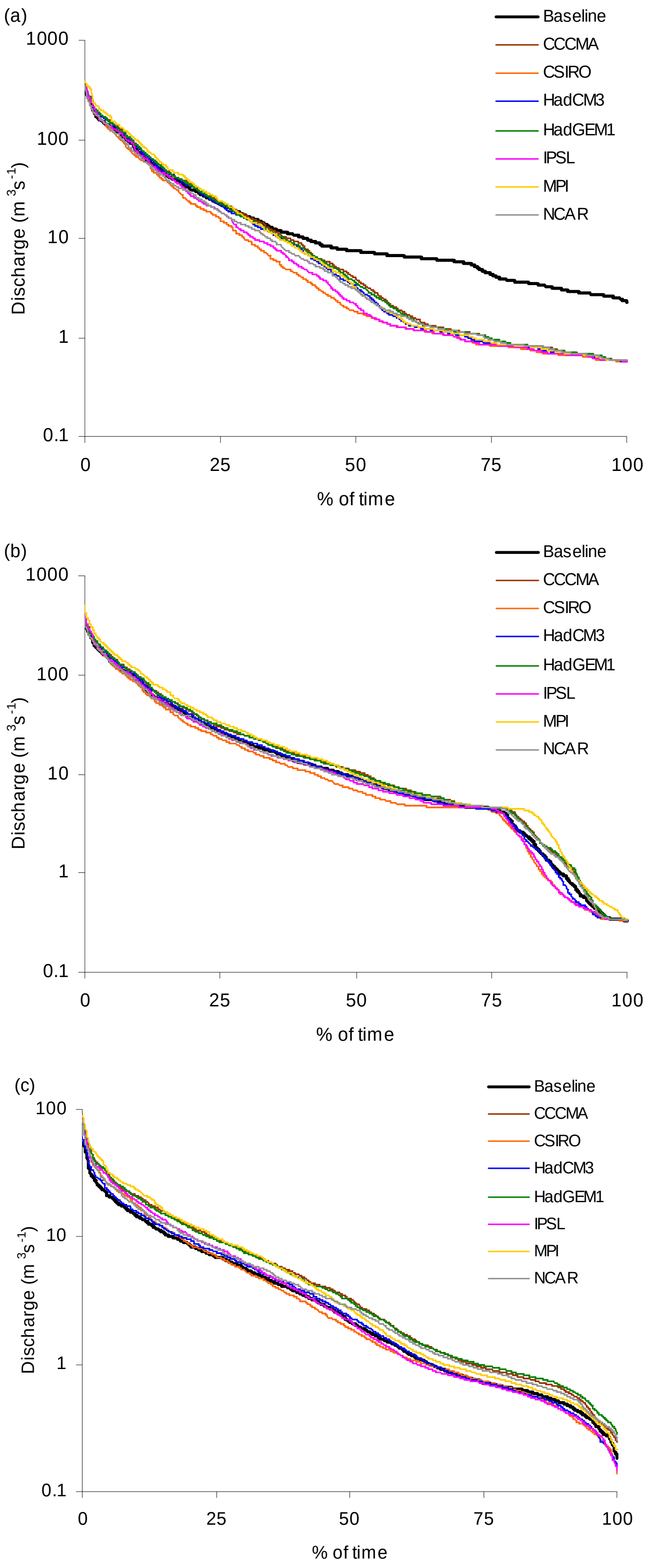

Figure 6.25. Flow duration curve for the CCG1 scenarios estimated using the Thornthwaite method perturbed PET (a) Thoubal, (b) Iril, (c) Nambul

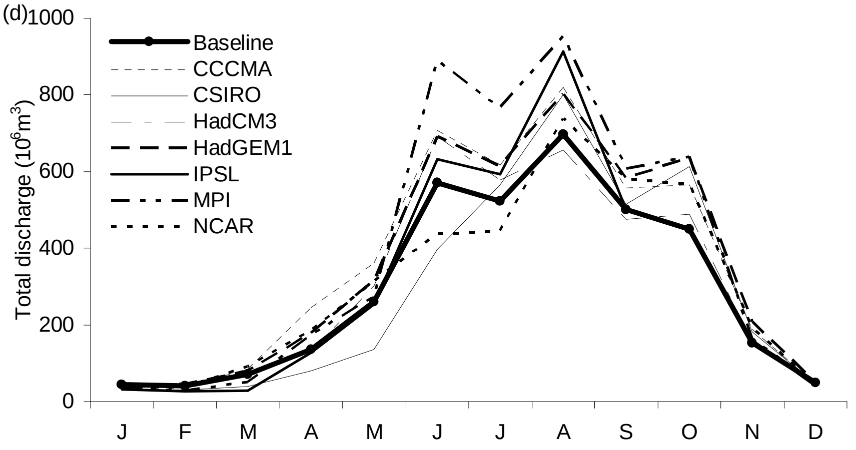

Figure 6.26. Mean monthly total river inflow into Loktak Lake for CCG1 scenarios estimated using the Thornthwaite method perturbed PET

Figure 6.27 present the monthly simulated discharge of the modelled sub-catchments for all CCG2 scenarios. The discharges simulated during monsoon period of the first and the third years show an increasing trend for all the CCG2 scenarios in all three sub-catchments while for the first and the fourth years, it tends to slightly decrease. The low flows are simulated higher for the Thoubal sub-catchment throughout the simulation period. The largest increase in the discharge (70% for Iril, 57% for Nambul and 51% for Thoubal) associated with the 6°C rise in temperature during June 2001. The changes in the discharges simulated by all the CCG2 scenarios for the three modelled sub-catchments (Thoubal, Iril and Nambul) follows a more consistent pattern (Figure 6.28). The discharge in all the modelled sub-catchments is shown to rise with the increase in global temperature from 1°C to 6°C. This pattern is similar to that identified earlier (Section 6.2.3.1) using the Hargreaves method of perturbing the PET data. The largest increase in the total annual discharge of 10%, 19% and 18% in Thoubal, Iril and Nambul sub-catchments respectively are associated with the 6ºC scenario (Table 6.7), although for the Thoubal mean discharge initially declines for the 1°C and 2°C scenarios. Peak flows in all three sub-catchments occur in June and increase with the progressively warmer scenarios. After this peak, discharges are relatively constant until October which, as previously noted (Section 6.2.1) experiences enhanced rainfall compared to the baseline. Discharges in August, which are the highest for the baseline period, are lower for all the scenarios in all three sub-catchments. Dry season flows in the Iril sub-catchment are relatively unchanged, in the Nambul they increase slightly whilst in the Thoubal they are lower.

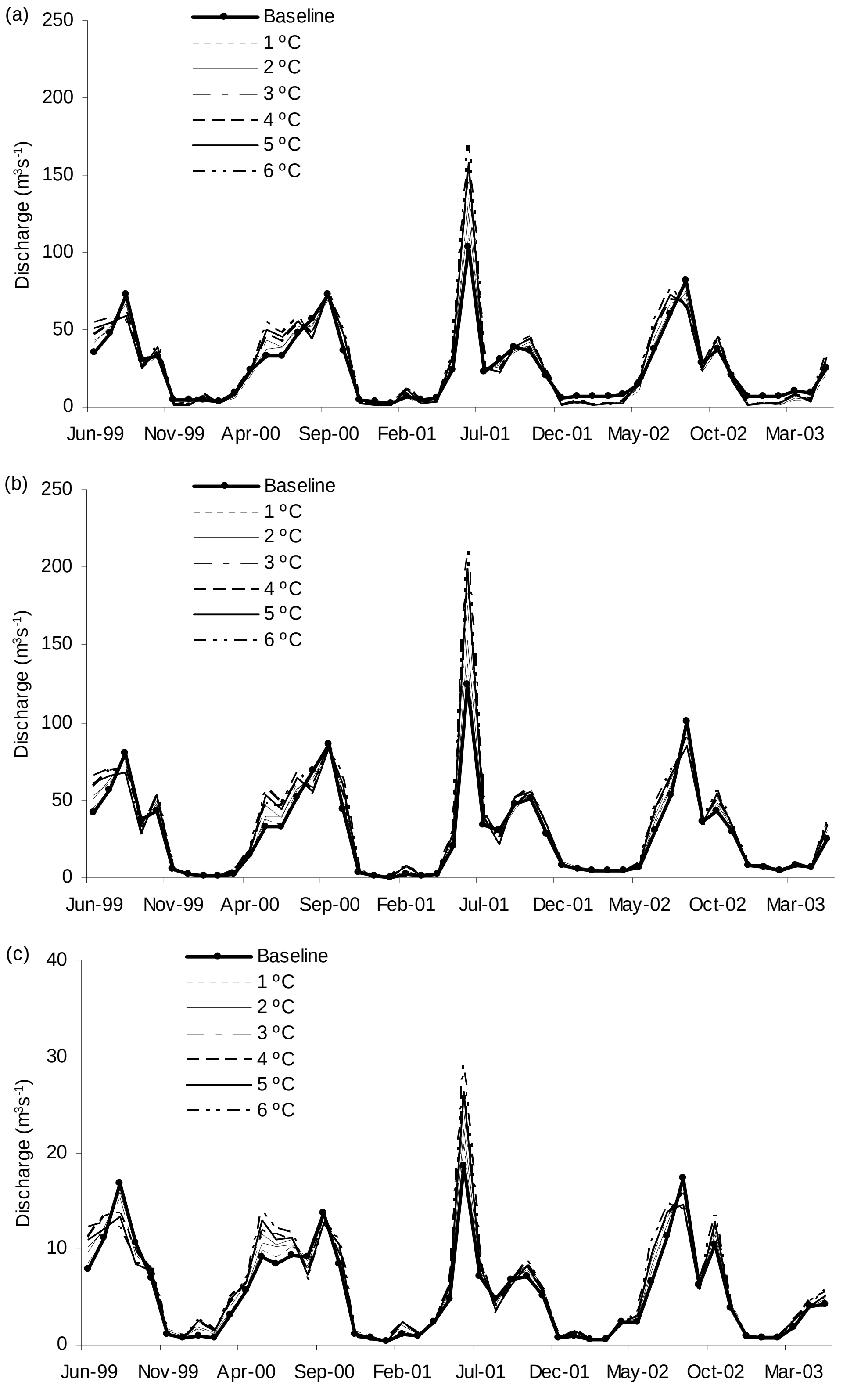

Figure 6.27. Perturbed monthly discharge in modelled sub-catchments for the CCG2 scenarios estimated using the Thornthwaite method perturbed PET during June 1999-May 2003 (a) Thoubal, (b) Iril (c) Nambul

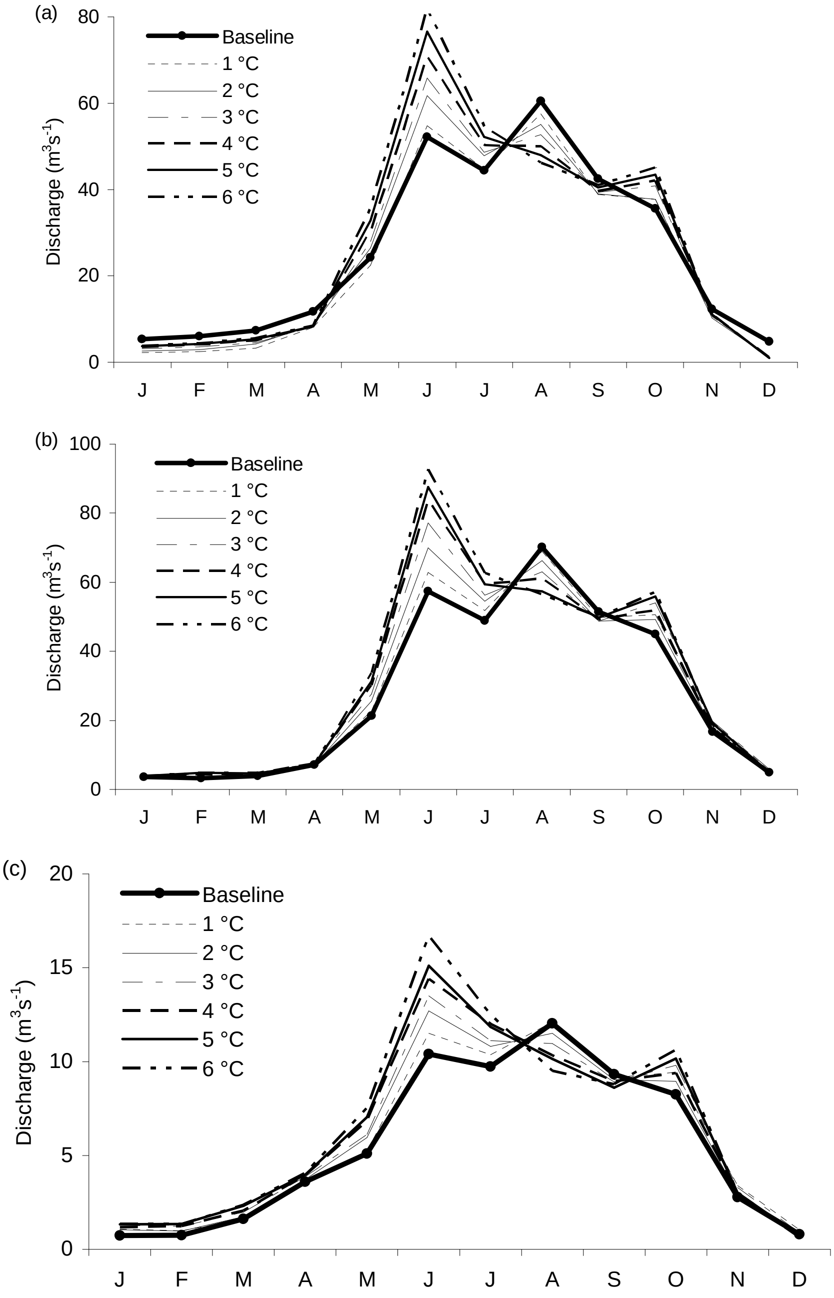

Figure 6.28. Mean monthly discharge for the CCG2 scenarios estimated using Thornthwaite method perturbed PET (a) Thoubal, (b) Iril, (c) Nambul

Figure 6.29 shows the flow duration curves for the three modelled sub-catchments for CCG2 scenarios during June 1999–May 2003. The simulated discharges for all the CCG2 scenarios show slight increased in the larger flows. However, the low flows are simulated quite similar to the baseline flow for the Iril and Nambul sub-catchment. However, the Thoubal sub-catchment shows a large decrease in the simulation for the low flows. The Q95 for the Thoubal River for all scenarios is estimated between 0.60 m^3s^{-1} and 0.65 m^3s^{-1} compared to the baseline Q95 of 2.69 m^3s^{-1}.

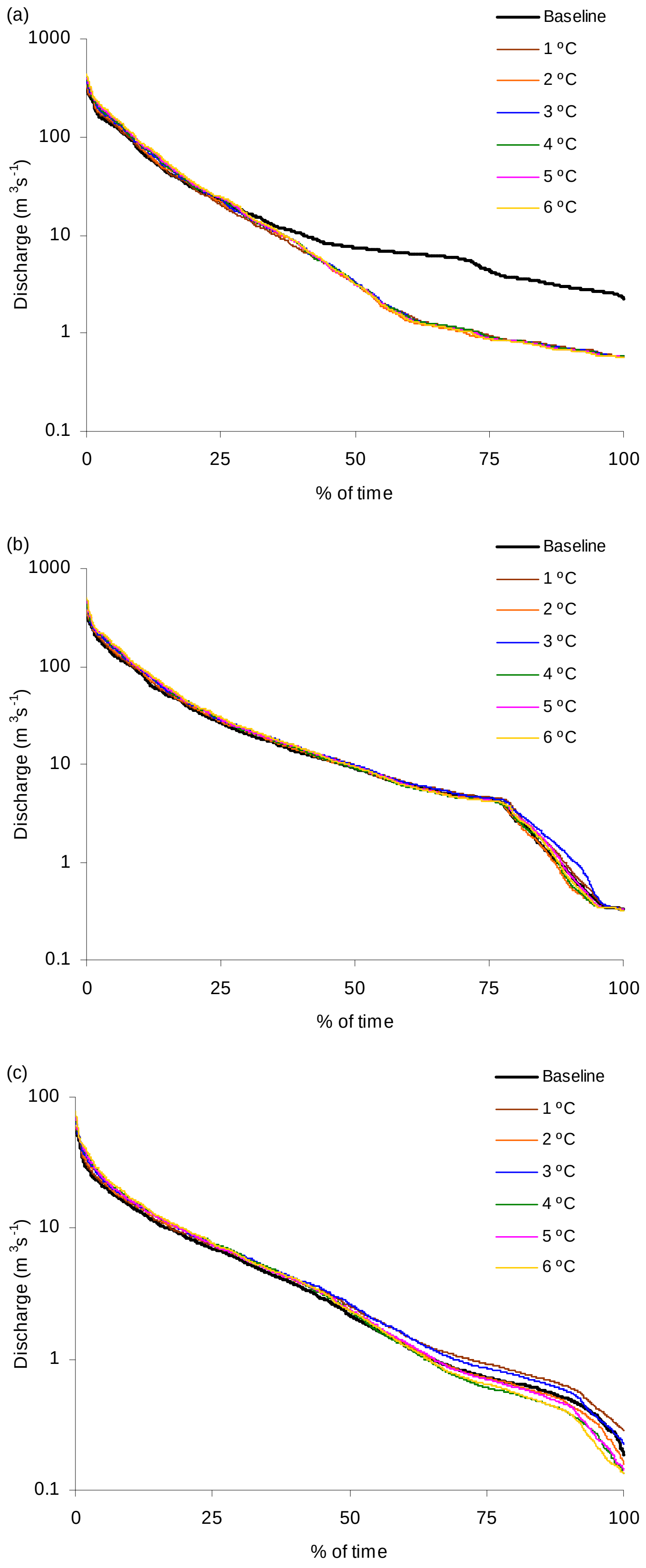

Figure 6.29. Flow duration curve for the CCG2 scenarios estimated using the Thornthwaite method perturbed PET (a) Thoubal, (b) Iril, (c) Nambul

Figure 6.30 shows the mean monthly total river inflow to Loktak Lake associated with each of CCG2 scenarios estimated using the Thornthwaite method perturbed PET. Similar to that estimated using the Hargreaves method perturbed PET (Section 6.2.3.1), the total inflows are simulated higher during the monsoon months for all scenarios. The mean total inflow for all CCG2 scenarios increases between 3% (1°C) and 17% (6°C). The total inflow into Loktak Lake increase almost linearly with increasing global mean temperature (Table 6.7; Figure 6.31).

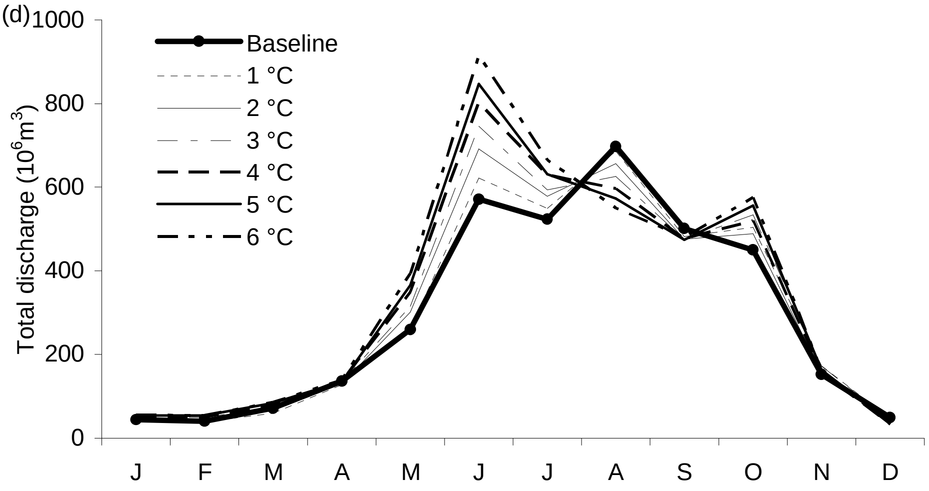

Figure 6.30. Mean monthly total river inflow into Loktak Lake for CCG2 scenarios estimated using the Thornthwaite method perturbed PET

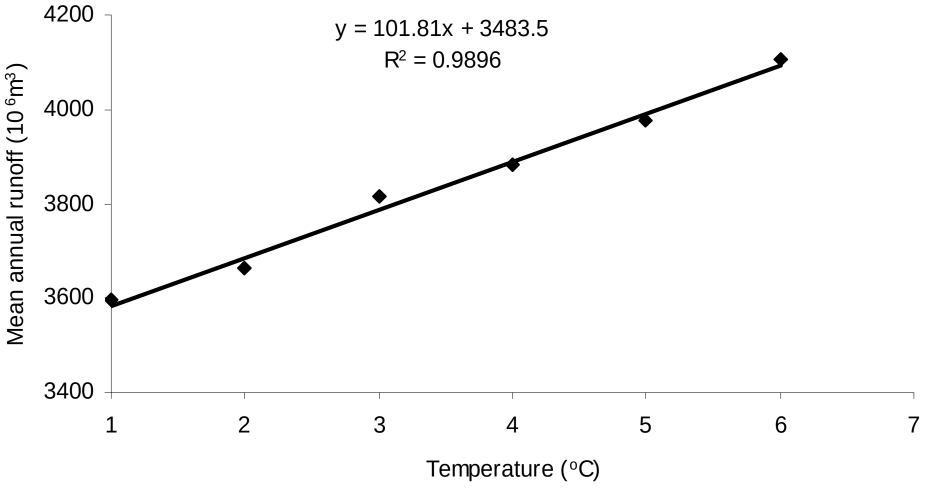

Figure 6.31. Relationship between temperature and total runoff from catchment area of Loktak Lake estimated using the Thornthwaite method perturbed PET

6.2.3.3. Comparison of catchment runoff simulated using Hargreaves and Thornthwaite perturbed PET

The runoff simulated using the Thornthwaite method for perturbing the original PET data tends to estimate higher discharges for the Iril and Nambul sub-catchments for all CCG1 scenarios (Table 6.8). Although the average annual evapotranspiration estimated using the Thornthwaite method is higher the Hargreaves method (Table 6.4 & 6.5), the mean daily discharges (Table 6.8) are higher due to the fact that there is high evapotranspiration losses during the dry period (November–February) which does not have much bearing on runoff which is already low at this time of year. However, using the Hargreaves perturbed PET data produces slightly higher discharges from the Thoubal sub-catchment for all CCG1 scenarios, except for the HadGEM1 GCM, which shows a slightly lower discharge (1%, Table 6.8). The largest variation of 2.9 m^3s^{-1} was estimated for the Iril sub-catchment for the MPI GCM. For the CCG2 scenarios, discharges estimated using the Hargreaves method of perturbing PET tends to simulate larger discharges for the Thoubal and Nambul sub-catchments with the increase in temperature from 1°C to 6°C compared to those estimated employing the Thornthwaite method of perturbing PET (Table 6.8). The largest increase (3.5 m^3s^{-1}) is associated with the 6°C rise in temperature for the Thoubal sub-catchment. For the Iril sub-catchment, the runoff simulated using the Hargreaves perturbed PET is lower for 1-3°C rises in global mean temperature but higher for the higher gains in global mean temperature (4-6°C, Table 6.8). In terms of total inflow into Loktak Lake from the catchment, the discharges simulated using Hargreaves method of perturbing PET tend to be lower compared to the Thornthwaite method for all CCG1 scenarios (Table 6.9). The variation in the total inflow estimated by these two methods is, however, quite small (0.7–8.4%). Largest changes are associated with the NCAR, CSIRO and HadGEM1 GCMs.

For the CCG2 scenarios, simulation carried out using Hargreaves method perturbing PET tend to produce larger discharges for the scenarios associated with gains global mean temperature by 3–6°C, compared to estimation using the Thornthwaite method perturbing PET. The magnitude of variation in the total inflow estimated by these two methods is quite small (0.13 - 8.4%, Table 6.9). However, for the 1°C and 2°C rise scenario, the Hargreaves perturbed PET results in lower discharges by 2.6% and 0.7%

respectively. The largest variations in the total inflow computed by the two methods is just 8.4% for the 6°C rise in global mean temperature (Table 6.9)

Table 6.8. Comparison of mean daily discharge simulated for the modelled sub-catchments (Q_H: discharge simulated using the Hargreaves method perturbed PET, Q_T: discharge simulated using the Thornthwaite method perturbed PET)

Scenarios	**Thoubal**		**Iril**		**Nambul**	
	Q_H (m^3s^{-1})	**Q_T (m^3s^{-1})**	**Q_H (m^3s^{-1})**	**Q_T (m^3s^{-1})**	**Q_H (m^3s^{-1})**	**Q_T (m^3s^{-1})**
CCG1						
CCCMA	25.8	25.8	29.2	31.5	7.6	7.7
CSIRO	20.6	20.5	23.7	25.8	5.9	6.2
HadCM3	25.4	24.9	28.3	29.7	5.9	5.9
HadGEM1	25.5	25.7	29.5	31.6	7.3	7.6
IPSL	23.0	22.8	26.1	28.2	6.5	6.7
MPI	28.3	28.2	32.8	35.7	7.8	8.1
NCAR	22.1	21.8	25.4	27.4	6.4	6.6
CCG2						
1°C	23.9	23.8	27.2	29.3	5.7	5.8
2°C	25.4	24.9	28.3	29.7	5.9	5.9
3°C	26.7	25.7	30.1	31.2	6.1	6.1
4°C	28.4	26.4	31.7	31.6	6.4	6.2
5°C	30.2	27.3	33.9	32.3	6.6	6.3
6°C	31.8	28.3	35.4	33.1	7.0	6.5

Table 6.9. Comparison of total inflow into Loktak lake (Q_H: discharge simulated using the Hargreaves method perturbed PET, Q_T: discharge simulated using the Thornthwaite method perturbed PET)

Scenarios	**Total Inflow into Loktak Lake**		
	Q_H (10^6m^3)	**Q_T (10^6m^3)**	**% difference Q_H vs Q_T**
CCG1			
CCCMA	4175	4272	-2.27
CSIRO	3296	3438	-4.13
HadCM3	3639	3664	-0.68
HadGEM1	4078	4250	-4.05
IPSL	3635	3758	-3.27
MPI	4458	4625	-3.61
NCAR	3358	3667	-8.43
CCG2			
1°C	3501	3595	-2.61
2°C	3639	3664	-0.68
3°C	3821	3816	0.13
4°C	4001	3881	3.09
5°C	4217	3976	6.06
6°C	4453	4107	8.42

6.3. Assessment of the impact of climate change on the water level regime of Loktak Lake

Runoff from the catchment area, as previously noted in Section 4.3.3, accounts for 90.8% of the total inflow into Loktak Lake. Alterations in catchment runoff due to the changes in meteorological conditions induced by climate change may have significant impacts on the water level regime of the lake. The implications of changes in runoff induced by climate change scenarios upon water level regime of Loktak Lake were investigated using the monthly water balance model previously developed in Chapter 4. For each climate change scenario, the same initial water level as the baseline simulation was employed. Revised river discharges for climate change scenarios were provided by results of MIKE SHE models and subsequent calculation of flows from ungauged sub-catchments discussed in the preceding section. The new perturbed meteorological time series data previously estimated using the delta factor approach were employed to modify direct rainfall, open water evaporation and evapotranspiration from the *phumdis*. The area of *phumdis* and abstractions for irrigation, domestic consumption and hydropower generation remain unchanged. Similarly, recorded volumes of barrage releases were retained with additional releases being calculated if water levels exceeded the full reservoir level (FRL). As previously noted in Section 6.2.2, the PET data were perturbed using two different methods (Hargreaves and Thornthwaite). Accordingly, the implications of climate change on lake water level regime are also assessed separately.

6.3.1. Changes in water level regime of Loktak Lake using PET data perturbed using the Hargreaves method.

Figure 6.32 shows the simulated lake water levels resulting from the CCG1 scenarios using the Hargreaves method to perturbed PET. For nearly all of these scenarios, lake water levels are higher throughout the simulation period 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 (Table 6.10) respectively compared to the baseline mean of 768.43 m amsl. 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 month for the HadCM3 GCM although the mean difference is smaller (0.47 m). The IPSL and NCAR GCMs increase mean lake water level by 0.24 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. The water levels simulated for the CSIRO GCM are lower compared to the baseline water levels. The mean annual water level for the CSIRO GCM is estimated to be lower by 0.47m. It is also the only GCM which simulated lower mean water level below the MDL.

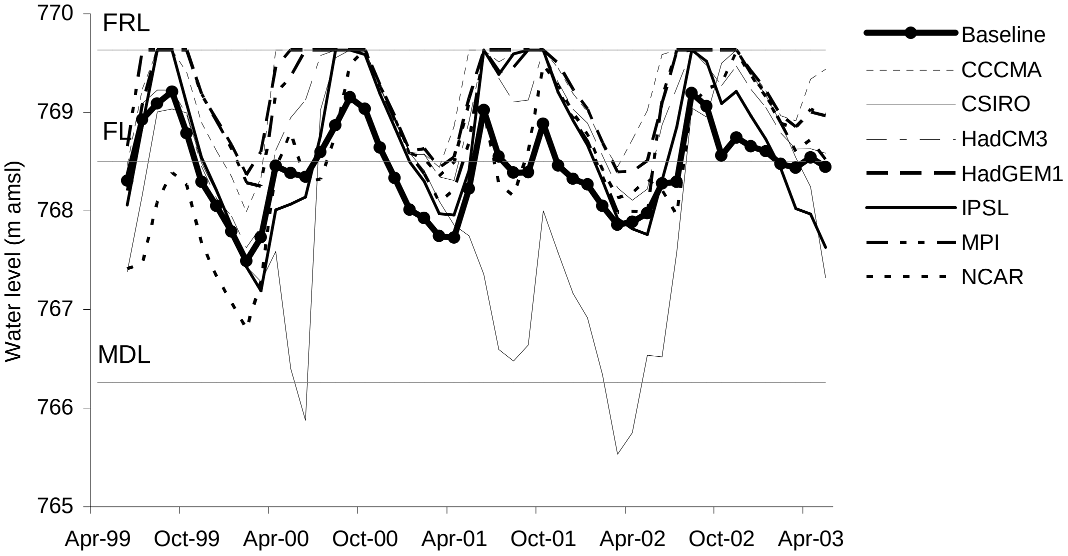

Figure 6.32. Simulated mean monthly Loktak Lake water levels under baseline conditions (June 1999–May 2003) using the Hargreaves method perturbed PET for CCG1 scenarios (FRL: full reservoir level, FL: flood level, MDL: minimum drawdown level)

Table 6.10. Mean monthly water level of Loktak Lake for CCG1 scenarios estimated using Hargreaves method perturbed PET

	Baseline (m amsl)	**CCCMA (m amsl)**	**CSIRO (m amsl)**	**HadCM3 (m amsl)**	**HadGEM1 (m amsl)**	**IPSL (m amsl)**	**MPI (m amsl)**	**NCAR (m amsl)**
Jan	768.17	768.79	768.13	768.62	768.88	768.43	768.77	768.40
Feb	767.99	768.56	767.77	768.39	768.66	768.12	768.48	768.16
Mar	767.94	768.53	767.36	768.26	768.57	767.78	768.23	768.15
Apr	768.15	769.14	767.36	768.42	768.85	767.94	768.53	768.53
May	768.26	769.43	767.00	768.66	769.06	767.97	768.64	768.80
Jun	768.49	769.33	766.78	768.97	769.14	768.53	769.27	768.23
Jul	768.59	769.50	767.84	769.32	769.43	768.96	769.63	768.00
Aug	768.88	769.62	768.52	769.40	769.58	769.62	769.63	768.52
Sep	768.95	769.63	768.56	769.36	769.63	769.60	769.63	768.93
Oct	768.82	769.57	769.03	769.38	769.63	769.35	769.63	769.17
Nov	768.54	769.31	768.74	769.12	769.40	769.04	769.32	768.95
Dec	768.34	769.04	768.42	768.83	769.13	768.73	769.04	768.66
Mean	**768.43**	**769.21**	**767.96**	**768.89**	**769.17**	**768.67**	**769.07**	**768.54**

The water level-duration curve (Figure 6.33) indicates that water levels in all CCG1 scenarios exceed the full reservoir 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 (CCCMA) to just one for NCAR which produces the smallest increase in water levels (Figure 6.34). Results for the CSIRO GCM also indicate that additional barrage releases would be necessary in three months (September 2000, October 2000 and November 2002). 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 (June 2000, March 2002 and April 2002) 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.

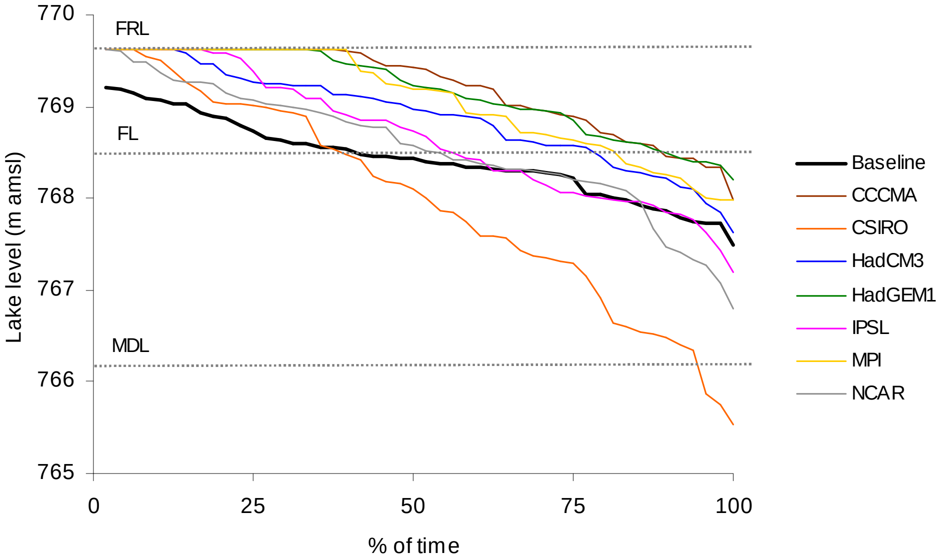

Figure 6.33. Water level-duration curve (June 1999–May 2003) estimated using the Hargreaves method perturbed PET for CCG1 scenarios

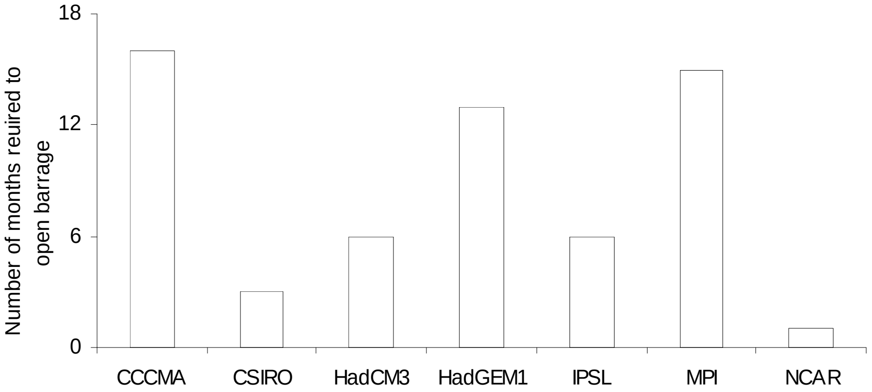

Figure 6.34. Number of months required to open Ithai barrage for additional release of water for CCG1 scenarios estimate using the Hargreaves method perturbed PET

The frequency of flooding in the surrounding areas of the lake is estimated to worsen with all CCG1 scenarios except for the CSIRO GCM (Figure 6.33). The percentage of time during which the water level in the lake is above the FL for these GCMs is estimated to be between 54% (NCAR) and 87% (CCCMA) compared to 40% during the baseline scenario.

Simulated water levels within Loktak Lake for the CCG2 scenarios are shown in Figure 6.35. Increases in rainfall and river flow result in higher mean lake water levels than the baseline for all the scenarios. The difference in mean lake water levels from the baseline rises almost linearly with increasing global mean temperature from 0.30 m for the 1°C scenario to 0.78 m for the 6°C scenario (Table 6.11, Figure 6.36). Months when water levels simulated for the CCG2 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 condition is the largest of the simulation period. Enhanced lake evaporation and *phumdi* evapotranspiration at this time of year, when river inflows and rainfall 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 (Figure 6.37). The number of months when these releases are necessary increases consistently with rising global mean temperature from two for the 1ºC scenario to 15 for the 6ºC scenario (Figure 6.38).

Table 6.11. Mean monthly water level of Loktak Lake for CCG2 scenarios estimated using the Hargreaves method perturbed PET

	Baseline (m amsl)	**1°C (m amsl)**	**2°C (m amsl)**	**3°C (m amsl)**	**4°C (m amsl)**	**5°C (m amsl)**	**6°C (m amsl)**
Jan	768.17	768.52	768.62	768.60	768.70	768.77	768.83
Feb	767.99	768.26	768.39	768.40	768.53	768.63	768.70
Mar	767.94	768.09	768.26	768.32	768.50	768.64	768.76
Apr	768.15	768.23	768.42	768.51	768.71	768.87	769.01
May	768.26	768.31	768.66	768.93	769.23	769.41	769.48
Jun	768.49	768.72	768.97	769.14	769.32	769.37	769.42
Jul	768.59	768.97	769.32	769.48	769.55	769.62	769.63
Aug	768.88	769.25	769.40	769.37	769.41	769.45	769.41
Sep	768.95	769.25	769.36	769.33	769.39	769.44	769.45
Oct	768.82	769.30	769.38	769.34	769.45	769.51	769.54
Nov	768.54	769.04	769.12	769.09	769.17	769.22	769.27
Dec	768.34	768.75	768.83	768.79	768.87	768.93	768.97
Mean	**768.43**	**768.72**	**768.89**	**768.94**	**769.07**	**769.16**	**769.21**

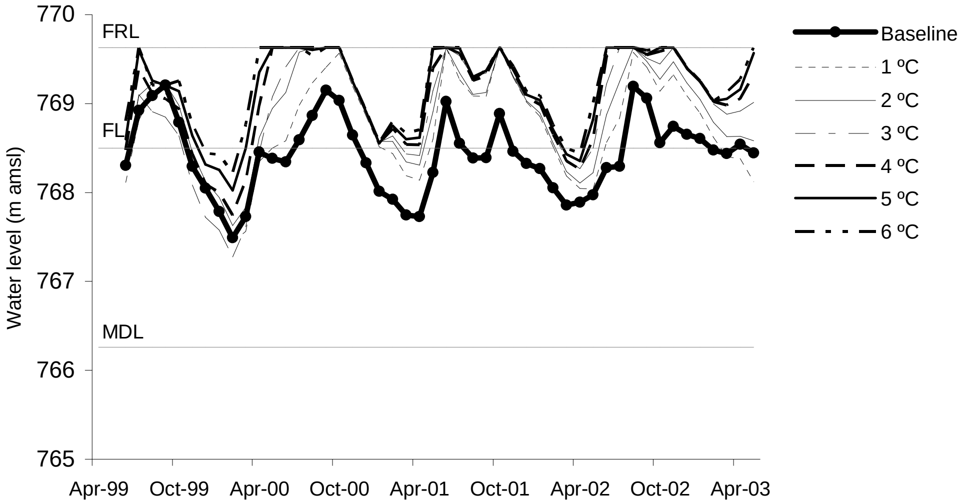

Figure 6.35. Simulated mean monthly Loktak Lake water levels under baseline conditions (June 1999–May 2003) using the Hargreaves method perturbed PET for CCG2 scenarios (FRL: full reservoir level, FL: flood level, MDL: minimum drawdown level)

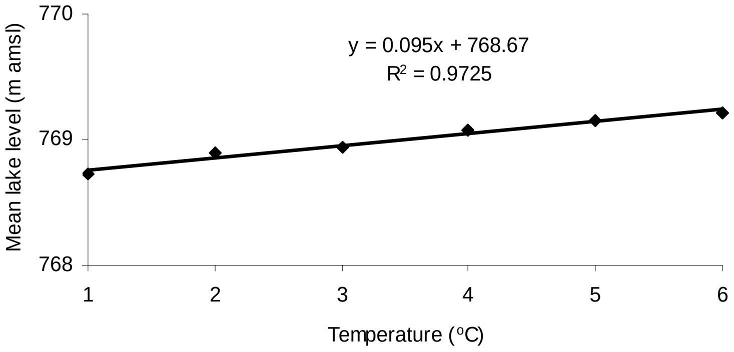

Figure 6.36. Relationship between temperature and mean lake level of Loktak Lake estimated using the Hargreaves method perturbed PET for CCG2 scenarios

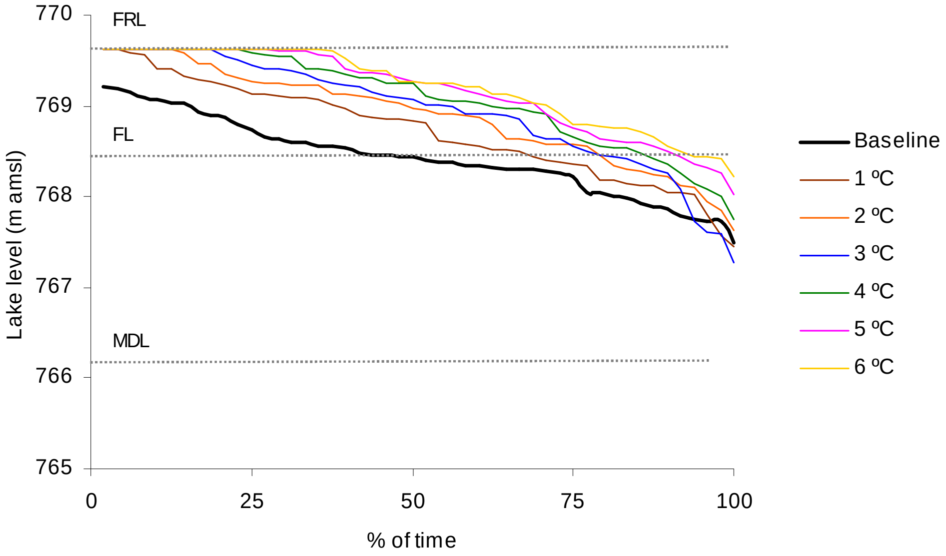

Figure 6.37. Water level-duration curve (June 1999–May 2003) using the Hargreaves method perturbed PET for CCG2 scenarios

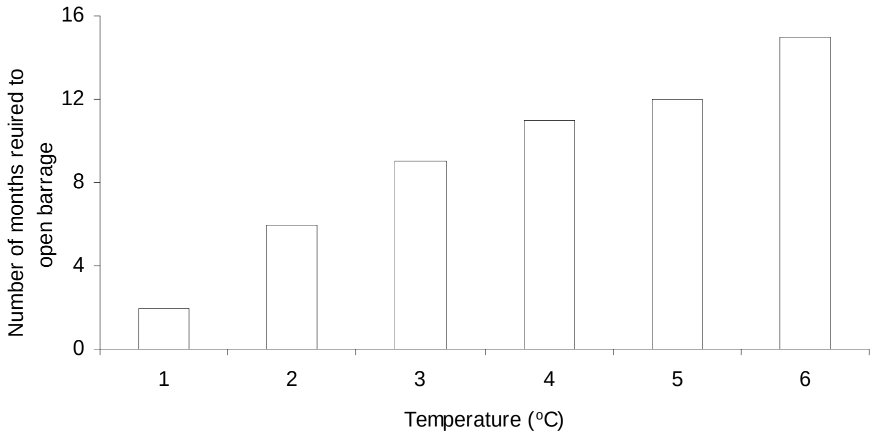

Figure 6.38. Number of months required to open Ithai barrage for additional release of water for CCG2 scenarios estimate using the Hargreaves method perturbed PET

Similar to the CCG1 scenarios, the frequency of flooding in the surrounding areas of the lake is estimated to increase for all CCG2 scenarios (Figure 6.37). The percentage of time during which the water level in the lake is above FL increases with increase in global mean temperature from 67% for the 1°C rise in temperature to 92% for 6°C rise in temperature. This percentage of time during which the water level is above FL is quite high as compared to the baseline condition of just 41%, indicating an enhanced flooding condition for all the CCG2 scenarios.

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. Although there is some uncertainty in the magnitude and direction of change in river flows within the three modelled sub-catchments associated with the CCG1 scenarios, all but the CSIRO GCM (Table 6.10) 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 CCG1 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 CCG1 scenarios additional releases will be necessary to maintain the safety of the Ithai Barrage. These releases are required for all the CCG2 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.

Figure 6.39 shows the total monthly volumes of water (original baseline release + additional releases for structural safety) released from Ithai Barrage calculated by the water balance model for the CCG1 scenarios. The largest releases are associated with MPI, CCCMA and HadGEM1 GCMs, which required additional annual mean releases of 991 × 10^6 m^3, 658 × 10^6 m^3 and 582 × 10^6 m^3 respectively (Table 6.12). Additional releases for barrage structural stability are minimal for CSIRO and NCAR (43 × 10^6 m^3 and 21 × 10^6 m^3 respectively). The maximum monthly release is estimated to be 1558 × 10^6 m^3 in June 2001 under MPI GCM scenario, which is below the maximum monthly barrage release (MBR) capacity of 2203 × 10^6 m^3 (PWD, 1967) provided by the present infrastructure. Hence, monthly releases associated with all CCG1 scenarios can safely be accommodated by opening all five sluice gates.

Table 6.12. Additional annual barrage releases from Ithai Barrage for all climate change scenarios estimated using the Hargreaves method perturbed PET

Scenario	June1999- May 2000 (10^6 m^3)	June2000- May 2001 (10^6 m^3)	June2001- May 2002 (10^6 m^3)	June2002- May 2003 (10^6 m^3)	Mean Annual (10^6 m^3)
CCG1					
CCCMA	382	661	921	668	658
CSIRO	0	174	0	0	43
HadCM3	0	157	354	80	148
HadGEM1	227	763	731	609	582
IPSL	179	86	155	295	179
MPI	597	1133	1251	985	992
NCAR	0	84	0	0	21
CCG2					
1 °C	0	0	103	0	26
2 °C	0	157	354	80	148
3 °C	0	298	692	231	305
4 °C	29	572	967	403	493
5 °C	213	663	1223	605	676
6 °C	484	871	1491	899	936

Figure 6.40 shows the total monthly volumes of water releases from the Ithai Barrage calculated by the water balance model for CCG2 scenarios. Similar to the CCG1 scenarios, all CCG2 scenarios resulted in additional releases for structural stability of the barrage. The amount of water released increases consistently with the rising temperature. With 1°C, the additional release was estimated to be 26 x 10^6 m^3 annually. This increases to a maximum of 936 × 10^6 m^3 for the 6°C scenario (Table 6.12). The maximum total monthly release was estimated to be 2085 × 10^6 m^3 in June 2001 for 6°C scenario, which again is well within the maximum barrage release capacity of 2203 × 10^6 m^3. Hence, all releases can safely be accommodated by opening the barrage gates.

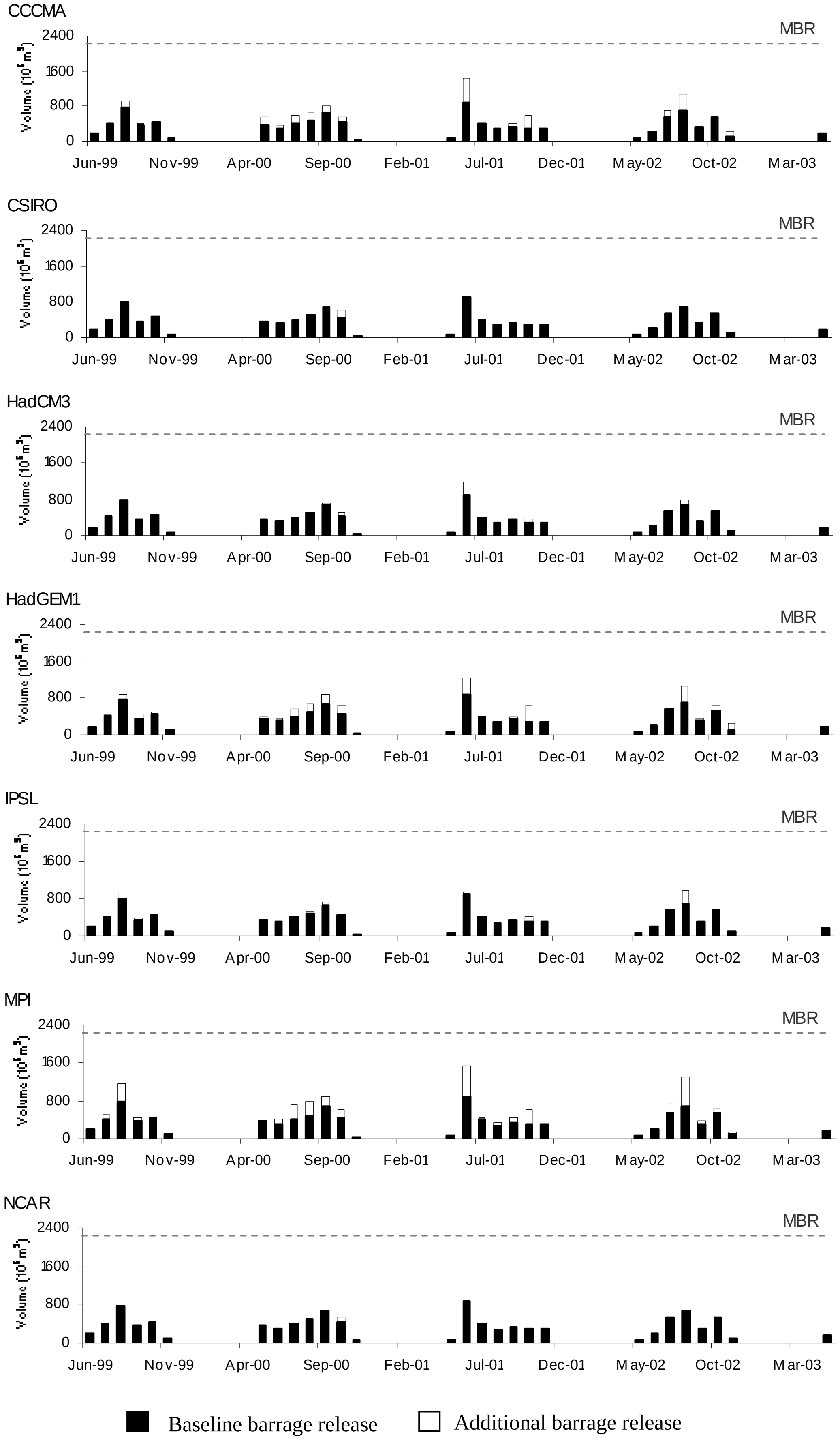

Figure 6.39. Total monthly barrage releases from Ithai Barrage (June 1999–May 2003) for CCG1 scenarios estimated using the Hargreaves method perturbed PET

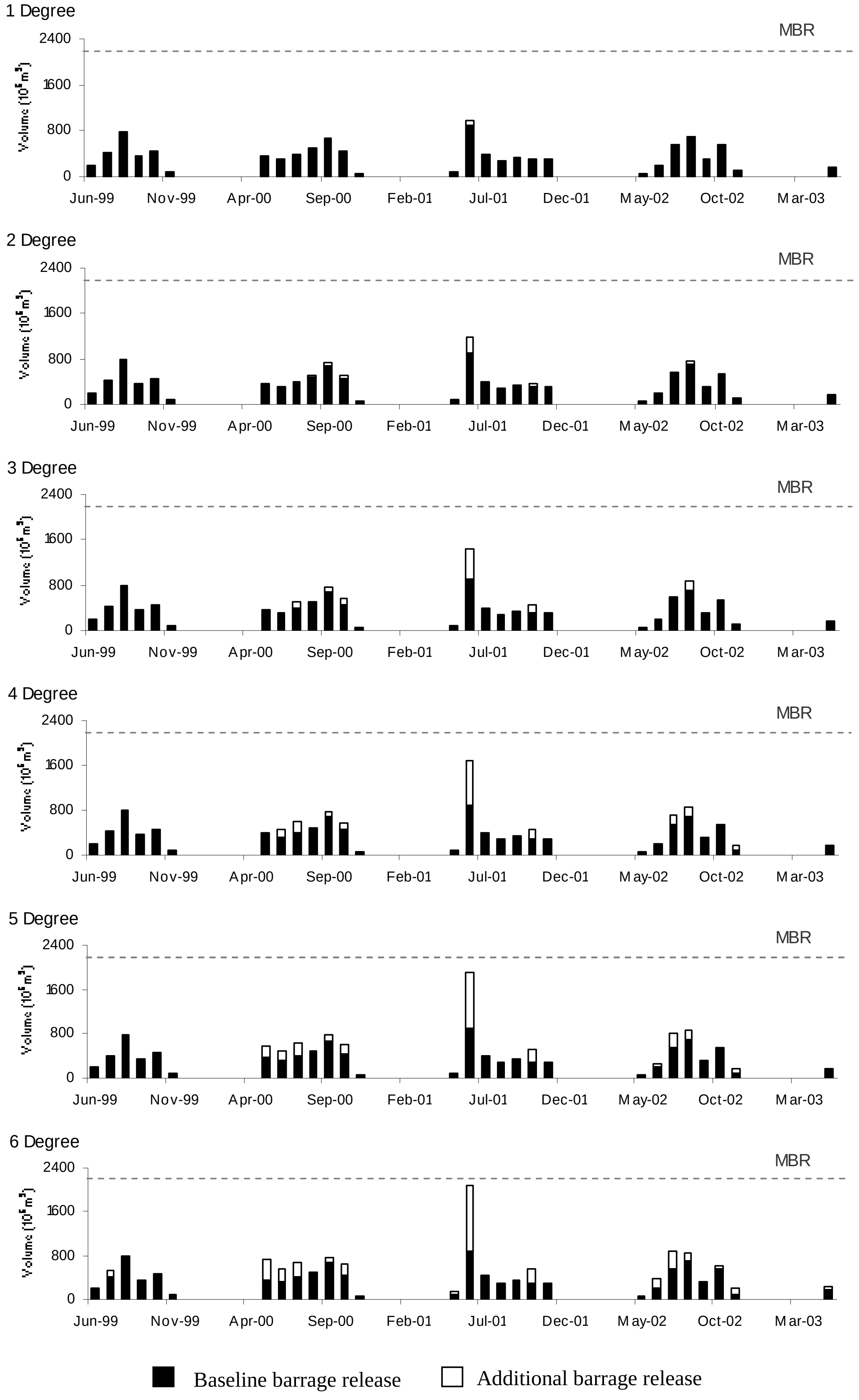

Figure 6.40. Total monthly barrage releases from Ithai Barrage (June 1999–May 2003) for CCG2 scenarios estimated using the Hargreaves method perturbed PET

With the rise in water level resulting from climate change scenarios, current abstractions from the lake for hydropower and irrigation purposes are possible for all climate change scenarios with the exception of three months for the CCG1 CSIRO scenario. In the baseline condition the hydropower sector was already abstracting 845 × 10^6 m^3 annually against its maximum desired demand of 896 × 10^6 m^3 (Section 6.2.1). Therefore, increased lake volume resulting from increased runoff from the catchment area will only result in very modest increases in hydropower generation at the cost of exacerbated flooding of lakeside communities and further deteriorating the ecological health of Loktak Lake. This high water level regime, as discussed in Section 2.5.2, is the main reasons for the deteriorating condition of the *phumdis*, especially in the KLNP area.

6.3.2. Changes in water level regime of Loktak Lake using PET data perturbed using the Thornthwaite method.

The simulated lake water levels resulting from the CCG1 scenarios employling PET data perturbed using the Thornthwaite method is as shown in Figure 6.41. As with the simulation using Hargreaves PET, all the scenarios under CCG1, except the CSIRO, estimate an increase in lake water levels compared to the baseline. The largest increases are associated with the CCCMA, HadGEM1 and MPI GCMs. The mean lake levels under these scenarios increase by 0.89, 0.92 and 0.81 m respectively compared to the baseline mean (Table 6.13). The HadCM3, IPSL and NCAR GCMs increase mean lake water level by 0.57, 0.45 and 0.41 m respectively. The water levels under CCCMA, HadCM3, HadGEM1 and MPI GCMs are higher than those of the baseline conditions in all 48-months of the simulation period while for IPSL and NCAR GCMs the water levels are higher in 42 and 35 months. The CSIRO GCM shows a trend of lower water levels which on average are 0.24 m below those of the baseline scenario.

Figures 6.41 and 6.42 shows that water levels in all scenarios of the CCG1 exceed the FRL at some point during the study period necessitating additional releases. The number of months when these releases are required varies between scenarios from 16 for both CCCMA and HadGEM1 GCMs to just three for NCAR and CSIRO (Figure 6.43). The water level-duration curve (Figure 6.42) also indicates that the frequency of flooding in the peripheral areas of the lake is exacerbated. The percentage of time during which the water level in the lake is above FL is estimated to be between 48% (CSIRO) and 100% (HadGEM1) compared to 40% for the baseline scenario.

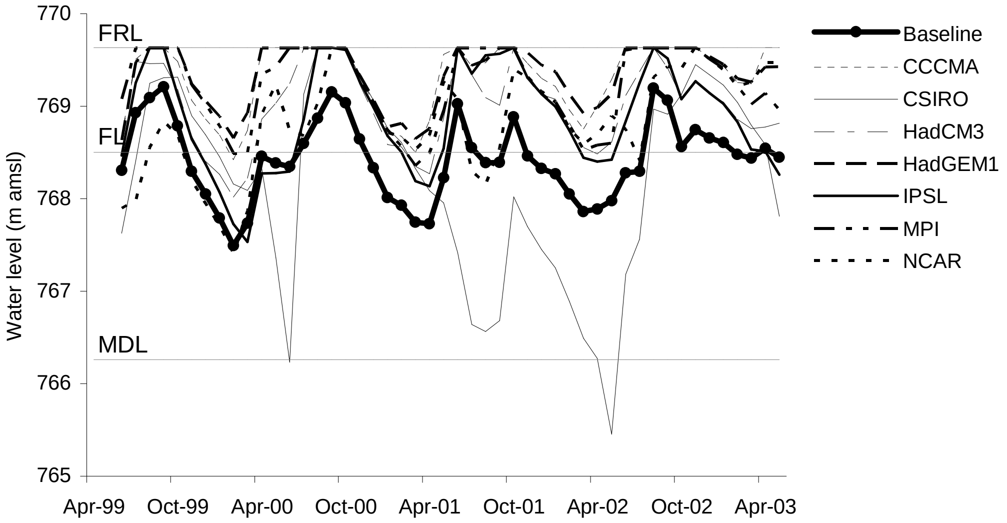

Figure 6.41. Simulated mean monthly Loktak Lake water levels under baseline conditions (June 1999–May 2003) using the Thornthwaite method perturbed PET for CCG1 scenarios

Table 6.13. Mean monthly water level of Loktak Lake for CCG1 scenarios estimated using the Thornthwaite method perturbed PET

	Baseline (m amsl)	**CCCMA (m amsl)**	**CSIRO (m amsl)**	**HadCM3 (m amsl)**	**HadGEM1 (m amsl)**	**IPSL (m amsl)**	**MPI (m amsl)**	**NCAR (m amsl)**
Jan	768.17	769.02	768.42	768.74	769.12	768.69	768.99	768.71
Feb	767.99	768.83	768.17	768.56	768.97	768.45	768.76	768.51
Mar	767.94	768.81	767.92	768.47	768.94	768.17	768.60	768.56
Apr	768.15	769.28	767.82	768.60	769.20	768.33	768.89	768.94
May	768.26	769.53	767.14	768.83	769.38	768.38	768.98	769.22
Jun	768.49	769.39	767.11	769.16	769.38	768.81	769.49	768.61
Jul	768.59	769.55	767.93	769.45	769.54	769.18	769.63	768.34
Aug	768.88	769.59	768.60	769.45	769.60	769.61	769.63	768.76
Sep	768.95	769.63	768.63	769.38	769.63	769.59	769.63	769.11
Oct	768.82	769.59	769.02	769.38	769.63	769.36	769.63	769.28
Nov	768.54	769.37	768.84	769.13	769.45	769.12	769.37	769.11
Dec	768.34	769.18	768.63	768.89	769.28	768.91	769.18	768.90
Mean	**768.43**	**769.31**	**768.19**	**769.00**	**769.34**	**768.88**	**769.23**	**768.84**

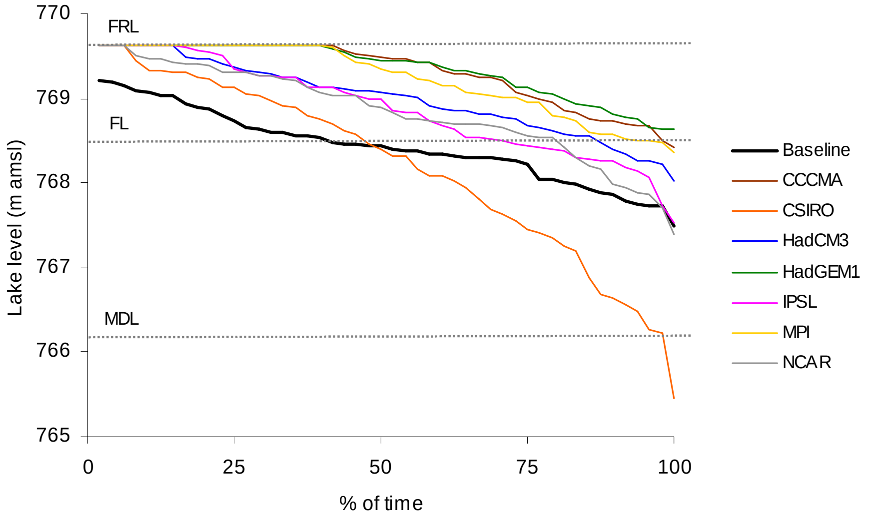

Figure 6.42. Water level-duration curve (June 1999–May 2003) estimated using the Thornthwaite method perturbed PET for CCG1 scenarios

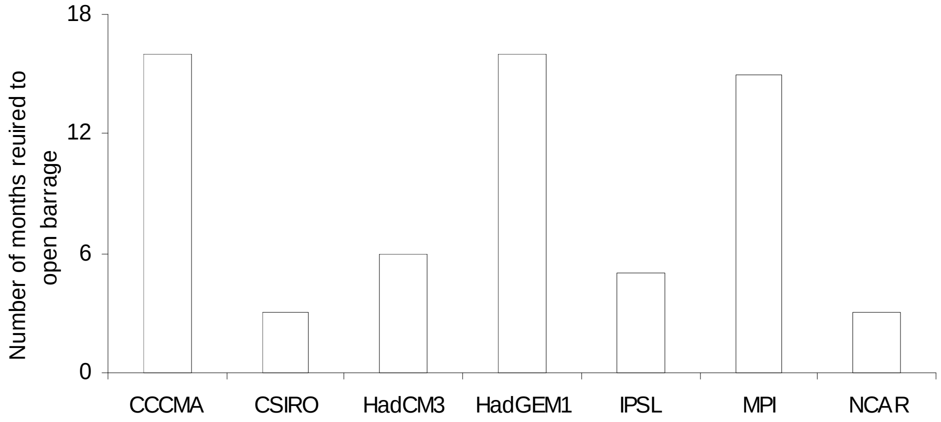

Figure 6.43. Number of months required to open Ithai barrage for additional release of water for CCG1 scenarios estimate using Thornthwaite method perturbed PET

Figure 6.44 shows the simulated water levels within Loktak Lake for the CCG2 scenarios. Unlike those estimated using Hargreaves method to perturb PET, the change in mean water levels of the lake from the baseline mean does not follow a consistent pattern with increasing temperature. For the 1°C scenario, water levels are on average 0.53 m higher. This increases to 0.66 m for the 3°C scenario before declining to 0.51 m for the 5ºC scenario and increasing slightly to 0.53 for 6°C (Table 6.14). The decrease in water level of the lake for the 4°C, 5°C and 6°C scenarios can be attributed to the high evapotranspiration rate (Table 6.5) and lower inflow into the lake (Table 6.7) compared to that simulated using the Hargreaves method (Tables 6.4 and 6.6).

Table 6.14. Mean monthly water level of Loktak Lake for CCG2 scenarios estimated using the Thornthwaite method perturbed PET

	Baseline (m amsl)	**1°C (m amsl)**	**2°C (m amsl)**	**3°C (m amsl)**	**4°C (m amsl)**	**5°C (m amsl)**	**6°C (m amsl)**
Jan	768.17	768.80	768.74	768.85	768.70	768.64	768.63
Feb	767.99	768.62	768.56	768.71	768.55	768.47	768.46
Mar	767.94	768.52	768.47	768.63	768.48	768.37	768.36
Apr	768.15	768.66	768.60	768.75	768.57	768.42	768.43
May	768.26	768.76	768.83	769.02	768.95	768.86	768.98
Jun	768.49	768.96	769.16	769.31	769.38	769.37	769.48
Jul	768.59	769.17	769.45	769.54	769.59	769.57	769.59
Aug	768.88	769.31	769.45	769.43	769.38	769.29	769.26
Sep	768.95	769.31	769.38	769.34	769.32	769.20	769.21
Oct	768.82	769.34	769.38	769.39	769.37	769.33	769.36
Nov	768.54	769.15	769.13	769.18	769.10	769.03	769.05
Dec	768.34	768.95	768.89	768.97	768.84	768.77	768.77
Mean	**768.43**	**768.96**	**769.00**	**769.09**	**769.02**	**768.94**	**768.96**

The water level-duration curve (Figure 6.45) indicates that in all CCG2 scenarios, the flooding frequency is increased. The percentage duration of time during the simulation period during which the lake level is above the FL is computed to vary between 81 (5°C rise in temperature) and 92% (3°C raise in Temperature). Results also shows that the lake water level for all scenarios of CCG2 exceeds the FRL at some point of time during the simulation period, indicating the requirement of additional releases. The number of months when these releases are required is shown in Figure 6.46.

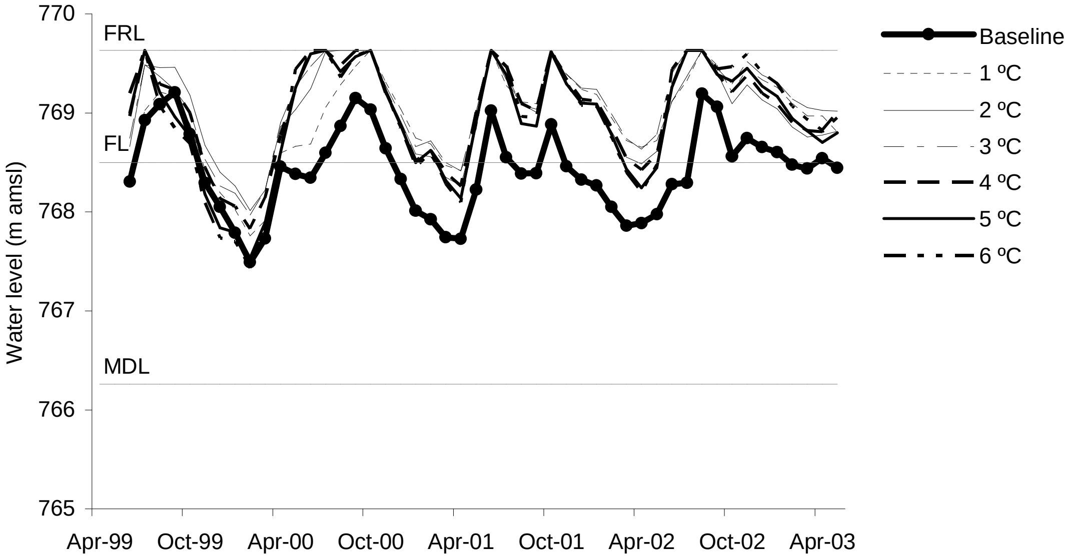

Figure 6.44. Simulated mean monthly Loktak Lake water levels under baseline conditions (June 1999–May 2003) using the Thornthwaite method perturbed PET for CCG2 scenarios

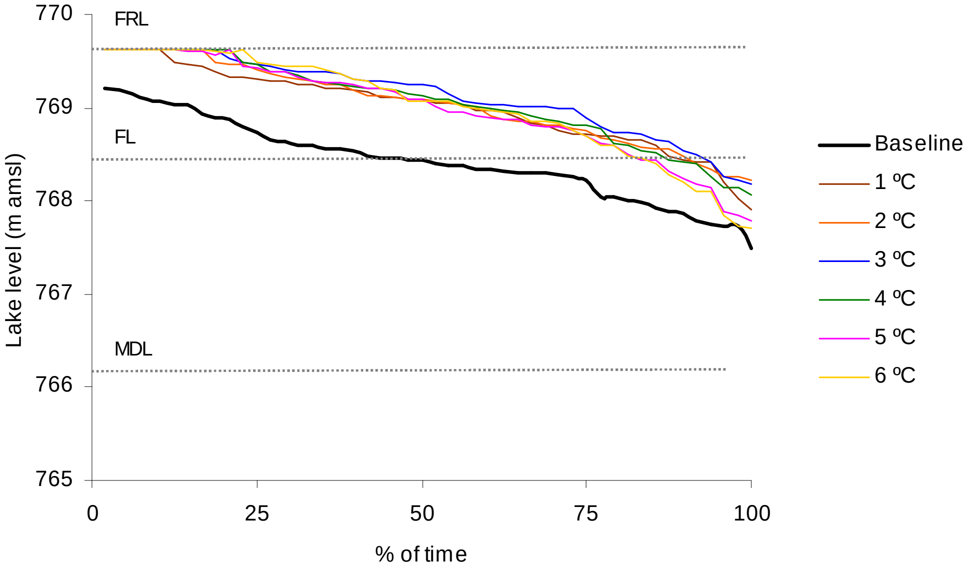

Figure 6.45. Water level-duration curve (June 1999–May 2003) estimated using Thornthwaite method perturbed PET for CCG2 scenarios

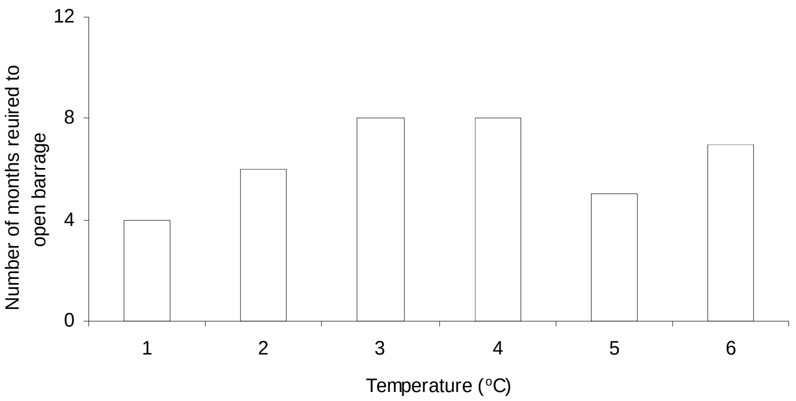

Figure 6.46. Number of months required to open Ithai barrage for additional release of water for CCG2 scenarios estimated using Thornthwaite method perturbed PET

Figures 6.47 and 6.48 show the total monthly water releases (original baseline release + additional releases for structural safety) for all the CCG1 and CCG2scenarios. For the CCG1 scenarios, the largest monthly release of 1615×10^6 m^3 was estimated during June 2001 for the MPI GCM. This can be safely accommodated by the present infrastructure which has the maximum barrage release capacity of 2203×10^6 m^3. Hence, all releases during the simulated period can safely be released by opening the barrages gates without compromising the structural stability of the barrage. The high additional releases for the CCG1 scenarios are associated with the MPI, HadGEM1 and CCCMA GCMs which require mean annual releases of 1093×10^6 m^3, 695×10^6 m^3 and 692×10^6 m^3 respectively, while minimum releases of 70×10^6 m^3 and 44×10^6 m^3 are associated with CSIRO and NCAR CGMs (Table 6.15). For the CCG2 scenarios, the largest mean annual additional release of 408×10^6 m^3 is associated with the 6°C scenario while the minimum release of 67×10^6 m^3 is associated with the 1°C (Table 6.15). The largest monthly total release was estimated to be 1693×10^6 m^3 during June 2001 for 6°C, which is well within the maximum barrage release capacity of 2203×10^6 m^3. Hence the barrage is capable of safely releasing all the releases for the CCG2 scenarios.

6.3.3. Comparison of Loktak Lake water level simulated using the Hargreaves and Thornthwaite perturbed PET

Table 6.16 summarises the impact of all CCG1 and CCG2 scenarios on the water level of Loktak Lake simulated using both Hargreaves and Thornthwaite method of perturbing PET. The water level simulated using the Hargreaves method tends to estimate lower lake levels compared to those using the Thornthwaite method for all

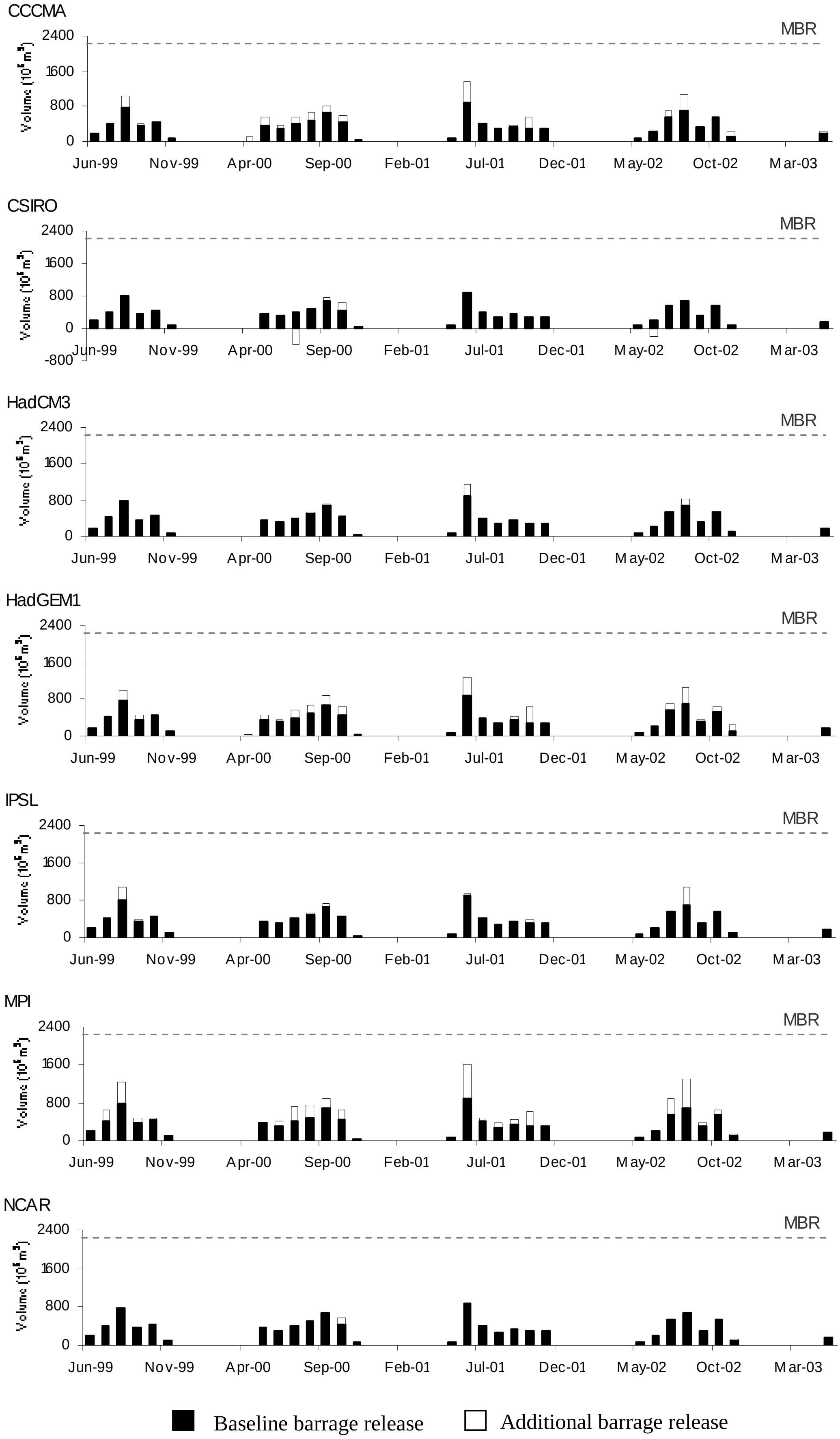

Figure 6.47. Total monthly barrage releases from Ithai Barrage (June 1999–May 2003) for CCG1 scenarios estimated using Hargreaves method perturbed PET

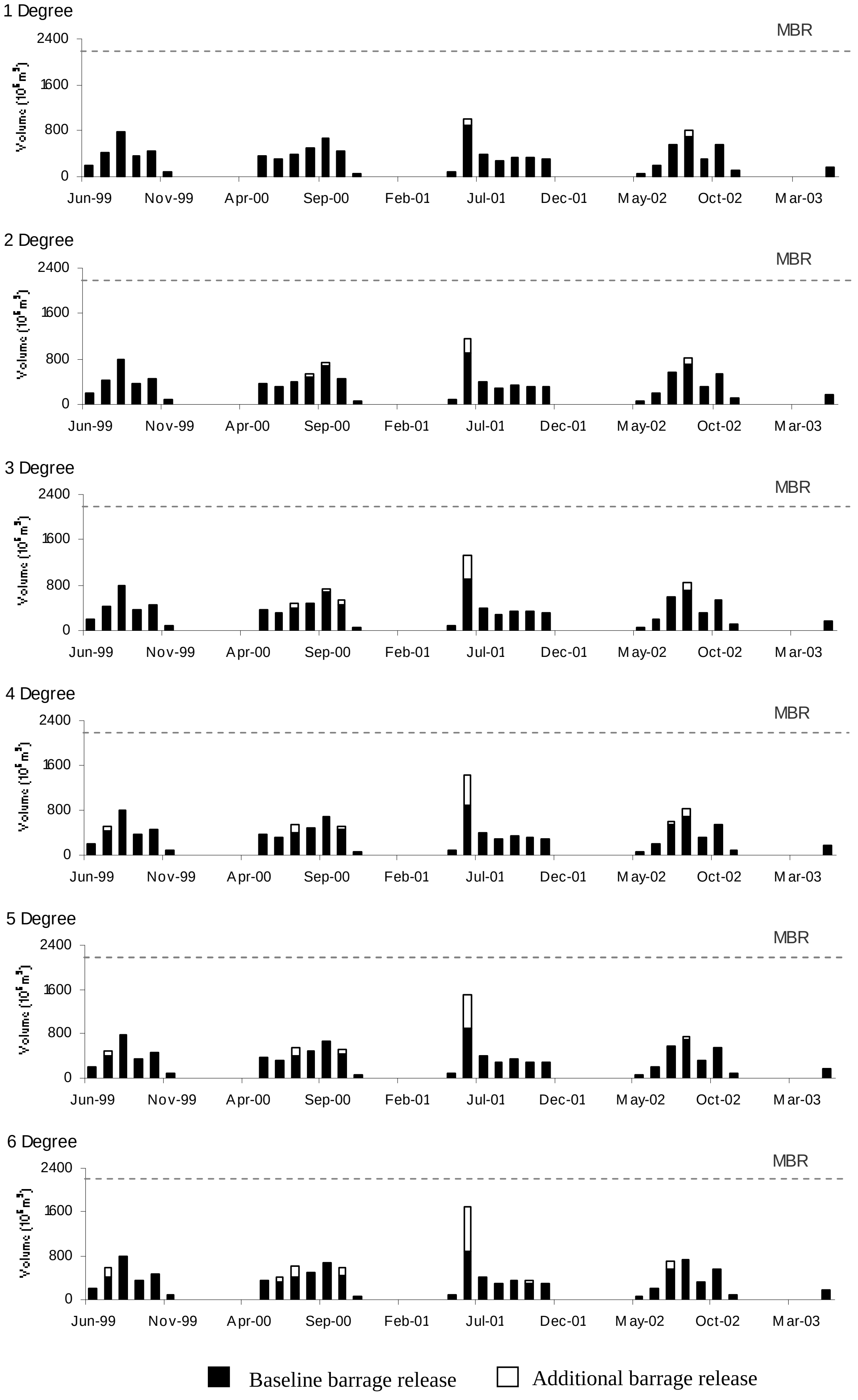

Figure 6.48. Total monthly barrage releases from Ithai Barrage (June 1999–May 2003) for CCG2 scenarios estimated using the Thornthwaite method modified PET

CCG1 scenarios. These lower water levels can mainly be attributed to the smaller inflow from the catchment area of the lake (Table 6.9). The variation in the annual mean lake level estimated using these two methods is however quite small ranging between 0.10 m for the CCCMA GCM and 0.30 m for the NCAR GCM. Figure 6.49 presents the mean monthly water level of the lake for all CCG1 scenarios simulated using both Hargreaves and Thornthwaite method of perturbing PET. It also demonstrates the small variations in the lake levels.

For the CCG2 scenarios, the water level simulated using Hargreaves method of perturbing PET shows a constant rise in the mean annual water level of the lake with the rise in global mean temperature from 1 to 6°C (Table 6.16). However, a mixed pattern is shown for the water levels simulated using the Thornthwaite method of perturbing PET. The mean annual water level rises with the rise in temperature from 1-3°C, and then falls slightly between 4-6°C. The variation in the annual mean lake level estimated using the two methods of perturbing PET, similar to the GGC1 scenarios, is quite small ranging between 0.05 m for the 4°C rise in temperature and 0.25 m for the 4°C rise in temperature. This small variation in the lake levels simulated by the two different methods is also demonstrated in plots of mean monthly water levels shown in Figure 6.50.

Table 6.15. Additional annual barrage releases from Ithai Barrage for all climate change scenarios estimated using the Thronthwaite method perturbed PET

Scenario	**June1999-May 2000 (10^6 m^3)**	**June2000-May 2001 (10^6 m^3)**	**June2001-May 2002 (10^6 m^3)**	**June2002-May 2003 (10^6 m^3)**	**Mean Annual (10^6 m^3)**
CCG1					
CCCMA	556	684	758	770	692
CSIRO	0	279	0	0	70
HadCM3	0	103	256	115	119
HadGEM1	423	778	797	781	695
IPSL	312	90	134	385	230
MPI	801	1133	1319	1119	1093
NCAR	0	142	0	34	44
CCCMA	556	684	758	770	692
CCG2					
1 ºC	0	8	140	120	67
2 ºC	0	103	256	115	119
3 ºC	0	229	483	185	225
4 ºC	98	227	559	165	263
5 ºC	70	241	620	106	260
6 ºC	176	426	848	180	408

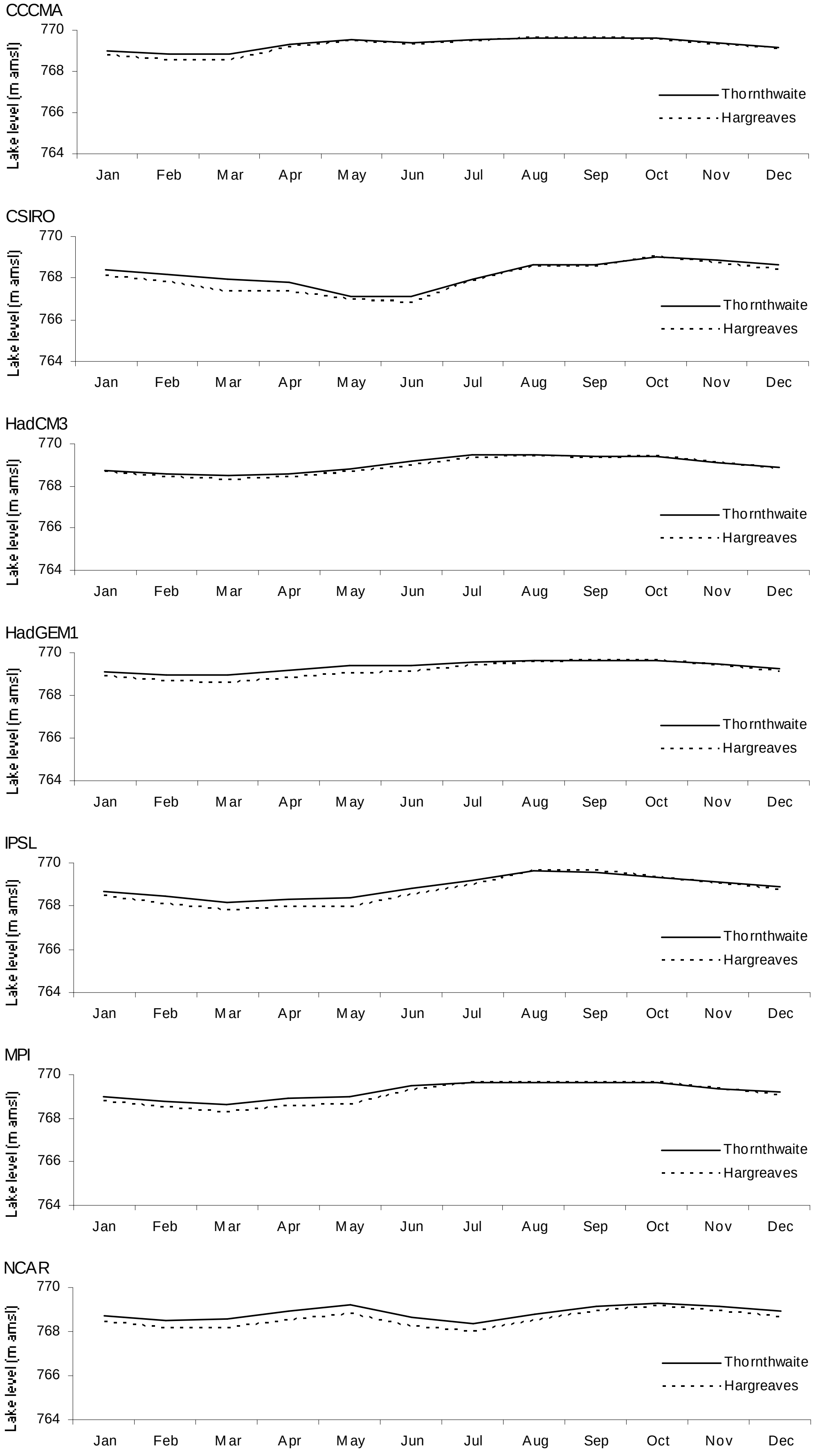

Figure 6.49. Mean monthly water level of Loktak Lake for all CCG1 scenarios (June 1999–May 2003)

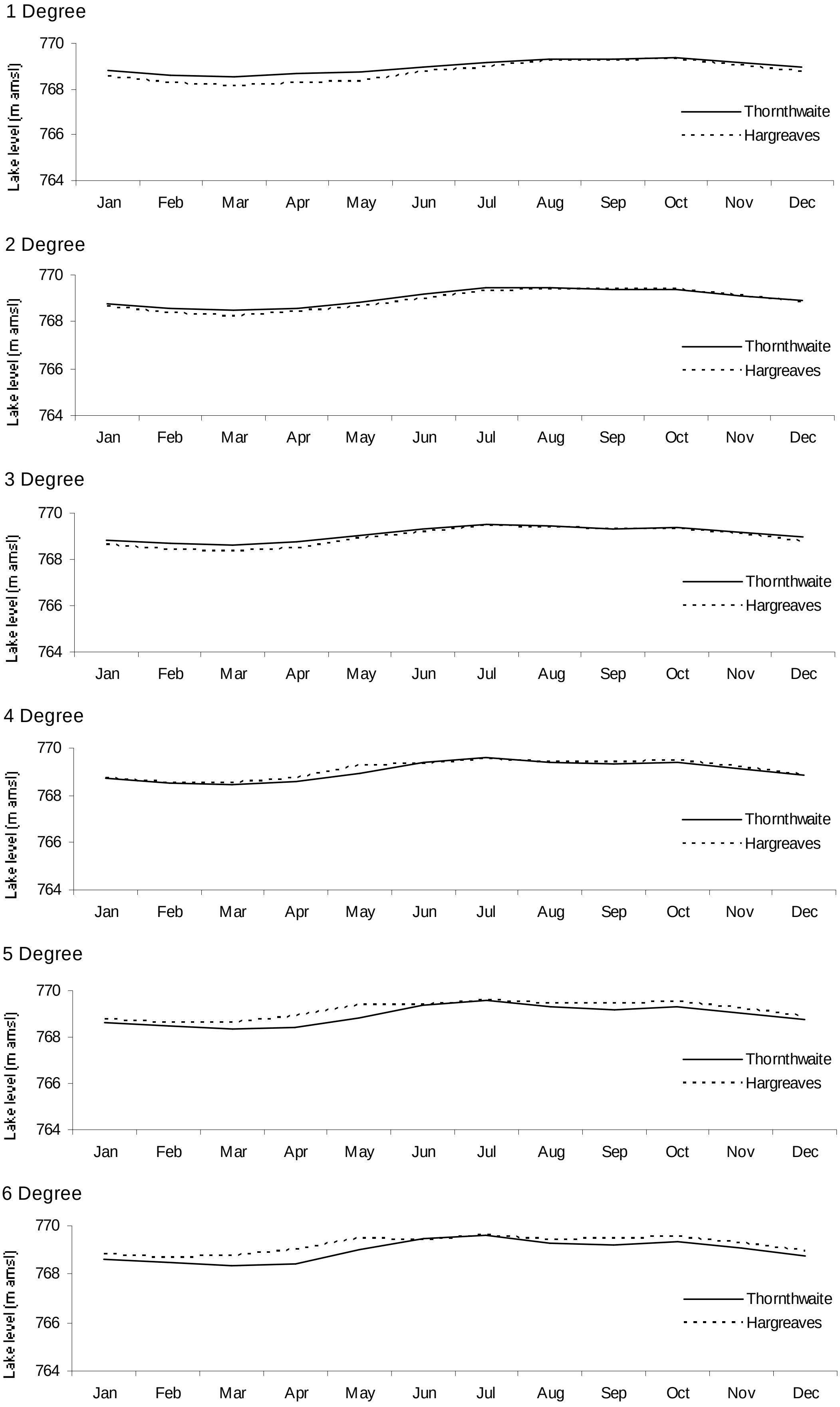

Figure 6.50. Mean monthly water level of Loktak Lake for all CCG1 scenarios (June 1999–May 2003)

Table 6.16. Comparison of the simulated mean annual water levels of Loktak Lake for all CCG1 and CCG2 scenarios

Scenario	**Mean annual water level**		**Difference**
	Simulated using Hargreaves method of perturbing PET (m amsl)	Simulated using Thornthwaite method of perturbing PET (m amsl)	(m)
CCG1			
CCCMA	769.21	769.31	0.10
CSIRO	767.96	768.19	0.23
HadCM3	768.89	769.00	0.11
HadGEM1	769.17	769.34	0.17
IPSL	768.67	768.88	0.21
MPI	769.07	769.23	0.16
NCAR	768.54	768.84	0.30
CCG2			
1°C	768.72	768.96	0.24
2°C	768.89	769.00	0.11
3°C	768.94	769.09	0.15
4°C	769.07	769.02	0.05
5°C	769.16	768.94	0.22
6°C	769.21	768.96	0.25

6.4. Summary

The catchment and the water balance models developed previously in Chapter 3 and 4 are successful in reproducing climate change induced runoff from the catchment as well as water levels of the lake. The total inflow into the lake was simulated to increase for all the climate change scenarios (CCG1 and CCG2) estimated using both PET perturbation methods (Hargreaves and Thornthwaite), except for the CSIRO GCM scenario. As a result of this increased inflow from the catchment area, the water levels of the lake were simulated higher than the baseline condition in all climate change scenarios except for the CSIRO GCM.

The variation in total inflow into the lake estimated using the two different PET perturbation methods is quite small (between 0.68- 8.43% for CCG1 scenarios and between 0.68-8.42% for CCG2 scenarios). The variation in the mean annual water level simulated employing these two different methods are very small (between 0.10-0.30 m for CCG1 scenarios and between 0.05-0.25 for CCG2 scenarios). Hence it implies that the change in the PET perturbation method doesn’t make a huge difference in the estimating of runoff from the catchment area of Loktak Lake.

Chapter 7 – Assessment of the sustainability of the Ithai Barrage operation options

7.1. Introduction

The chapter assesses the sustainability of the four barrage operation (BO) options formulated in Chapter 6, three of which favour each of the main stakeholders (hydropower – BO1, agriculture – BO2 and ecological – BO3) and one integrated option (BO4) in the light of the climate change scenarios (CCG1 and CCG2).

The assessment is carried out using the lake water balance model developed in Chapter 4. Revised river discharges of the modelled sub-catchments for the climate change scenarios are provided by the results from MIKE SHE models and subsequent calculation of flows from ungauged sub-catchments. The new perturbed meteorological time series data previously estimated using the delta factor approach are used as input into the water balance model. The area of *phumdis* and abstractions for hydropower, agriculture and domestic consumption remain unchanged. Assessments are made for changes in the additional releases, including whether they can be accommodated by the existing barrage gates. In addition, changes in the frequency of inundation of the surrounding areas as well as the ability of the lake to sustain abstractions or ground the *phumdis* are investigated. The barrage releases are retained with additional releases being calculated if water levels exceeded the full reservoir level (FRL). The impacts of the climate change scenarios on the barrage operation options are discussed in the following sections.

7.2. Sustainability of barrage operation Option 1 – prioritization to hydropower demand (BO1)

As discussed in Section 5.4.1, this barrage operation option is focussed in providing water for hydropower generation at the rate of 28.4 m^{3}s^{-1} throughout the year. The only pre-requisite criterion for this option to be fulfilled is that at no point, the water level of the lake should go below the MDL of 766.2 m amsl. The water level regime of BO1 (developed in Section 5.4.1) will be considered as the baseline water level regime against which the simulated water levels for the climate change scenarios will be compared in this section

7.2.1. Impacts of Group 1 climate change scenarios (CCG1) on barrage operation Option 1

Figures 7.1 and 7.2 show the simulated monthly lake water levels between June 1999–May 2003 resulting from the CCG1 scenarios with prioritization to hydropower demand employing the Hargreaves (hereafter referred to as CCG1$_H$-BO1) and the Thornthwaite methods of perturbing PET (hereafter referred to as CCG1$_T$-BO1) respectively. The water levels simulated for similar GCM under CCG1$_H$-BO1 and CCG1$_T$-BO1 follow similar pattern with difference in mean annual water levels varying between 0.12 m for the CCCMA and HadCM3 GCMs to 0.42 m for the CSIRO GCM (Table 7.1).

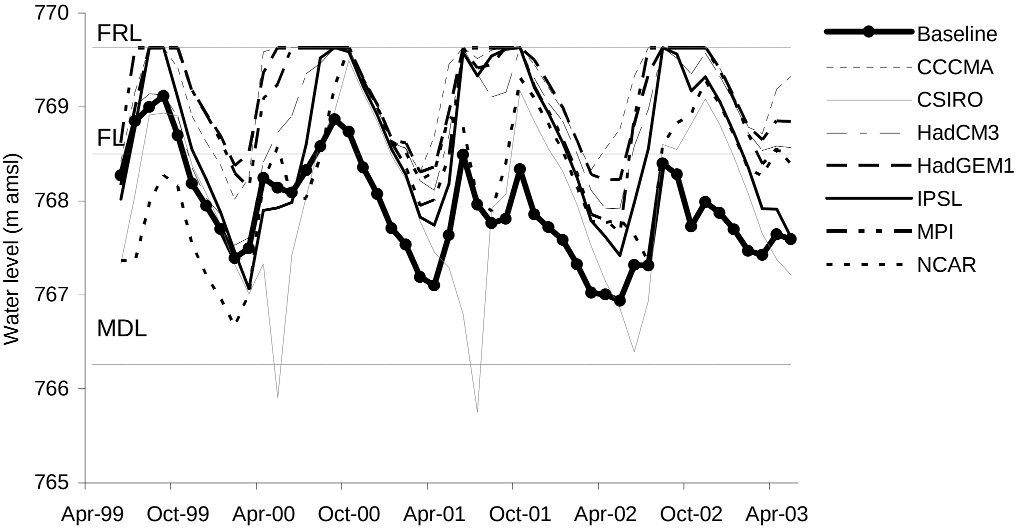

Figure 7.1. Simulated monthly Loktak Lake water levels for CCG1$_H$-BO1 scenarios (June 1999–May 2003)

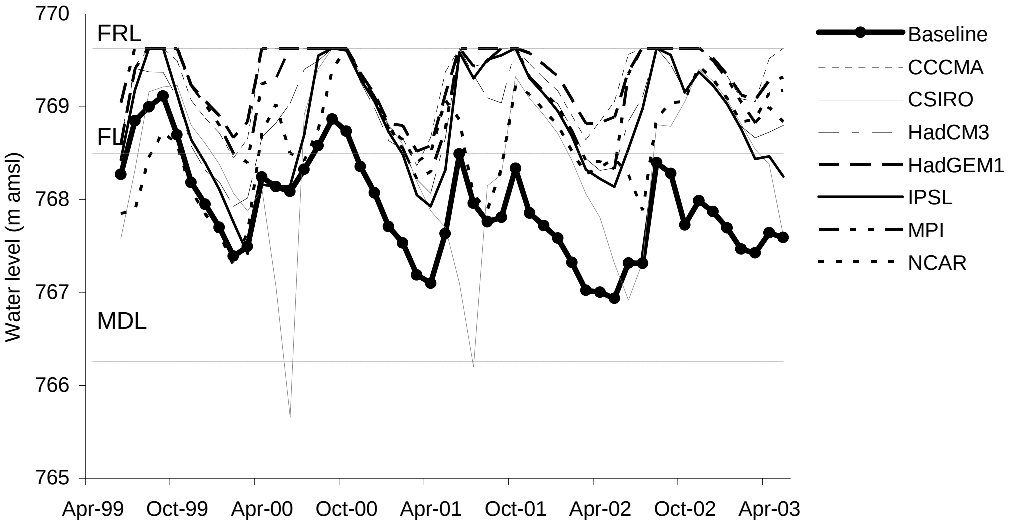

Figure 7.2. Simulated monthly Loktak Lake water levels for CCG1$_T$-BO1 scenarios (June 1999–May 2003)

The annual mean lake water levels for the CCG1$_H$ -BO1 and CCG1$_T$ -BO1 scenarios, when compared to the baseline condition, were simulated to be higher for all GCMs varying between 0.06-1.25 m for CCG1$_H$ -BO1 and between 0.48-1.39 m for CCG1$_T$ -BO1 (Table 7.1). Figure 7.1 and Figure 7.2 indicates that for all the GCMs for CCG1$_T$-BO1 and all GCMs, except CSIRO in CCG1$_H$-BO1, the water levels exceed the FRL at some point of time during the simulation period necessitating additional barrage releases. The number of months during which the additional releases are required varied between 1-19 for CCG1$_H$ -BO1 scenarios and between 2-19 for CCG1$_T$ -BO1 scenarios compare to zero month in the baseline (BO1) water level regime. The largest number of months requiring additional releases is associated with the MPI GCM for both CCG1$_H$-BO1 and CCG1$_T$-BO1. Figures 7.3 and 7.4 demonstrates that total barrage releases including the additional releases simulated by the water balance model can safely be accommodated by opening the barrage gates. Hence the structural integrity of the barrage is not compromised for all CCG1$_H$-BO1 and CCG1$_T$-BO1scenarios.

Table 7.1. Simulated mean annual water levels of Loktak Lake for all CCG1$_H$-BO1 and CCG1$_T$-BO1 scenarios

Scenario	**Mean annual Lake level for CCG1$_H$-BO1 scenarios (m amsl)**	**Difference from baseline (m)**	**Mean annual Lake level for CCG1$_T$-BO1 scenarios (m amsl)**	**Difference from baseline (m)**
Baseline (BO1)	767.91		767.91	
CCCMA	769.16	1.25	769.28	1.37
CSIRO	767.97	0.06	768.39	0.48
HadCM3	768.82	0.91	768.94	1.03
HadGEM1	769.11	1.20	769.30	1.39
IPSL	768.62	0.71	768.83	0.92
MPI	769.01	1.10	769.18	1.27
NCAR	768.29	0.38	768.63	0.72

The water levels were simulated to be lower then the MDL for two months for the CSIRO GCM for both the CCG1$_H$-BO1 and CCG1$_T$-BO1 scenarios indicating the inability of the lake to satisfy the demands of hydropower and agriculture sectors (Figures 7.1 and 7.2). The rest of the GCMs show adequate storage of water in the lake to satisfy the demands from both the stakeholders throughout the simulation period. The water level-duration curves (Figure 7.5) indicate that the water level in all CCG1$_H$-BO1 scenarios exceeds the FL for longer periods varying from 33% (CSIRO) and 88% (CCCMA) of the simulation period compared to just 15% during the baseline period indicating a drastic increase in the frequency of flooding in the surrounding area of the

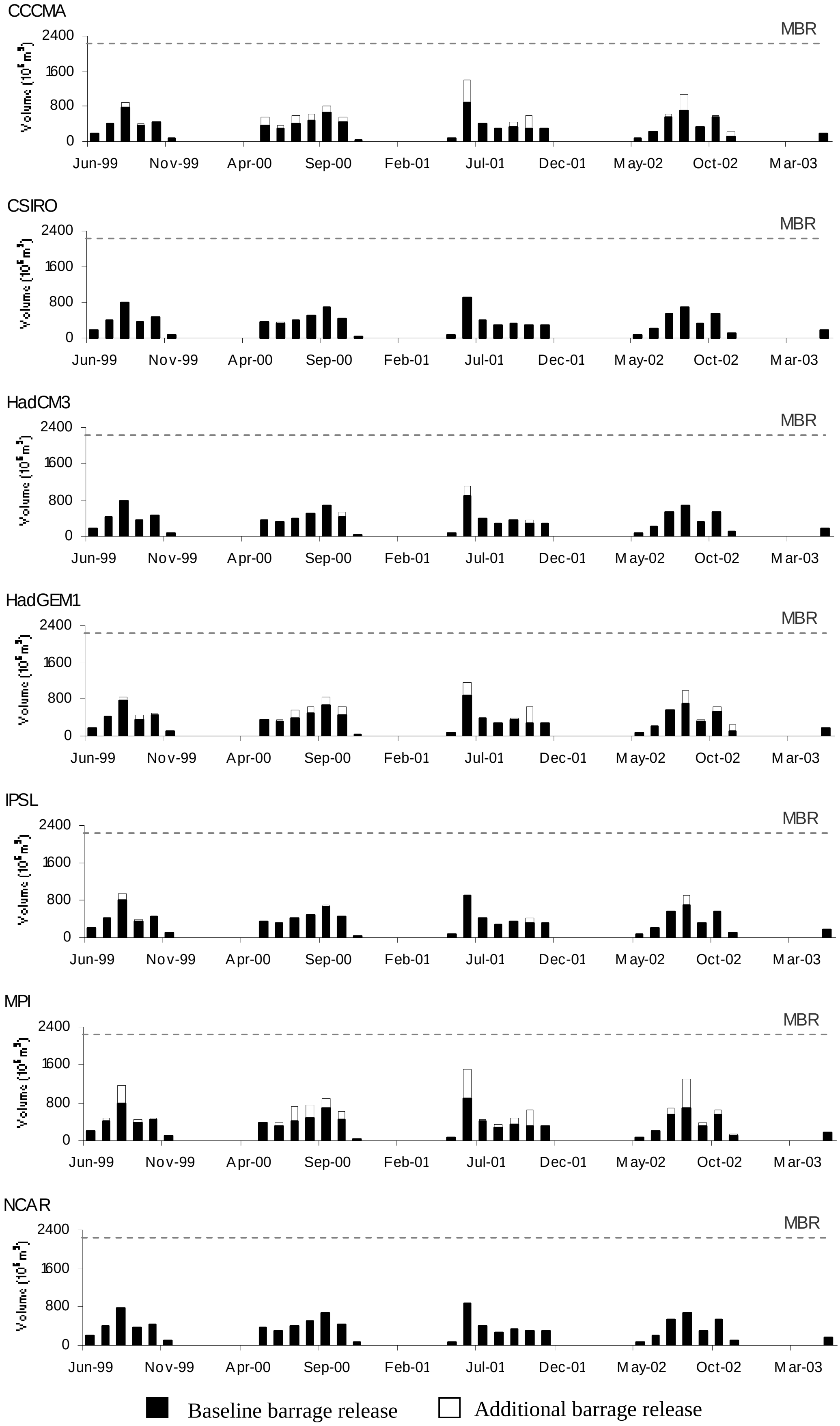

Figure 7.3. Total monthly barrage releases from Ithai Barrage for $CCG1_H$-BO1 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

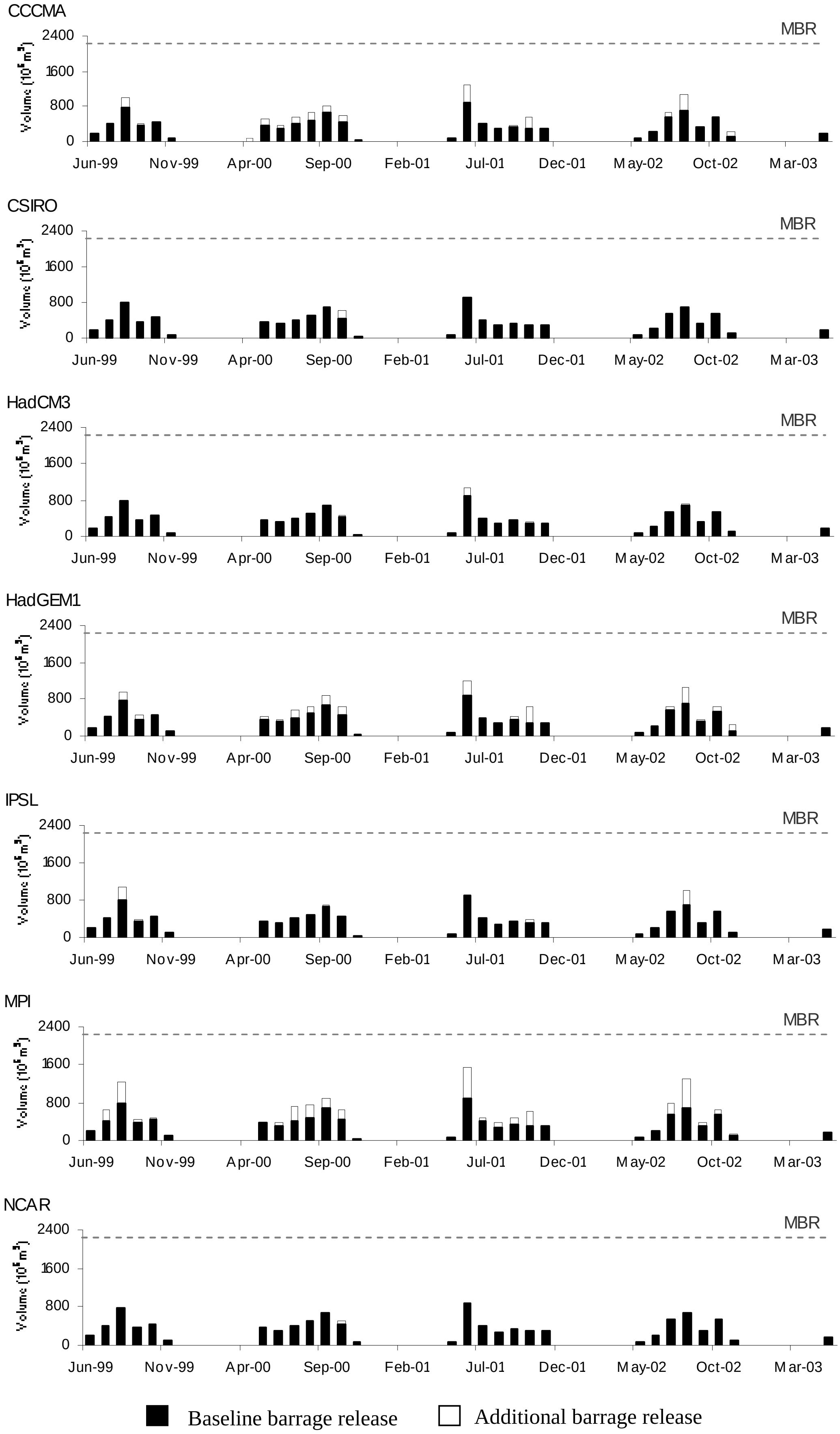

Figure 7.4. Total monthly barrage releases from Ithai Barrage for CCG1$_T$-BO1 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

lake. Similar trend is also observed for all CCG1$_T$-BO1 scenarios (Figure 7.6) with the water level exceeding the FL for a duration varying between 52% (CSIRO) and 96% (CCCMA) of the simulation period. Similar to the baseline condition, all CCG1$_H$-BO1 and CCG1$_T$-BO1 scenarios have water levels above the desire ecological level for grounding the *phumdis* during December, January and February. However, with higher water level during these months for all the climate change scenarios when compared to the baseline as demonstrated in Figure 7.7 are expected to worsen the deteriorating condition of the *phumdis.*

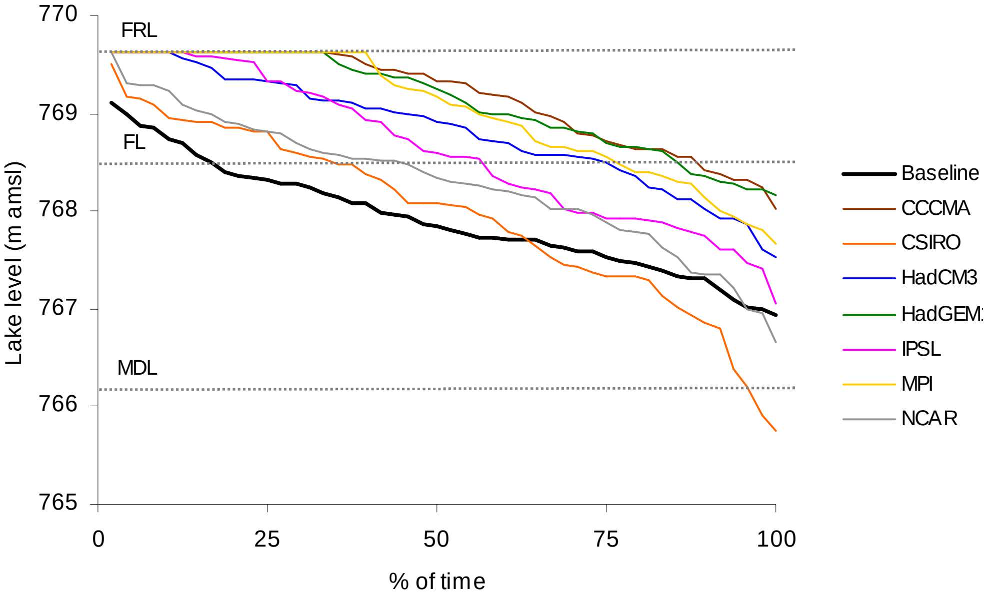

Figure 7.5. Water level-duration curve for all CCG1$_H$-BO1 scenarios (June 1999–May 2003)

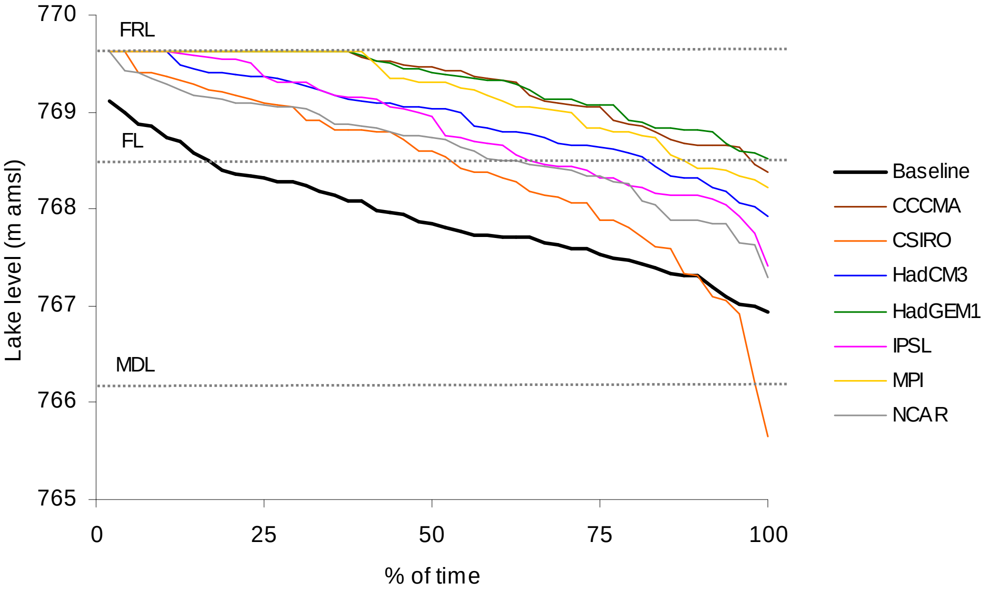

Figure 7.6. Water level-duration curve for all CCG1$_T$-BO1 scenarios (June 1999–May 2003)

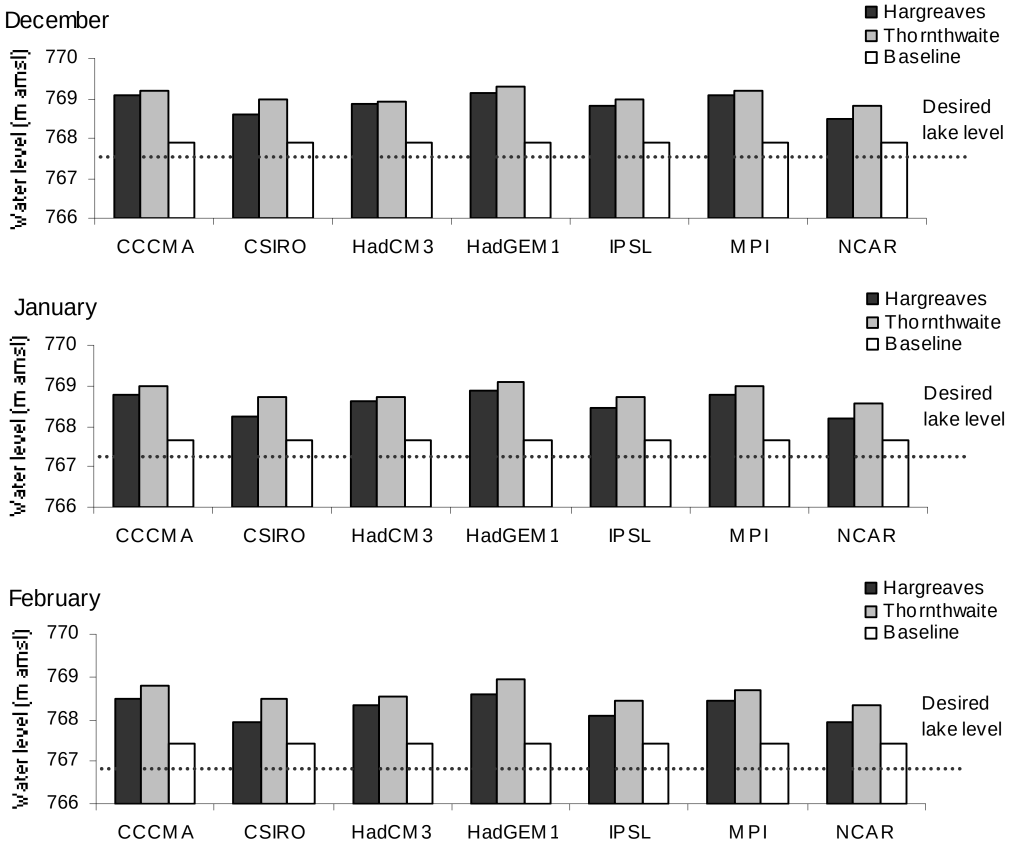

Figure 7.7. Mean monthly water level for CCG1$_H$-BO1 and CCG1$_T$-BO1 scenarios compared against the desired ecological lake level for grounding of phumdis

7.2.2. Impacts of Group 2 climate change scenarios (CCG2) on barrage operation Option 1

The simulated lake water levels for the CCG2 scenarios with prioritization to hydropower demand using the Hargreaves (hereafter referred to as CCG2$_H$-BO1) and Thornthwaite method (hereafter referred to as CCG2$_T$-BO1) of perturbing PET are shown in Figures 7.8 and 7.9 for the period June1999–May2003. The water levels simulated for the 1-3°C rise in global mean temperature scenarios for CCG2$_T$-BO1 are higher compared to the similar scenarios for CCG2$_H$-BO1, and for 3-6°C vice versa. When compared to the baseline condition, all CCG2$_H$-BO1 and CCG2$_T$-BO1 scenarios simulated higher mean annual water level (Table 7.2). For CCG2$_H$-BO1, the mean annual water level rises gradually with the rise in temperature with a maximum increase of 1.26 m associated with the 6°C rise in temperature. However, for CCG2$_T$-BO1, changes in mean lake water level does not follow a similar pattern and the maximum increase in the mean annual water level (1.13 m) is associated with a 3°C rise in global mean temperature.

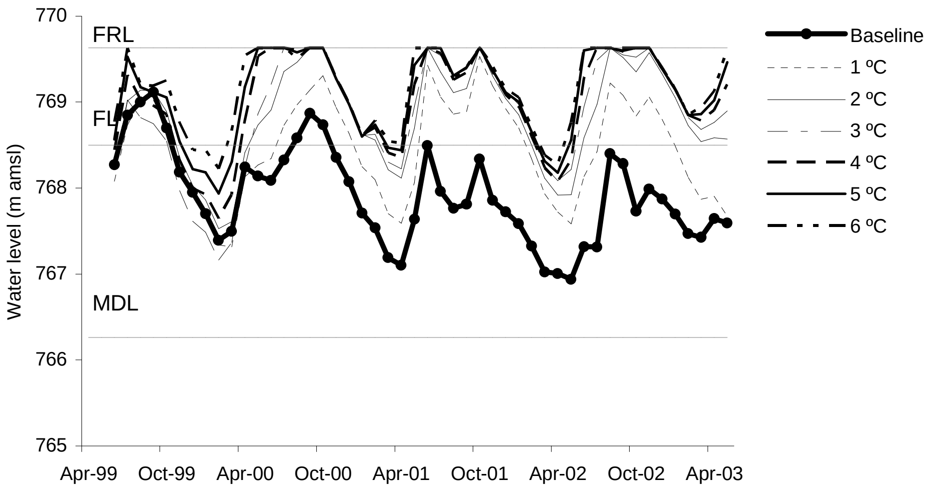

Figure 7.8. Simulated monthly Loktak Lake water levels for CCG2$_H$-BO1 scenarios (June 1999–May 2003)

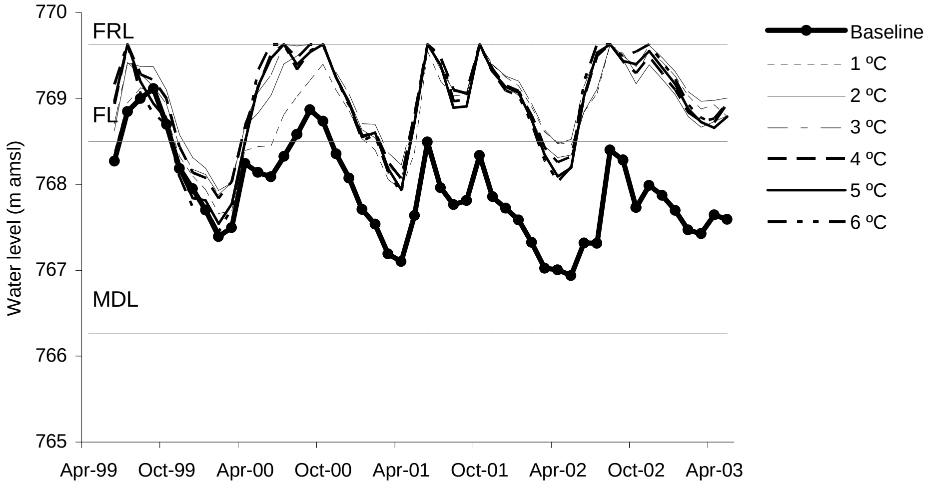

Figure 7.9. Simulated monthly Loktak Lake water levels for CCG2$_T$-BO1 scenarios (June 1999–May 2003)

Table 7.2. Simulated mean annual water levels of Loktak Lake for all CCG2$_H$-BO1 and CCG2$_T$-BO1 scenarios

Scenario	Mean annual Lake level for CCG2$_H$-BO1 scenarios (m amsl)	Difference from baseline (m)	Mean annual Lake level for CCG2$_T$-BO1 scenarios (m amsl)	Difference from baseline (m)
Baseline (BO1)	767.91		767.91	
1°C	768.46	0.55	768.83	0.92
2°C	768.82	0.91	768.94	1.03
3°C	768.86	0.95	769.04	1.13
4°C	769.00	1.09	768.98	1.07
5°C	769.10	1.19	768.91	1.00
6°C	769.17	1.26	768.92	1.01

The water level-duration curves (Figures 7.10 and 7.11) indicate that the water levels in all CCG2$_H$-BO1 and CCG2$_T$-BO1 scenarios are above the FL for much of the simulation period. The flooding frequency increases drastically from just 15% of the simulation period above FL for the BO1 baseline condition to between 50-89% for the CCG2$_H$-BO1 scenarios and between 79-83% for the CCG2$_T$-BO1 scenarios. This barrage operation option shows that the water levels in all CCG2$_H$-BO1 and CCG2$_T$-BO1 scenarios are above the MDL indicating the availability of adequate water in the lake to satisfy the hydropower as well as the agriculture demands which the baseline BO1 water regime was able to do the same. All CCG2$_H$-BO1 and CCG2$_T$-BO1 scenarios have water level above the desire ecological level for grounding the *phumdis* during December, January and February as demonstrated in Figure 7.12. The grounding of the *phumdis* does not take place in the baseline condition as well (Section 6.4.1), however, water levels higher than the baseline condition during these three months for all CCG2$_H$-BO1 and CCG2$_T$-BO1 scenarios will exacerbate the deteriorating health of the *phumdis*.

All CCG2$_T$-BO1 scenarios and all CCG2$_H$-BO1 scenarios, except 1°C rise scenario, have water levels exceeding the FRL at some point during the simulation period envisaging additional releases. The number of months during which it necessitate additional release of water varies between 5-17 for CCG2$_H$-BO1 scenarios and between 2-9 for CCG2$_T$-BO1 scenarios. However, the total water released including the additional release can be released through the opening of the existing barrage gates without the fear of overtopping as shown in Figures 7.13 and 7.14.

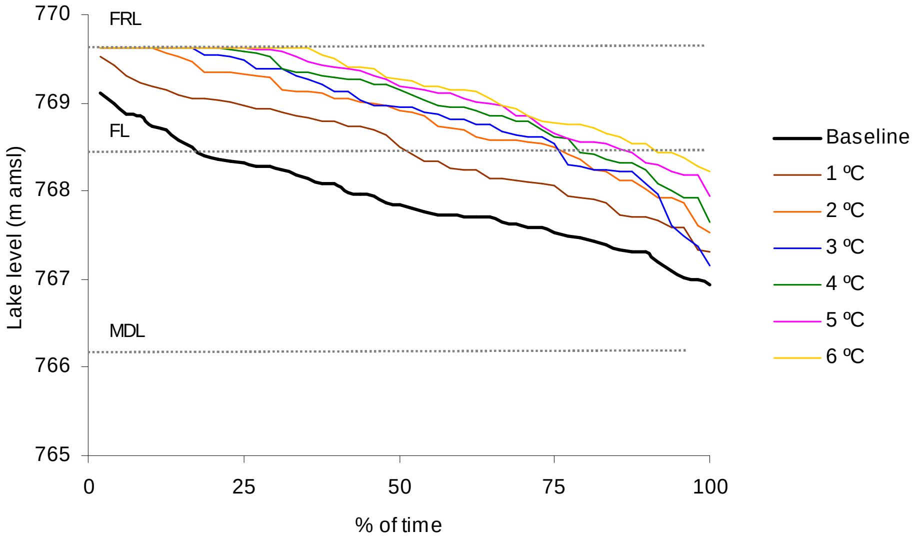

Figure 7.10. Water level-duration curve for all CCG2$_H$-BO1 scenarios (June 1999–May 2003)

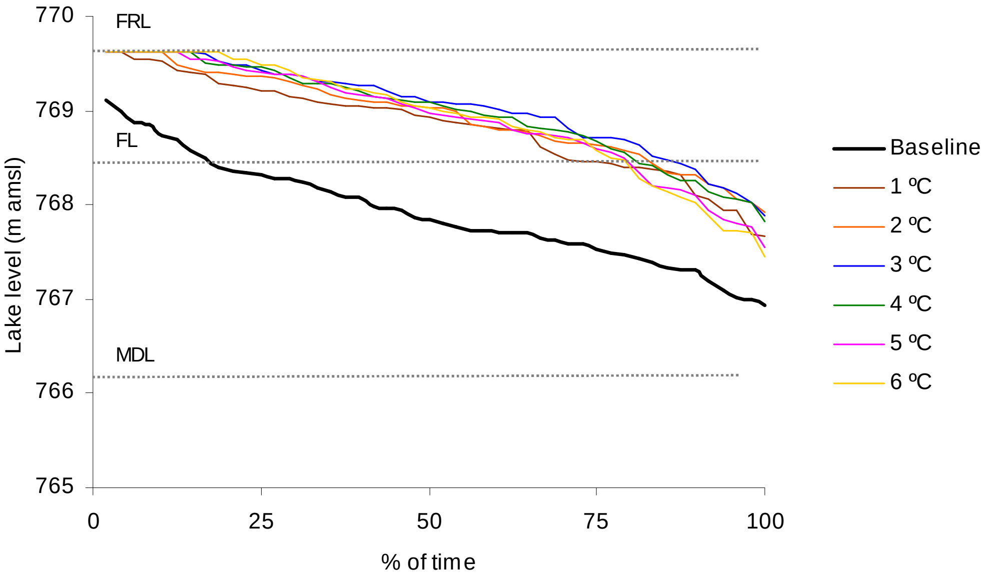

Figure 7.11. Water level-duration curve for all CCG2$_T$-BO1 scenarios (June 1999–May 2003)

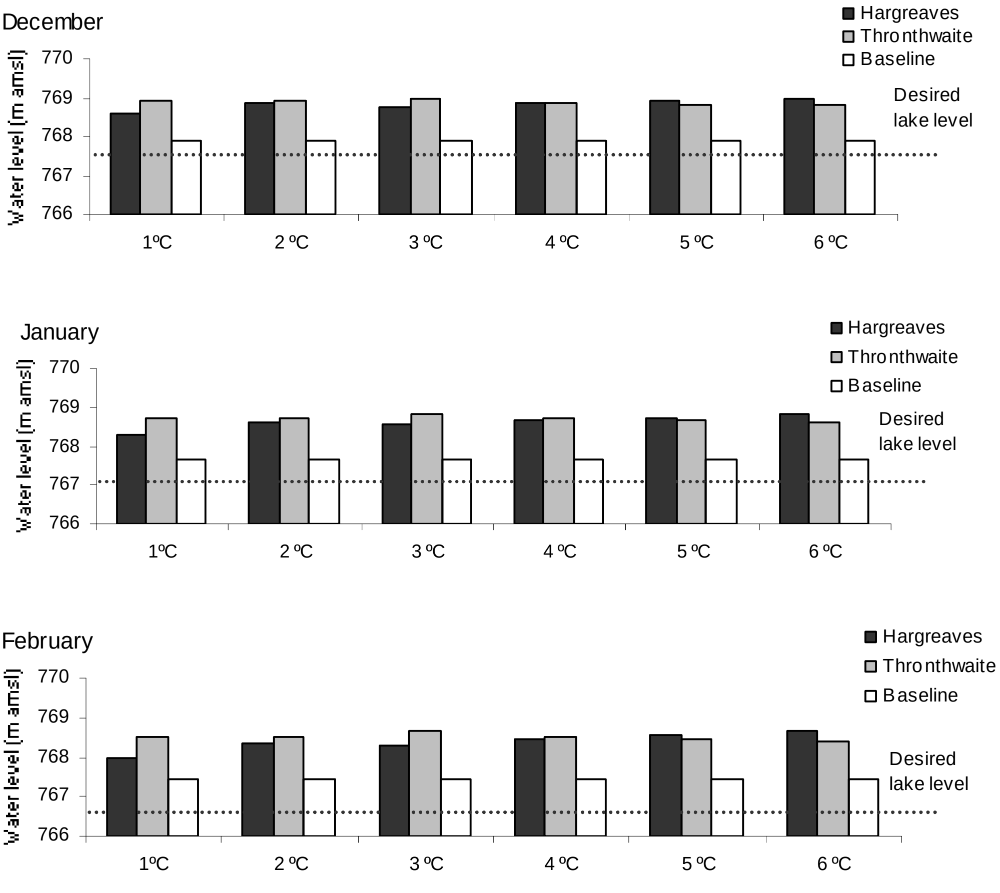

Figure 7.12. Mean monthly water level for CCG2$_H$-BO1 and CCG2$_T$-BO1 scenarios compared against the desired ecological lake level for grounding of phumdis

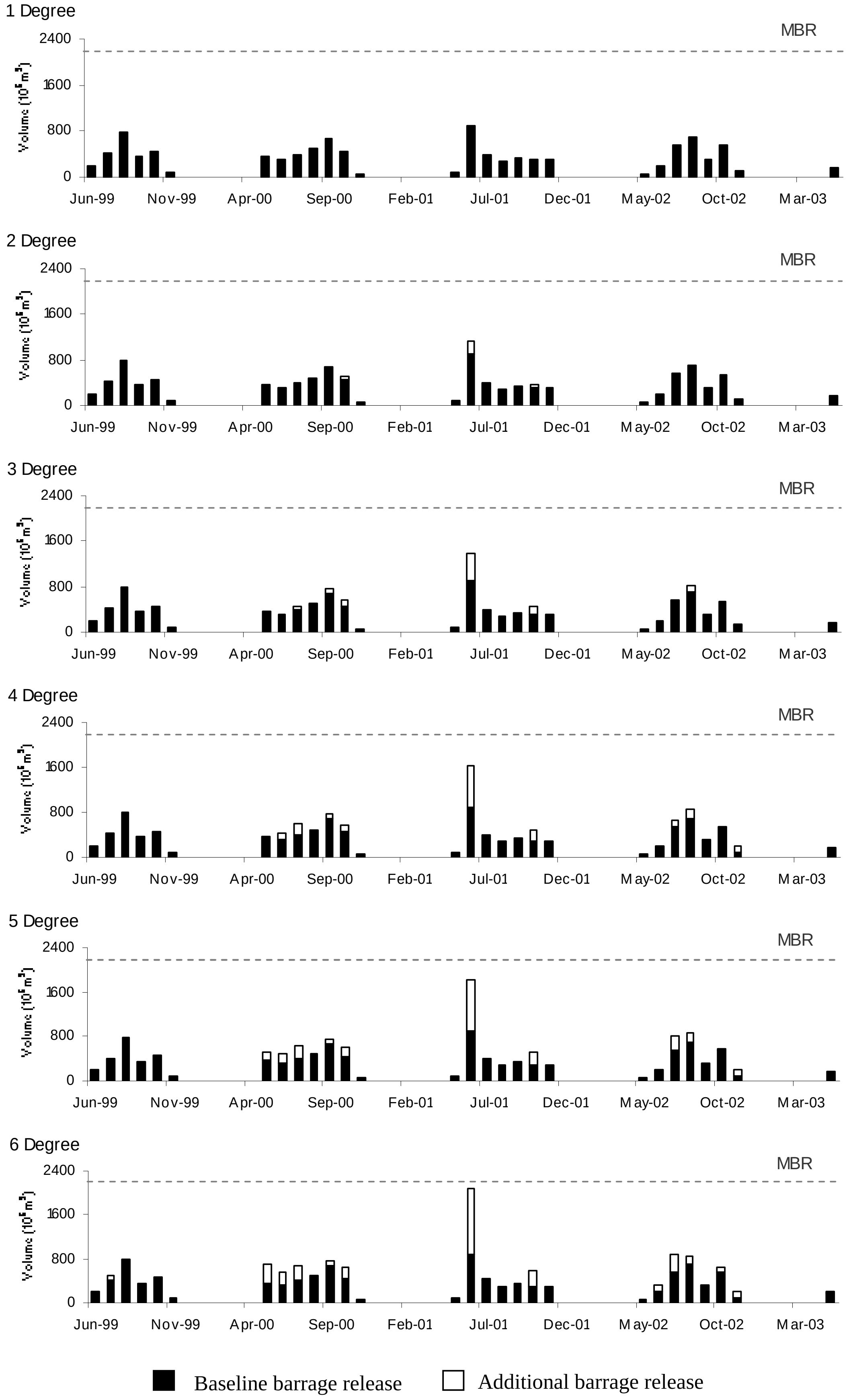

Figure 7.13. Total monthly barrage releases from Ithai Barrage for CCG2$_H$-BO1 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

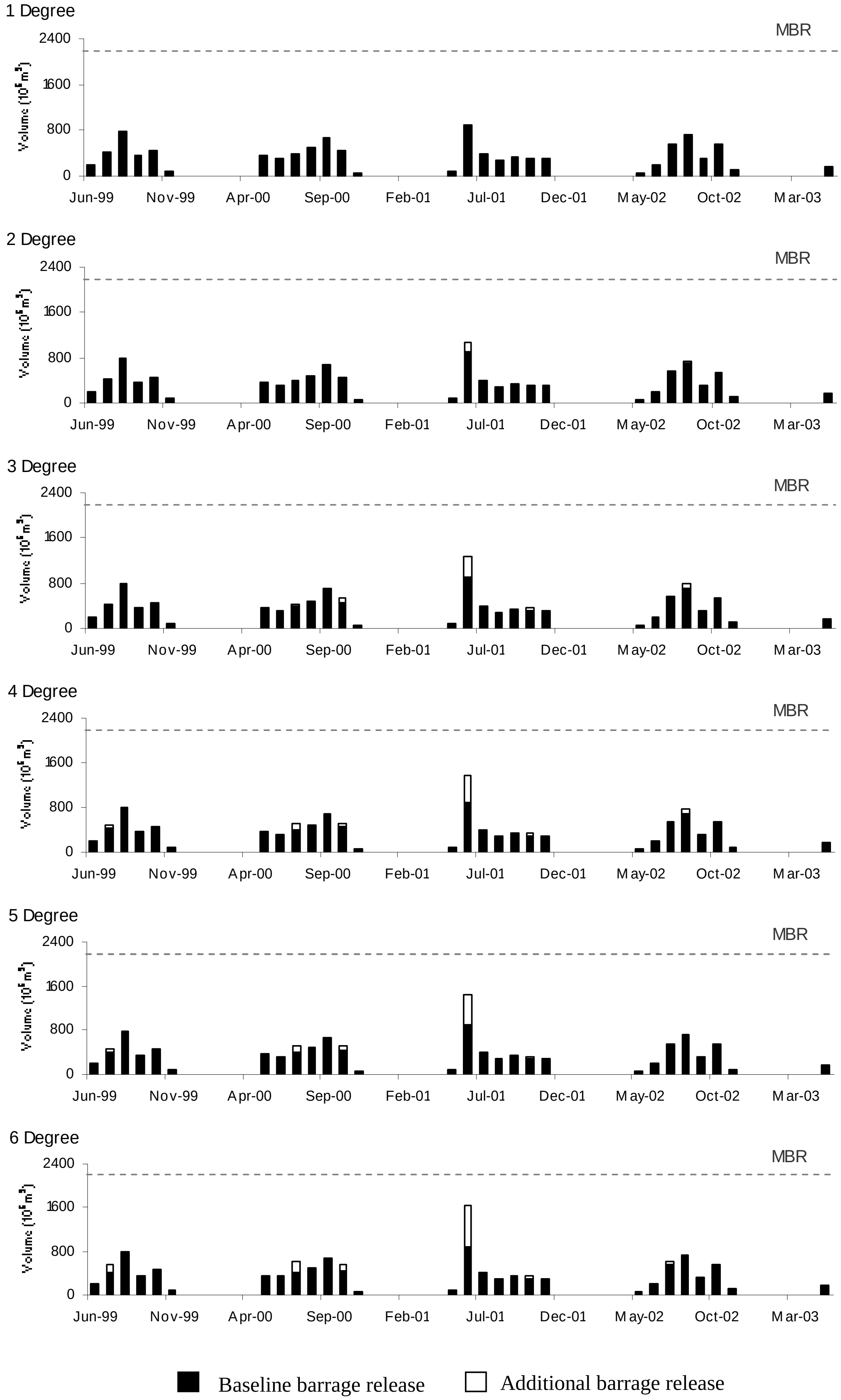

Figure 7.14. Total monthly barrage releases from Ithai Barrage for CCG2$_T$-BO1 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

7.3. Sustainability of barrage operation Option 2 – prioritization to agriculture demand (BO2)

As discussed in Section 5.4.2, this barrage operation option is aimed at supplying water to satisfy the agricultural demand. The desired agricultural demand (total of the Loktak Lift Irrigation Project and Imphal Barrage Project) was estimated to be 222×10^6 m^3 during November–February each year. The water level regime of BO2 (developed in Section 5.4.2) will be considered as the baseline water level regime against which the simulated water levels for the climate change scenarios will be compared in this section.

7.3.1. Impacts of Group 1 climate change scenarios (CCG1) on barrage operation Option 2

The simulated monthly lake water levels for the CCG1 scenarios with prioritization to agriculture demand using the Hargreaves (hereafter referred to as $CCG1_H$-BO2) and Thornthwaite (hereafter referred to as $CCG1_T$-BO2) methods of perturbing PET are shown in Figures 7.15 and 7.16 for the periods June 1999–May 2003. The water levels simulated for similar GCM under $CCG1_H$-BO2 and $CCG1_T$-BO2 scenarios follows similar pattern with difference in mean annual water levels varying between 0.12 m for the IPSL GCM to 0.43 m for the CCCMA GCM. The $CCG1_T$-BO2 scenarios tends to simulate high water level for all GCM compared to those simulated by the same GCM for $CCG1_H$-BO2 (Table 7.3).

Table 7.3. Simulated mean annual water levels of Loktak Lake for all $CCG1_H$-BO2 and $CCG1_T$-BO2 scenarios

Scenario	**Mean annual Lake level for $CCG1_H$-BO2 scenarios (m amsl)**	**Difference from baseline (m)**	**Mean annual Lake level for $CCG1_T$-BO2 scenarios (m amsl)**	**Difference from baseline (m)**
Baseline (BO2)	767.31		767.31	
CCCMA	768.93	1.62	769.36	2.05
CSIRO	767.82	0.51	768.02	0.71
HadCM3	768.41	1.10	768.54	1.23
HadGEM1	768.87	1.56	769.08	1.77
IPSL	768.16	0.85	768.28	0.97
MPI	768.75	1.44	768.95	1.64
NCAR	767.73	0.42	768.01	0.70

Figures 7.15 and 7.16 indicate that in all scenarios, except the CSIRO GCM, water levels exceed the FRL at some point during the simulation period for both $CCG1_H$-BO2 and $CCG1_T$-BO2 scenarios. However, the results of total barrage releases including the additional releases for each scenario, as demonstrated by Figures 7.17 and 7.18 can

comfortably be released using the existing gate infrastructure provided in the Ithai Barrage. The maximum number of months in which additional barrage releases are required is associated with the MPI GCM (17 for CCG1$_H$-BO2 and 18 for CCG1$_T$-BO2). The flooding frequency of the surrounding area of the lake increases in all the climate change scenarios when compared to the baseline condition (Figure 7.19 and 7.20). The CCG1$_H$-BO2 scenarios exceed the FL for periods varying between 17-71% of the simulation period compared to just 10% during the baseline period. Similar trend is also estimated for all CCG1$_T$-BO2 scenarios with the water levels exceeding the FL for a duration varying between 25-100% of the simulation period.

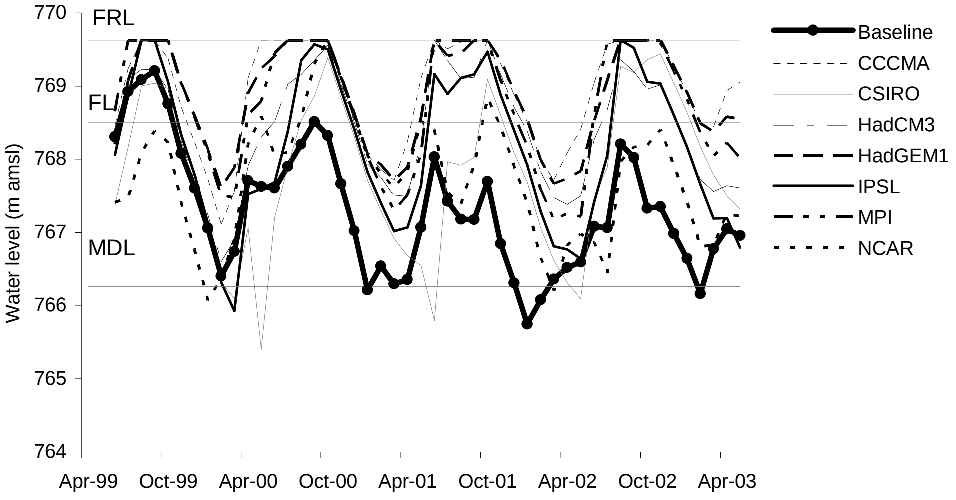

Figure 7.15. Simulated monthly Loktak Lake water levels for CCG1$_H$-BO2 scenarios (June 1999–May 2003)

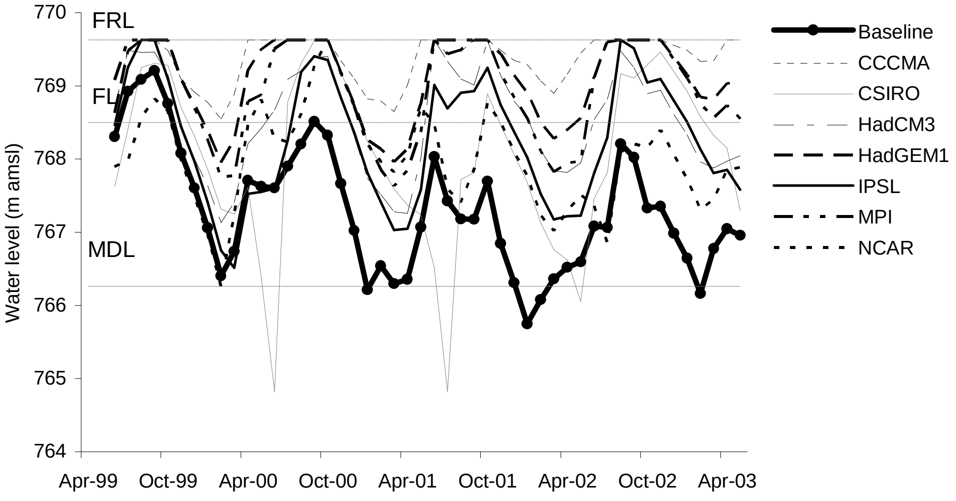

Figure 7.16. Simulated monthly Loktak Lake water levels for CCG1$_T$-BO2 scenarios (June 1999–May 2003)

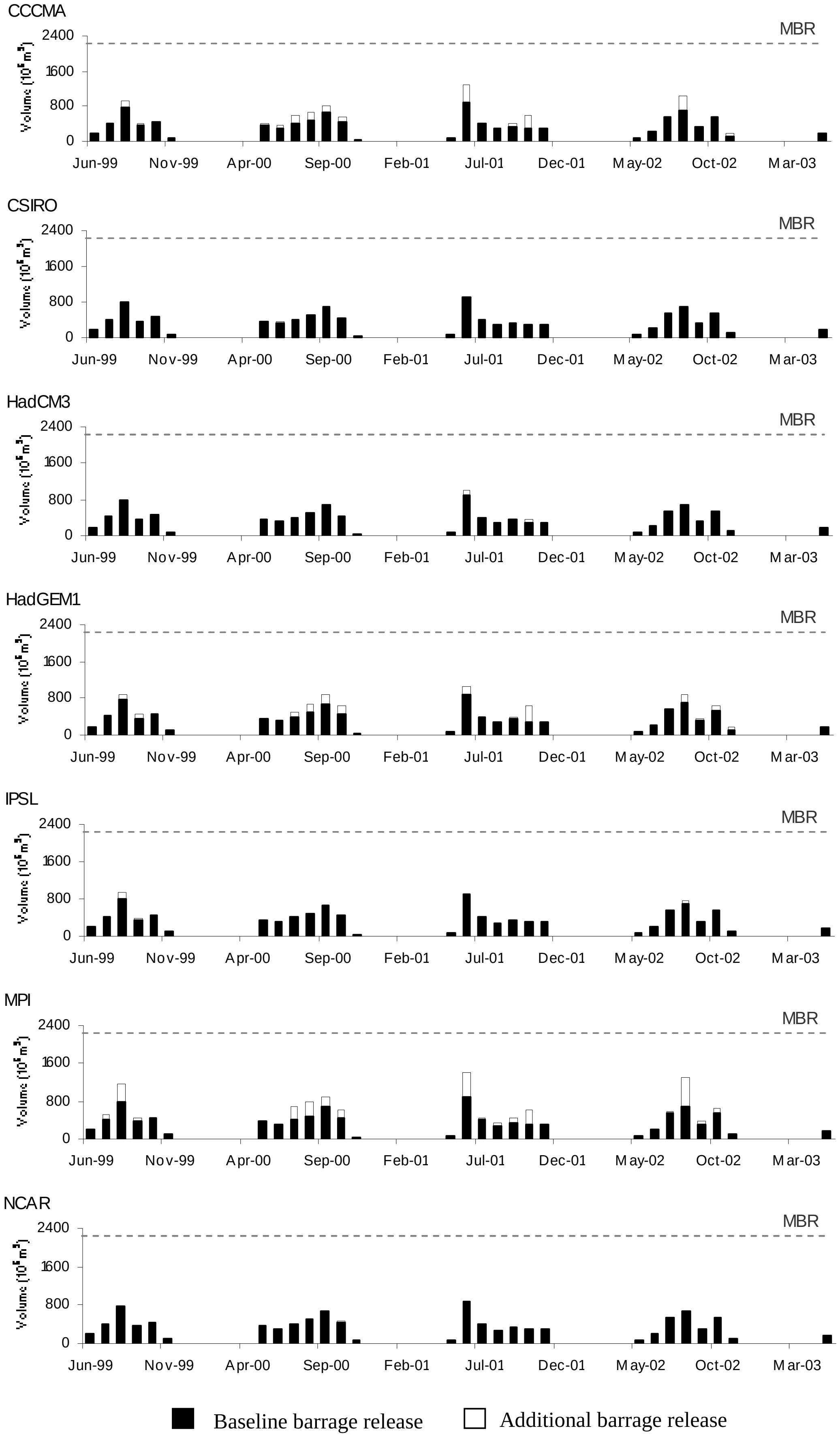

Figure 7.17: Total monthly barrage releases from Ithai Barrage for CCG1$_H$-BO2 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

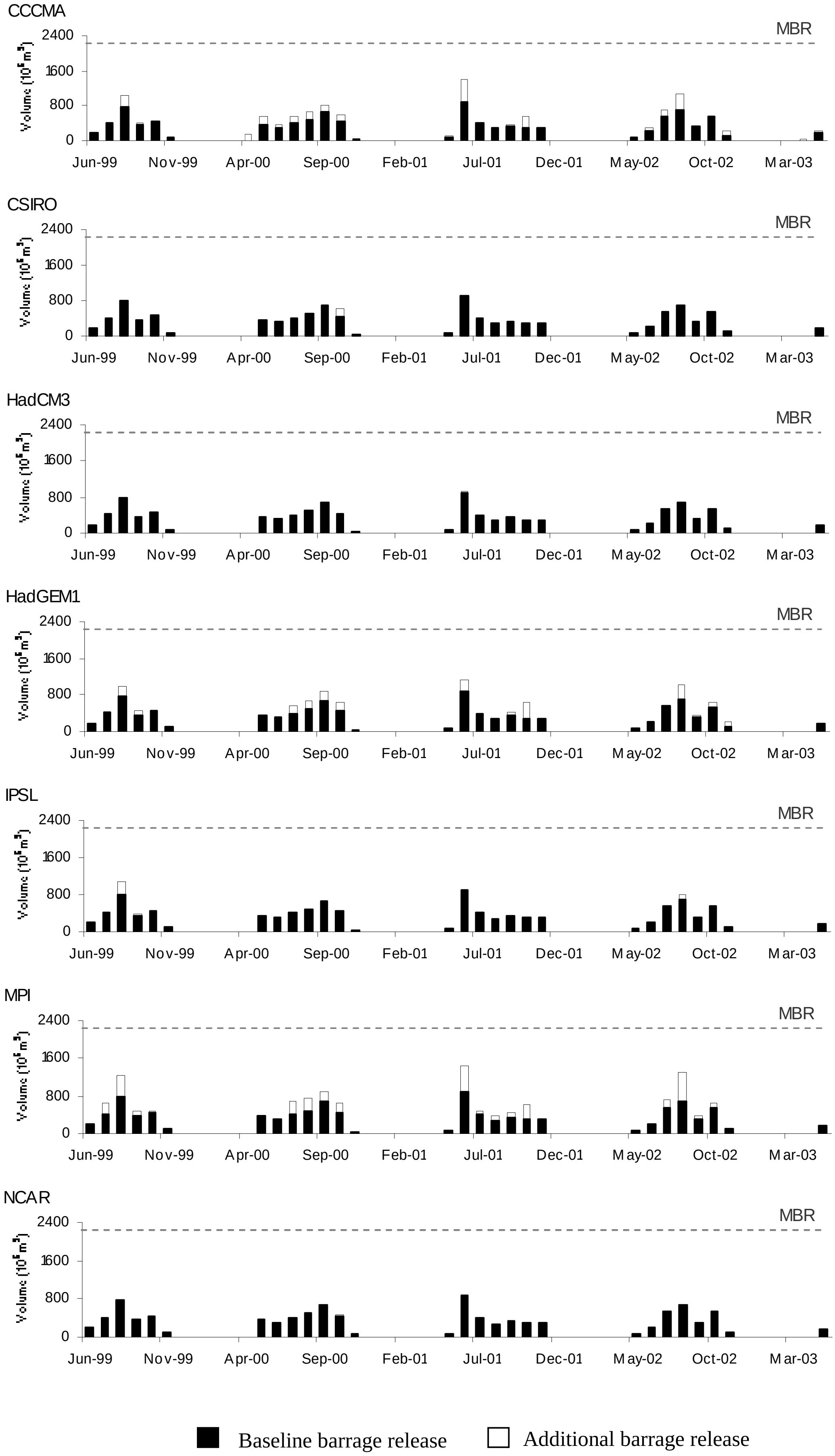

Figure 7.18. Total monthly barrage releases from Ithai Barrage for CCG1$_T$-BO2 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

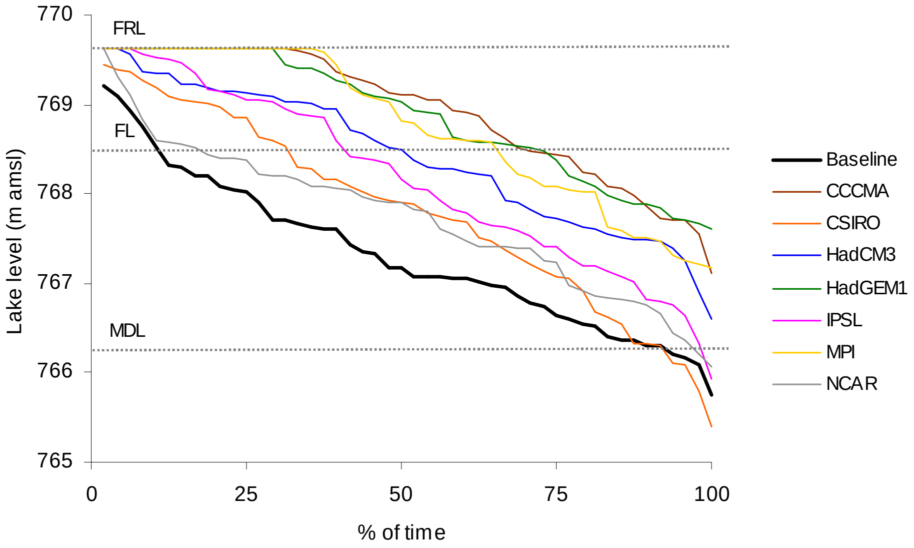

Figure 7.19. Water level-duration curve for all CCG1$_H$-BO2 scenarios

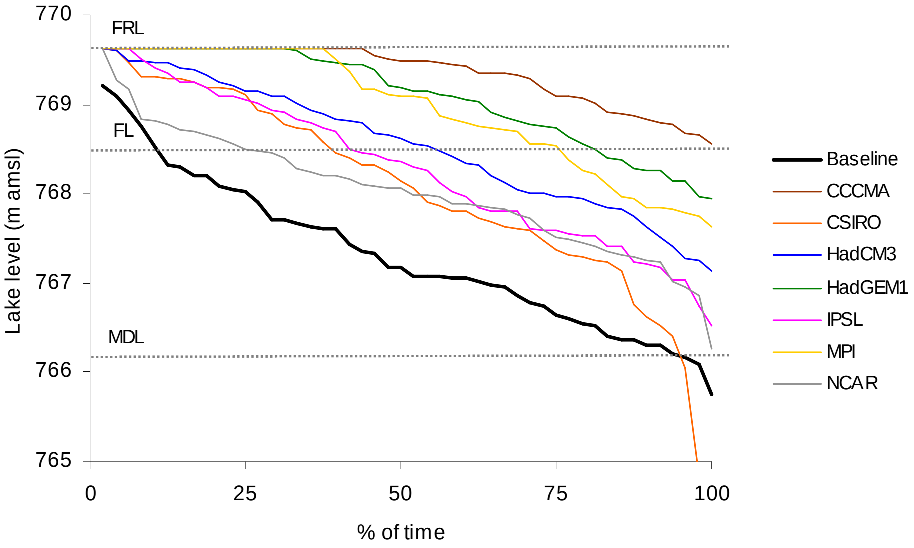

Figure 7.20. Water level-duration curve for all CCG1$_T$-BO2 scenarios

The water level in the lake for the CSIRO, NCAR and IPSL GCMs for the CCG1$_H$-BO2 goes below the MDL for 4, 2 and 1 months respectively (Figure 7.19). For CCG1$_T$-BO2 scenario, only the CSIRO GCM has water level below MDL for 3 months during the simulation period (Figure 7.20). Therefore, the lake will not be able to provide water to satisfy demands from hydropower and agriculture sectors. The water levels during December, January and February for all CCG1$_H$-BO2 and CCG1$_T$-BO2 scenarios are much higher than the baseline water level during these months (Figure 7.21). As a result of the high water levels during these three months for all the climate change scenarios, in contrast to its baseline condition, will not be able to ground the *phumdis*, hence will exacerbate its deterioration.

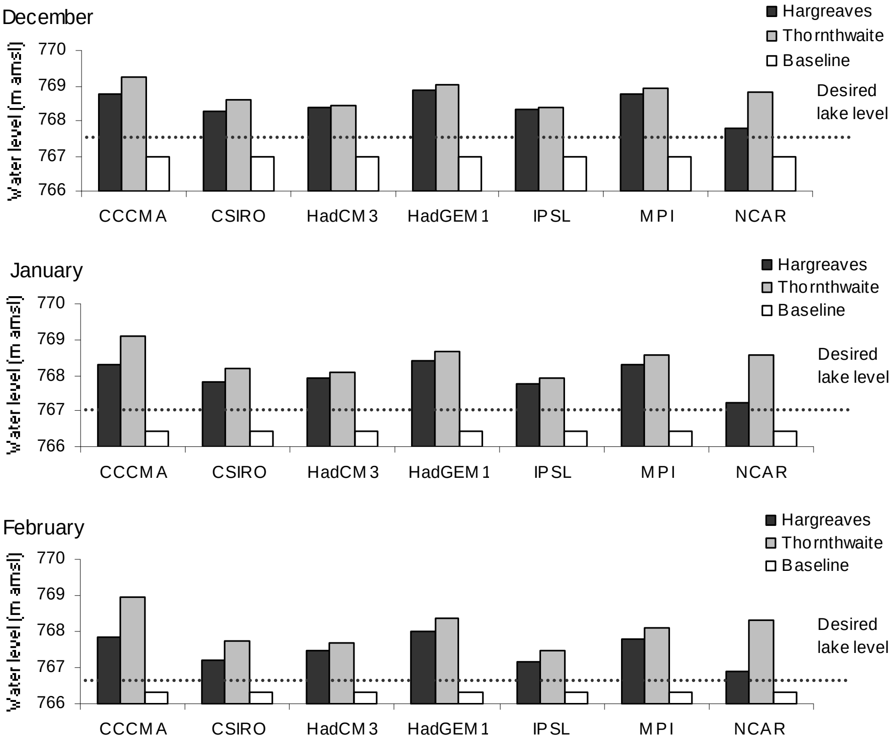

Figure 7.21. Mean monthly water level for CCG1$_H$-BO2 and CCG1$_T$-BO2 scenarios compared against the desired ecological lake level for grounding of phumdis

7.3.2. Impacts of Group 2 climate change scenarios (CCG2) on barrage operation Option 2

Figures 7.22 and 7.23 show the simulated monthly lake water levels between June 1999–May 2003 resulting from the CCG2 scenarios with prioritization to agriculture demand using the Hargreaves (hereafter referred to as CCG2$_H$-BO2) and Thornthwaite (hereafter referred to as CCG2$_T$-BO2) methods of perturbing PET. Similar to results for BO1 (Section 7.2.2), the water level simulated for the 1-3°C rise in global mean temperature scenarios for CCG2$_T$-BO2 are higher than similar scenarios for CCG2$_H$-BO2, whereas for the 3-6°C scenarios CCG2$_T$-BO2 simulated lower water levels. The mean annual water levels for CCG2$_H$-BO2 scenarios rise gradually with the rise in temperature with a highest mean annual water level (768.95 m amsl) associated with the 6°C rise in temperature (Table 7.4). The CCG2$_T$-BO2 scenarios do not follow similar pattern and the highest mean annual water level (768.75 m a msl) is associated with the 3°C rise. The water level-duration curves (Figures 7.24 and 7.25) indicate the increase in flooding frequency in all CCG2$_H$-BO2 and CCG2$_T$-BO2 scenarios. The number of months during which water level are above FL increases between 19-76% of the simulation period for the CCG2$_H$-BO2 scenarios and between 26-63% for the CCG2$_T$-BO2 scenarios compared to 10% during the baseline condition.

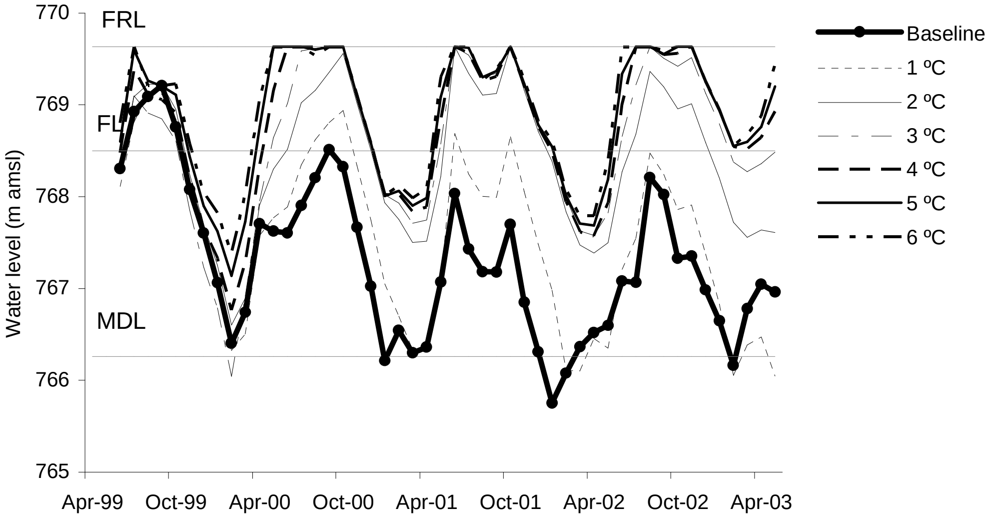

Figure 7.22. Simulated monthly Loktak Lake water levels for CCG2$_H$-BO2 scenarios (June 1999–May 2003)

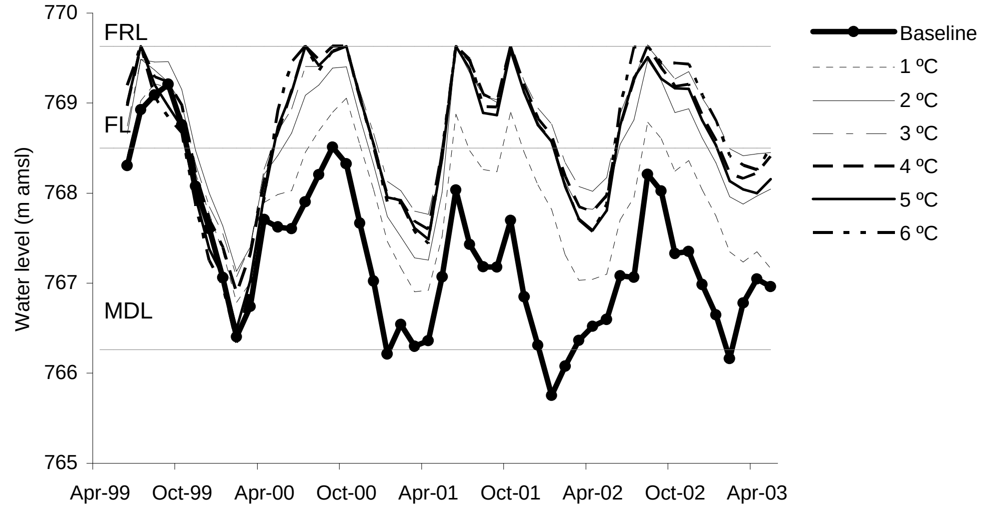

Figure 7.23. Simulated monthly Loktak Lake water levels for CCG2$_T$-BO2 scenarios (June 1999–May 2003)

Table 7.4. Simulated mean annual water levels of Loktak Lake for all CCG2$_H$-BO2 and CCG2T-BO2 scenarios

Scenario	Mean annual Lake level for CCG2$_H$-BO2 scenarios (m amsl)	Difference from baseline (m)	Mean annual Lake level for CCG2$_T$-BO2 scenarios (m amsl)	Difference from baseline (m)
Baseline (BO2)	767.31		767.31	
1°C	767.56	0.25	767.99	0.68
2°C	768.41	1.10	768.54	1.23
3°C	768.60	1.29	768.75	1.44
4°C	768.77	1.46	768.68	1.37
5°C	768.88	1.57	768.57	1.26
6°C	768.95	1.64	768.63	1.32

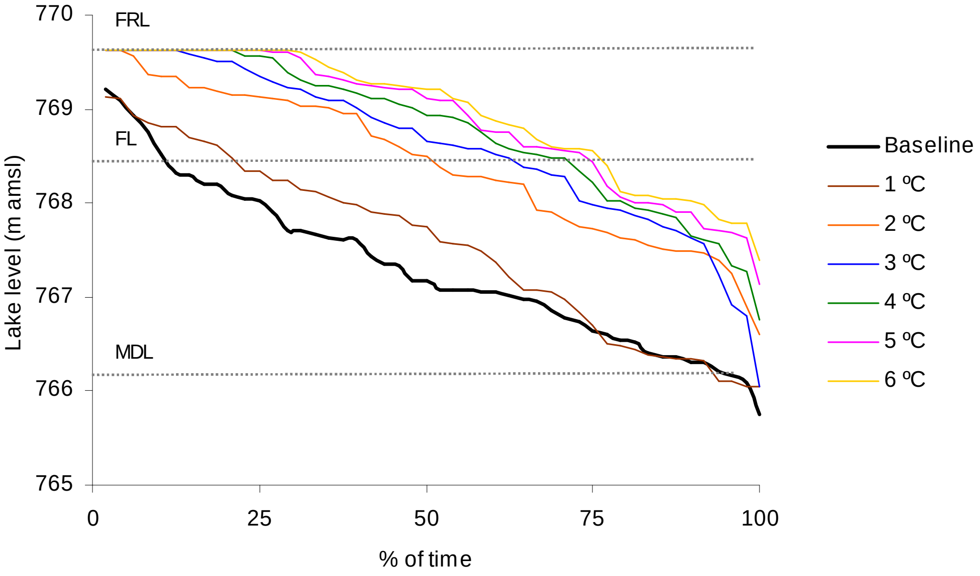

Figure 7.24. Water level-duration curve for all CCG2$_H$-BO2 scenarios

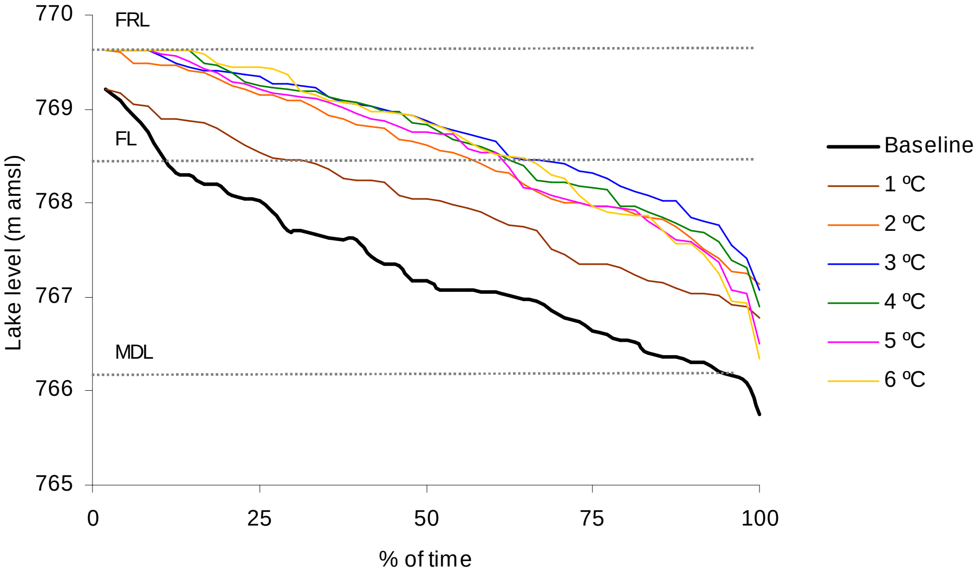

Figure 7.25. Water level-duration curve for all CCG2$_T$-BO2 scenarios

Figure 7.26 demonstrates that for all climate change scenarios the simulated water levels are much higher than the baseline water level during December, January and February, except for 1°C rise scenarios under the CCG2$_H$-BO2 during December. As a result of these high water levels, all CCG2$_T$-BO2 scenarios and all CCG2$_H$-BO2 scenarios, except the 1°C scenario, in contrast to its baseline condition, will not be able to ground the *phumdis*. This will lead to further deterioration of the *phumdis* in the lake. This barrage operation regime also shows the water level exceeds the FRL for at some point during the simulation period for all climate change scenarios except for the 1°C rise scenario, necessitating the release of additional water. The number of months during which additional release are required varies between 1-7 for CCG2$_H$-BO2 scenarios and between 2-14 for CCG2$_T$-BO2 scenarios compared to zero month during the baseline condition. The releases, however, along with the original release can comfortably be accommodated by the existing infrastructure as demonstrated in Figures 7.27 and 7.28.

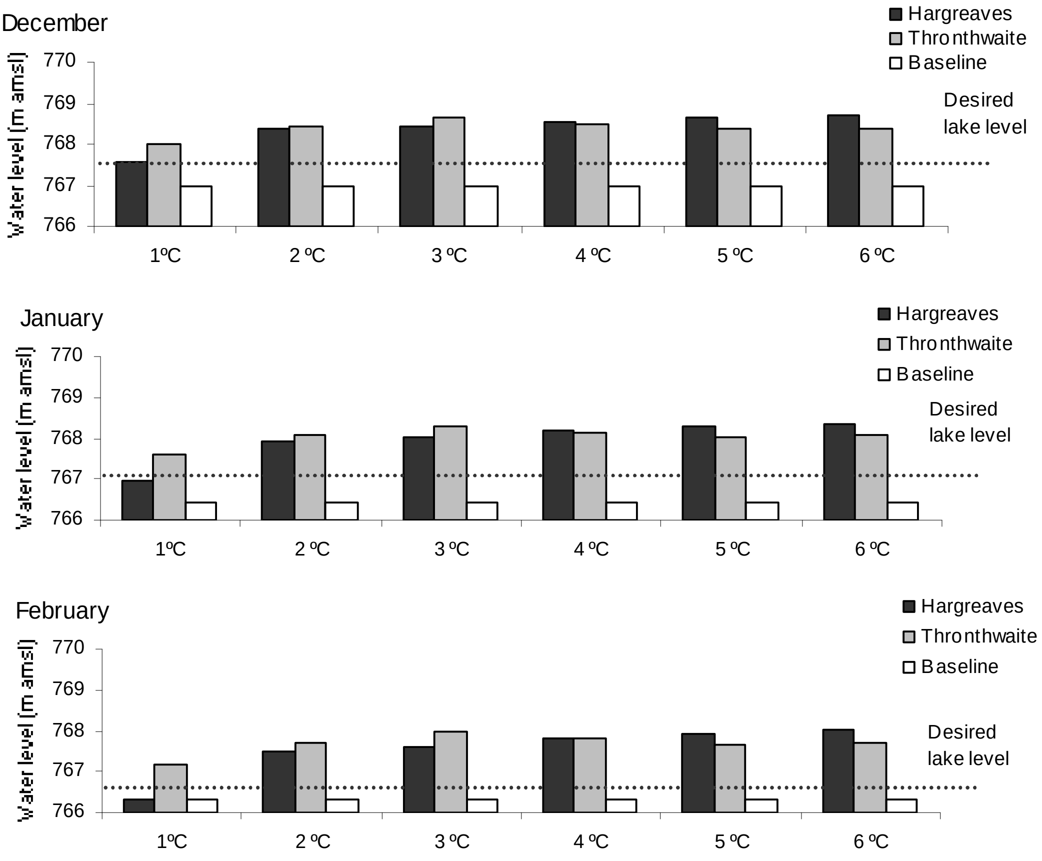

Figure 7.26. Mean monthly water level for CCG2$_H$-BO2 and CCG2$_T$-BO2 scenarios compared against the desired ecological lake level for grounding of phumdis

7.4. Sustainability of barrage operation Option 3 – prioritization to ecological demand (BO3)

As discussed in Section 5.4.3, the aim of this barrage operation (BO3) is to maintain the water levels in the lake to 768.55 m, 768.21 m and 767.89 m amsl during December, January and February respectively. In this section, the water level regime of BO3 (developed in Section 5.4.3) will be considered as the baseline water level regime against which the simulated water levels for the climate change scenarios will be compared.

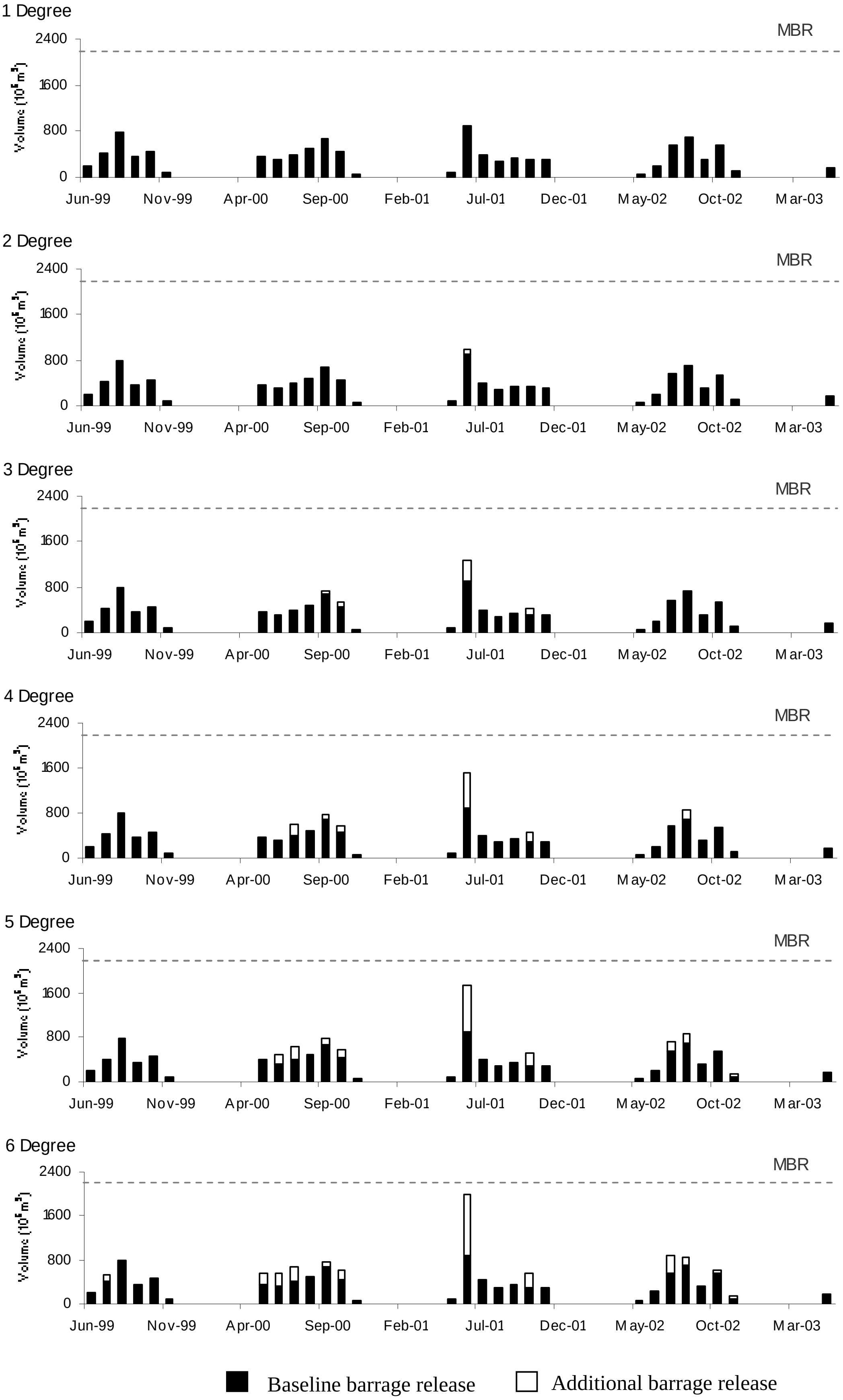

Figure 7.27. Total monthly barrage releases from Ithai Barrage for CCG2$_H$-BO2 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

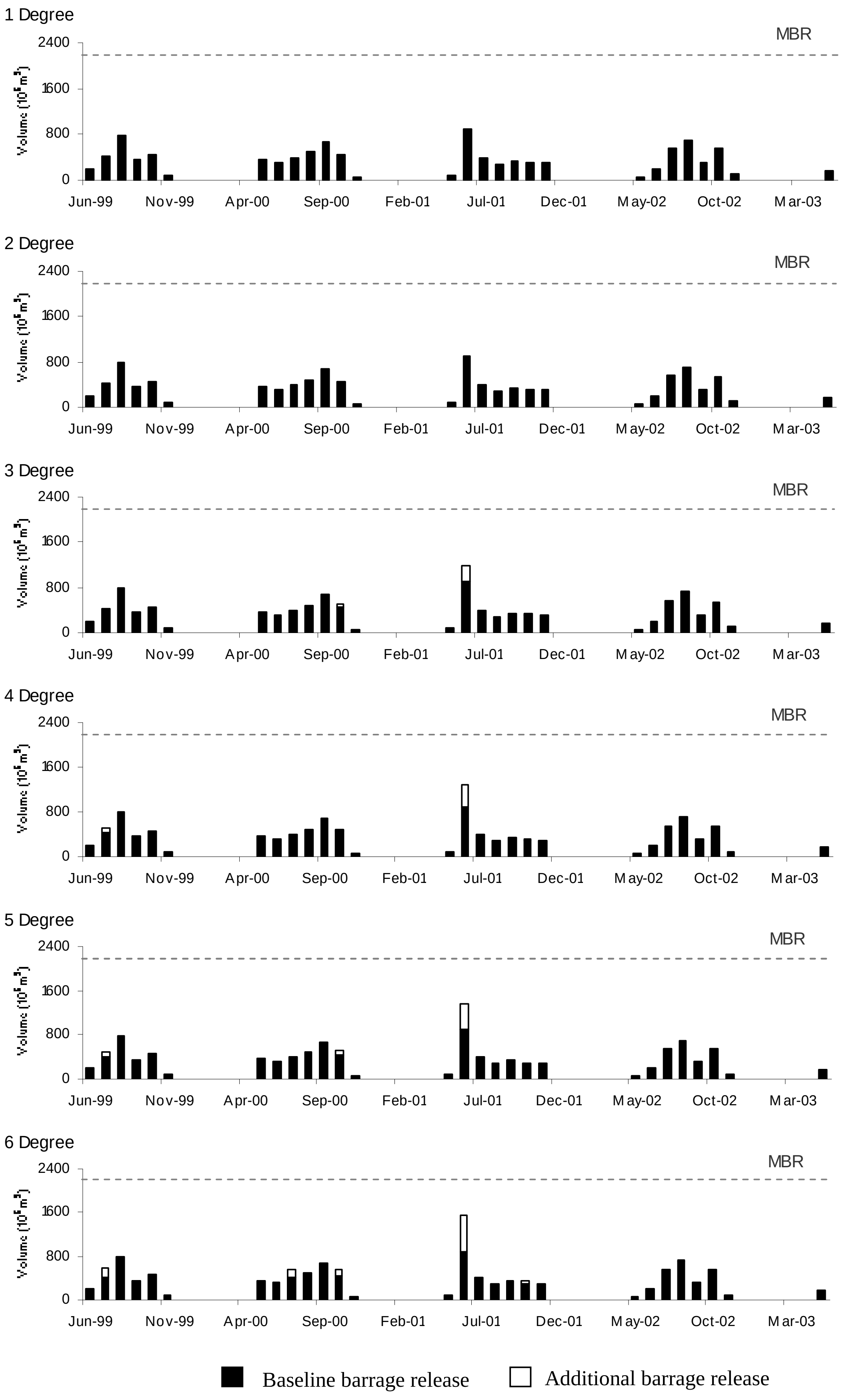

Figure 7.28. Total monthly barrage releases from Ithai Barrage for CCG2$_T$-BO2 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

7.4.1. Impacts of Group 1 climate change scenarios (CCG1) on barrage operation Option 3

Figures 7.29 and 7.30 shows the simulated monthly water level of Loktak Lake for all CCG1 scenarios with prioritization to ecological demand using the Hargreaves (hereafter referred to as CCG1$_H$-BO3) and Thornthwaite (hereafter referred to as CCG1$_T$-BO3) methods of perturbing PET. Similar water level regimes for same GCM are observed for all CCG1$_H$-BO3 and CCG1$_T$-BO3 scenarios. The mean annual water level when compared to the baseline condition (BO3) increases for all the scenarios (Table 7.5). The increase in the water level varies between 0.16-0.90 m for the CCG1$_H$-BO3 scenarios and between 0.28-0.89 m for the CCG1$_T$-BO3 scenarios.

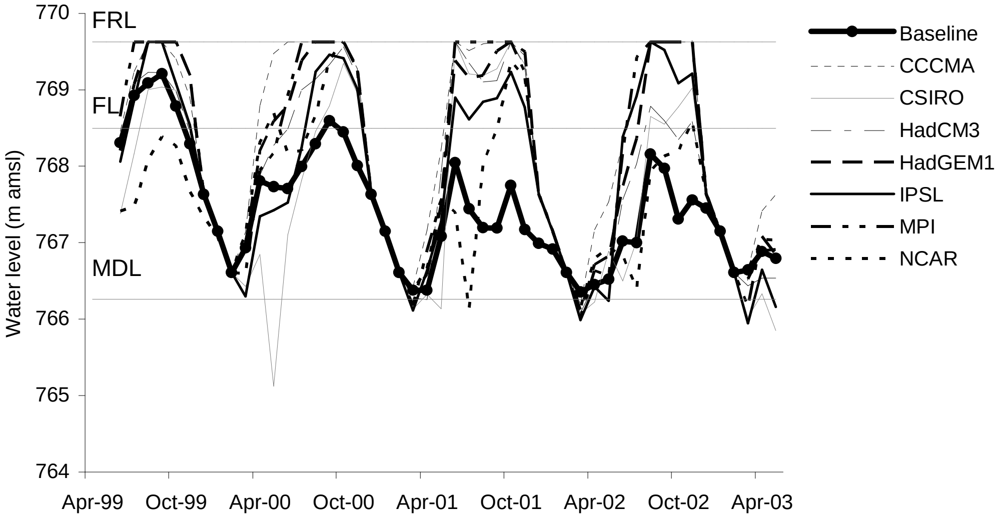

Figure 7.29. Simulated monthly Loktak Lake water levels for CCG1$_H$-BO3 scenarios (June 1999–May 2003)

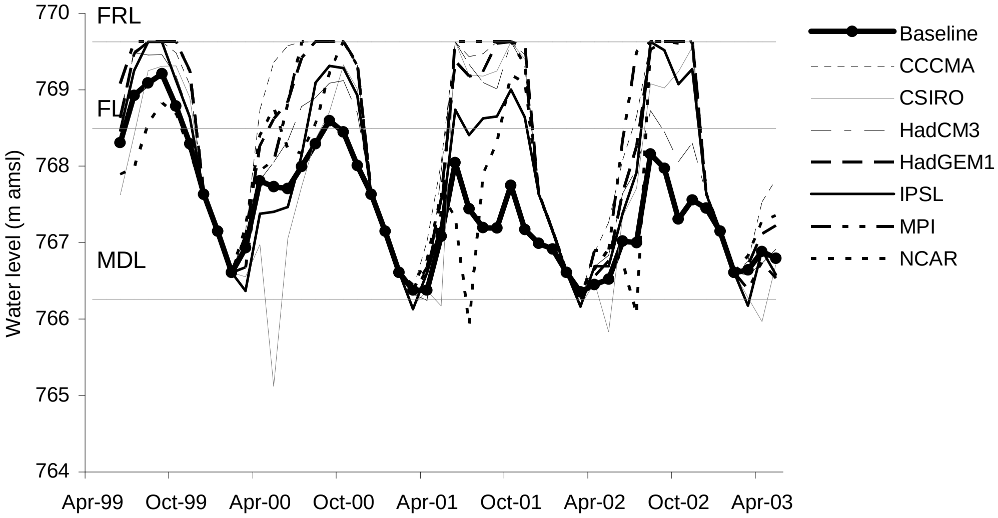

Figure 7.30. Simulated monthly Loktak Lake water levels for CCG1$_T$-BO3 scenarios (June 1999–May 2003)

Table 7.5. Simulated mean annual water levels of Loktak Lake for all CCG1$_{H}$-BO3 and CCG1$_{T}$-BO3 scenarios

Scenario	Mean annual Lake level for CCG1H-BO3 scenarios (m amsl)	Difference from baseline (m)	Mean annual Lake level for CCG1T-BO3 scenarios (m amsl)	Difference from baseline (m)
Baseline (BO3)	767.46		767.46	
CCCMA	768.36	0.90	768.35	0.89
CSIRO	767.62	0.16	767.74	0.28
HadCM3	767.95	0.49	767.95	0.49
HadGEM1	768.18	0.72	768.22	0.76
IPSL	767.89	0.43	767.87	0.41
MPI	768.22	0.76	768.24	0.78
NCAR	767.62	0.16	767.80	0.34

This barrage operation option is able to provide low water level to satisfy the grounding of the *phumdis* during December, January and February for all CCG1H-BO3 and CCG1T-BO3 scenarios similar to that during the baseline condition as shown in Figure 7.31. Although the water levels are low during the dry season, during the monsoon months water levels for all scenarios of both CCG1$_{H}$-BO3 and CCG1$_{T}$-BO3 exceed the FRL at some point during the simulation period as shown in the water level-duration curve (Figures 7.32 and 7.33). The number of months during which the water level exceeds the FRL varies between 1-17 for the CCG1$_{H}$-BO3 scenarios and between 2-17 for the CCG1$_{T}$-BO3 scenarios compared to zero month during the baseline condition (BO3). The water levels for the MPI GCM for both CCG1$_{H}$-BO3 and CCG1$_{T}$-BO3 were estimated to exceed FRL for as much as 17 months. Similar to the baseline condition, the total barrage releases of both the climate change scenarios, which is the sum total of the original barrage releases and additional releases, can easily be released downstream by opening of the five barrage gates without risking the structural stability of the barrage as demonstrated in Figures 7.34 and 7.35.

The major concern for this barrage operation is that the water levels for all GCMs for CCG1$_{H}$-BO3 and for all CCG1$_{T}$-BO3, except the CCCMA and HadGEM1 GCMs, goes below the MDL (Figures 7.32 and 7.33). In case of the CSIRO GCM, the water level is below the MDL for as much as seven months for CCG1$_{H}$-BO3 and six months for CCG1$_{T}$-BO3. Hence, all the climate change scenarios except the CCCMA and HadGEM1 GCMs for CCG1$_{T}$-BO3 will be unable to meet the demands from the hydropower and agriculture sectors. The flooding frequency also increases for all the climate change scenarios (Figures 7.32 and 7.33). The CCG1$_{H}$-BO3 scenarios exceeds the FL for periods varying between 17-51% of the simulation period and CCG1$_T$-BO3 scenarios between 29-52% compared to just 10% during the baseline period

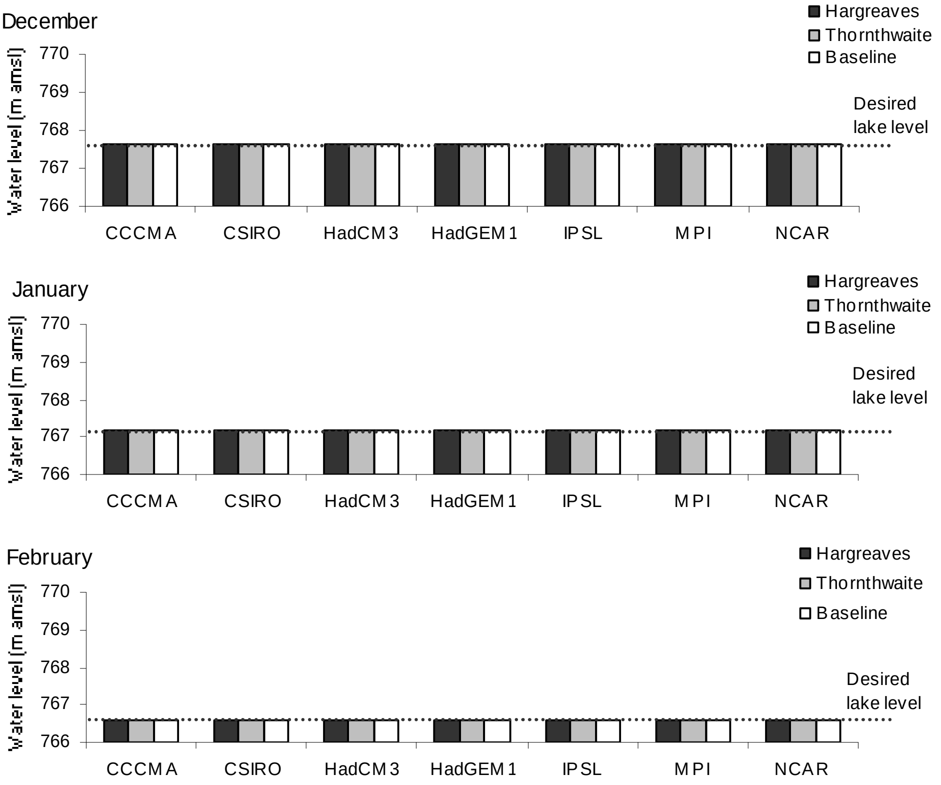

Figure 7.31. Mean monthly water level for CCG1$_H$-BO3 and CCG1$_T$-BO3 scenarios compared against the desired ecological lake level for ground of phumdis

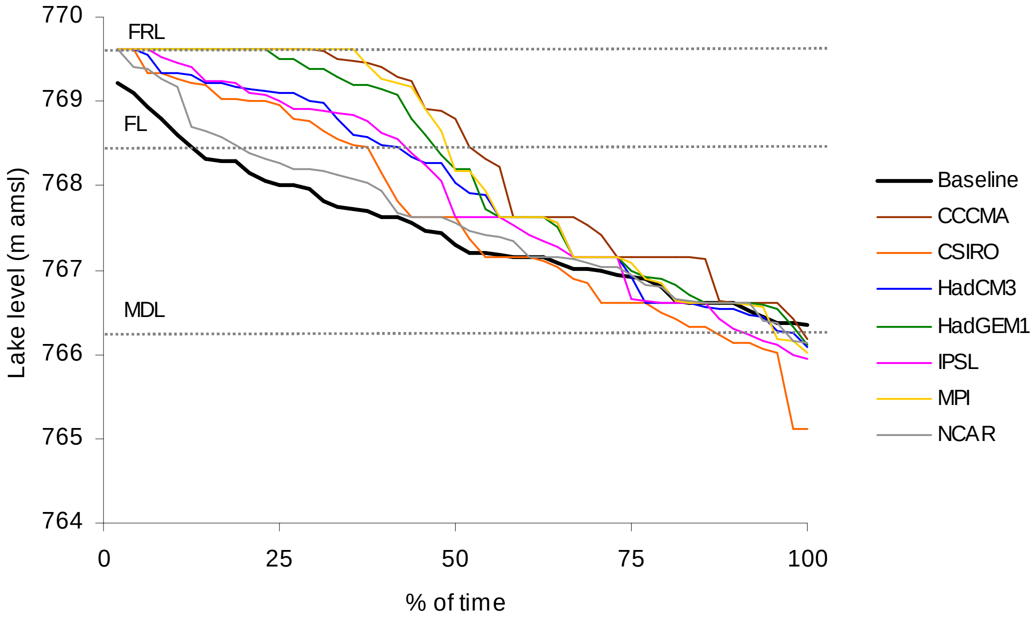

Figure 7.32. Water level-duration curve for all CCG1$_H$-BO3 scenarios

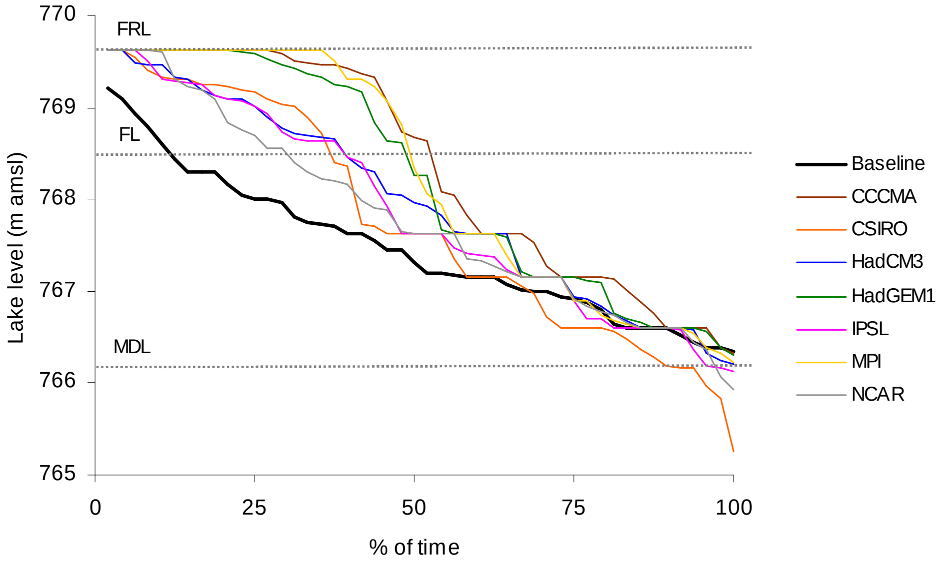

Figure 7.33. Water level-duration curve for all CCG1$_T$-BO3 scenarios

7.4.2. Impacts of Group 2 climate change scenarios (CCG2) on barrage operation Option 3

The simulated monthly lake water levels for the period June 1999–May 2003 for the CCG2 scenarios with prioritization to agriculture demand using the Hargreaves (hereafter referred to as CCG2$_H$-BO3) and Thornthwaite (hereafter referred to as CCG2$_T$-BO3) methods of perturbing PET are shown in Figures 7.36 and 7.37. The water levels simulated for all CCG2$_H$-BO3 and CCG2$_T$-BO3 scenarios follow a similar pattern with the maximum difference in mean annual water levels being 0.24 m for the 5°C rise in global mean temperature (Table 7.6). When compared with the baseline condition (BO3), all CCG2$_H$-BO3 and CCG2$_T$-BO3 scenarios simulated higher mean annual water levels. The maximum increase is associated with the 6°C rise scenarios (0.90 m for CCG2$_H$-BO3 and 0.68 m for CCG2$_T$-BO3).

Table 7.6. Simulated mean annual water levels of Loktak Lake for all CCG2$_H$-BO3 and CCG2$_T$-BO3 scenarios

Scenario	Mean annual Lake level for CCG2$_H$-BO3 scenarios (m amsl)	Difference from baseline (m)	Mean annual Lake level for CCG2$_T$-BO3 scenarios (m amsl)	Difference from baseline (m)
Baseline (BO3)	767.46		767.46	
1°C	767.68	0.22	767.77	0.31
2°C	767.95	0.49	767.95	0.49
3°C	768.07	0.61	768.03	0.57
4°C	768.22	0.76	768.09	0.63
5°C	768.31	0.85	768.07	0.61
6°C	768.36	0.90	768.14	0.68

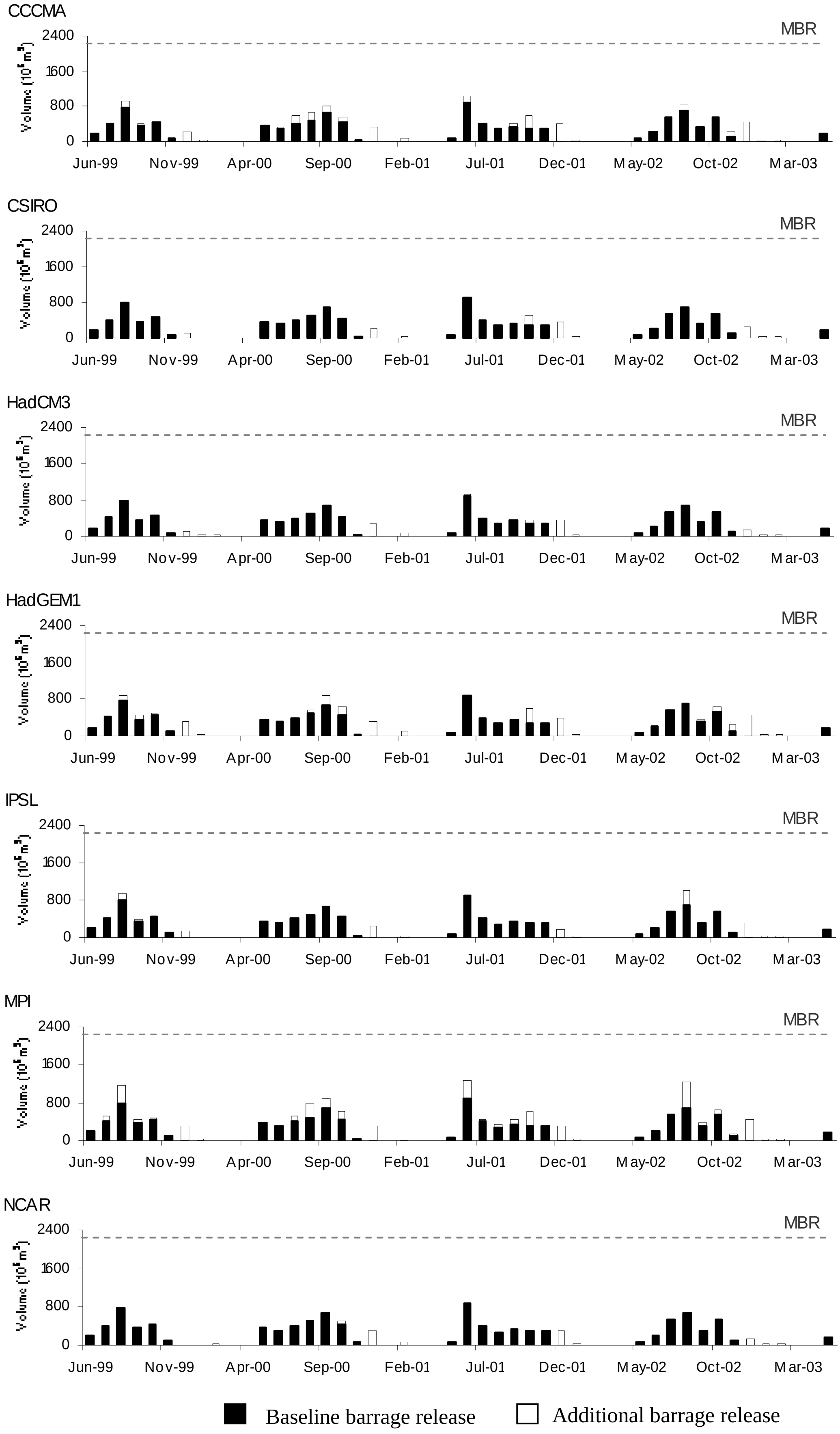

Figure 7.34. Total monthly barrage releases from Ithai Barrage for CCG1H-BO3 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

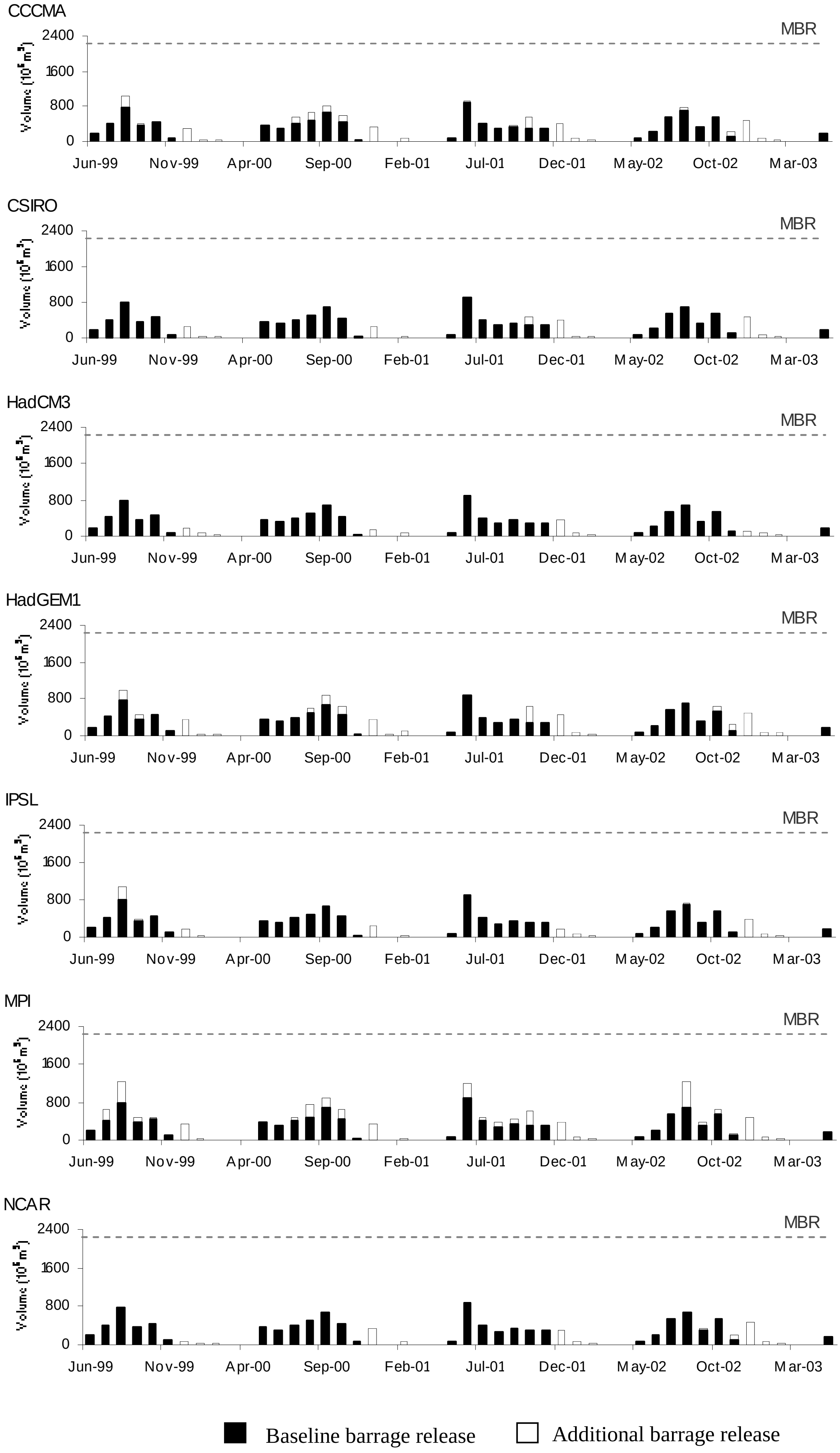

Figure 7.35. Total monthly barrage releases from Ithai Barrage for CCG1$_T$-BO3 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

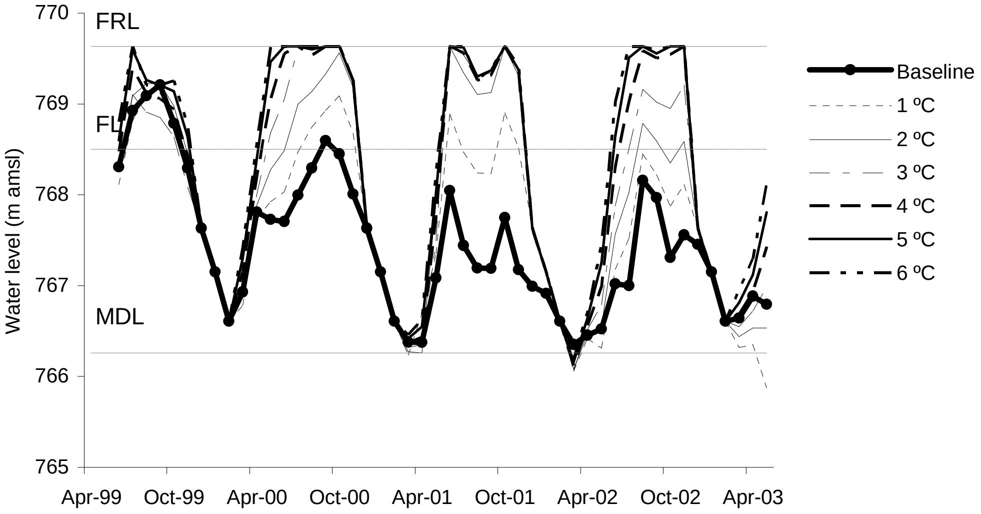

Figure 7.36. Simulated monthly Loktak Lake water levels for CCG2$_H$-BO3 scenarios (June 1999–May 2003)

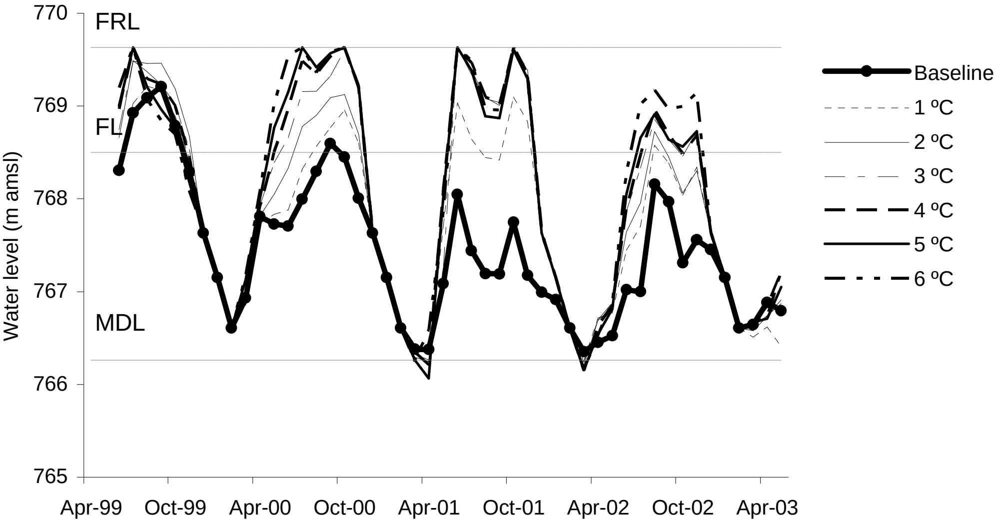

Figure 7.37. Simulated monthly Loktak Lake water levels for CCG2$_T$-BO3 scenarios (June 1999–May 2003)

As demonstrated in Figure 7.38, the water level during December, January and February for all the climate change scenarios (both CCG2$_H$-BO3 and CCG2$_T$-BO3) are lowered enough to satisfy the ecological demands for grounding the *phumdis*, which is in line with the base line condition. However, the water level drops below the threshold MDL for all CCG2$_H$-BO3 and CCG2$_T$-BO3 scenarios as indicated by the water level-duration curves (Figure 7.39 and Figure 7.40). Therefore it results in conflicts with the demands from other stakeholders (hydropower and agriculture). The flooding frequency is estimated to increase for all the climate change scenarios. The duration for which the water level exceeds the FL during the simulation period varies between 24-52% for the CCG2$_H$-BO3 scenarios and between 28-48% for the CCG2$_T$-BO3 scenarios compared to just 10% during the baseline period. The water level for all scenarios, except the 1°C rise, exceeds the FRL at some point of time necessitating addition releases to prevent the barrage been overtopped. However, these releases in addition to the original baseline releases can comfortably be accommodated by opening the barrage gates as shown in Figures 7.41 and 7.42

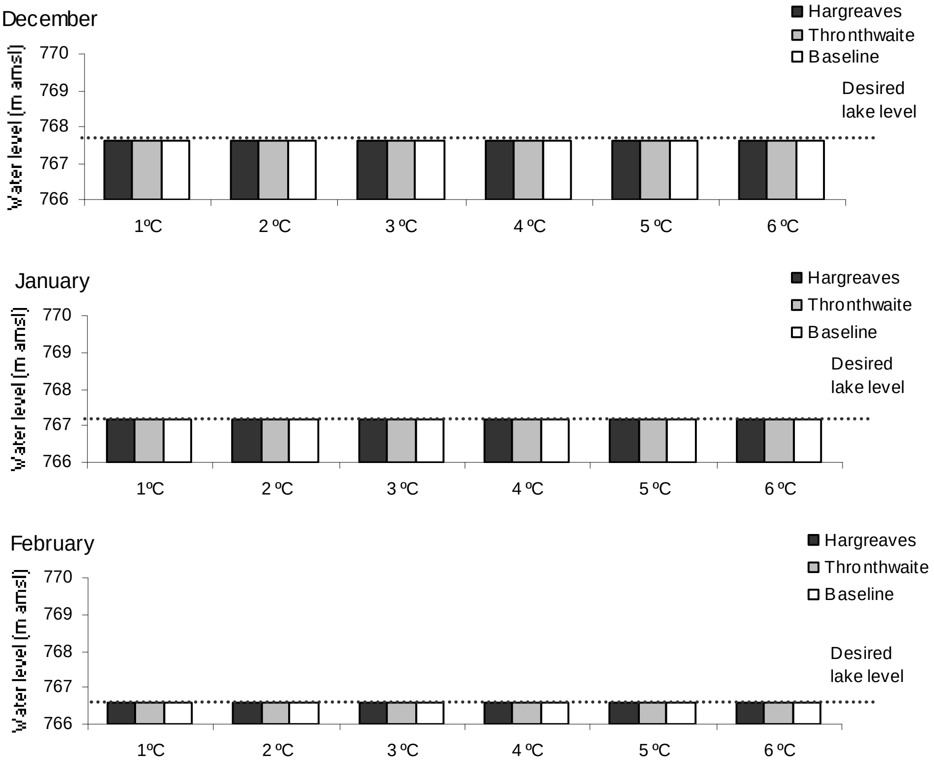

Figure 7.38. Mean monthly water level for CCG2$_H$-BO3 and CCG2$_T$-BO3 scenarios compared against the desired ecological lake level for ground of phumdis

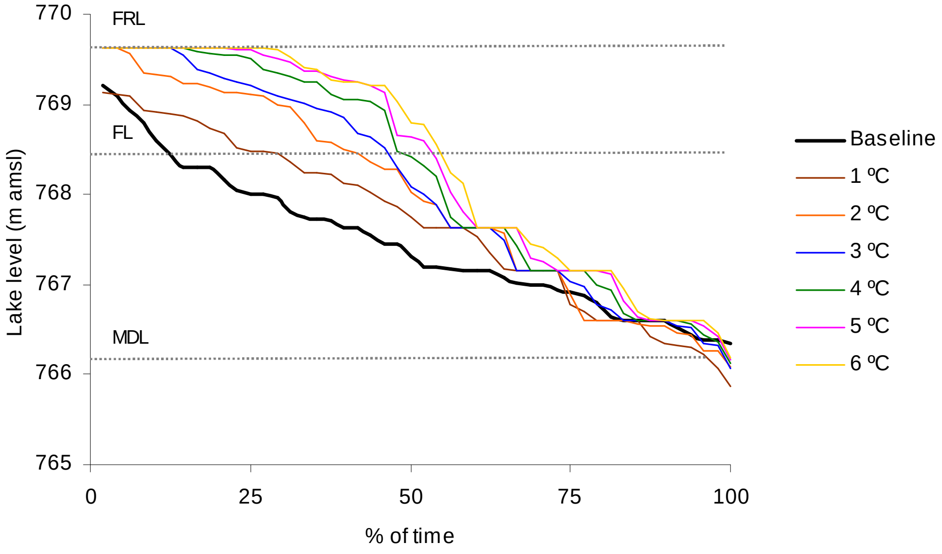

Figure 7.39. Water level-duration curve for all CCG2$_H$-BO3 scenarios

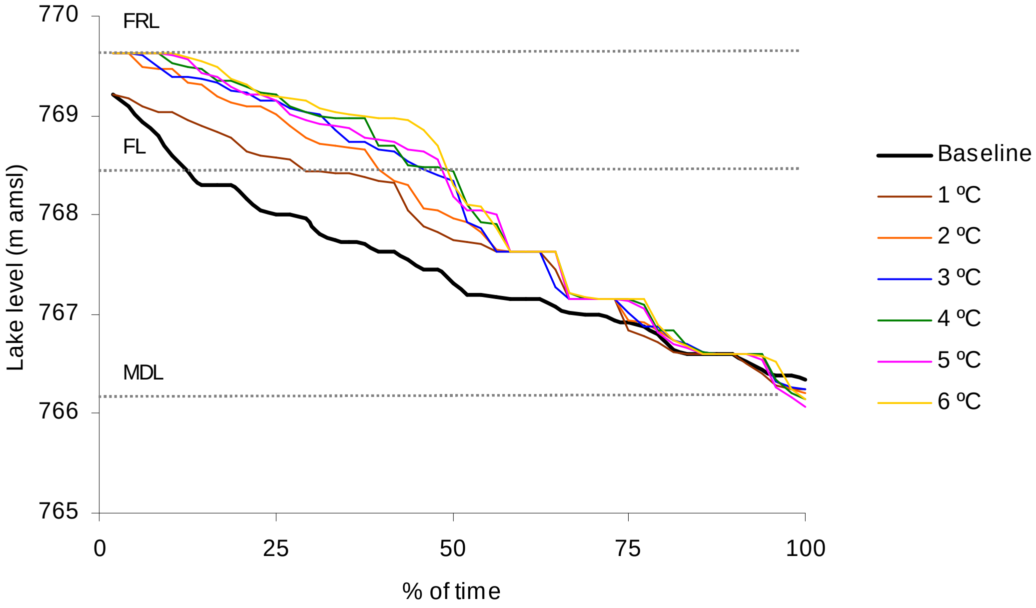

Figure 7.40. Water level-duration curve for all CCG2$_T$-BO3 scenarios

7.5. Sustainability of barrage operation Option 4 – integrated option (BO4)

As discussed in Section 5.4.4, this integrated barrage operation option (BO4) aims to satisfy the demands of all the major stakeholders– hydropower, agriculture and ecological. In addition, it also incorporates the flooding of the communities around the lake. In this section, the water level regime of BO4 (developed in Section 5.4.4) will be considered as the baseline water level regime against which the simulated water levels for the climate change scenarios will be compared.

7.5.1. Impacts of Group 1 climate change scenarios (CCG1) on barrage operation Option 4

The simulated monthly lake water levels for the period June 1999–May 2003 for the CCG1 scenarios for the integrated option employing the Hargreaves (hereafter referred to as CCG1$_H$-BO4) and Thornthwaite (hereafter referred to as CCG1$_T$-BO4) methods of perturbing PET are shown in Figures 7.43 and 7.44. They demonstrate a similar water level regime for the same GCMs with the difference in mean annual water levels varying between 0.02 m for the CCCMA and HadCM3 GCMs to 0.07 m for the CSIRO GCM (Table 7.7).

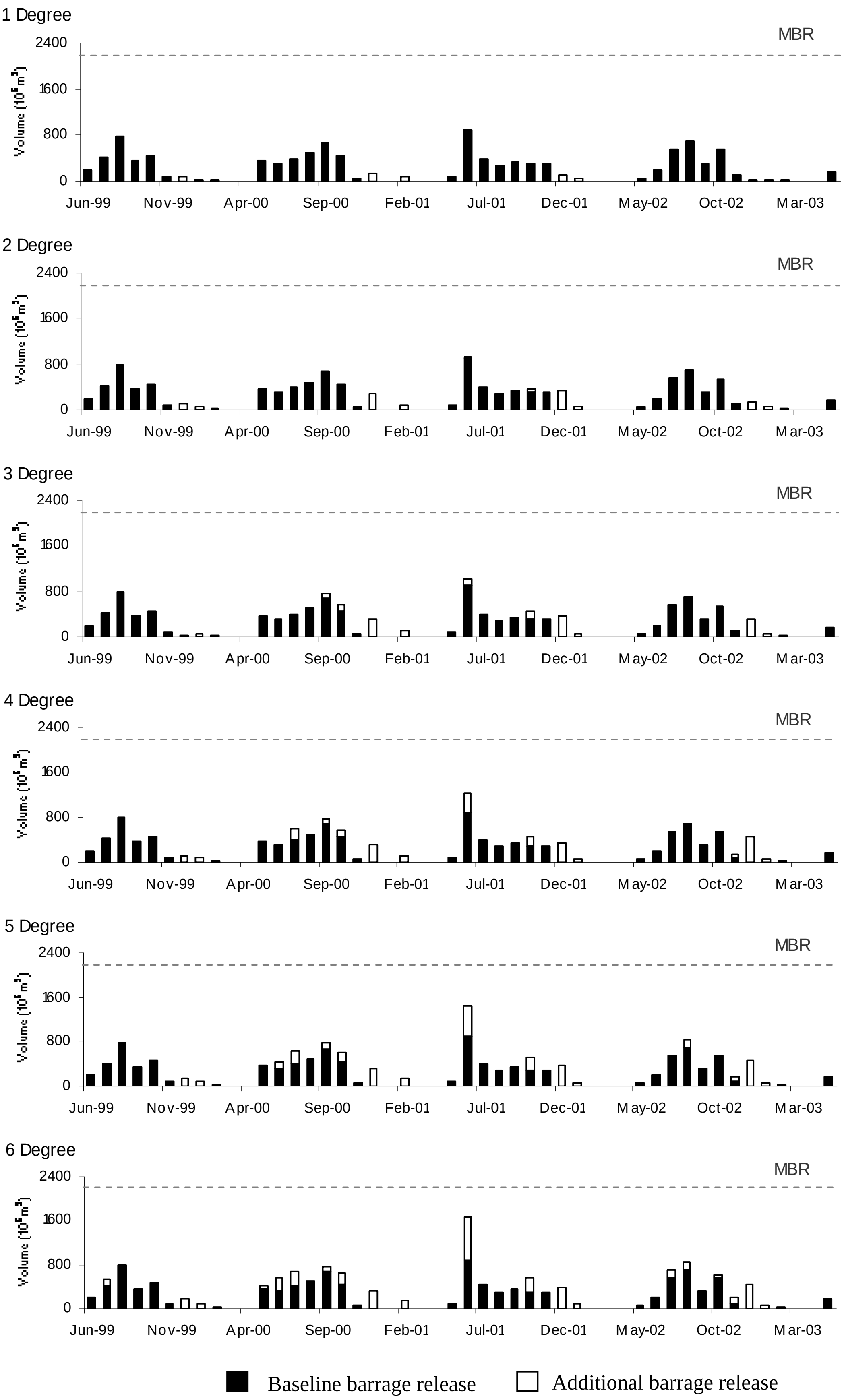

Figure 7.41. Total monthly barrage releases from Ithai Barrage for CCG2$_H$-BO3 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

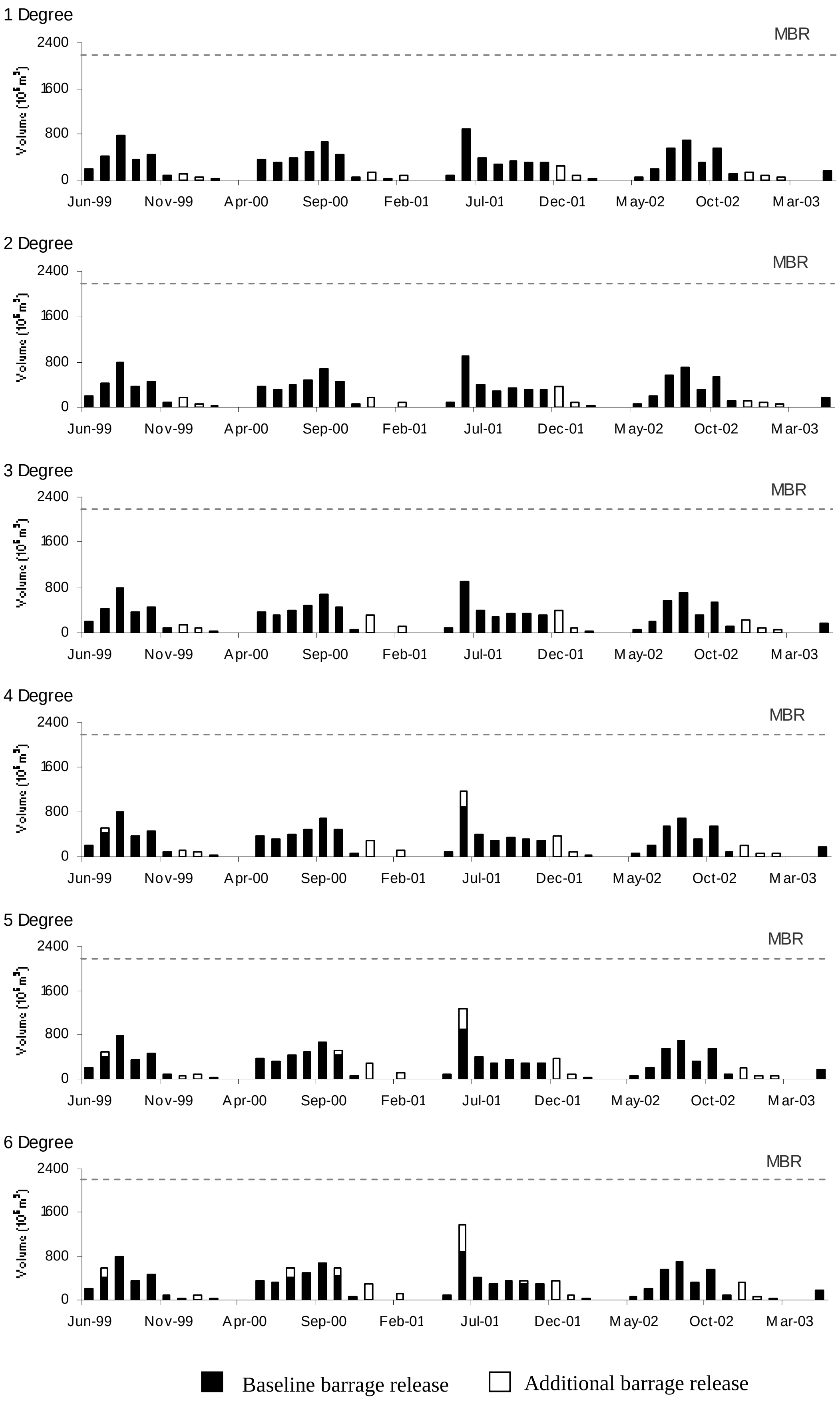

Figure 7.42. Total monthly barrage releases from Ithai Barrage for CCG2$_T$-BO3 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

Table 7.7. Simulated mean annual water levels of Loktak Lake for all CCG1$_H$-BO4 and CCG1$_T$-BO4 scenarios

Scenario	Mean annual Lake level for CCG1$_H$-BO4 scenarios (m amsl)	Difference from baseline (m)	Mean annual Lake level for CCG1$_T$-BO4 scenarios (m amsl)	Difference from baseline (m)
Baseline (BO4)	767.18		767.18	
CCCMA	767.84	0.66	767.87	0.69
CSIRO	767.31	0.13	767.38	0.20
HadCM3	767.64	0.46	767.66	0.48
HadGEM1	767.73	0.55	767.79	0.61
IPSL	767.58	0.40	767.60	0.42
MPI	767.70	0.52	767.75	0.57
NCAR	767.51	0.33	767.55	0.37

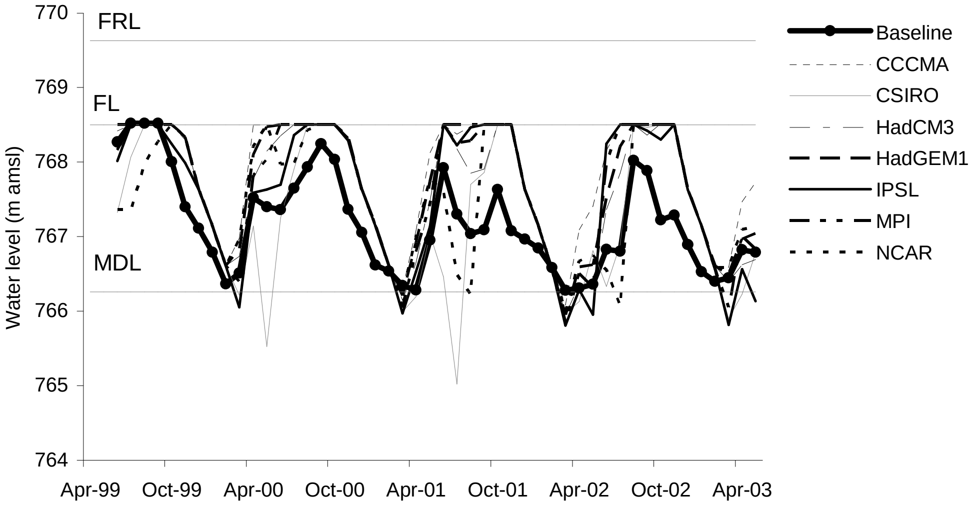

Figure 7.43. Simulated monthly Loktak Lake water levels for CCG1$_H$-BO4 scenarios (June 1999–May 2003)

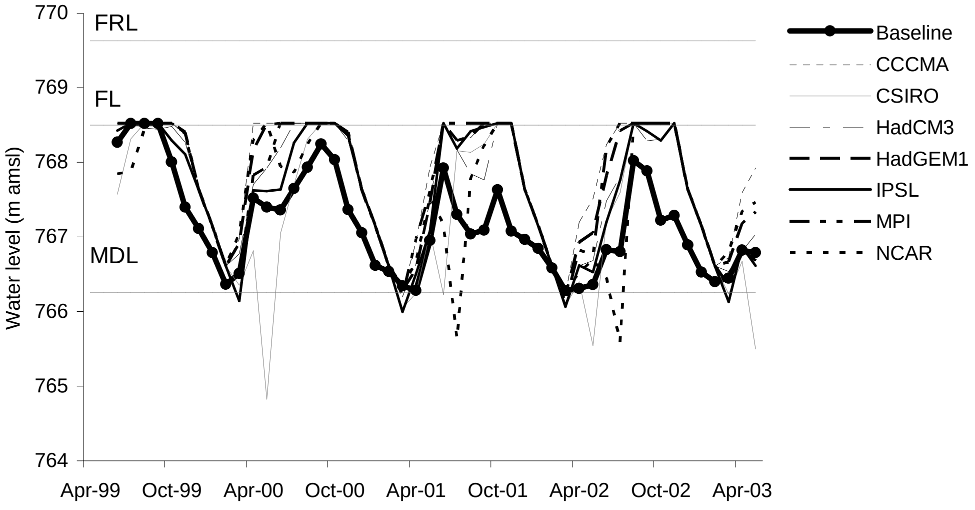

Figure 7.44. Simulated monthly Loktak Lake water levels for CCG1$_T$-BO4 scenarios (June 1999–May 2003)

The mean annual lake water levels, when compared to the baseline condition (BO4), were simulated to be higher for all CCG1$_H$-BO4 and CCG1$_T$-BO4 scenarios (Table 7.7). The largest increase in water level was associated with the CCCMA GCM for both CCG1$_H$-BO4 (0.66 m) and CCG1$_T$-BO4 (0.69 m). The water level-duration curves (Figures 7.45 and 7.46) demonstrate the feasibility of maintaining the water below FL throughout the simulation period in line with the baseline condition (BO4). Figure 7.47 shows that this barrage operation option successfully lower the lake water level during December, January and February to satisfy the ecological demands. The total barrage releases including the flood and ecological releases can safely be accommodated by opening of the existing barrage gates as demonstrated in Figures 7.48 and 7.49.

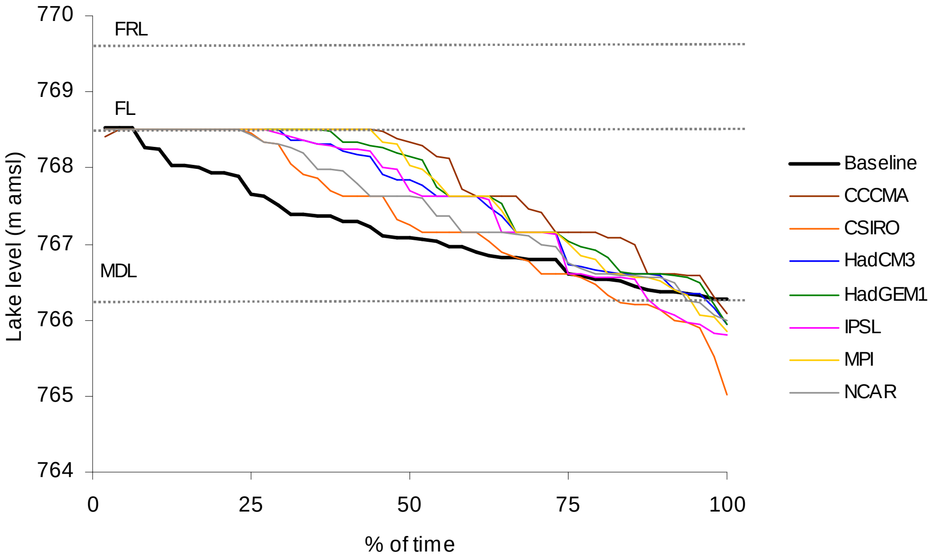

Figure 7.45. Water level-duration curve for all CCG1$_H$-BO4 scenarios

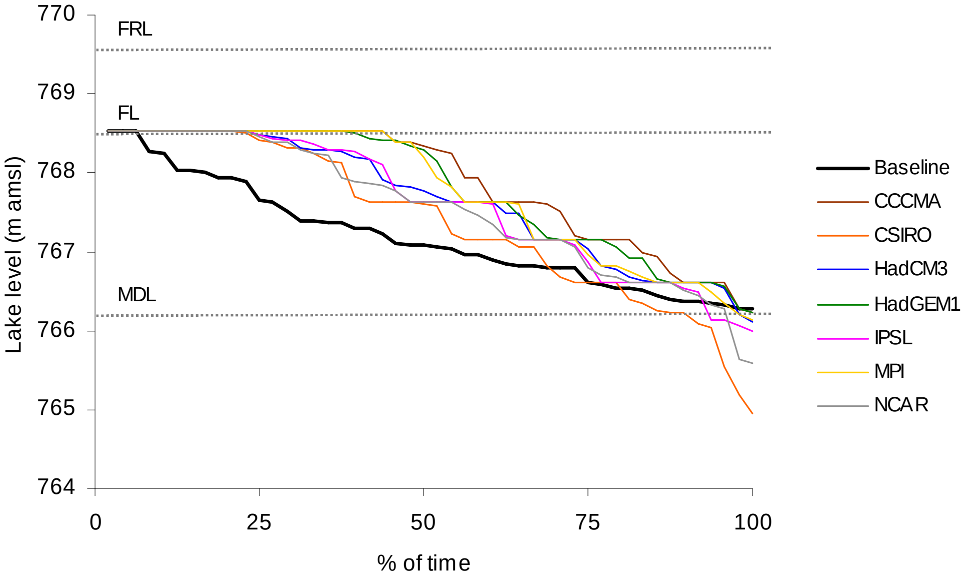

Figure 7.46. Water level-duration curve for all CCG1$_T$-BO4 scenarios

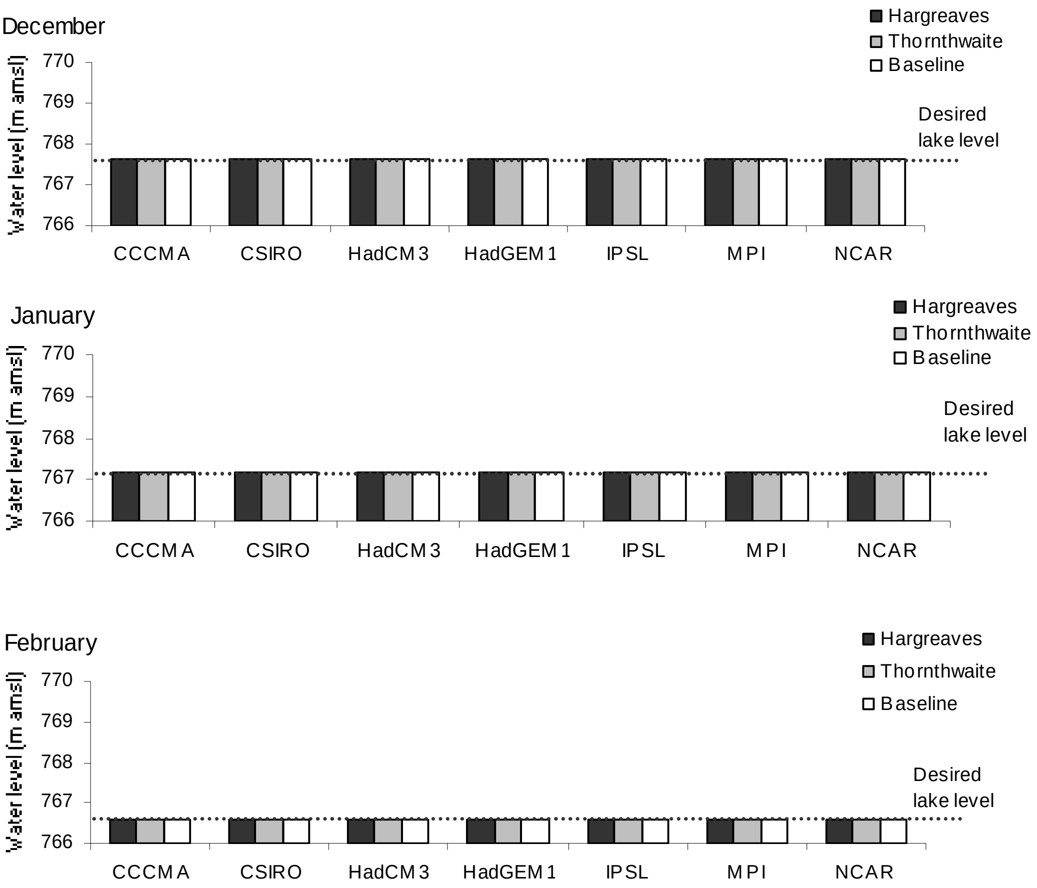

Figure 7.47. Mean monthly water level for CCG1$_H$-BO4 and CCG1$_T$-BO4 scenarios compared against the desired ecological lake level for ground of phumdis

However, the major issue for the integrated barrage operation option with climate change scenarios is that in all CCG1$_H$-BO4 and CCG1$_T$-BO4 scenarios, the water level falls below the threshold MDL indicating the inability of the lake to supply water for hydropower as well as agriculture sectors (Figure 7.45 and 7.46). For the CSIRO GCM, the water level in the lake goes below MDL for as much as 9 months for CCG1$_H$-BO4 and 8 months for CCG1$_T$-BO4 scenarios.

This demonstrates that the barrage management option (BO4), which was a viable option for all the stakeholders (Section 5.5) will be impacted by the climate change scenarios of all the GCMs (CCCMA, CSIRO, HadCM3, UKMO HadGEM1, IPSL, MPI and NCAR) for a 2ºC rise in global mean temperature and will no longer be able to satisfy the demands from various stakeholders.

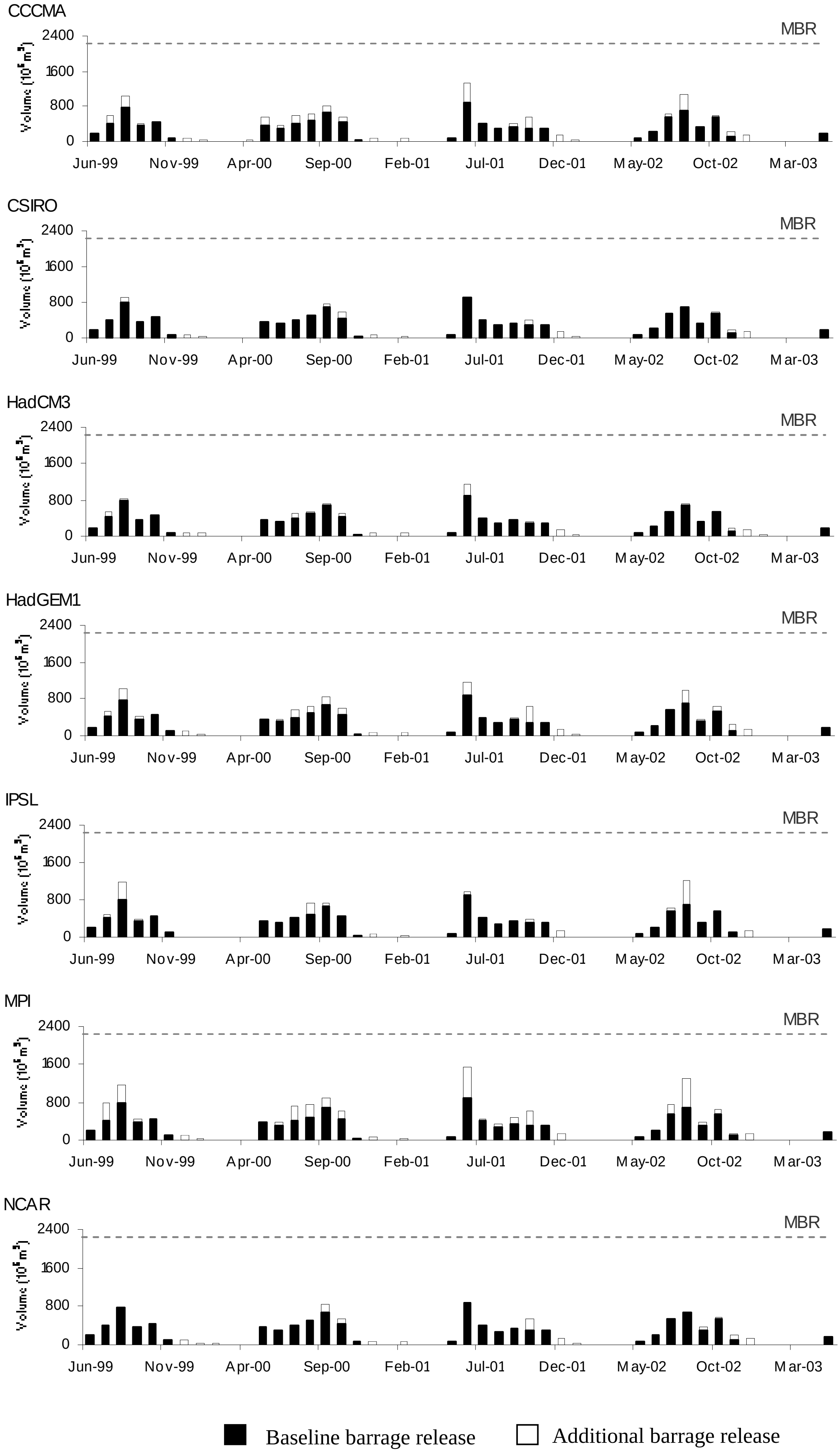

Figure 7.48. Total monthly barrage releases from Ithai Barrage for CCG1$_H$-BO4 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

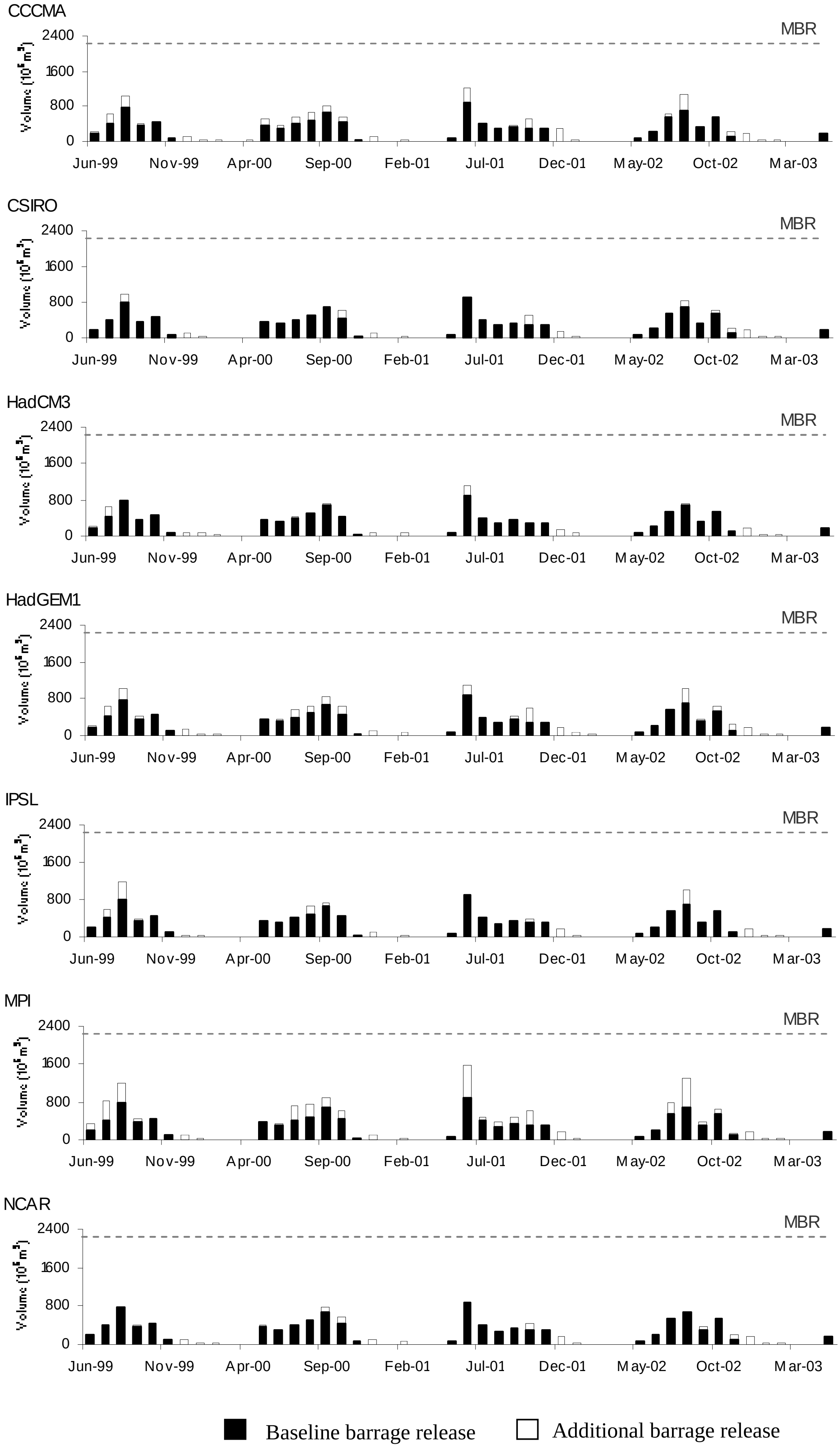

Figure 7.49. Total monthly barrage releases from Ithai Barrage for CCG1$_T$-BO4 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

7.5.2. Impacts of Group 2 climate change scenarios (CCG2) on barrage operation Option 4

Figures 7.50 and 7.51 show the simulated monthly lake water levels between June 1999–May 2003 resulting from the CCG2 scenarios with integrated barrage operation option (BO4) employing the Hargreaves (hereafter referred to as $CCG2_H$-BO4) and Thornthwaite methods (hereafter referred to as $CCG2_{T-}$BO4) of perturbing PET. The water level simulated by all $CCG2_H$-BO4 scenarios are higher compared to those simulated by $CCG2_T$-BO4 scenarios except for the 2°C rise scenario. However the variation in the mean annual water level between the two different methods is very small (varying between 0.02 m for the 1°C to 0.17 m for the 6°C rise in global mean temperature).

The mean annual water levels, when compared to the baseline condition (BO4), are higher for all $CCG2_H$-BO4 and $CCG2_T$-BO4 scenarios. The increase in the water level varies between 0.45-0.63 m for $CCG2_H$-BO4 scenarios and 0.43-0.51 m for $CCG2_T$-BO4 scenarios (Table 7.8). The largest increase in the water levels is associated with 6°C rise for $CCG2_H$-BO4 scenarios and 3°C for $CCG2_T$-BO4 scenarios.

Table 7.8. Simulated mean annual water levels of Loktak Lake for all CCG2H-BO4 and CCG2T-BO4 scenarios

Scenario	Mean annual Lake level for CCG2-$BO1_H$ scenarios (m amsl)	Difference from baseline (m)	Mean annual Lake level for CCG2-$BO1_H$ scenarios (m amsl)	Difference from baseline (m)
Baseline	767.18		767.18	
1°C	767.63	0.45	767.61	0.43
2°C	767.64	0.46	767.66	0.48
3°C	767.71	0.53	767.69	0.51
4°C	767.75	0.57	767.68	0.50
5°C	767.78	0.60	767.64	0.46
6°C	767.81	0.63	767.64	0.46

The new water level regime is also able to satisfy the ecological requirements by grounding the *phumdis* on the lake bed during December, January and February as demonstrated in the Figure 7.52, which is in line with the baseline condition. The water level-duration curves (Figures 7.53 and 7.54) demonstrate the ability of this barrage operation option to maintain a water level regime below the FL throughout the simulation period for all climate change scenarios. The total barrage releases (original baseline release and the additional flood and ecological releases) can be accommodated by the current barrage infrastructure as shown in Figures 7.55 and 7.56.

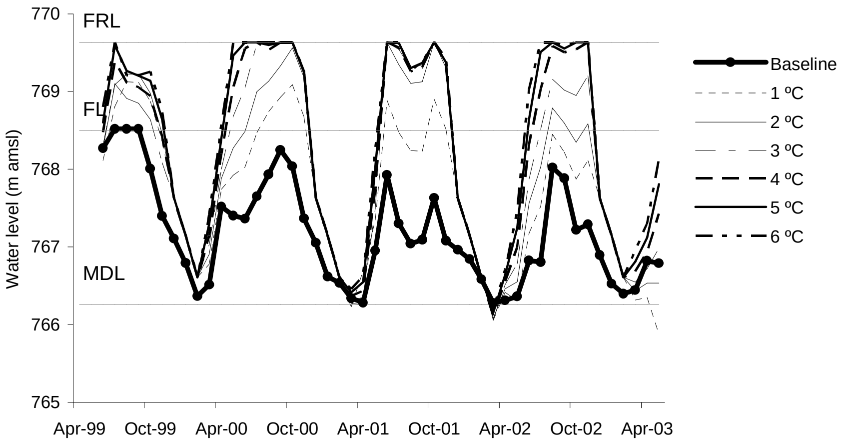

Figure 7.50. Simulated monthly Loktak Lake water levels for $CCG2_H$-BO4 scenarios (June 1999–May 2003)

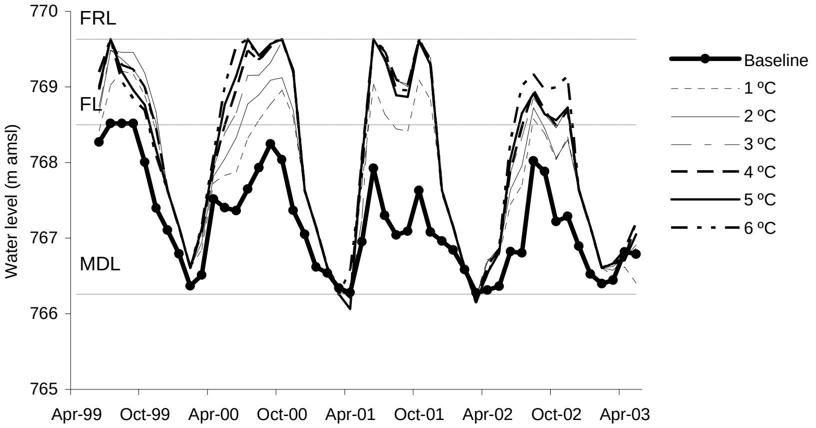

Figure 7.51. Simulated monthly Loktak Lake water levels for $CCG2_T$-BO4 scenarios (June 1999–May 2003)

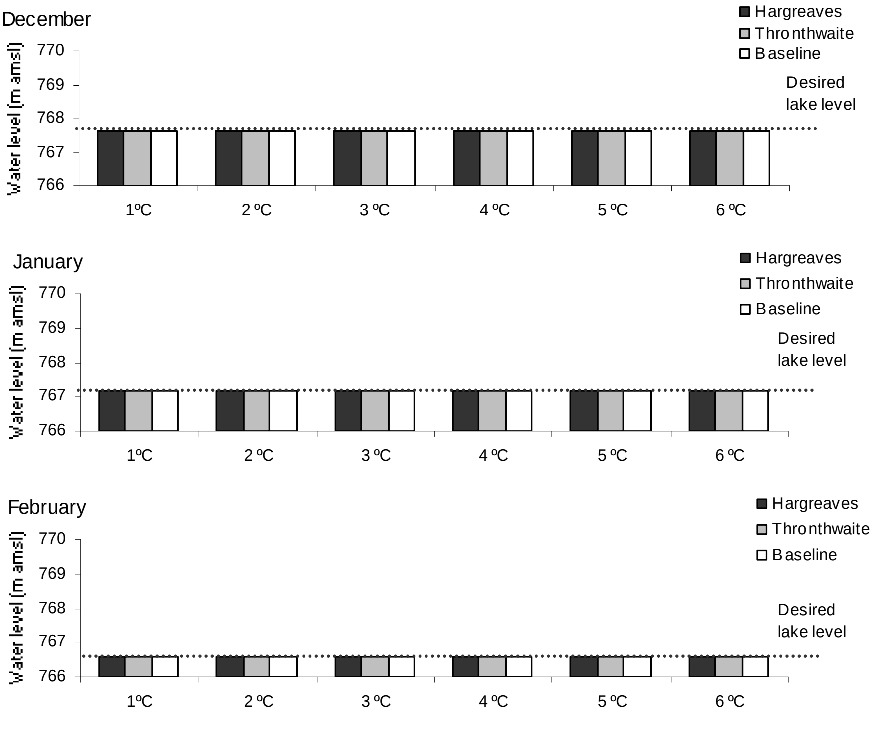

Figure 7.52. Mean monthly water level for $CCG2_H$-BO4 and $CCG2_T$-BO4 scenarios compared against the desired ecological lake level for grounding of phumdis

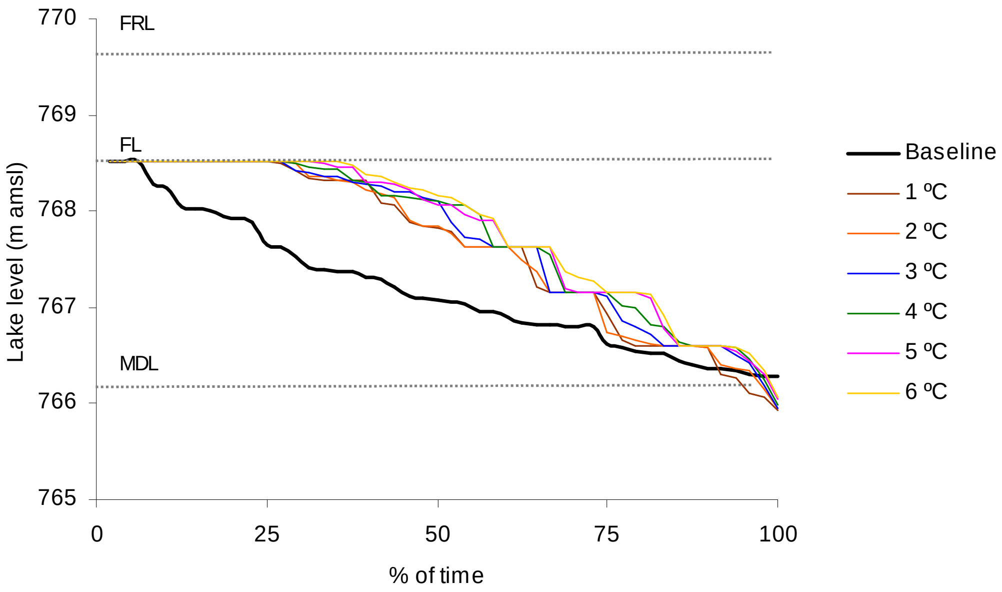

Figure 7.53. Water level-duration curve for all CCG2$_H$-BO4 scenarios

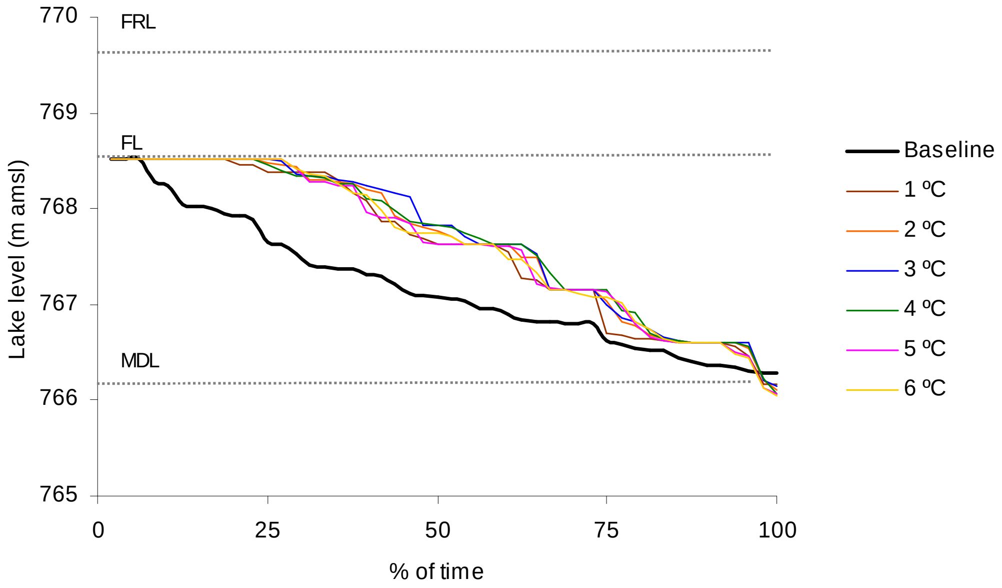

Figure 7.54. Water level-duration curve for all CCG2$_T$-BO4 scenarios

Similar to the Group 1 climate change scenarios (CCG1$_H$-BO4 and CCG1$_T$-BO4), all scenarios of Group 2 (CCG2$_H$-BO4 and CCG2$_T$-BO4) also simulated water levels below the MDL for some period of time during the simulation period indicating the inability to met the demands from the hydropower and agriculture sector (Figures 7.98 and 7.100). Therefore, the integrated barrage operation option (BO4) which holds good for the present situation is not sustainable for the climate change scenarios generated by the HADCM3 GCM for prescribed warming of global mean temperature of 1, 2, 3, 4, 5 and 6°C.

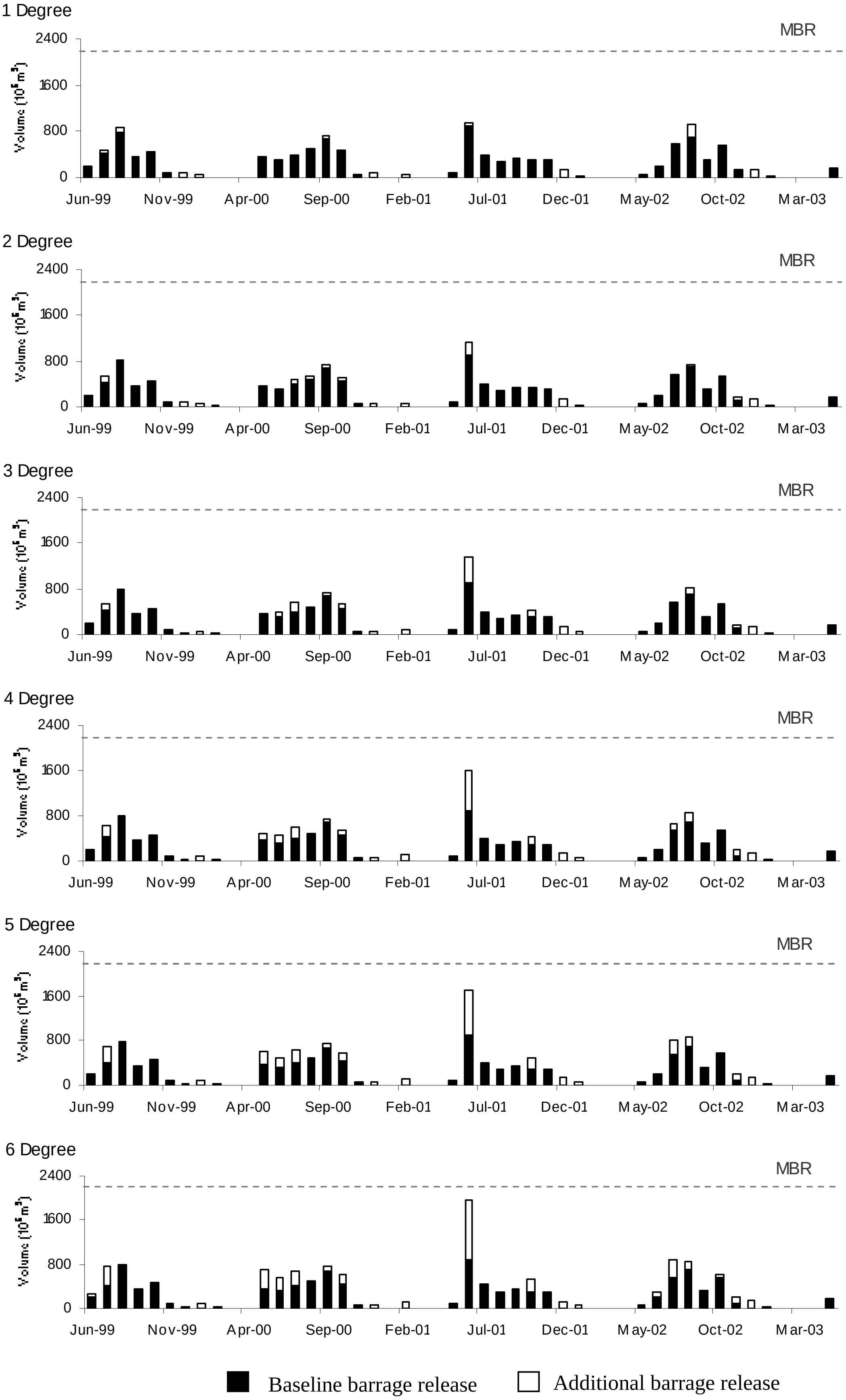

Figure 7.55. Total monthly barrage releases from Ithai Barrage for CCG2$_H$-BO4 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

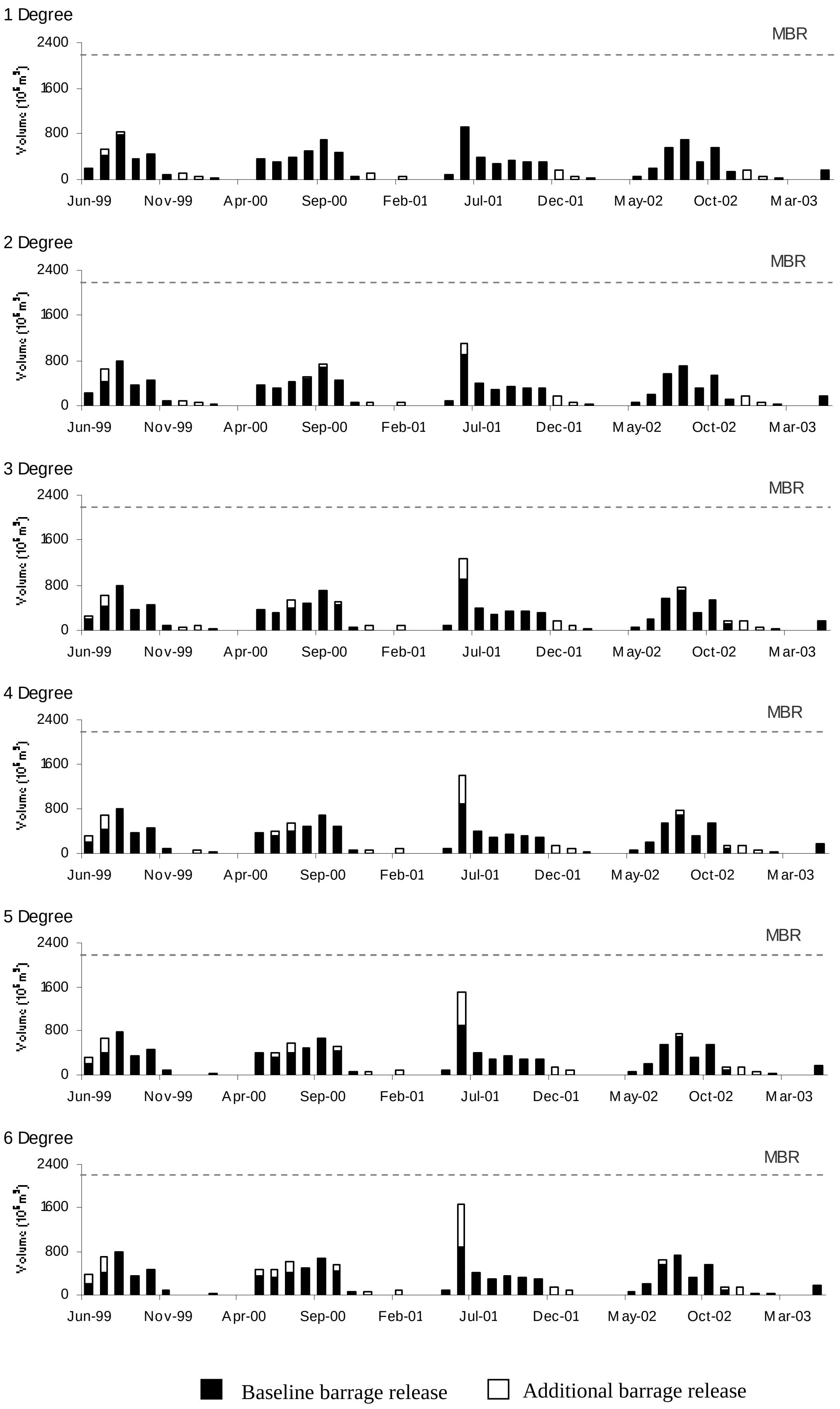

Figure 7.56. Total monthly barrage releases from Ithai Barrage for CCG2$_T$-BO4 scenarios (June 1999–May 2003) (MBR: maximum barrage release capacity)

7.6. Summary

This chapter demonstrates that all four barrage options will be impacted by the climate change scenarios. The BO4 (integrated option), which was a viable option for all the stakeholders (Section 5.5) under the current climate condition, will no longer be able to satisfy the demands from various stakeholders for almost all the climate change scenarios investigated. The lake water level for BO4 was estimated below the MDL for some period during the simulation period for all the climate change scenarios. The CSIRO GCM was simulated to have water levels below the MDL for as much as 9 months for $CCG1_H$-BO4 and 8 months for $CCG1_T$-BO4 scenarios. The BO1 (prioritization to water hydropower), BO2 (prioritization to agriculture) and BO3 (prioritization to ecological demands) all shows drastic increase in the flooding frequency of the surrounding lake area for all the climate change scenarios. Water levels during the dry season for BO1 and BO2 were simulated to be higher than the ecological requirements and hence will accelerate deterioration of the *phumdis* for almost all the climate change scenarios.

Chapter 8 – Conclusions and recommendations for future research and management

8.1. Conclusions

The unwise use of wetlands has reduced their ability to perform useful functions such as water retention and flood control and, in many cases, valuable products such as food, fuel and fodder (Joosten, 2009; Whigham, 2009). Global climate change may further impact these ecosystems and will influence efforts to conserve and manage them. For many freshwater wetlands, the most important projected impacts of climate change are associated with changes in the amount and seasonal distribution of precipitation, higher evapotranspiration due to warmer temperature and the combined effects of these changes upon runoff from their catchments (e.g. Hartig et al., 1997; Mortsch, 1998; Conly and van der Kamp, 2001)

Loktak Lake, an internationally important wetland in northeast India that provides valuable goods and services to local communities as well as supporting high biodiversity, has been subjected to a variety of ecological modifications over the last three decades. The key issue the lake is currently facing is the alteration of its hydrological regime from a natural wetland with fluctuating water levels into a reservoir with more or less constant water level brought about by the construction of Ithai Barrage for the commissioning of the Loktak Hydro Electric Project in 1983. This alteration in the water level regime underlies all the major problems the lake is currently subjected to. The most concerning is the deteriorating condition of the *phumdis*, especially in the KLNP area. The presence of this distinctive floating vegetation mass underpins its ability to sustain a large biodiversity and provide socio-economic goods in the form of food, fodder, fuel, construction materials and medicinal plants to local communities. The lack of baseline data, limited awareness of the functions and values of the wetland and institutional frameworks have further complicated the problems of Loktak Lake. Climate change represents an additional source of potential hydrological change that have the potential to further contributed to the problems of the lake. As noted in Section 2.7, no thorough study in this area has been carried out so far. Accordingly, this thesis has attempted to provide a new understanding of the hydro-ecological functioning of Loktak Lake, its sensitivity to a range of climate change scenarios, and the implication for ability to restore an ecologically-driven hydrological regime that satisfies the water demands of multiple stakeholders.

The first comprehensive synthesis of the hydro-ecological characteristics of Loktak Lake is based on data collected from various government agencies including the Loktak Development Authority, State Departments of Remote Sensing, Forests and Environment, and Irrigation and Flood Control as well as other international sources such as Wetlands International and the United States Geological Survey. Although the Loktak Lake has been the subject of several studies over the past six decades, these have mainly focused on flood control and optimal utilization of water resources to meet the demands from the accelerated economic development in the region. The most significant water resources development has been the construction of the Ithai Barrage to impound water from the Manipur River and its tributaries for hydropower generation and agricultural purposes. The project was designed to withdraw 42 m^3s^{-1} of water from the lake for the generation of 105 MW of hydropower and another 16.8 m^3s^{-1} to irrigate an area of 240 km^2. However, the irrigation scheme has been non-functional for the past eight years and the water levels in the lake are presently operated solely to satisfy the demands from the hydropower sector while ignoring the demands from other stakeholders.

The comparative assessment of the hydrological conditions of the lake in the pre and post Ithai Barrage periods presented in Section 2.5 provides an understanding of the changes brought about by the construction of the barrage as well as a bench mark against which to judge the extent to which the natural hydrological regime can be restored. After the construction of Ithai Barrage, the highest mean monthly water level of the lake increased by 0.33 m (from 768.65 m amsl to 768.98 m amsl), leading to increased flooding in the peripheral areas of the lake. However, a more critical alteration was observed during the low water level period. The minimum mean monthly water level increased by 2.03 m (from 765.55 m amsl to 767.58 m amsl). This increase in the low water levels in the lake means that most of the *phumdis* remain afloat throughout the year, depriving them of nutrient uptake from the lake bed (Section 2.5.2). The high water level regime during the study period (June 1999–May 2000) suggested on average only 27% of the thick *phumdis* within the lake and only 11% of thick *phumdis* in the KLNP area are grounded annually (i.e. *phumdis* thickness > water depth, Section 2.6.1). This high water level regime is one of the main causes for the degradation of *phumdis* in the lake. This is 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), resulting in major ecological changes.

In order to understand the contribution of runoff from the catchment area into the lake, the synthesised hydro-meteorological and related data for the lake and its catchment were employed in the development of rainfall-runoff models for three gauged sub-catchments (Thoubal, Iril and Nambul) using the coupled MIKE SHE / MIKE 11 modelling system (Chapter 3). As discussed in Section 3.4, owing to the paucity of data, the approach to model calibration and validation was to initially calibrate the model of Thoubal sub-catchment with available observed discharge data and then to apply the same calibrated parameter values to models developed for the Iril and Nambul sub-catchments as validation. The coupled MIKE SHE / MIKE 11 sub-catchment models proved successful in their ability to reproduce the observed discharges in the Thoubal, Iril and Nambul sub-catchments. The performance of the three models can be classified as either “excellent” or “very good” according to the classification scheme of Henriksen et al. (2008). The application of calibrated parameter values from one sub-catchment model (Thoubal) to the models of the other sub-catchments and the resulting good model performance suggest a robust calibration. The discharges from the four ungauged sub-catchments of Loktak Lake (Imphal, Kongba, Khuga and Western sub-catchment excluding Nambul) were estimated by weighting the simulated discharge by catchment area of the nearest MIKE SHE modelled sub-catchments. This simultaneous assessment of the runoff from all the seven sub-catchments of the Loktak Lake is the first comprehensive assessment made so far to quantify the total inflow of water from the catchment area.

These newly generated runoff data for the seven sub-catchments were combined with meteorological data and current abstractions in the formulation of a water balance model (Chapter 4). The water balance model of the Loktak Lake, (Equation 4.1) shows that inflows into the lake are provided by direct precipitation onto the lake surface and runoff from the sub-catchments that drain into the lake, while the outflows of water occur through evapotranspiration from the *phumdis*, evaporation from the open water surface of the lake, barrage releases and abstractions for agriculture, domestic consumption and hydropower generation. Due to constraints on the availability of data for some water balance components, the model was implemented using a monthly time step. The water balance model is successful in reproducing a water level regime similar to the observed water level regime of the lake. As discussed in Section 4.2.1, the model yields statistical values of 0.81 and 0.80 for the correlation coefficient (R) and Nash–Sutcliffe coefficient (R2) respectively, which according to the classification scheme of Henriksen et al. (2008) is classified as 'very good'. This adds confidence to the modelling approach for the sub-catchments using the coupled MIKE SHE / MIKE 11 modelling system and the subsequent evaluation of the discharges from the ungauged sub-catchments. The key point here is the fact that, despite using no calibration factor, the water balance model is able to simulate water levels that are very similar to the observed levels.

As demonstrated in Section 4.3.3, runoff from the sub-catchments of Loktak Lake and barrage releases from Ithai are the major components (90.7% of the total inflow and 67.5% of the total outflow from the lake respectively) of the water balance of the lake. These terms thus play a significant role in the maintenance of the water level regime and on water availability within the lake. Direct rainfall onto the lake surface area including the *phumdis* accounts for just 9.3% of the total inflow into the lake. The other outflow components of the water balance model, hydropower abstraction, evaporation, evapotranspiration, agriculture and domestic abstractions account for 22.2%, 4.3%, 3.7%, 1.3% and 1.2% of the annual total respectively.

Employing the Loktak Lake water balance model three barrage operation options that prioritise the requirements of the major stakeholders (hydropower – BO1, irrigation – BO2 and lake ecosystem – BO3) were developed (Chapter 5). A fourth option (BO4), which aims to balance the requirements of these stakeholders was also investigated. As discussed in Section 5.4.1, the water level regime for BO1 is able to satisfy the agriculture demands as well as reduce flooding in the surrounding areas of the lake. However, it is unable to satisfy the ecological requirement since water levels are still high preventing grounding of the phumdis, which is vital to the existence and functioning of the lake ecosystem. The BO2 water level regime, as discussed in Section 5.4.2, is the only regime where the simulated water level goes below the minimum drawdown level (MDL), the water level below which abstractions are not possible. Under the BO2 regime this occurs in four months and this option would not be viable for the National Hydro Power Corporation (NHPC), which operates the hydropower scheme. However, from the ecological demands point of view, the new water level regime for BO2 is able to satisfy the requirement for low water levels during the critical months of December, January and February. During the month with the lowest water level (February) for the BO2, 94% of the total thick *phumdis* in the Loktak Lake are grounded (i.e. *phumdis* thickness > water depth, Figure 5.9) compared to the maximum of just 27% during the baseline condition. Similarly, in the KLNP area, the new regime enhances the grounding of thick *phumdis* to 88% compared to 11% during the baseline condition.

The new water level regime under BO3 (Section 5.4.3) demonstrates that the water levels during December, January and February are lowered enough to meet the desired ecological requirements. The new regime is able to ground 26%, 83% and 91% of the thick *phumdis* within the lake during December, January and February, respectively (Table 5.3). In the critical KLNP area, during the same months 10%, 67% and 79% of the *phumdis* are grounded (Table 5.3). The BO4 water level regime is also able to provide adequate water for abstraction by the hydropower and irrigation sectors. It also shows a marked improvement in the flooding pattern in the peripheral areas of the lake. However, flooding, although improved, still occurs in five months under this new water level regime, which will still incur losses to the communities in the surrounding areas of the lake.

Compared to these three options (BO1, BO2 and BO3), the water level regime under BO4 is a more viable option to all the stakeholders including the lakeshore communities. Crucially it is capable of satisfying both the low water level requirements for the ecological health of the lake while preventing floods in the lake shore communities, whilst simultaneously enhancing the hydropower and agriculture abstractions compared to the current baseline condition (Section 5.4.4). The BO4 water level regime is able to ground 73%, 80% and 93% of the thick *phumdis* within the lake and 48%, 75% and 85% of the thick *phumdis* in the KLNP area during December, January and February respectively (Table 5.4). The hydropower sector, on an average annual basis, is able to abstract $869.83 \times 10^6 m^3$ of water for hydropower generation which is more than its current baseline abstraction of 845.01 × 10^6m^3. The irrigation sector has the largest shortfall in the supply of water being the last on the priority list of the four stakeholders considered. As shown in Table 5.5, the irrigation sector gets 70 × 10^6m^3 of water annually compared to the desired demand of 222 × 10^6m^3. However, the amount of water allocated for the irrigation sector under the BO4 regime is higher (46%) compared to its current baseline allocation of 48 × 10^6m^3 annually. This increase in water allocation for the irrigation sector translates to an increased agricultural area of 36 km^2 (96 km^2 from 60 km^2).

Implications of climate change on runoff from the sub-catchments of Loktak Lake and, in turn, the impacts on the water level regime of the lake were assessed by forcing meteorological inputs to the catchment and water balance models based upon a number of climate scenarios. Two groups of climate change scenarios were investigated in Chapter 6. Group 1 (CCG1) uses results from seven different GCMs for an increase in global mean temperature of 2°C (Section 6.2), whilst Group 2 (CCG2) is based on results from HadCM3 GCM for increases in global mean temperature between 1ºC and 6ºC (Section 6.2). As noted in Section 6.2.2, two different methods for PET estimation (Hargreaves and Thornthwaite) were employed in this thesis to perturb the original PET data to assess the sensitivity of catchment runoff and subsequently Loktak Lake water level regime, to the choice of PET evaluation methods.

For the CCG1 scenarios, the mean daily discharge from Loktak sub-catchments varies across GCMs and between sub-catchments for the simulation carried out using the Hargreaves method of perturbing PET data. The relative magnitude of the changes in simulated discharges for all GCMs in all the three sub-catchment generally follows the rainfall pattern (Section 6.2.3.1). The mean annual total river inflow into the lake (i.e. the combined flow of all three modelled sub-catchments and four ungauged sub-catchments) for all CCG1 scenario, except the CSIRO, shows an increasing trend, varying between 2% (NCAR) and 27 % (MPI). The CSIRO shows a decline in the mean annual total river flow into the lake by 6%. Similar to the simulation carried out using Hargreaves perturbed PET, the discharge simulated using the Thornthwaite method of perturbing PET for CCG1 scenarios also shows variation across GCMs and between sub-catchments (Section 6.2.3.2). The simulated discharges for all GCMs also closely follow the rainfall pattern. The total river inflow from the catchment area into the lake estimated using the Thornthwaite perturbed PET also shows an increasing trend for all the GCMs CSIRO. The CSIRO GCM shows a decline in the total inflow into the lake by 2%, while for the rest of GCMs under CCG1 scenarios, the magnitude of the increase in the mean annual total river flow varies between 5% (NCAR and HadCM3) and 32% (MPI). As discussed in Section 6.2.3.3, when comparing the discharge simulated between the two different methods employed to perturb PET, the total river inflow computed using the Hargreaves perturbed PET tends to be lower compared to the Thornthwaite method for all CCG1 scenarios. The variation in the total inflow estimated by these two methods is however relatively small (0.68 - 8.43%).

In contrast to the CCG1 scenarios, the discharge simulated for all the CCG2 scenarios for both the Hargreaves and Thornthwaite methods of perturbing PET, increases constantly with increasing global mean temperature from 1°C to 6°C for all three modelled sub-catchments (Sections 6.2.3.1 and 6.2.3.2). For both PET methods, the highest increase in the mean daily discharge for all the three sub-catchments is associated with 6°C rise in temperature. A similarly increasing trend is also observed in the mean annual total inflow into the lake with the rise in global mean temperature for both PET methods. The mean annual total inflow into the lake computed using the Hargreaves perturbed PET tends to be larger for the scenarios associated with the increase in global mean temperature of 3-6°C, compared to those estimated using the Thornthwaite methods for perturbing PET. The magnitude of variation in the total inflow estimated by these two methods is small (0.13 - 8.42%, Section 6.2.3.3). However, for the 1°C and 2°C rise scenario, the Hargreaves perturbed PET results in lower discharges by 2.61% and 0.68% respectively.

The mean annual water level of the lake has simulated to be higher compared to the observed baseline for all CCG1 GCMs except for the CSIRO, for both PET perturbation methods (Sections 6.3.1 and 6.3.2). For the simulation carried out using the Hargreaves method of perturbing PET, the increase in the water level varies between 0.11 m (NCAR GCM) and 0.78 m (CCCMA GCM), while for the Thornthwaite method of perturbing PET the increase in the mean water level varies between 0.41 m (NCAR GCM) and 0.92 m (HadGEM1). For the CSIRO GCM, the mean lake level decreases by 0.47 m for the Hargreaves method and 0.24 m for the Thornthwaite method. The water levels simulated using the Hargreaves methods tend to be lower compared to those simulated using the Thornthwaite method for all CCG1 scenarios (Section 6.3.3). The variation in the annual mean lake level estimated using these two methods is, however, quite small ranging between 0.10 m (CCCMA GCM) and 0.30 m (NCAR GCM).

For all CCG2 scenarios, the water level estimated using the Hargreaves method of perturbing PET is higher when compared to the baseline condition. The difference in the mean lake water level from the baseline rises almost linearly with increase in global mean temperature from 0.30 m for 1°C to 0.78 m for the 6°C (Section 6.3.1, Figure 6.34). Water levels estimated using the Thornthwaite method of perturbing PET are also higher when compared to the baseline condition. However, unlike those estimated using the Hargreaves method, levels simulated using the Thornthwaite method of perturbing PET do not follow a consistent pattern with the increase in temperature (Section 6.3.2). Similar to the CCG1 scenarios, the water levels simulated for all CCG2 scenarios using the Hargreaves methods tends to be lower compared to those simulated using the Thornthwaite method (Section 6.3.3). The variation in the annual mean lake level estimated using these two methods is again small, ranging between 0.11 m (2°C) and 0.25 m (6°C).

In Chapter 7, the sustainability of the four barrage options (BO1, BO2, BO3 and BO4) developed in Chapter 5 were assessed in the face of the two climate change scenarios (CCG1 and CCG2) for both PET data perturbation methods (Hargreaves and Thornthwaite). The water levels for all $CCG1_H$-BO1 scenarios (i.e. barrage operation option with prioritization to hydropower for climate change Group 1 scenarios estimated using Hargreaves perturbed PET) and $CCG1_{T-}$ BO1 (i.e. barrage operation option with prioritization to hydropower for climate change Group 1 scenarios estimated using Thornthwaite perturbed PET) are higher compared to the baseline (BO1) water levels (Section 7.1) with all $CCG1_T$-BO1 scenarios and all except the CSIRO for $CCG1_H$-BO1 scenarios exceeding the full reservoir level (FRL) at some point of time during the simulation period. As a result of this high water level, it is not possible to satisfy the ecological demands of all $CCG1_H$-BO1 and $CCG1_T$-BO1 scenarios. The flooding frequency (water level > FL) increases drastically from just 15% of the simulation period for the baseline period to between 33-88% for the $CCG1_H$-BO1 scenarios and between 52-96% for $CCG1_T$-BO1 scenarios. The water levels for the CSIRO GCMs are also estimated to fall below the MDL for both $CCG1_H$-BO1 and

$CCG1_T$-BO1 scenarios, so that hydropower generation would be prevented for 2 months.

The water levels for all $CCG2_H$-BO1 scenarios (i.e. barrage operation option with prioritization to hydropower for climate change Group 2 scenarios estimated using Hargreaves perturbed PET) and $CCG2_T$-BO1 (i.e. barrage operation option with prioritization to hydropower for climate change Group 2 scenarios estimated using Thornthwaite perturbed PET) are simulated to be higher when compared to the baseline condition (BO1). The major impact of the climate change scenarios is the increase in flooding frequency from just 15% of the simulation period for the baseline period to between 50-89% for the $CCG2_H$-BO1 scenarios and between 79-83% for $CCG2_T$-BO1 scenarios. Similar to its baseline condition, the water level does not fall below the MDL so that hydropower generation is not prevented. However, high water levels during the dry season will impact the ecosystem

For all the $CCG1_H$-BO2 scenarios (i.e. barrage operation option with prioritization to irrigation for climate change Group 1 scenarios estimated using Hargreaves perturbed PET) and all $CCG1_T$-BO2 scenarios (i.e. barrage operation option with prioritization to irrigation for climate change Group 1 scenarios estimated using Thornthwaite perturbed PET) the water levels during December, January and February are estimated to be much higher than the ecological requirement and hence the *phumdis* are not grounded. The flooding frequency also increases from 10% of the simulation period for the baseline condition (BO2 regime) to between 16-73% for the $CCG1_H$-BO2 scenarios and between 25-100% for $CCG1_T$-BO2 scenarios.

The water levels for all $CCG2_H$-BO2 scenarios (i.e. barrage operation option with prioritization to irrigation for climate change Group 2 scenarios estimated using Hargreaves perturbed PET) are above the FL between 19-75% of the duration compared to just 10% during the baseline condition (BO2 regime) indicating enhanced flooding frequency with climate change. The $CCG2_T$-BO2 scenarios (i.e. barrage operation option with prioritization to irrigation for climate change Group 2 scenarios estimated using Thornthwaite perturbed PET) also show a similar pattern of enhanced flooding with the water levels above the FL between 27-63% of the simulation period. All

$CCG2_T$-BO2 scenarios and all $CCG2_H$-BO2 scenarios except for 1°C have high water levels during the dry season such that there will be consequences for the *phumdis*.

There is also a trend towards enhances flooding for all $CCG1_H$-BO3 scenarios (i.e. barrage operation option with prioritization to ecological demands for climate change Group 1 scenarios estimated using Hargreaves perturbed PET) and all $CCG1_T$-BO3 scenarios (i.e. barrage operation option with prioritization to ecological demands for climate change Group 1 scenarios estimated using Thornthwaite perturbed PET). The water level for all $CCG1_H$-BO3 scenarios is estimated to be above the FL by between 18-51% and for all $CCG1_T$-BO3 scenarios between 28-52% compared to just 10% during its baseline condition (BO3 regime). Though all $CCG1_H$-BO3 scenarios are able to satisfy the ecological demands, the water level goes below the MDL for all the scenarios indicating the inability to supply water to hydropower and irrigation sectors for some duration during the simulation period. For the $CCG1_T$-BO3 scenarios, the CSIRO, HadCM3, IPSL, NCAR and MPI GCMs results in water level below the MDL.

All $CCG2_H$-BO3 scenarios (i.e. barrage operation option with prioritization to ecological demands for climate change Group 2 scenarios estimated using Hargreaves perturbed PET) and all $CCG2_T$-BO3 scenarios (i.e. barrage operation option with prioritization to ecological demands for climate change Group 2 scenarios estimated using Thornthwaite perturbed PET) water levels fall below the MDL at some point during the simulation period. This indicates an inability to supply water to hydropower and irrigation sectors. This compares with the baseline (BO3 regime) when water levels never fall below the MDL. The water levels for all $CCG2_H$-BO3 scenarios are above the FL between 23-55% of the duration compared to just 10% during the baseline condition. All $CCG2_T$-BO3 scenarios also show similar pattern of enhanced flooding, with the water levels rising above the FL between 28-51% of the simulation period.

The integrated barrage operation option (BO4), which was considered as the most viable option under the current water level regime, is highly impacted by both the climate change scenarios. Although the water level regime of all $CCG1_H$-BO4 (i.e. integrated barrage operation option for climate change Group 1 scenarios estimated using Hargreaves perturbed PET), $CCG1_T$-BO4 (i.e. integrated barrage operation option for climate change Group 1 scenarios estimated using Thornthwaite perturbed PET),

$CCG1_H$-BO4 (i.e. integrated barrage operation option for climate change Group 2 scenarios estimated using Hargreaves perturbed PET) and $CCG1_T$-BO4 scenarios (i.e. integrated barrage operation option for climate change Group 2 scenarios estimated using Thornthwaite perturbed PET) could satisfy the ecological demands and prevent flooding in the area surrounding Loktak Lake, water levels fall below the MDL at some point during the simulation period indicating the inability to supply any water to the hydropower and irrigation sectors for some point of time. As discussed in Section 5.5, is not an acceptable option to the LHEP. This demonstrates that management options which hold good and are able to satisfy the demands from various stakeholders of the lake for the current situation are likely to be impacted by the global climate change. In particular, attempts to balance the ecological demands of the lake with abstractions from the hydropower and agriculture are shown to experience problem due to lower dry season water levels which restrict abstraction at that time of year.

8.2. Future recommendations

This thesis has successfully developed multiple options for the management of the hydrological regime of the Loktak Lake, on the basis that the latter is the key driver to the maintenance of the overall health of the lake ecosystem. A range of model-based approach have provided understanding of the hydro-ecological characteristics of the lake and its catchments along with an assessment of the possible implications of the global climate change scenarios. These insights provide a scientific basis for future conservation and management efforts at Loktak Lake. This thesis has also identified certain areas where further researches and investment are needed to underpin more in the effective management of the lake.

8.2.1. Research recommendations

(a) Effect of landuse changes on catchment runoff: Changes in the landuse pattern within the Loktak catchment will affect the runoff pattern and hence the water level regime of the lake. The ever increasing population and economic development in the region will leads to major modifications of landuse which in turn are likely to alter runoff from the catchment. In addition, global climate change through its alteration in the meteorological parameters (especially rainfall and evapotranspiration) is also likely to impact the vegetation composition.

(b) Extension of PET perturbation evaluation method: The analysis presented in this thesis reveals only small variations between the simulations of the catchment runoff undertaken using the PET data perturbed employing the Thornthwaite and Hargreaves methods. However, previous studies have noted more marked differences in the climate change signals when different PET estimation methods were employed. For example, Kingston and Taylor (2010) employed Hargreaves, Penman-Monteith and Priestley-Taylor methods in the Mitano Basin, southwestern Uganda and reported marked variation in the PET climate change signal between the three methods. Similarly, Kingston et al. (2009) showed difference in the climate change signal for a global analysis employing same PET evaluation methods. Hence, it would be worthwhile to extend the PET evaluation methods in the assessment of the implication of climate change on Loktak Lake to other methods (eg. Priestley-Taylor, Blaney-Criddle, Jensen-Haise) and re-evaluate the catchment runoff and in turn lake water level to compared with the estimation carried out using Thornthwaite and Hargreaves methods.

(c). Sensitivity of model parameterization: Models were calibrated/ validated using a traditional iterative manual calibration process. This only provides only one set of parameter for each model. Sensitivity of the model to parameterization could be investigated using an auto-calibration method which is available within MIKE SHE. Selection of number of models from an auto-calibration run, which are statistically similar model performance would enable simulation of climate change for a number of equally calibrated model. This will provide insides into parameter uncertainty on discharge simulation and in turn on the lake water level.

(d). Water quality modelling: Deteriorating water quality is also another issue confronted by the lake due to runoff from the surrounding agricultural fields and from urban areas including the city of Imphal. Preliminary assessment carried out by LDA suggested the lake water quality especially in the KLNP has deteriorated (pH - 4.1; 58,000 ml^{-1} value for standard plate count for bacteria). Regular monitoring of water quality needs be carried out. A water quality model of the lake could be developed to understand the physical mechanism that controls the position and momentum of pollutants within the lake (e.g. Rasmussen et al., 2009). Such a model would provide the opportunity of assessing the impacts of alternative water level management upon water quality as well as the potential to assess the impacts of modified land use with the catchment such as further increases in the area under agriculture.

8.2.2. Management recommendations

(a) Integrated management: The government agencies (for example the Forest Department, Irrigation and Flood Control Department, NHPC and the Fisheries Department) involve in the conservation of Loktak Lake have previously adopted sectoral approaches for developing action plans. These are mainly driven by targets without understanding their implications for other sectors. These action plans often lead to lack of coordination amongst several other agencies working in the same area with different objectives. For the effective conservation and management of Loktak Lake and its resources on a long term basis, there needs to be a major shift in the management approach adopted so far. A more integrated approach that considers all the stakeholders of Loktak Lake should be adopted. In addition, there needs to be more transparency in data sharing procedure between different government agencies. The Integrated Water Resource Management (IWRM) approach (UNESCO, 2003) which was also adopted in this thesis, is recommended in order to facilitate a broad understanding and management planning at the catchment level. This will enable coordinated management of Loktak Lake and its related resources to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of Loktak ecosystem. This approach needs to be supported by adequate regulatory and policy mechanisms

(b) Monitoring: Like many other project based monitoring programmes, the monitoring of the hydro-meteorological parameters carried out by LDA under the SDWRML project ceased at the end of the project. The availability of adequate long-term data is vital for effective management of Loktak Lake. Hence, efforts should me made to re-establish all the hydro-meteorological stations used earlier by the LDA. In addition, extension should be made to establish stream gauging stations in the ungauged sub-catchments (Imphal, Kongba, Khuga and selected larger streams from the Western sub-catchment). The data from these stations can be used to validate and further improve the catchment modelling approach adopted in this thesis.

Monitoring of the distribution and extent of *phumdis* should also continue with a smaller time interval (for example annually or once in every two years) so that a better understanding of the *phumdis's* relationship with the lake hydrology can be established. The measurement of the thickness of *phumdis* is a very cumbersome exercise. The one-off measurement of the thickness of *phumdis* carried out under the SDWRML took two years to complete the survey for the entire lake. Hence, it is recommended to repeat the exercise of measuring the *phumdis* thickness once every five year. It is also recommended that the same transects used earlier by LDA should be used so that comparative assessment between the data collected at various time intervals can be carried out.

(c) Bathymetric survey: Accurate estimation of the elevation-volume-area relationship is critical to the operation of Ithai Barrage and is the key component of the water balance model developed in this thesis. The barrage gates are operated to maintain a water level regime in the lake which provides adequate corresponding water volume for the hydropower abstraction. Slight alteration in the relationship will have implication on the operation policy of the barrage by NHPC. The high sedimentation rate owing to the practise of *jhum* cultivation in the catchment area of the lake is likely to have direct implications on the lake volume. Hence, it is recommended that bathymetric surveys of the lake should be undertaken atleast once every five year. It should be noted that bathymetric surveys should be carried to the maximum level of 796.63 m amsl (FRL). This will provide an opportunity to compare and validate the extrapolated elevation-volume-area relationship developed in this thesis.

(d) Database: A centralized database to collate all information pertaining to the conservation and management of Loktak Lake including hydro-meteorological data, landuse, topography, water abstraction by various stakeholders and *phumdis* should be maintained, ideally with the LDA. This centralized database will also facilitate in storing the data from various agencies in an identical standard data format. Such a database will facilitate the updating of the analysis undertaken in this thesis and prevent the need to obtain data including government organisations which can be time consuming and expensive undertaking.

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