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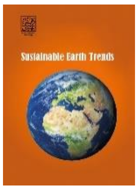

Modeling water quality of Chitgar lake: evaluation of the effectiveness of various water treatment scenarios on lake water quality

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ABSTRACT

Chitgar Lake in Tehran city faces challenges in maintaining water quality due to nutrient loading and potential eutrophication. A water treatment plant (WTP) established in 2016 plays a crucial role in improving Chitgar Lake's water quality. The treatment process involves screening, coagulation, filtration, and disinfection, reducing TP to below 0.02 mg/L before releasing the water into the lake. A water quality model was developed to assess the impacts of external and internal nutrient and organic loading on lake management. This study investigates the impact of different WTP operational scenarios on water quality parameters using a water quality model. The results show that the lake experiences water quality issues, with a minimum DO level of 3.96 mg/L and maximum TP and Chl-a levels exceeding standard levels. The river water undergoes significant improvements after treatment, with nutrient reductions, Chl-a, and turbidity. The study highlights the critical need for continuous monitoring and effective treatment strategies to maintain Chitgar Lake's water quality well above standard conditions. The model serves as a valuable tool for assessing management strategies and optimizing water treatment plant operations, helping to control eutrophication and preserve the lake's recreational value. The simulation scenarios indicate that the most effective strategy for maintaining water quality in Chitgar Lake is the continuous operation of the water treatment plant during both the refilling and recycling periods. This approach successfully keeps key parameters, such as Chl-a and TP, within acceptable limits, effectively preventing eutrophication and ensuring the lake's suitability for recreational activities.

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1. Introduction

Ensuring that the water quality of recreational lakes meets established standards is essential. Water pollution has serious implications for social and economic development in areas affected by contamination (Calamita et al., 2021; Duc et al., 2021). Contaminated water during recreational activities can lead to outbreaks of illnesses such as gastrointestinal and respiratory diseases (Fewtrell and Kay, 2015). The excessive accumulation of phosphorus and nitrogen in lakes and water supplies poses threats to aquatic ecosystems and wildlife by promoting eutrophication (Evtimova and Donohue, 2014; Xing et al., 2014). Over the past four decades, eutrophication has emerged as a major global challenge to freshwater quality (Naselli-Flores et al., 2005). This process tends to be more pronounced in man-made lakes compared to natural ones, exacerbated by harmful operational practices in reservoirs that worsen water quality issues (Naselli-Flores, 1999; Xie et al., 2011; Meng et al., 2015). Consequently, sustainable development requires comprehensive water quality management. Understanding the impact of nutrient loading on lake water quality is crucial for developing effective solutions to eutrophication. Managing nutrient levels in lakes and reservoirs can help mitigate this process (Bueche, 2008). To thoroughly assess aquatic systems with changing water quality parameters, it is essential to consider short-term variations. Over the past two decades, water quality modeling has proven to be a valuable tool for managing water quality in reservoirs, lakes and rivers (Isazadeh et al., 2005; Sullivan and Rounds, 2005; Afshar and Saadatpour, 2008). Duc et al. (2021) and Calamita et al. (2021) reported the importance of the modeling to predict future water quality for developing water management plan. Xing et al. (2014) reported that the best scenario for controlling the eutrophication is reducing the nutrients inflow from upstream. Liu et al. (2014) modelled 16 scenarios for simulating the water quality of the Dianchi Lake, emphasizing on nutrints inflow controlling.

Chitgar Lake, an artificial reservoir, was constructed to enhance recreational and tourism offerings in the western part of Tehran. Operational since February 2013 and officially inaugurated in May of the same year, the lake is fed by water from the Kan River. A water treatment plant, established in October 2016 with a capacity of 0.4 m³/s, plays a vital role in maintaining water quality. During the refilling period from January to April and the recycling period from May to December, the plant effectively removes total phosphorus, suspended solids, algae, and bacteria from the incoming water. The treatment process consists of several steps: screening, micro-straining, coagulation, flocculation, sedimentation, filtration, and disinfection, achieving a TP concentration of less than 0.02 mg/L before the water is released into the lake.

An essential aspect of managing surface water resources involves developing predictive models to assess operational and structural strategies aimed at improving water quality. Such models facilitate the formulation of a water conservation plan for the recreational use of the lake. By utilizing monthly input data, it could be anticipated that a high-resolution water quality model will provide detailed outcomes (Hughes and Slaughter, 2016; Sadeghian et al., 2018; Zhang and You, 2024; Das, 2025). While some researchers advocate for complex models, others emphasize the importance of high-quality observations and the accuracy of theoretical frameworks as critical factors in evaluating model effectiveness.

In this study, a water quality model was developed, specifically designed to assess the impacts of both external and internal nutrient and organic loading on lake management through several treatment senarios. Studies focussing on this topic in relation to urban lakes are rare and knowledge of the ecological dynamics and effective management strategies for controlling eutrophication in urban lakes is lacking. This innovative model offers a comprehensive framework for understanding how water quality in Chitgar Lake responds to various management strategies, thereby advancing the scientific approach to effective lake management.

One of the key innovations of this research is its ability to assess the efficacy of the Water Treatment Plant (WTP) in removing phosphorus and preventing eutrophication. By simulating different operational scenarios, we can analyze how varying treatment efficiencies during the recycling and refilling phases influence water quality outcomes. The study also explores four distinct scenarios to enhance water quality management from both ecological and economic perspectives:

1. Normal operations during both the recycling and refilling periods (50 percent efficiency of treatment).
2. WTP operation solely during the refilling period (50 percent efficiency of treatment).
3. WTP operation exclusively during the recycling period (50 percent efficiency of treatment).
4. WTP operation involving only physical treatment throughout both periods (20 percent efficiency of treatment).

Through these modeling scenarios, we aim to identify effective strategies for managing water quality in Chitgar Lake. By leveraging the insights gained from this model, we can implement targeted management practices that lead to better water quality outcomes, thereby improving the overall ecological health and recreational value of the lake. In fact, this study will explore that does higher treatment efficiencies improve water quality of the Lake. This research represents a significant step forward in the strategic management of lake ecosystems.

2. Material and methods

2.1. Study Area

Chitgar Lake is situated in northwest Tehran, surrounded by urban infrastructure and a planted forest. This shallow lake has an average depth of 3.5 meters and spans an area of 132 hectares, with a maximum depth of 9.5 meters located in the southern overflow region, which includes three islands (Fig. 1). To minimize water loss, the lake bed is lined with membrane and textile layers. At an elevation of 1,267.5 meters above sea level, the lake has a total volume of 6,900,000 m^3, though this capacity decreases to approximately 5,200,000 m^3 by the end of the dry season. Fresh water flowing from the Kan River is diverted into the lake during the winter, causing annual fluctuations in water depth due to evaporation and refilling processes. Water quality monitoring in Chitgar Lake began at five stations in May 2013, as detailed by Emam et al. (2016) and Bayat et al. (2019).

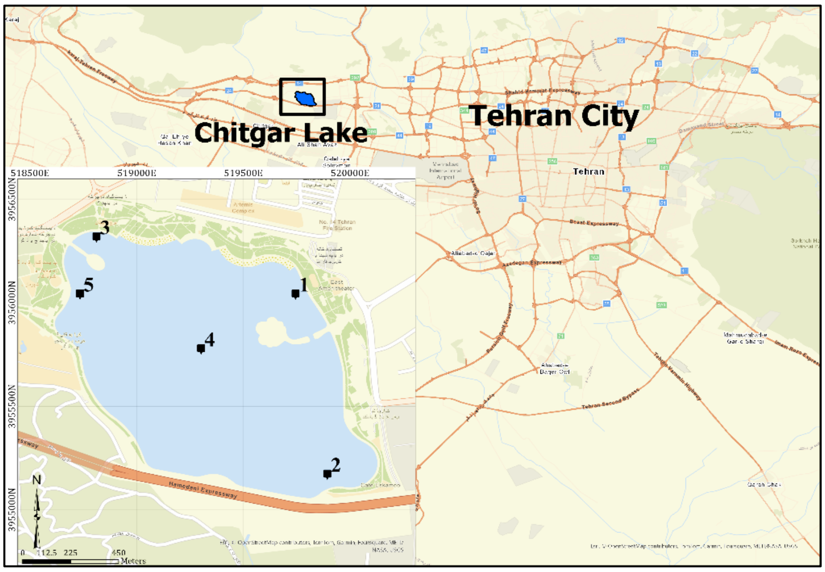

Fig. 1. The Chitgar Lake in Tehran city and the monitoring stations.

2.2. Model framework

For research aimed at managing the water quality of recreational lakes, simple models are recommended. These models not only provide comprehensive simulation results but also reduce run times. Given the relatively small size and area of Chitgar Lake, a zero-dimensional model was developed to simulate the water quality of the reservoir. This model was utilized to predict the reservoir's response to changes in total phosphorus loading from the Kan River during the refilling period, which lasts from January to April for two to four months. Additionally, the model was employed to forecast the water quality of Chitgar Lake during the recycling process, spanning approximately eight to ten months from May to December. In this phase, the model assessed the water quality response to different treatment methods, including physical and physico-chemical processes.

2.3. Model setup

The model developed for this study was written in VBA as an excel Macro and it integrates various water quality parameters and meteorological data to assess the dynamics of Chitgar Lake from 2013 to 2021. The key components of the model include:

Water Quality Parameters:

- Dissolved Oxygen (DO): Essential for aquatic life, indicating the health of the ecosystem.
- Total Suspended Solids (TSS): Affects light penetration and, consequently, photosynthesis.
- Total Phosphorus (TP) and Total Nitrogen (TN): Nutrients that can lead to eutrophication if present in excess.
- Nitrates (NO_3^-) and Phosphates (PO_4^{3-}): Specific forms of nitrogen and phosphorus contributing to nutrient cycling.
- Silica (SiO_2): Important for diatom growth, influencing primary production.
- Temperature (Temp.): Affects metabolic rates of organisms.
- Chlorophyll-a (Chl-*a*): Indicates phytoplankton biomass and overall primary productivity.

Processes Described in the Model:

- The model includes comprehensive descriptions of primary production (photosynthesis by phytoplankton and macrophytes) and secondary production (growth of higher trophic levels).
- It also describes cycles of TN, TP, silica, and DO, highlighting their interconnections and impacts on lake health.

Meteorological Data:

- Data collected from the Chitgar Meteorology Station includes air temperature, relative humidity, cloud cover, precipitation, wind speed, and wind direction. These factors influence evaporation rates, nutrient runoff, and overall lake conditions.

Operational Data:

- Additional variables such as water level, water volume, and flow rates were provided by the Chitgar Lake operational team to ensure accurate modeling of hydrological dynamics.

Water quality parameters for this research were measured at five stations and obtained from the water quality laboratory of Chitgar Lake. The model incorporates detailed process descriptions for primary and secondary production, as well as the cycles of total nitrogen (TN), total phosphorus (TP), silica, and dissolved oxygen (DO). Chlorophyll-a (Chl-a) was included to represent phytoplankton dynamics in the lake, along with other primary producers such as macrophytes and macroalgae. TP, TN, phosphate (PO_4^{3-}), nitrate (NO_3^-), DO, temperature, total suspended solids (TSS), and silica (SiO_2) were analyzed using a spectrophotometer (Hach DR3900) and a DO sensor (Hach LDO). Chl-a was measured using the standard method (method no. 10200 H).

Meteorological data from 2013 to 2021 were obtained from the Chitgar Meteorology Station and included air temperature, relative humidity, cloud cover, precipitation, wind speed, and wind direction. Additional variables such as water level, water volume, and flow were provided by the Chitgar Lake operational team.

3. **Results and discussion**

The statistics presented in Table 1 provide a comprehensive summary of the key water quality parameters analyzed in this study from 2013 to 2021. The mean and median values illustrate the central tendencies of DO, nitrates, TN, orthophosphate, TP, and Chl-*a*, while the maximum and minimum values indicate the range of these parameters. Notably, the exceedance of standard levels for DO, Chl-a, and TP raises potential water quality concerns. The minimum DO level of 3.96 mg/L suggests that the lake has experienced oxygen depletion. Furthermore, the maximum recorded values for TP and Chl-a were 0.20 mg/L and 0.059 mg/L, respectively, both exceeding standard levels. Elevated TP levels can significantly contribute to algal blooms, as increases in this parameter can stimulate the growth of algae and phytoplankton. Rubel et al. (2019) reported similar findings regarding the impact of elevated TP on algal growth in Kaptai Lake. Higher concentrations of Chl-a are often associated with eutrophication phenomena, particularly as its levels in Chitgar Lake consistently surpassed standard thresholds. Sudha and Sangeetha (2017) observed comparable results regarding the increase in Chl-a due to high nutrient levels in Lake Chinna Eri. Additionally, Lindim et al. (2015) emphasized that reducing external phosphorus loads is crucial for managing phytoplankton blooms.

Table 1. Sample statistics of variables used in modelling (2013 to 2021).

	DO (mg/L)	**$N\text{-}NO_3^-$ (mg/L)**	**TN (mg/L)**	**PO_4^{3-} (mg/L)**	**TP (mg/L)**	**Chl-*a* (mg/L)**
Mean	8.28	1.27	2.00	0.022	0.039	0.004
Median	8.03	1.23	1.90	0.015	0.04	0.003
Max	11.50	5.00	5.05	0.20	0.20	0.059
Min	3.96	0.35	0.01	0.004	0.006	0.001
Standard level	>5.00	-	-	-	<0.13	<0.01

The statistics for water quality parameters are presented in Table 2. The median values and ranges indicate notable variations in the water quality of the Kan River. TP in the river ranges from 0.03 to 0.40 mg/L, with a median of 0.07 mg/L. Additionally, elevated levels of turbidity and TN suggest pollution in the upstream section of the river. Similar findings regarding heightened nutrient concentrations due to upstream pollution have been reported by Li et al. (2009) and Zhang et al. (2019) in the Han River. The results also reveal significant improvements in the Kan River's water quality after treatment. Reductions in TN, phosphate (PO_4^{3-}), chlorophyll-a (Chl-a), and TP at the outlet indicate lower algal biomass and improved water clarity. These reductions can be attributed to the removal of suspended solids and turbidity agents from the river water. The water treatment plant (WTP) employs microstrainers and sand filters to effectively eliminate total suspended solids (TSS) from the water. Turbidity levels significantly decreased from 10.80 NTU at the inlet to 0.90 NTU at the outlet. Overall, the data underscores the positive impact of the treatment plant on enhancing water quality parameters in Chitgar Lake.

Table 2. Water quality data for Kan River and Chitgar Lake water treatment plant’s inlet and outlet.

Variables	**Standard Level**	**Kan River**		**Treatment plant**			
				Inlet (Median)		**Outlet (Median)**	
		Median	Range	Refilling	Recycling	Refilling	Recycling
DO (mg/L)	>5	8.10	6.90-11.42	-	-		-
N-NO_3^- (mg/L)	-	4.00	1.00-7.30	2.10	1.10	0.80	0.60
TN (mg/L)	-	2.70	1.00-7.50	2.00	1.30	0.90	0.90
PO_4^{3-} (mg/L)	-	0.06	0.02-0.40	0.05	0.03	0.01	0.01
TP (mg P/L)	<0.13	0.07	0.03-0.40	0.05	0.03	0.01	0.01
Chl-*a* (µg/L)	<10	1.20	0.0001-11	0.01	3.40	0.01	0.80
Turbidity (NTU)	-	44.97	0.31-355.0	10.00	2.9	0.80	0.90

Over the nine years of monitoring water variables, the performance of the proposed model was evaluated by comparing simulated results with measured data. The simulated variables presented in Figs. 2 to 5 offer a comprehensive overview of how different treatment scenarios impact water quality parameters in the lake. Fig. 2 illustrates the first scenario, where varying treatment efficiencies during the recycling and refilling processes result in consistent trends in TN, NO_3^-, Chl-*a*, TP, and PO_4^{3-} levels. The model results closely align with the measured data, indicating the effectiveness of the treatment processes in improving water quality. In this scenario, all parameters experience a substantial decline, with TP and Chl-a remaining below standard levels for the following two years. Fig. 3, which depicts a scenario with 50% treatment efficiency during refilling only, shows fluctuations in Chl-a and TN levels. In this case, TP and Chl-a remain at high levels while TN decreases. Chl-a is projected to increase dramatically during warm seasons, surpassing threshold concentrations due to the lack of treatment and recycling of water in the lake. The high nutrient content present in the lake water and sediment will gradually be released into the water body in the future. Fig. 4, representing 50% treatment efficiency during the recycling period only, highlights changes in Chl-a concentrations over the same period. This scenario indicates that only Chl-a concentrations will gradually increase. Although the simulated concentrations remain below threshold levels, increased nutrient input from river water will promote the growth of algae and phytoplankton in the lake. Lastly, Fig. 5 shows a scenario with 20% treatment efficiency during both recycling and refilling, indicating variations in TP and Chl-a. In this scenario, which represents physical treatment of both inlet and lake water, Chl-*a* concentrations will gradually increase, ultimately exceeding standard levels. Chl-*a* levels also exhibit significant fluctuations, peaking during warmer months, indicating periods of heightened algal activity, likely linked to nutrient availability. In contrast, TP levels show a relatively stable trend, with minor increases that align with peaks in Chl-a, suggesting a direct relationship between phosphorus inputs and algal growth.

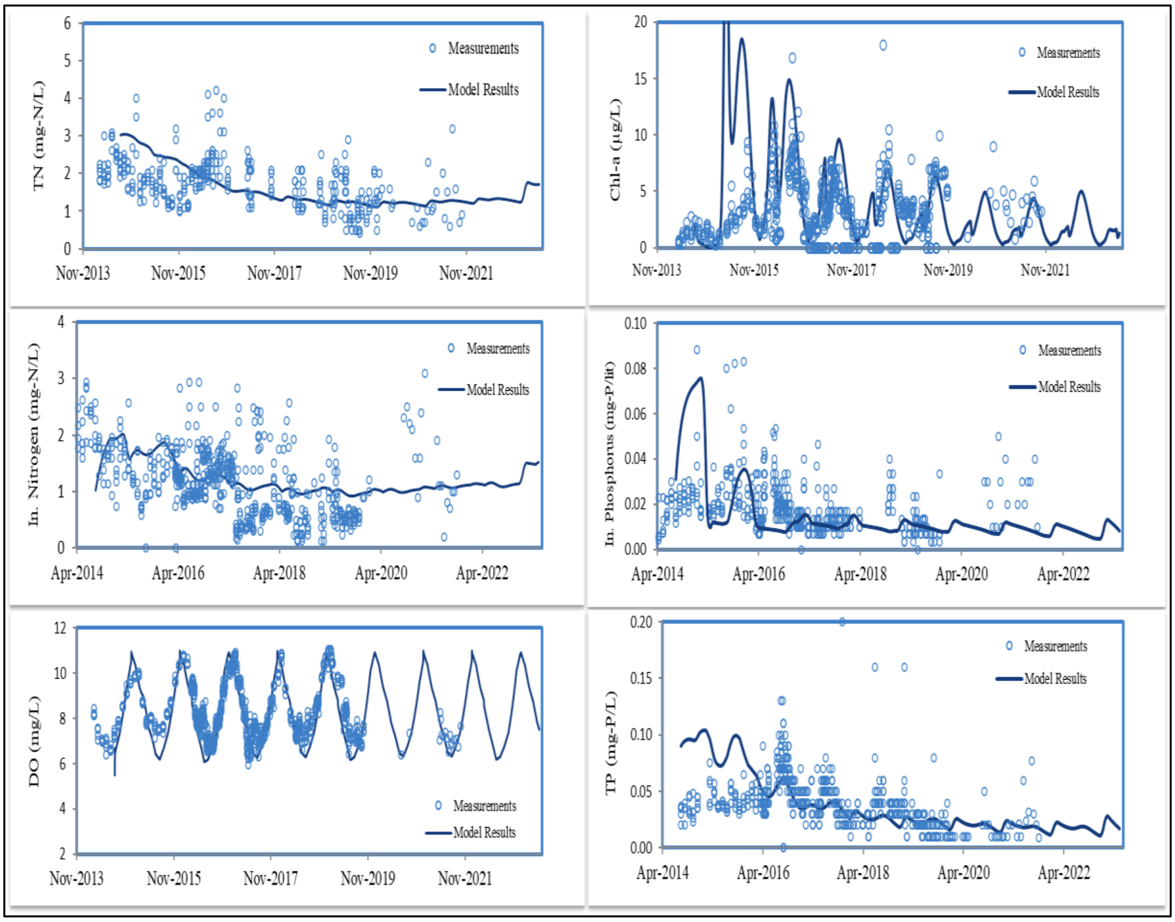

Fig. 2. First scenario- 50 percent efficiency of treatment in both refilling and recycling time.

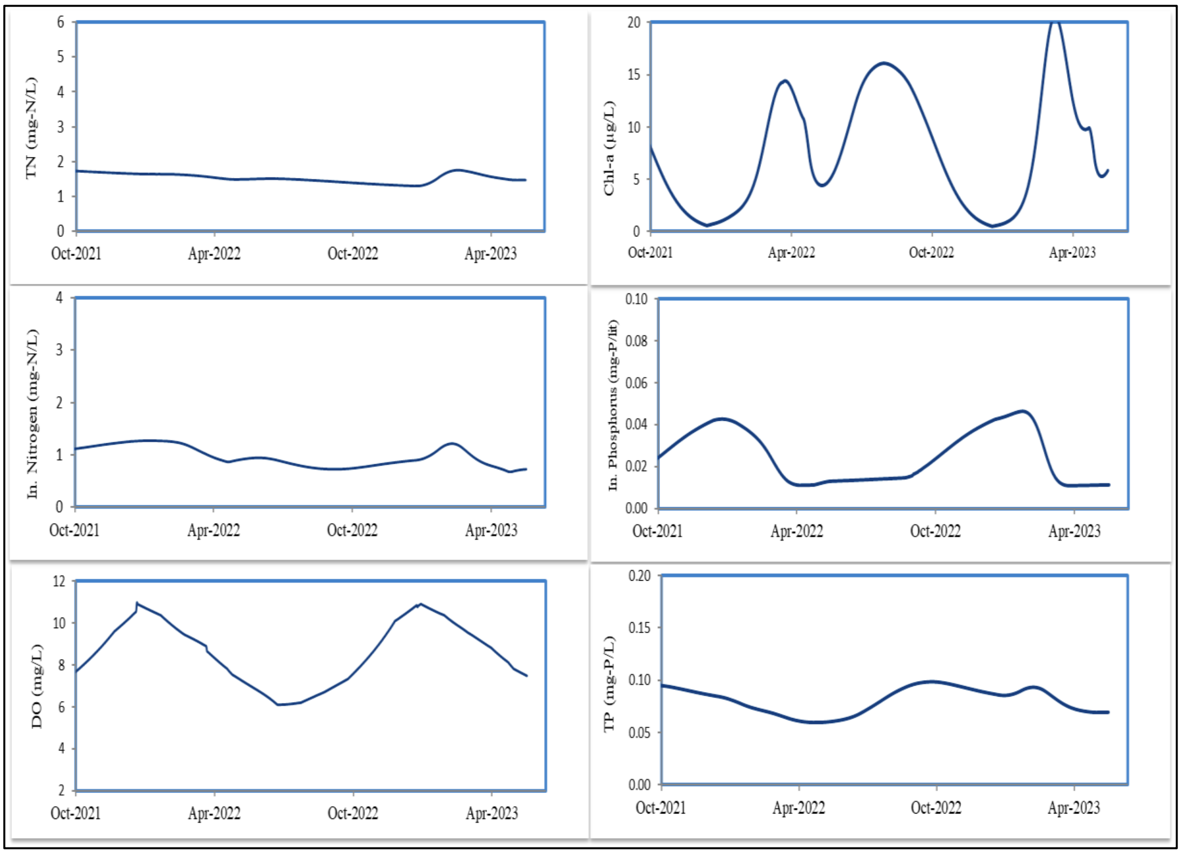

Fig. 3. Second scenario- 50 percent efficiency of treatment in refilling time only.

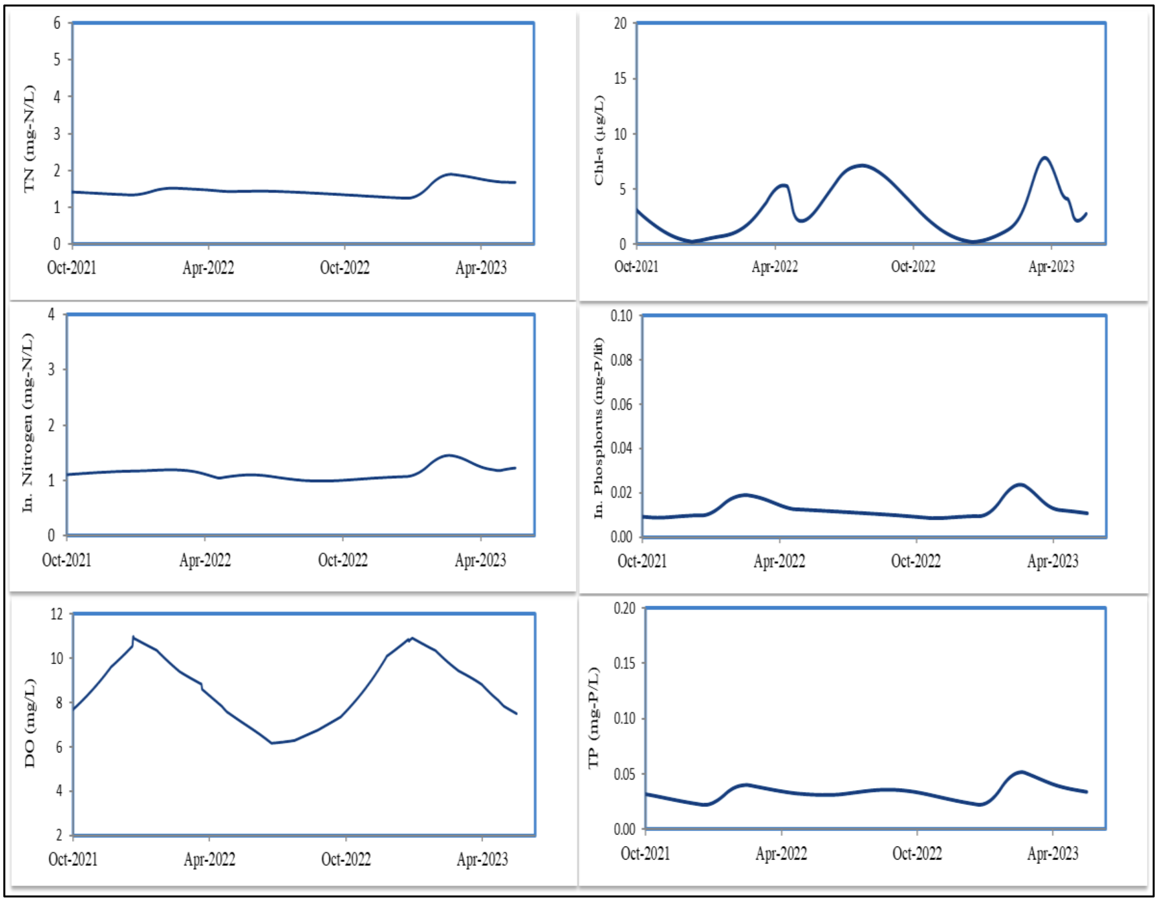

Fig. 4. Third scenario- 50 percent efficiency of treatment in the time of recycling only.

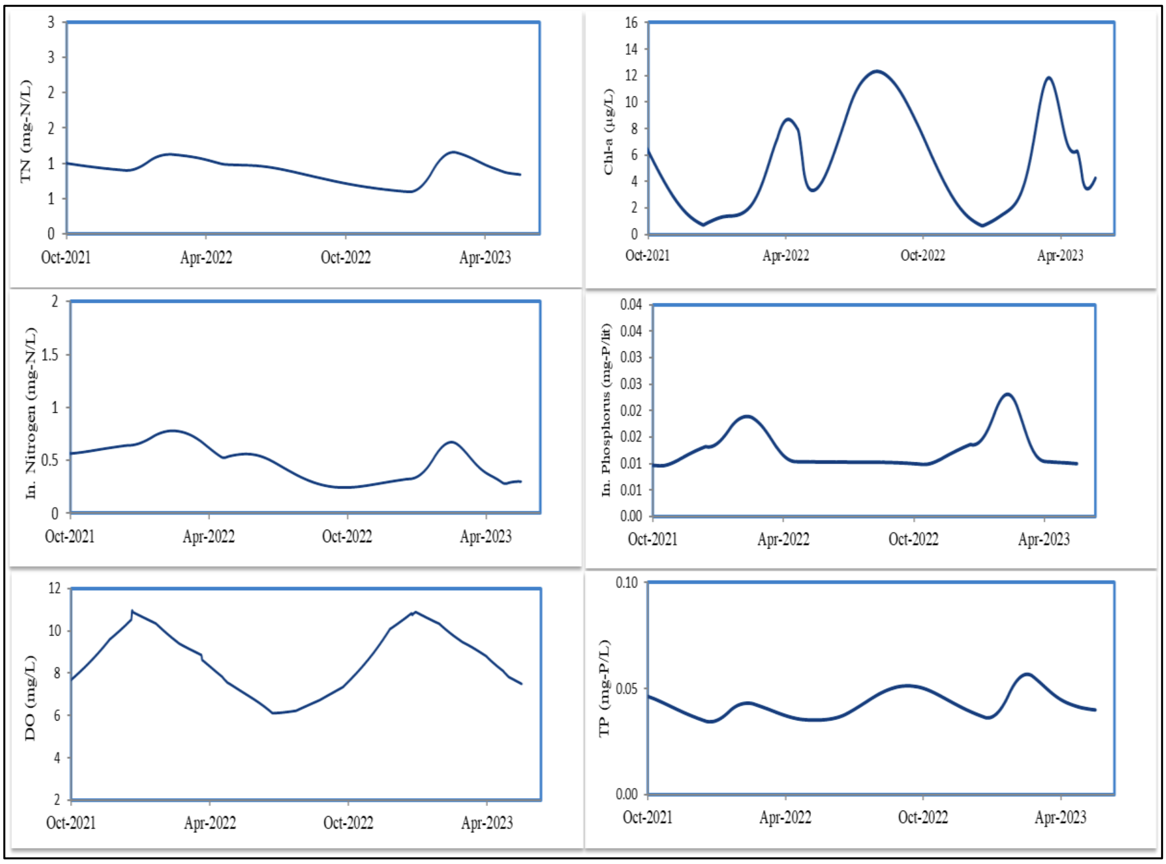

Fig. 5. Forth scenario- 20 percent efficiency of treatment in the time of recycling and refilling (physical treatment).

This study highlights the critical importance of monitoring and analyzing water quality parameters over an extended period, specifically from 2013 to 2021. The comprehensive summary in Table 1 provides valuable insights into the central tendencies and variability of key parameters, including DO, nitrates, TN, orthophosphate, TP, and Chl-*a*. The exceedance of standard levels for DO, Chl-a, and TP indicates potential water quality issues that necessitate immediate management interventions. Notably, a minimum DO level of 3.96 mg/L suggests oxygen depletion in the lake, while elevated TP levels could lead to algal blooms, adversely affecting water clarity and overall ecosystem health.

Table 2 presents statistics for the Kan River and Chitgar Lake water treatment plant, illustrating variations in water quality parameters before and after treatment. High turbidity, TN, and TP levels in the Kan River denote upstream pollution, but significant improvements are observed post-treatment, with reductions in TN, PO_4^{3-}, Chl-*a*, and TP at the outlet. The marked decrease in turbidity levels underscores the treatment plant's effectiveness in removing suspended particles and enhancing water clarity. Overall, these results affirm the positive impact of the treatment plant on water quality in Chitgar Lake. As reported by Bayat et al. (2021-b), implementing water treatment processes has significantly reduced Chl-*a* and TP levels.

The simulated variables shown in Figs. 2 to 5 provide further insights into the treatment plant's efficiency in enhancing water quality parameters. Ideally, a management strategy that treats both lake and river water with at least 50% efficiency (Fig. 2) demonstrates the best outcomes, maintaining all parameters within acceptable limits. This success is attributed to the complete volume of lake water passing through the treatment plant during the recycling period. These findings align with the results of Xing et al. (2014), which reported that reducing nutrient inflow is the most effective strategy for controlling algae growth by emphasizing on phosphorus reduction. Liu et al. (2014) modeled various scenarios regarding the water quality of Dianchi Lake and found that the most effective results were achieved by controlling nutrient loading from the watershed. Their research emphasizes the critical role of inflow nutrients management in mitigating pollution and improving lake health, highlighting the need for strategic interventions in nutrient management practices.

However, scenarios depicted in Figs. 3, 4, and 5 indicate challenges with lower treatment efficiencies. For instance, the second scenario reveals persistent high levels of TP and Chl-*a* due to insufficient treatment during refilling, resulting in algal blooms and nutrient accumulation. The third scenario, focusing treatment only during recycling, shows gradual increases in Chl-*a* concentrations, posing risks to water quality and ecosystem health. While Chl-*a* levels increase, they remain below standards and are lower than in the second and fourth scenarios.

The fourth scenario, involving physical treatment alone, raises concerns as Chl-*a* concentrations exceed standard levels. This emphasizes the necessity for robust treatment processes to mitigate water quality degradation. Interestingly, even with a minimum efficiency of 20%, treating both inlet and lake water yields better control over algal blooms compared to treating inlet water alone at 50% efficiency. Though Chl-*a* concentrations exceed the threshold in both scenarios, the fourth scenario shows lower levels than the second. Additionally, TP concentrations double in the second scenario, highlighting the intricate relationship between TP and Chl-*a* levels. As noted by Lindim et al. (2011), the significant inverse relationship suggests that phytoplankton rapidly consume orthophosphate, converting it to organic phosphorus.

4. Conclusion

The simulation scenarios indicate that the most effective strategy for maintaining water quality in Chitgar Lake is the continuous operation of the water treatment plant during both the refilling and recycling periods. This approach successfully keeps key parameters, such as Chl-*a* and TP, within acceptable limits, effectively preventing eutrophication and ensuring the lake's suitability for recreational activities. The least favorable scenario occurs when only the inlet water is treated, as this results in insufficient treated water volume to cover the entire lake. Therefore, treating both lake and refilling water is essential to manage nutrient levels and prevent algal blooms. In conclusion, this study underscores the need for continuous monitoring, efficient treatment strategies, and proactive management to protect water quality in freshwater ecosystems. By aligning treatment processes with environmental standards and implementing measures to control nutrient influx and algal growth, sustainable water quality management can be achieved, preserving water quality for recreational use and other purposes. Furthermore, developing a model to simulate nutrient concentration trends in lake water could aid in better management and cost-effective treatment strategies, not only controlling algal blooms but also reducing overall treatment expenses. While we have obtained useful results from a zero-dimensional model, it is advisable to employ a two- or three-dimensional model to comprehensively evaluate the effects of all nutrient parameters, including changes in fish species and population sizes.

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