Water quality simulation for rehabilitation of a eutrophic lake in Selangor, Malaysia

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Abstract. More than 50 % of lakes worldwide, including 60 % in Malaysia, are contaminated by eutrophication due to excessive nutrient inputs. These nutrients include phosphorus and nitrogen derived from agriculture, industry and domestic wastes. Eutrophication is an undesirable lake condition characterized by turbid water and dominated by abundant growth of algae, resulting in suppressed macrophytes and in reduced ecosystem services. Healthy lakes provide ecosystem services that have been valued to be worth billions to the Malaysian Gross Domestic Production annually. Rehabilitation of eutrophic lakes located in urban areas is therefore urgently needed. A recreational lake located in Selangor Malaysia has shown persistent signs of eutrophication with chlorophyll-a level fluctuating between 10 and 25 µg/L. Left untreated, the lake water quality will deteriorate further, potentially inducing a regime shift to hyper-eutrophic condition, caused by intense interaction between water column phosphorus and sediment phosphorus. Based upon water and sediment quality data compiled over the last eight years, this paper presents analysis and model simulations for implementation of a sustainable program for controlling eutrophication using low cost technology.

1. Introduction

Eutrophication is a common feature in shallow tropical lakes surrounded by large human settlements. Eutrophic lakes are characterized by turbid water with an abundance of floating algae, induced by excessive nutrients such as phosphorus (P) and nitrogen (N) that enter the lakes from the surrounding settlements. A typical example is the Sunway Lagoon (SL) lake located in the state of Selangor, Malaysia. With an area of 5 acres, the SL is relatively small compared to the surrounding catchment of 700 acres. Situated below mean sea level and without any natural outflow, SL is vulnerable to accumulation of nutrients and other pollutants flowing into the lake from the surrounding human settlements. After some 20 years in existence, the accumulation of nutrients in SL, particularly P and N, in the sediments is significant. The accumulated nutrients in the sediments are constantly released back into the water column to stimulate algae growth. Consequently, SL water quality has gradually deteriorated to the grade of Malaysia Class IIIB, based upon the sample survey conducted on 24 to 25 June 2010. This deterioration of lake water quality is, however, common as virtually all tropical shallow lakes located within large human settlements will eventually become eutrophic. This unintentional “cultural” eutrophication in shallow tropical lakes is caused by accumulation of nutrients P and N in the
It is important to minimize the accumulation of nutrients P and N in the sediment layers. This can best be achieved by flushing out water near the sediment layer, where the nutrients concentrations are much higher than those near the water surface. Reducing nutrients near the sediment will reduce the release of nutrients from the sediments back into the water column. High accumulation of nutrients in the sediments can induce high nonlinear interaction between sediments and water column, which can be facilitated via a low DO and a high pH environment. This undesirable water environment can be created by cyanobacteria activity that could promote the occurrence of highly undesirable and potentially irreversible hyper-eutrophic condition in SL in the future. Nutrients and heavy metals can potentially be released from the sediment layers into the water column if the aquatic conditions are suitable, for example if pH is above 8. Pore-water diffusion of nutrients will lead to potentially high concentration of P and N in the water column, especially near the bottom. For example, a P concentration of 20 mg/kg in the sediment could readily give rise to a P concentration of 1 mg/L in the water in immediate contact with the sediments if the pH is above 8, particularly at higher pH of 9 to 10. High pH could be facilitated and sustained by cyanobacteria activity promoted by high P concentration. This phenomenon of self-reinforcing feedback loop can induce a regime shift to hyper-eutrophication. High nutrient flushing rate will reduce the intensity of regime shift in SL and reduce the level of eutrophication. The objectives of this paper are: (1) to collect and collate environmental and limnology data relevant to eutrophication in SL, (2) to develop a robust mathematical model for regime shift in SL based upon the data compiled and (3) to propose effective eutrophication control measures for SL based upon the developed model that are low-cost and low-maintenance. Important regime shift thresholds critical to eutrophication control will be estimated for SL. This paper contributes to a development of methodology for eutrophication study and control that is applicable to all tropical shallow lakes worldwide.

2. Literature review on regime shift
There are ample signs of regime shift in SL to potentially undesirable hypereutrophic condition if the current trend is not reversed by means of effective control measures. A brief literature review on regime shift in ecosystems would provide useful scientific insights for this paper. The stability of ecosystems subject to external perturbations and internal feedback is a major topic in many fields in contemporary science [1], particularly for climate change studies. Increasing concern has been directed to the scenario known as catastrophic regime shift, where a relatively small change in the environmental conditions can lead to a sudden quantum jump from one state to another [2]. Catastrophic regime shifts are known to pose a serious threat to ecosystems, the control of which requires a reliable set of early warning indicators or thresholds [3]. Global climate change has the potential of inducing catastrophic regime shifts because of the complex nonlinear interactions across space and time involved in climate phenomena. Predicting the tipping point when a state begins to lose its stability and shifts to an alternative and undesirable state remains a daunting challenge. The mass conversion of heathland to grassland in north-western Europe during the past decades is a typical example of how tipping points threaten the biodiversity and ecosystem services delivered by biota [4]. Many large shallow lakes in China such as the Dianchi, Chaohu and Taihu, have already shifted to highly eutrophic conditions [5], that have vastly impaired the valuable ecosystem services provided. These lakes are plagued by persistent turbid water and annual toxic algae blooms, because of the excessive inputs of P and N from fertilizers over decades. Severe eutrophication in Lake Dianchi [5] in Kunming Yunnan (average depth of 4.4 m and surface area of 330 km²) has impaired critical ecosystem services such as fresh water supply for 7 million people and ecotourism [6]. The ecosystem of Lake Chaohu (average depth of 3.1 m and surface area of 780 km²) began to show a regime shift from the clear water state in early 1970s to the turbid state during early 1980s. Since the 1990s, the lake has been confronted with persistent signs of further regime shift to severe eutrophication [7]. At the low trophic level of 2.92, the trophic status of Lake Taihu is considered undesirable, due to the serious and persistent eutrophication in the lake [8, 9]. At these three large eutrophic lakes, the Chinese government has invested billions trying to prevent the occurrence of toxic algae blooms and to sustain portable water supplies for the surrounding cities,
totalling more than 20 million people. The following three subsections provide a brief overview of the important concept of regime shift and its associated thresholds, which are highly relevant to this paper.

2.1. **Positive feedbacks and bi-stability post deforestation**
Availability of P in soils is a major factor limiting vegetation growth for natural ecosystems and agricultural systems [10]. P is not replenished biologically once it is lost from the soil [11]. Once removed from the soil, P becomes available for vegetation growth over very slow geologic time scales [12]. However, under conditions of limited P, soil microbes help in mitigating P losses and in enhancing P availability. Hence, the loss of microbial biomass due to deforestation increases P losses and decreases P availability. The interaction between vegetation growth, microbial abundance and P-cycling that drives the P-vegetation-microbial system was incorporated into a simulation model to study vegetation regime shift. Simulation results suggest that the systems most susceptible to regime shift are those that were previously deforested or those where the amount of P stored in the recalcitrant organic pool is low. A bi-stable equilibrium was observed after a significant loss of P exceeding a certain threshold. When deforestation occurred under limited P availability threshold, both the vegetation and the microbial biomass were not able to recover, and the system shifted to the low vegetation stable state for long duration [13].

2.2. **Bi-stability of mangrove forests and freshwater plants**
Remote sensing imagery in southern Florida confirms the sharp boundaries between freshwater hardwood hammock communities and halophytic communities such as mangroves. Competition among plant species [14, 15] and self-reinforcing feedback between coastal vegetation and vadose zone salinity are involved in maintaining this ecotone [16]. Along salinity gradients, this feedback creates a bi-stable equilibrium in which either halophytic habitat or freshwater plant communities dominate as alternative stable states. Literature shows how transpiration of mangroves and freshwater plants respond differently to vadose zone salinity, thus altering the salinity through feedback. Simulation models demonstrate how self-reinforcing feedback, together with physical template including salinity gradients and sunlight, control the bi-stability between halophytic and freshwater communities [17, 18]. Regions of bi-stability along gradients of salinity have the potential for large-scale regime shifts following large pulse disturbances such as hurricane, tidal surges in Florida, or tsunamis in other regions. The size of the region of bi-stability can be large for low-lying coastal habitats such as the Florida Everglades because of the high saline water table, which can extend several km inland due to salinity intrusion. This threat can be heightened potentially by climate change and sea level rise.

2.3. **Bi-stability in reef oyster subject to sediment accumulation**
Efforts over the past two decades to restore native oyster populations in the Chesapeake Bay have been extensive but largely ineffective [19]. However, recent restoration efforts and field experiments to revitalize reef oyster populations subject to sedimentation indicate that elevated reef height beyond certain thresholds can offset heavy sedimentation, promote oyster survival, encourage growth and improve disease resistance. This suggested the existence of alternative stable states for the ecosystem consisting of live oysters, reef height and sediment volume [20]. Bifurcation analysis performed on a system of three ordinary differential equations indicates that the initial reef heights dominate the outcomes of the equilibrium. This bifurcation analysis provided a theoretical framework for investigating strategy for restoration of degraded reef oyster populations. Alternative stable states can be triggered by environmental disturbances in various ecosystems, such as grasslands [21], kelp forests [22], coral reefs [23] and lakes [24]. For lakes, a system consisting of two ordinary differential equations (ODE) representing P and Chl-a [24] is adopted in this paper for analysing regime shift thresholds in eutrophic lake. Critical parameters determining the status of eutrophication are P loading into the lake (µg/L/day) and P flushing rate (day⁻¹) or its inverse, the P retention time (day).
3. Materials and methods

The SL lake has water inflow via surface runoff and groundwater but has no natural outflow, resulting in a persistent accumulation of P and N in the sediments. Currently, after each heavy rain, excess water in the lake is allowed to overflow a weir into the adjoining retention pond, to avoid flooding the vicinity. Some nutrients and pollutants are removed along with the surface water been drained; but the actual quantum of nutrients and pollutants been drained from SL is unknown. We propose to regularly pump off water at a deeper water level of 7.5 m to remove more nutrients. Quantum of water and key elements (P, N, BOD and Chl-a) removed will be recorded for regime shift simulation and analysis by means of equations (1) and (2), to be described in a later section.

3.1. Retention time R and flushing rate F

It is beneficial to remove nutrient-rich water located near the sediment layers to reduce the accumulation of nutrients in the sediments. For this regime shift analysis, we introduce the concept of retention time $R$ (days) or its inverse i.e. the concept of flushing rate $F$ (day$^{-1}$). Thus, we define $F = 1/R$. Consider a lake of volume $V = 10^6$ m$^3$, with a pollutant $T$ of concentration $C_T$ kg/m$^3$. Assume that the water is flushed out at the rate of $W = (10^3$ m$^3$/day). Then the hydraulic retention time $R = V/W = 10^6$ m$^3$/(10$^3$ m$^3$/day) = 10$^3$ days. The total mass $M$ of $T$ is $M = 10^6$ m$^3$ x $C_T$ kg/m$^3$ = 10$^6$ $C_T$ kg. Suppose now that the concentration of $T$ near the bottom sediment is 10 times higher or 10$^2$ $C_T$ kg/m$^3$. Further, suppose that we flush out the lake water near the bottom sediment (with concentration 10$^2$ $C_T$ kg/m$^3$) at the same rate of $W = (10^3$ m$^3$/day). The mass of $T$ flushed out per day is 10$^6$ $C_T$ kg/m$^3$ x 10$^3$ m$^3$/day = 10$^9$ $C_T$ kg/day. The retention time $R_T$ of pollutant $T$ is $R_T = 10^6$ $C_T$ kg/10$^3$ $C_T$ kg/day = 10$^2$ day; while the hydraulic retention time $R$ is still 10$^3$ days. Therefore, the hydraulic flushing rate $F$ is 1/10$^3$ day = 0.001 per day = 0.001 d$^{-1}$. On the other hand, the pollutant $T$ flushing rate $F_T$ is 1/10$^2$ day = 0.01 per day = 0.01d$^{-1}$. This means that $F_T = 10 F$ or the pollutant $T$ flushing rate $F_T$ is 10 time higher than the hydraulic flushing rate $F$. It is therefore beneficial to flush out water near the sediment to remove as much nutrients as possible with the same hydraulic flushing rate $F$.

3.2. Fish tank experiment

A laboratory experiment in the staging facility in Sunway University was conducted to study the effect of fish respiration on dissolved oxygen (DO) level in water. For this purpose, 20 tilapias with different weights, ranging between 70 g to 335 g each, were selected and only one tilapia is placed into a tank for each experiment (figure 1). The dimension of tanks, water depth and water volume are presented in table 1. Figure 1 shows the fish tanks used in this experiment. The water in each tank is aerated overnight to saturation. In the next morning (at the start of the experiment), for each tank, the first readings of DO, temperature and water level are recorded, after which the aerator is turned off. Subsequently, DO level in the water is measured at regular intervals until the end of the day. The experiment is continued until 68 sets of data with various combinations of tank dimension and fish weight are obtained.
### Table 1. Dimension, fish mass, and specific respiration rates of the five tanks in the experiment.

| Tank | Length (m) | Width (m) | Water depth (m) | Water volume (L) | Fish mass (g) | Specific respiration rate (g O₂/kg fish/day) |
|------|------------|-----------|-----------------|------------------|---------------|---------------------------------------------|
| 1    | 0.780      | 0.340     | 0.177           | 46.94            | 85            | 3.5                                         |
| 2    | 0.590      | 0.295     | 0.156           | 27.15            | 95            | 2.1                                         |
| 3    | 0.800      | 0.340     | 0.185           | 50.32            | 155           | 3.0                                         |
| 4    | 0.750      | 0.370     | 0.226           | 62.72            | 200           | 3.7                                         |
| 5    | 0.750      | 0.370     | 0.269           | 74.65            | 335           | 2.4                                         |

### 3.3. Water and sediment quality sampling

A sampling survey was conducted on 24 to 25 June 2010 to define the water and sediment quality in SL. The water samples were collected at 10 spatially separated sampling locations at three water depths: surface (0.5 m), mid-depth (3.5 m) and lake bottom (7.5 m). Sediments were collected at 10 separate locations. Overall the water quality was classified as Malaysia Standard Class IIB. The surface water dissolved oxygen (DO) levels were generally below 5 mg/L, indicating a DO-stressed environment detrimental to aquatic lives including fish. In addition, a water quality and sediment quality survey was conducted on 23 January 2017. Water quality samples were collected at three depths of 0.5 m (surface), 3.5 m (mid-depth) and 7.5 m (bottom) below water surface. From December 2016 to May 2017, monthly water quality sampling was conducted at three depths (0.5, 3.5, 7.5 m below water surface) for six months. Water quality parameters sampled include temperature, pH, BOD, DO, ammonia, nitrate nitrogen, phosphorus, chlorophyll-a, total coliform and *Escherichia coli*.

### 4. Water and sediment quality data

#### 4.1 Water and sediment quality in 2010

Overall, DO varied between 1.26 mg/L to 4.74 mg/L from bottom to surface. Temperature was between 28 °C and 31 °C, and pH was neutral at 7. Concentration of chlorophyll-a (Chl-a) varied between 5 and 15 µg/L, suggesting a meso-eutrophic condition. With total kjeldahl nitrogen (TKN) concentration varying between 0.2 and 0.9 mg/L and total phosphorus (TP) between 0.1 and 0.4 mg/l, the water is considered as nutrients rich, capable of supporting vibrant Chl-a growth to a eutrophic level. The sediments were tested for 17 heavy metals at 10 locations. The heavy metal concentrations were generally low except for iron, aluminium and manganese. However, the concentrations for P and N are high, reflecting a eutrophic lake condition capable of supporting vibrant algae growth. Table 2 is a summary of concentrations of five key elements in the sediments sampled in 25 to 26 June 2010, indicating an undesirable water quality condition in the sediments.

### Table 2. Concentrations of five key elements in the sediments 2010.

| Component     | Range of value | Level | Comment      |
|---------------|----------------|-------|--------------|
| TP (mg/kg)    | 22 to 81       | High  | Undesirable  |
| TN (mg/kg)    | 68 to 246      | High  | Undesirable  |
| TOC (% w/w)   | 0.4 to 1.5     | High  | Undesirable  |
| Iron (mg/kg)  | 5225 to 13190  | High  | Undesirable  |
| Aluminium (mg/kg) | 8921 to 83890 | High  | Undesirable  |
4.2 Water and Sediment quality survey in January 2017
The results indicated that the overall water quality has deteriorated from Class IIB to Class III and the lake is eutrophic. Further, the N concentration in the sediments measuring 739 mg/kg (based upon an average of 3 sampling locations) has increased by 600 % as compared to that in 2010 (between 68 and 246 mg/kg based upon 10 sampling locations). Survey results for biochemical oxygen demand (BOD$_5$), DO and Chl-a at these 3 depths respectively indicated high and undesirable levels. The sediment quality measured on 23 January 2017 is summarized in table 3, indicating a water quality standard of Class III. Therefore, there is an urgent need to improve water quality in SL.

Table 3. Three sediment quality parameters sampled on 23 January 2017.

| Component | Average value | Level | Comment |
|-----------|---------------|-------|---------|
| TP (mg/kg) | 61.0          | High  | Undesirable |
| TN (mg/kg) | 739           | High  | Undesirable |
| TOC (% w/w) | 0.5           | High  | Undesirable |

4.3 Monthly Water Quality Sampling Between 2016 and 2017
High levels of BOD, NH$_3$N and Chl-a recorded during the six months of sampling is shown in figure 2, indicating a eutrophic lake condition tipping gradually towards hyper-eutrophic. More data is available in [25]. A sustainable low-cost solution to control SL eutrophication is proposed in this paper. In general, an oligotrophic lake (not eutrophic) should have Chl-a level below 2 µg/L; while a meso-eutrophic lake should have Chl-a between 2 to 9 µg/L. Levels of Chl-a exceeding 9 µg/L is considered eutrophic and undesirable.

Figure 2. (a) DO, (b) BOD, (c) NH$_3$N and (d) Chl-a sampled at three depths (0.5, 3.5 and 7.5 m below water surface) from Dec 2016 to May 2017.

5. Simulation results
To control SL eutrophication, a simple, sustainable and cost-effective method is proposed. Lake water at a depth of 7.5 m will be removed at daily frequency to flush out P-rich lake water [25]. The system of two ODE representing the evolution of Chl-a (equation (1)) and P (equation (2)) in SL is given in equations (1) and (2), with the definitions, units, and values of process parameters shown in table 4. Further details are available elsewhere [26]. The P-flushing rate denoted by $F_T$ (day$^{-1}$) is represented by $h$ in equation (2). Three flushing scenarios are simulated: (a) $h = 0$ day$^{-1}$, (b) $h = 1/(200$ days$)$ = 0.005 day$^{-1}$ and (c) $h = 1/(100$ days$)$ = 0.01 day$^{-1}$, representing zero flushing, flushing with 200-days retention
and flushing with 100-days retention respectively. The corresponding simulation results are demonstrated in figure 3.

\[
\frac{dA}{dt} = bPA - \left( g + \frac{s}{z_e} + h \right) A \tag{1}
\]

\[
\frac{dP}{dt} = l + r + e g A - b A P - h P \tag{2}
\]

Table 4. Definition, units and value of variables and parameters.

| Symbol | Definition                        | Unit          | Value       |
|--------|-----------------------------------|---------------|-------------|
| b      | Algal growth rate per unit        | L/μg P/d      | 0.900       |
| g      | Zooplankton grazing rate          | d⁻¹           | 0.030       |
| s      | Algal sinking rate                | m/d           | 0.085       |
| h      | Flushing rate                     | d⁻¹           | (a) 0.0, (b) 0.005, (c) 0.01 |
| e      | P excretion rate associated with grazing | μg P/μg chl | 0.650       |
| l      | External P loading rate           | μg P/L/d      | 0.01 – 0.13 |
| r      | Internal P sediment recycling rate | μg P/L/d      | Computed    |
| z_e    | Thickness of epilimnion           | m             | 7.000       |

Figure 3. Simulated results for three scenarios of retention period: (a) No flow \((h = 0.0 \text{ d}^{-1})\), (b) 200 days \((h = 0.005 \text{ d}^{-1})\) and (c) 100 days \((h = 0.01 \text{ d}^{-1})\).

With zero flushing, regime shift tipping point is reached at an external P loading rate of 0.8 μg/L/d, and the Chl-a concentration may peak at 50 μg/L, as may be seen from figure 3(a). A P flushing rate of 0.005 day⁻¹, corresponding to a retention time of 200 days, can extend the regime shift tipping point to external P loading of 1.0 μg/L/d, and the Chl-a concentration may peak at 40 μg/L as illustrated in figure 3(b). A P flushing rate of 0.01 day⁻¹, corresponding to a retention time of 100 days, can extend the regime shift tipping point to external P loading of 1.2 μg/L/d, and the Chl-a concentration may peak at 35 μg/L, as may be seen from figure 3(c). Given that the lake is shallow, and the temperature is high all year round, SL is vulnerable to eutrophication [24].
Hence, in addition to increasing P flushing, other additional measures should be considered, including reduction of fish density. For this purpose, a series of lab experiments as described in section 3.2 was conducted to measure fish specific respiration rates under lab conditions. Figure 4 demonstrates the decline in DO due to fish respiration in three of the fish tanks. The dimension, fish mass, and specific respiration rates in the five tanks are given in table 1, indicating specific respiration rate of between 2.1 to 3.7 g O₂/kg fish/day for sedentary fish at 23 ºC that are inactive most of the time. In SL where fish compete for resources in an environment of higher temperature of around 29 ºC, the specific respiration rate should be higher. Numerical simulations were performed for a fish pond with depth of 0.6 m, reaeration rate of 2 d⁻¹, and specific respiration rate of 5 g O₂/kg fish/day, fish feeding rate of 2 % per day wet weight and fish density of 0.8 kg/m³. The simulation results indicated fish will be killed because of low DO, without an aerator [27]. It is therefore important to reduce fish density in SL to 0.1 kg/m³ or less to ensure adequate DO. With a depth of 8 m, SL reaeration rate will be less than 2 d⁻¹, limiting oxygen replenishment from atmosphere.

6. Discussion and conclusion
Although the causes of lake eutrophication regime shift have been broadly understood, the theoretical foundation of eutrophication is still lacking. Hence, eutrophication remains a daunting environmental problem that is difficult to resolve. With high annual temperature and abundant sunlight in the tropics, eutrophication is accelerated by large and persistent influx of nutrients such as P generated by anthropogenic activities. A high concentration of these nutrients in the lake stimulates algae to grow wildly, leading to depletion of DO in the lake water. The accumulation of P in the sediment and the release of P from sediment back into the water column are dominant processes driving regime shift. The persistence of eutrophication is dominated by important ecological thresholds and the existence of multiple regimes within a lake. The knowledge on regime shift thresholds associated with eutrophication is a prerequisite in lake restoration efforts to improve the lake ecosystem. The analysis performed in this paper provides the fundamental knowledge and insights on the regime shift and its thresholds for SL and offers sustainable solutions for controlling eutrophication. It is concluded that a sustainable and cost-effective rehabilitation program for SL is a frequent removal of nutrient rich lake water from a depth of 7.5 m. This daily flushing of P rich water will delay the tipping point of lake regime shift from 0.8 µg/L/d to 1.2 µg/L/d and significantly reduce P and Chl-a level. Reduction of fish density to 0.1 kg/m³ or less may also be beneficial in improving overall water quality and increasing DO levels. Increased DO may inhibit release of P from sediment to water column. The methodology developed in this paper may be applicable to other tropical shallow lakes for the analysis and control of eutrophication.
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