Vietnam Journal of Earth Sciences, 46(3), 411-431, https://doi.org/10.15625/2615-9783/20925

Vietnam Journal of Earth Sciences
https://vjs.ac.vn/index.php/jse

Temporal and spatial variation in water quality in the Son La hydropower Reservoir, Northwestern Vietnam

Thien Cuong Tran[1], Xuan-Duc Do[2*], Huu Tuan Do[1], An Thinh Nguyen[3], Van Hien Dao[1], Minh Tran[4]

[1]*Faculty of Environmental Sciences, VNU University of Science, Vietnam National University, Hanoi, Vietnam*
[2]*Department of Climate Change and Sustainability Science, VNU School of Interdisciplinary Sciences and Arts, Vietnam National University, Hanoi, Vietnam*
[3]*VNU University of Economics and Business, Vietnam National University, Hanoi, Vietnam*
[4]*Institute of Regional Sustainable Development, Vietnam Academy of Social Sciences, Hanoi, Vietnam*

Received 17 March 2024; Received in revised form 20 May 2024; Accepted 10 June 2024

ABSTRACT

The Son La hydropower reservoir (S.L.R.) is the largest water reservoir in Vietnam. Da River water has been treated for drinking and domestic purposes; water quality management is essential for the safety of ecosystems and human health. This study was conducted to determine changes in water quality indicators [pH, dissolved Oxygen (D.O.), total suspended solids (T.S.S.), chemical oxygen demand (C.O.D.), ammonium (NH_4^+), nitrite (NO_2^-), and coliform] in the Da River in 2010 and the Son La hydropower reservoir during 2014-2023. The results of mean annual values of Da river water quality and Son La hydropower reservoir were, specifically: pH (7.8; 7.4), D.O. (4.3; 6.2), T.S.S. (112; 5), C.O.D. (15; 8.7), NH_4^+ (0.17; 0.3), NO_2^- (0.009; 0.04), and coliform (1,723; 747). Water quality parameters significantly varied between rive and reservoir water: D.O., T.S.S., C.O.D., and Coliform. pH, T.S.S., and C.O.D. slightly decreased; however, Dissolved oxygen (D.O.), NH_4^+, NO_2^-, and coliform demonstrated an increasing trend during 2014-2023. The impact of the Son La Dam (S.L.D.) on water quality was relatively straightforward: increasing the concentration of dissolved oxygen and the self-cleaning ability of pollutants. Periodic water impoundment was divided (April to August) into a low water level of 175 m, impoundment (January to March), a median water level of 190m, and a high water level of 215 m (September to December) to period. However, the impact of the staged impoundment on water quality, especially in 2014-2023, remains unclear, except D.O., T.S.S., NH_4^+, NO_2^- and Coliform exceeded limits or were lower is not significant for living water under the Vietnam regulation, specifically: D.O. (5.36, 5.52; ≥ 6), T.S.S. (25.13; ≤ 25), NH_4^+ (0.3331; 0.3), NO_2^- (0.0504; 0.05), coliform (1,018.5; ≤ 1,000). Results from the current study provide valuable information for reservoir and river water pollution source management and reduce potential risks to exposed ecosystems, livelihoods, and human health.

Keywords: Hydropower reservoir, temporal and spatial, multivariate statistical analysis, Son La, water quality.

1. Introduction

Hydropower is a significant source of renewable electricity, with a share of 16%–17% of the total world electricity generation (Killingtveit., 2019), and it is currently the leading renewable energy source in most Asian countries (Vaidya et al., 2021; Li Chen et al., 2020). Hydropower reservoirs play a fundamental role in storing water, producing electricity, promoting the local economy,

*Corresponding author, Email: ducxd@vnu.edu.vn

irrigation of agricultural land, providing clean water activities, tourism, water quality, and landscape conservation (Hadjibiros et al., 2005). Despite hydropower's benefits, these structures can also trigger substantial environmental impacts such as water supply to communities, flood control, and greenhouse gas reduction (Silva et al., 2021). Water quality inside the reservoir is affected principally by meteorological, hydrological, and geological factors and land use (Dalu et al., 2018; Jerves et al., 2020; Vega et al., 2018). The construction of dams causes many problems. Some significant impacts associated with dams and their recommended mitigation measures for water quality management are pH, BOD_5, and T.S.S. (Tiwari et al., 2022). Most dams seasonally reduce the concentrations of total suspended solids by large percentages (50%–99%) through sediment trapping (Winton et al., 2023). The ecological hydropower reservoir water quality in the mainstream (previously known as the River) is good, in the status above good (Ye L. et al., 2023). Dam construction and operation may affect water quality parameters because they regulate river flow and change the flow regime (Mostafazadeh et al., 2024). Reservoirs help reduce the health effects of heavy metals dissolved in aquifers (Zhao Z. et al., 2024).

Understanding changes over time in water quality in hydropower reservoirs is essential to assess the environmental impact of dam construction and protect freshwater resources (Zhao et al., 2013). The water quality of hydropower reservoirs has significant implications for water management and regional development (Xia et al., 2018). After water impoundment in a hydropower reservoir, the chemical oxygen demand (C.O.D.) tends to decrease due to changes in flow in the reservoir. In contrast, the biological oxygen demand (BOD_5) increases due to flood and decomposition of phytoplankton biomass, and the ammonium (NH_4^+) concentration increases as a result of human activities (Li et al., 2019). Fluctuations in the water level are essential for changing the water quality in reservoirs (Heikal., 2010). Hydropower dams significantly reduce turbidity, silt, and total suspended solids (T.S.S.) in the water from upstream to the reservoir, whereas the concentrations of nitrate (NO_3^-) and phosphorus in the reservoir water decline (Cruz et al., 2015). The reservoir water quality may be assessed using a range of parameters, such as BOD_5, nitrate, phosphorus, dissolved oxygen, and metals, because these are the essential elemental ingredients in freshwater reservoirs (Bhateria et al., 2016). The water quality analysis uses physicochemical parameters in the reservoir, such as pH, turbidity, clarity, T.S.S., water hardness, phosphate (P), nitrate (NO_3^-), dissolved oxygen (D.O.), and biochemical oxygen (BOD_5) (Medudhula et al., 2012).

The water quality in hydroelectric reservoirs can be described by the BOD_5, dissolved oxygen (D.O.), NH_4^+, NO_2^-, NO_3, heavy metals (Fe), and coliforms regularly sampled during the 5-year post-impoundment period for analysis (Gao et al., 2016). The flow regime of the River has changed markedly over the last century. Increased diversions and the construction of dams result in lower average monthly and annual flows compared with natural conditions. Moreover, the extent of average annual floods declined (Maheshwari et al., 1995). Agriculture in watersheds contributes more than 70% of the delivered N and P (Richard et al., 2008). Livestock contributes significantly to the environmental impact of 73% of water pollution of both N and P (Leip et al., 2015). In addition, fisheries in the reservoir contributed to the pollution of N and P (Ma et al., 2009). The total phosphorus input in the reservoir was mainly provided by surface inflows, rain, and bottom sediments (Holas et al., 1999). The results are high T.S.S. values and large amounts of C.O.D., nitrogen, and phosphorus. The seasonal parameters of tropical reservoirs include pH conductivity, turbidity, temperature, and dissolved oxygen (Atobatele et al., 2008). The changing pH of the water is often related to climatic factors such as rainfall, sunlight hours, and depth in the reservoir water (Maberly., 2008). At the same time, the increase in C.O.D. and nitrogen concentration depends on the flow from the basin and the retention time in the reservoir (Fukushima et al., 2000). The seasonal increased concentration of NH_4 in the reservoirs depends mainly on transporting nutrients from the sub-basins and rivers (Yang et al., 2013). Over time, the reservoir water's clarity improves. This corresponds to decreased T.S.S. concentration and increased D.O. in the reservoir water (Eimers et al., 2005). At the same time, the flow in the basin combined with the reservoir depth does not influence the Fe content in the reservoir water (Norton, 2008). At the same time, the parameters of nitrogen and coliforms change over time and space (Varol et al., 2012). The T.S.S. concentration in the reservoir significantly influences water clarity and depends on the dry and flood seasons: in the dry season, it is only 60% (Lizotte et al., 2014). The conversion from nitrogen to NH_4^+ and NO_2 mainly occurs in the summer from April to August, corresponding to floods (Lerat et al., 1990). Simultaneously, the density of total coliforms increases in summer, which is associated with the leaching of grazing animals from the basin. The increased coliform density with depth is mainly due to their association with particles (An et al., 2002). Ammonium (NH_4^+) increases with depth, and the decrease in nitrate (NO_3^-) with depth in the reservoir could be due to denitrification in the bottom layers and nitrification in the surface layers (Noori et al., 2018). The effects of rain, deforestation, chemical fertilizers, and pesticides influence the seasonal variability of the parameters (Ibrahim., 2010). Seasonal fluctuations in the water levels affect the solubility of total phosphorus (total P), nitrate (NO_3^-), and nitrite (NO_2^-) in the reservoir water (Geraldes., 2005). The nitrogen nutrient flow in the reservoir shows a good correlation with the concentrations of NH_4^+, NO_3^-, and NO_2^-. The abundance of biomass, phytoplankton, and nutrient status positively correlates with increased BOD_5 and coliforms in reservoir water by year (Adamovich., 2019). The hydropower reservoir water quality considers a range of water levels related to the annual operation of the reservoir; surface water quality parameters in each water level are analyzed and rated good or bad to measure the temporal and spatial changes in water quality in the reservoir during the 20 years after the hydroelectric dam impoundment (Xiang et al., 2021).

Dams are a significant issue in the sustainable management of finite water resources, particularly in arid and semi-arid regions, making plain the need for dams for hydropower and irrigation (Altinbilek., 2002). Various reservoirs have been serving as the most critical drinking water sources due to the uneven distribution of precipitation and severe river pollution (Gu et al., 2014). Deteriorating water quality or physicochemical parameters (pH, D.O., C.O.D., T.S.S., and microbiological parameters using World Health Organization (WHO) of rivers is of significant concern; this is especially true for rivers being used as drinking water sources (Shrivastava et al., 2015). Processes occurring in the watershed can adversely influence drinking water reservoirs, and understanding linkages between these processes and reservoir water quality provides the basis for protecting or improving source water quality for maintaining safe drinking water (Cooke et al., 2001). Reservoirs play a more and more critical role in providing potable water in many developing countries. Drinking water quality is one of the most significant factors affecting human health. However, drinking water quality in many countries, especially developing countries, is undesirable, and poor drinking water quality has induced many waterborne diseases (Li et al., 2019). Water is a threat to human health. The results also help to undertake proper management strategies and incorporate monitoring programs that study river water to implement safety measures to protect human health (Hasan et al., 2021). The contribution to the drinking water supply from lakes and reservoirs is increasing due to their better water quality (Zhang et al., 2023).

Dissolved Oxygen (D.O.) is one of the most essential factors for aquatic animals, especially those that derive dissolved oxygen from the water. D.O. levels indicate water quality (Bulbul et al., 2022). The pH value is used as a standard to measure the properties of water, and alterations in drinking water pH affect the gut microbiota's composition in humans (Yehia., 2021). T.S.S. is a significant cause of water quality deterioration, leading to aesthetic issues and higher water treatment costs (Bilotta et al., 2008). Chemical oxygen demand (C.O.D.) and biochemical oxygen demand (B.O.D.) with irreplaceable significance are comprehensive indicators for evaluating water quality (Qi et al., 2021). The toxic effects of ammonium (NH_4^+) nitrite (NO_2^-) in river water depend dramatically on their natural or synthetic origins and chemical structures (Spataru, 2022). The water in reservoirs appeared safe; however, coliforms and opportunistic pathogenic bacteria such as Pseudomonas aeruginosa were identified on other selective media. This study illustrates that storage reservoirs in the drinking water distribution system have low microbiological water quality due to opportunistic pathogens, and therefore, water quality must be controlled (Lee et al., 2006).

Most studies have focused on assessing water quality and its relationship with meteorological and anthropic variables in eutrophic reservoirs (Winton et al., 2019). However, the application of multivariate statistical analysis in tropical reservoirs is limited (Ling et al., 2017; Marques et al., 2019). Statistical analysis and prediction play an essential role in processing surface water quality time series, with tools such as outlier detection, normality tests, and trend detection, among others, granting an excellent first approach (Fu et al., 2012). To perform an integrated statistical analysis of water quality, it is necessary to consider hydrological, meteorological, and anthropic activities. Multivariate statistical analysis, such as principal component analysis and correlation analysis, facilitates integrated water quality data analysis because it identifies factors influencing water quality (Chen et al., 2015; Varol., 2020). Water samples were collected in the wet (May) and dry (August) seasons. Multivariate statistical analysis was applied to deduce associations and identify pollution sources (Njuguna et al., 2020). These methods exhibit a practical approach to assessing and forecasting the water quality of reservoirs and can be used as a tool for water quality management (Varol., 2020).

Son La Reservoir is the largest hydropower reservoir in Vietnam, with an area of 225 km^2. The Son La hydropower reservoir was formed on the Da River in northwest Vietnam in 2012. The lake water level fluctuates by approximately 40 m, which is 20 times higher than the fluctuation of natural river water. Reservoir water levels rise and fall, causing upstream and downstream erosion (EVN., 2006). Large volumes of water stored in the Son La hydropower reservoir stimulate earthquake activity (Le et al., 2012). In addition to the primary goal of generating electricity for the Son La hydroelectric power plant with an installed capacity of 2,400 MW, it is essential to regulate the Hoa Binh hydropower reservoir's flood water and supply water for production and domestic use in the basin. The Son La hydroelectricity plant and dam are essential regarding socioeconomic and national conditions, room, and security. The Da River provides drinking and domestic water with a capacity of 300,000 m^3/day for an estimated 100,000 households in Hanoi, the capital of Vietnam. The Da River water has been treated for drinking and domestic purposes, and water quality management is essential for the safety of ecosystems and human health. This study aimed to assess temporal and spatial variation in water quality in the Son La hydropower reservoir during 2014–2023 with 2 specific objectives: (1) changes in the water quality index in the front and after the dam compartment; (2) Periodic impoundment drives annual changes in water quality indices. Results from the current study provide valuable information for identifying the critical pollution indicators for water source management and reducing potential risks to human health.

2. Materials and Methods

2.1. Research area

The reservoir basin covers an area of 11,075 km^2, with coordinates 21°15'15" to 22°45'10" North, 102°50'10" to 104°35'15" East (Fig. 1). The mainstream (Da River) and three tributaries Nam Muc River, Nam Na River, and Nam Mu River) supply water to the Son La hydropower reservoir (Fig. 1). The Nam Muc River has a length of 128 km and a sub-basin area of 1,618 km^2. The Nam Na River has a length of 109.4 km, corresponding to a sub-basin area of 2,949 km^2. The Nam Mu River has a length of 183.7 km, corresponding to a sub-basin area of 2,972 km^2 (Do et al., 2020). Their water levels regulate the yearly regime to produce electricity: the low water level of 175 m (from April to August) corresponds to a capacity of 2,756 million m^3, and the average water level of 190 m (from January to March) corresponds to a capacity of 6,504 million m^3, and the high water level of 215 m (from September to December) corresponds to a capacity of 9,260 million m^3.

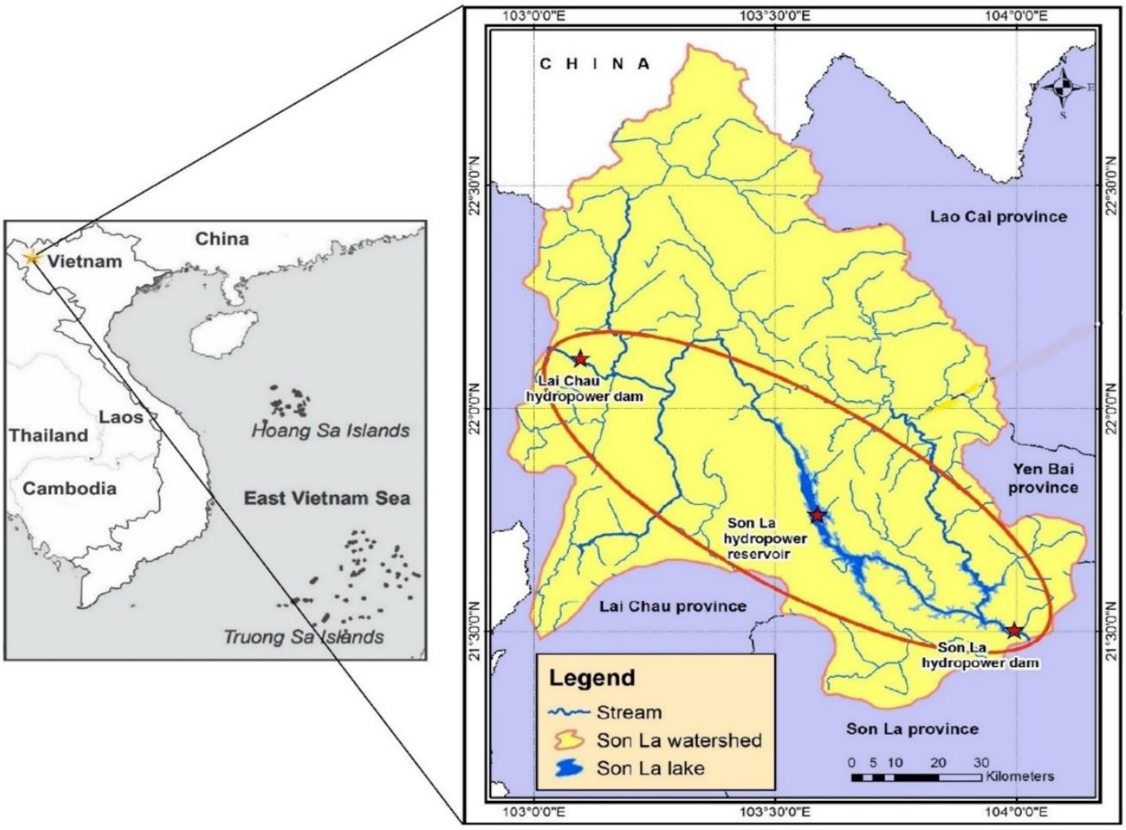

Figure 1. Map of Son La hydropower reservoir in the basin of Northern Vietnam

2.2. Data collection

Ten monitoring stations have been operated by the Son La Hydropower Company in the study area since 2014, including SL1 (Downstream of Lai Chau Dam), SL2 (Trang village, Le Loi commune), SL3 (Hang Tom Bridge), SL4 (Nam Tac Confluence), SL5 (Nam Ma Confluence), SL6 (Ca Nang Stream Confluence), SL7 (Nghe Tong), SL8 (Phieng Lanh town), SL9 (Nam Mu Confluence), and SL10 (Dam Upstream). Figure 2 and Table 1 show that the SL1, SL2, SL3, SL4, SL5, SL6, SL7, SL8, SL9, and SL10 stations monitored the water quality of the Son La hydropower reservoir. The monitoring frequency is four times yearly in March, May, August, and November. Monitoring data of surface water quality (pH, D.O., T.S.S., BOD_5, C.O.D., NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, Total Fe and Coliform) at 10 stations (SL1–SL10) during 2014–2023 were collected. pH and D.O. values were measured by the Sension156 portable equipment (H.A.C.H., U.S.); BOD_5 and C.O.D. were determined by the (H.A.C.H., U.S.); T.S.S. was detected by the analytical method (T.C.V.N. 6625:2000); and total Fe was detected by the (S.M.E.W.W. 3111B:2012). The portable model 556 equipment (YIS, U.S.) was used to determine the concentrations of NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, and total. Fe in water. Coliforms were detected by the (QTNB-QTPT-05). The average values of quality in May and August were used for the rainy season, corresponding to a capacity of 2,756 million m^3 at the water level of 175 m. The average values of quality in March were used for the dry season at a water level of 190 m, corresponding to a capacity of 6,504 million m^3. The average values of quality in November were calculated to represent the dry season with a capacity of 9,260 million m^3 at a water level of 215 m.

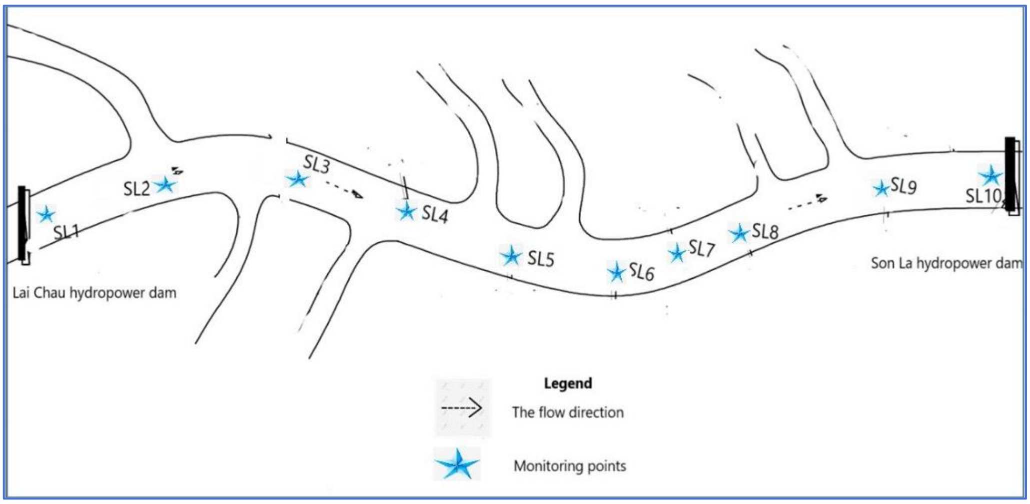

Figure 2. Location of the monitoring points

Table 1. Simulate sampling location of surface water from Son La hydropower reservoir in the period 2014 –2023

No	Sampling location	Symbol	No	Sampling location	Symbol
1	Downstream of Lai Chau Dam	SL1	6	Ca Nang Stream Confluence	SL6
2	Trang village, Le Loi commune	SL2	7	Nghe Tong	SL7
3	Hang Tom Bridge	SL3	8	Phieng Lanh town	SL8
4	Nam Tac Confluence	SL4	9	Nam Mu Confluence	SL9
5	Nam Ma Confluence	SL5	10	Dam Upstream	SL10

2.3. Statistical Analysis

The R-Studio package was used for statistical analysis of the monitoring data. Surface water quality data was log-transformed for homogeneity and tested to fit a statistical significance and normal distribution using the Shapiro-Wilk (Table 2), and Cor. test (Table 3). Significant differences and correlations among variations were determined using one-way analysis to analyze variance (ANOVA) and Pearson coefficients (r). Significant differences in data between the water level and between dry and rainy seasons were analyzed using the Independent-Samples T-Test. Figures were drawn using Origin Pro 2018 v9.5.0 and R-Studio.

With probability (p-value) > 0.05, the data are considered to be normally distributed. Based on the 10-year average variables of the surface water quality monitoring dataset, the 9/11 variables (Table 2) have a normal distribution. Therefore, the annual average value and standard deviation of the seven monitoring parameters in 2014–2023 can be (Table 2 and 3).

Table 2. Verification of reservoir water quality monitoring data using the Shapiro-Wilk from 2014 to 2023

COD	W = 0.94	p-value > 0.05	Normally distributed
BOD_5	W = 0.93	p-value > 0.05	Normally distributed
pH	W = 0.95	p-value > 0.05	Normally distributed
DO	W = 0.85	p-value > 0.05	Normally distributed
TSS	W = 0.96	p-value > 0.05	Normally distributed
NH_4^+	W = 0.79	p-value < 0.05	Not normally distributed
NO_2^-	W = 0.91	p-value > 0.05	Normally distributed
NO_3^-	W = 0.86	p-value > 0.05	Normally distributed
PO_4^{3-}	W = 0.91	p-value > 0.05	Normally distributed
total.Fe	W = 0.95	p-value > 0.05	Normally distributed
Coliform	W = 0.77	p-value <0.05	Not normally distributed

Table 3. Check the statistical significance of lake water monitoring data using the Cor. test for the period 2014–2023

pH	t=-16.5	df = 8	p-value < 0.01	Statistical significance
DO	t = 5.9	df = 8	p-value < 0.01	Statistical significance
TSS	t = -10.9	df = 8	p-value < 0.01	Statistical significance
NH_4^+	t = 5.53	df = 8	p-value < 0.01	Statistical significance
NO_2^-	t = 2.83	df = 8	p-value < 0.05	Statistical significance
COD	t = -3.18	df = 8	p-value < 0.05	Statistical significance
Coliform	t = 4.36	df = 8	p-value < 0.01	Statistical significance
total. Fe	t = 2.15	df = 8	p-value > 0.05	No statistical significance
BOD_5	t = -1.59	df = 8	p-value > 0.05	No statistical significance
NO_3^-	t = 0.73	df = 8	p-value > 0.05	No statistical significance
PO_4^{3-}	t = 0.15	df = 8	p-value > 0.05	No statistical significance

With probability <0.05, the average data during 2014–2023 (Table 3) of seven lake water quality parameters are considered statistically significant, including pH, DO, TSS, NH_4^+, NO_2^-, COD, and coliform. These parameters can be used to forecast change trends and quality correlations over temporal and spatial variations.

3. Results and discussions

3.1. Results

3.1.1. Changes in water quality indicator impoundments before and after the impoundment of reservoir dam

Tables 4 and 5 show the comparative data on the values of water quality parameters (pH, D.O., T.S.S., C.O.D., NH_4^+, NO_2^-, Coliform impoundment before and after Son La hydropower reservoir dams impoundment. Water quality indicators' values differed in 2010 and from 2014 to 2023. The mean water quality indicators of the Da River from SL1 to SL10 (2010) and the Son La hydropower reservoir from SL1 to SL10 during 2014–2023 were, specifically: pH (7.8 ± 0.5; 7.4 ± 0.3), D.O. (4.3 ± 0.8; 6.2 ± 10.3), T.S.S. (112 ± 94; 5 ± 53.1), C.O.D. (15 ± 7.1; 8.7 ± 2.9), NH_4^+ (0.17 ± 0.1; 0.3 ± 0.6), NO_2^- (0.009 ± 0.01; 0.04 ± 0.04), and coliform (1,723 ± 3,332; 747 ± 857) during 2014–2023 after impoundment of Son La hydropower reservoir dams. The values of all monitored water quality parameters were lower than the limits of national technical regulation on Surface water quality (Level A: Good water quality) Vietnamese guideline (Q.C.V.N. 08:2023/B.T.N.M.T.) (pH: 6.5–8.5; D.O. mg/L: ≥ 6.0, T.S.S.: ≤ 25 mg/L, C.O.D.:≤ 10 mg/L, NH_4^+: 0.3 mg/L, NO_2^-: 0.05 mg/L, coliform: ≤ 1,000 MPN/100 ml) (M.O.N.R.E., 2023). The concentrations of T.S.S., C.O.D., and coliform in 2010 before impoundment varied within to, specifically: 4.3 mg/L, 112 mg/L, 15 mg/L, 1,723 MPN/100 mL, which exceeded the Q.C.V.N. 08:2023/B.T.N.M.T. regulation (Table 5). The D.O. concentrations in the hydropower reservoir were significantly higher. They showed significantly higher values than those in the Da River, reflecting the reservoir's role in increasing the dissolved oxygen concentration ($p<0.05$). The T.S.S., C.O.D., and coliform concentrations in front of the dam compartment were significantly higher than those after the dam impoundment, reflecting the role of the reservoir in settling the sediment and suspended solids and the self-cleaning ability of pollutants such as chemical oxygen demand and coliform bacteria ($p<0.05$).

Table 4. Group distribution of surface water parameters of Son La hydropower Reservoir

Years	**pH(-)**	**DO(mg/L)**	**TSS(mg/L)**	**COD(mg/L)**	**NH_4^+ (mg/L)**	**NO_2^- (mg/L)**	**Coliform(MPN/100mL)**
2010	7.8 ± 0.5	4.3 ± 0.8	112 ± 94	15 ± 7.1	0.17 ± 0.1	0.009 ± 0.01	1,723 ± 3,332
2014	7.87 ± 0.49	4.43 ± 0.48	21.8 ± 9.49	12.4 ± 5.79	0.026 ± 0.01	0.034 ± 0.04	273.5 ± 535
2015	7.68 ± 0.40	4.40 ± 0.55	18.3 ± 9.06	11.3 ± 2.73	0.052 ± 0.05	0.026 ± 0.004	306.1 ± 463
2016	7.71 ± 0.17	4.61 ± 32.0	19.1 ± 32.5	10.2 ± 1.82	0.048 ± 0.02	0.024 ± 0.003	318.9 ± 273
2017	7.57 ± 0.16	4.65 ± 0.12	16.4 ± 149.6	9.6 ± 2.13	0.070 ± 0.11	0.016 ± 0.02	331.9 ± 464
2018	7.47 ± 0.17	4.80 ± 0.10	15.3 ± 30.7	8.3 ± 0.69	0.078 ± 0.01	0.007 ± 0.01	368.7 ± 676
2019	7.46 ± 0.19	5.04 ± 0.30	15.8 ± 3.78	6.9 ± 0.36	0.052 ± 0.01	0.005 ± 0.01	342.0 ± 1,230
2020	7.36 ± 0.17	6.04 ± 0.40	13.6 ± 3.4	9.04 ± 0.15	0.30 ± 0.06	0.062 ± 0.05	1,450 ± 935
2021	7.27 ± 0.25	5.89 ± 0.79	12.70 ± 30.8	8.71 ± 2.09	0.43 ± 0.80	0.062 ± 0.03	976 ± 775
2022	7.21 ± 0.28	5.88 ± 1.40	12.41 ± 31.3	8.61 ± 2.17	0.50 ± 0.95	0.068 ± 0.03	1,140 ± 874
2023	7.18 ± 0.20	5.68 ± 1.44	11.27 ± 10.6	8.45 ± 1.31	0.73 ± 1.24	0.089 ± 0.06	1346 ± 691
Median	7.4	6.2	25	8.7	0.3	0.04	747
Min	6.4	5.1	3.0	1.8	0.0002	0.001	0.0
Max	8.7	150	522	32	7.93	0.30	3,700
Pearson's(r)	- 0.98	0.90	-0.96	- 0.74	0.89	0.70	0.83

Notes: Data are presented as: The average value ±Standard deviation

The increasing trend of water quality values in the period 2014–2023 was found for D.O. (*r=0.90*), NH_4^+ (*r=0.89*), NO_2^- (*r=0.70*), coliform (*r=0.83*), possibly as the results of agriculture in the river basin and increasing aquaculture in the reservoir (Fig. 4). In contrast, pH (*r=-0.98*), T.S.S. (*r=-0.96*), and C.O.D. (*r=-0.74*) (Fig. 3) showed a decreasing trend during this period. The construction of dams in the upstream areas of Son La hydropower and the trapping of sediments and suspended solids in upstream reservoirs may be responsible for the reduction of T.S.S., and the process of reducing biomass decomposition in the reservoir may be responsible for the reduction of C.O.D. and pH in the Son La hydropower reservoir.

Table 5. Variation in pH, dissolved oxygen (D.O.), total suspended solids (T.S.S.), chemical oxygen demand (C.O.D.), ammonium (NH_4^+), nitrite (NO_2^-), and coliform in front of the dam compartment in 2010 and after the dam compartment from 2014 to 2023

Parameters	In front of the dam compartment (2010)			After the dam compartment (2014–2023)			QCVN 08:2023/BTNMT regulation (National technical regulation on Surface water quality) (M.O.N.R.E., 2023).
	Max	Min	Mean	Max	Min	Mean	
pH	8.4	7.3	7.8	8.7	6.4	7.4	6.5–8.5 (A)
DO (mg/L)	5.8	3.15	4.3	150	5.1	6.2	≥ 6.0 (A)
TSS (mg/L)	507	13	112	522	3.0	25	≤ 25 (A)
COD (mg/L)	35	2.4	15	32	1.8	8.7	≤ 10 (A
NH_4^+ (mg/L)	0.44	0.008	0.17	7.93	0.0002	0.3	0.3 (Value limit)
NO_2^- (mg/L)	0.07	0.001	0.009	0.30	0.001	0.04	0.05 (Value limit)
Coliform (MPN/100ml)	11,000	230	1,723	3,700	0.00	747	≤ 1,000 (A)

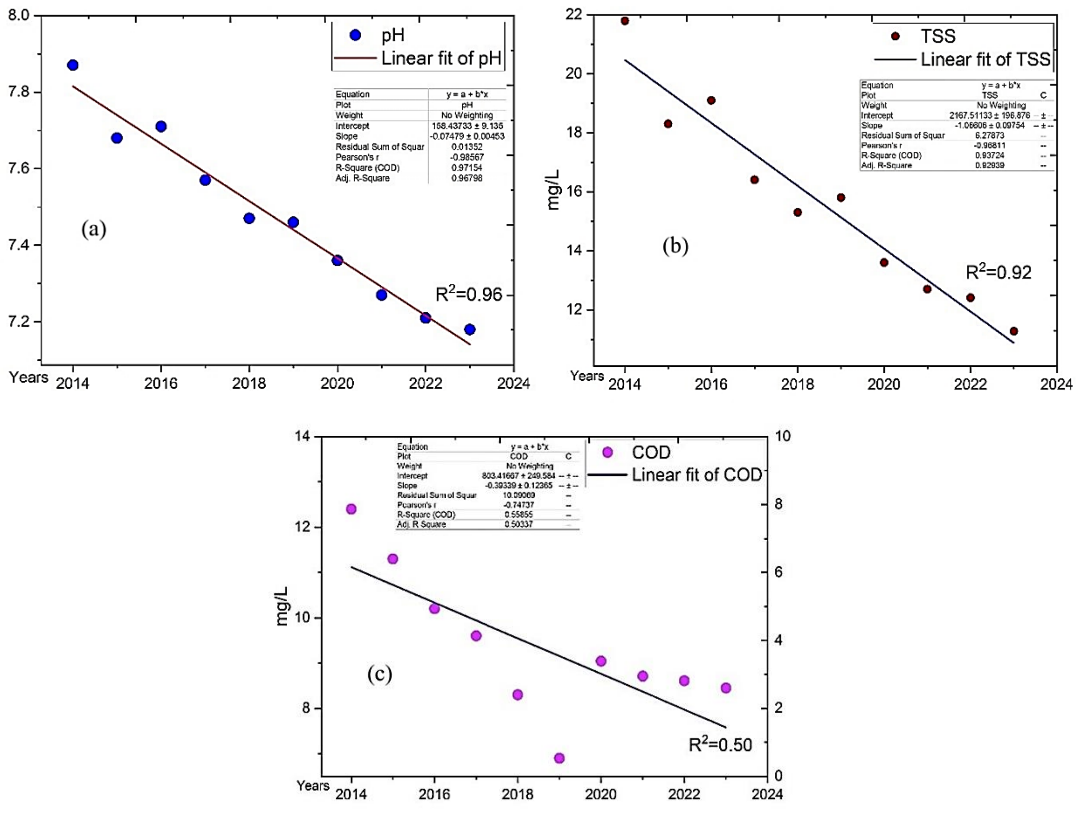

Figure 3. Three physicochemical parameters of surface water tend to decrease during 2014–2023

The concentrations of NH_4^+, NO_2^-, and coliform in water were slight to strongly correlated (*r=0.92, r= 0.88, r=0.90; p<0.01*) (Fig. 5), implying that the Non-point sources of organic matter and nutrients from agriculture, domestic release, and aquaculture in reservoirs were possibly responsible for water quality. In addition, Fig. 5 shows that the concentrations of T.S.S., pH, and C.O.D. in water are strongly correlated (*r=0.99, r = 0.75, r=0.76; p<0.01*), reflecting the role of hydropower reservoirs in the self-cleaning ability of pollutants.

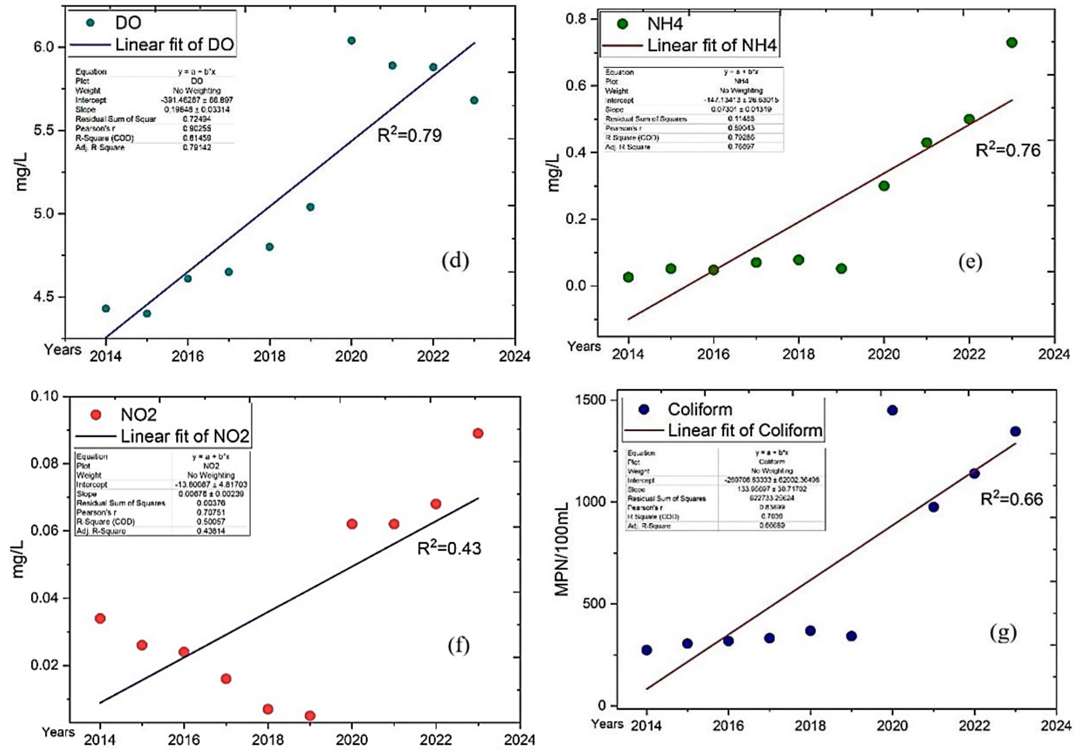

Figure 4. Four water parameters tend to increase during 2014–2023

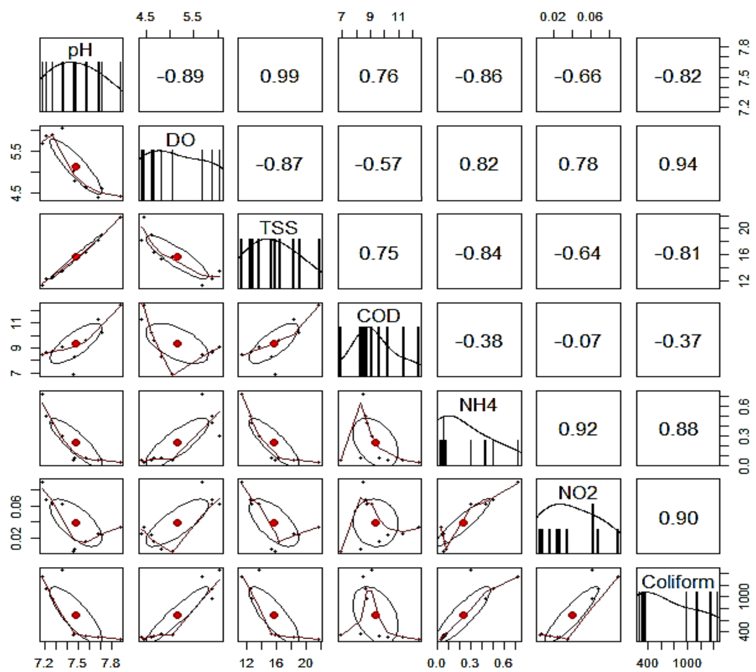

Figure 5. Correlation coefficient (r) between physicochemical parameters of the Son La hydropower reservoir in the period 2014–2023

3.1.2. Periodic impoundment drives changes in interannual water quality indices

Table 6 shows the comparative data on the values of water quality parameters (pH, D.O., T.S.S., C.O.D., NH_4^+, NO_2^-, coliform) at water levels of 175 m, 190 m, and 215 m in the Son La hydropower reservoir from 2014 to 2023. The values of water quality parameters were different among the water level 175 m, which corresponds to a capacity of 2,756 million m^3; water level 190 m, which corresponds to a capacity of 6,504 million m^3; and water level 215 m, which corresponds to a capacity of 9,260 million m^3.

Table 6. Reservoir operating water level in the period 2014–2023

No	Month	Reservoir water level (m)	Reservoir capacity (million m^3)	Legend
1	April - August, low water level	175	2,756	W_{min}
2	January - March, median water level	190	6,504	W_{median}
3	September - December, the highest water level	215	9,260	W_{max}

Table 7 shows the values of water quality indices during 2014-2023 (level of 175 m; 190 m; 215 m) were, specifically: pH (6.5–8.7; 6.5–8.7; 6.4–8.3), D.O. (0.7–151; 3.4–7.3; 2.1–7.2 mg/L), T.S.S. (3.0–522; 3.0–40; 6–39 mg/L), C.O.D. (1.8–24; 2.04–32; 4.5–29 mg/L), NH_4^+ (0.0003- 6.4; 0.06–0.49; 0.0002–8.09 mg/L), NO_2^- (0.0007–0.3; 0.002–0.18; 0.002–0.50 mg/L), Coliform (0.0–3,200; 0.0–3,700; 0.0–3,200 MPN/100mL). The mean yearly values of water quality were, specifically (Fig. 6, and Table 7): pH (7.36±0.31; 7.36±0.36; 7.34±0.33), D.O. (6.84 ± 14.5; 5.40±0.84; 5.52±1.01 mg/L), T.S.S. (35.3±73.5; 14.2±6.63; 16.3±7.79), C.O.D. (8.36±2.35; 8.56±;3.86; 9.33± 2.80 mg/L), NH_4^+ (0.282± 0.61; 0.219± 0.183; 0.333±0.813), NO_2^- (0.042±0.045; 0.040±0.028; 0.050±0.05), coliform (673±755; 612±803; 1,019±1,033).

The values of all monitored water quality parameters at water levels of 175 m to 190 m and 215 m were lower than the limits of the national technical regulation on Surface water quality (Level A: Good water quality) Vietnamese guideline (Q.C.V.N. 08:2023/B.T.N.M.T.), except D.O. at water levels of 190 and 215 m, T.S.S. at water level of 175 m, and coliform at water level of 215 m (M.O.N.R.E., 2023). The concentrations of D.O. at water levels of 190 m and 215 m, which correspond to a dry season, were 5.40 and 5.52 mg/L, respectively, which is lower than the Q.C.V.N. 08:2023/B.T.N.M.T. regulation (≥ 6.0 mg/L). The concentrations of T.S.S. at a water level of 175 m, which corresponds to a rainy season, were significantly higher and exceeded the Q.C.V.N. 08 MT:2023/B.T.N.M.T. regulation (≤ 25 mg/L) and showed significantly higher values than those at water levels of 190 m and 215 m. The concentrations of coliform at a water level of 215 m (dry season) exceeded the Q.C.V.N. 08:2023/B.T.N.M.T. regulation (≤ 1,000 MPN/100 ml).

Figure 7 shows ammonium (NH_4^+) at water levels of 175m, 190 m and 215 m demonstrated the strong correlation with NO_2^- and coliform (*r=0.88, p<0.05; r=0.63, p<0.05; r=0.78, p<0.05*), (*r=0.84, p<0.05; r=0.80, p<0.05; r=0.72, p <0.05*), (*r=0.91, p<0.05*). At a water level of 215 m, which corresponds to a capacity of 9,260 million m^3 in dry season NH_4^+ medium correlation with coliform (*r=0.33, p< 0.05*), and NO_2^- medium correlation with coliform (*r=0.40, p<0.05*). Thus, in the rainy and dry seasons, which correspond to capacities of 2,756 million m^3, 6,504 million m^3, and 9,260 million m^3, water quality indices NH_4^+, NO_2^-, and coliform in the reservoir were all high. This is possibly due to the non-point sources of organic matter and nutrients in the water flows into the reservoir, and the population, tourism, agriculture, and aquaculture in Sonla hydropower reservoirs reservoir were possibly responsible for water quality.

Table 7. Group distribution of surface water parameters of the Son La hydropower reservoir by water level

Years	pH (-)	DO (mg/L)	TSS (mg/L)	COD (mg/L)	NH_4^+ (mg/L)	NO_2^- (mg/L)	Coliform (MPN/100mL)
Surface water parameters at water level of 175 m							
2014	7.8±0.49	4.5±0.42	21.5±9.9	11.2±3.8	0.025±0.01	0.026±0.03	275±543
2015	7.6±0.38	5.0±0.48	17.7±9.52	7.8±2.8	0.062±0.055	0.007±0.004	325±442
2016	7.3±0.16	19.7±44.7	32.3±44.7	6.1±1.31	0.040±0.039	0.004±0.004	193±297
2017	7.4±0.18	5.3±0.1	118±200	5.8±1.24	0.034±0.015	0.002±0.0	415±525
2018	7.2±0.15	5.3±0.1	39±40	9.2±0.98	0.300±0.0	0.050±0.0	685±594
2019	7.3±0.17	5.6±0.3	15±5	9.1±0.44	0.300±0.0	0.050±0.0	87±90
2020	7.4±0.14	5.9±0.5	14±5	9.0±0.13	0.300±0.0	0.075±0.08	1,635±870
2021	7.2±0.25	5.8±0.6	37±41	8.4±1.53	0.555±1.15	0.063±0.05	830±671
2022	7.2±0.28	5.5±1.7	37±42	8.4±1.91	0.645±1.36	0.070±0.04	977±745
2023	7.2±0.21	5.6±1.5	22±11	8.5±1.26	0.560±0.45	0.079±0.02	1,311±701
Median	7.31	6.79	25.13	8.345	0.2818	0.0425	673
Min	6.5	4.6	3.0	1.8	0.0003	0.0007	0.0
Max	8.7	151	522	24	6.4	0.3	3,200
Pearson's (r)	-0.72	-0.69	-0.73	0.93	0.93	0.89	0.76
Years	**pH (-)**	**DO (mg/L)**	**TSS (mg/L)**	**COD (mg/L)**	**NH_4^+ (mg/L)**	**NO_2^- (mg/L)**	**Coliform (MPN/100mL)**
Surface water parameters at water level of 190 m							
2014	8.0±0.62	4.3±0.62	23.7±8.25	14.8±7.6	0.022±0.02	0.044±0.05	180±248
2015	7.2±0.34	4.2±0.32	9.7±5.8	10.4±1.96	0.126±0.01	0.01±0.0	311±398
2016	7.2±0.12	5.2±0.18	11.7±1.5	4.59±1.17	0.02±0.0	0.003±0.0	210±281
2017	7.2±0.13	5.1±0.11	13±1.6	5.35±1.82	0.058±0.0	0.003±0.0	75±103
2018	7.5±0.10	5.3±0.12	14.2±1.1	9±0.0	0.3±0.0	0.05±0.0	800±910
2019	7.5±0.11	5.5±0.28	12±0.0	9.12±0.36	0.3±0.0	0.05±0.0	160±215
2020	7.3±0.08	6.1±0.10	13.3±1.8	9±0.0	0.3±0.0	0.05±0.0	1,380±1,150
2021	7.3±0.21	5.8±0.85	12.6±4.4	7.7±1.86	0.263±0.2	0.055±0.0	777±697
2022	7.3±0.25	6.1±0.86	11.8±4.6	7.6±2.26	0.315±0.2	0.060±0.0	916±812
2023	7.1±0.21	6.0±0.90	20±10.8	7.9±1.53	0.492±0.2	0.075±0.0	1,371±662
Median	7.36	5.36	14.2	8.546	0.2196	0.040042	618
Min	6.5	3.4	3	2.04	0.06	0.002	0.0
Max	8.7	7.3	40	32	0.49	0.18	3,700
Pearson's (r)	-0.4	0.9	-0.6	-0.3	0.8	0.7	0.7
Years	**pH (-)**	**DO (mg/L)**	**TSS (mg/L)**	**COD (mg/L)**	**NH_4^+ (mg/L)**	**NO_2^- (mg/L)**	**Coliform (MPN/100mL)**
Surface water parameters at water level of 215 m							
2014	7.91±0.25	4.26±0.37	20.8±9.6	12.7±6.05	0.032±0.0	0.042±0.1	364±692
2015	7.5±0.42	4.85±0.50	16.5±8.4	7.46±2.19	0.065±0.0	0.006±0.0	507±530
2016	7.03±0.13	5.27±0.09	16.5±2.7	7.54±2.00	0.035±0.0	0.002±0.0	390±122
2017	7.45±0.11	5.22±0.10	14.7±5.3	9.4±0.92	0.272±0.1	0.048±0.0	160±323
2018	7.3±0.09	5.36±0.08	18.6±8.1	9.0±0.0	0.300±0.0	0.050±0.0	180±240
2019	7.3±0.13	6.02±0.09	12±0.0	9.0±0.0	0.300±0.0	0.050±0.0	2,880±218
2020	7.3±0.24	6.32±0.42	12.5±1.5	9.12±0.24	0.300±0.0	0.048±0.0	1,150±757
2021	7.2±0.29	6.1±1.01	15.5±8.4	10.1±2.55	0.335±0.2	0.065±0.0	1,469±857
2022	7.1±0.30	6.4±1.01	14.3±7.3	9.9±2.02	0.389±0.2	0.070±0.0	1,693±967
2023	7.2±0.21	5.4±1.76	12.0±10.6	8.9±1.00	1.303±2.3	0.123±0.1	1,392±733
Median	7.329	5.52	16.34	9.312	0.3331	0.0504	1,018.5
Min	6.4	2.1	6	4.5	0.0002	0.002	0.00
Max	8.3	7.2	39	29	8.09	0.50	3,200
Pearson's (r)	-0.6	0.7	-0.7	-0.6	0.7	0.8	0.6

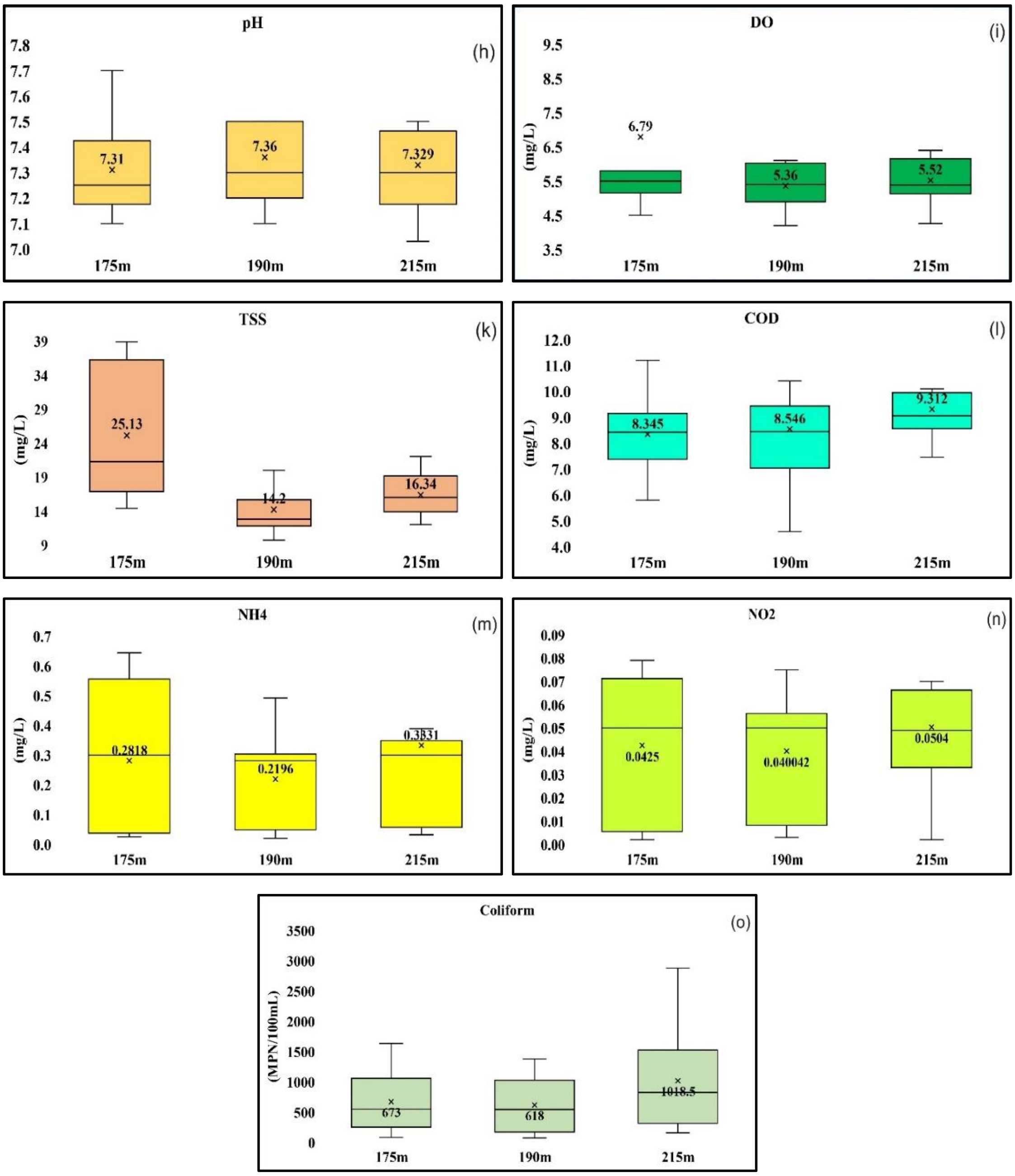

Figure 6. Water quality indices at water levels of 175–190 and 215 m

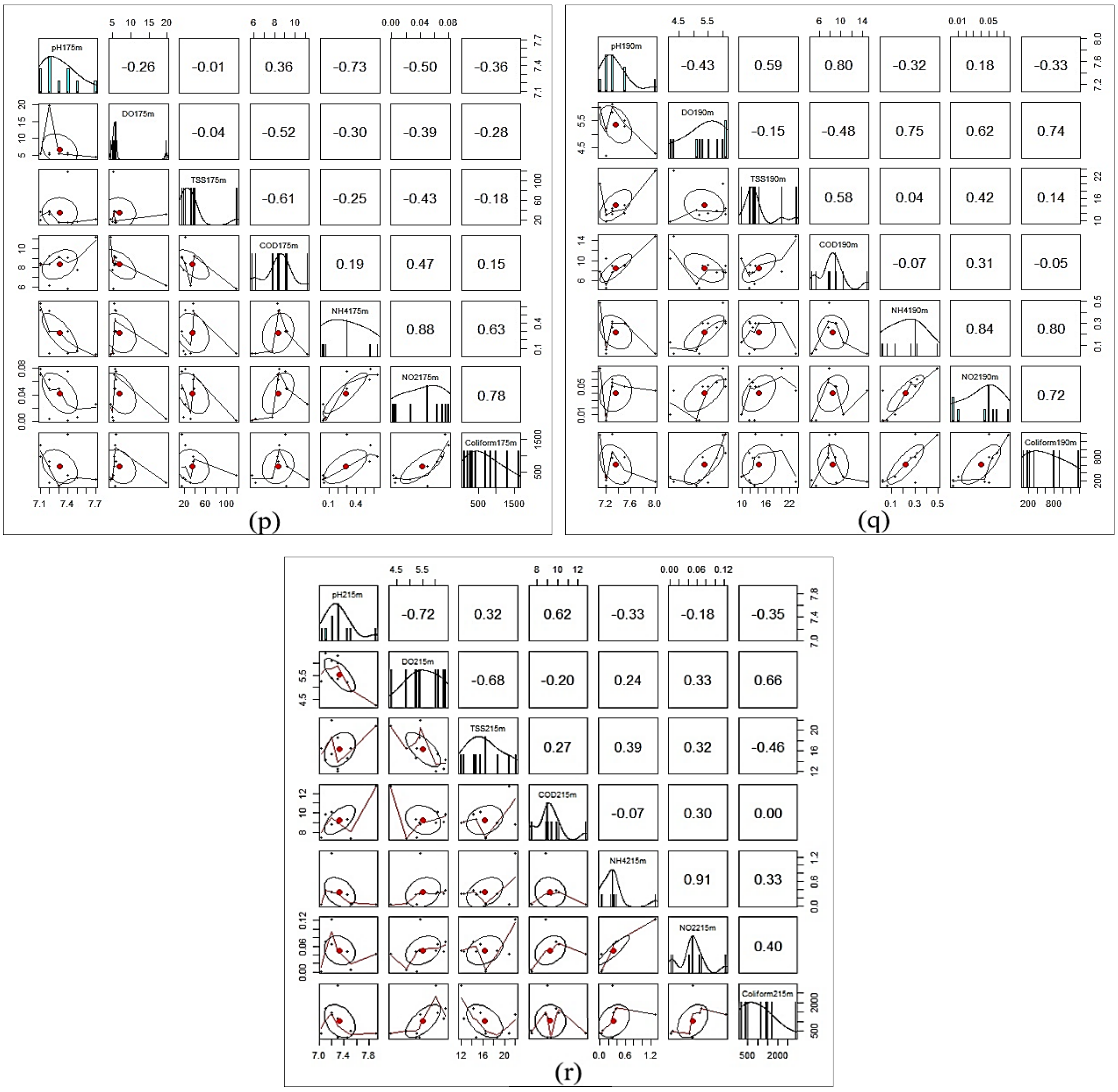

Figure 7. The correlation coefficient (r) between the physicochemical parameters of the Son La hydropower reservoir at 175 m, 190 m, and 215 m water levels corresponding to reservoir capacities of 2,756 million m^3, 6,504 million m^3, and 9,260 million m^3

3.2. Discussions

The impact of the Son La hydropower Dam (S.L.D.) on reservoir water quality showed that the significantly better values of reservoir water Da River were, specifically, dissolved oxygen (D.O.). The Son La hydropower reservoir increased the concentration of dissolved oxygen (D.O.) in water because D.O. is one of the most essential components in the dynamics and characterization of aquatic ecosystems (Coura., 2021). The stabilized reservoir, whose quality is characterized as "higher" than River water (Samiotis et al., 2018), and the water quality showed better conditions in the reservoir than in the River. This result is consistent with previous studies because the water-dissolved reservoir oxygen increased by 5.32% and 8.10%, respectively, compared with the water river (Tomczyk et al., 2021). In addition, the concentrations of D.O. at water levels of 190 m and 215 m in the Son La hydropower reservoir, which corresponds with the dry season, were lower at a water level of 175m in the rainy season because the dissolved oxygen (D.O.) showed high fluctuations in summer at all reservoirs, indicating the existence of seasonal effects (Park and Kang., 2022). D.O. in the reservoir has seasonal changes (Lliev and Hadjinikolova., 2013). In this same sense, in the case of the reservoir, changes in the dissolved oxygen are given by water temperature and the intensity of biological processes such as photosynthesis, respiration, and decomposition of organic matter (Rajwa Kuligiewicz et al., 2015) due to changing hydrometeorological conditions (Rajwa et al., 2014), air temperature and nutrients (Dordoni et al., 2022).

The water quality indicators of T.S.S., C.O.D., and Coliform in the Da River were significantly higher. They showed significantly higher values than the Son La hydropower reservoir, reflecting the role of the reservoir in the self-cleaning ability of pollutants. This result is consistent with previous studies on the role of pollutant assimilation or water self-purification in the reservoir (Wei et al., 2009). The reservoir significantly decreased turbidity (mean, 38%) and concentrations of total solids (23%) than river water (Fantin et al., 2016). The decrease in flow rate affects the deposition of the sediment, thus reducing the amount of total suspended solids (T.S.S.) (Li et al., 2019). In addition, trapping sediments and suspended solids in upstream reservoirs may reduce T.S.S. in the study area (Kummu et al., 2007). The Da River flow in the rainy season decreased between 5% and 43% and increased to an average of 71.6% in the dry season in the Dam post-impact period (Yen et al., 2019). Son La hydropower reservoir, the concentrations of T.S.S. in water at the water level of 175 m correspond with a capacity of 2,756 million m^3 in the rainy season, higher concentrations of T.S.S. at water levels of 190 m and 215 m. Under the influence of different slope gradients, slope lengths, and rainfall intensities, these physical characteristics would affect the runoff generation and T.S.S. loads. Thus, Human activities significantly impact total runoff; for instance, severe rainfall erosion occurs in agricultural land (Chen et al., 2019). At the same time, it shows that the self-purification of pollutants is the largest during the abundant water period and the smallest during the dry water period (Do et al., 2020; Zhang et al., 2022). C.O.D. levels increased before impoundment but decreased because of the water's self-purification capacity (Do et al., 2019; Rong et al., 2021). These C.O.D. and T.S.S. reductions were caused primarily by reductions in flow in the reservoir, which led to enhanced sedimentation (Li et al., 2018). The Coliform reductions show the self-purification mechanism by the Son La hydropower reservoir water higher in the Da River.

In the rainy season, a water level of 175 m corresponds with a capacity of 2,756 million m^3, and in the dry season, at a water level of 190 m and 215 m corresponds with a capacity of 6,504 million and 9,260 million m^3, water quality indices NH_4^+, NO_2^-, coliform in the Sonla hydropower reservoir were are all high. In addition, this study's result shows that the concentrations of NH_{4+}, NO_{2-}, and coliform in the Son La hydropower reservoir are slightly too strongly correlated. This result is consistent with previous studies, implying that the pollutants derive from similar sources (Ha et al., 2011). The pollutants containing nitrogen are transformed into NH_{4+} and NO_2^- of the Son La hydropower reservoir (Do et al., 2020). High values of NO_2^- and NH_4^+ are caused mainly by the agricultural use of the catchment (Tomczyk et al., 2021). Non-point sources of organic matter and nutrients from agriculture, domestic release, and aquaculture in the Sonla hydropower reservoir were possibly responsible for water quality (Do et al., 2020). The microorganisms within the water are prime sources to cause different waterborne diseases like Diarrhea, Cholera, Scabies, Asthma, etc. (Shultana et al., 2022). Therefore, specific measures, such as controls on point source pollution control and tailings, should be taken to maintain drinking water safety and aquatic ecosystem health (Wang et al., 2018).

Water quality indicators values of pH, D.O., T.S.S., C.O.D., NH_4^+, NO_2^-, and Coliform of Son La hydropower reservoirs (S.L.R.) were lower than the regulation limits for living water in Vietnam (Q.C.V.N. 08:2023/B.T.N.M.T.) (MONRE., 2023). In addition, the input water of Son La hydropower reservoirs from Lai Chau hydropower reservoirs, the mean yearly values of water quality were, specifically: pH (6.3–6.8), D.O. (5.5–6.3), T.S.S. (2–30), and C.O.D. (6.1–20.7) (Do et al., 2019). The output water of Son La hydropower reservoir is the primary input to supply water to Hoa Binh hydropower reservoir and Da River water of Hoa Binh hydropower reservoirs has been treated for drinking and domestic with quality indicators values of pH, D.O. fluctuated from 7.1–7.6 mg/L, 6.4–7.4 mg/L, and the value of T.S.S. is 200–250 mg/L in the flood season, 20–30 mg/L in the dry season (Nguyen et al., 2018). It is suggested that river water be treated before its use for drinking and other domestic purposes (Beshiru et al., 2018). Thus, the water quality of Da River in Lai Chau, Son La, and Hoa Binh hydropower reservoirs is still good; it is relatively safe water and meets the demand for drinking and other purposes.

This result is consistent with previous studies; results from the discussion further support the new findings of this study, which revealed that D.O. parameters in Son La hydropower reservoir water are higher than those in Da river water. This shows that the biogeochemical process in the reservoir bed has stabilized after more than 10 years of dam construction and water storage. The decrease in T.S.S. concentration or turbidity is considered a higher sediment deposition process in reservoir flow than in river flow. Reducing biomass decomposition in the reservoir bed may cause a decrease in the C.O.D. parameter concentration. The pH in the Son La hydropower reservoir water decreased, which may be related to the depth of the reservoir water. The parameter groups NH_4^+, NO_2^-, and coliform increase mainly due to waste sources from residential areas, agriculture, fish cages, and tourism. The water quality of Son La hydropower reservoirs changes over time and space. Still, it is better than Da River water, demonstrating the ability to self-clean and assimilate pollutants, making the lake water clean and safe for health.

4. Conclusions

Water quality indicators impoundment before and after the impoundment of the Son La hydropower reservoir Dam in the Da River mainstream varied considerably in 2010 and during 2014–2023. Water quality indicator values of pH, D.O., T.S.S., C.O.D., NH_4^+, NO_2, and coliform were lower than the regulation limits for living water in Vietnam. The D.O. concentrations in the hydropower reservoir were significantly higher than those in the Da River, reflecting the role of the reservoir in increasing the concentration of dissolved oxygen. The concentrations of T.S.S., C.O.D., and Coliform in Da River water in 2010 exceeded the for living water Vietnam regulation (≤ 25 mg/L; ≤ 10 mg/L; ≤ 1,000 MPN/100ml), and showed significantly higher values than the reservoir, reflecting the role of reservoir for the self-cleaning ability of pollutants. The results demonstrated an increase trend of D.O., NH_4^+, NO_2^-, and Coliform and a decrease trend of pH, T.S.S., and C.O.D. of the reservoir during 2014–2023. Water quality indicator values of pH, D.O., T.S.S., C.O.D., NH_4^+, NO_2^-, and coliform at 175 m, 190 m, and 215 m were lower than the regulation limits for living water in Vietnam. The concentrations of T.S.S. in water at the water level of 175 m in the rainy season exceeded the Vietnam regulation. The Coliform quality indicator at the water level of 215 m (dry season) exceeded limits for living water in the Vietnam regulation. The concentrations of D.O. at the water level of 190 m and 215 m corresponding with the dry season were lower than the Vietnam regulation. After ten years of water impoundment from 2014 to 2023, Da River was relatively safe; water has been treated for drinking and domestic purposes. Further study should be conducted to clarify the sources and self-purification mechanism by which the hydropower reservoir supplies water for daily use. In addition, water quality pollutant load and water quality management in the whole river system of the Son La Hydropower reservoir basin should be conducted.

Acknowledgments

All data and information related to the water quality of Son La Hydropower reservoir are retrieved and used with the permission of Son La Hydropower Company for scientific purposes.

References

Adamovich B.V., Medvinsky A.B., Nikitina L.V., Radchikova N.P., Mikheyeva T.M., Kovalevskaya R.Z., Zhukova T.V, 2019. Relations between variations in the lake bacterioplankton abundance and the lake trophic state: Evidence from the 20-year monitoring. Ecological Indicators, 97, 120–129.

Adrian L., Gilles B., Josette G., 2015. Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environmental Research Letters, 10, 1–13.

Altinbilek D., 2002. The role of dams in development. Water Science and Technology, 45(8), 169–180.

An Y.J., Kampbell D.H., Peter B.G., 2002. Escherichia coli and total coliforms in water and sediments at lake marinas. Environmental Pollution, 120(3), 771–778.

Atobatele, Oluwatosin E., Ugwumba O.A., 2008. Seasonal variation in the physicochemistry of a small tropical reservoir (Aiba Reservoir, Iwo, Osun, Nigeria). African Journal of Biotechnology, 7(12), 1962–1971.

Beshiru A., Okareh O.T., Chigor V.N., Igbinosa E.O., 2018. Assessment of water quality of rivers that serve as water sources for drinking and domestic functions in rural and pre-urban communities in Edo North, Nigeria. Environmental monitoring and assessment, 190, 1–12.

Bhateria R., Jain D., 2016. Water quality assessment of lake water: a review. Sustainable Water Resources Management, 2(2), 161–173.

Bilotta G.S., Brazier R.E., 2008. Understanding the influence of suspended solids on water quality and aquatic biota. Water Research, 42(12), 2849–2861.

Bonanomi G., Senatore M., Migliozzi A., De Marco A., Pintimalli A., Lanzotti V., Mazzoleni S., 2015. Decomposition of submerged plant litter in a Mediterranean reservoir: A microcosm study. Aquatic Botany, 120, 169–177.

Brankov J., Milijašević D., Milanović A., 2012. The Assessment of the Surface Water Quality Using the Water Pollution Index: A Case Study of the Timok River (The Danube River Basin), Serbia. Archives of Environmental Protection, 38(1), 49–61.

Bulbul Ali A., Mishra A., 2022. Effects of dissolved oxygen concentration on freshwater fish: A review. International Journal of Fisheries and Aquatic Studies, 10, 113–127.

Catherine E.M., Winter J.G., Scheider W.A., Watmough S.A., Nicholls K.H., 2005. Recent Changes and Patterns in the Water Chemistry of Lake Simcoe. Journal of Great Lakes Research, 31(3), 322–332.

Cooke G.D., Kennedy R.H., 2001. Managing drinking water supplies. Lake and Reservoir Management, 17(3), 157–174.

Coura M.R., Cordova J.E., Oliveira S.C., 2021. Analysis of surface water quality changes after filling hydroelectric reservoirs in the Amazon, Brazil. Environmental Process, 8(2), 573–592.

Chen K., Chen H., Zhou C., Huang Y., Qi X., Shen R., Liu F., Zuo M., Zou X., Wang J., Zhang Y., Chen D., Chen X., Deng Y., Ren H., 2020. Comparative analysis of surface water quality prediction performance and identification of key water parameters using different machine learning models based on big data. Water Research, 171, 115454.

Chen P., Li L., Zhang H., 2015. Spatio-temporal variations and source apportionment of water pollution in Danjiangkou Reservoir Basin, Central China. Water, 7(12), 2591–2611.

Chen X., Xu G., Zhang W., Peng H., Xia H., Zhang X., Ke Q., Wan J., 2019. Spatial variation pattern analysis of hydrologic processes and water quality in Three Gorges Reservoir Area. Water, 11(12), 2608.

Dalu T., Wasserman R.J., 2018. Cyanobacteria dynamics in a small tropical reservoir: Understanding spatio-temporal variability and influence of environmental variables. The Science of the Total Environment, 643, 835–841.

Do X.D., Luu D.H., Do H.T., 2019. The Evolutions for Water Quality of Son La Hydropower Reservoir from Environmental Monitoring Data (2010-2018)", V.N.U. Journal of Science: Earth and Environmental Sciences, 35(3), 1–21.

Do X.D., Luu D.H., Do H.T., 2020. Self-Cleaning Ability of Pollutants Containing Nitrogen and Phosphorus Transformed into NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, of Son La Hydropower Reservoir, V.N.U. Journal of Science: Earth and Environmental Sciences, 36(3), 12–24.

Dordoni M., Seewald M., Rinke K., Schmidmeier J., Barth J.A.C., 2022. Novel evaluations of sources and sinks of dissolved oxygen via stable isotopes in lentic water bodies. The Science of the Total Environment, 838, 156541.

Dzung N.K., Tri D.Q., 2018. Water quality of Hoa Binh Reservoir. International Symposium on Lowland Technology (I.S.L.T. 2018), Sept, 26–28, ISBN: 978.604.82.2483.7.

Fantin C.I., Pedrollo O., Girard P., Zeilhofer P., Hamilton S.K., 2015. Changes in river water quality caused by a diversion hydropower dam bordering the Pantanal floodplain. Hydrobiologia, 768(1), 223–238.

Fantin-Cruz I., Pedrollo O., Girard P., 2016. Changes in river water quality caused by a diversion hydropower dam bordering the Pantanal floodplain. Hydrobiologia, 768, 223–238.

Fu L., Gan Wang Y., 2012. Statistical tools for analyzing water quality data. Water quality monitoring and assessment, In Tech Open, 143–168.

Fukushima T., Ozaki N., Kaminishi H., Harasawa H., Matsushige K., 2000. Forecasting the changes in lake water quality in response to climate changes, using past relationships between meteorological conditions and water quality. Hydrological Processes, 14(3), 593–604.

Gao Q., Li Y., Cheng Q., Yu M., Hu B., Wang Z., Yu Z., 2016. Analysis and assessment of the nutrients, biochemical indexes and heavy metals in the Three Gorges Reservoir, China, from 2008 to 2013. Water Research, 92, 262–274.

Geraldes A.M., Boavida M.J., 2005. Seasonal water level fluctuations: Implications for reservoir limnology and management. Lakes and Reservoirs. Research and Management, 10(1), 59–69.

Gu Q., Deng J., Wang K., Lin Y., Li J., Gan M., Ma L., Hong Y., 2014. Identification and assessment of potential water quality impact factors for drinking-water reservoirs. International Journal of Environmental Research and Public Health, 11(6), 6069–6084.

Ha N.T.H., Sakakibara M., Sano S., Nhuan M.T., 2011. Uptake of metals and metalloids by plants growing in a lead–zinc mine area, Northern Vietnam. Journal of Hazardous Materials, 186, 1384–1391.

Hadjibiros K., Katsiri A., Andreadakis A, Koutsoyiannis D., Stamou A., Christofides A., Efstratiadis A., Sargentis G.F., 2005. Multi-criteria reservoir water management, Global Network for Environmental Science and Technology, 7, 386–394.

Hasan M.F., Nur-E-Alam M., Salam M.A., Rahman H., Paul S.C., Rak A.E., Ambade B., Towfiqul Islam, A.R.M., 2021. Health risk and water quality assessment of surface water in an urban river of Bangladesh. Sustainability, 13(12), 6832.

Ibrahim B., Auta J., Balogun J., 2010. An assessment of the physico-chemical parameters of Kontagora reservoir, Niger state, Nigeria. Bayero Journal of Pure and Applied Sciences, 2(1), 1–6.

Jerves-Cobo R., Forio M.A.E., Lock K., Van Butsel J., Pauta G., Cisneros F., Nopens I., Goethals P.L.M., 2020. Biological water quality in tropical rivers during dry and rainy seasons: A model-based analysis. Ecological Indicators, 108, 105769.

Jiri H., Marketa H., Vladimir C., 1999. Pollution by phosphorus and nitrogen in water streams feeding the Zelivka drinking water reservoir. Water Science and Technology, 39(12), 207–214.

Killingtveit Å., 2019. Hydropower. In T. Letcher (Ed.), Managing Global Warming, Academic Press, 265–315.

Kummu M., Varis O., 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. Geomorphology, 85(3–4), 275–293.

Le T.S., 2012. Research on forecasting stimulated earthquakes in Son La Hydropower reservoir area, independent state-level project. Institute of Geophysics, Hanoi, 272.

Lee D., Kim S., Park S.J., 2006. Effect of reservoirs on microbiological water qualities in a drinking water distribution system. Journal of Microbiology and Biotechnology, 16(7), 1060.

Lerat Y., Lasserre P., Corre P.L., 1990. Seasonal changes in pore water concentrations of nutrients and their diffusive fluxes at the sediment-water interface. Journal of Experimental Marine Biology and Ecology, 135(2), 135–160.

Li P., Wu J., 2019. Drinking water quality and public health. Exposure and Health, 11(2), 73–79.

Li Z., Ma J., Guo J., Paerl H. W., Brookes J D., Xiao Y., Lunhui L., 2019. Water quality trends in the Three Gorges Reservoir region before and after impoundment (1992–2016). Ecohydrology & Hydrobiology, 19(3), 317–327.

Li Z., Ma J., Guo J., Paerl H.W., Brookes J.D., Xiao Y., Fang F., Ouyang W., Lunhui L., 2019. Water quality trends in the Three Gorges Reservoir region before and after impoundment (1992–2016), Ecohydrology & Hydrobiology, 19(3), 317–327.

Ling T.Y., Gerunsin N., Soo C.L., Nyanti L., Sim S.F., Grinang J., 2017. Seasonal changes and spatial variation in water quality of a large young tropical reservoir and its downstream River. Journal of Chemistry, 1–16.

Lizotte R.E., Knight S.S., Locke M.A., Bingner R.L., 2014. Influence of integrated watershed scale agricultural conservation practices on lake water quality. Journal of Soil and Water Conservation, 69(2), 160–170.

Lliev I., Hadjinikolova L., 2013. Seasonal and vertical dynamics of the water temperature and oxygen content in Kardzhali reservoir. Agricultural Science and Technology, 5(2), 1313–8820.

Ma J., Ding Z., Wei G., Zhao H., Huang T., 2009. Sources of water pollution and evolution of water quality in the Wuwei basin of Shiyang river, Northwest China. Journal of Environmental Management, 90(2), 1168–1177.

Maberly S.C., 2008. Diel, episodic and seasonal changes in pH and concentrations of inorganic carbon in a productive lake. Freshwater Biology, 35(3), 579–598.

Maheshwari B.L., Walker K.F., McMahon T.A., 1995. Effects of regulation on the flow regime of the River Murray, Australia. Regulated Rivers. Research & Management, 10(1), 15–38.

Mahmoud H., 2010. Impact of Water Level Fluctuation on Water Quality and Trophic State of Lake Nasser and its Khors, Egypt. Egyptian Journal of Aquatic Biology and Fisheries, 14(1), 75–86.

Marques É.T., Gunkel G., Sobral M.C., 2019. Management of tropical river basins and reservoirs under water stress: Experiences from northeast Brazil. Environments, 6(6), 62.

Medudhula, Thirupathaiah, Samatha C.H., 2012. Chintha Sammaiah. Analysis of water quality using physico-chemical parameters in lower manair reservoir of Karimnagar district, Andhra Pradesh. International Journal of Environmental Sciences, 3(1), 1–9.

Ministry of Industry - Vietnam Electricity Group, 2006. Environmental impact assessment report of Son La Hydropower project construction project, Hanoi.

Ministry of Natural Resources and Environment of Vietnam (M.O.N.R.E.)., 2023. National technical regulation on surface water quality (Q.C.V.N. 08-MT:2023/B.T.N.M.T.).

Mostafazadeh R., Nasiri Khiavi A., 2024. Changes in the characteristics of water quality parameters under the influence of dam construction. Environment, Development and Sustainability, 1–19.

Njuguna S.M., Onyango J.A., Githaiga K.B., Gituru R.W., Yan X., 2020. Application of multivariate statistical analysis and water quality index in health risk assessment by domestic use of river water. Case study of Tana River in Kenya. Process Safety and Environmental Protection, 133, 149–158.

Noori R., Berndtsson R., Franklin A.J., Rabiee A.M., 2018. Temporal and depth variation of water quality due to thermal stratification in Karkheh Reservoir, Iran. Journal of Hydrology, Regional Studies, 19, 279–286.

Norton S.A., Coolidge K., Amirbahman A., Bouchard R., Kopáček J., Reinhardt R., 2008. Speciation of Al, Fe, and P in recent sediment from three lakes in Maine, U.S.A. Science of The Total Environment, 404(2–3), 276–283.

Park K.D., Kang D.H., Jo W.G., Yang M., 2022. Analysis Temporal and Spatial Changes of Water Quality in Domestic Hydropower Dam Reservoirs. Journal of Environmental Science International, 31(5), 373–388.

Qi M., Han Y., Zhao Z., Li Y., 2021. Integrated Determination of Chemical Oxygen Demand and Biochemical Oxygen Demand. Polish Journal of Environmental Studies, 30(2), 1785–1794.

Rajwa A., Bialik R.J., Karpiński M., Luks B., 2014. Dissolved oxygen in rivers: Concepts and measuring techniques. In Bialik R., Majdański M., Moskalik M. (Eds.), Achievements. Springer, 337–350.

Rajwa-Kuligiewicz A., Bialik R.J., Rowiński P.M., 2015. Dissolved oxygen and water temperature dynamics in lowland rivers over various timescales. Journal of Hydrology and Hydromechanics, 63(4), 353–363.

Richard B., Alexander., Richard A., Smith., Gregory E., Schwarz., Elizabeth W., Boyer., Jacqueline V., Nolan., John W., Brakebill., 2008. Differences in Phosphorus and Nitrogen Delivery to The Gulf of Mexico from the Mississippi River Basin. Environmental Science & Technology, 42(3), 822–830.

Rong X., Lijing W., Hong L., BinghuiZheng., 2021. Temporal and spatial variation in water quality in the Three Gorges Reservoir from 1998 to 2018. Science of The Total Environment, 768(10), 144866.

Samiotis G., Trikoilidou E., Tsikritzis L., 2018. Comparative water quality assessment between a young and a stabilized hydroelectric reservoir in Aliakmon River, Greece. Environ Monit Assess, 190, 234.

Shrivastava A., Tandon S.A., Kumar R., 2015. Water quality management plan for Patalganga River for drinking purpose and human health safety. International Journal of Scientific Research in Environmental Sciences, 3(2), 0071–0087.

Shultana S., Khan R.A., 2022. Water quality assessment, reasons of river water pollution, impact on human health and remediation of polluted river water. G.S.C. Advanced Research and Reviews, 10(2), 107–115.

Silva S.N., Castillo J.Á.D., 2021. An approach of the hydropower: Advantages and impacts. A review. Journal of Energy Research and Reviews, June, 10–20.

Spataru P., 2022. Influence of organic ammonium derivatives on the equilibria between NH_{4+}, NO_{2-} and NO_{3-} ions in the Nistru River water. Scientific Reports, 12(1), 13505.

Tiwari P., Tiwari M.P., 2022. Evaluation of water quality and dam for sustaining the fish population dynamics. Applied Water Science, 12(9), 233.

Tomczyk P., Wiatkowski M., 2021. Impact of a small hydropower plant on water quality dynamics in a diversion and natural river channel. Journal of Environmental Quality, 50(5), 1156–1170.

Vaidya R.A., Molden D.J., Shrestha A.B., Wagle N., Tortajada C., 2021. The role of hydropower in South Asia's energy future. International Journal of Water Resources Development, 37(3), 367–391.

Varol M., 2020. Spatio-temporal changes in surface water quality and sediment phosphorus content of a large reservoir in Turkey. Environmental Pollution, 259, 113860.

Varol M., 2020b. Use of water quality index and multivariate statistical methods for the evaluation of water quality of a stream affected by multiple stressors: A case study. Environmental Pollution, 266, 115417.

Varol M., Gökot B., Bekleyen A., Şen B., 2012. Spatial and temporal variations in surface water quality of the dam reservoirs in the Tigris River basin, Turkey. Catenna, 92, 11–21.

Vega A.S., Lizama K., Pastén P.A., 2018. Water quality: Trends and challenges. In Donoso G. (Ed.), Water policy in Chile, Springer, 25–51.

Wang X., Zhang L., Zhao Z.,, Cai, Y., 2018. Heavy metal pollution in reservoirs in the hilly area of southern China: Distribution, source apportionment and health risk assessment. Science of the Total Environment, 634, 158–169.

Wei G., Yang Z., Cui B., Li B., Chen H., Bai J.H., Dong S.K., 2009. Impact of Dam Construction on Water Quality and Water Self-Purification Capacity of the Lancang River, China. Water Resour Manage, 23, 1763–1780.

Winton R.S., Calamita E., Wehrli B., 2019. Reviews and syntheses: Dams, water quality and tropical reservoir stratification. Biogeosciences, 16(8), 1657–1671.

Winton R.S., López-Casas S., Valencia-Rodríguez D., Bernal-Forero C., Delgado J., Wehrli B. and Jiménez-Segura L., 2023. Patterns and drivers of water quality changes associated with dams in the Tropical Andes. Hydrology and Earth System Sciences, 27(7), 1493–1505.

Xia J., Xu G., Guo P., Peng H., Zhang X., Wang Y., Zhang W., 2018. Tempo-Spatial Analysis of Water Quality in the Three Gorges Reservoir, China, after its 175 m Experimental Impoundment. Water Resources Management, 32(9), 2937–2954.

Yang L., Lei K., Meng W., Fu G., Yan W., 2013. Temporal and spatial changes in nutrients and chlorophyll-α in a shallow lake, Lake Chaohu, China: An 11-year investigation. Journal of Environmental Sciences, 25(6), 1117–1123.

Ye L., Chen K., Cheng J., Tan L., Zhang M., Zhang X., Cai Q., 2023. Ecological water quality of the Three Gorges Reservoir and its relationship with land covers in the reservoir area: implications for reservoir management. Frontiers in Environmental Science, 11, 1196089.

Yehia H.M.A.S., Said S.M., 2021. Drinking water treatment: pH adjustment using natural physical field. Journal of Biosciences and Medicines, 9(6), 55–66.

Yen C., Picco L., Bao T., 2019. Hydopower Dam and Hydrological Alternation on the Da River in Son La, Vietnam. J. For. Sci. Technol, 7, 124–132.

Yuretich R.F., Cerling T.E., 1983. Hydrogeochemistry of Lake Turkana, Kenya: Mass balance and mineral reactions in an alkaline lake. Geochimica et Cosmochimica Acta, 47(6), 1099–1109.

Zhang X., Chen P., Han Y., Chang X., Dai S., 2022. Quantitative analysis of self-purification capacity of non-point source pollutants in watersheds based on SWAT model. Ecological Indicators, 143, 109425.

Zhang Y., Deng J., Qin B., Zhu G., Zhang Y., Jeppesen E., Tong Y., 2023. Importance and vulnerability of lakes and reservoirs supporting drinking water in China. Fundamental Research, 3(2), 265–273.

Zhao P., Tang X., Tang J., Wang C., 2013. Assessing Water Quality of Three Gorges Reservoir, China, Over a Five-Year Period From 2006 to 2011. Water Resources Management, 27(13), 4545–4558.

Zhao Z., Wang S., Lu, W., Yang W., Li S., 2024. Water quality assessment, possible origins and health risks of toxic metal (loid) s in five cascade reservoirs in the upper Mekong. Journal of Cleaner Production, 441, 141049.