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Evaluating the effectiveness of inlet-focused interventions on the water quality and ecosystem services of urban lakes in the tropics

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Wastewater treatment infrastructure has not kept pace with rapid urbanization in many large cities across the tropics. This has resulted in severe organic pollution affecting urban lakes and reservoirs, with lakeside communities demanding action to protect and restore the water resources. This study compares two restoration interventions aimed at addressing the quality and quantity of inflows of untreated wastewater: diversion channels and sewage treatment and compares these with no intervention measures. The study examines how choice of intervention impacts water quality and the delivery of ecosystem services across eight urban lakes in Bengaluru. The results indicate that, while diversion channels can significantly improve water quality in the target lake, they also present trade-offs that may affect other ecosystem services such as commercial fisheries, groundwater recharge and flood regulation, as well as pushing the wastewater problem downstream. Interventions need to be aligned with the intended uses and management priorities across the city scale. Effective wastewater treatment is clearly the ideal solution for cities, but when wastewater infrastructure is lacking, diversion channels provide some localized benefits. Even with sewage treatment, our study shows that a mix of other local interventions, including constructed wetlands, may be necessary, particularly in tropical monsoon climates, to achieve water quality to sustain biodiversity, fisheries and other provisioning, regulatory and cultural services.

KEYWORDS

ecosystem service, intervention, sewage treatment, urban lakes, wastewater management, water quality index

1 Introduction

Water resources management is central to achieving sustainable development goals (Cosgrove and Loucks, 2015). In urban environments, lakes and reservoirs provide essential ecosystem services including flood regulation, groundwater recharge and recreation, while simultaneously facing intense anthropogenic stress (Da Silva et al., 2021). Among the most pressing challenges is pollution from untreated domestic and industrial wastewater, particularly in rapidly urbanizing tropical regions (Lele and Sengupta, 2018).

The degradation of urban lakes has both immediate and long-term consequences, affecting ecological integrity and the benefits these ecosystems deliver to society (Pickard et al., 2021). The resulting decline in water quality negatively influences biodiversity and reduces the ecosystem services provided by urban lakes (Jamwal et al., 2023).

In many low-middle income countries, wastewater treatment infrastructure has not kept pace with rising populations and the continuous discharge of untreated or poorly treated municipal wastewater and discharges from urban drains have severely impacted water quality of lakes (Gradilla-Hernández et al., 2020). In cities like Bengaluru, pollution of lakes is primarily driven by pollutants from domestic wastewater, surface runoff and industries (Lele and Sengupta, 2018).

Despite global commitments such as UN Sustainable Development Goal (SDG) 6.3.2, to achieve good ambient water quality, data on lake health from many low and middle-income tropical countries remain sparse (United Nations Environment Programme (UNEP), 2024). Urban reservoirs are particularly sensitive to organic pollution and elevated nutrient levels, underscoring the importance of managing inflows and pollutant sources (Kristensen, 2004; Jamwal et al., 2023).

Shallow urban lakes in tropical and subtropical regions face severe water quality challenges from direct untreated wastewater inflows, where seasonal rainfall dynamics introduce large fluctuations in inflow volume and pollutant concentrations (May et al., 2021; Irvine et al., 2023). Yang et al. (2022) highlighted that, despite meeting discharge standards, STP effluents can still cause measurable water quality deterioration in a receiving water body. Kubo et al. (2020) showed that progressive installation of advanced wastewater treatment significantly reduced phosphate loading to a receiving lake, but it can still have low water quality due to non-point pollution sources unaddressed by treatment upgrades. These two studies highlight the limits of inlet focused interventions when catchment-scale pollution persists.

The water quality degradation in lakes has cascading effects on biodiversity, ecosystem functioning and public health. Organic pollution reduces dissolved oxygen concentrations, creating hypoxic conditions that threaten aquatic life and fisheries (Alok and Mohapatra, 2018; Jamwal et al., 2023). Additionally, deoxygenation contributes to increased greenhouse gas emissions, such as methane, from lakes (Pickard et al., 2021). Release of methane from lakes is planned to be included in national inventories under the IPCC framework. This dual ecological and climate burden reinforces the urgency of restoring water quality of urban lakes.

Restoring water quality of lakes can enhance urban water security and environmental sustainability (Cosgrove and Loucks, 2015; Vasistha and Ganguly, 2020). While international policies, such as SDG 6.3 and 6.6 address pollution control and ecosystem restoration, implementation gaps in many low-middle income countries remain significant due to limited monitoring and weak regulatory enforcement (Irvine et al., 2023; United Nations Environment Programme (UNEP), 2017, 2021, 2024).

In India, the Environment (Protection) Rules (1989) set discharge standards for treated effluents but lack holistic metrics to assess overall lake health (Jayakumar, 1987). Although multiple legislations mandate pollution control and lake conservation, they often lack specific water quality criteria or clearly defined institutional responsibilities (Ghosh, 2016; The News Minute, 2018; Gunda et al., 2019). Under the National Plan for Conservation of Aquatic Ecosystems (NPCA), lake water quality is monitored using the "designated best uses" framework developed by the Central Pollution Control Board (Press Information Bureau (PIB), 2023). However, only 41% of NPCA-supported projects focus on conservation and restoration and a mere 10% outline specific water quality goals or management strategies (Jainer, 2020).

Urban lakes across Indian cities have experienced severe water quality deterioration driven by rapid urbanization and direct discharge of untreated or partially treated wastewater into lake inflows (Vasistha and Ganguly, 2020). Qureshimatva et al. (2015) identified domestic effluent as the primary driver at Chandlodia Lake, Ahmedabad. Despite this evidence, systematic comparison of water quality outcomes across multiple lakes under different intervention types remains limited in the Indian context (Vasistha and Ganguly, 2020.

Bengaluru's network of over 200 human-made lakes has been subject to growing research on degradation, governance and restoration outcomes (Lele and Sengupta, 2018; Alok and Mohapatra, 2018). However, most studies have been limited to monitoring and reporting water quality data with limited exploration of using the findings to inform decision-making. Widespread pollution from untreated sewage and industrial effluent has been documented across the city's lakes and have noted a near-complete absence of systematic monitoring data (Alok and Mohapatra, 2018; Ramachandra et al., 2020). Ramachandra et al. (2020) assessed 40 Bengaluru lakes pre and post rejuvenation and found that only 10% achieved good water quality while 53% remained in very poor condition, concluding that restoration outcomes were critically dependent on whether effective pollution management had been implemented alongside physical lake works. Pickard et al. (2021), comparing Bellandur and Jakkur lakes, demonstrated that the contrast between a lake receiving raw sewage and one receiving treated wastewater produced methane concentration differences of three orders of magnitude, establishing that inlet treatment measures have larger consequences on ecosystem services. Jamwal et al. (2023) established that restoration benefits in tropical urban lakes are contingent on sustained management, with lakes receiving well-maintained treated inflows delivering measurably better water quality outcomes. Raj and Jamwal (2024) documented how maintenance deterioration of constructed wetlands at Jakkur Lake reduced treatment effectiveness over time.

In Bengaluru, the Greater Bengaluru Authority (GBA, previously the Bruhat Bengaluru Mahanagara Palike (BBMP)) is the custodian of the majority of the lakes [Greater Bangalore Authority (GBA), 2026; BBMP, n.d.]. Restoration activities included desilting, deweeding, construction of Reinforced Cement Concrete (RCC) drains for sewage or wastewater deviation, installation of silt traps and construction of wetlands (BBMP, n.d.). Specific technical interventions, such as diversion channels at point-source inlets are used to prevent untreated or partially treated wastewater flow into the cities lakes (Lele and Sengupta, 2018; The Hindu, 2019; Financial Express, 2023; Bangalore Mirror, 2023). Additional measures at the inlets include settling tanks and constructed wetlands (Economic Times, 2016; Lele and Sengupta, 2018). Many urban lakes receive treated effluent from sewage treatment plants (STPs) and this effluent has become the main dry-season water source (Economic Times, 2017; Lele and Sengupta, 2018). Despite treatment, these effluents remain high in nutrients and can trigger harmful cyanobacterial blooms in receiving lakes (Kubo et al., 2020; Jamwal et al., 2023; Fang et al., 2022).

Given the diversity of interventions to address water quality of lakes, this study compares the impact of three intervention categories (diversion channels, STP discharge and no interventions) on lake water quality and ecosystem services across 8 urban lakes in Bengaluru. Subsequently, the study discusses the benefits and limitations of various interventions to inform future urban lake management and policy decisions.

2 Materials and methods

2.1 Data collection and analytical framework

Lakes were selected based on a set of criteria that included location within the city, post-monsoon water spread area, presence of encroachment, estimated lake catchment population density and the presence and operational status of (STPs). The initial list of lakes was compiled using Google Earth and QGIS (version 3.28.4). This was followed by multiple rounds of ground-truthing to assess site conditions and validate the initial lake list. During these field visits, detailed field notes were recorded on inlet-based interventions to manage untreated or partially treated wastewater.

Further classification of the lakes into intervention categories was based on field observations, discussions with lake group members, on-site staff and local residents. Additional information about the lakes was collected including economic activities being carried and the restoration history. Since most lakes lacked regular water quality monitoring and a clear benchmark for defining a "healthy lake," a Water Quality Index (WQI) was used to quantify water quality. The WQI requires only a limited set of parameters and provides predetermined weights and thresholds for assessment. A summary of the data collection and analysis process is presented in Figure 1.

2.2 Study area

Bengaluru, the capital of Karnataka, India, spans 721 km^2 (Greater Bangalore Authority (GBA), 2025; Greater Bengaluru Authority (GBA) GIS viewer, 2026) and is located at an altitude of 920 m above mean sea level (Alok and Mohapatra, 2018). The projected population for the city for 2024 is 14.7 million (Census 2011, n.d.). The terrain of the city rests on three major watersheds: the Koramangala and Challaghatta Valley, Vrishabhavathi Valley and Hebbal Valley. Official estimates list 210 lakes in the city (BBMP, n.d.). However, ground-level assessments suggest only 81 now exist (Raghuram, 2024).

The lakes in Bengaluru receive water through storm drains originally designed to carry rainwater and surface runoff to lakes for storage and subsequent uses such as irrigation and groundwater recharge. However, within the present urban landscape, these lakes primarily function as water receiving and storage structures, while also serving as public nature spaces. Currently, storm drains provide inflow throughout the year, with non-monsoon inflows largely associated with wastewater discharge from domestic and commercial areas. Over time, these drains, initially constructed according to the natural drainage profile of the catchment, have undergone significant modifications, resulting in increasingly complex drainage patterns. Furthermore, lakes can receive treated water from STPs that includes wastewater from outside the catchment.

To capture variations in lake characteristics and intervention types, 8 lakes located within BBMP limits were selected (Table 1; Figure 2). These lakes represent the commonly adopted inlet-based intervention strategies in Bengaluru—diversion channels and STPs (Figure 3). Lakes where inlet channels were fully diverted to prevent the entry of wastewater were classified under the Diversion Channel (DC) category (two lakes: DE and DD). In instances where diversion structures were present but did not fully divert inflow, the lakes were grouped under the DC* category (one lake: AG). Lakes that received inflows from both STPs (treated effluent) and untreated wastewater entering through storm drains were categorized as Partial Treatment (PT) (three lakes: SA, HU and JK). Lastly, lakes that had no structural interventions at their inlets were designated to the No Intervention (NI) category (two lakes: HD and NR).

2.2.1 Water sample collection timing and location

Water sampling was conducted only when no rainfall had occurred within the lake catchment during the preceding seven days. This was verified using local weather reports and through consultations with residents and lake guards. Samples were collected between 8:30 a.m. and 12:00 p.m. from accessible locations with flowing outlet water. In less accessible areas, samples were collected using a clean stainless-steel bucket attached to a nylon rope.

For physical water quality measurements, YSI probes were used either by directly placing the sensors in flowing water or in freshly collected bucket samples where direct access was not possible. Each field measurement was conducted in triplicate, with fresh water collected for every reading across all three sampling rounds. For chemical analyses, water samples were collected in 1 L and 500 mL opaque white HDPE bottles. Prior to sampling, bottles were cleaned with phosphate-free detergent, rinsed with tap water followed by distilled water, air-dried and pre-rinsed with sample water. Immediately after collection, samples were stored in ice boxes containing ice packs and later transferred to a laboratory refrigerator maintained at 4 °C, following APHA protocols (American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF), 2005; Table 2).

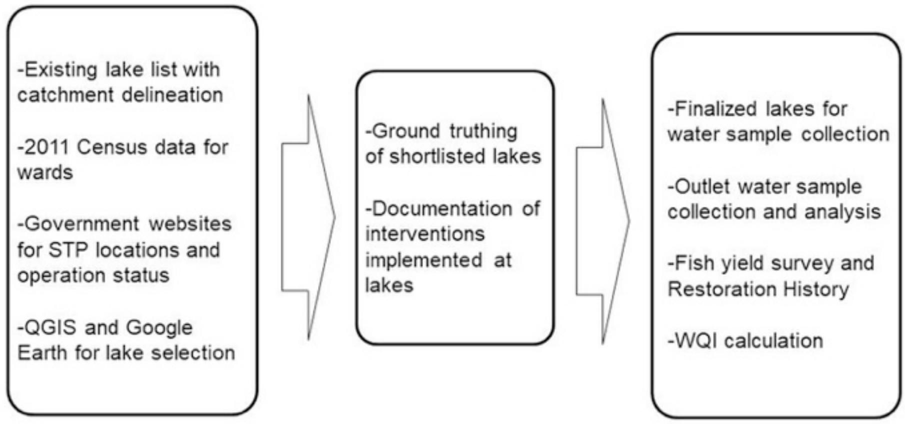

FIGURE 1
Lake selection and data analysis flowchart.

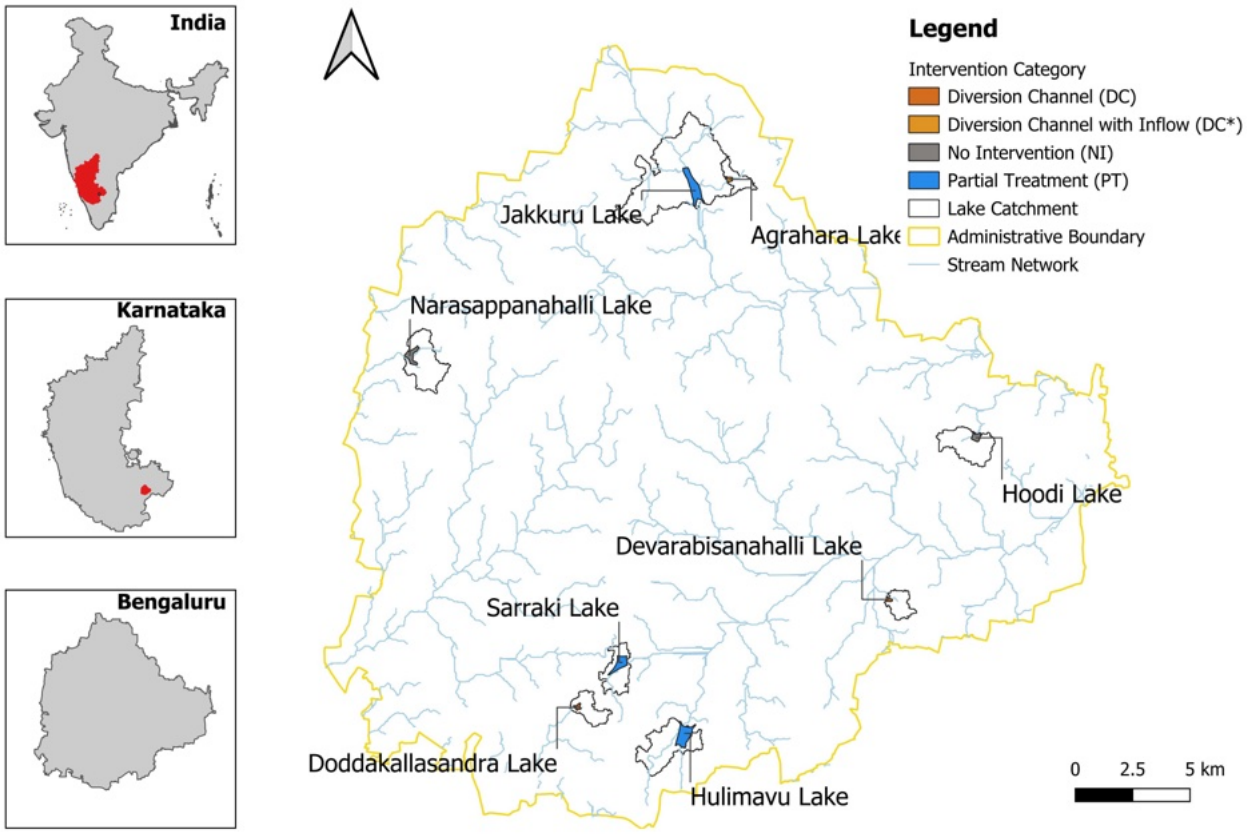

FIGURE 2
Map showing lake locations and their catchments in Bengaluru city, Karnataka, India.

2.2.2 Water sample collection frequency and parameters measured

Each lake was sampled three times between February and July 2022. Each round of sampling was considered as independent observations for the study lakes. During the first two sampling rounds, three replicate water samples (1 L each) were collected from each site and water quality was analyzed using either field probes or standard laboratory methods (see Table 2). In the third sampling round, a single composite sample (1 L and 500 mL) was collected per site, followed by triplicate laboratory analyses to improve analytical reliability. The measured water quality parameters, analytical methods and relevant standards are presented in Table 2. Microbiological parameters were outside the

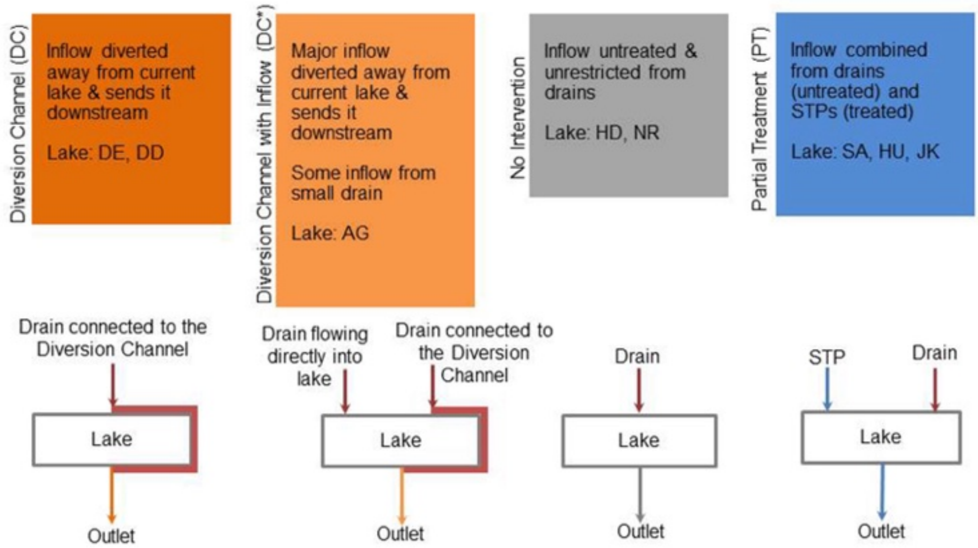

FIGURE 3
Schematic diagram showing the intervention locations and inflows entering the lakes for the different intervention categories.

TABLE 1 Summary of lake and catchment features.

Intervention category	Lake name (code)	Lake area (Ha)	Lake catchment area (km^2)	STP treated inflow 2022 (MLD)*
DC	Devarabisanahalli lake (DE)	3.9	1.08	0
	Doddakallasandra lake (DD)	5.2	1.39	0
DC*	Agrahara lake (AG)	4.5	0.97	0
NI	Hoodi lake (HD)	9.1	2.67	0
	Narasappanahalli lake (NR)	17.3	3.14	0
PT	Sarrakki lake (SA)	23.0	1.95	4.61
	Hulimavu lake (HU)	39.1	3.53	6.98
	Jakkur lake (JK)	51.6	12.29	15.00

*Based on BWSSB STP website (https://stpp.bwssb.gov.in/) and on ground interviews.

scope of this study as the lakes assessed are not used for swimming or direct-contact recreation.

YSI probes used for field measurements were calibrated against YSI standard solutions according to manufacturer guidelines within 24 h before being used in the field. For parameters measured in the laboratory, standard solutions were prepared and shelf-stable quality check solutions, and both were run alongside analyses following APHA protocols and standard methods (Table 2). For all sampling rounds, the relative standard deviation (RSD) among sample replicates was maintained at $\leq$15% (Mitchell, 2006; USGS, 2016).

2.2.3 Fish yield data collection and lake rejuvenation history survey

Data on fish yield and sales were collected through interviews with local fishing communities. Information included commonly caught species, estimated weekly catch (kg per week) and associated income from its sale. Restoration histories for the lakes were obtained by contacting lake group members to contextualize observations and intervention timelines (Supplementary Tables 9, 10).

2.3 Preliminary data analysis

The dataset was saved in.xlsx and.csv formats for analysis. The mean and standard deviation of water quality parameters for each intervention were calculated using MS Excel. For statistical analyses, the dataset was analyzed in R software (R Core Team, 2023) using the.csv file. The distribution of each parameter was assessed for skewness and kurtosis using the "moments" package (Komsta and Novomestky, 2022), and normality was assessed using Shapiro-Wilk test (Shapiro and Wilk, 1965; R Core Team, 2023; Da Silva et al., 2021; Castro et al.,

TABLE 2 Summary of water quality parameters measured.

Parameter type	Parameter	Method/instrument used		Standard/protocol followed	Additional notes
Physical	pH	YSI probes		Calibrated in laboratory as per manufacturer guidelines	Measured in the field
	Electrical conductivity (EC)				
	Dissolved oxygen (DO)				
	Temperature (Temp)				
	Total Suspended Solids (TSS)	APHA-—2540 D		American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF), 2005	Laboratory analysis
Chemical	Total Biochemical Oxygen Demand (TBOD)	APHA-—5210 B			Laboratory analyses. Blanks and standard solutions used
	Total Chemical Oxygen Demand (TCOD)	APHA-—5220 B			
	Nitrate (NO_3-N)	HACH DR300 pocket colorimeter		American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF), 2005 protocol for sample preservation & processing	
	Ammonium-nitrogen (NH_4-N)	Merck spectroquant prove 600	Merck kit (Cat. No. 114752 & 100683)		
	Total nitrogen (TN)		Merck kit (Cat. No. 114963 & 114773)		
	Total phosphorus (TP)		Merck kit (Cat. No. 114687 & 114848)		
	Phosphate (PO_4-P)		Merck kit (Cat. No. 114848 & 114842)		
	Phenolphthalein and Total Alkalinity (Ph.Al, T.Al)	APHA-—2320 B		American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF), 2005	

2023). Spearman correlation analysis (Spearman, 1904; R Core Team, 2023) was conducted to examine relationships among parameters (Da Silva et al., 2021). The Kruskal-Wallis test (Kruskal and Wallis, 1952; R Core Team, 2023) was used to assess whether differences in parameter concentrations across intervention categories were statistically significant (Da Silva et al., 2021). For significant differences detected ($p < 0.05$), Dunn's multiple comparison test with Bonferroni adjustment was conducted for *post-hoc* pairwise comparisons (Dunn, 1964; Ogle et al., 2025). All graph plots were generated using "ggplot2" (Wickham, 2016) and "ggpubr" (Kassambara, 2023) packages.

2.3.1 Water Quality Index calculation

Given the complexity of water quality as a multi-parameter concept, composite tools such as Water Quality Indices (WQIs) are especially valuable (Tiwari and Mishra, 1985; Singh, 1992; Mishra and Patel, 2001; Naik and Purohit, 2001; Ravikumar et al., 2013). The Water Quality Index (WQI) that integrates parameters such as Ammonium, Dissolved Oxygen and Biological Oxygen Demand to classify surface water bodies was used for analysis (Gazzaz et al., 2012; Uddin et al., 2021). The index employs quality function curves and predefined weights established by expert consensus (Khuan et al., 2002; Uddin et al., 2021), making it suitable for assessing water quality in regions without specific legal or policy criteria.

The Water Quality Index (WQI) was estimated for the 8 lakes, using outlet water quality data, following the formula and sub-index equations published by Uddin et al. (2021) without any changes. The WQI was calculated as a weighed sum of six sub-indices (Formula 1). Sub-index values were calculated using the best-fit equations and threshold values defined in Uddin et al. (2021; Table 3). All calculations were done in MS Excel.

WQI formula $= 0.22SI_{DO} + 0.19SI_{BOD} + 0.16SI_{COD} + 0.15SI_{AN} + 0.16SI_{SS} + 0.12SI_{pH}$ (1)

TABLE 3 WQI sub index calculations for the water quality parameters used (Uddin et al., 2021).

Water quality parameter	Threshold value	Best fitted sub-index equations
DO (% saturation)	For $x \leq 8$	$SI_{DO} = 0$
	For $x \geq 92$	$SI_{DO} = 100$
	For $8 < x < 92$	$SI_{DO} = -0.395 + 0.03x^2 - 0.0002x^3$
BOD (mg/L)	For $x \leq 5$	$SI_{BOD} = 100.4 - 4.23x$
	For $x > 5$	$SI_{BOD} = 108e^{(-0.055x)} - 0.1x$
COD (mg/L)	For $x \leq 20$	$SI_{COD} = -1.33x + 99.1$
	For $x > 20$	$SI_{COD} = 103e^{(-0.0157x)} - 0.04x$
NH_3-N (mg/L)	For $x \leq 0.3$	$SI_{AN} = 100.5 - 105x$
	For $0.3 < x < 4$	$SI_{AN} = 94e^{(0.573x)} - 5\|x\text{-}2\|$
	For $x \geq 4$	$SI_{AN} = 0$
SS (mg/L)	For $x \leq 100$	$SI_{SS} = 97.5e^{(-0.00676x)} + 0.05x$
	For $100 < x < 1{,}000$	$SI_{SS} = 71e^{(-0.0016x)} + 0.015x$
	For $x \geq 1{,}000$	$SI_{SS} = 0$
pH	For $x \leq 5.5$	$SI_{pH} = 17.02 - 17.2x + 5.02x^2$
	For $5.5 < x \leq 7$	$SI_{pH} = -242 + 95.5 \times -6.67x^2$
	For $7 < x < 8.75$	$SI_{pH} = -181 + 82.4x - 6.05x^2$
	For $x \geq 8.75$	$SI_{pH} = 536 - 77x + 2.76x^2$

3 Results

3.1 Water quality profile across interventions

Concentrations of nutrients and organic pollution parameters showed a clear intervention-driven gradient. Lakes with diversion channels, DC and DC* categories, had the lowest overall concentrations (Figures 4–7; Supplementary Table 1). PT category lakes displayed intermediate nutrient concentrations. They had the highest organic concentration, but better DO levels than NI category lakes. NI showed the highest nutrient and chemical pollution levels. They also exhibited high variability, particularly in DO and nutrients. This indicates toward variable inflow quality and a less stable lake system within NI. Variation in pollutant concentrations was lower in PT compared to NI. Overall, PT showed partial improved water quality compared to NI, but were below the water quality levels observed in DC and DC*.

3.1.1 Physical parameters

DC and DC* categories had pH in the alkaline range, lower and closer to neutral in NI category and intermediate in PT category (Figure 4). Temperature (Temp) showed minimal variation amongst intervention categories. Electrical Conductivity (EC) displayed a clear intervention gradient, with NI exhibiting the highest concentrations and variability (1,853 ± 398.6 µS/cm), followed by PT and DC*, with DC category having the lowest values (353 ± 154 µS/cm; Figure 4). DC* showed the highest mean DO concentration (8.1 ± 4.61 mg/L), followed by DC and PT, while NI recorded the lowest concentrations with high variability (2.7 ± 4.66 mg/L. TSS concentrations were similar for all the intervention categories with high within group variability.

3.1.2 Organic and oxidizable matter profile

Interventions differed clearly in organic matter concentration. DC recorded the lowest TBOD (1.8 ± 1.2 mg/L; Figure 5). DC* showed slightly higher TBOD than DC (5.5 ± 1.5 mg/L). NI exhibited elevated TBOD (9.4 ± 5.6 mg/L). PT showed high mean TBOD value with variability (14.7 ± 12.37 mg/L). Similarly, TCOD concentration was lowest in DC (27.8 ± 7.97 mg/L). DC* showed moderate increases relative to DC, consistent with partial inflow exposure (Figure 5). NI had the highest TCOD (170.7 ± 55.58 mg/L). TCOD concentration of PT was moderate (80.1 ± 31.61 mg/L).

3.1.3 Nutrient profile

Nitrogen species exhibited a consistent pattern across intervention categories. NO_3-N concentrations were lowest in DC and DC* categories (Figure 6). PT category showed slightly higher mean NO_3-N value (1.0 ± 0.95 mg/L). NI category displayed greater variability (2.3 ± 4.54 mg/L). NH_3-N remained minimal in DC (0.01 ± 0.016 mg/L) and DC* (0.02 ± 0.012 mg/L), increased moderately in PT (0.2 ± 0.21

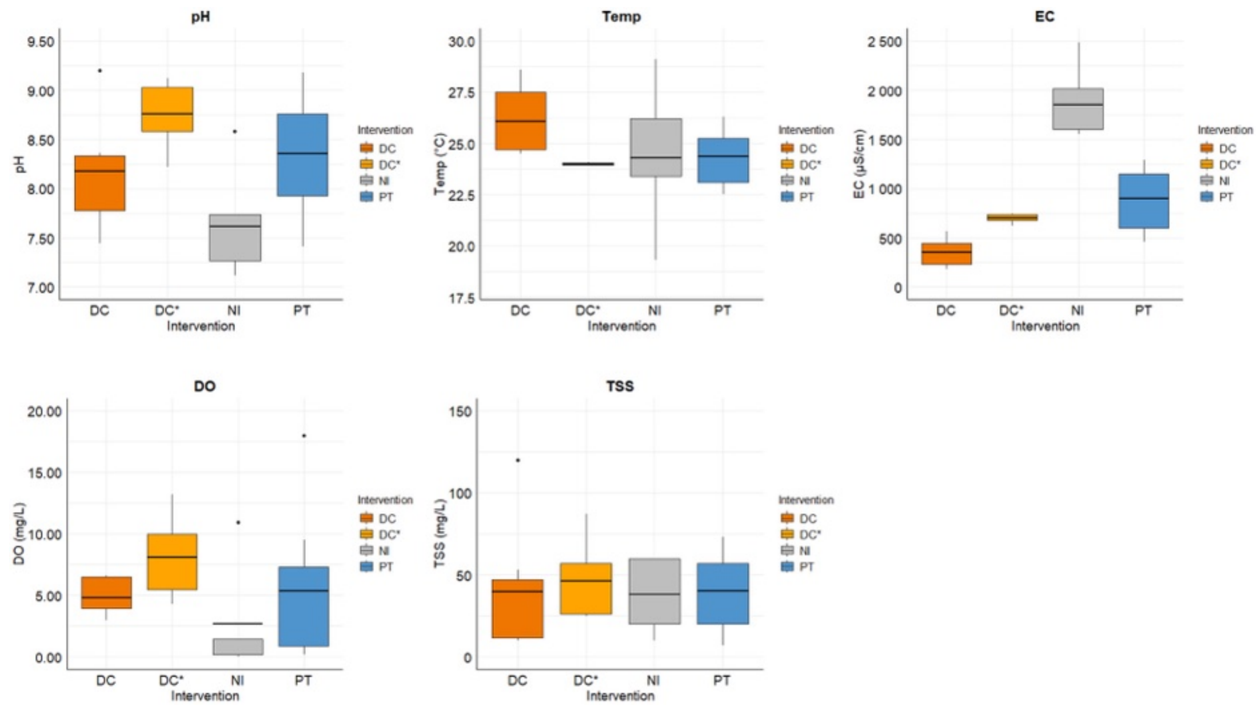

FIGURE 4
Boxplots of physical parameters concentrations across intervention categories, showing mean (line) and 25th and 75th percentiles (boxes).

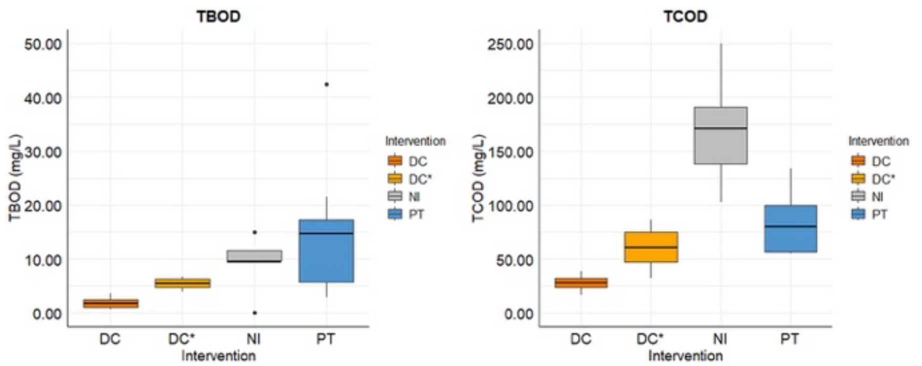

FIGURE 5
Boxplots of organic and oxidizable matter across intervention categories, showing mean (line) and 25th and 75th percentiles (boxes).

mg/L) and was higher and more variable in NI (0.2 ± 0.16 mg/L). NH_4-N concentrations were lowest and stable under DC and DC* (Figure 6), increased in PT and were elevated and highly variable in NI (23.7 ± 41.37 mg/L). TN showed a clear gradient, with very low and stable values in DC and DC*, moderate concentrations in PT and the highest levels and variability in NI category (Figure 6). Overall, diversion channels limited nitrogen accumulation, PT demonstrated partial mitigation and absence of intervention resulted in substantial high Nitrogen concentration.

PO_4-P concentrations were lowest in DC and DC* categories (Figure 7). NI category lakes exhibited the highest PO_4-P concentrations (2.9 ± 0.74 mg/L), reflecting untreated phosphorus inputs. PT category showed intermediate PO_4-P concentrations (1.7 ± 1.45 mg/L). TP followed a similar pattern. DC and DC* recorded the lowest TP levels (Figure 7). NI recorded the highest TP concentrations (4.3 ± 1.51 mg/L). PT showed moderate TP values with greater variability (2.5 ± 1.68 mg/L). Overall, diversion channels minimized Phosphorus in the lakes, PT achieved partial reduction and absence of intervention resulted in elevated levels.

Among the 14 measured water quality parameters, 10 parameters (DO, TSS, NO_3-N, NH_4-N, TN, PO_4-P, TP, Total Alkalinity (T.Al), TBOD and TCOD) did not follow a normal distribution, as determined by the Shapiro-Wilk test. The remaining parameters exhibited approximately normal distributions, albeit with some skewness. Consequently, non-parametric statistical tests were employed for subsequent analysis. Detailed results of the normality and skewness tests are provided in Supplementary Table 2.

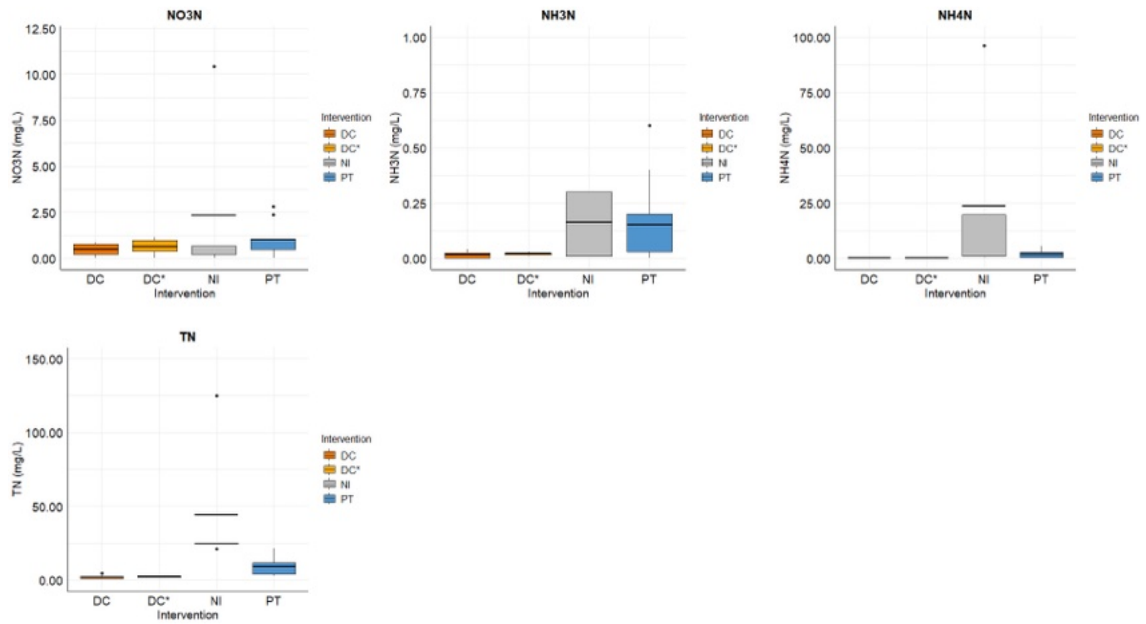

FIGURE 6
Boxplots of Nitrogen species concentration across intervention categories, showing mean (line) and 25th and 75th percentiles (boxes).

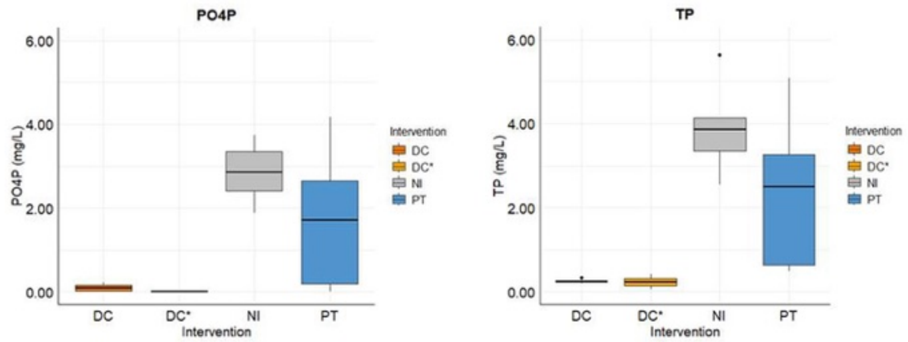

FIGURE 7
Boxplots of Phosphorus species concentration across intervention categories, showing mean (line) and 25th and 75th percentiles (boxes).

3.2 Correlation between chemical parameters

The Spearman correlation test revealed several statistically significant associations among water quality parameters across the eight lakes (Table 4; Supplementary Figure 1). A strong positive correlation was observed between pH and DO.

Significant correlations were also found among NH_4-N, TN, PO_4-P, TP, T.Al, EC and TCOD. These interrelated patterns underscore the complex biogeochemical processes linking nutrient inputs, organic loading and water chemistry in urban lakes. The observed correlations emphasize the cumulative effects of pollution sources on lake water quality.

3.3 Impact of interventions on chemical characteristics of different lakes

The Kruskal–Wallis test identified 8 water quality parameters that exhibited statistically significant differences among the intervention categories, including EC, NH^4-N, TN, PO^4-P, TP, TBOD, TCOD and T.Al (Table 5). Dunn's post-hoc pairwise test (Bonferroni-adjusted *p* value) confirmed that these differences were driven primarily by concentration differences between diversion channel interventions (DC and DC* categories) and the NI category (as the control; Table 5).

The DC category showed the most number of water quality parameters with significant difference in concentration compared to NI category, with lower concentrations across

7 parameters, including EC, NH_4-N, TN, PO_4-P, TP, TCOD and T.Al (Table 5; Figures 4–7; Supplementary Table 1), due to the diversion of untreated inflows from domestic and industrial sources. The DC* category showed significant lower concentration for nutrients when compared to NI (Table 5; Figures 5–7), indicating the benefit of partial inflow diversion. PT category generally showed lower concentrations than NI for most parameters, but not significantly (Table 5; Figures 4, 6, 7). The reduced concentration for most parameters in PT lakes can be attributed to STP treated effluent being a significant part of the inflow. In contrast, elevated TBOD levels in PT category lakes were observed compared to NI lakes (Table 5; Figures 5).

For TBOD, neither DC nor DC* categories differed significantly from NI category (Table 5). The only significant difference for this parameter was between DC and PT (Table 5), indicating that TBOD was lower at DC lakes than at PT lakes (Figure 5), which receive mixed inflow. Similarly, DC vs. PT showed significant difference in TP concentration (Table 5; Figure 7). Taken together, these results indicate a gradient in water quality parameter across the intervention categories. DC achieved the lowest concentrations across the widest range of parameters and DC* demonstrated improvement in water quality with reduced nutrient concentrations. PT showed no statistically significant difference relative to NI, with PT lakes recording intermediate to elevated values due to receiving nutrient-rich treated effluent and organic-rich untreated wastewater (Table 5; Figures 4–7; Supplementary Table 1).

These results indicate that a subset of parameters can differentiate lake water quality across intervention categories. Parameters selected for further analysis and WQI calculation included DO, TBOD, TCOD, NH_3-N, TSS and pH, in accordance with the Water Quality Index framework.

TABLE 4 Water quality parameters with significant strong correlation ($p < 0.001$).

Parameter 1	Parameter 2	Correlation value
pH	DO	0.91
EC	TCOD	0.85
	NH_4-N	0.71
	TN	0.85
	PO_4-P	0.76
	TP	0.79
	T.Al	0.94
TCOD	NH_4-N	0.61
	TN	0.76
	TP	0.75
	T.Al	0.77
NH_4-N	TN	0.81
	PO_4-P	0.85
	TP	0.91
	T.Al	0.72
TN	PO_4-P	0.80
	TP	0.89
	T.Al	0.88
PO_4-P	TP	0.87
	T.Al	0.83
TP	T.Al	0.82

3.4 Water Quality Index

The Water Quality Index (WQI) was computed for each sampling event, following which the mean WQI was calculated for each intervention category (Figure 8; Supplementary Tables 3–6). Based on WQI classification, values from 81–100 denote "Clean", 60–80 indicate "Slightly Polluted" and 0–59 reflect 'Polluted' status as per the WQI framework.

WQI values clearly varied across intervention categories (Figure 8; Supplementary Table 6). DC category lakes were consistently within the "Clean" category (WQI = 93 ± 11.6), indicating effective diversion of wastewater and sustained better water quality. DC* category also largely remained within the "Clean" range (WQI = 83 ± 7.4), though with slightly lower

TABLE 5 Water quality parameters showing statistically significant difference across intervention categories (Kruskal-Wallis test (χ^2) and Dunn's *post-hoc* pairwise test (Z)).

Parameter	χ^2	DC—NI (Z)	DC*−NI (Z)	PT—NI (Z)	Other significant pairwise difference (Z)
EC	17.7***	−4.2***	NS (−2.0)	NS (−2.2)	
NH_4-N	14.0**	−2.9*	−2.8*	NS (−0.9)	
TN	17.8***	−3.9***	−3.0*	NS (−1.9)	
PO_4-P	13.1**	−2.7*	−3.2**	NS (−1.3)	
TP	17.0***	−3.4**	−2.9*	NS (−1.1)	DC—PT (−2.8*)
TBOD	10.9*	NS (−2.1)	NS (−0.4)	NS (0.8)	DC—PT (−3.3**)
TCOD	17.0***	−4.1***	NS (−1.9)	NS (−2.0)	
T.Al	15.3**	−3.8***	NS (−2.4)	NS (−2.0)	

Significance thresholds: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, NS = not significant. Comparisons are directional (negative Z indicates lower values in the first named group relative to the second).

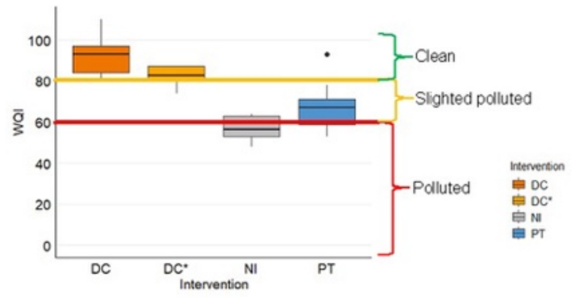

FIGURE 8
Water Quality Index (WQI) of the intervention categories.

mean values, reflecting minor influence of residual inflows. PT category lakes predominantly fell within the "Slightly polluted" category (WQI = 67 ± 13.2), indicating partial water quality under mixed inflow conditions. NI category lakes recorded the lowest WQI (56 ± 6.8), mostly within the "Polluted" to lower "Slightly polluted" range, reflecting degraded conditions in the absence of any interventions. Overall, complete diversion maintained clean water quality status, partial diversion retained generally good quality, mixed inflows led to moderate impairment and lack of intervention resulted in poor water quality.

4 Discussion

Most prior studies on Bengaluru's urban lakes have been limited to monitoring and reporting water quality data, with limited exploration of how these findings can inform restoration decisions (Alok and Mohapatra, 2018; Ramachandra et al., 2020). This study addresses that gap by integrating water quality measurements, on-ground inlet-based intervention infrastructure implemented for restoration of urban lakes and ecosystem service indicators across 8 lakes under three intervention categories. The study demonstrates integration of multiple datasets to support evidence based urban lake restoration planning.

4.1 Water quality outcomes across intervention categories

4.1.1 Water quality characteristics across intervention categories

The water quality patters across intervention categories were broadly consistent, with DC having the lowest concentrations for most measured parameters, followed by DC* and PT, while NI had overall high concentrations for the measured water quality parameters. All intervention categories recorded pH within the Central Pollution Control Board (CPCB) recommended range of 6.5–8.5 for Class D water use [waters supporting aquatic life; Central Pollution Control Board (CPCB), n.d.], although DC* approached the upper bound of this range (Figure 4). Temperature showed minimal variation across categories (Figure 4). EC displayed a clear intervention gradient, with NI exhibiting the highest values (1,853 ± 398.6 µS/cm) and DC the lowest (353 ± 154 µS/cm; Figure 4), consistent with the well-documented role of urban and industrial discharges in elevating ionic concentrations through salt inputs that also influence T.Al and NH_4-N oxidation (Leoni et al., 2018). DO levels in DC, DC*, and PT exceeded the CPCB minimum of 4.0 mg/L for Class D [Central Pollution Control Board (CPCB), n.d.], whereas NI frequently fell below this threshold and below the Class III (fishery guideline) of 3.0–5.0 mg/L (Environmental Quality Report (EQR), 2020), indicating oxygen stress driven by continuous untreated inflows. TSS concentrations were similar across categories (Figure 4) and largely within the Class III recommended range of 50–150 mg/L (Environmental Quality Report (EQR), 2020), suggesting that suspended solids are governed by factors beyond intervention type alone.

Organic and oxidizable matter concentrations followed a similar pattern (Figure 5). DC recorded the lowest TBOD (Figure 5), below the Class III recommended range of 3.0–6.0 mg/L (Environmental Quality Report (EQR), 2020), while DC* showed slightly elevated values (5.5 ± 1.5 mg/L) within this range, consistent with limited residual inflow exposure. NI exceeded the Class III TBOD standard, reflecting untreated organic inputs. PT exhibited the highest mean TBOD (14.7 ± 12.37 mg/L) with high variability, and in instances exceeding NI, reflecting both nutrient-driven phytoplankton respiration (not offset by photosynthesis in dark conditions) and the partial inflow of organic-rich untreated effluent (Jamwal et al., 2023; Kubo et al., 2020). TCOD showed a similar pattern, with DC (27.8 ± 7.97 mg/L) within the Class III recommended range of 25.0–50.0 mg/L (Environmental Quality Report (EQR), 2020), whereas NI recorded the highest values (170.7 ± 55.58 mg/L), exceeding all guidelines (Environmental Quality Report (EQR), 2020) and reflecting strong chemical pollution from untreated inflows. PT showed moderate TCOD (80.1 ± 31.61 mg/L), above the Class III recommended range, suggesting only partial reduction of organic and chemical load through treated effluent inflow (Figure 5). The interaction among TCOD, TN, and TP through nutrient cycling processes further sustains elevated chemical oxygen demand in less managed systems (Yang et al., 2022). Overall, diversion channels reduced total organic and oxidizable matter burden, while mixed or untreated inflows increased oxygen demand in the lakes.

Nitrogen and Phosphorus species exhibited consistent patterns across intervention categories. NO3-N concentrations were lowest in DC and DC* (Figure 6), followed by PT with NI displaying the highest concentration values with greater variability (2.3 ± 4.54 mg/L), indicating episodic inputs. NH_3-N remained within the Class III recommended range of 0.3–0.9 mg/L (Environmental Quality Report (EQR), 2020) across all categories. NH_4-N was lowest and stable under DC and DC* (Figure 6) and elevated and highly variable in NI (23.7 ± 41.37 mg/L), indicating ammonium inputs from untreated sewage (Da Silva et al., 2021). TN followed the same pattern, with lowest values in DC and DC*, moderate concentrations in PT, and the highest concentrations and variability in NI. Phosphorus followed a similar pattern, with NI recorded the highest PO_4-P (2.9 ± 0.74 mg/L) and TP (4.3 ± 1.51 mg/L), while DC and DC* recorded the lowest levels and PT showed intermediate values (PO_4-P- 1.7 ± 1.45 mg/L; TP- 2.5 ± 1.68 mg/L; Figure 7).

The strong positive correlation between pH and DO (Table 4) observed across all categories likely reflects enhanced daytime photosynthesis, whereby algal activity elevates dissolved oxygen and shifts bicarbonate equilibria toward higher pH (Stumm and Morgan, 1981). The significant positive correlation among NH_4-N, TN, PO_4-P, TP, T.Al, EC, and TCOD (Table 4) points to a common source of nutrient and ionic enrichment, consistent with inputs of untreated domestic and industrial wastewater (Da Silva et al., 2021). The positive correlation between T.Al and TCOD (Table 4) reflects alkalinity-driven stimulation of organic matter decomposition and altered nitrogen cycling (Qureshimatva et al., 2015; Yang et al., 2022).

4.1.2 Water Quality Index (WQI) across intervention categories

Lakes with diversion channels (DC and DC*) recorded the highest WQI values and were classified as "Clean". PT category lakes, which received mixed inflows of treated and untreated effluents, were classified as "Slightly polluted", while NI category lakes fell into the "Polluted" category (Figure 8). The water quality of DC can be attributed to prevention of untreated wastewater entry during the dry season and dilution of pollutants during the monsoon overflows. The water budget in these lakes is primarily composed of rainfall. Overflows from storm drains with the diversion channel enter the lakes only during high rainfall events, during which pollutant concentrations are diluted by rainwater and mitigated by the diversion channel design. Such lakes also tend to have extensive macrophyte growth (Supplementary Photos 1, 2) which may further enhance the water quality by assimilating excess nutrients and organic pollutants (Brix, 1994; Song et al., 2019).

The DC* category lake received some dry-season inflows (∼3% of total volume; Supplementary Table 7), contributing to a slightly lower WQI value than the DC category lakes. Nevertheless, it remained within the "Clean" classification due to the diversion of the majority of polluted inflows. This lake also exhibited a lower presence of shoreline vegetation compared to DC category lakes, which could be resulting in reduced benefits in nutrient and organic pollutant reduction (Brix, 1994; Song et al., 2019; Raj and Jamwal, 2024).

PT category lakes retained water during the non-monsoon period (February–July 2022) and had inlet-focused interventions, received a combination of wastewater from storm drains and treated effluent from STPs as recorded during field observations. This mixed inflow resulted in only partial treatment, leading to reduced Water Quality Index (WQI) values, categorizing these lakes as "Slightly polluted". These lakes were recorded to have either had a constructed wetland or setting tank at their inlets to handle treated water or wastewater inflow (Supplementary Table 10), but not for both types of inflows or not of adequate capacity. As a result, improvement in water quality was limited. The relative contributions from constructed wetlands or setting tanks were not quantified separately in the study. These outcomes are consistent with the broader pattern documented across Bengaluru's lake network, with Ramachandra et al. (2020) noted that only 10% out of 40 restored lakes achieved good water quality, attributing poor outcomes primarily to continued inflow of untreated or partially treated sewage.

Within the PT category, Sarrakki Lake (SA), which underwent restoration between 2020 and 2021 and was equipped with both settling tanks and constructed wetlands at its inlets, exhibited higher water quality compared to Jakkur Lake (JK), where restoration was carried out earlier between 2008 and 2012 (Supplementary Table 10). The infrastructure at JK has not been adequately maintained in recent years, as reported in Raj and Jamwal (2024), and field observations during this study noted the accumulation of biomass and pollutants in its wetland treatment basin. These materials are documented to be susceptible to being flushed into the main lake body during heavy rainfall events (Da Silva et al., 2021), and could contribute to JK having a lower WQI compared to SA (Supplementary Table 3). Hulimavu Lake (HU), which had not undergone recent restoration during the study period, exhibited the lowest WQI among the partially treated (PT) lakes (Supplementary Table 3). The absence of maintenance or effective inlet treatment infrastructure would be a likely contributing factor to the poor water quality observed in HU. Similar lakes have been documented to accumulate pollutants in the dry season, resulting in deteriorating water quality if inflows are not managed correctly (Da Silva et al., 2021).

NI category lakes were the most polluted with the lowest WQI values (Supplementary Table 3, 6), with field observations confirming these lakes received untreated water from storm drains. Lake Narasappanahalli Lake (NR) reported to receives both domestic and industrial effluent, including heavy metals and other toxic chemicals (Ram, 2017).

4.2 Ecosystem services trade-offs across intervention categories

The water quality outcomes documented above are accompanied by trade-offs in ecosystem service potential that are equally important for urban lake management decisions. Although lakes with diversion channels (DC and DC* categories) exhibited better water quality, they retained lower water volume compared to lakes receiving mixed inflows. This reduced water availability during the dry season is associated with differing ecosystem service potential and stakeholder opportunities. Low pre-monsoon water levels in these lakes suggest a more storage capacity availability for excess runoff, which may contribute to flood buffering and potential groundwater recharge in urban lakes (Ravikumar et al., 2013). These outcomes were not measured in this study, and the extent of such ecosystem services will be dependent on site-specific conditions. The relative benefits of such lakes are therefore contingent on the ecosystem services prioritized by the city.

In contrast, PT lakes, receiving mixed inflows retain water throughout the pre-monsoon season, as recorded during the study period. Such lakes offer different ecosystem service opportunities.

TABLE 6 Details from fish catch survey carried out at lakes with fishing contracts.

Lake	Fish yield approximate (kg/week)	Fish varieties	Monthly income approximate (INR)
Sarrakki (SA)	175	Raghu, Katla, Mirgal, Jilabi	5,500
Jakkur (JK)	75	Raghu, Katla and Mirgal	4,000

Sustained water in these lakes supports year-round groundwater recharge (Ravikumar et al., 2013), which was not directly measured in this study. These lakes also sustained economic activities such as commercial fishing. Among the three lakes in the PT category, two, SA and JK, had active fishing contracts during the study period, contributing to local livelihoods (Table 6).

4.3 Study limitations and future scope

This study was conducted over several months in the pre-monsoon season (February–July 2022). This temporal scope was chosen as water quality in tropical urban lakes is typically poorest during the dry season when pollutant concentrations are undiluted by rainfall, and inflows are dominated by wastewater (Da Silva et al., 2021; May et al., 2021). Monsoon sampling was not included as it raises many logistical challenges around comparable sampling locations and personal safety and the pollution signal is typically masked by the high volumes of rainfall. We acknowledge that the single-season design is a limitation of the study that warrants further consideration. The dataset should accordingly be understood as an initial characterization of pre-monsoon water quality under current intervention conditions, rather than a comprehensive assessment of year-round intervention effectiveness. Such data are limited for urban lakes in Bengaluru (Alok and Mohapatra, 2018). A comprehensive year-round evaluation of pollutant loading could utilize new technologies, such as drone technology for sampling and satellite observations of water quality (Hamzah et al., 2024; Tyler et al., 2016), to collect samples from consistent locations at higher sampling frequencies.

Urban lake water quality is shaped by a complex interplay of factors that extend well beyond the scope of individual restoration interventions. Catchment characteristics, including land use, population density and the distribution of domestic and industrial pollution sources, determine the baseline pollution load entering a lake through both point and diffuse sources (Kristensen, 2004; Lele and Sengupta, 2018). Upstream pollution inputs are particularly difficult to attribute and manage, as storm drains frequently carry untreated wastewater from multiple points within and beyond the immediate catchment, with human modifications to drainage and stream networks further complicating the pollution pathways (Yang et al., 2022). Interventions such as diversion channels and sewage treatment plants can reduce pollution loads, but their effectiveness is constrained by these catchment-scale dynamics and the volume of upstream inputs, which may not always originate from hydrologically obvious sources (Kubo et al., 2020; Pickard et al., 2021). Observed differences in water quality across lakes should therefore not be attributed solely to the nature or quality of restoration or interventions, but considered in the context of each lake's catchment, pollution history and the cumulative influence of upstream inputs (Da Silva et al., 2021; Jamwal et al., 2023). Governance practices present an additional layer of influence, with current institutional arrangements often unable to keep pace with on-ground changes and effective lake management requiring inter-departmental coordination, regular catchment mapping and the adoption of flexible, adaptive monitoring frameworks grounded in scientific approaches rather than prescriptive solutions (Lele and Sengupta, 2018; Ghosh, 2016). Disentangling the relative contribution of catchment inputs and intervention measures to observed water quality outcomes remains a challenge and an important direction for future work.

4.4 Conclusions

Urban lakes in tropical countries play a crucial role in supporting local economies, enhancing food and water security and generating income for dependent communities (May et al., 2021; Jamwal et al., 2023).With urbanization rapidly expanding, the infrastructure is unable to keep up, resulting in declining water quality and reduced ecosystem services. The findings of this study demonstrate that inlet-focused interventions have led to measurable improvements in lake water quality. However, the nature of these interventions results in trade-offs that influence the ecosystem services each lake inlet intervention can offer (Figure 9).

Where the primary objective is to eliminate untreated wastewater inflow effectively and rapidly, the construction of diversion channels at the main inlet would be the most efficient solution. This approach also enables the lake to remain dry during the pre-monsoon season, enhancing the lake's function as a reservoir for capturing storm water and flood runoff during the monsoon. However, the lack of consistent inflow reduces the lake's capacity to support year-round groundwater recharge and economic activities such as commercial fishing. Moreover, such diversions do not address the pollution problem at the source but instead transfer it downstream.

In contrast, lakes those receive treated inflow from sewage treatment plants (STPs) and aim to retain water year-round offer different advantages. These systems can enhance the availability of freshwater for groundwater recharge and support economic uses like commercial fishing. Nevertheless, the benefits are compromised when untreated wastewater from storm drains also enters the lake. The positive impact of addressing dry-season inflows from storm drains is evident in the case of Sarrakki Lake (SA), which exhibited improved water quality. However, space and financial constraints may limit the feasibility of such comprehensive interventions everywhere. Additionally, because these lakes remain full throughout the year, they often lack the storage capacity needed to buffer flood events effectively.

Therefore, the choice of intervention must align with the intended primary functions of the lake and the ecosystem services

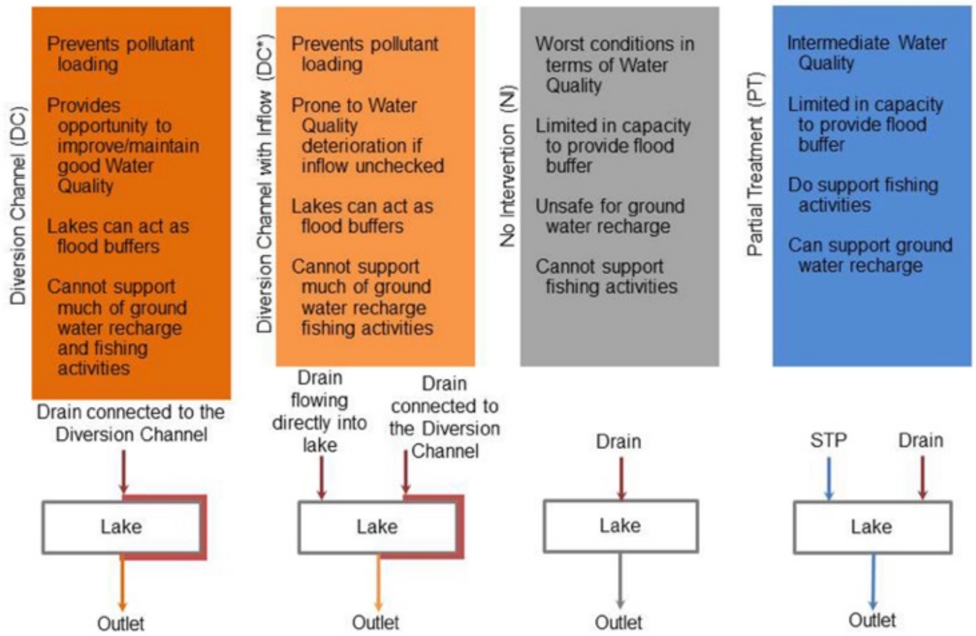

FIGURE 9
Summary of lake inlet intervention categories with corresponding trade-offs.

prioritized by city planners and stakeholders. A clear identification of these goals is essential for designing appropriate, context specific management strategies that maximize ecological, hydrological and socio-economic benefits.

Data availability statement

The original contributions presented in the study are included in the Supplementary file, further inquiries can be directed to the corresponding author.

Author contributions

SB: Formal analysis, Project administration, Data curation, Methodology, Writing – original draft, Software, Investigation, Resources, Visualization, Funding acquisition, Conceptualization. PJ: Conceptualization, Funding acquisition, Writing – review & editing, Investigation, Resources, Formal analysis, Validation, Supervision, Methodology. LC: Funding acquisition, Supervision, Methodology, Investigation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2026.1857439/full#supplementary-material

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