Lakes of Malaysia: Water quality, eutrophication and management

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Abstract

The present study was undertaken to evaluate and verify the water quality status and trophic state of 15 major lakes and reservoirs in Malaysia. The lake water quality assessments were based on the National Water Quality Index (NWQI), while the trophic state assessments were based on Carlson's Trophic State Index (TSI). The findings of this water quality assessment, based on data collected between September and October 2012, indicated that a majority of the lakes were classified as Class II (Clean) waters suitable for recreational use. The results of the trophic state assessments, however, indicated that all of the lakes were eutrophic, meaning they were nutrient-rich, they could experience algae blooms or macrophyte problems, and they were likely to exhibit poor water quality. Sustainable management measures and strategies are suggested to address the eutrophication problems of Malaysian lakes and reservoirs, with the national responses on lake and reservoir management also being discussed.

Key words

catchment, eutrophication, lake basin management, trophic state, tropical reservoir.

INTRODUCTION

The lakes and reservoirs of Malaysia are important water resources contributing to the socio-economic transformation of the country. Most of these inland water bodies provide important resource-provisioning services, including supplying fresh water, aquaculture and fisheries, hydroelectricity and regulating services, as well as providing natural flood mitigation and unique freshwater habitats and functioning as ecotourism and recreational sites. Pollution from nutrients and sediment that drain into them from their catchments, however, is becoming a serious threat to Malaysian lakes, causing deterioration of water quality to varying degrees. Enrichment of lakes with nutrients is widespread, noting that >60% of the 90 major Malaysian lakes studied in 2005 were eutrophic (Sharip & Yusop 2007; NAHRIM 2009), demanding immediate collaborative action to address this serious national water issue.

Eutrophication is part of an ageing process that eventually affects all inland water bodies, with lakes filling up over a timescale of millennia, and turning into marshlands and ultimately becoming terrestrial lands (Rast & Holland 1988). Human-induced landscape alterations in lake drainage basins, however, contribute significantly to accelerated eutrophication. This occurs particularly when large nutrient loads associated with either non-point sources (e.g. run-off or drainage from agricultural lands) and/or point sources (e.g. discharges of untreated or partially treated sewage) contribute to increased growth of algae or macrophytes (Smith 2003; ILEC 2005). Excessive growth of algae or macrophytes can reduce lake water quality and threaten their functioning and ecosystem services. The ramifications of lake eutrophication are often not recognized, however, until the associated explosion of biological productivity takes place because of such factors as complex lake response dynamics and long water retention times (ILEC 2005). Addressing these impacts usually has a high price, as lake restoration measures are usually hampered by the nonlinearity of lake responses to changes and the significant funding and time typically required for effective rehabilitation (Nakamura 2007).

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In spite of these realities, a comparative study to evaluate and confirm the trophic status of lakes, using actual data, has not yet been carried out in Malaysia. Despite an increasing number of publications on lakes and reservoirs, compared with earlier findings in 2005 (Sharip & Yusop 2007; NAHRIM 2009), most lake studies in Malaysia have been conducted sporadically focusing on individual lakes or reservoirs and were conducted in different institutions for differing purposes (Sharip & Zakaria 2007). Following the preliminary study in 2005 that applied findings from the literature and computation of estimated total phosphorus (TP) concentrations based on dominant land uses (Sharip & Yusop 2007), the objective of the present study is to evaluate and verify the trophic state of selected major lakes and reservoirs in the country on the basis of observed data.

The Carlson's Trophic State Index (TSI; Carlson 1977) and the Malaysian Department of Environment Water Quality Index (DOE-WQI, DOE 2011) have been widely used to assess trophic state and water quality status in Malaysian lakes and reservoirs (Shuhaimi-Othman *et al.* 2007; Akademi Sains Malaysia 2010; Ismail & Najib 2011). Accordingly, the TSI and WQI were used in the present study. The TSI estimates biological productivity on the basis of total phosphorus (TP), Secchi depth transparency and/or chlorophyll-a concentrations, whereas the DOE-WQI evaluates water quality on the basis of pH, dissolved oxygen (DO), total suspended solids (TSS) and ammonia nitrogen (A-N) concentrations, biological oxygen demands (BODs) and chemical oxygen demands (CODs). The present study focused on the assessment of the trophic condition and water quality of Malaysian lakes during a dry season because Carlson's TSI was developed for summer values (Carlson 1977). Despite the seasonal and interannual differences, in terms of environmental conditions and community structure, the dry period was selected to provide an evaluation of the ecological variation of Malaysian lakes and reservoirs during this season, which represents a 'worst-case' scenario for identifying eutrophication control and management needs. It is noted that, prior to this survey, the majority of the studied lakes and reservoirs in Malaysia experienced a water level decrease ranging from 0.5 to 1 m below normal water levels.

MATERIALS AND METHODS

Study area

Of the 56 lakes reported as being eutrophic during the 2005 preliminary study (NAHRIM 2009), a total of 15 of these lakes were included in this assessment. The locations of these water bodies are shown in Figure 1. The selected lakes, either natural or manmade, ranged from small to large (surface areas between 0.02 and 369 km^2) and included both clear and coloured (humic) water systems located in peat swamp areas (Table 1). All lakes were located in the Peninsular or West Malaysia.

Water sampling and analysis

Measurements of water quality were performed during September–October 2012 at two to four sampling sites on each lake. The dissolved oxygen (DO) and chlorophyll-a concentrations, turbidity and pH were measured with a multiparameter probe (YSI 6600). Water samples were collected at 0.5 m below the water surface with a Van Dorn sampler, stored in 1-litre PE bottles and preserved in these containers at 4 °C prior to transportation to laboratory for analysis of biochemical oxygen demand (BOD), chemical oxygen demand (COD) and ammonia nitrogen (A-N). All analyses were based on Standard Methods (APHA 1992). Total suspended solids (TSS) were measured at most sampling sites in accordance with HACH (2003). Water samples were also analysed for total phosphorus (TP), using a modified Kjeldahl digestion method and colorimetric analysis (stannous chloride method), while Secchi depth transparency (m) was measured with a standard Secchi disc. Unless otherwise stated in Table 2, all TP, BOD, COD and A-N analyses were carried out by an external accredited laboratory.

The DOE-WQI was calculated on the basis of the subindex (SI) of six parameters, multiplied by the weighting factors, as illustrated in Equation 1 (DOE 2011):

$$WQI = 0.22(SI\ DO) + 0.19(SI\ BOD) + 0.16(SI\ COD) + 0.15(SI\ AN) + 0.16(SI\ SS) + 0.12(SI\ pH) \quad (1)$$

The WQI was classified according to the DOE National Water Quality Standard (NWQS), which assessed the suitability of the water for recreational and water supply uses (DOE 2011). The trophic state index was calculated in accordance with Carlson (1977), as illustrated in Equations (2), (3) and (4):

$$TSI(TP) = 10\left(6 - \frac{In\,\frac{48}{TP}}{In(2)}\right). \quad (2)$$

$$TSI(chla) = 10\left(6 - \frac{2.04 - 0.68 InChla}{In(2)}\right). \quad (3)$$

$$TSI(SD) = 10\left(6 - \frac{InSD}{In(2)}\right). \quad (4)$$

Table 1. Characteristic of study lakes in Malaysia

No	Lake	Position	Surface area (km^2)	Main river system	Water system	Lake type	Land use	(Data source)
1	Talang	2°47.1′, 102°8.1′	3.7	Pahang River	Clear	Man-made	75% Forested	(NAHRIM 2009)
2	Kelinchi	2°46.4′, 102°6.1′	1.9	Pahang River	Clear	Man-made	75% Forested	(NAHRIM 2009)
3	Sg Terip	2°45.5′, 102°0.8′	2.25	Linggi River	Clear	Man-made	90% Forested	(NAHRIM 2009)
4	Bukit Merah	5°1.4′, 100°40.0′	41	Kurau River	Clear	Man-made	46% forested	Akademi Sains Malaysia 2010;
5	Chenderoh	4°57.8′, 100°57.4′	25	Perak River	Clear	Man-made	33% Agriculture	Azwin 2013, unpublished data
6	Raban†	5°0.1′, 100°56.6′	0.375	Perak River	Clear	Man-made	33% Agriculture	Azwin 2013 unpublished data
7	Chini	3°25.9′, 102°54.9′	2	Pahang River	Coloured	Natural	50% Agriculture	(NAHRIM 2009)
8	Sembrong	1°58.7′, 103°11.2′	8.5	Batu Pahat River	Clear	Man-made	84% Agriculture	(NAHRIM 2012)
9	Kenyir	4°59.7′, 102°47.4′	369	Terengganu River	Clear	Man-made	99% Forested	(Akademi Sains Malaysia 2010)
10	Bera	3°7.8′, 102°36.4′	6	Pahang River	Coloured	Natural	50% Agriculture	(NAHRIM 2009)
11	Ulu Lepar	3°42.5′, 102°56.2′	4.69	Pahang River	Mix	Natural	Mixed	(NAHRIM 2009)
12	Durian Tunggal	2°21.1′, 102°18.9′	3.5	Melaka River	Clear	Man-made	75% Agriculture	(NAHRIM 2009)
13	Ayer Keroh	2°16.5′, 102°18.1′	0.5	Melaka River	Clear	Man-made	Mixed	(NAHRIM 2009)
14	Aman	3°6.2′, 101°37.5′	0.0224	Kelang River	Clear	Man-made	Mixed	(NAHRIM 2009)
15	Layang	1°33.4′, 103°54.0′	6.6	Johor River	Clear	Man-made	50% Agriculture	(NAHRIM 2009)

†Lake Raban is considered part of Chenderoh Reservoir in the present study as it forms a subcatchment of the reservoir system.

Data analysis

Pearson's correlation was used to analyse the relationships between environmental variables. Linear regression was employed to assess the relationships between Secchi depth, TP and chlorophyll-a concentrations with the percentage area developed in the catchments. This area was derived from land-use data in the literature (NAHRIM 2009, 2012; Akademi Sains Malaysia 2010). Environmental variables were log-transformed where necessary to improve normality.

RESULTS

Water quality status

The WQI in the studied lakes was in the range of 62–90, being within Class II–III of the NWQS. The respective subindices for DO ranged between Class II and III, pH was in Class II, BOD ranged between Class II and V, COD ranged between Class II and III, and A-N ranged between Class II and IV. The mean DO concentrations were between 5.03 and 11.07 mg L^{-1} (Table 2). Lake Bera exhibited the lowest mean DO, indicative of Class III of NWQS. This low DO value, however, was much higher than those (1.36–4.0 mg L^{-1}) previously reported in the literature (Furtado & Mori 1982), likely being associated with coloured or peaty water containing high concentrations of organic tannins. High DO concentrations (exceeding 8 mg L^{-1}) were reported for Sembrong and the Upper Layang reservoirs, as well as in Aman and Ayer Keroh lakes. High DO concentrations, such as in Sembrong Reservoir, were consistent with the values reported in the literature (Singh *et al.* 2013). The DO values were strongly correlated with chlorophyll-a ($r = 0.390$, $P < 0.001$), pH ($r = 0.748$, $P < 0.001$), temperature ($r = 0.414$, $P < 0.001$) and COD ($r = 0.283$, $P < 0.05$) (Table 3). The increased DO values in the four lakes noted above could be attributable to the release of oxygen from photosynthetic activities by the excessive algal communities in those lakes. Light greenish-coloured waters were observed in all four lakes, being consistent with high chlorophyll-a values and indicating an abundance of algae. Photosynthetic activities by such massive algae communities consume and remove carbon dioxide (CO_2) to produce oxygen, which also increases the levels of hydroxide in the water, subsequently increasing the pH values (King 1970).

Most lakes exhibited high BOD and A-N concentrations exceeding the Class II specification of NWQS. With

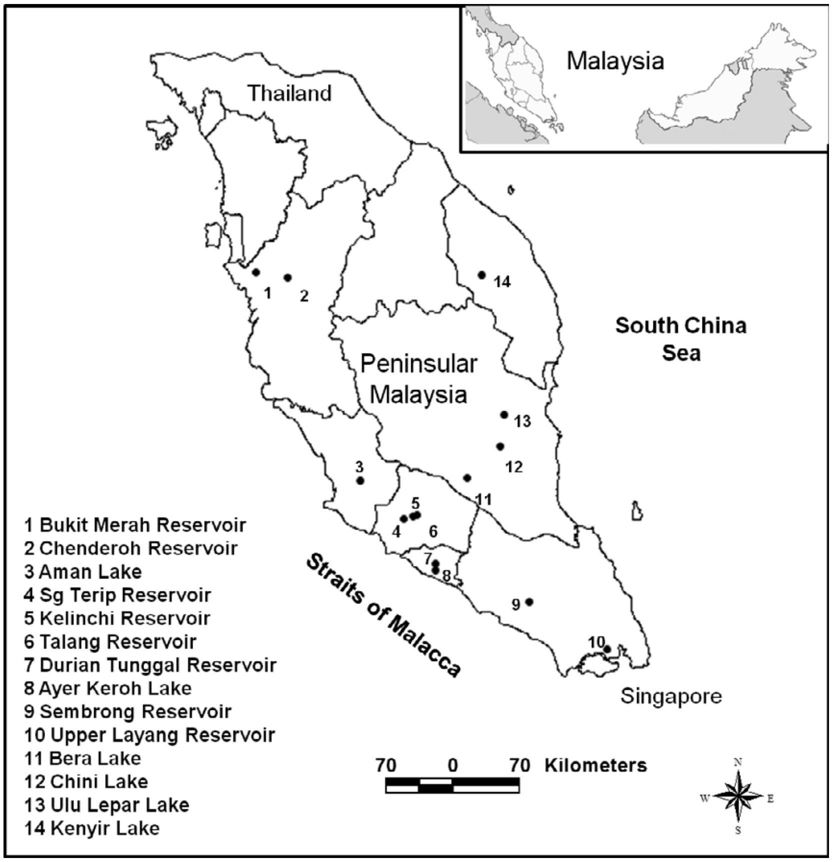

Fig. 1. Location of study lakes in Malaysia.

the exception of Bera and Ulu Lepar lakes, and Chenderoh Reservoir, all the lakes exhibited high BODs exceeding Class II. All lakes had mean COD values below Class II, except for Sembrong Reservoir, which had a mean COD of 33.1 mg L^{-1}. Many lakes also experienced high A-N concentrations, with values reaching Class IV for Sembrong and Chenderoh-Raban reservoirs. High A-N and organic loadings to Malaysian rivers have been attributed to the discharge of untreated or inadequately treated domestic sewage and poultry farms and from agro-based industries and manufacturing industries to surface waters (Abdullah 1995; Hanum *et al.* 2009; DOE 2011). Bukit Merah and Sembrong reservoirs, and Ulu Lepar Lake, exhibited high TSS concentrations, which could be attributed to erosion from land clearance activities in the upstream river basins. Qualitative observations during the sampling at Bukit Merah Reservoir indicated that increased turbidity levels were linked to high TSS loads from sand-mining activities.

Trophic condition

Secchi disc depth is a measure of water clarity, with lower readings indicating turbid water associated with either suspended particles or phytoplankton biomass. Correlation analysis showed that Secchi depth had a negative relationship with turbidity ($r = -0.745$, $P < 0.001$), chlorophyll-a ($r = -0.482$, $P < 0.001$), TSS ($r = -0.693$, $P < 0.001$) and conductivity ($r = -0.414$, $P < 0.001$). Mean TP and chlorophyll-a concentrations were in the range of 0.26–3.4 mg L^{-1} and 2.8–20.9 μg L^{-1}, respectively (Table 4). The TP concentrations in all lakes were generally high, exceeding 0.1 mg L^{-1} (i.e. hypereutrophic). High TP concentrations exceeding 0.05 mg L^{-1} can stimulate algae or macrophyte bloom (Carlson & Simpson 1996). Mean TP concentrations were positively correlated with TSS ($r = 0.297$, $P < 0.05$) and negatively correlated with temperature ($r = -0.406$, $P < 0.001$) and Secchi depth ($r = 0.275$, $P < 0.05$). Both measured and computed TSI (TP) values indicated that the lakes were eutrophic. The measured TSI (TP) in most lakes had increased by >25% of the TSI (TP) computed from the land-use data. Chlorophyll-a concentrations in Bukit Merah, Sembrong and Upper Layang reservoirs, as well as in Ayer Keroh and Aman lakes, exceeded 10 mg L^{-1}, indicating eutrophic conditions. Linear regression indicated that chlorophyll-a concentrations increased with an

Table 2. Malaysian lake water quality status, September–October 2012

Lake	Mean temperature (°C)	Mean DO (mg L^{-1})	Mean BOD (mg L^{-1})	Mean COD (mg L^{-1})	Mean NH_3-N (mg L^{-1})	Mean TSS (mg L^{-1})	Mean pH	WQI	Condition	Class (INQWS)
Sg Terip	29.85	6.91	NA	NA	NA	9.0	7.02	NA	—	—
Kelinchi†	29.67	6.3	NA	NA	NA	28.0	6.71	NA	—	—
Talang	29.71	7.3	NA	NA	NA	13.5	7.68	NA	—	—
Bukit Merah	29.29	6.73	*6.18*	17.45	*0.31*	*50.5*	6.32	82	*Clean*	II
Chenderoh	29.84	6.82	*2.26*	6.16	*1.01*	22.2	7.09	88	*Clean*	II
Chini	30.99	6.64	*6.25*	6.83*	0.20*	14.25*	6.06	87	*Clean*	II
Sembrong	30.48	8.18	*11.9*	*33.07*	*1.91*	*54.33*	8.20	62	*Slightly polluted*	III
Kenyir	29.23	6.93	*3.04*	9.33	*0.47*	9.75	6.74	88	*Clean*	II
Bera	29.83	*5.03*	2.63	6.85	*0.43*	17	6.05	82	*Clean*	II
Ulu Lepar	32.26	6.49	*3.0*	9.85	*0.56*	*51.5*	6.69	83	*Clean*	II
Durian Tunggal	31.32	7.39	*3.64*	13.38	0.23	11.2	7.22	90	*Clean*	II
Ayer Keroh	32.27	11.1	*5.67*	16.07	*0.47*	38	7.45	85	*Clean*	II
Aman	31.04	11.07	*6.40**	19.5*	*0.31**	46	9.04	78	*Clean*	II
Layang	30.01	8.51	*4.88*	12.78	*0.77*	12.8	6.84	85	*Clean*	II

*Analyses performed at NAHRIM Water Quality Laboratory. †Based on one sample; data in *italic* in category Class III of water quality index; data in *italic* and underlined in Class IV; data in *italic*, bold and underlined in Class V. BOD, biochemical oxygen demand; COD, chemical oxygen demand; DO, dissolved oxygen concentration; NA, not available; NH_3-N, ammonia nitrogen; TSS, total suspended solids concentration; WQI, water quality index.

increasing percentage of developed area in the catchment (Chl-a = $0.155x + 1.716$, $R^2 = 0.603$, $P < 0.01$), while Secchi depths decreased with the increasing percentage of developed area in the catchment (SD = $-0.024x + 2.6196$, $R^2 = 0.561$, $P < 0.01$) (Fig. 2). The TP concentrations did not significantly increase with the increasing percentage of land development.

DISCUSSION

Comparison of water quality and trophic conditions

Water quality generally refers to the quality of water required for different categories of use, such as water supply, recreation and irrigation. The DOE-WQI classification used in the present study was developed for flowing (lotic) waters such as rivers and streams. They did not, however, take into consideration lentic water characteristics such as long water retention time and complex response dynamics. Based on this classification, all the studied lakes, except for Sembrong Reservoir, met the Class II requirements with no adverse water quality problems. This classification, however, did not consider water residence time and algal growth-limiting nutrients, especially total phosphorus (TP), which can induce eutrophication. Thus, the classification may not be applicable to still or non-flowing (lentic) waters, such as in lakes and reservoirs.

The present study produced divergent TSI values on the basis of Secchi depth, and TP and chlorophyll-a concentrations. Most lakes in the present study were reservoirs, exhibiting high TP concentrations, and the TP–chlorophyll-a relationship may deviate from the nutrient loading response that was developed for temperate lakes, such as Carlson's TSI (Carlson 1977). Reservoirs are recognized to be more coloured, attributable to non-algal turbidity, subsequently affecting light penetration into the water column for promoting algal growth (Thornton & Rast 1993). Furthermore, the shorter water residence time in some reservoirs leads to faster flushing of dissolved nutrients and algae (Thornton & Rast 1993). For hypereutrophic lakes, the deviant relationship between TSI (TP) and TSI (chlorophyll-a) also has been recognized in semi-arid and Florida water bodies, likely being a result of other factors such as light and total nitrogen (TN) that limit algal growth (Canfield 1983; Thornton & Rast 1993).

The percentage difference in the present study of the TSI values for phosphorus, calculated from the measured data and that computed from land use, ranges between 19% and 49%. The underestimates of TSI (TP) can likely be attributed to the use of general land use and TP

Table 3. Correlation coefficient (*r*) between environmental variables and their level of significance

	DO	SD†	Cond†	Turbidity†	T	pH	Chl†	SS†	COD†	AN†	TP†	BOD†
SD†	−0.182	1	—	—	—	—	—	—	—	—	—	—
	0.118	—	—	—	—	—	—	—	—	—	—	—
Cond†	0.172	−0.414**	1	—	—	—	—	—	—	—	—	—
	0.140	0.000	—	—	—	—	—	—	—	—	—	—
Turbi-	0.075	−0.745**	0.321*	1	—	—	—	—	—	—	—	—
dity†	0.521	0.000	0.005	—	—	—	—	—	—	—	—	—
T	0.414**	−0.144	−0.020	−0.117	1	—	—	—	—	—	—	—
	0.000	0.217	0.864	0.317	—	—	—	—	—	—	—	—
pH	0.748**	−0.071	0.433**	0.053	0.237*	1	—	—	—	—	—	—
	0.000	0.543	0.000	0.650	0.040	—	—	—	—	—	—	—
Chl†	0.390**	−0.482**	0.321**	0.189	0.187	0.226	1	—	—	—	—	—
	0.001	0.000	0.005	0.105	0.107	0.051	—	—	—	—	—	—
SS†	0.358**	−0.693**	0.422**	0.736**	0.032	0.361**	0.327**	1	—	—	—	—
	0.002	0.000	0.000	0.000	0.788	0.001	0.004	—	—	—	—	—
COD†	0.283*	−0.245*	0.438**	0.175	0.018	0.204	0.542**	0.310**	1	—	—	—
	0.017	0.039	0.000	0.144	0.881	0.088	0.000	0.009	—	—	—	—
AN†	0.170	−0.192	0.372**	0.221	−0.003	0.229	0.227	0.418**	0.400**	1	—	—
	0.156	0.109	0.001	0.065	0.981	0.055	0.057	0.000	0.001	—	—	—
TP†	−0.173	−0.275*	0.138	0.197	−0.406**	−0.190	−0.155	0.297*	0.008	0.178	1	—
	0.150	0.020	0.253	0.099	0.000	0.113	0.196	0.012	0.947	0.138	—	—
BOD†	0.119	−0.128	−0.070	−0.020	−0.011	0.170	0.125	0.046	0.071	−0.167	−0.025	1
	0.324	0.289	0.559	0.867	0.926	10.156	0.298	0.702	0.555	0.165	0.835	—

Grey boxes indicate level of significance: *correlation is significant at 0.05 level (2-tailed); **correlation is significant at 0.01 level (2-tailed); †variables were natural log-transformed. A-N, ammonia nitrogen; BOD, biochemical oxygen demand; Chl, chlorophyll concentration; COD, chemical oxygen demand; Cond, electrical conductivity; DO, dissolved oxygen concentration; SD, Secchi depth transparency; SS, suspended solids concentration; T, temperature; TP, total phosphorus concentration.

relationships (Omernik 1977), which was a simplified approach and based on USA watershed data. The TP concentrations in the present study did not exhibit a linear relationship with an increasing percentage of development. This is likely attributable to differing TP loadings associated with Malaysian land uses. Linear regression of TP concentration and the increasing percentage of development was improved ($R^2 > 0.3$) when natural and urban lakes were omitted from the analysis.

All the lakes in the present study can be categorized as hypereutrophic, based on TSI (TP) concentrations, despite most of them having water quality of Class II, which is suitable for recreational purposes and water supply with conventional treatment. Qualitative observations indicated that some of these lakes displayed negative symptoms of eutrophication. Examples were excessive algal growth in Aman and Ayer Keroh lakes, widespread macrophyte growth in Chini Lake and serious algal and macrophyte blooms in Sembrong Reservoir. According to Thornton and Rast (1993), however, the use of Carlson's trophic state in lakes beyond the temperate climate must be performed with caution. In semi-arid zone reservoirs, where eutrophication is a common occurrence, analysis of a larger dataset enables the determination of a different threshold of values to be incorporated into water quality criteria for managing lakes (Thornton & Rast 1993). For warm water tropical lakes, which describe those in Malaysia, higher mean temperatures and stronger solar irradiance, especially during the dry season, contribute to stronger chemical stratification (Lewis 1987). The lack of water flow can aggravate eutrophication conditions. Accordingly, critical threshold values for SD, TP and chlorophyll-a must be determined for such lakes, using actual data, with the results being adopted in lake management efforts.

The present study suggests that a water quality classification for lake ecosystems that considers different water body conditions and uses must be developed for Malaysia. Both TP and total nitrogen (TN) must be included in the parameters considered for such systems in determining

Table 4. Mean values of trophic status indicator (TSI) parameters and status in September–October 2012

Lake	Secchi depth, SD (m)	TSI (SD)	Chlorophyll-a, Chl-a (μg L^{-1})	TSI (Chl-a)	Total phosphorus, TP (mg L^{-1})	TSI (TP)	TSI (TP) predicted from land use†
Sg Terip	2.7	45.4	2.8	40.8	0.38	89.8	45.8
Kelinchi	–	–	2.0	37.4	2.09	87.4	50.0
Talang	1.6	52.8	4.8	45.1	0.66	97.6	50.0
Bukit Merah	0.6	77.4	16.1	56.6	0.81	104.1	60.3
Chenderoh	0.7	64.4	3.1	41.7	3.43	101.4	75.4
Raban	1.6	66.4	4.8	48.0	0.70	100.2	75.4
Chini	0.8	65.3	8.7	51.8	0.46	91.9	68.2
Sembrong	0.3	79.4	16.8	58.3	1.39	104.9	68.2
Kenyir	3.8	41.6	3.6	42.7	0.30	86.4	60.3
Bera	1.4	54.3	7.9	52.0	0.45	90.5	68.2
Ulu Lepar	0.3	77.7	5.4	46.8	0.54	94.5	60.3
Durian Tunggal	1.2	50.1	5.4	47.0	0.38	92.8	75.4
Ayer Keroh	0.5	70.9	17.3	57.2	0.26	82.6	60.3
Aman	0.2	77.4	20.9	61.8	NA	NA	69.4
Layang	1.2	58.0	15.6	57.2	1.45	109.3	68.2

Underlined data indicate value in eutrophic range, based on Carlson (1977) TSI criteria; †from NAHRIM 2005.

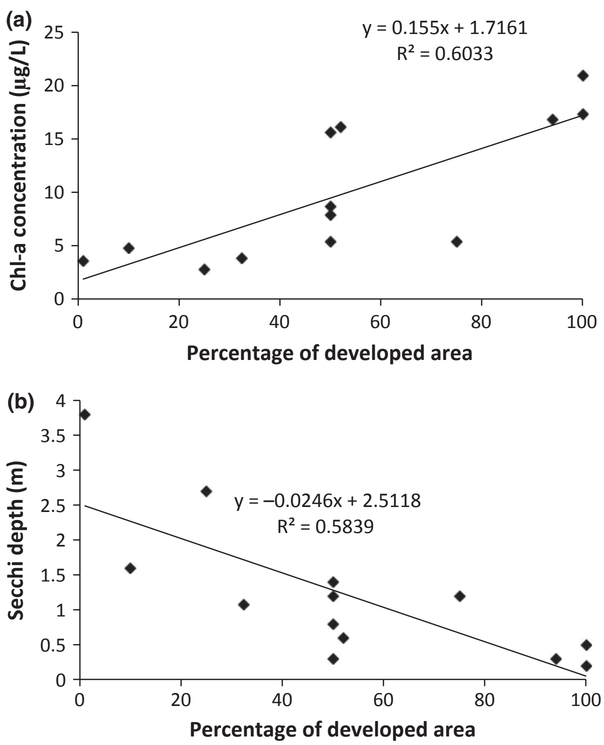

Fig. 2. Relationship between (a) mean chlorophyll-a concentration and (b) Secchi depth, with percentage of developed area in the catchment.

the NWQS. In many countries, including Japan, Australia and New Zealand, different water quality criteria and standards have been developed for and applied to lakes, rivers, groundwater and coastal waters. Stringent criteria for identifying the algal biomass-limiting nutrient concentrations (mainly TP and TN, which are a proxy of phytoplankton biomass in nutrient-rich environments) also have been imposed for lakes (ANZECC/ARMCANZ 2000; Okada & Peterson 2000). Putrajaya Lake is currently the only lentic water body in Malaysia for which an ambient lake water quality standard other than the Class II of NWQS has been developed and enforced. The Putrajaya Lake water quality standard (Perbadanan Putrajaya 1998) regulates chlorophyll-a, TP, oil and grease concentrations and transparency, in addition to enforcing stringent limits for chemical and microbial parameters such as faecal coliform, nitrate, cadmium and mercury.

The sources of water quality degradation in lakes have often been linked to agricultural and urban land-use practices (Carpenter *et al.* 1998; Foley *et al.* 2005). Widespread land clearance and agricultural activities increase erosion in lake catchments, with the transport of eroded materials containing nutrients and sediment into streams and lakes (Foley *et al.* 2005). Nakasone and Kuroda (1999) found the water quality in irrigation reservoirs in Japan to reflect the water quality of the run-off from their watersheds, with high nutrient concentrations in the water being attributed to fertilizer applications on agricultural lands. Land-use alterations resulting from unplanned development activities within their catchments were a major problem faced by Malaysian lakes, including Chini Lake and Bukit Merah and Sembrong reservoirs

(Akademi Sains Malaysia 2010; NAHRIM 2012). Land-use alterations, being mostly forested areas converted to agricultural lands and mixed development, are likely to contribute to increased run-off of nutrient-rich sediment to many of the studied lakes. In fact, the present study highlighted a strong association of catchment alteration to increased biological productivity and reduced water transparency.

Approach and measures for managing eutrophication of lakes and reservoirs

The results of the present study support the initial findings obtained in 2005 for Malaysia, as well as the need to address eutrophication problems throughout the country. Management strategies and programmes to regulate nutrient inputs at the source have been suggested worldwide for eutrophication control (Rast & Holland 1988). These include introducing nutrient control measures and policies for controlling external nutrient loads, specifically total phosphorus (TP) (Gulati & Donk 2002), which have been regulated in the USA and European countries (Lewis *et al.* 2011). Gradual TP reduction through diversion of effluent discharges from lakes resulted in successful eutrophication control in Lake Washington (Edmondson & Lehman 1981). In many other lakes, however, reducing nutrient loads alone has failed to resolve eutrophication problems (Carpenter *et al.* 1999). These lakes may have reached a hysteresis or irreversible state, likely resulting from extended periods of excessive TP loading, such that reducing their TP load alone is no longer sufficient to reverse their advanced eutrophication status (Carpenter *et al.* 1999). Further in-lake treatment techniques may be needed to alleviate water quality problems in such highly degraded lakes (Holdren *et al.* 2001), including such methods as aeration and dredging (Cooke *et al.* 2005). These techniques, however, only address eutrophication symptoms and provide only short-term remedies, meaning they also must be supported by long-term rehabilitation mechanisms to be effective (Holdren *et al.* 2001).

As lakes generally act as sinks for pollutants flowing into them from their surrounding catchments, managing their watersheds is a key driver for successfully controlling lake eutrophication (Holdren *et al.* 2001; Nakamura 2007; Sharip & Jusoh 2010). Strategies involving sustainable watershed and land-use management practices can improve water quality and reduce eutrophication, while also maintaining socio-economic expansion (Holdren *et al.* 2001; Foley *et al.* 2005). Such strategies include application of conservation tillage and terraces to reduce erosion and the placement of controlled ecosystems (e.g. retention ponds, constructed wetlands, buffer strips and riparian vegetation) to intercept surface run-off and filter sediment-bound nutrients (Carpenter *et al.* 1998; Holdren *et al.* 2001; Foley *et al.* 2005), especially in agriculture and open areas within the catchment, thereby protecting against their drainage into lakes and other water bodies. Strategies that include development of catchment management and development plans have successfully enabled Putrajaya Lake to remain in the highest lake water quality class (Class I–II), suitable for recreational uses, and maintaining a mesotrophic condition with a TP concentration below 0.05 mg L^{-1} (Perbadanan Putrajaya 2000; Salamat 2003; Majizat *et al.* 2010). By establishing management objectives and targets for specific lakes, such catchment plans can provide effective direction to guide managers to develop land uses that incorporate appropriate drainage and sewerage master plans and proper control measures to control nutrients and sediment loads.

National response on lake and reservoir management

The national response for addressing the critical issue of lake eutrophication in Malaysia included the endorsement of a national strategic plan for lake management by the National Water Resources Council on 1 November 2012. The strategic plan, developed through various multistakeholder consultations, was published in 2009 (Abdullah 2009), containing eight strategies, as summarized in Table 5. Addressing six thematic issues associated with lake management, namely governance, management, research, capacity building, information management and community stakeholder participation, this strategic plan established the direction for respective stakeholders to collaborate in managing lakes and reservoirs in a sustainable manner (Akademi Sains Malaysia & NAHRIM 2009).

The endorsement generally supported the National Water Resources Policy, which was previously approved on 29 March 2012, and embraced the integrated lake basin management (ILBM) approach as a management instrument to develop and manage inland water bodies for sustainable use. The strategies focused on empowering the Ministry of Natural Resources and Environment (NRE) as the lead ministry and the Drainage and Irrigation Department of Malaysia as a principal implementing agency to oversee and coordinate implementation of ILBM and resolve eutrophication problems (Akademi Sains Malaysia & NAHRIM 2009). This endorsement also appointed the National Hydraulic Research Institute of Malaysia (NAHRIM) as the national focal point for lake resources research, with the task, among others, of

Table 5. National strategy for sustainable management of lakes and reservoir (modified from Akademi Sains Malaysia and NAHRIM 2009)

Strategy number	Strategy	Action
Strategy I	Ministry of Natural Resources and Environment as Lead Ministry and DID as implementing Agency on integrated lake and reservoir management	National
Strategy II	NAHRIM as a National Lake Research Centre under NRE	National
Strategy III	Establish a Steering Committee on Lakes	National
Strategy IV	Establish Lake Management Committee at State Level	State
Strategy V	Development of a Detailed Action Plan	National
Strategy VI	Support the role of local communities in Lake Management	National and State
Strategy VII	Strengthen existing legal framework on lake management through appropriate legislation	National and State
Strategy VIII	Enhance networking and strengthen international strategic alliances	National

developing an outline for continued multidisciplinary research and development (R&D) on lakes, including the design and execution of a study on the sustainable development and management of lake resources (Akademi Sains Malaysia & NAHRIM 2009). In addition to becoming the centre of reference for technology development through lake research, this centre of excellence also becomes a central database for Malaysian lake information.

The main pillar for successful implementation of ILBM is effective governance, including institutional arrangements. Institutions, whether governmental or non-governmental, are important components in any lake basin management strategy, as they play a central role in developing and implementing action plans to address lake basin issues and challenges (ILEC 2005; RSCE – Shiga University & ILEC 2011). Although traditional or non-governmental institutions have become drivers for successful ILBM implementation in many lakes, including lake Biwa in Japan and lake Chilika in India (ILEC 2005; Pattnaik 2007; RSCE – Shiga University & ILEC 2011), central governmental organizations are important drivers in many other lakes in countries that are of federal origin, such as Malaysia. The absence of a central management authority was identified as a major issue for ILBM implementation in many lakes in the country (Akademi Sains Malaysia 2010; NAHRIM 2012). The fragmented approach to management of water bodies, including lakes and their surrounding catchments, arises from the responsibilities that were undertaken by multiple, and often non-coordinated, authorities (Sharip & Zakaria 2007). This factor contributed to their limited ability to regulate continuing alteration of the catchment landscape, in addition to deterioration of the lake environment and its resources (Sharip & Jusoh 2010). Establishment of a dedicated lake management committee at the federal and state levels was one of the important strategies aimed at improving lake basin governance mechanisms and strengthening institutional pillars for ensuring successful implementation of ILBM at the national and state levels. The proposed lake standing committee at the federal level has become a platform for interministry and interagency dialogues for the overall framework, coordinating policies, finance and implementation of ILBM in lakes all over the country, particularly for trans-jurisdictional lake systems (Akademi Sains Malaysia & NAHRIM 2009). The proposed state lake committees will govern ILBM implementation for lakes within their state jurisdictions, including ensuring that all lakes and reservoirs and their basins are gazetted as protected zones and established as environmentally sensitive areas (Akademi Sains Malaysia & NAHRIM 2009).

The development of a detailed action plan is an important strategy for addressing the eutrophication of lakes. To be developed on the basis of the preliminary findings in the strategic plan (Akademi Sains Malaysia & NAHRIM 2009), it should include development of a comprehensive catchment management and development plan that (i) establishes the overall management objective and the targeted water quality standard and TSI value (depending on the uses of the lake, such as water supply, recreation, irrigation, flood mitigation or some combination thereof); (ii) develops operational and management programmes to implement works identified and establishes a monitoring and maintenance plan and research and development (R&D) programme; and (iii) includes recommendations for governance and the establishment of a management committee by stakeholders, as well as provision for adequate human and financial resources. The action plan should also contain a detailed assessment, based on the current health and condition of each lake. Preliminary information to support this planning programme has been gathered since 2009, with a total of 26 lake briefs prepared to date by respective lake managers, following the guidelines proposed by the International Lake Environment Committee (ILEC) (Nakamura & Rast 2012). The lake briefs provide information to facilitate implementation of ILBM, which combines the assessment of the environmental state of the lakes with the management and governance issues and challenges. The lake briefs enable identification of governance issues related to different lakes that cut across state and national levels and contribute inputs for the national road map for improved implementation of ILBM to ensure the health of inland water resources in Malaysia. Furthermore, preparation of the lake briefs encourages lake managers to recognize the importance of water quality assessments, enabling them to improve their management approaches by developing resources sustainably, engaging stakeholders to overcome lake issues and challenges, and ultimately leading to ecosystem improvements.

In acknowledging the importance of the regulatory framework in the success of sustainable lake management, strengthening legislation is recognized as one of the most important strategies to be adopted. Such regulations as the Environmental Monitoring Act and Clean Water Act adopted in Japan and the Philippines have contributed to the successful regulation of environmental degradation in Biwa Lake in Japan and Laguna Lake in the Philippines, respectively (ILEC 2005; RSCE – Shiga University & ILEC 2011). This existing legislation has been used to protect water resources by imposing actions against any unsustainable practices that degrade the environment. Similarly, in the State of Selangor in Malaysia, the Selangor Water Enactment was introduced in 1999 to protect the catchment of lakes by gazetting the areas as protected water zones throughout the State (Selangor Waters Management Authority 1999). Introduction of the Federal Territory of Putrajaya Licensing and Registration of Activities on the Lake Regulations 2004, and the Control of Activities on the Lake By-Laws 2004, have provided the legislative instruments for the Putrajaya Corporation, which is the regulatory and development authority to effectively control and manage activities in Putrajaya Lake and its wetlands, to protect their water quality and ecosystem health (Majizat *et al.* 2009).

Local communities also have important roles in sustaining lake and reservoir management efforts (ILEC 2005). Successful management of some lakes in the West and other Asian countries stems from strong public awareness and a willingness to protect and enhance lake surroundings. Individuals and lake associations also have contributed to water quality monitoring of lakes in Wisconsin, USA (Thornton 2013), and to the restoration and integrated management of Chilika Lake, India (Pattnaik 2007). Engaging local communities in lake management has enabled not only the sharing of traditional knowledge about the lakes (ILEC 2005), but also their participation in efforts to rehabilitate and better manage the ecosystems. The establishment of aboriginal community groups (e.g. the Association for the Protection of Chini Lake, locally known as Persatuan Pelindung Tasik Chini) has helped increase awareness among local communities, as well as their participation in the conservation of Chini Lake. Lake communities have a strong attachment to the lakes around which they live. Indeed, the concept of 'attachment to place' is widely accepted in social science as having a significant influence on stakeholder behaviour for achieving positive stakeholder perceptions of the sustainable use and value of lake environments. Promoting and engaging the public in restoring and protecting lake catchments also will help sustain lake ecosystem health.

Finally, increasing and strengthening strategic alliances with international agencies will facilitate the sharing of experiences among lake managers and administrators in different countries. Such relationships will inculcate improved management approaches under changing environmental and climate conditions. In addressing the ILBM governance pillars, it is hoped that the strategies adopted and developed will provide an effective and sustainable long-term governance framework for controlling the eutrophication of lakes in Malaysia.

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