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Article in *Lakes & Reservoirs Research & Management* · February 2010

DOI: 10.1111/j.1440-1770.2010.00421.x

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Integrated lake basin management and its importance for Lake Chini and other lakes in Malaysia

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Abstract

This report discusses the concept and progress of IWRM/IRBM in Malaysia, with a subsequent focus on the problems and challenges facing Lake Chini, one of the two largest freshwater lakes in the country. Lake Chini is located within the Pahang River Basin, the largest river basin in Peninsular Malaysia. The lake is a popular tourist destination, and the various infrastructure developments needed to enhance its marketability have resulted in degradation of the natural environment, as well as infestation of aquatic plants over most of the lakes' surface area. This report also discusses the need for integrated basin management as the logical approach for holistic management of the entire Pahang River Basin, in order to ensure the management of Lake Chini for sustainable use, including retention of its importance, not only for eco-tourism, but also as the source of the livelihood of the indigenous people living in the lake ecosystem and catchment area.

Key words

ecosystem, Integrated River Basin Management, Integrated Water Resources Management, Lake Chini, modelling, Pahang River Basin.

INTRODUCTION

Although fresh water represents the smallest percentage of the total water available on our planet, it is critical to the fulfilment of human needs for living. In addition to providing a water supply for meeting drinking needs, irrigating crops and agricultural areas and operating industrial processes, fresh water also sustains terrestrial and aquatic habitats needed for the growth of a myriad of indigenous plant and animal species. Increasing water demands and deterioration of existing water resources, however, as a result of water pollution and unsustainable water uses have led to water scarcity in many parts of the world (UNEP 2006; Jorgensen & Rast 2007), highlighting the need to manage water resources holistically within a lake basin in order to sustain life and the natural environment.

THE STATUS OF INTEGRATED WATER RESOURCES MANAGEMENT AND INTEGRATED RIVER BASIN MANAGEMENT IN MALAYSIA

Since its inception >6 decades ago, Integrated Water Resource Management (IWRM) is being widely adopted throughout the world as an attempt to manage water in a sustainable manner. Integrated River Basin Management (IRBM), which is a subset of IWRM, has been promoted as a means of more realistically managing water resources, based on a basin approach.

Our constant need to manage and improve water delivery efficiency, increasing infrastructure costs to build new reservoirs, new water treatment and transfer systems, rehabilitation of degraded rivers, and climatic variability are some of the main factors necessitating many countries to embrace IWRM and IRBM as water resources management approaches. Implementation of such holistic water management approaches, however, remains a global challenge, especially for most developing countries.

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Accepted for publication 2 September 2009.

Both IWRM and IRBM approaches require concerted efforts from relevant stakeholders involved in managing and/or using water resources. Lack of strong political support and interagency collaboration in managing the available water resources, comprehensive policies, regulatory framework and financial sustainability are some limitations that impede successful implementation of integrated water resource management in these countries.

Integrated Water Resource Management and IRBM are concepts that have been supported in Malaysia for more than a decade as a result of rising water demands, deteriorating water quality in rivers, and environmental challenges in the form of floods, droughts and climate change (Zakaria & Sharip 2007). Degradation of river water quality is considerable, with 10% of the 146 river basins in Malaysia being classified as polluted in 2005. Another 35% are classified as slightly polluted (DOE 2006). The IWRM approach was embraced by the federal government with the establishment of a National Water Resources Council, comprising all the state government heads, following the water crisis in the country in 1997. The subsequent unanimous decision by the members of the council to accept the need to implement IRBM in Malaysia, and to formulate river basin master plans for all 189 river basins management units (RBMU) identified in the country, is a significant acknowledgement by the government of the need to ensure sustainable development of its water resources (Zainal Abidin 2004; Zakaria & Sharip 2007).

Acknowledging the importance of institutions in driving the IWRM and IRBM concept, a river basin organization known as Selangor Water Management Authority or Lembaga Urusan Air Selangor (LUAS) was formed in Selangor State. Supported by the Selangor Waters Management Authority Act 1999, LUAS duly assumed the dual functions of a management and enforcement agency to implement IWRM at the river basin level within the State of Selangor (Zainal Abidin 2004). In Kedah, another state in Malaysia, new legislation embracing IRBM was introduced to replace the obsolete Kedah Water Enactment, 1921 (Zakaria & Sharip 2007).

Integrated River Basin Management plans were also developed in the two states in cooperation with the Danish government, through the DANIDA programme (Jusoh J, unpubl. data, 2008). The Selangor River Basin, which is characterized by a more developed catchment and mixed land use, and the Kedah River Basin, which typifies the rural watershed and agriculture-setting, represent two models for future river basin development in Malaysia (Jusoh J, unpubl. data, 2008).

The different management styles adopted by the two river basins (a single agency approach by LUAS governing the Sungai Selangor basin; an interagency committee managing the Sungai Kedah basin; Zainal Abidin 2004) represent two approaches for IRBM implementation in Malaysia.

Sectoral policies, strategies and plans, however, are still being used as an instrument in planning and managing most other water resources in Malaysia (Zakaria & Sharip 2007; Tan & Mokhtar 2009), either at the district, municipal or state level. The establishment of the Ministry of Natural Resources and Environment, and consolidation in 2004 of key government agencies dealing with land and water resources and environment within the ministry, was a significant attempt to amalgamate and strengthen land and water resource planning and management in the country (Zakaria & Sharip 2007).

Similar to rivers, inland waterbodies in Malaysia also experience water-quality degradation, either in the form of eutrophication or sedimentation. Sporadic scientific research and development activities, lack of a central database for compilation of scientific information and lake data, fragmented policies and governance, lack of institutions vested for lake management, limited stakeholder participation and involvement, and capacity building for lake and reservoir management are key issues hindering the implementation of sustainable lake management in Malaysia (Sharip & Zakaria 2007). Development of a national lake vision and strategic framework for lake management in Malaysia, which is currently being pursued, might provide the institutional framework needed to address the issue of lake management.

Most of the lakes in Malaysia, natural or man-made (reservoirs), are an important part of the country's river systems. The largest two freshwater lakes in Malaysia (Lake Chini; Lake Bera) are located in the same river basin (Pahang River Basin). Reservoirs constructed for water supply storage, hydroelectricity generation and/or flood controls and silt retention are an integral part of many other major river basins in the country. As a lake is also part of the catchment basin, integrated management of a river basin will also presumably sustain the lake environment contained therein.

The unique characteristics and complex response dynamics of lakes have differing management implications, however, in terms of sustained actions and involved costs (Nakamura 2007), particularly after a lake system has been degraded. The nonlinear nature of the eutrophication processes and the hysteresis phe-

nomenon inhibit restoration of a degraded lake system to its original undegraded condition (Nakamura 2007). Furthermore, restoring degraded lakes often requires multiple mitigation measures, and involves a long time period (Phillips *et al.* 1999; Gulati & Donk 2002). Lack of experience with an ecosystem-based approach also constrains any implementation and use of IWRM as the management instrument for lake basins (Jorgensen & Rast 2007). As most lakes are usually located within a micro-scale catchment in the upstream or tributaries of major rivers, managing lakes might seem easier from the lake basin perspective, compared with the whole river basin.

Furthermore, another challenge in ecosystem-based lake management approach is the availability of sufficient knowledge or understanding of the state of the lake ecosystem. The complexity of the ecosystem physical-chemical-biological processes and linkages requires the development of tools to assess the condition of a lake. Many countries have engaged in lake-model development not only to address this need, but also as a synthesis and overview tool to develop management options to address such complex ecosystems (Jorgensen & Rast 2007). The remainder of this report attempted to assess the importance of the Pahang River/Lake Chini Basin, and the challenges faced by Lake Chini. It includes a preliminary assessment of the Lake Chini ecosystem, with the development of a tailored, complex model through a coupled three-dimensional hydrodynamic and ecosystem simulation.

PAHANG RIVER BASIN

The Pahang River Basin is the largest river basin in Peninsula Malaysia, with a total catchment area of $\approx 27\,000\text{ km}^2$. Located within $101^\circ 30'E$ – $103^\circ 30'E$ and $3^\circ 00'N$ – $4^\circ 45'N$, it consists of five sub-basins (Pahang River Basin, Bertam River Basin, Bekapor River Basin, Mentiga River Basin and Bera River Basin), comprising nine districts in Pahang State and two districts in Negeri Sembilan State (Tan & Mokhtar 2009). The Pahang River is surrounded by the central Mountain Range along its western and north-western side, flowing for a distance of 440 km downstream into the South China Sea in the east. The river basin exhibits a humid equatorial climate, and receives an average annual rainfall between 2000 and 3000 mm. It is also one of the most vital water resources in Malaysia. Water-related issues were common in some parts of this large river basin, however, including deteriorating water quality, due to lack of an IWRM plan or a strong coordination body to manage the river basin (Tan & Mokhtar 2009).

Nevertheless, this river basin provides important freshwater storage, both natural and man-made, which address both human and ecological needs. There are seven lakes and reservoirs located within the Pahang River Basin (Sultan Abu Bakar Reservoir located at the upstream end, Lake Bera, Lake Bintau, Repas Lama, Repas Baru Reservoir, Paya Bungor-Ulu Lepar Lake and Lake Chini at the downstream end; NAHRIM, unpubl. data, 2005). Lake Chini, because of its close proximity to the Pahang River, is directly influenced by changes in the river basin, especially during the monsoon season. Lake Chini is the main focus of this report, and its importance, issues and current conditions are discussed in subsequent sections.

LAKE CHINI, MALAYSIA

Natural and socio-economic importance

Lake Chini is the second largest freshwater lake in Malaysia. It is connected to Pahang River by the meandering Chini River having a total length of 4.8 km. The lakes are situated in the Pekan District, and have a total catchment area of 4975 ha (Mohamed *et al.* 1994; Fig. 1). The lake is surrounded by hilly areas and undulating land, being comprised of 202 ha of open water and 700 ha of swamp area (Department of Wildlife and National Parks 1987). Lake Chini is an alluvial riparian swamp system, thereby representing the most endangered type of ecosystem in the country (Hebauer *et al.* 1999). The lake has a unique shape, being comprised of 12 small lakes interconnected by natural channels.

Lake Chini has recreational value, as well as being of ecological importance in terms of its biodiversity. It possesses natural landscapes and social-cultural attractions (Mohamed *et al.* 1994) for promotion of eco-tourism development. Lake Chini's diverse flora and fauna are of national and international conservation value (Department of Wildlife and National Parks 1987). Its various indigenous plant and animal species, either microscopic or macroscopic, are an important gene pool of scientific interest (Department of Wildlife and National Parks 1987). An 1998 assessment of its ecology by Wetlands International Asia Pacific – International Lake Environment Committee indicated the existence of 91 species of phytoplankton, 37 species of aquatic herbaceous plants, 25 species of freshwater swamp and swamp forest floral species, and 323 species of lowland forest plant species in Lake Chini. In an earlier 1987 survey by the Department of Wildlife and National Park, two rare and vulnerable plant species, *Aponogeton undulatus* and *Barclaya kunstleri*, were discovered in Lake Chini, with the occurrence recorded as the second and

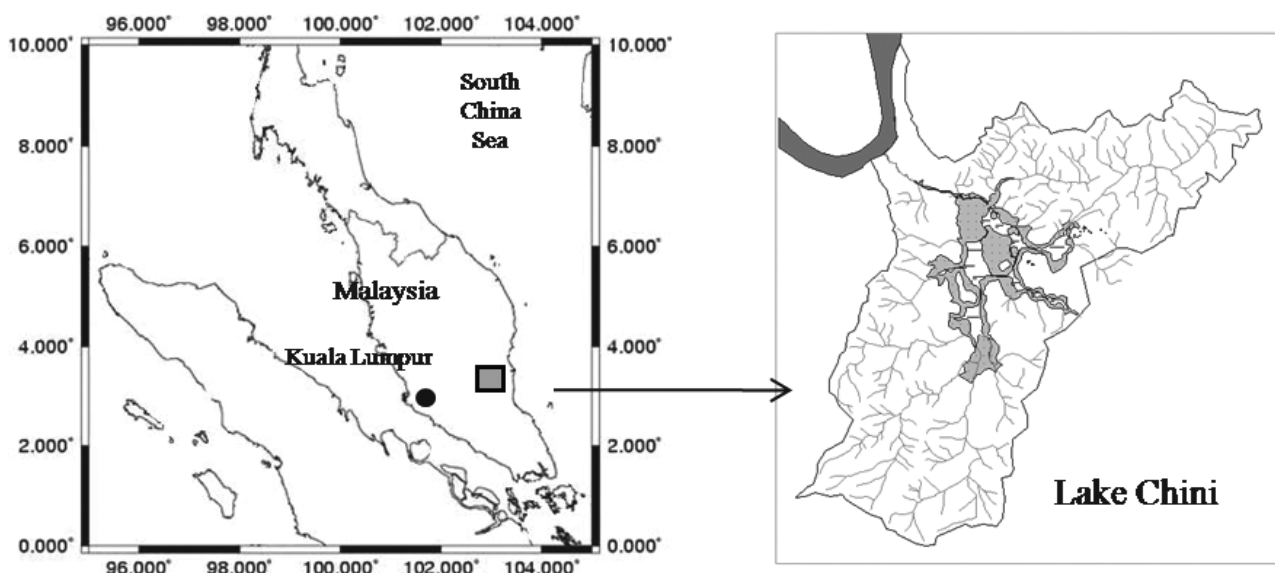


Fig. 1. Location of the study area.

fifth known locality respectively, of such species in Peninsular Malaysia.

Lake Chini also is a home to 38 species of freshwater fishes, 98 species of birds, 22 species of mammals, 3 species of amphibians and 12 species of reptiles, including *Scleropages formosus* and the tiger *Panthera Tigris*, being recognized as an endangered fish and mammal species respectively, in the vicinity of the lake (Wetland International 1998). There are at least two mammals and three reptiles classified under the International Union for Conservation of Nature (IUCN) list of vulnerable species, and six species of birds categorized as near-threatened under the World List of Threatened Birds (Wetland International 1998). Being a wetland that experiences seasonal inundation, Lake Chini is a significant habitat for breeding, spawning and nursery grounds for both resident and migratory fish species (Wetland International 1998).

Lake Chini also functions as monsoonal water storage site, reducing the frequency, level and velocity of floods (Shuhaimi-Othman *et al.* 2007) in downstream areas from the outflow of Pahang River. The wide swampy area forms a natural water retention system.

Lake Chini is also a home to >400 indigenous people of the Jakun Tribe living at five settlements (Gumum settlement, Tg. Puput settlement, Chendahan settlement, and Melai and Ulu Melai settlements; Omar 2005). The lake is an important source of fisheries for the local people. A 1993 survey in 1993 (DARA, unpubl. data, 1994) indicated that fishing is the sole economic revenue for 11.5% of the total head of households. Some local communities are involved in tourism activities (boat opera-

tors, tourist guides, craft sellers). As few of these settlements are located near the lakeshore, with some having no other direct road access, Lake Chini is also an important and immediate travel mode.

The Federal Department of Town and Country Planning has also delineated Lake Chini as an environmentally sensitive area to be preserved, as included in the National Physical Plan (Federal Department of Town and Country Planning 2005). Furthermore, ecotourism has been acknowledged as an important socioeconomic activity for Lake Chini area residents (Federal Department of Town and Country Planning 2005), with continuous development being planned by the state government to promote the lake as an important tourist destination.

Issues and challenges

A number of stressors, in the form of economic development to augment the socio-economic activities, have affected the lake catchment for >20 years. There has been a significant land use change within the catchment, including the conversion of forested areas to agriculture areas, and mining and logging activities. Conversion of primary forest to secondary forest began long before the 1990s, with 60% of the catchment area having been logged (Department of Wildlife and National Parks 1987). Conversion of secondary forest to agriculture area (mainly rubber and oil palm plantation) was widespread, involving 807 ha of forested land on the east side of Lake Chini (Shuhaimi-Othman *et al.* 2007). This alteration might have been one of the

factors that influences hydrological imbalances that have resulted to low lake water levels.

In an effort to sustain the Lake Chini water system, and increase socioeconomic and tourism activities (Mohamed *et al.* 1994), a weir was constructed in 1995 across Chini River downstream of the lake to retain the water level for navigation purposes. This transformed the lake from a semi-lotic system to a lentic system (Shuhaimi-Othman *et al.* 2007), thereby altering the overall lake ecosystem.

This alteration might have resulted in degradation of the lake environment. Previous studies have indicated changes in Lake Chini's trophic state from an oligotrophic lake (Mohamed *et al.* 1994; Wetland International 1998) to a mesotrophic lake (Shuhaimi-Othman *et al.* 2007) and subsequently to a eutrophic lake (Shuhaimi-Othman & Lim 2006; Sharip & Yusop 2007).

The lake, which once was famous because of its lotus plant (*Nelumbo nucifera*) species composition, was slowly been replaced by a submerged non-native macrophyte (*Cabomba furcata*; Shuhaimi-Othman *et al.* 2007). *Cabomba furcata* is one species of the Cabombaceae family, being originally found in South America (Orgaard 1991). The plant was widely distributed in its native area, characterized by a dry season and a prolonged period of high water levels (Orgaard 1991). The dry and wet seasonal pattern in Lake Chini also appears to be suitable for the growth of *Cabomba furcata*. The appearance of exotic and weedy plant species such as *Salvinia Molesta* and *Hydrilla Veticilata* (Wetland International 1998; Gan & Bidin 2005) in Lake Chini provides another threat to its ecological biodiversity.

Biodiversity loss was eminent with the alteration of the Lake Chini ecosystem. Inundation of riparian wetland had resulted in the death of many vegetation and swamp forest trees in low-lying areas surrounding the lake, including the extirpation of *Eugenia cf. spicata* and *Fragaria fragrans* trees (Wetland International 1998), and significant losses of *Syzygium* sp. (Gan & Bidin 2005). Uncommon species, such *Barclaya Kuntleri* and *Aponogeton undulatus*, might be a threat to Lake Chini if further degradation of the lake environment is not controlled. The dynamic pattern of plant community succession is associated with environmental changes (Lacoul & Freedman 2006), particular agricultural-caused eutrophication (Egertson *et al.* 2004). Anthropogenic degradation of wetlands usually associated with nutrient enrichment has been found to lead to homogenization of biotic communities, resulting in significant changes in the composition of plant species (Lougheed *et al.* 2008). A change of

water quality and trophic state in Lake Chini might have promoted more-tolerant plants able to ameliorate in degraded environment to prosper, whereas native and sensitive species disappeared.

The diversity of fish in Lake Chini has also changed with habitat alteration. The weir expanded the open water area, flooding swampy forest and riparian zone, and reducing the water velocity in the lakes. This hydraulic change promotes the abundance of fish species adapted to reduced water velocity, while also reducing the abundance of the riverine fish that migrate into Lake Chini during monsoon season (Wetland International 1998). The water-quality deterioration has caused a reduction in the number of fish in the lakes (Wetland International 1998), disrupting the related socioeconomic possibilities of the local communities (Omar 2005), particularly the indigenous people that were dependent solely on the fisheries activities for their economic well-being.

Mining activities are also a threat to the Lake Chini ecosystem. Re-activation of the formerly closed iron mine on the south-eastern boundary of the lake has resulted in an increased concentration of heavy metals, particularly barium and manganese, in the lakes (Shuhaimi-Othman *et al.* 2008). The Pahang River inflow during the monsoon season has also been identified as a source of heavy metals, particularly iron and aluminium in some parts of the lakes (Shuhaimi-Othman *et al.* 2008).

Degradation of the lake environment also contributed to a decreased number of tourists visiting Lake Chini (Wetland International 1998), thereby significantly affecting the local communities dependent mainly on tourism activities as sources of their livelihood. There is a need to control land use changes within the catchment area, and balance socioeconomic development needs and environmental sustainability, in order to retain Lake Chini as a tourist destination.

Lake Chini is presently governed by the State Government of Pahang, through the administration of the Pekan District Office. Sectoral management of the catchment is currently in place, including the Forestry Department of Peninsular Malaysia, Department of Wildlife and National Parks, Drainage and Irrigation Department, Department of Environment, and Department of Director General of Lands and Mines, which administer Lake Chini's forest reserve, wildlife and biodiversity, lakes and river system, water quality, and land and mineral resources respectively. Such sectorally based lake basin management results in an inability to control the continuous alteration within the catchment, and subsequently regulate deterioration of the lake environment and its complex ecosystem.

ASSESSMENT OF LAKE CHINI ECOSYSTEM

Methods and model development

An assessment of Lake Chini was carried out in year 2007, involving field measurements and development of a hydrodynamic-ecosystem model. The model attempted to describe the present situation of the Lake Chini ecosystem, and develop a tool to assist in the management of Lake Chini.

A hydrographic survey was conducted on 21–22 June 2007, to provide basic lake shoreline and depth data for boundary simulations. Bathymetric soundings were conducted, using a *Navisound 215* dual frequency echo sounder model, with depth value measured at 210 kHz frequency. Offshore positioning and navigation were based on TRIMBLE DSM GPS 212 and HYDROPAM (version 2.3) navigation software, with the collected raw data being processed with NAVEDIT (version 2.3) for spike editing. This positioning was with reference to Universal Transverse Mercator (UTM) Zone Grid 48 North (World Geodetic System, WGS 84 Datum).

In situ measurements of the temperature, pH, dissolved oxygen (DO) concentration, electrical conductivity and total dissolved solids (TDS) concentrations were carried out at 10 stations, using a YSI 6600 multiparameter probe. Water samples were collected, using a Niskin sampler, being stored, preserved and transported to the laboratory for nutrient, chlorophyll-a, dissolved organic matter (DOM) and particulate organic matter (POM) measurements. Sampling and analysis of ammonium, nitrate, phosphate, total phosphorus, total nitrogen and organic matter were based on standard methods (APHA 1992, HACH 2003).

Meteorological parameters required for hydrodynamic modelling were based on data measured at the Kuantan Airport meteorological station. The needed data included wind speed and direction, solar radiation, rainfall, relative humidity and cloud cover. Water level and temperature data, continuously measured at 10 min interval with a water level logger RBR Model TGR-2050, were used for model validation.

The three-dimensional hydrodynamic model (COSMOS) employs a rectilinear grid in a Cartesian coordinate system, with a fine mesh of width cell size of 30 m × 30 m, to include the thinnest water area of Lake Chini's unique shape. The model employs an explicit time-marching scheme, of which the grid resolution limits the computational time step. The mathematical model is based on the well-known horizontal fluid motion and flow continuity equation, as illustrated in Equations 1–4.

Horizontal fluid motion:

$$\begin{aligned} \frac{\partial u}{\partial t} + \frac{\partial}{\partial x}(uu) + \frac{\partial}{\partial y}(vu) + \frac{\partial}{\partial z}(wu) = \\ -f_0 \times v - g \times \frac{\partial \zeta}{\partial x} - \frac{g}{\rho} \int_z^0 \frac{\partial \rho}{\partial x} dz - \frac{1}{\rho} \frac{\partial P_a}{\partial x} + \frac{\partial}{\partial x} \left(A_x \frac{\partial u}{\partial x} \right) \\ + \frac{\partial}{\partial y} \left(A_y \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(A_z \frac{\partial u}{\partial z} \right) \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{\partial v}{\partial t} + \frac{\partial}{\partial x}(uv) + \frac{\partial}{\partial y}(vv) + \frac{\partial}{\partial z}(wv) = \\ f_0 \times u - g \times \frac{\partial \zeta}{\partial y} - \frac{g}{\rho} \int_z^0 \frac{\partial \rho}{\partial y} dz - \frac{1}{\rho} \frac{\partial P_a}{\partial y} + \frac{\partial}{\partial x} \left(A_x \frac{\partial v}{\partial x} \right) \\ + \frac{\partial}{\partial y} \left(A_y \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left(A_z \frac{\partial v}{\partial z} \right) \end{aligned} \quad (2)$$

Flow continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (3)$$

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial}{\partial x} \left(\int_{-H}^{\zeta} u dz \right) + \frac{\partial}{\partial y} \left(\int_{-H}^{\zeta} v dz \right) \quad (4)$$

where u , v and w are the velocity components (cm s^{-1}) in the x , y and z direction respectively; ζ is the sea surface level (cm); A_x , A_y and A_z are the coefficients of eddy viscosity ($\text{cm}^2 \text{s}^{-2}$) in the x , y and z directions respectively; ρ is the seawater density (g cm^{-3}); f_0 is the Coriolis parameter (s^{-1}); and P_a is the atmospheric pressure ($\text{g cm}^{-2} \text{s}^{-1}$).

The general description of the coupled physical and biological model is given in Equation 5, as follows:

$$\begin{aligned} \frac{\partial B}{\partial t} + (\mathbf{v} \times \nabla)B + (w + w_p) \frac{\partial B}{\partial z} = \\ [\nabla \times (K_H \nabla)]B + \frac{\partial}{\partial z} \left(K_z \frac{\partial B}{\partial z} \right) + \left(\frac{dB}{dt} \right)^* + q, \end{aligned} \quad (5)$$

where B is the standing stock or concentration of an arbitrary compartment; $\mathbf{v} = (u, v)$ is the horizontal component of flow velocity; w is the vertical velocity component; w_p is the sinking rate for a particulate organic compartment; $\nabla = (\partial/\partial x, \partial/\partial y)$ is the horizontal gradient operator; K_H and K_z are the horizontal and the vertical components of eddy diffusivity respectively; $(dB/dt)^*$ is the local change in standing stock; and q the fluxes due to external source/sink (e.g. nutrient loading from the land, benthic nutrient release, oxygen consumption).

The main forcing function for Lake Chini was the meteorological condition. As the river discharges into the lake was very small, a constant inflow discharge value of 0.05 m s^{-1} at Gumum River and Merupuk River (Muhammad-Barzani *et al.* 2007), which are main influent tributaries.

ies to Lake Chini, was considered for the modelling effort. A different bottom friction coefficient was used in the model simulation to include vegetation influences on water flows. High roughness coefficients were employed for the dense macrophytes, which were assumed to be located along the littoral region of the small islands within the lake. The bottom friction coefficient was calculated from the roughness coefficient, according to the Manning formula.

The pelagic ecosystem water-quality model employed the three-dimensional EUTROP Model, simulating 11 compartments of carbon and inorganic substances in the water column (Table 1). As a result of limited data availability, the model only employed the kinetics of plant nutrient uptake in the ecosystem. The model assumes material passes between the plants and the pelagic ecosystem.

DISCUSSION AND RECOMMENDATIONS

The bathymetry survey characterized Lake Chini as a very shallow water system, with an average depth of only 1.9 m (Fig. 2). The total surface area of the lake during the dry period is only 1.67 km².

Field observations indicated a spatial variation of water quality between the lakes, consistent with previous water-quality studies (Shuhaimi-Othman *et al.* 2007). The mean DO concentration ranged between 3.1 and 6.5 mg L⁻¹. The DO concentration was lower at the lake bottom, compared with the surface concentration, with mean values of 2.87 and 5.82 mg L⁻¹ respectively. The mean measured chlorophyll-a, total nitrogen and total phosphorus concentration ranges were 0.99–3.29 µg L⁻¹, 8.84–17.18 µM-N and 0.59–1.34 µM-P respectively. The measured chlorophyll-a concentration were low, although the nutrient concentrations indicated a eutrophic condition.

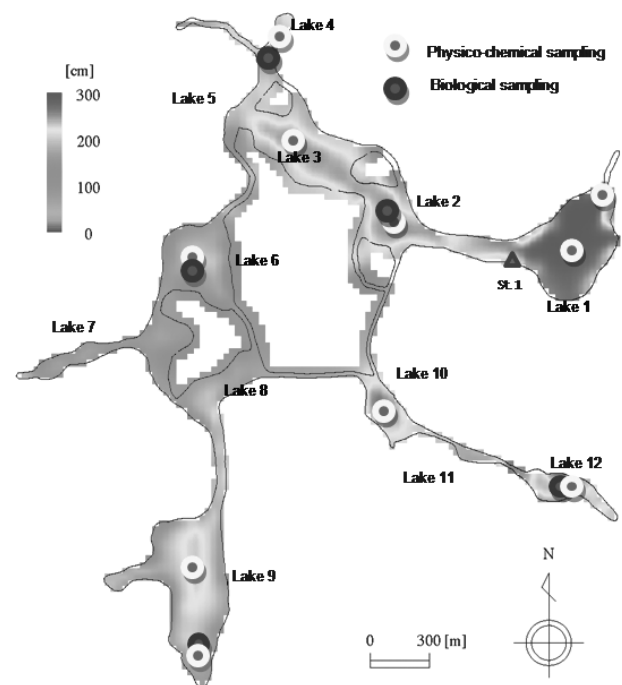


Fig. 2. Bathymetry of computational domain and sampling locations.

Being a wetland, primary production constitutes a vital component of the Lake Chini ecosystem. The low chlorophyll-a concentrations, however, did not appear to be sufficient to support high organic productivity. Primary productivity in the shallow lakes and swamp was influenced largely by macrophytes and algal epiphytes (Ikusima & Furtado 1982; Kroes 1986; Mohamed *et al.* 1994). Field observations indicated widespread dominance and abundant growths of submerged *Cabomba* spp. in many parts of the lakes, which might drive the primary productivity within the system. The presence of

Table 1. State variable and initial condition of pelagic model

Variable	Symbol	Unit	Value	Note
Phytoplankton biomass	P	mgC m ⁻³	60–140	Based on chlorophyll-a observation
Intracellular phosphorus quota of phytoplankton	SQP	–	0.1–0.2	
Intracellular nitrogen quota of phytoplankton	SQN	–	1.1–2.4	
Zooplankton biomass	Z	mgC m ⁻³	6–14	1/10 of phytoplankton
Particulate organic matter	POC	mgC m ⁻³	3000–5000	Based on the site observation
Dissolved organic matter	DOC	mgC m ⁻³	4800–5200	Based on the site observation
Phosphate concentration	PO ₄	µMol L ⁻¹	10–150	Based on the site observation
Ammonium concentration	NH ₄	µMol L ⁻¹	0–50	Based on the site observation
Nitrite concentration	NO ₂	µMol L ⁻¹	3–70	Based on the site observation
Nitrate concentration	NO ₃	µMol L ⁻¹	0–100	Based on the site observation
Dissolved oxygen (DO) concentration	DO	mgO ₂ L ⁻¹	5–8	Based on the site observation

emergent plants, mainly *Pandanus helicopus* and *Lepironia articulata*, along the littoral region might also contribute to the primary production. Further assessment of the biological production of the dominance macrophyte is needed to better understand the influences of aquatic plant species composition and succession to the Lake Chini ecosystem.

The average DOM and POM values were ≈ 5 and 7 mg L^{-1} respectively. This observation implied organic rich water in the lake, and suggested high level of production of the organic matter, a typical characteristic of shallow wetland waters (Wetzel 2001). A high POM concentration might be attributable to the decomposition of submerged and emerged plants, or the mortality of the attached algae.

The hydrodynamic simulations exhibited a close fit between the measured and simulated water temperature profile (Fig. 3). The simulated and observed water levels, however, disagreed. An increase in water level of 20 cm, recorded during 19–20 June, and which is equivalent to a water volume of 0.32 million m^3 stored solely in the lakes, and not covering the containment within the large swamp area, indicated the primary water source was due either to extreme rain events within the lake catchment area or to inflows from the Pahang river. This proposition could not be confirmed, however, because of the lack of

meteorological or rain gauge data from within the Lake Chini catchment, as well as inadequate water level measurements at the confluence of Chini River and Pahang River during the study period.

The simulated results indicated a spatial water-quality variation between the lakes. The simulated distribution of the DO concentration at different depth (Fig. 4) indicated the existence of DO stratification concentrations. Lower DO concentrations, reaching anoxic level at some points in the study, were found in the deeper areas. The low DO concentrations, especially at the lake bottom, suggested a high oxygen consumption, perhaps due to high decomposition activity (Wetzel 2001). The spatial variation of the surface DO concentrations between the lakes ranged from 4 to 6 mg L^{-1} (Fig. 5). A higher DO concentration was observed at Lake 1.

The observed nutrient values suggested that the nutrient concentrations exhibit dramatic spatial and temporal variations, as reflected in the model simulations. The total phosphorus and total nitrogen concentrations between the lakes ranged from 1 to 3 mg C m^{-3} (Fig. 5). Lower phosphorus concentrations were observed in Lakes 11 and 12. Higher total nitrogen concentrations were found in Lakes 6 and 7. The simulation and observed results indicated that the Lake Chini ecosystem

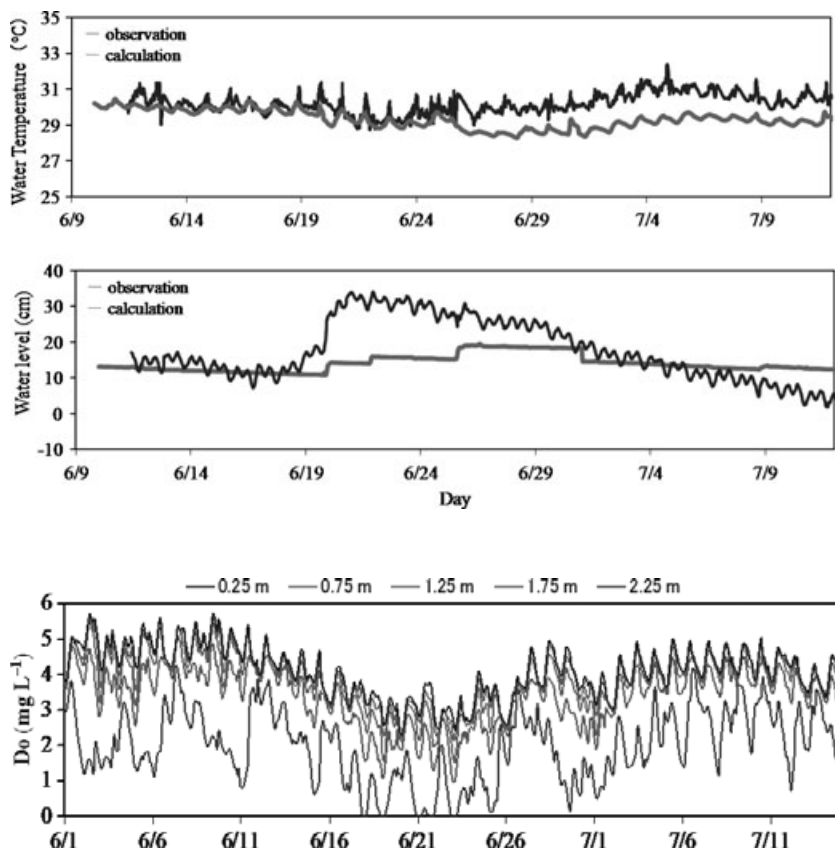


Fig. 3. Observed and simulated water level and water temperature in Lake Chini from June 11 to July 11 2009.

Fig. 4. Simulated variation of dissolved oxygen of start from June 1st to July 11th 2007.

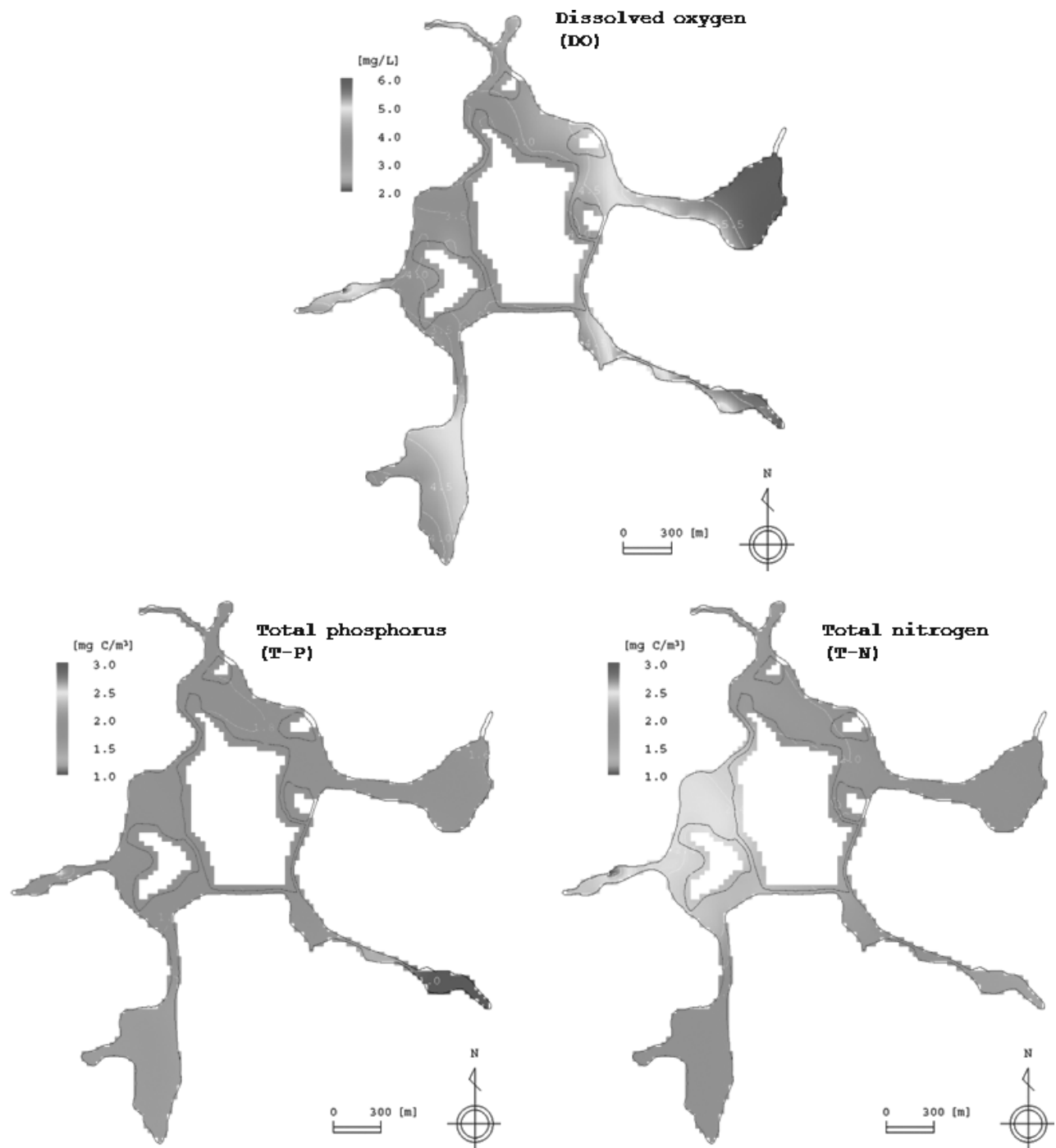


Fig. 5. Simulated distributions of dissolved oxygen, total nitrogen and total phosphorus concentration in mg L^{-1} at the surface on July 6th 2007.

is being enriched. The nutrient enrichment might be attributable to external nutrient inputs from agriculture practices, deforestation and wastewater discharges (Shuhaimi-Othman & Lim 2006; Muhammad-Barzani *et al.* 2007; Shuhaimi-Othman *et al.* 2007), or internal loading from lake sediments. Further model refinement is needed to include the influences of the physiology of

the different types of macrophytes and their spatial distribution within the lakes, in order to consider the interactions between the plants and pelagic ecosystem, and how they affect the nutrient cycle and water quality.

The present model was developed on the basis of dry season conditions. It was able to demonstrate the spread and transfer of DO, nutrient and other biological param-

ter within the lakes. Additional intervening variables, however, including water level fluctuations and hydrological variations within the catchment, must be accounted for in order to include the influences of dynamic ecosystem changes. There is also a need to develop a model for the wet season, to include the effects of the main Pahang River inflows, and how the water inflows drive the system's physical forcing. The expansion of waterbody spreading over the large swamp area contributes to the nutrient and organic carbon cycle between the land and water systems. Further assessment relating the dynamic seasonal boundary changes between the waterbody and the dry land will provide a better understanding on the overall ecological processes and interactions between the wetland and lake water systems.

The lack of available data might limit the development of comprehensive model that could provide a greater understanding of the overall ecosystem, and assist in the design of a scientifically sound, ecosystem-based management approach for Lake Chini. Nevertheless, this study illustrates the need to address the gaps in the critical data needed to develop a more complete model that incorporates the complex structure and dynamics of each ecological unit in this lake ecosystem. The models must be supported by the catchment model to incorporate socioeconomic and development changes within the catchment. As the lake water quantity and quality is strongly influenced by the Pahang River inflows, these factors must be included in the model to provide a complete picture of the sustainable management needs for this lake ecosystem. Development of an institutionalized model that includes the lake stakeholders might be the means for ensuring its applicability as a management tool that allows various lake stakeholders to manage the Lake Chini Basin for sustainable use. Integrated basin management is clearly important for Lake Chini, and any lake management initiative must be further integrated into the Pahang River Basin management structure in order to ensure long-term sustainable management of the lake and its wetland system.

CONCLUSIONS

Lake Chini is one of the most unique freshwater lakes, and an important wetland system to be preserved in Malaysia. This preliminary assessment of Lake Chini indicated degradation of this ecosystem. The water quality varied spatially between the lakes, with considerable nutrient enrichment being evident. Land use changes within the lake's catchment, and human interventions to change the natural hydraulic system, including erection of a weir at the downstream end of the lake, were signifi-

cant factors disrupting the natural hydro-ecosystem over the years. External nutrient input from agriculture areas, settlements, logging activities and illegal mining practices have significantly contributed to eutrophication and water-quality changes in Lake Chini. As the Lake Chini catchment is located within the macro-scale Pahang River Basin, there is a need to further study the direct influences of the Pahang River to the lakes, in order to facilitate sustainable rehabilitation measures for Lake Chini.

Development of a more in-depth ecosystem-based model will provide a necessary tool to assist restoration and sustainable management efforts directed to the lake and its basin. The complex response dynamics of the Lake Chini ecosystem necessitate the need to holistically manage its catchment area and water system. Furthermore, the need for implementation of integrated basin management should also encompass the Pahang River Basin, mainly because of its integrating nature and impacts on the Lake Chini ecosystem. This approach will enhance the IWRM and IRBM initiatives in Malaysia directed to more holistic management of its waterbodies.

ACKNOWLEDGEMENTS

The authors would like to thank Ir. Dr Salmah Zakaria for her role and support in this project, and for her helpful comments on the manuscript. Special thanks are also given to Norsarimah Shahlan and Syaiful Bahren Saadudin for helping in the field sampling work, and to Chuden CTI Ltd, which contributed in this research. This research was supported by the Ministry of Natural Resources and Environment of Malaysia.

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