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Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 4, December 2026 issue

Water Season Quality Variation Bringing Pollutant Load into the Largest Hydropower Reservoir in Vietnam after the Dam Impoundment (2014-2024)

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Key Words	Hydropower, Son La Reservoir, Pollution load, Water quality
DOI	https://doi.org/10.46488/NEPT.2026.v25i04.D1916 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Do, X-D., 2026. Water season quality variation brings pollutant load into the largest hydropower reservoir in Vietnam after the dam impoundment (2014-2024). *Nature Environment and Pollution Technology*, 25(4), D1916. https://doi.org/10.46488/NEPT.2026.v25i04. D1916

ABSTRACT

Hydropower reservoirs, such as the Son La reservoir on the Da River is the largest in Vietnam and are critical for electricity generation and water regulation, and water supply. However, post impoundment changes in flow regimes and pollutant transport pose potential risks to downstream ecosystems and water security. This study identifies trends in water flow and seasonal fluctuations in pollutant concentrations, determines correlations between runoff and water quality, and quantifies the seasonal pollutant load entering the reservoir. Data were collected between 2014 and 2024 from four major inflows (Da, Nam Na, Nam Muc, and Nam Mu Rivers). Monitoring focused on nine parameters, including dissolved oxygen (DO), total suspended solids (TSS), BOD_5, COD, and various nutrients. The pollutant load (PL) was calculated using a material balance equation: $\mathrm{PL} = \mathrm{Q} * \mathrm{C_i} * 10^{-6} * 365 * 24 * 60 * 60$. Analysis was performed using SPSS 2.0 and R-Studio, utilizing correlation tests for normality, one-way ANOVA, and Pearson correlation coefficients (r) to evaluate seasonal variations. Water flow showed an increasing trend (except in the Nam Muc River), with rainy season flows significantly higher than dry season flows. While DO, total iron, and nutrients showed increasing trends, TSS, BOD_5, and COD decreased, likely due to upstream sediment trapping. The average annual pollutant load was 3.403.604 tonnes, with the rainy season accounting for 63.1% to 92.4% of the total. TSS comprised 75% of the total load. Correlation analysis revealed that dam operations and seasonal discharge significantly

influence pollutant concentrations. These results provide a vital scientific basis for monitoring water quality and managing pollution in hydropower basins to safeguard regional water resources.

1. INTRODUCTION

River flows are important for basin ecosystems and are the main source of water for hydropower reservoirs (Branche 2017). Research on pollutant load is meaningful for environmental flow management in the basin of hydropower reservoirs (Jager et al., 2008). Determination of the pollutant load in the dry season and the flood season is for pollutant management to achieve the goal of water quality control in both seasons (Choi et al., 2015). Pollutant loads under different flow conditions and regimes are used for analysis, targeting water quality recovery, and identifying appropriate best management practices in the basins (Kim et al., 2012).

Recent research on pollutant loads in hydropower reservoir basins highlights the complex interplay of various sources and their impacts. Studies have examined point and non-point source pollution in rivers feeding reservoirs, using models to predict pollution loads and analyze permissible levels (Chong, 2003). Sediment sources and associated pollutants have been investigated using geochemical fingerprinting, revealing significant contributions from mining and agricultural activities (Bravo et al., 2024). The Soil and Water Assessment Tool (SWAT) has been employed to evaluate spatial and temporal distributions of nitrogen, phosphorus, and heavy metal loads, identifying seasonal patterns and key pollution sources (Wulin et al., 2024). Additionally, research has focused on the self-cleaning ability of reservoirs regarding nitrogen and phosphorus-containing pollutants, calculating emission rates and self-cleaning capacities based on various factors such as pollutant concentrations and hydraulic retention time (Do et al., 2020). These studies provide valuable insights for watershed management and pollution mitigation strategies.

The pollution load of total suspended solids (TSS) in hydropower reservoir basins is influenced by various factors (Bayram et al., 2016) found that the Borçka Dam in Turkey effectively trapped TSS and reduced turbidity due to its long hydraulic residence time. In China's Danjiangkou Reservoir Basin (Zhuang et al., 2016) identified critical source areas for nonpoint source pollution, with 70% of pollutant loads originating from 30% of the basin area (Chong., 2003) developed models to forecast point and nonpoint source pollution loads in the Xiangxi River Basin of the Three Gorges Reservoir Area. In Malaysia's Kenyir Hydropower Reservoir (Wahab et al., 2023) observed varying sediment load production across sub-catchments, with anthropogenic activities, hydrological factors, and climate change contributing to sedimentation. These studies emphasize the importance of comprehensive watershed management and stakeholder involvement in addressing TSS pollution in hydropower reservoir basins.

The pollution load of COD and BOD_5 in hydropower reservoir basins is a significant concern. Studies on the Three Gorges Reservoir show that agricultural non-point sources are the main pollution source, contributing up to 70.4% of COD loads (Li., 2006). Before impoundment, the total annual loads of COD and BOD_5 were 4.49×10^6 and 9.80×10^5 tons, respectively (Li., 2005). In the Miyun Reservoir, non-point sources account for 73% of COD and 71% of BOD loads (Xiao., 2003). The Zhangze Reservoir study reveals that urban domestic sources are the primary contributors, accounting for 65.47% of COD loads (Yang et al., 2022). These studies highlight the importance of addressing both point and non-point sources in reservoir basins. Urban areas, particularly in the Three Gorges Reservoir, are identified as major pollution discharge regions, emphasizing the need for targeted pollution control measures (Li., 2005; Li., 2006).

The pollution load of NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-} in hydropower reservoir basins is a significant concern. Studies have shown that these pollutants primarily originate from agricultural activities, livestock breeding, and domestic sources (Tong et al., 2017; Zhuang et al., 2016). In the Son La hydropower reservoir, approximately 10,323 tons of nitrogen and 5,454 tons of phosphorus were added annually, with the reservoir demonstrating a self-cleaning capacity of 8,117 tons per year for NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-} pollutants (Do et al., 2020). Research in the Three Gorges Reservoir area identified dry lands and forestlands as the main sources of non-point source pollution, contributing over 90% of the nitrogen and phosphorus load (Xia., 2012). To address this issue, experts recommend prioritizing the treatment of sloping farmlands, implementing soil and water conservation measures, and focusing on critical source areas, which typically contribute about 70% of the pollution load from 30% of the basin area (Zhuang et al., 2016).

In the research related to pollutant loads, the quantification of river pollutant loads is mainly integrated with the calculations of non-point pollution sources and point pollution sources in the river basin. Nutrients from non-point sources are carried by annual river flow of quantified watersheds (Li et al., 2005). The distribution of pollutant loads in the stream is calculated to determine the pollution in the river basin (Cheng et al., 2006). Estimating pollutant load in surface water in different river basins is used to quantify the pollutant load at the source (Amaya et al., 2012). The actual pollutant load received via the stream is estimated and simulated through calculations on the model to properly understand pollution sources and pollutant loads on river flows (Huang et al., 2013). Fluctuation of water quality in catchment flows is quantified to provide reasonable and scientific options for pollution control and water protection (Nuen et al., 2020). Up to now, studies on pollutant load estimation have based on discharge trend analysis, the relationship between runoff flows and pollutant concentration, seasonal load distribution ratio are not well-understood. Therefore, it is essential to fill this relevant information to quantify the transport capacity of dry season and flood season stream pollutant loads in hydropower reservoirs.

Currently, there are methods to calculate pollutant loads on river basin runoff, however, the method to estimate pollutant load is based on discharge or flow rate (Q) and concentration (C_i) of pollutants. The stream pollutant load is estimated from discharge and pollutant concentration data by multiplying the mean concentration by the mean flow rate (Ferguson., 1987). The flow and water quality in the dry season and in the flood season are based on data analyzed at monitoring stations and seasonally analyzed flow and water quality characteristics, the relationships between water discharge and pollutant load is analyzed to estimate the pollutant load of the basin (Jeong et al., 2000). The discharge and water quality of the study basin are monitored and analyzed to estimate the pollutant load (Shin et al., 2005). Pollutant load on the catchment scale is calculated based on water quality monitoring data (concentration) and water flow rate data at the monitoring stations (Shrestha et al., 2008). Pollutant load on the dry season and flood season flows is determined by the average value of the concentration (Ci) with the average discharge (Wi) (Zhu et al., 2015). The stream pollutant load is estimated based on water quality data and the flow (Park et al., 2025). Calculation of river flow pollutant load is based on daily discharge data, baseline discharge, and pollutant concentration (Xin et al., 2017). For research on the estimation of flow pollutant load in the dry season and flood season, it is necessary to determine the relationship between flow characteristics and flow rate with pollutant concentration. The discharge loads of organic matter, nitrogen, and phosphorus compounds are strongly correlated with the annual river flow rate, the difference in flow rate affects the dry season and flood season pollutant load (Niemirycz et al.,1999). Pollutant load estimation based on the dry season and wet season the stream and water quality is based on runoff characterization and is a basin assessment and management process to address surface water depletion (Eom et al., 2010). The relationship between flows and the change of water quality concentration in the dry season and the flood season in the reservoir basin are analyzed by estimating the pollutant load distributed according to the stream characteristics of the reservoir basin (Park et al., 2011). The distribution flows in river flows are influenced by the seasons, the dry season is more stable than the flood season (Bowers et al., 2012). Changes in flow regimes and pollutant loads need to be considered to develop appropriate hydrological recommendations for the watershed (Zeiger et al., 2017).

The Da River is a major tributary of the Red River system in Vietnam, covering an area of 52,900 km^2 and providing water for agriculture and drinking to millions of people (Le Viet Son et al., 2019). It plays a crucial role in the region's hydrology and economy. The river system has experienced significant changes due to dam construction, particularly affecting sediment transport. At the Son Tay station, the Red River's sediment load decreased by 91% between 1958-1987 and 2009-2021, with major declines observed after the Hoa Binh dam's operation in 1988 and further reductions since 2009 (Nguyen et al, 2023). The Da River also contributes to CO_2 emissions, with the highest pCO_2 and outgassing rates measured downstream of the Hoa Binh Dam (Le et al., 2017). These changes highlight the importance of effective water resource management in this transnational river basin (Van et al., 2024).

Most studies rely on general discharge trend analysis and mean concentration data to estimate basin pollution. However, seasonal load distribution ratios and the specific transport capacity of pollutant loads during distinct dry and flood seasons remain insufficiently understood. Additionally, while general relationships between runoff and concentration are established, there is a critical lack of information regarding how varying flow characteristics influence the precise transport of organic matter, nitrogen, and phosphorus within hydropower reservoir basins. This is a research gap that needs to be filled.

The Son La Reservoir the largest hydropower one in Vietnam with capacity of 2,400 MW-plays crucial role in renewable electricity generation and water regulation in northern Vietnam. It has been operated since 2012 after 7 years of construction (2005-2012). It locates in the Da River system which supply domestic and irrigation water for Dien Bien, Lai Chau, Hoa Binh, and Son La province, and one of water sources for the second largest delta (Red River) in Vietnam. In addition, Da River also provides drinking and domestic water capacity of 300,000 m^3/day for estimated 100,000 households of Hanoi- capital of Vietnam. The capacity will subject to increase to 1,365,000 m^3/day by 2030 and 1,890,000 m^3/day by 2050. Although Da River water has been treated for drinking and domestic purposes, water quality management is essential for safety of consuming ecosystems and human health.

In this study, our main objective is to analyze the pollutant discharge load in the dry season and the flood season of the river system in the basin of the hydropower reservoir. We consider and approach 4 specific goals in this research: (1) identify changes related to flow rate trends and seasonal fluctuations in surface water pollution concentrations in river flows; (2) the correlation between seasonal runoff rate and pollutant concentration; (3) the pollutant load of the basin in the dry season and the flood season is quantified; (4) and used to estimate the capacity of hydropower dams to change the pollutant load downstream.

2. MATERIALS AND METHODS

2.1. Research area

The reservoir has a water surface area of 224 km^2, it is 175 km long. The reservoir basin has an area of 11,075 km^2 including the mainstream (Da River) and three tributaries Nam Muc River, Nam Na River, and Nam Mu River) that supply water to the Son La hydropower reservoir (Figure 1). Nam Muc river has a length of 128 km with a sub-basin area of 1,618 km^2. Nam Na river has a length of 109.4 km corresponding to the sub-basin area is 2,949 km^2. Nam Mu river has a length of 183.7 km, corresponding to the sub-basin area of 2,972 km^2. Some hydropower dams have been constructed in the mainstream (Da River) and three tributaries before the water flows into Son La hydropower reservoir: Lai Chau dam in Da River, Nam Muc dam in Nam Muc River, Nam Na 1 and 2 dams in Nam Na River, and Huoi Quang dam in Nam Mu River. Dry season (from January to March and from October to December) is characterized by low rainfall (350 mm/year). The rainfall in flood season (from April to September) is 1,577 mm/year. Figure 1 shows four rivers supplying water to Son La hydropower reservoir with coded water flow and surface water quality monitoring points (S1 – S4). Monitored water flow (Q) and surface water quality entering Son La hydropower reservoir with nine parameters including: TSS, BOD_5, COD, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, total Fe are used to regulations on assessment of wastewater receiving capacity and carrying capacity of river and lake water sources 76/2017/TT-BTNMT regulation [Monre., 2017]. The average value of water flow and surface water quality parameters at four monitoring points are for ten years 2014 - 2023 (Source: Hydrometeorological Station of the Northwest Region and Son La Hydropower Company).

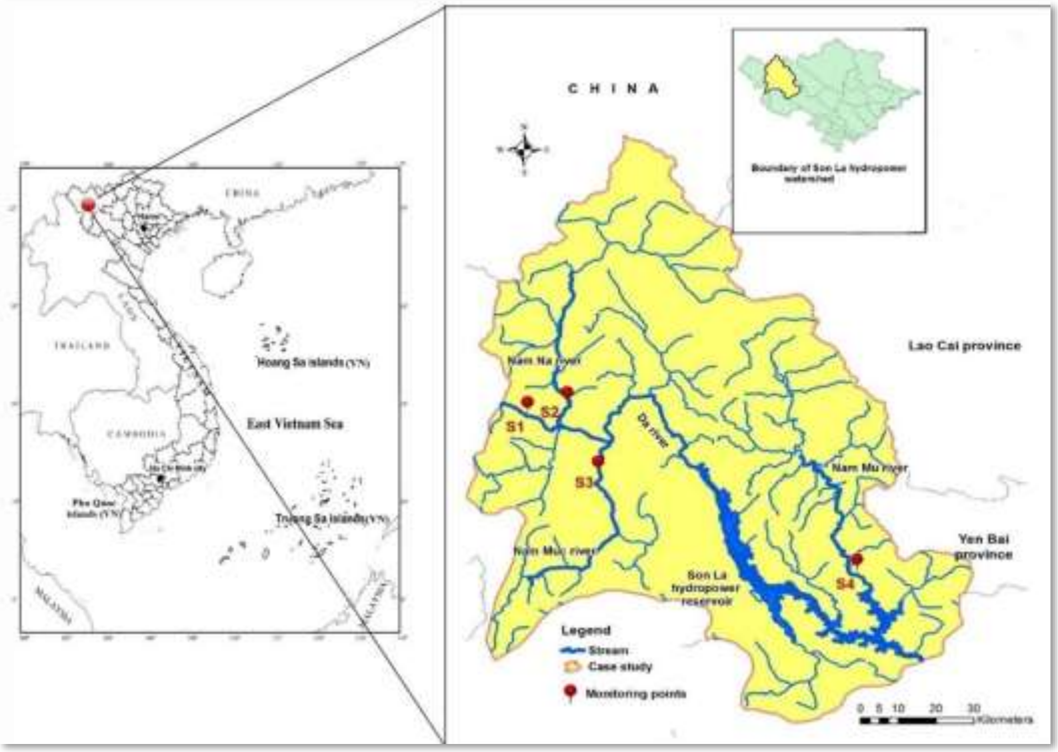


Fig. 1: Location of monitoring points in the river system of Son La Hydropower reservoir basin in Northwestern Vietnam

2.2. Monitoring data

In the study area, five monitoring stations have been operated by the Son La Hydropower Company since 2014, including S1 (Da River), S2 (Nam Na River), S3 (Nam Muc River), S4 (Nam Mu River) (Fig. 1). S1, S2, S3, and S4 stations have been monitored the flow and water quality of rivers entering the Son La hydropower reservoir (inflow). The monitoring frequency is 4 times per year in March, May, August, and November. Monitoring data of water flow (Q) and surface water quality (DO, TSS, BOD_5, COD, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, and total Fe) at 4 stations (S1 - S4) during 2014 - 2024 were collected, and DO values were measured by the Sension156 portable equipment (HACH, US); BOD_5 and COD were determined by the (HACH, US); TSS was detected by the analytical method (TCVN 6625:2000); Total Fe was detected by the (SMEWW 3111B:2012). The portable model 556 equipment (YIS, US) was used to determine the concentrations of NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, and total Fe in water. Average values of water flow and quality in March and November were calculated to represent dry season; those in May and August were used for rainy season.

Table 1. Location of flow rate monitoring and sampling of surface water in a river flows for the period 2014 -2024

No	Location of monitoring points	Symbol
1	Da river	S1
2	Nam Na river	S2
3	Nam Muc river	S3
4	Nam Mu river	S4

Table 2. Group distribution of of flow rate monitoring and sampling of surface water in a river flows into Son La hydropower Reservoir in the period 2014 -2024

Years	DO (mg/L)	TSS (mg/L)	BOD_5 (mg/L)	COD (mg/L)	NH_4^+ (mg/L)	NO_2^- (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	total.Fe (mg/L)
Da River (S1)									
2014	4.13 ± 0.59	40.0 ± 8.15	4.95 ± 0.30	20.4 ± 10.1	0.05 ± 0.01	0.13 ± 0.06	0.45 ± 0.10	0.14 ± 0.01	0.21 ± 0.21
2015	5.05 ± 0.46	30.0 ± 9.87	5.10 ± 0.27	7.00 ± 0.71	0.07 ± 0.05	0.01 ± 0.001	0.15 ± 0.08	0.04 ± 0.02	0.84 ± 0.56
2016	5.05 ± 0.09	25.5 ± 11.7	5.03 ± 0.22	6.15 ± 0.68	0.02 ± 0.001	0.001 ± 0.01	0.06 ± 0.01	0.03 ± 0.01	0.18 ± 0.08
2017	5.20 ± 0.01	139.8 ± 214	4.88 ± 0.41	6.60 ± 1.67	0.04 ± 0.02	0.01 ± 0.02	0.29 ± 0.30	0.59 ± 0.95	0.26 ± 0.17
2018	5.38± 0.01	42.8 ± 215.0	4.38 ± 0.41	9.00 ± 1.67	0.30 ± 0.02	0.05 ±0.02	0.40 ± 0.30	0.08 ± 0.95	0.36 ± 0.17
2019	5.80 ± 0.22	12.0 ± 0.15	4.00 ± 0.42	9.00 ± 0.65	0.30 ± 0.001	0.05 ± 0.001	0.52 ± 0.01	0.08 ± 0.01	0.33 ± 0.01
2020	5.73 ± 0.34	15.0 ± 3.31	4.201 ±0.34	9.00 ± 0.001	0.30 ± 0.001	0.17 ± 0.130	0.43 ± 0.02	0.09 ± 0.07	0.35±0.078
2021	6.10 ± 0.46	36.9 ± 39.4	3.88 ± 0.54	7.40 ± 2.26	0.30 ± 0.001	0.10 ± 0.09	0.40 ± 0.07	0.15 ± 0.15	0.26 ±0.14
2022	6.35 ± 0.62	41.4 ± 36.3	3.68 ± 0.60	6.98 ± 3.11	0.40 ± 0.00	0.10 ± 0.09	0.48 ± 0.08	0.14 ± 0.15	0.27±0.13
2023	6.57 ± 0.01	22.3 ± 0.15	3.49 ± 0.41	6.20 ± 0.83	0.45 ± 0.05	0.11 ± 0.002	0.13 ± 0.30	0.13 ± 0.57	0.23±0.16
2024	6.80 ± 0.01	20.3 ± 8.5	3.31 ± 0.28	5.44 ± 1.63	0.50 ± 0.001	0.12 ± 0.140	0.13 ± 0.07	0.13 ± 0.02	0.21±0.08
Median	5.65	38.72	4.26	8.48	0.25	0.08	0.31	0.15	0.32
Min	4.13	12.00	3.31	5.44	0.02	0.00	0.06	0.03	0.18
Max	6.80	139.75	5.10	20.48	0.50	0.17	0.52	0.59	0.84
Pearson's(r)	0.98	-0.27	-0.97	-0.54	0.94	0.50	-0.03	-0.05	-0.35
Years	DO (mg/L)	TSS (mg/L)	BOD_5 (mg/L)	COD (mg/L)	NH_4^+ (mg/L)	NO_2^- (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	total.Fe (mg/L)
Nam Na river (S2)									
2014	3.80 ± 0.76	34.0 ± 12.63	6.18 ± 0.36	23.5 ± 2.20	0.02 ± 0.04	0.16 ± 0.01	0.40 ± 0.13	0.09 ±0.58	0.26 ±0.27
2015	4.18 ± 0.78	19.75 ± 9.18	5.08 ± 0.08	9.75 ± 3.11	0.08 ± 0.04	0.01 ± 0.001	0.32 ±0.147	0.14 ±0.151	0.25 ±0.08
2016	5.20 ± 0.12	72.0 ± 68.6	5.45 ± 0.53	7.23 ± 1.56	0.03 ± 0.02	0.001± 0.001	0.06 ±0.001	0.05 ±0.026	0.74 ±0.91
2017	5.25 ± 0.09	22.7 ± 10.1	5.43 ± 0.26	8.20 ± 2.57	0.11 ± 0.11	0.02 ± 0.020	0.44 ±0.252	1.15 ±1.902	0.32 ±0.20
2018	5.35 ± 0.15	24.7 ± 5.54	4.30 ± 0.46	9.00 ± 0.001	0.30 ± 0.001	0.05 ± 0.001	0.44 ±0.074	0.08 ±0.001	0.46 ±0.25
2019	5.88 ± 0.29	19.0 ± 7.03	4.00 ± 0.01	9.00 ± 0.001	0.30 ± 0.001	0.05 ± 0.001	0.40 ±0.001	0.08 ±0.001	0.33 ±0.05
2020	6.28 ± 0.46	20.7 ± 12.5	3.73 ± 0.23	5.85 ± 2.18	0.30 ± 0.001	0.03 ± 0.018	0.40 ±0.071	0.35 ±0.494	0.38 ±0.19
2021	6.70 ± 0.59	17.7 ± 12.9	3.30 ± 0.30	6.70 ± 2.27	0.35 ± 0.05	0.04 ± 0.011	0.39 ±0.089	0.37 ±0.537	0.38 ±0.19
2022	7.10 ± 0.76	15.4 ± 12.6	2.95 ± 0.36	5.63 ± 2.20	0.43 ± 0.04	0.04 ± 0.015	0.39 ±0.129	0.40 ±0.576	0.45 ±0.27
2023	7.47 ± 0.15	6.38 ± 9.41	2.62 ± 0.03	4.19 ± 0.61	0.49 ± 0.011	0.04 ± 0.001	0.43 ±0.022	0.32 ±0.008	0.40 ±0.005
2024	7.87 ± 0.12	3.32 ± 0.75	2.23 ±0.01	2.80 ± 0.001	0.54 ± 0.005	0.03 ± 0.020	0.45 ±0.001	0.34 ±0.001	0.41 ±0.002
Median	5.91	23.26	4.11	8.35	0.27	0.04	0.37	0.31	0.40
Min	3.80	3.32	2.23	2.80	0.02	0.00	0.06	0.05	0.25
Max	7.87	72.00	6.18	23.50	0.54	0.16	0.45	1.15	0.74
Pearson's(r)	0.99	-0.65	-0.98	-0.75	0.97	-0.28	0.44	0.17	0.11
Years	DO (mg/L)	TSS (mg/L)	BOD_5 (mg/L)	COD (mg/L)	NH_4^+ (mg/L)	NO_2^- (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	total.Fe (mg/L)
Nam Muc river (S3)									
2014	4.40 ± 0.22	27.50 ± 3.64	4.00 ±0.707	11.50 ±3.84	0.04 ± 0.02	0.04 ± 0.038	0.43 ±0.165	0.08 ±0.049	0.39 ±0.11
2015	4.45 ± 0.72	10.25 ± 6.86	4.60 ±1.231	8.75 ±2.59	0.07 ± 0.05	0.01 ± 0.002	0.15 ±0.073	0.03 ±0.008	0.27 ±0.03
2016	5.33 ± 0.11	22.50 ± 10.7	5.00 ±0.001	6.58 ±1.08	0.04 ± 0.02	0.001 ±0.002	0.06 ±0.001	0.03 ±0.001	0.15 ±0.07
2017	5.43 ± 0.04	35.25 ± 38.5	5.13 ±0.719	7.78 ±1.10	0.11 ± 0.11	0.02 ± 0.020	0.20 ±0.146	0.04 ±0.022	0.15 ±0.09
2018	5.35 ± 0.11	21.25 ± 5.76	4.53 ±0.65	9.18 ±0.30	0.30 ± 0.001	0.05± 0.0001	0.44 ±0.041	0.08 ±0.001	0.32 ±0.03
2019	5.60 ± 0.25	16.00 ± 6.92	4.03 ±0.04	9.00 ±0.001	0.30 ± 0.001	0.05 ±0.0001	0.42 ±0.015	0.09 ±0.005	0.31 ±0.01
2020	5.93 ± 0.27	20.63 ± 10.4	4.50 ±0.430	7.75 ±1.57	0.33 ± 0.04	0.04 ± 0.015	0.33 ±0.043	0.07 ±0.022	0.19 ±0.01
2021	6.15 ± 0.39	20.20 ± 11.4	4.53 ±0.602	7.30 ±2.08	0.33 ± 0.04	0.05 ± 0.015	0.33 ±0.043	0.08 ±0.029	0.16 ±0.04
2022	6.40 ± 0.47	19.80 ± 12.2	4.53 ±0.763	7.13 ±2.90	0.43 ± 0.04	0.05 ± 0.023	0.35 ±0.050	0.08 ±0.033	0.18 ±0.08
2023	6.62 ± 0.15	20.68 ± 6.73	4.52 ±0.001	6.81 ±1.89	0.48 ± 0.21	0.05 ± 0.002	0.36 ±0.013	0.08 ±0.001	0.16 ±0.01

2024	6.86 ± 0.54	20.26 ± 5.35	4.52 ±1.231	6.50 ±0.50	0.53 ± 0.02	0.06 ±0.0001	0.38 ±0.002	0.08 ±0.001	0.15 ±0.01
Median	5.68	21.30	4.53	8.02	0.27	0.04	0.31	0.07	0.22
Min	4.400	10.250	4.000	6.501	0.035	0.004	0.060	0.026	0.146
Max	6.865	35.250	5.125	11.500	0.534	0.058	0.438	0.085	0.387
Pearson's(r)	0.97	-0.16	-0.03	-0.67	0.96	0.71	0.39	0.63	-0.59
Years	DO (mg/L)	TSS (mg/L)	BOD_5 (mg/L)	COD (mg/L)	NH_4^+ (mg/L)	NO_2^- (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	total.Fe (mg/L)
Nam Mu river (S4)									
2014	4.95 ± 0.05	14.50 ± 0.50	4.65 ±0.350	13.00 ± 3.00	0.04 ± 0.001	0.01 ± 0.001	0.23 ± 0.02	0.11 ±0.056	0.25 ±0.25
2015	4.75 ± 0.65	11.50 ± 5.50	5.15 ±0.150	10.00 ± 2.00	0.09 ± 0.07	0.01 ± 0.004	0.13 ± 0.07	0.03 ±0.024	0.19 ±0.12
2016	5.18 ± 0.15	9.75 ± 1.920	5.08 ±0.130	6.78 ± 2.45	0.03 ± 0.01	0.001± 0.001	0.06 ±0.001	0.03 ±0.001	0.07 ±0.001
2017	5.30 ± 0.10	15.25 ± 4.08	4.98 ±0.043	5.68 ± 2.11	0.11 ± 0.11	0.01 ± 0.021	0.15 ±0.147	0.04 ±0.022	0.13 ±0.10
2018	5.38 ± 0.11	13.75 ± 2.48	4.20 ±0.346	9.00 ± 0.001	0.30 ± 0.001	0.05 ± 0.001	0.40 ±0.001	0.08 ±0.001	0.30 ±0.001
2019	5.63 ± 0.29	12.0 ± 0.001	4.00 ±0.001	9.00 ± 0.001	0.30 ± 0.001	0.05 ± 0.001	0.40 ±0.001	0.08 ±0.001	0.30 ±0.001
2020	5.70 ± 0.21	12.75 ± 2.47	4.03 ±0.234	6.48 ±1.703	0.34 ± 0.030	0.05 ± 0.003	0.40 ±0.031	0.06 ±0.017	0.68 ±0.646
2021	5.83 ± 0.27	12.68 ± 3.15	3.86 ±0.283	5.78 ± 2.242	0.40 ± 0.050	0.06 ± 0.003	0.45 ±0.035	0.06 ±0.025	0.29 ±0.077
2022	6.03 ± 0.33	12.70 ± 3.80	3.70 ±0.336	5.08 ± 2.834	0.45 ± 0.031	0.07 ± 0.003	0.50 ±0.040	0.06 ±0.030	0.31 ±0.101
2023	6.24 ± 0.04	12.79 ± 0.50	3.51 ±0.001	4.38 ± 1.57	0.52 ± 0.001	0.08 ± 0.001	0.55 ±0.001	0.06 ±0.001	0.47 ±0.001
2024	6.18 ± 0.71	12.7 ± 0.001	3.33 ±0.039	3.68 ±2.41	0.58 ± 0.001	0.09 ±0.022	0.60 ±0.040	0.06 ±0.024	0.50 ±0.003
Median	5.56	12.77	4.23	7.17	0.29	0.04	0.35	0.06	0.32
Min	4.75	9.75	3.33	3.68	0.03	0.001	0.06	0.03	0.07
Max	6.24	15.25	5.15	13.00	0.58	0.09	0.60	0.11	0.68
Pearson's(r)	0.98	-0.02	-0.92	-0.83	0.97	0.96	0.90	-0.03	0.65

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

2.3. Calculation of stream pollutant load

Jorgensen S A introduced the mixed- flow reaction principle equation, therefore, we apply this principle to determine the characteristics of a flow carrying a pollutant load (Equation 1), (Jorgensen., 1987).

$$\frac{Vdc_i}{dt} = Qc_{i0} - Qc_i \quad \frac{Vdc_i}{dt} = Qc_{i0} - Qc_i - V * k * c_i \qquad (1)$$

In which: C_{io} is the pollutant concentration in the stream; Q is the flow rate (the discharge flow rate). The material balance flow equation (1) allows calculation of river stream pollutant load based on flow rate Q and concentration of surface water pollutant in stream C.

The general formula to calculate the total amount of pollutants generated is:

$$E = \frac{C*F*3600}{1000} \qquad (2)$$

In which: E is the pollution load; C is the concentration at the time of measurement; F is the discharge flow rate at the time of measurement; 3600 is the number of seconds in an hour. Applying formula (2) to calculate the seasonal river flow pollutant load in the basin. Pollutant load from the main flow system of four rivers brought into Son La hydropower reservoir annually in the period 2014 -2020 is calculated based on river water flow and concentration of pollutants measured at 4 hydrology stations S1 – S4. (Figure1).

Pollutant load of river in each year during 2014–2024 is calculated as follows:

$$PL = Q * C_i * 10^{-6} * 365 * 24 * 60 * 60 \quad (3)$$

Where PL is the pollutant load (tonnes/year); Q is the water flow (m^3/s), Ci is the concentration of the pollutant i in river water (mg/L) at each monitoring station (S1, S2, S3, S4).

The unit is converted by multiplying the number of days per year (365), and the number of second per day (24 hours/day x 60 minutes/hour x 60 seconds/minute).

This research describes the correlation between the flow rate variable in the dry season Q_d and the flood season Q_r with the variable surface water quality concentration in the seasonal river flow C_i (variable x) in the period 2014 – 2023. Using the formula to calculate the sample correlation coefficient (Pearson.,1909). Using the correlation coefficient (r), as a way to infer correlation for the case of two related variables x and y (Asuero et al., 2006). The correlation coefficient r of two variables is determined by the formula.

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})}^2} \qquad (4)$$

2.4. Statistical analysis

SPSS 20.0 package was used for statistical analysis of monitoring data. Data of water flow and surface water quality was log–transformed for homogeneity and tested to fit a normal distribution by using the Cor. Test to check the statistical significance. With probability <0.05, the average data during 2014-2024 of nine rivers water quality parameters are considered statistically significant, including DO, TSS, BOD_5, COD, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, and total. Fe. Significant differences and correlations among variations were performed using one-way ANOVA and Pearson coefficients (r), respectively. Significant differences on data between the inflow and outflow and between dry and rainy seasons were analyzed using Independent–Samples T Test. Figures are drawn by using the Origin Pro 2018 v9.5.0. Monitoring data processing: Water flow data measured at hydrological stations and surface water quality data are analyzed using an R programming language (R-Studio).

Table 1. Check the statistical significance of four monitoring points in rives into Son La hydropower reservoir (SLR) are for eleven years monitoring data using the Cor. test for the period 2014 – 2024

Da River (S1)	**Test statistic value**	**Probability value**
DO	t = 13.341	p-value < 0.01
TSS	t = 12.510	p-value < 0.05
BOD_5	t = 11.765	p-value < 0.05
COD	t = 10.139	p-value < 0.05
NH_4^+	t = 8.2823	p-value < 0.01
NO_2^-	t = 7.7520	p-value < 0.01
NO_3^-	t = 9.0206	p-value < 0.05
PO_4^{3-}	t = 14.635	p-value < 0.01
total. Fe	t = 11.394	p-value < 0.01
Nam Na River (S2)	Test statistic value	Probability value
DO	t = 22.007	p-value < 0.01
TSS	t = 5.5512	p-value < 0.01
BOD_5	t = 13.972	p-value < 0.01
COD	t = 7.4517	p-value < 0.01
NH_4^+	t = 9.8740	p-value < 0.05

NO_2^-	t = 12.257	p-value < 0.01
NO_3^-	t = 4.5416	p-value < 0.05
PO_4^{3-}	t = 5.5224	p-value < 0.05
total. Fe	t = 6.3530	p-value < 0.01
Nam Muc River (S3)	Test statistic value	Probability value
DO	t = 14.249	p-value < 0.01
TSS	t = 4.4883	p-value < 0.05
BOD_5	t = 10.183	p-value < 0.01
COD	t = 7.5876	p-value < 0.01
NH_4^+	t = 11.618	p-value < 0.01
NO_2^-	t = 5.0460	p-value < 0.05
NO_3^-	t = 4.7445	p-value < 0.05
PO_4^{3-}	t = 4.4979	p-value < 0.05
total. Fe	t = 3.2443	p-value < 0.05
Nam Mu River (S4)	Test statistic value	Probability value
DO	t = 14.6710	p-value < 0.01
TSS	t = 4.66415	p-value < 0.05
BOD_5	t = 7.2097	p-value < 0.01
COD	t = 4.4056	p-value < 0.05
NH_4^+	t = 12.974	p-value < 0.01
NO_2^-	t = 10.692	p-value < 0.01
NO_3^-	t = 6.3045	p-value < 0.01
PO_4^{3-}	t = 2.0118	p-value < 0.05
total. Fe	t = 2.5764	p-value < 0.05

3. RESULTS AND DISCUSSION

3.1. Water flow of river system

The values of water flow variables on the four monitoring stations are shown in Figure 2. Da River has the highest value of water flow and is also the main flow supplying water to the Son La hydropower reservoir, followed by Nam Na River, Nam Mu River, and Nam Muc River (Figure 2). The decreasing trend of water flow was observed for the Nam Muc River. A decrease in water flow in the Nam Muc River in this period is possibly due to the construction and operation of the Nam Muc dam that keeps water for hydropower generation and agricultural irrigation (Figure 2). By contrast, the water flow of the Da River, Nam Na River, and Nam Mu River of the reservoir tends to increase during 2014 - 2024. As the mainstream, Da River has a higher water flow than the three river tributaries.

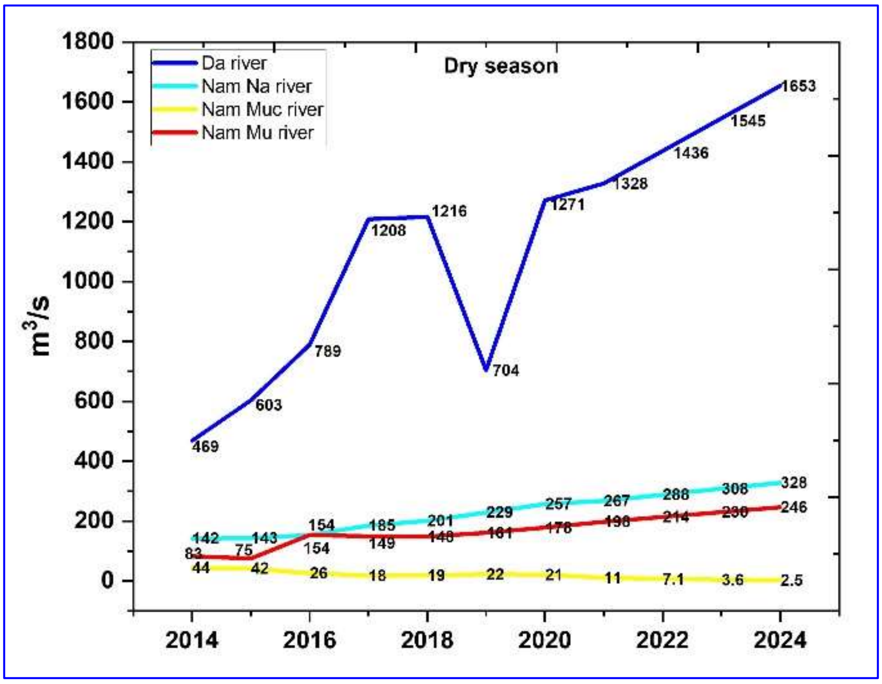


Fig. 2. The water flow rate tends to increase, and to decrease by dry season during 2014 -2024 in the Son La hydropower reservoir basin

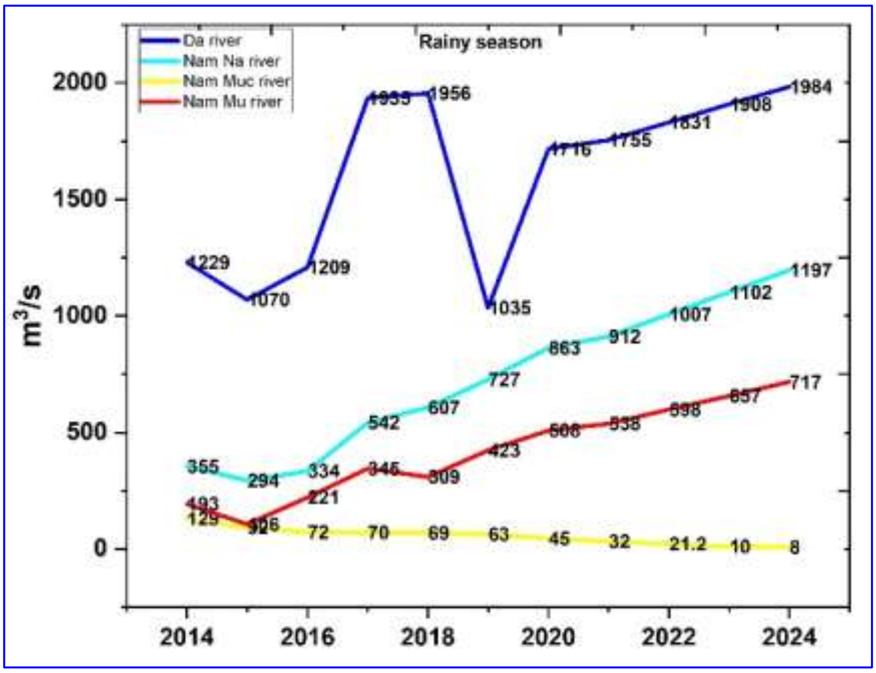


Fig. 3. The water flow rate tends to increase, and to decrease by rainy seson during 2014 -2024 in the Son La hydropower reservoir basin

In the dry season, the average water flows of the Da River (S1), Nam Na River (S2), Nam Mu River (S4), and Nam Muc River (S3), were 1,056, 217, 154 and 24m^3/s, respectively; those in rainy season were 1,564, 674, 370, and 88m^3/s (Figure 2). Water flows in rainy season in all monitoring stations were significantly higher than those in dry season ($p<0.05$), due to higher water amount flowing into the reservoir in rainy season. On the river systems S1, S2, S3, S4, there are small hydroelectric plants with the function of regulating flow. In the rainy season, large amounts of water flow into rivers in the basins, so hydroelectric plants release water to ensure dam safety, so water flow tends to increase. The dry season water flow into Son La hydropower reservoir increased significantly due to the process of regulating the flow of small hydroelectric dams on the river system. The operation of the hydropower dam has reduced the downstream water flow during the rainy season by about 35% and increased the water flow in the dry season by about 226% (Le et al., 2014).

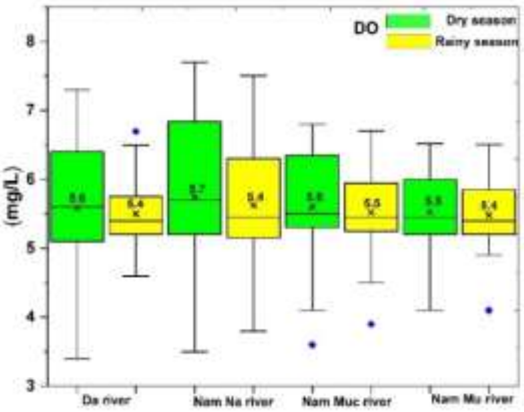
3.2. Water quality of river system

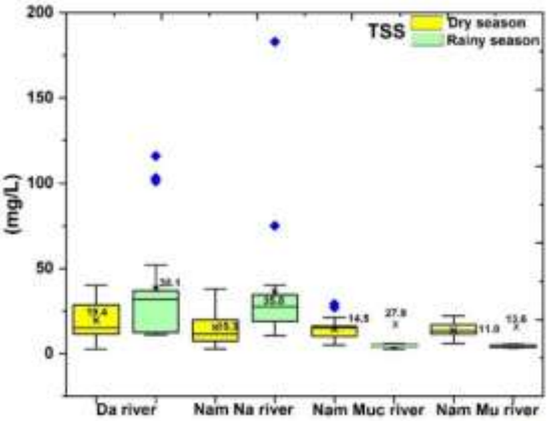
The comparative data on the values of water quality parameters (TSS, BOD_5, COD, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, and total Fe) in the dry season and the rainy season of the river system of Son La hydropower reservoir from 2014 to 2024. The values of water quality parameters in the seasonal flow were different amongst the Da River (S1), Nam Na River (S2), Nam Muc River (S3), Nam Mu River (S4).

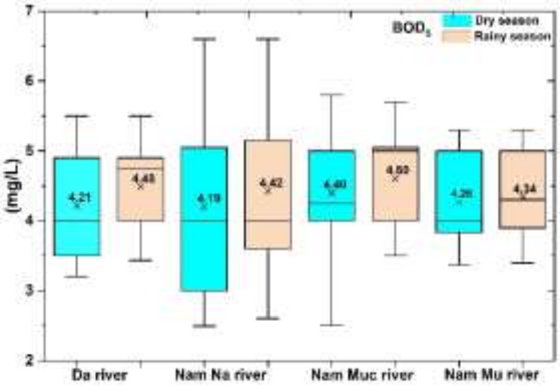
The values of water quality parameters during 2014 -2022 (dry season; rainy season) were, specifically: DO: 5.6 - 5.5 mg/L (S1), 5.7 - 5.6 mg/L (S2), 5.6 - 5.5 mg/L (S3), 5.5 - 5.5 mg/L (S4); TSS: 19.5 - 63.1 mg/L (S1), 15.4 - 35.9 mg/L (S2), 14.5 - 28.0 mg/L (S3), 11.9 -13.7 mg/L (S4); BOD_5 : 4.22 - 4.49 mg/L (S1), 4.2 - 4.4 mg/L (S2), 4.4 - 4.6 mg/L (S3), 4.3 - 4.3 mg/L (S4); COD: 9.51 -8.12 mg/L (S1), 8.97 - 8.64 mg/L (S2), 8.0 - 8.14 mg/L (S3), 7.71 - 7.34 mg/L (S4); NH_4^+: 0.23 - 0.20 mg/L (S1), 0.26 - 0.22 mg/L (S2), 0.25 - 0.22 mg/L (S3), 0.27 - 0.24 mg/L (S4); NO_2^-: 0.05 - 0.10 mg/L (S1), 0.05 - 0.04 mg/L (S2), 0.04 - 0.03 mg/L (S3), 0.04 - 0.04 mg/L (S4); NO_3^-: 0.38 - 0.33 mg/L (S1), 0.34- 0.39 mg/L (S2), 0.31 - 0.30 mg/L (S3), 0.34 - 0.31 mg/L (S4); PO_4^{3-}: 0.08-0.22 mg/L (S1), 0.11 - 0.50 mg/L (S2), 0.06 - 0.06 mg/L (S3); total Fe: 0.25 - 0.40 mg/L (S1), 0.27 - 0.52 mg/L (S2), 0.22 - 0.23 mg/L (S3), 0.27 - 0.32 mg/L (S4).

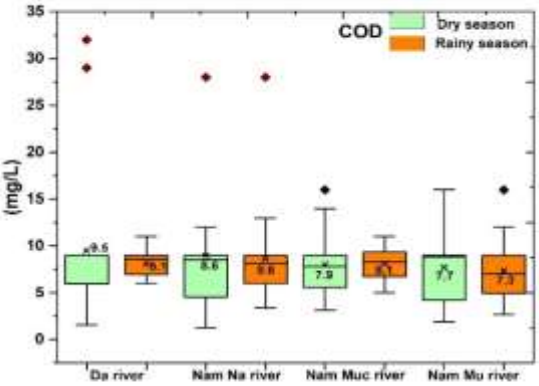
Figure 3 show the mean yearly values of water quality were, specifically: the Da River with DO (5.5 ± 0.8), TSS (41.2 ± 80.4), BOD_5 (4.3 ± 0.7), COD (8.8 ± 5.3), NH_4^+ (0.21 ± 0.15), NO_2^- (0.07 ± 0.08), NO_3^- (0.35 ± 0.19), PO_4^{3-} (0.14 - 0.34), total Fe (0.32 ± 0.28). The Nam Na river with DO (5.7 ± 1.2), TSS (25.6 ± 29.1), BOD_5 (4.3 ± 1.1), COD (8.8 ± 6.1), NH_4^+ (0.23 ± 1.65), NO_2^- (0.04 ± 0.05), NO_3^- (0.36 - 0.15), PO_4^{3-} (0.30 ± 0.74), total Fe (0.39 ± 0.36). The Nam Muc river with DO (5.6 ± 0.8), TSS (21.2 ± 16.1), BOD_5 (4.5 ± 0.74), COD (8.07 ± 2.5), NH_4^+ (0.23 ± 0.16), NO_2^- (0.03 ± 0.02), NO_3^- (0.3 ± 0.14), PO_4^{3-} (0.06 ± 0.03), total Fe (0.22 - 0.10). The Nam Mu river with DO (5.5 ± 0.6), TSS (12.7 ± 3.34), BOD_5 (4.3 ± 0.63), COD (7.5 ± 3.2), NH_4^+ (0.25 ± 0.17), NO_2^- (0.04 ± 0.02), NO_3^- (0.32 ± 0.17), PO_4^{3-} (0.06 ± 0.03), total Fe (0.29 ±

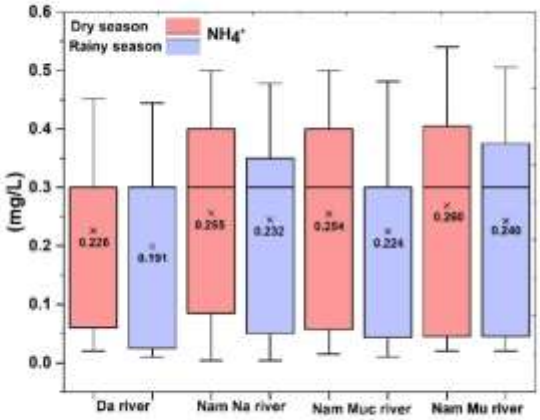
0.28). The values of all monitored water quality parameters were lower than the limits regulated for irrigation water following Vietnamese guideline QCVN 08-MT:2015/BTNMT [27] (DO: ≥ 4 mg/L, TSS: 50 mg/L, BOD_5: 15 mg/L, COD: 30 mg/L, NH_4^+: 0.9 mg/L, NO_2^-: 0.05 mg/L, NO_3^-: 10 mg/L, PO_4^{3-}: 0.3 mg/L, and total Fe: 1.5 mg/L) with the exception of NO_2^- (MONRE, 2015). The concentrations of NO_2^- in 2014 and 2021-2023 at Da river, and Nam Na river varied within 0.05 - 0.20 mg/L which exceeded the QCVN 08-MT:2015/BTNMT regulation (0.05 mg/L). The increase trend of water quality values in the period 2014 - 2023 was found for DO ($r=0.84$), NH_4^+ ($r = 0.93$), NO_2^- ($r=0.28$), NO_3^- ($r=0.47$), PO_4^{3-} ($r=0.39$), total Fe ($r=0.91$), possibly as the results of agriculture in the river basin and increasing aquaculture in the reservoir. This result is consistent with previous studies (Brian et al., 1996 ; Karine et al., 2006; Do et al., 2020). The formation of hydroelectric dams in the basin affects seasonal changes in water quality concentrations in the stream. The stream's ammonium (NH_4^+) concentration increases due to seasonal increase in circulation downstream of the dam (Isaac et al., 2018; Ito., 1987). In addition, increase in the concentration of NH_4^+, NO_2^-, NO_3^-, PO_4^{3-} in river flows is related to the accumulation and metabolism of nitrogen and phosphorus nutrients due to discharges from the basin into the stream (Zhang et al., 2014). The high concentration of phosphate in the annual runoff indicates pollution from untreated source discharge into river (Houri et al., 2007). In contrast, TSS ($r=0.95$), BOD_5 ($r=0.65$), and COD ($r=0.48$) showed a decrease trend in this period. The construction of dams in the upstream areas of Son La hydropower plant, namely Lai Chau, Nam Muc, Nam Na 1 and 2, and Huoi Quang dams and trapping of sediments and suspended solids in upstream reservoirs may be responsible for the reduction of TSS in the study area. The annual decrease in TSS concentrations is associated with the construction of hydropower reservoirs in the basin, large amounts of silt and suspended solids in river flows are trapped in the reservoirs (Kummu et al., 2007). Concentration of BOD_5, COD decreases due to seasonal variation in the stream (Dou et al., 2016). Thus, the regulation of river water by hydropower dams and discharge from the basin is an important factor affecting the concentration of stream pollution.

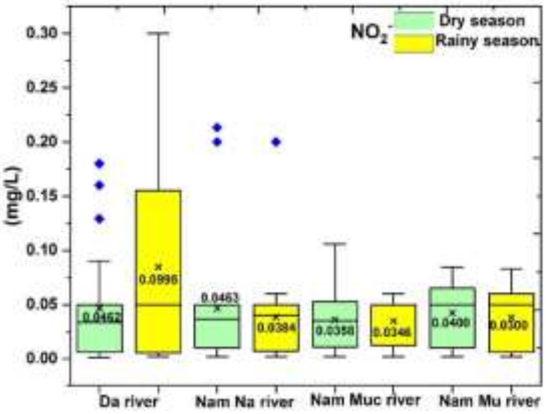

DO
Dry season
Rainy season
(mg/L)
3
4
5
6
7
8
5.6
5.4
5.7
5.4
5.5
5.5
5.5
5.4
Da river
Nam Na river
Nam Muc river
Nam Mu river


TSS
Dry season
Rainy season
(mg/L)
0
50
100
150
200
19.4
38.1
15.1
35.5
14.5
27.9
11.0
13.6
Da river
Nam Na river
Nam Muc river
Nam Mu river


BOD5
Dry season
Rainy season
(mg/L)
2
3
4
5
6
7
4.21
4.48
4.19
4.42
4.40
4.60
4.26
4.34
Da river
Nam Na river
Nam Muc river
Nam Mu river


COD
Dry season
Rainy season
(mg/L)
0
5
10
15
20
25
30
35
9.5
8.1
8.6
8.6
7.9
8.1
7.7
7.3
Da river
Nam Na river
Nam Muc river
Nam Mu river


Dry season
Rainy season
NH4+
(mg/L)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.226
0.191
0.255
0.232
0.254
0.224
0.268
0.240
Da river
Nam Na river
Nam Muc river
Nam Mu river


NO2-
Dry season
Rainy season
(mg/L)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.0462
0.0856
0.0463
0.0384
0.0358
0.0346
0.0408
0.0300
Da river
Nam Na river
Nam Muc river
Nam Mu river

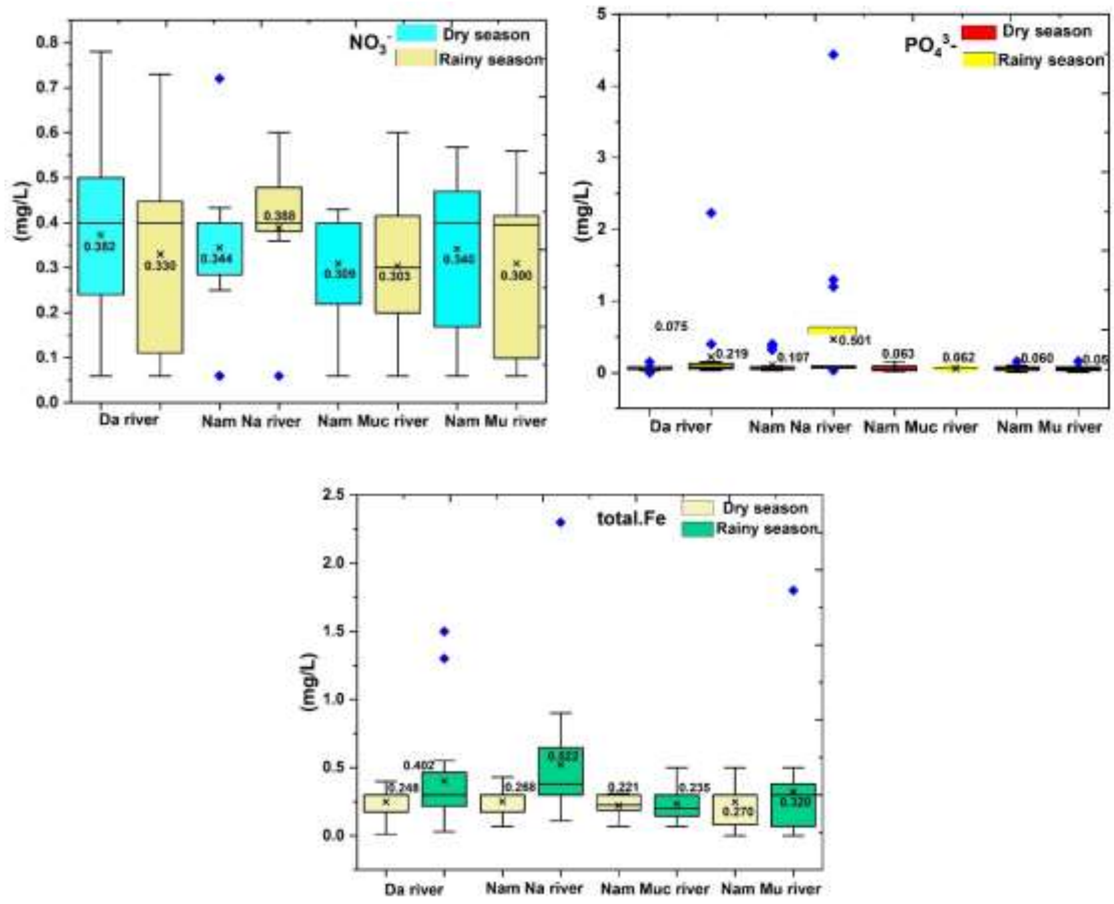


Fig. 3: Change of DO, TSS, BOD_5, COD, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, total.Fe concentrations in river flows in the dry season and the rainy season from 2014 to 2024

3.3. Relationship between water flow and pollutant concentration

Figure 4 shows the statistical relationship in the dry season between the water flow variable, Q_d of rivers in the basin of Son La hydropower reservoir, and the pollution concentration of eight parameters with correlation coefficient (r) determined. The $Q_{dry\ season}$ (Q_d) of has a positive correlation coefficient (r>0 positive correlation) with the concentrations of five surface water quality parameters, namely: NH_4^+ at locations (S1), (S2) and (S4); NO_3^- at locations (S1) and (S2), PO_4^{3-} in the S1, total Fe at locations S1 and S2, S3 and S4. In which, for NH_4^+, total Fe at locations (S1, S2, S4) and NO_3^- at locations (S1, S4), the correlation coefficient (r) with Q_d is range 0.5 to 1 (strong correlation), for PO_4^{3-} (S1, S2, S4) the correlation coefficient (r) with Q_d is < 0.29 (weak correlation). The $Q_{dry\ season}$ has a negative correlation coefficient r<0 (inverse correlation) with the concentrations of four surface water parameters including: TSS at locations S1, S2, S4; BOD_5 at locations S1, S2, S3, S4; COD at locations S1, S2, S4; NO_2^- at locations S1, S2, S3. Thus, in the dry season, when the water flow rate increases the concentration of five surface water quality parameters NH_4^+, total Fe, NO_3^-, PO_4^{3-} increases but the concentration of the four parameters TSS, BOD_5, COD, NO_2^- reduces.

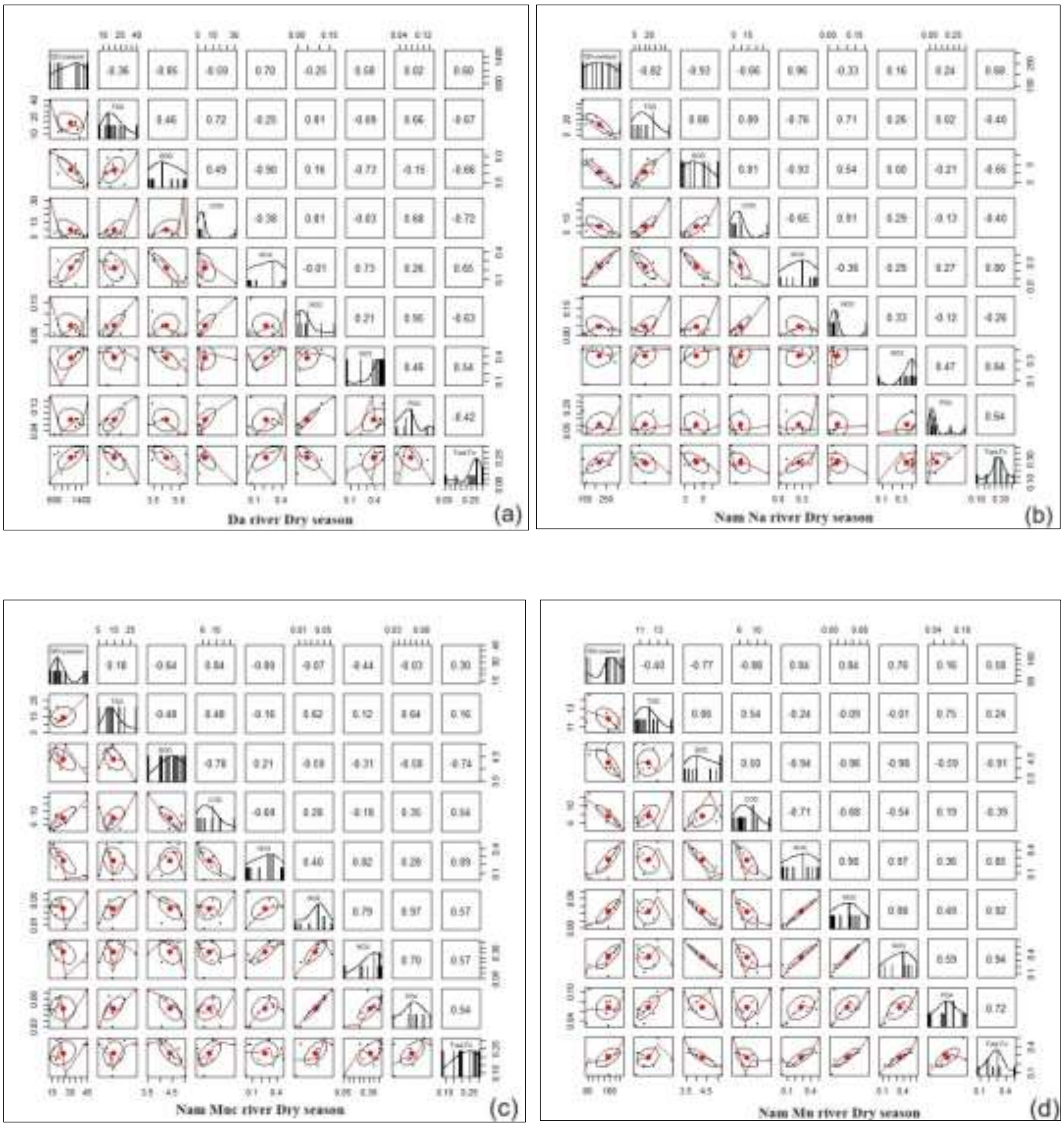


Fig. 4: Correlation between flow rate and dry season stream pollutant concentration in the Da River (a), Nam Na River (b), Nam Muc River (c), and Nam Mu River (d) during 2014 - 2024

Figure 4 shows the statistical relationship in the rainy season between the water flow variable, $Q_{\text{rainy season}}$ (Q_r) and the pollution concentration of nine parameters. The correlation value (r) between river water flow with the concentration of surface water pollutants in the rainy season is different were different amongst the Da River (S1), Nam Na River (S2), Nam Muc River (S3), Nam Mu River (S4). The water flow rate Q_r has a positive correlation coefficient r> 0 (positive correlation) with the concentrations of surface water quality parameters, including: NH_4^+, NO_2^-, NO_3^-, PO_4^{3-} at locations S1, S2 and S4; total Fe at locations S3 and S4; TSS at locations S1 and

S4. In rainy season, the Q_r has a negative correlation coefficient $r < 0$ (inverse correlation) with the concentration of surface water parameters including: BOD_5, COD at locations S1, S2, S3 and S4.

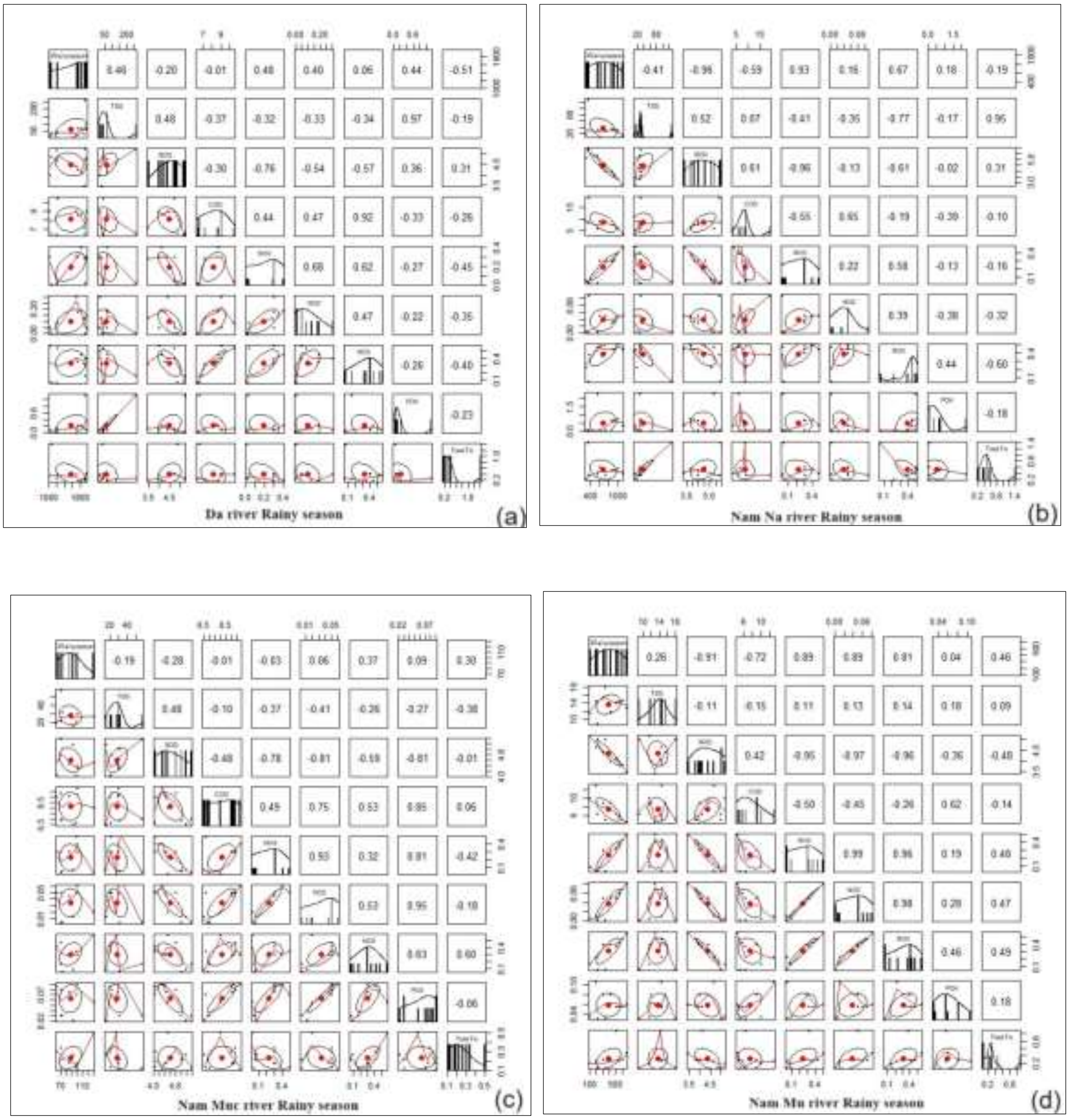


Fig. 5: Correlation between flow rate and rainy season stream pollutant concentration in the Da River (a), Nam Na River (b), Nam Muc River (c), and Nam Mu River (d) during 2014 – 2024

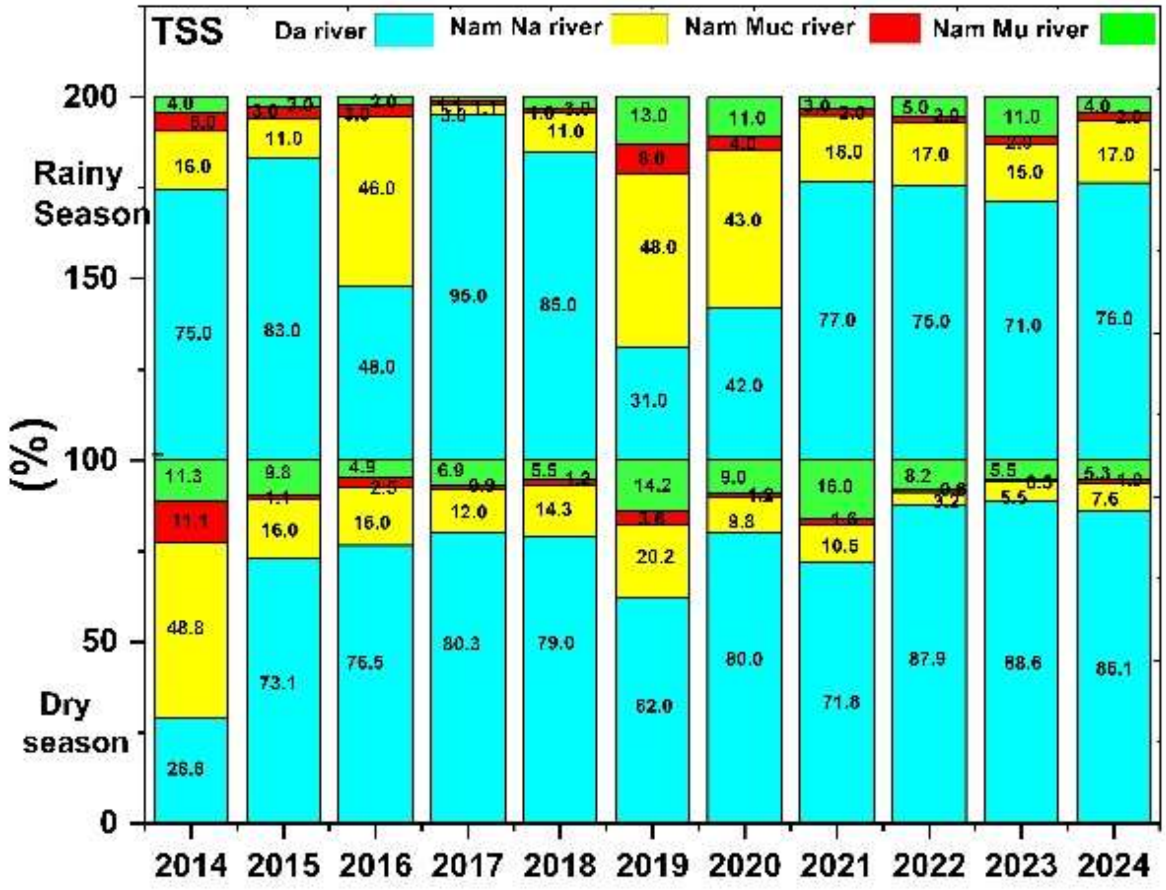
This result is consistent with previous studies, the operation of man-made dams changes the natural flow regime of the river such as reducing flow in the rainy season and increasing the flow in the dry season (Li et al., 2017). The operation of dams affects the annual flow rate, the concentration of dissolved substances NO_3^-, NH_4^+, PO_4^{3-} in downstream increase, the concentration of dissolved solids and suspended solids TSS reduces (Stow et al., 2001; Stanley., 2002; Haque et al., 2018). Increasing the biomass decomposition process in the upstream reservoir, thus the concentration of BOD_5, COD in the downstream flow decreases (Le et el., 2014). Total Fe concentration increases in low flow regime and decreases during flood period (Heikkinen.,1990). Thus, the process of accumulating water to build dams on river flows is considered an important and decisive factor in the correlation between flow rate and river flow pollution concentration in the dry season and the flood season in the river basin Son La hydropower reservoir area.

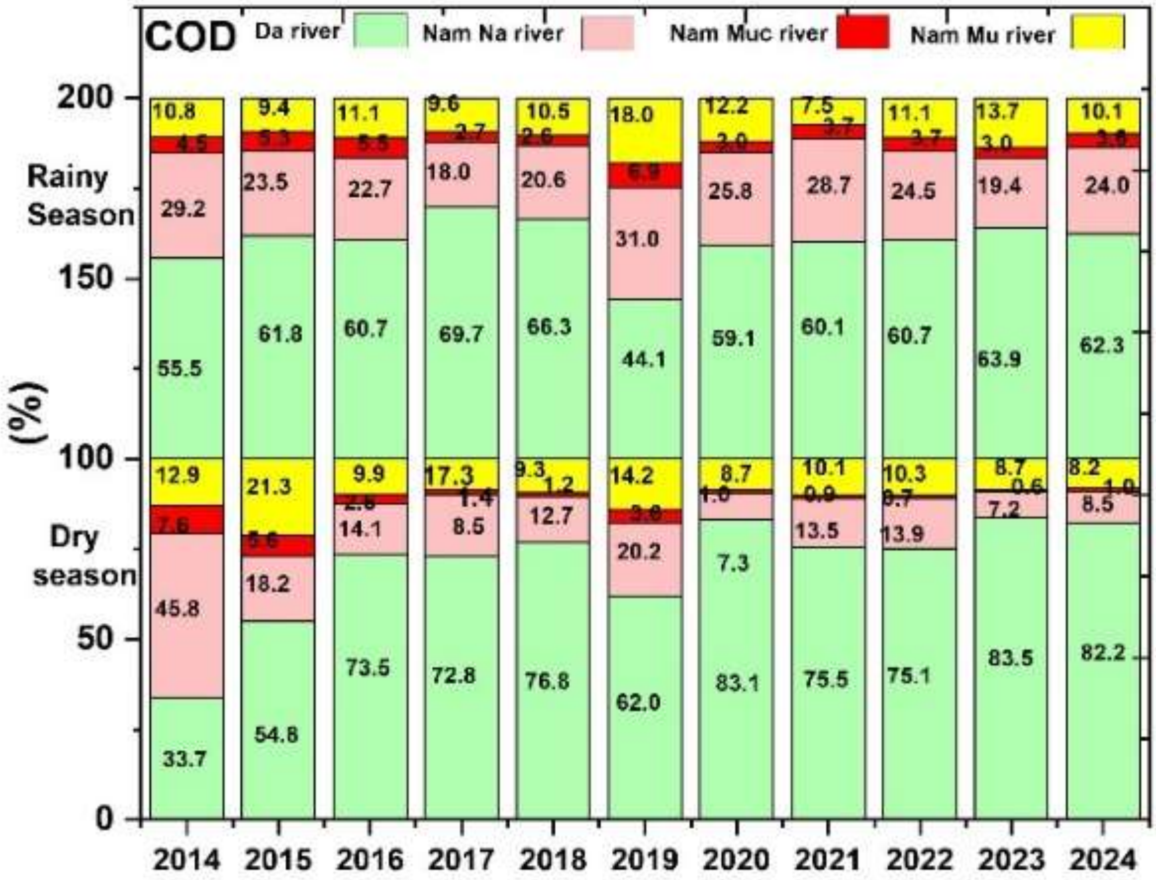
3.4. Pollutant load of river system

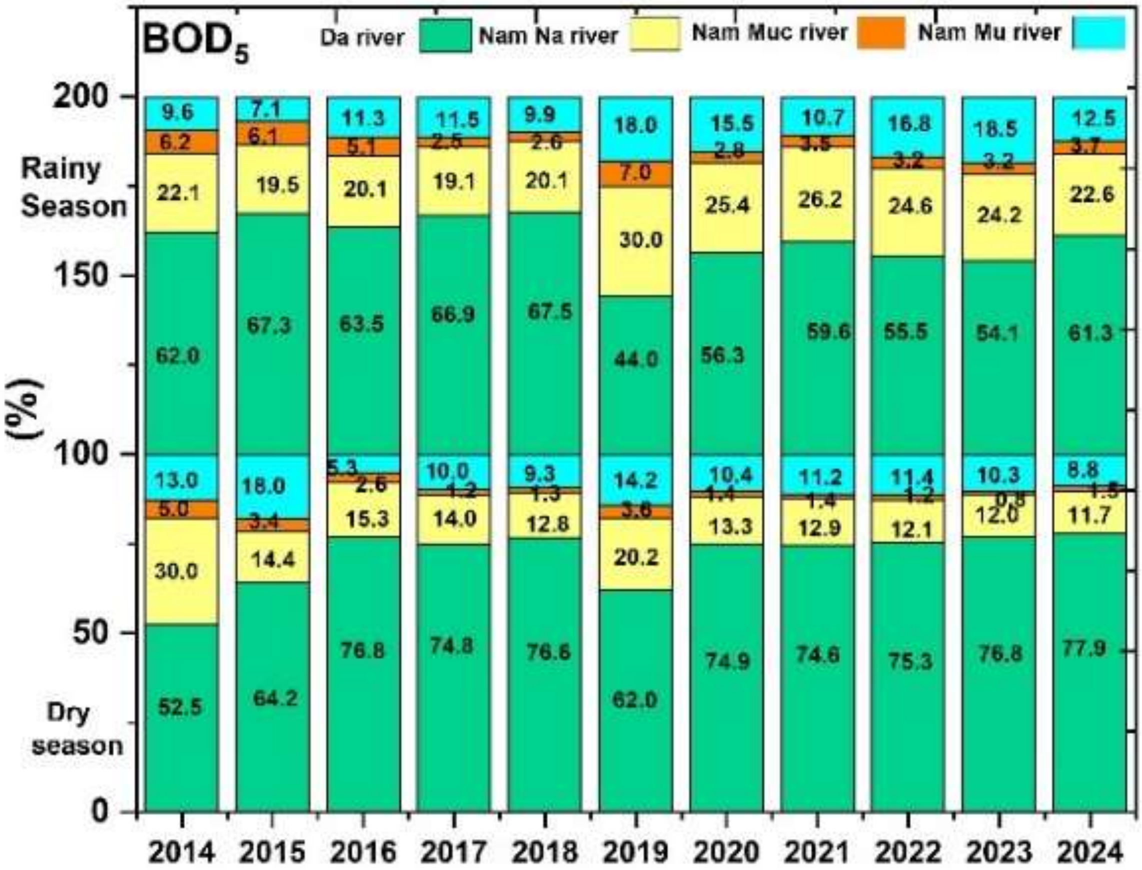
The pollutant load of the river system of the Son La hydropower reservoir fluctuated from 2014 to 2023. During 2014 - 2024, the pollutant loads of four rivers entering the reservoir (S1, S2, S3, and S4) varied within 11,581,848-9,714,484 (average: 3,403,604) tones/year, respectively. The lowest and highest pollutant loads were obtained in 2017 and 2022, respectively. Pollutant load of river system in the rainy season was significantly higher than that in the dry season ($p < 0.001$), mainly due to the higher water flow in rainy season. Pollutant load in rainy season accounted for 63.1 - 92.4% (average: 77.2%) of the yearly pollutant load. In rainy season, the pollutant load in the inflow varied within (1,037,197 - 8,976,742; average: 2,762,709 tones/year) was significantly higher than that in the dry season (372,913–1,098,830; average: 640,894 tones/year) ($p < 0.01$).

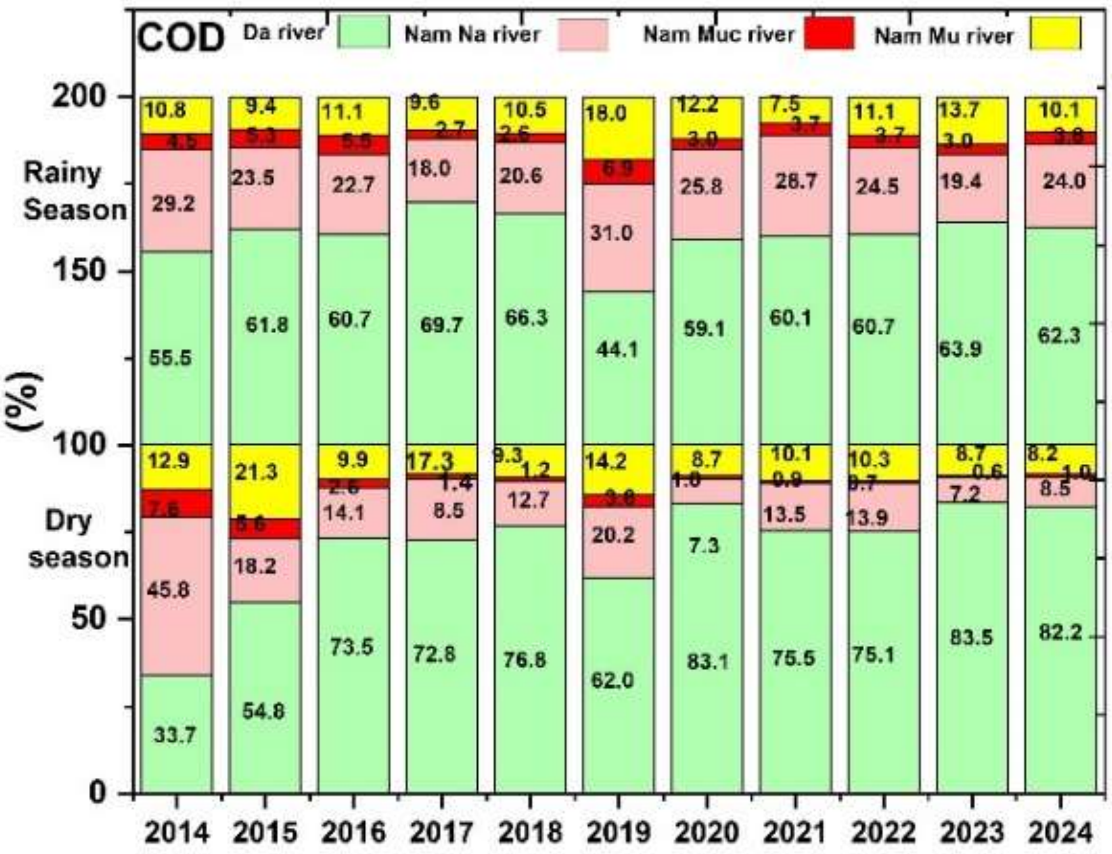
Pollutant load of composite parameters (TSS, BOD_5, COD, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, and total Fe) also fluctuated greatly by seasons and years (2014 - 2024). The average pollutant loads (tones/year) in the following order: TSS (318,191) > COD (62,308) > BOD_5 (34,359) > NO_3^- (3,061) > Fe (2,924) > NH_4^+ (2,107) > PO_4^{3-} (1,776) > NO_2^- (725). Figure 6 shows TSS, COD, BOD_5, NO_3^-, Fe, NH_4^+, PO_4^{3-}, and NO_2^- accounted for 75, 15, 8, 0.7, 0.7, 0.5, 0.4, and 0.2% of the yearly pollutant loads, respectively. Cultivating on sloping land in the Son La hydropower reservoir basin increases the rate of soil erosion and runoff, carrying dissolved solids with rainwater. This may contribute to the rise in Total Suspended Solids (TSS) pollution load in the basin, affecting sedimentation processes and increasing sediment accumulation in the hydropower reservoir (Tran et al., 2012). The decomposition of organic matter in reservoirs and the relationship between COD and BOD_5 vary depending on the reservoir between the dry and rainy seasons, indicating that these two parameters have high pollution loads following the basin's flow (Straškrabová et al., 1993; Du et al., 2024). Seasonal variations in BOD_5 and COD concentrations have been observed, with the highest average BOD_5 levels recorded in February (dry season) and the lowest in May (rainy season), while COD peaked in September (rainy season) (Noskovič et al., 2017). The increase in pollutant loads of NO_3^-, Fe, NH_4^+, PO_4^{3-}, and NO_2 is primarily caused by waste sources from the reservoir basin, mainly from non-point sources (NPS). These pollutants mainly originate from agricultural, domestic, livestock, and cage aquaculture waste within the reservoir basin (Yang et al., 2022; Shen et al., 2014; Zhuang et al., 2016; Chen et al., 2024). Additionally, the pollutant loads of these parameters in rivers also depend on rainfall and sediment transport within the basin (Chen et al., 2024; Shen et al., 2014). Therefore, watershed pollution control measures should be prioritized to manage the water quality of hydropower reservoirs that supply domestic water, such as the Sơn La hydropower reservoir in Northwest Vietnam.

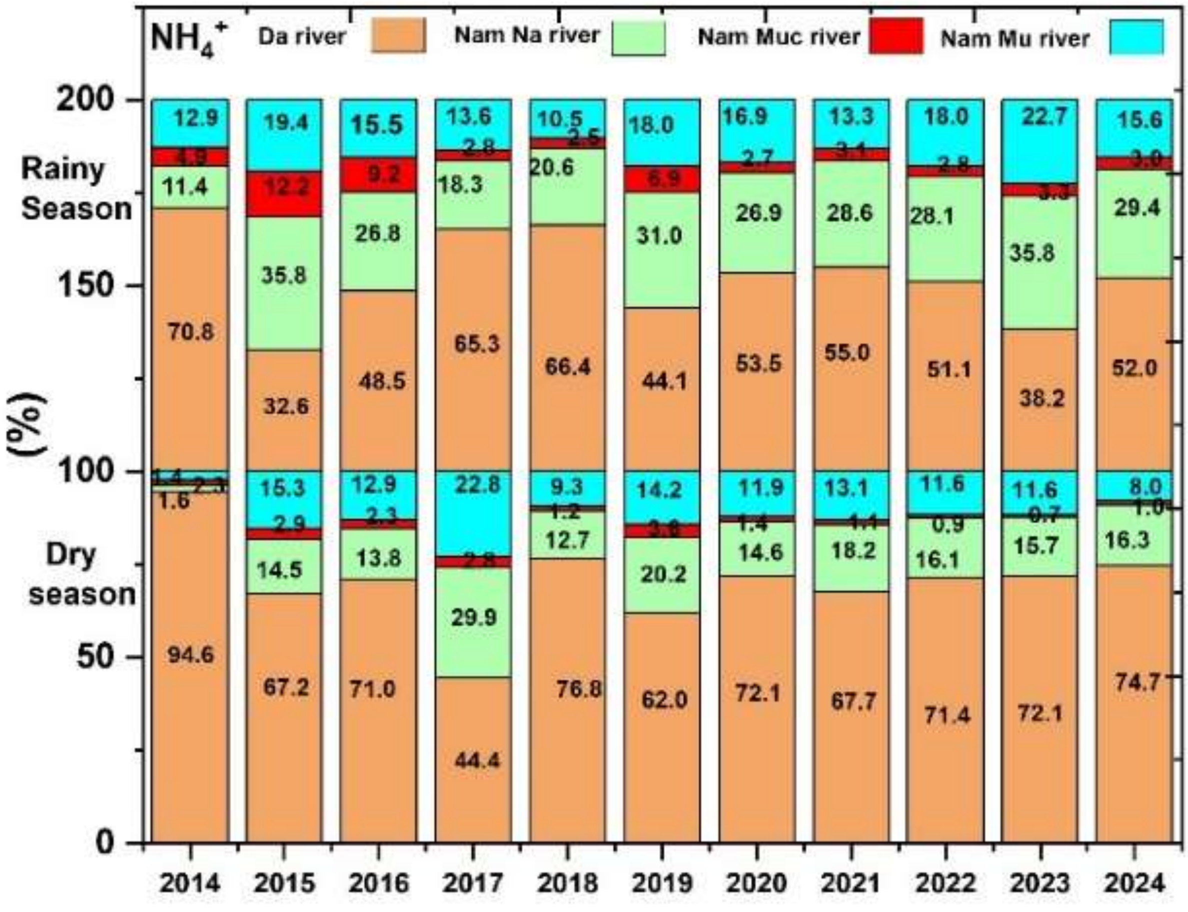
Total pollutant load demonstrated the strong negative correlation with water flow: TSS ($r= -0.81$, $p<0.001$), BOD_5 ($r= - 0.82$, $p<0.001$), COD ($r= -0.79$, $p<0.001$), NH_4^+ ($r =- 0.73$, $p<0.001$), NO_3^- ($r=-0.77$, $p<0.001$), PO_4^{3-} ($r=-0.75$, $p<0.001$), and total Fe ($r=-0.78$, $p<0.001$). Total pollutant load demonstrated the strong correlation with water flow, NO_2^- ($r=-0.67$, $p<0.001$).

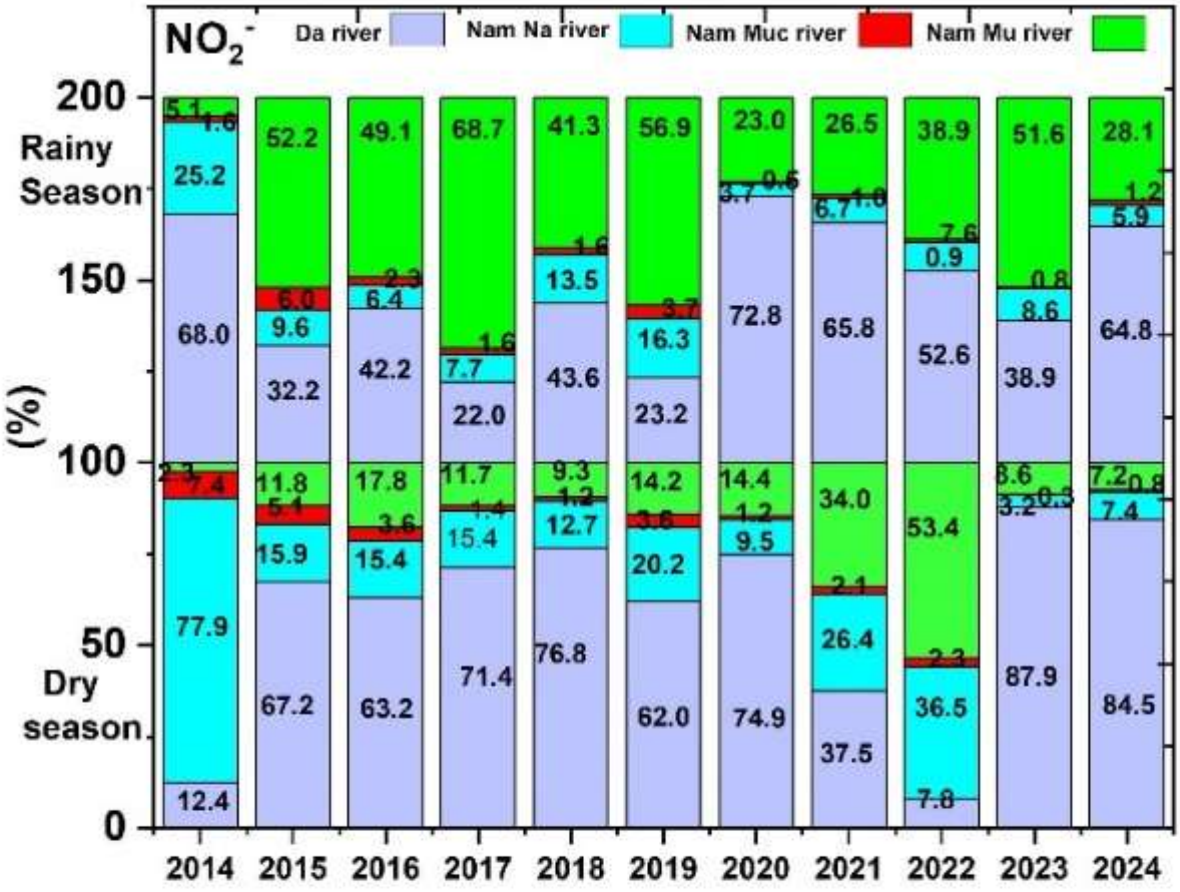


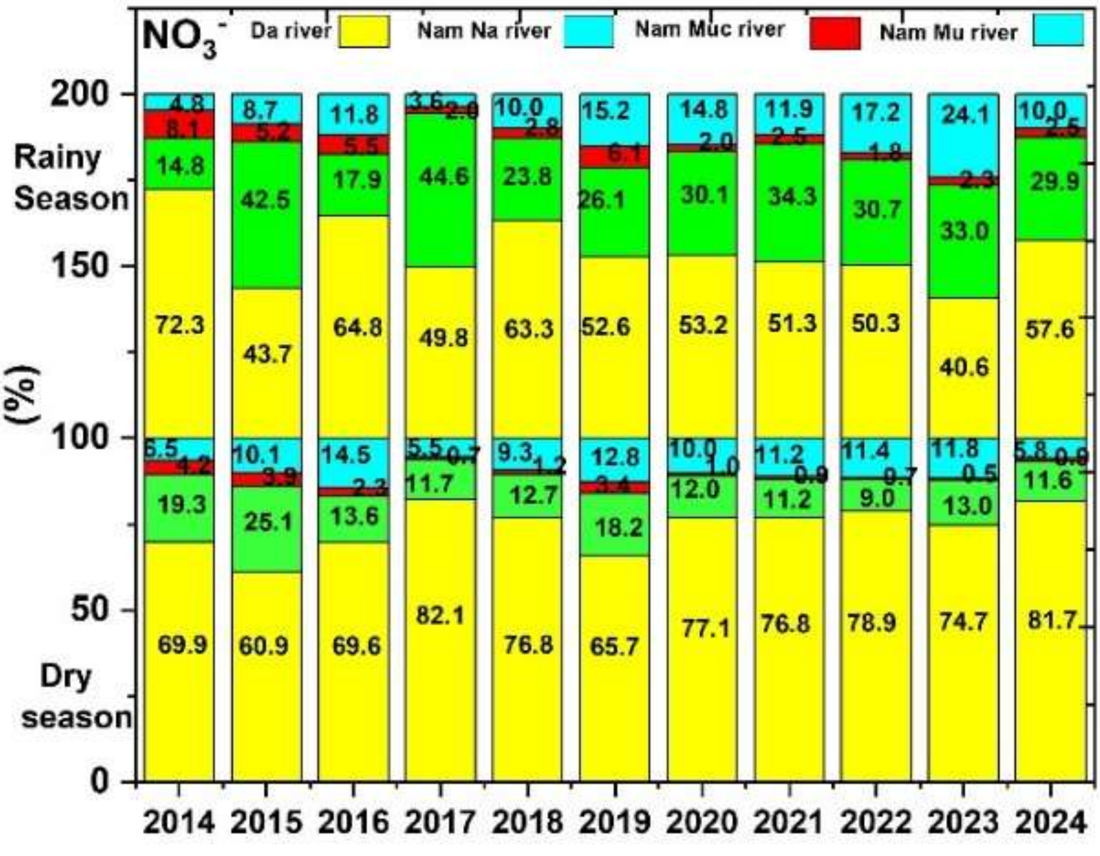

COD
Da river 🟩
Nam Na river ▨
Nam Muc river 🟥
Nam Mu river 🟨
(%)
Rainy Season
Dry season
0
50
100
150
200
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
10.8
4.5
29.2
55.5
9.4
5.3
23.5
61.8
11.1
5.5
22.7
60.7
9.6
2.7
18.0
69.7
10.5
2.6
20.6
66.3
18.0
6.9
31.0
44.1
12.2
3.0
25.8
59.1
7.5
3.7
28.7
60.1
11.1
3.7
24.5
60.7
13.7
3.0
19.4
63.9
10.1
3.6
24.0
62.3
12.9
7.6
45.8
33.7
21.3
5.6
18.2
54.8
9.9
2.6
14.1
73.5
17.3
1.4
8.5
72.8
9.3
1.2
12.7
76.8
14.2
3.6
20.2
62.0
8.7
1.0
7.3
83.1
10.1
0.9
13.5
75.5
10.3
0.7
13.9
75.1
8.7
0.6
7.2
83.5
8.2
1.0
8.5
82.2


BOD_5
Da river 🟩
Nam Na river 🟨
Nam Muc river 🟧
Nam Mu river 🟦
(%)
Rainy Season
Dry season
0
50
100
150
200
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
9.6
6.2
22.1
62.0
7.1
6.1
19.5
67.3
11.3
5.1
20.1
63.5
11.5
2.5
19.1
66.9
9.9
2.6
20.1
67.5
18.0
7.0
30.0
44.0
15.5
2.8
25.4
56.3
10.7
3.5
26.2
59.6
16.8
3.2
24.6
55.5
18.5
3.2
24.2
54.1
12.5
3.7
22.6
61.3
13.0
5.0
30.0
52.5
18.0
3.4
14.4
64.2
5.3
2.6
15.3
76.8
10.0
1.2
14.0
74.8
9.3
1.3
12.8
76.6
14.2
3.6
20.2
62.0
10.4
1.4
13.3
74.9
11.2
1.4
12.9
74.6
11.4
1.2
12.1
75.3
10.3
0.8
12.0
76.8
8.8
1.5
11.7
77.9


COD
Da river
Nam Na river
Nam Muc river
Nam Mu river
Rainy Season
Dry season
(%)
0
50
100
150
200
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
10.8
4.5
29.2
55.5
12.9
7.6
45.8
33.7
9.4
5.3
23.5
61.8
21.3
5.6
18.2
54.8
11.1
5.5
22.7
60.7
9.9
2.6
14.1
73.5
9.6
2.7
18.0
69.7
17.3
1.4
8.5
72.8
10.5
2.6
20.6
66.3
9.3
1.2
12.7
76.8
18.0
6.9
31.0
44.1
14.2
3.6
20.2
62.0
12.2
3.0
25.8
59.1
8.7
1.0
7.3
83.1
7.5
3.7
28.7
60.1
10.1
0.9
13.5
75.5
11.1
3.7
24.5
60.7
10.3
0.7
13.9
75.1
13.7
3.0
19.4
63.9
8.7
0.6
7.2
83.5
10.1
3.0
24.0
62.3
8.2
1.0
8.5
82.2


NH$_4^+$
Da river
Nam Na river
Nam Muc river
Nam Mu river
Rainy Season
Dry season
(%)
0
50
100
150
200
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
12.9
4.9
11.4
70.8
1.4
2.3
1.6
94.6
19.4
12.2
35.8
32.6
15.3
2.9
14.5
67.2
15.5
9.2
26.8
48.5
12.9
2.3
13.8
71.0
13.6
2.8
18.3
65.3
22.8
2.8
29.9
44.4
10.5
2.5
20.6
66.4
9.3
1.2
12.7
76.8
18.0
6.9
31.0
44.1
14.2
3.6
20.2
62.0
16.9
2.7
26.9
53.5
11.9
1.4
14.6
72.1
13.3
3.1
28.6
55.0
13.1
1.1
18.2
67.7
18.0
2.8
28.1
51.1
11.6
0.9
16.1
71.4
22.7
3.3
35.8
38.2
11.6
0.7
15.7
72.1
15.6
3.0
29.4
52.0
8.0
1.0
16.3
74.7


NO_2^-
Da river
Nam Na river
Nam Muc river
Nam Mu river
Rainy Season
Dry season
(%)
0
50
100
150
200
2014: 5.1, 1.6, 25.2, 68.0, 2.3, 7.4, 77.9, 12.4
2015: 52.2, 6.0, 9.6, 32.2, 11.8, 5.1, 15.9, 67.2
2016: 49.1, 2.3, 6.4, 42.2, 17.8, 3.6, 15.4, 63.2
2017: 68.7, 1.6, 7.7, 22.0, 11.7, 1.4, 15.4, 71.4
2018: 41.3, 1.6, 13.5, 43.6, 9.3, 1.2, 12.7, 76.8
2019: 56.9, 3.7, 16.3, 23.2, 14.2, 3.6, 20.2, 62.0
2020: 23.0, 0.6, 3.7, 72.8, 14.4, 1.2, 9.5, 74.9
2021: 26.5, 1.0, 6.7, 65.8, 34.0, 2.1, 26.4, 37.5
2022: 38.9, 7.6, 0.9, 52.6, 53.4, 2.3, 36.5, 7.8
2023: 51.6, 0.8, 8.6, 38.9, 8.6, 0.3, 3.2, 87.9
2024: 28.1, 1.2, 5.9, 64.8, 7.2, 0.8, 7.4, 84.5


NO_3^-
Da river
Nam Na river
Nam Muc river
Nam Mu river
Rainy Season
Dry season
(%)
0
50
100
150
200
2014: 4.8, 8.1, 14.8, 72.3, 6.5, 4.2, 19.3, 69.9
2015: 8.7, 5.2, 42.5, 43.7, 10.1, 3.9, 25.1, 60.9
2016: 11.8, 5.5, 17.9, 64.8, 14.5, 2.3, 13.6, 69.6
2017: 3.6, 2.0, 44.6, 49.8, 5.5, 0.7, 11.7, 82.1
2018: 10.0, 2.8, 23.8, 63.3, 9.3, 1.2, 12.7, 76.8
2019: 15.2, 6.1, 26.1, 52.6, 12.8, 3.4, 18.2, 65.7
2020: 14.8, 2.0, 30.1, 53.2, 10.0, 1.0, 12.0, 77.1
2021: 11.9, 2.5, 34.3, 51.3, 11.2, 0.9, 11.2, 76.8
2022: 17.2, 1.8, 30.7, 50.3, 11.4, 0.7, 9.0, 78.9
2023: 24.1, 2.3, 33.0, 40.6, 11.8, 0.5, 13.0, 74.7
2024: 10.0, 2.5, 29.9, 57.6, 5.8, 0.9, 11.6, 81.7

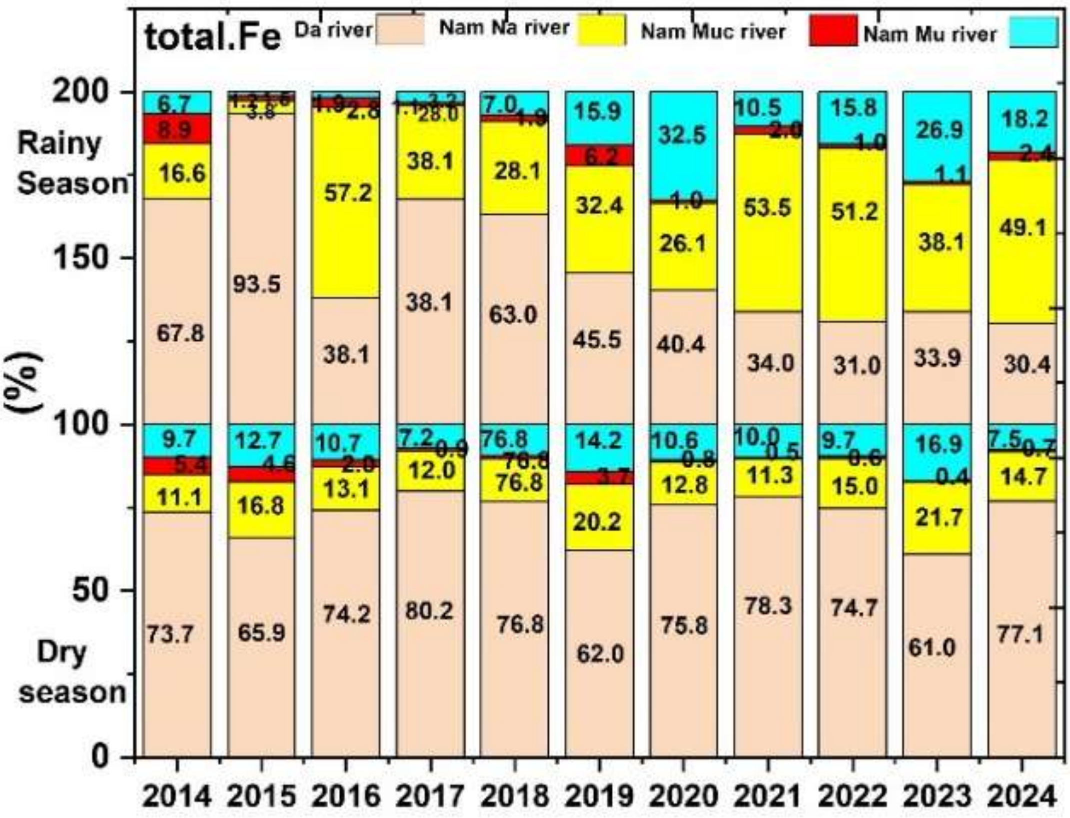


Fig. 6: Pollutant load ratio in the dry season, and rainy season in the Son La hydropower reservoir basin river flow during 2014 – 2024

Figure 6 shows that the Da River has a large water flow, corresponding to the highest pollution load transported to the reservoir compared to the three smaller rivers, namely the Nam Na, Nam Muc, and Nam Mu Rivers. This is because the Da River serves as the primary water source for agriculture in 25 provinces and cities and provides drinking water for more than 30 million people in both urban and rural areas. The basin holds significant economic and historical value (Le et al., 2019). Additionally, the pollution load in the Son La hydropower reservoir basin may primarily depend on the flow regulation process between the dry and rainy seasons by hydropower plants in the basin (Do et al., 2019, and 2020). At the same time, the quantity of contaminants being released into rivers is rising in direct correlation with the growth of the human population, and river flows through agricultural, residential, and cattle sectors, making it easier to detect river contamination (Suhardono et al. 2025). The physicochemical parameters indicated that the values of total nitrogen exceed the limits established in the ECA in 82% of the data obtained, pH in 13%, and phosphorus in 1%. In the evaluation of inorganic parameters, data from the LChin1S monitoring point showed that lead and zinc levels exceeded the values established in the ECA by 8% and 3%, respectively. Regarding the ICA-PE of the dry and wet seasons

(Camargo Hinostroza et al. 2025). These changes highlight the importance of effective water resource management in the transboundary river basin of Northwestern Vietnam today.

4. CONCLUSIONS

This study provides a comprehensive assessment of the water flow and pollutant load dynamics in the Son La hydropower reservoir basin from 2014 to 2024. The results indicate that while most monitored water quality parameters generally complied with Vietnamese irrigation standards, nitrite (NO_2^-) concentrations frequently exceeded regulatory limits, specifically during 2014 and the 2021–2024 period. A distinct temporal trend was observed over the decade: dissolved oxygen (DO), ammonium (NH_4^+), and other nutrients showed increasing trends, while total suspended solids (TSS), BOD_5, and COD decreased. The reduction in TSS and organic matter is primarily attributed to the sediment-trapping effects of upstream reservoirs such as the Lai Chau and Nam Muc dams. The quantification of pollutant loads revealed an average annual transport of 3,403,604 tonnes, characterized by extreme seasonal variability. The rainy season is the dominant period for pollutant transport, accounting for 63.1% to 92.4% of the total yearly load. Among the pollutants, TSS was the most prominent, representing 75% of the total load, followed by COD (15%) and BOD_5 (8%). Statistical analysis confirmed a strong correlation between seasonal discharge and pollutant concentrations, highlighting the profound impact of dam operations and land-use activities - particularly agriculture and cage aquaculture—on the reservoir's water chemistry. These findings have significant implications for the management of the Da River system, which serves as a vital source of domestic and agricultural water for millions in Northern Vietnam. Effective watershed management must prioritize non-point source pollution control and account for the cumulative effects of the reservoir cascade. Future research should focus on the self-purification mechanisms within these reservoirs and the development of integrated monitoring across the entire river system to safeguard regional water security.

ACKNOWLEDGEMENTS

The authors would like to express gratitude to Son La Hydropower Company and the Meteorological and Hydrological Station of the Northwest Region for their generosity in supporting this study. All data and information are retrieved and used with the permission of Son La Hydropower Company and the Meteorological and Hydrological Station of the Northwest Region for scientific purposes.

AUTHOR CONTRIBUTIONS

Writing Review, Data Curation, Statistical analysis, Writing-Original draft, Writing-Review and Editing: Xuan - Duc Do

DECLARATION OF CONFLICT OF INTEREST

The author declare no conflict of interest could have appeared to influence the work reported in this paper.

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