Application of PCLake Model to Predict Water Quality in Tropical Reservoirs, a Case Study of Khlong Luang Ratchalothorn Reservoir

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Abstract. *This study addresses a previously unexamined water quality issue in the Khlong Luang Ratchalothorn (KLR) reservoir, which suffered severe eutrophication in 2018 due to the cyanobacteria Microcystis aeruginosa. This phenomenon led to the development of green scum, alterations in color, foul odors, and diminished dissolved oxygen levels, negatively impacting the reservoir's usability. Utilizing the calibrated and validated PCLake water quality model, the research assessed the impact of varying reservoir inflow scenarios—minimum, average, and maximum—based on rainfall data from 2013 to 2022 on Chlorophyll a (Chla) levels. Additionally, the effects of reducing nutrient and suspended solids loading by 10%, 30%, and 50% were evaluated under worst-case scenarios. Findings indicate that the reservoir maintains an eutrophic status across drought, normal, and wet conditions, with drought having the most significant adverse impact on water quality, potentially persisting for up to two years. Despite a 50% reduction in nutrient and suspended solids, the reservoir does not transition to a mesotrophic state; however, water users do not face significant challenges even under these extreme conditions. This research offers new insights into effective strategies for managing water quality in similar aquatic systems.*

Keywords:

Chlorophyll a, nutrient, PCLake, rainfall, water resources

1. Introduction

Beyond the typical Southwest Monsoon, the proximity of Thailand to the west coast of the tropical Pacific Ocean makes its rainfall distribution susceptible to the influences of the El Niño/Southern Oscillation (ENSO) [1]. Between 2007 and 2016, Thailand experienced the impacts of the ENSO phenomenon, notably in 2011, marked by a severe flood and storm [2]. While the influence of climate change on ENSO remains an ongoing area of research, the Intergovernmental Panel on Climate Change (IPCC) predicts that the frequency of extreme El Niño and La Niña events is expected to rise over the next century due to global warming [3]. Limsakul and Singhruck [4], and Rojpratak and Supharatid [5] observed that, generally, Thailand experiences more frequent occurrences of either extreme rainfall during strong La Niña years or intense droughts during strong El Niño years.

The Eastern Economic Corridor (EEC) project, part of the 20-year national strategic plan (2018-2037), concentrates on developing three provinces in the eastern region, namely Rayong, Chonburi, and Chachoengsao, into special economic areas and pivotal centers for the country's economic growth. As a consequence of this project, there has been a notable rise in water consumption demands for both domestic and industrial sectors. According to projections from the Royal Irrigation Department, by 2036, the demand is estimated to reach 1,000 million m^3/year, representing a 22.52% increase from the demand observed in 2018 [6]. Typically, the rainy season in the eastern regions of Thailand commences in May and persists until October, with peak rainfall occurring from June to August [5]. Meteorological data collected by the Meteorological Department from 2013 to 2022 reveals significant fluctuations in total annual precipitation across the eastern region, ranging from a maximum of 2,184.3 mm to a minimum of 1,721.7 mm. Given these variations, accurately forecasting water quality in reservoirs under various weather conditions, particularly during severe droughts, is crucial for implementing effective water management strategies.

The Khlong Luang Ratchalothorn (KLR) reservoir, a Royal initiative, holds significant importance as a water reservoir in the eastern region. It serves multiple purposes, including providing water for agriculture, aquaculture, and domestic consumption, while also playing a crucial role in flood mitigation during the rainy season in lower areas such as Phan Thong and Phanat Nikhom districts. Additionally, the KLR reservoir serves as a backup water source for the Bang Phra reservoir, which is the primary water supply source for Chonburi province, supporting the production and service sectors in the EEC area. The originality of this study is underscored by its examination of a previously unaddressed water quality issue in the KLR reservoir, which experienced severe eutrophication in 2018 due to the cyanobacteria Microcystis aeruginosa. This led to the formation of green scum on the water's surface and along the edges, resulting in color changes, unpleasant odors, and reduced dissolved oxygen levels, thereby impacting the reservoir's usability [7]. By employing the PCLake water quality model, this research aims to develop effective strategies for mitigating water quality degradation, offering new insights into the management of similar aquatic systems.

The PCLake model, which can be accessed for free, offers a user-friendly interface through a Microsoft Excel spreadsheet, making it easy to solve equations and generate model output, thus enhancing usability. It serves as an integrated ecological model for non-stratified lakes, encompassing phytoplankton, macrophytes, and basic food webs within a closed nutrient cycle [8]. Although initially tailored for temperate lakes, the phytoplankton module within the PCLake model demonstrated satisfactory to good predictive accuracy for chlorophyll a (Chla) levels in the KLR reservoir during calibration (in 2020) and validation (in 2022) stages [9]. Hence, the validated PCLake model was chosen as the suitable option for assessing water quality in this study. In this study, the calibrated and validated PCLake model was adopted to evaluate the effect of different water inflow scenarios based on the rainfall data of year 2013-2022 on Chla in KLR reservoir. The results should be able to provide insight into the influence of rainfall to the water quality in this reservoir. The predicted Chla will be used to specify the trophic status that is the criteria for water resource allocation and water quality mitigation measures.

2. Methodology

2.1 Research Area

The Khlong Luang Ratchalothorn (KLR) reservoir is a versatile hydraulic engineering project, offering irrigation, public water supply, and flood control services. Situated at 13°23'00" N and 101°22'40" E in Ban Khlong sub-district, Tha Boon Mi district, Koh Chan, Chonburi province, Thailand, it is situated at an elevation of 35.5 m above sea level within a tropical climate zone. The reservoir was constructed on the Khlong Luang river, a tributary in the Bang Pakong basin, draining approximately 525 km^2 of mountainous and plain areas. With an average depth of 3.67 m and a length of 5 km at normal water levels, the reservoir covers a surface area of 27 km^2, with a capacity of 99 million m^3 and a hydraulic retention time of around 355 days. Calculations based on reservoir fetch reveal potential wavelengths of 15.10 m, with half exceeding the average water depth, indicating thorough mixing [10, 11].

Chonburi province hosts rain gauges at five meteorological stations: Chonburi Meteorological Station, Koh Sichang Meteorological Station, Pattaya Meteorological Station, Sattahip Meteorological Station, and Laem Chabang Meteorological Station. For this study, rainfall data from the Chonburi Meteorological Station, located closest to the KLR reservoir were utilized. Notably, the meteorological station is situated approximately 39 km to the west of the KLR reservoir and is located at an elevation of 2.48 meters above mean sea level. Over the periods 1993-2002, 2003-2012, and 2013-2022, the 10-year total annual average rainfall from this station showed an increasing trend, measuring 1,252.6 mm, 1,350.3 mm, and 1,293.8 mm, respectively. The average monthly air temperature is lowest in December at 23°C, and highest in April at 35°C.

2.2 Model Set-Up

In this study, both the phytoplankton module and the transport processes module of the PCLake were utilized, with calculations conducted on a daily basis. Monthly water sampling was planned to be carried out at the KLR reservoir, with sampling points shown in Fig. 1. A total of ten sampling sites were selected, comprising four at the entrance (S7–S10) and six within the reservoir (S1–S6). Surface water samples were gathered using the grab sampling technique in accordance with the procedures outlined by APHA et al. [12]. The sampling period spanned two periods: the first from September 2019 to December 2020, and the second from January to September 2022. The parameters analyzed included total phosphorus (TP), phosphate (PO_4^{2-}), ammonium (NH_4^+), nitrate (NO_3^-), Total Kjeldahl nitrogen (TKN), Chlorophyll a (Chla), and suspended solids (SS), following standard procedures outlined by APHA et al. [12]. Water temperature was measured using a bulb thermometer, while water clarity was assessed using a Secchi disk.

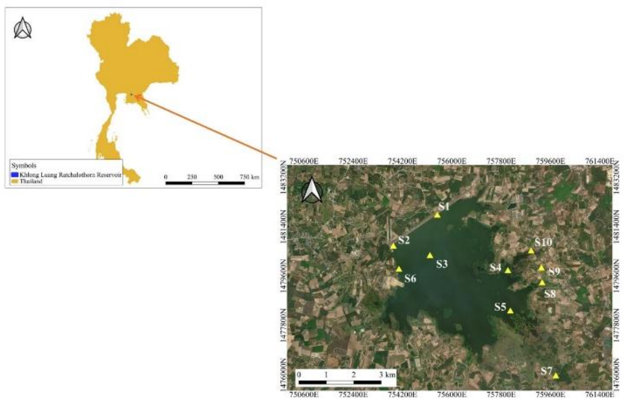

Fig. 1 depicts the positioning of sampling points (S1–S10) within the Khlong Luang Ratchalothorn (KLR) reservoir, located in Chonburi province, Thailand.

Daily water levels and volumes of reservoir inflow and outflow, daily average wind speed, daily average evaporation rate, and daily average global radiation data were obtained from the sources mentioned in [9].

The PCLake model comprises seven extensive modules [9]. In this study, the model was utilized to maintain the mass balance of dissolved substances and particles in the water layer, with a primary focus on simulating suspended phytoplankton, particularly Chla. Consequently, only the phytoplankton and transport process modules were employed.

2.3 Simulation Scenarios

In this study, rainfall variations were identified as the primary drivers influencing nutrients and suspended solids from nonpoint sources flowing into reservoirs, assuming unchanged land use. Rainfall was categorized as an indicator of drought, normal, and wet conditions, corresponding to minimum, average, and maximum water inflow into the reservoir, respectively. Analysis of rainfall data from 2013 to 2022, recorded by the Chonburi Meteorological Station, revealed that 2015 experienced the lowest total rainfall of 1,046.0 mm, indicating a drought condition. However, as water storage in the KLR reservoir only began in 2018, hydrologic data for 2015 was unavailable. Despite this, statistical analysis comparing the monthly rainfall of 2015 and 2019 (1,081.8 mm) showed no significant difference ($p < 0.05$). Consequently, 2019 was selected as representative of the drought period. Conversely, 2016, with the highest total rainfall (1,463.2 mm), was chosen to represent the wettest condition. Again, due to the absence of hydrologic data for 2016, conditions in 2022, with similar total rainfall (1,441.6 mm), were used instead. This decision was based on the finding that the average total rainfall from 2018 to 2022 (1285.4 mm) did not differ significantly ($p < 0.05$) from the average total rainfall from 2013 to 2022 (1293.8 mm).

Due to insufficient water quality monitoring data in 2019, 2022, and the average of 2018-2022, daily water quality throughout these periods was estimated using available data. Key parameters such as dissolved oxygen (DO), total phosphorus (TP), total nitrogen (TN), Chlorophyll a (Chla), suspended solids (SS), and Secchi Disk (SD) were calculated through linear interpolation or extrapolation based on the closest available data of water inflow and the respective variables [13, 14]. Additionally, phosphate fraction (PO_4^{2-}) or the fraction of phosphorus bound to organic matter (Org-P) was determined from the average proportion of each species to total phosphorus from available data. Similarly, fractions of ammonium (NH_4^+), nitrate (NO_3^-), or nitrogen bound to organic matter (Org-N) were calculated from the average contribution of each species to the total nitrogen of the available data [15]. The proportions of organic and inorganic matter in the incoming water were derived from the proportion of these components to the total suspended solids, which were assumed to be equal to those of the sedimentary layer.

As field data for the initial trophic status were unavailable for each scenario in this study, literature data were used. From the study of Boondao et al. [7], it was found that the KLR reservoir (Fig. 1) could transition between 3 states: mesotrophic, eutrophic, and hypertrophic. Therefore, all three potential initial trophic states were defined for each scenario. The phytoplankton concentrations corresponding to different trophic statuses are detailed in Table 1. Sediment characteristics and water temperature were determined based on the calibration process outlined in the research conducted by Wongpipun et al. [9]. Table 2 presents the initial values, input factors, and time-series data derived from actual field observations for each scenario. Subsequently, the daily constant values of cExtSpDet (specific extinction of detritus) were calculated according to [9]. These calculated values were then utilized by replacing the default value of cExtSpDet in the model with the maximum calculated value, as detailed in Table 3.

The drought situation (scenario 1) is expected to have the most pronounced adverse impact on water quality. Evidence suggests that this situation can persist for up to two consecutive years between 2013 and 2022, warranting simulation. For the second year of the simulation, the time series input data were precisely replicated from the first year. Additionally, the effects of 10%, 30%, and 50% reductions in nutrient loading and suspended solids on Chla were also evaluated.

Table 1 Concentrations of individual phytoplankton species in reservoir waters with various initial trophic status

Initial trophic status	Concentration of each phytoplankton species within the water (gDW/m^3)			Sources
	Diatoms	Green algae	Blue-green algae	
Mesotrophic	0.41	0.01	0.03	PCLake model’s default values for clear lake
Eutrophic	0.50	0.50	3.00	PCLake model’s default values for turbid lake
Hypertrophic	4.29	0.95	39.81	Dantas et al. [16]

Table 2 Initial values, input factors, and time-series data of variables used in various simulations in the PCLake model

Description	Variable	Value			Unit
		scenario 1: drought situation	scenario 2: normal situation	scenario 3: wet situation	
Initial value	Lake depth	3.21	3.14	3.46	m
	Dry-weight fraction of solid in sediment	0.246	0.246	0.246	g of dry-weight/g of sediment
	Organic fraction of dry-weight sediment	0.102	0.102	0.102	g of dry-weight/g of dry-weight sediment
Input factors	Lake dimensions, conveyed in terms of fetch	5,168	5,168	5,168	m
	Iron content of inorganic matter	0.032	0.032	0.032	g of iron/g of dry-weight
	Oxygen concentration in inflow	2.31	2.73	2.41	mg of oxygen/L
	Aluminum content of inorganic matter	0.021	0.021	0.021	g of aluminum/g of dry-weight
	Daily light	1,148 to 7,110 (4,872 ± 1,175)	2,879 to 7,122 (5,055 ± 699)	1,583 to 7,591 (5,101 ± 1,320)	W/m^2
Time-series	Monthly water temperature	24 to 30 (28 ± 2) [1]	24 to 30 (28 ± 2)	24 to 30 (28 ± 2)	ºC
	Daily wind	0 to 3.94 (1.28 ± 0.60)	0.68 to 2.70 (1.38 ± 0.32)	0.56 to 3.94 (1.48 ± 0.64)	m/s
	Daily inflow	0.05 to 157.38 (11.78 ± 19.47)	1.04 to 130.47 (19.98 ± 21.35)	0.01 to 321.95 (27.95 ± 44.18)	mm/d
	Daily outflow	0 to 33.77 (8.27 ± 8.50)	1.46 to 34.02 (12.94 ± 6.90)	0 to 78.44 (21.30 ± 21.36)	mm/d
	Daily phosphorus loading	0 to 0.598 (0.016 ± 0.053)	0 to 0.083 (0.015 ± 0.016)	0 to 0.111 (0.017 ± 0.025)	g of phosphorus/ m^2 • d
	Daily phosphate loading	0 to 0.099 (0.005 ± 0.010)	0 to 0.040 (0.007 ± 0.008)	0 to 0.055 (0.008 ± 0.012)	g of phosphorus /m^2 • d

[1] mean ± SD

Table 2 (cont.)

Description	Variable	Value			Unit
		scenario 1: drought situation	scenario 2: normal situation	scenario 3: wet situation	
Time-series	Daily phosphorus bound to organic matter	0 to 0.051 (0.001 ± 0.004)	0 to 0.004 (0.0008 ± 0.0009)	0 to 0.008 (0.0009 ± 0.0014)	g of phosphorus /m^2 • d
	Daily nitrogen loading	0.0002 to 1.625 (0.041 ± 0.138)	0 to 0.249 (0.048 ± 0.047)	0 to 0.470 (0.052 ± 0.080)	g of nitrogen/m^2 • d
	Daily ammonium loading	0.000002 to 0.048 (0.004 ± 0.008)	0 to 0.049 (0.007 ± 0.010)	0 to 0.050 (0.006 ± 0.011)	g of nitrogen/m^2 • d
	Daily nitrate loading	0.00004 to 0.414 (0.012 ± 0.037)	0 to 0.115 (0.016 ± 0.021)	0 to 0.217 (0.020 ± 0.036)	g of nitrogen/ m^2 • d
	Daily nitrogen bound to organic matter	0.00009 to 1.187 (0.024 ± 0.100)	0 to 0.158 (0.024 ± 0.024)	0 to 0.243 (0.026 ± 0.040)	g of nitrogen/ m^2 • d
	Daily detritus loading	0 to 0.787 (0.047 ± 0.094)	0 to 1.276 (0.102 ± 0.153)	0 to 4.018 (0.156 ± 0.417)	g of dry-weight/ m^2 • d
	Daily inorganic matter loading	0 to 6.931 (0.414 ± 0.830)	0 to 11.231 (0.902 ± 1.345)	0 to 35.374 (1.371 ± 3.676)	g of dry-weight/ m^2 • d

Table 3 cExtSpDet (specific extinction of detritus) used for different scenarios

Scenario	cExtSpDet (m^2/gDW)
1 (drought situation)	0.672
2 (normal situation)	0.508
3 (wet situation)	0.538

3. Results and Discussion

3.1 Simulation Scenarios

Rainfall data obtained from the Chonburi Meteorological Station showed occurrences of both drought and wet conditions between 2013 and 2022. The simulated chlorophyll a (Chla) levels in the Khlong Luang Ratchalothorn (KLR) reservoir under drought, normal, and wet conditions, considering different initial trophic statuses, are illustrated in Fig. 2, 3, and 4, respectively.

The study found that regardless of the initial trophic status of the KLR reservoir, the simulated Chla levels remained stable from July onward. This is consistent with the research by Wongpipun et al. [9], which found that the initial concentrations of diatoms, green algae, and blue-green algae in the reservoir had no effect on the long-term prediction of Chla levels in the PCLake model. In the drought simulation (scenario 1), the reservoir maintained

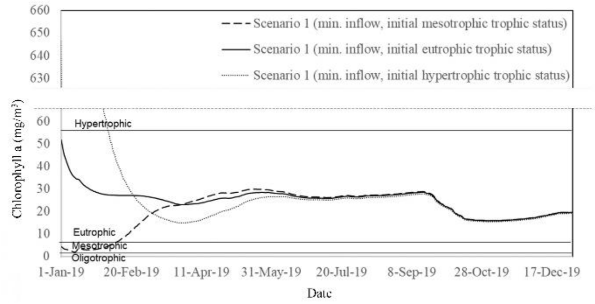

Fig. 2 Simulated time-series of chlorophyll a concentration in the drought scenario with varying initial trophic states

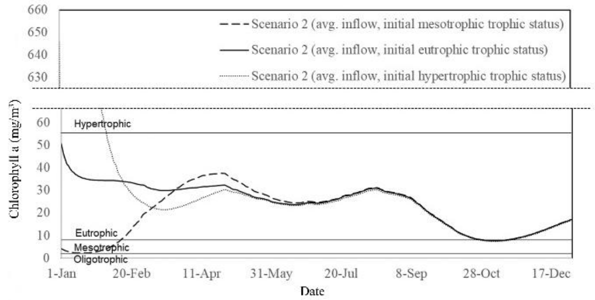

Fig. 3 Simulated time-series of chlorophyll a concentration in the normal scenario with varying initial trophic states

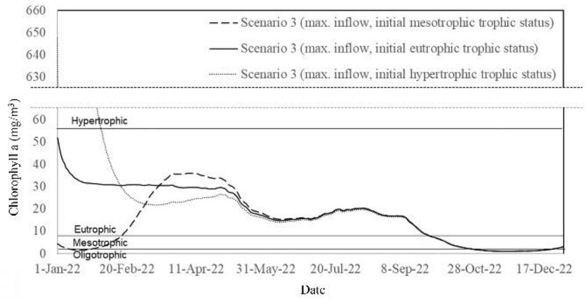

Fig. 4 Simulated time-series of chlorophyll a concentration in the wet scenario with varying initial trophic states

a eutrophic condition throughout the year, likely due to reduced water discharge during dry periods. This prolonged retention time facilitates phytoplankton growth [17, 18].

Laspidou et al. [18] and Coppens et al. [15] both observed increased Chla levels in reservoirs and natural lakes during periods of decreased rainfall. In scenario 2, termed the normal scenario where inflows were averaged over the available data period, the reservoir maintains a eutrophic state throughout the year, albeit with a reduced severity in the last three months compared to scenario 1. In scenario 3, referred to as the wet scenario, the trophic status exhibits less eutrophication and transitions towards mesotrophic/oligotrophic levels by September, likely due to shorter retention times. Notably, Chla levels derived from all three simulations remain below 85 mg/m³, the threshold posing problems for water use in consumption, agriculture, and aquaculture [19].

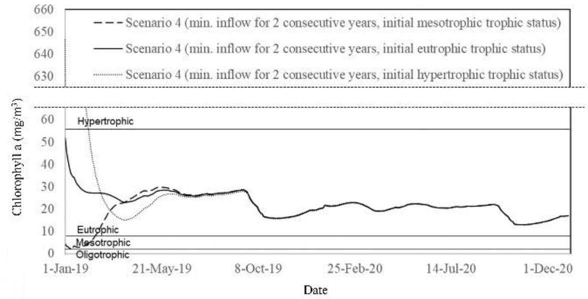

Fig. 5 Simulated time-series of chlorophyll a concentration in a 2-year continuous drought situation with varying initial trophic states

The results of the Chla simulation during a continuous 2-year drought scenario are depicted in Fig. 5. This figure showcases the reservoir maintaining its eutrophic status over the course of a 2-year period. In efforts to enhance the trophic status of the reservoir, simulations were conducted to reduce nutrient and suspended solid loads by 10%, 30%, and 50%, as depicted in Fig. 6, 7, and 8, respectively.

From Fig. 6 to 8, Chla concentrations were observed to be 18.46±3.55 mg/m^3, 15.21±2.85 mg/m^3, and 11.36±2.03 mg/m^3 under scenarios where nutrient loading and suspended solids were reduced by 10%, 30%, and 50%, respectively. The data indicate a decrease in Chla concentration corresponding to the reduction in nutrient and suspended solid levels. Despite the differences in each scenario, the reservoir consistently maintains its eutrophic status across all scenarios. This aligns with the research by Rolighed et al. [20], which found that nutrient levels would need to be reduced by nearly 100% to achieve mesotrophic status.

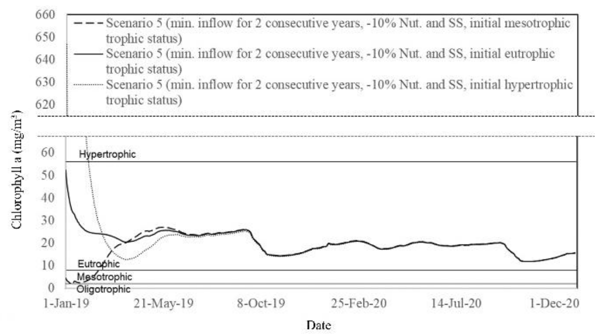

Fig. 6 Simulated time-series of chlorophyll a concentration in a 2-year continuous drought scenario with a 10% reduction in nutrient loading and suspended solids, considering different initial trophic states

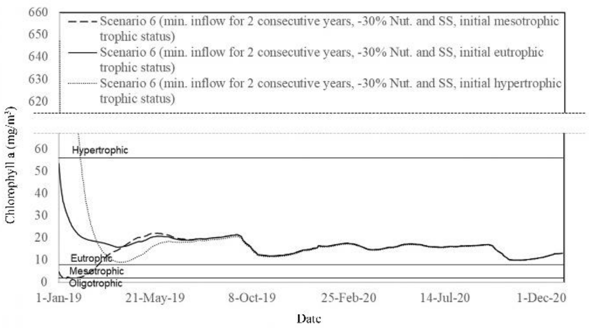

Fig. 7 Simulated time-series of chlorophyll a concentration in a 2-year continuous drought scenario with a 30% reduction in nutrient loading and suspended solids, considering different initial trophic states

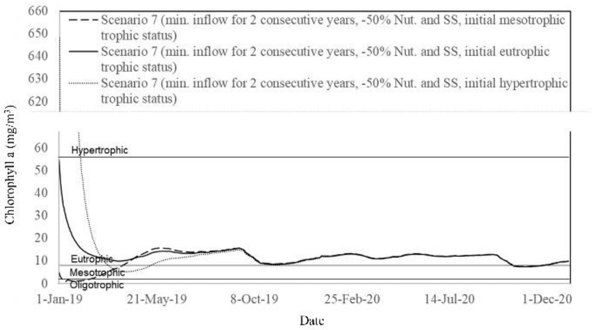

Fig. 8 Simulated time-series of chlorophyll a concentration in a 2-year continuous drought scenario with a 50% reduction in nutrient loading and suspended solids, considering different initial trophic states

However, the concentrations of Chla do not reach hypertrophic levels (> 56 mg/m³) [21]. Since water usage is restricted during drought conditions, the impact of water quality on water users is limited.

To mitigate nutrient loading and suspended solids, implementing appropriate soil and water conservation management techniques or best management practices (BMPs) such as constructed wetlands and bioretention/rain gardens can be effective [22]. These BMPs can be deployed at different spatial levels, including on-site, sub-regional, and regional placement levels, with selection based on geographic parameters and land availability [23].

When evaluating the potential area for operating an artificial wetland at the KLR reservoir, approximately 2,592,894 m^2 were identified. These areas were chosen from degraded lands or those with no current land use, lacking vegetation cover, primarily along the stream, and characterized by flat terrain. The hydrological loading rate and the pollutant removal efficiency (nutrients and suspended solids) were established as 0.052 $m^3/m^2 \cdot d$ and 54%, respectively [24], allowing for the removal of pollutants at a rate of 23% of all entering the reservoir.

Despite these efforts, achieving mesotrophic status during a 2-year drought situation is considered unattainable. Hence, alternative measures for reservoir restoration are necessary. For example, biomanipulation, as successfully applied to Lake Zwemlust in the Netherlands [25], and strategies such as littoral development and fisheries management show promise for water source restoration [26]. Additionally, the deployment of floating balls to shade the water surface has proven effective in reducing evaporation and algae growth, as demonstrated by their application at the 0.71 km^2 Los Angeles reservoir [27].

Since the water quality data used as input for the PCLake model in this study was estimated from available data, the predicted Chla levels can only serve as preliminary information for planning water quality management.

4. Conclusion

Based on the preliminary assessment, it was found that regardless of the initial trophic status of the Khlong Luang Ratchalothorn (KLR) reservoir, simulated chlorophyll a (Chla) levels remained stable from July onward under drought, normal, and wet conditions. In the most severe scenario, drought, the reservoir maintained an eutrophic state throughout the year, potentially persisting for up to two years from 2013 to 2022. Even with a 50% reduction in nutrient and suspended solids loading, the reservoir only transitioned to a reduced eutrophic state, rather than achieving a mesotrophic state. However, this situation does not pose significant issues for water users, as Chla levels have not reached a point of concern.

The predicted Chla levels in this study can be used to determine the trophic status, serving as a criterion for water resource allocation. Furthermore, alternative measures are necessary to restore the reservoir to a mesotrophic state during a two consecutive-year drought situation.

To effectively apply the PCLake model for predicting Chla levels in various water bodies, it is essential to input several key data points. These include the initial concentrations of different phytoplankton species, the starting water depth, sediment characteristics, fetch, as well as hydrological, meteorological, and water quality data. Additionally, the constant cExtSpDet (specific extinction of detritus) must be included.

In this study, we employed the PCLake water quality model, which is based on ecological and hydrological principles related to nutrient cycling and trophic dynamics. This model enables us to simulate a range of scenarios and evaluate their effects on water quality indicators like Chla levels. To improve the accuracy of Chla predictions using the PCLake model, it is crucial to gather field data pertinent to the cExtSpDet constant—identified as one of the most sensitive parameters for Chla calculations. This data collection should encompass organic solids, Chla concentrations, Secchi disk (SD) measurements, and specific extinction rates for diatoms, green algae, and blue-green algae, covering the entire duration of the study.

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