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Seasonal Water Quality Variation and Pollutant Loads Entering the Largest Hydropower Reservoir in Vietnam after Dam Impoundment (2014–2024)

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Open Access under CC BY 4.0.**ABSTRACT**

The Son La Reservoir on the Da River, the largest hydropower reservoir in Vietnam, is critical for electricity generation, 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), BOD₅, COD, and various nutrients. The pollutant load (PL) was calculated using a material balance equation. Analysis was performed using SPSS 20.0 and RStudio, using 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, BOD₅, 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%–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 scientific basis for monitoring water quality and managing pollution in hydropower basins to safeguard regional water resources.

1. INTRODUCTION

River flows are important to basin ecosystems and are the main source of water for hydropower reservoirs (Branche 2017). Research on pollutant loads is important for environmental flow management in hydropower reservoir basins (Jager et al. 2008). Determining pollutant loads during the dry and flood seasons supports pollution management and water quality control in both seasons (Choi et al. 2015). Pollutant loads under different flow conditions and regimes are analyzed to support water quality recovery and identify 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 nonpoint source pollution in rivers feeding reservoirs, using models to predict pollution loads and analyze permissible levels. Sediment sources and associated pollutants have been investigated using geochemical fingerprinting, revealing

significant contributions from mining and agricultural activities (Bravo-Linares 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 (Chen et al. 2024). Research has also focused on the self-cleaning ability of reservoirs with respect to nitrogen- and phosphorus-containing pollutants, calculating emission rates and self-cleaning capacities based on 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 pollutant 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 because of 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 subcatchments, 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 loads of COD and BODs in hydropower reservoir basins are a significant concern. Studies on the Three Gorges Reservoir show that agricultural nonpoint sources are the main pollution source, contributing up to 70.4% of COD loads. Before impoundment, the total annual loads of COD and BODs were 4.49×10^6 and 9.80×10^5 tons, respectively (Li 2005). In the Miyun Reservoir, nonpoint sources account for 73% of COD and 71% of BOD loads (Wang et al., 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 nonpoint 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).

The pollution loads of NH_4^+ , NO_2^- , NO_3^- , and PO_4^{3-} in hydropower reservoir basins are 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 drylands and forestlands as the main sources of nonpoint source pollution, contributing over 90% of the nitrogen and phosphorus load (Wu et al. (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 research on pollutant loads, the quantification of river pollutant loads is mainly integrated with calculations of nonpoint and point pollution sources in the river basin. Nutrients from nonpoint sources are carried by annual river flow from quantified watersheds (Li et al. 2005). The distribution of pollutant loads in streams is calculated to determine pollution in the river basin (Cheng et al. 2006). Estimating pollutant loads in surface waters of different river basins is used to quantify the pollutant load at the source (Amaya et al. 2012). The actual pollutant load received via a stream is estimated and simulated through model calculations to better understand pollution sources and pollutant loads in river flows (Huang et al. 2013). Fluctuations in water quality in catchment flows are quantified to provide scientifically supported options for pollution control and water protection (Nuen et al. 2020). To date, studies on pollutant load estimation have been based on discharge trend analysis and relationships between runoff and pollutant concentration, while seasonal load distribution ratios remain poorly understood. Therefore, this information is needed to quantify the transport capacity of stream pollutant loads during the dry and flood seasons in hydropower reservoirs.

Currently, pollutant loads in river-basin runoff are generally estimated from discharge or flow rate (Q) and pollutant concentration (C_i). Stream pollutant load is estimated from discharge and pollutant concentration data by multiplying the mean concentration by the mean flow rate (Ferguson 1987). Dry- and flood-season flow and water quality are based on data analyzed at monitoring stations, and relationships between water discharge and pollutant load are analyzed to estimate basin pollutant loads (Jeong et al. 2000). The discharge and water quality of the study basin are monitored and analyzed to estimate pollutant loads (Shin et al. 2005). Pollutant loads at the catchment scale are calculated from water quality monitoring data (concentration) and

water flow-rate data at monitoring stations (Shrestha et al. 2008). Pollutant loads in dry- and flood-season flows are determined using the average concentration (C_i) and average discharge (W_i) (Zhu et al. 2015). Stream pollutant loads are also estimated from water quality and flow data (Park et al. 2025). Calculation of river-flow pollutant loads is based on daily discharge data, baseline discharge, and pollutant concentration (Xin et al. 2017). Estimating pollutant loads during the dry and flood seasons requires determining the relationships among flow characteristics, flow rate, and pollutant concentrations. Discharge loads of organic matter, nitrogen, and phosphorus compounds are strongly correlated with annual river flow rate, and differences in flow rate affect dry- and flood-season pollutant loads (Niemirycz et al. 1999). Pollutant load estimation based on dry- and wet-season streamflow and water quality uses runoff characterization as part of basin assessment and management to address surface-water depletion (Eom et al. 2010). Relationships between flow and changes in water quality concentrations during the dry and flood seasons are analyzed by estimating pollutant loads distributed according to stream characteristics of the reservoir basin (Park et al. 2011). River flows are influenced by season, with dry-season flow being more stable than flood-season flow (Bowers et al. 2012). Changes in flow regimes and pollutant loads should be considered when developing 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 km² 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 in 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 began operation in 1988 and further reductions since 2009 (Nguyen et al. 2023). The Da River also contributes to CO₂ emissions, with the highest pCO₂ and outgassing rates measured downstream of the Hoa Binh Dam. These changes highlight the importance of effective water resource management in this transboundary river basin (Hai 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. While general relationships between runoff and concentration are established, there is also a lack of information on how

varying flow characteristics influence the transport of organic matter, nitrogen, and phosphorus within hydropower reservoir basins. This represents a research gap that needs to be addressed.

The Son La Reservoir, the largest hydropower reservoir in Vietnam with a capacity of 2,400 MW, plays a crucial role in renewable electricity generation and water regulation in northern Vietnam. It has operated since 2012 after seven years of construction (2005–2012). It is located in the Da River system, which supplies domestic and irrigation water to Dien Bien, Lai Chau, Hoa Binh, and Son La provinces and is one of the water sources for Vietnam's second-largest delta, the Red River Delta. In addition, the Da River provides a drinking and domestic water supply capacity of 300,000 m³ day⁻¹ for an estimated 100,000 households in Hanoi, the capital of Vietnam. The capacity is expected to increase to 1,365,000 m³ day⁻¹ by 2030 and 1,890,000 m³ day⁻¹ by 2050. Although Da River water is treated for drinking and domestic purposes, water quality management is essential for ecosystem and human health.

The main objective of this study is to analyze pollutant discharge loads during the dry and flood seasons in the river system of the hydropower reservoir basin. The study addresses four specific objectives: (1) identify changes in flow-rate trends and seasonal fluctuations in surface-water pollutant concentrations in river flows; (2) determine the correlation between seasonal runoff rate and pollutant concentration; (3) quantify basin pollutant loads during the dry and flood seasons; and (4) estimate the capacity of hydropower dams to alter downstream pollutant loads.

2. MATERIALS AND METHODS

2.1. Research Area

The reservoir has a water surface area of 224 km² and is 175 km long. The reservoir basin has an area of 11,075 km², 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 (Fig. 1). The Nam Muc River is 128 km long and has a sub-basin area of 1,618 km². The Nam Na River is 109.4 km long and has a sub-basin area of 2,949 km². The Nam Mu River is 183.7 km long and has a sub-basin area of 2,972 km². Several hydropower dams have been constructed on the mainstream (Da River) and the three tributaries before water enters the Son La hydropower reservoir: Lai Chau Dam on the Da River, Nam Muc Dam on the Nam Muc River, Nam Na 1 and 2 dams on the Nam Na River, and Huoi Quang Dam on the Nam Mu River. The dry season (January–March and October–December) is characterized by low rainfall

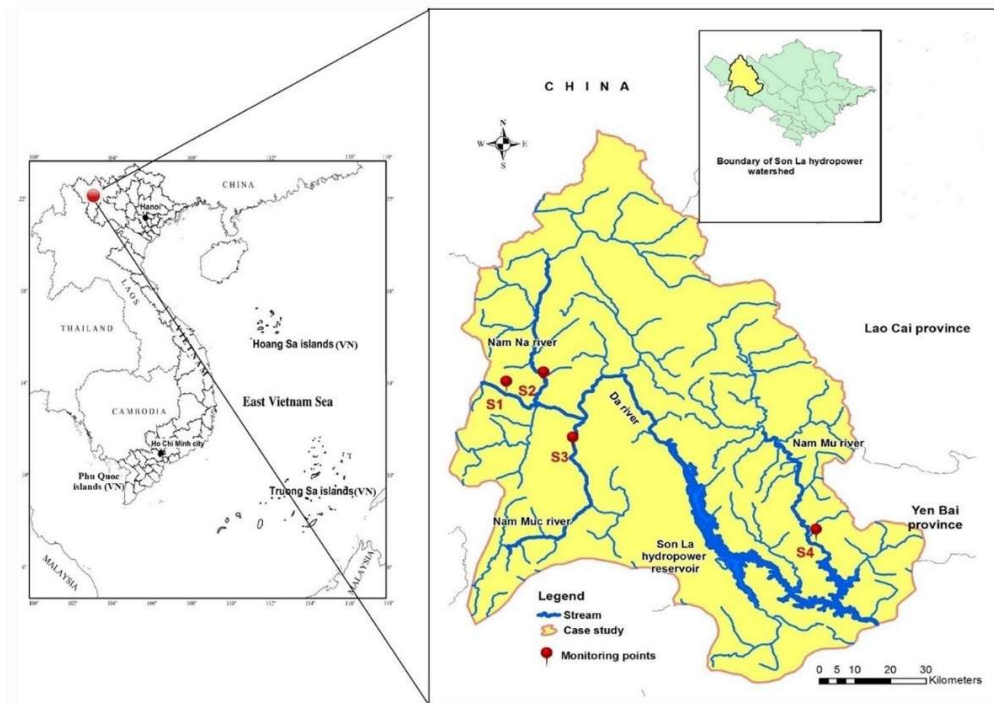


Fig. 1: Location of monitoring points in the river system of the Son La hydropower reservoir basin in Northwestern Vietnam.

(350 mm year⁻¹). Rainfall during the flood season (April–September) is 1,577 mm year⁻¹. Fig. 1 shows the four rivers supplying water to the Son La hydropower reservoir and the coded water-flow and surface-water-quality monitoring points (S1–S4). Monitored water flow (Q) and nine surface-water-quality parameters entering the Son La hydropower reservoir, including DO, TSS, BOD₅, COD, NH₄⁺, NO₂⁻, NO₃⁻, PO₄³⁻, and total Fe, were used in accordance with the regulation on assessment of wastewater receiving capacity and carrying capacity of river and lake water sources, 76/2017/TT-BTNMT (MONRE 2017). Average water-flow and surface-water-quality values at the four monitoring points are available for the ten years 2014–2024 (Source: Hydrometeorological Station of the Northwest Region and Son La Hydropower Company).

2.2. Monitoring Data

In the study area, four 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), and S4 (Nam Mu River) (Fig. 1). Stations S1, S2, S3, and S4 have been used to monitor the flow and water quality of rivers entering the Son La hydropower reservoir (inflow). Monitoring was conducted four times per year, in March, May, August, and November. Monitoring data for water flow (Q) and surface-water quality (DO, TSS, BOD₅, COD, NH₄⁺, NO₂⁻, NO₃⁻, PO₄³⁻, and total Fe) at four stations (S1–S4) during 2014–2024 were collected. DO values were measured

using Sension156 portable equipment (HACH, US); BOD₅ and COD were determined by the HACH method/equipment (HACH, US); TSS was determined using the analytical method TCVN 6625:2000; and total Fe was determined using SMEWW 3111B:2012. Portable model 556 equipment (YIS, US) was used to determine the concentrations of NH₄⁺, NO₂⁻, NO₃⁻, PO₄³⁻, and total Fe in water. Average water-flow and water-quality values in March and November were calculated to represent the dry season; those in May and August represented the rainy season.

2.3. Calculation of Stream Pollutant Load

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

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

Table 1: Locations of flow-rate monitoring and surface-water sampling in river flows during 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: Distribution of flow-rate monitoring and surface-water sampling data for river flows entering the Son La hydropower reservoir during 2014–2024.

Years	DO (mg L ⁻¹)	TSS (mg L ⁻¹)	BOD ₅ (mg L ⁻¹)	COD (mg L ⁻¹)	NH ₄ ⁺ (mg L ⁻¹)	NO ₂ ⁻ (mg L ⁻¹)	NO ₃ ⁻ (mg L ⁻¹)	PO ₄ ³⁻ (mg L ⁻¹)	total Fe (mg L ⁻¹)
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
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
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

Table Cont....

Years	DO (mg L ⁻¹)	TSS (mg L ⁻¹)	BOD ₅ (mg L ⁻¹)	COD (mg L ⁻¹)	NH ₄ ⁺ (mg L ⁻¹)	NO ₂ ⁻ (mg L ⁻¹)	NO ₃ ⁻ (mg L ⁻¹)	PO ₄ ³⁻ (mg L ⁻¹)	total Fe (mg L ⁻¹)
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.

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

The general formula for calculating the total amount of pollutants generated is:

$$E = \frac{C \cdot F \cdot 3600}{1000} \quad \dots(2)$$

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.

Equation (2) was applied to calculate the seasonal river-flow pollutant load in the basin. The pollutant load from the main flow system of the four rivers entering the Son La hydropower reservoir annually during 2014–2024 was calculated from river water flow and pollutant concentrations measured at four hydrological stations (S1–S4) (Fig. 1).

The pollutant load of each river in each year during 2014–2024 was calculated as follows:

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

Where PL is the pollutant load (tonnes year⁻¹), Q is the water flow (m³ s⁻¹), and C_i is the concentration of pollutant i in river water (mg L⁻¹) at each monitoring station (S1, S2, S3, and S4). Units were converted by multiplying by the number of days per year (365) and the number of seconds per day (24 hours day⁻¹ × 60 minutes hour⁻¹ × 60 seconds minute⁻¹).

This study describes the correlation between the dry-season flow-rate variable Q_d and flood-season flow-rate variable Q_r and the surface-water-quality concentration variable C_i (variable x) in seasonal river flow during 2014–2024. The sample correlation coefficient was calculated using the formula of Pearson (1909). The correlation coefficient (r) was used to infer the relationship between two related variables, x and y (Asuero et al. 2006). The correlation coefficient r of the two variables was determined using the following formula:

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

2.4. Statistical Analysis

SPSS 20.0 was used for statistical analysis of the monitoring data. Water-flow and surface-water-quality data were log-transformed for homogeneity and tested for normality using the Cor. Test to assess statistical significance. At a probability of <0.05, the average data for 2014–2024 for nine river-water-quality parameters were considered statistically significant: DO, TSS, BOD₅, COD, NH₄⁺, NO₂⁻, NO₃⁻, PO₄³⁻, and total Fe. Significant differences and correlations among variations were analyzed using one-way ANOVA and Pearson correlation coefficients (r), respectively. Significant differences between inflow and outflow data and between dry and rainy seasons were analyzed using an independent-samples t-test. Figures were prepared using OriginPro 2018 v9.5.0. Water-flow data measured at hydrological stations and surface-water-quality data were analyzed using the R programming language in RStudio.

Table 3: Statistical significance of data from four monitoring points in rivers entering the Son La hydropower reservoir (SLR) based on eleven years of monitoring data using the Cor. Test for 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

Water-flow values at the four monitoring stations are shown in Fig. 2. The Da River has the highest water flow and is the main flow supplying water to the Son La hydropower reservoir, followed by the Nam Na, Nam Mu, and Nam Muc Rivers (Fig. 2). A decreasing trend in water flow was observed in the Nam Muc River. This decrease during the study period may be due to the construction and operation of the Nam Muc Dam, which retains water for hydropower generation and agricultural irrigation (Fig. 2). By contrast, water flow in the Da, Nam Na, and Nam Mu Rivers tended to increase during 2014–2024. As the main river, the Da River has a higher water flow than the three tributaries.

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 24 m³ s⁻¹, respectively; those in the rainy season were 1,564, 674, 370, and 88 m³ s⁻¹, respectively (Figs. 2 and 3). Water flows during the rainy season at all monitoring stations were significantly higher than those during the dry season ($p < 0.05$) because of the greater amount of water flowing into the reservoir during the rainy season. Small hydropower plants on river systems S1, S2, S3, and S4 regulate flow. During the rainy season, large amounts of water flow into rivers in the basins, and hydropower plants release water to ensure dam safety; therefore, water flow tends to increase. Dry-season water flow into the Son La hydropower reservoir increased significantly because of flow regulation by small hydropower dams on the river system. Hydropower-dam operation has reduced downstream water flow during the rainy season by about 35% and increased water flow during the dry season by about 226% (Le et al. 2014).

3.2. Water Quality of River System

Water-quality parameters (TSS, BOD₅, COD, NH₄⁺, NO₂⁻, NO₃⁻, PO₄³⁻, and total Fe) were compared between the dry and rainy seasons in the river system of the Son La hydropower reservoir from 2014 to 2024. Seasonal water-quality values differed among the Da River (S1), Nam Na River (S2), Nam Muc River (S3), and Nam Mu River (S4).

The values of water-quality parameters during 2014–2024 (dry season; rainy season) were as follows: DO, 5.6–5.5 mg L⁻¹ (S1), 5.7–5.6 mg L⁻¹ (S2), 5.6–5.5 mg L⁻¹ (S3), and 5.5–5.5 mg L⁻¹ (S4); TSS, 19.5–63.1 mg L⁻¹ (S1), 15.4–35.9 mg L⁻¹ (S2), 14.5–28.0 mg L⁻¹ (S3), and 11.9–13.7 mg L⁻¹ (S4); BOD₅, 4.22–4.49 mg L⁻¹ (S1), 4.2–4.4 mg L⁻¹ (S2), 4.4–4.6 mg L⁻¹ (S3), and 4.3–4.3 mg L⁻¹ (S4); COD, 9.51–8.12 mg L⁻¹ (S1), 8.97–8.64 mg L⁻¹ (S2), 8.0–8.14 mg L⁻¹ (S3), and 7.71–7.34 mg L⁻¹ (S4); NH₄⁺, 0.23–0.20 mg L⁻¹ (S1), 0.26–0.22 mg L⁻¹ (S2), 0.25–0.22 mg L⁻¹ (S3), and 0.27–0.24 mg L⁻¹ (S4); NO₂⁻, 0.05–0.10 mg L⁻¹ (S1),

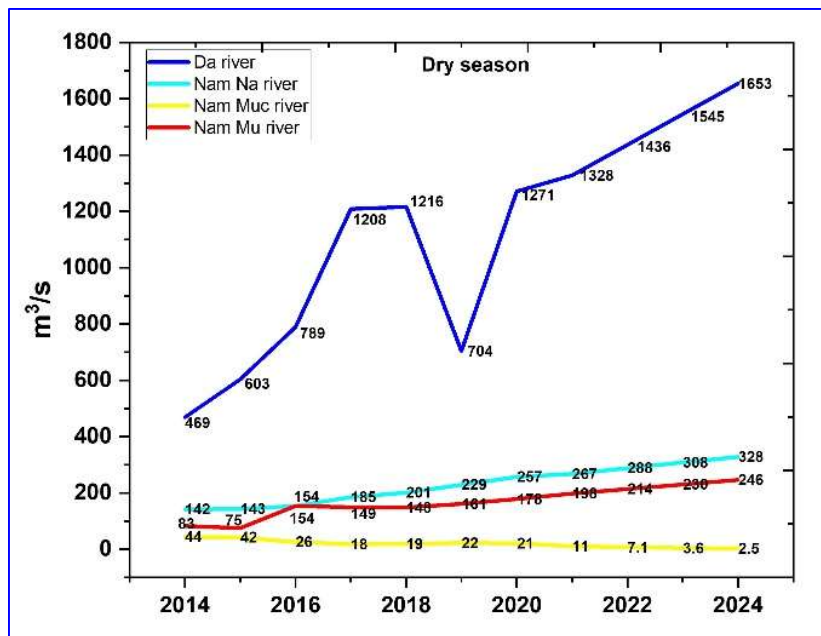


Fig. 2: Dry-season water-flow trends in the Son La hydropower reservoir basin during 2014–2024.

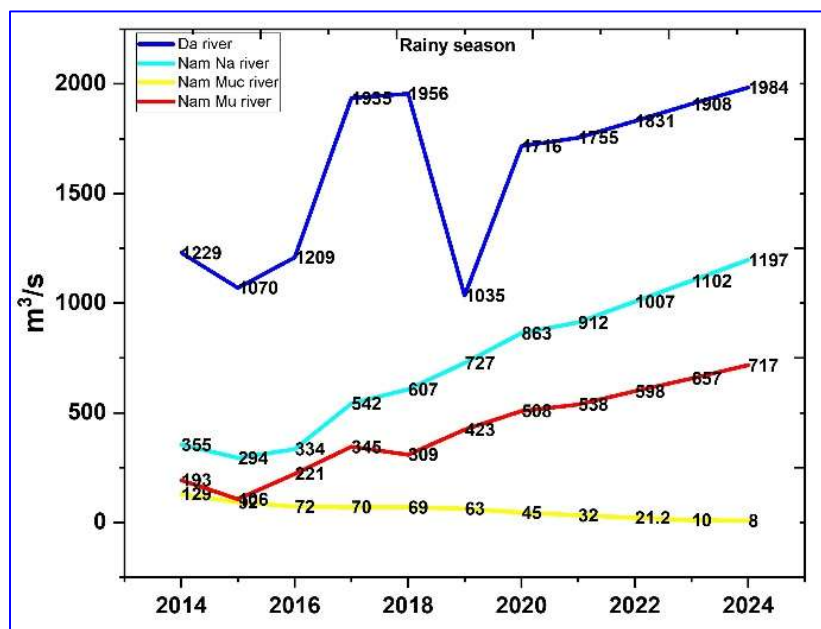


Fig. 3: Rainy-season water-flow trends in the Son La hydropower reservoir basin during 2014–2024.

0.05–0.04 mg L⁻¹ (S2), 0.04–0.03 mg L⁻¹ (S3), and 0.04–0.04 mg L⁻¹ (S4); NO₃⁻, 0.38–0.33 mg L⁻¹ (S1), 0.34–0.39 mg L⁻¹ (S2), 0.31–0.30 mg L⁻¹ (S3), and 0.34–0.31 mg L⁻¹ (S4); PO₄³⁻, 0.08–0.22 mg L⁻¹ (S1), 0.11–0.50 mg L⁻¹ (S2), and 0.06–0.06 mg L⁻¹ (S3); and total Fe, 0.25–0.40 mg L⁻¹ (S1), 0.27–0.52 mg L⁻¹ (S2), 0.22–0.23 mg L⁻¹ (S3), and 0.27–0.32 mg L⁻¹ (S4).

Fig. 4 shows the mean annual water-quality values. For the Da River, the values were DO (5.5 ± 0.8), TSS (41.2 ± 10.4), BOD₅ (4.3 ± 0.7), COD (8.8 ± 0.53), NH₄⁺ (0.21 ± 0.015), NO₂⁻ (0.07 ± 0.008), NO₃⁻ (0.35 ± 0.19), PO₄³⁻ (0.14 ± 0.034), and total Fe (0.32 ± 0.028). For the Nam Na River, the values were DO (5.7 ± 1.2), TSS (25.6 ± 0.29), BOD₅ (4.3 ± 1.1), COD (8.8 ± 0.61), NH₄⁺ (0.23 ± 0.065), NO₂⁻ (0.04

± 0.005), NO_3^- (0.36 ± 0.015), PO_4^{3-} (0.30 ± 0.07), and total Fe (0.39 ± 0.036). For the Nam Muc River, the values were DO (5.6 ± 0.8), TSS (21.2 ± 1.61), BOD_5 (4.5 ± 0.74), COD (8.07 ± 0.25), NH_4^+ (0.23 ± 0.016), NO_2^- (0.03 ± 0.002), NO_3^- (0.3 ± 0.014), PO_4^{3-} (0.06 ± 0.003), and total Fe (0.22 ± 0.010). For the Nam Mu River, the values were DO (5.5 ± 0.6), TSS (12.7 ± 3.34), BOD_5 (4.3 ± 0.63), COD (7.5 ± 0.32), NH_4^+ (0.25 ± 0.017), NO_2^- (0.04 ± 0.002), NO_3^- (0.32 ± 0.017), PO_4^{3-} (0.06 ± 0.003), and total Fe (0.29 ± 0.028).

All monitored water-quality parameters were below the limits specified for irrigation water in the Vietnamese guideline QCVN 08-MT:2015/BTNMT (DO: $\geq 4 \text{ mg L}^{-1}$, TSS: 50 mg L^{-1} , BOD_5 : 15 mg L^{-1} , COD: 30 mg L^{-1} , NH_4^+ : 0.9 mg L^{-1} , NO_2^- : 0.05 mg L^{-1} , NO_3^- : 10 mg L^{-1} , PO_4^{3-} : 0.3 mg L^{-1} , and total Fe: 1.5 mg L^{-1}), except for NO_2^- (MONRE 2015). NO_2^- concentrations in 2014 and 2021–2023 in the Da and Nam Na Rivers ranged from 0.05 to 0.20 mg L^{-1} , exceeding the QCVN 08-MT:2015/BTNMT limit of 0.05 mg L^{-1} . Increasing trends during 2014–2023 were reported for DO ($r = 0.84$), NH_4^+ ($r = 0.93$), NO_2^- ($r = 0.28$), NO_3^- ($r = 0.47$), PO_4^{3-} ($r = 0.39$), and total Fe ($r = 0.91$), possibly as a result of agriculture in the river basin and increasing aquaculture in the reservoir. This result is consistent with previous studies (Brian et al. 1997, Karine et al. 2006, Do et al. 2020). The formation of hydropower dams in the basin affects seasonal changes in water-quality concentrations in the stream. Ammonium (NH_4^+) concentration in the stream increases because of seasonal increases in circulation downstream of the dam (Isaac et al. 2018, Ito 1987). In addition, increases in NH_4^+ , NO_2^- , NO_3^- , and PO_4^{3-} concentrations in river flows are related to the accumulation and metabolism of nitrogen and phosphorus nutrients due to discharges from the basin into the stream (Zhang et al. 2014). High phosphate concentrations in annual runoff indicate pollution from untreated discharges into the river (Houry et al. 2007). In contrast, TSS ($r = -0.95$), BOD_5 ($r = -0.65$),

and COD ($r = -0.48$) reportedly showed decreasing trends during this period. The construction of dams upstream of the Son La hydropower plant, namely the Lai Chau, Nam Muc, Nam Na 1 and 2, and Huoi Quang dams, and the trapping of sediment and suspended solids in upstream reservoirs may be responsible for the reduction in TSS in the study area. The annual decrease in TSS concentrations is associated with the construction of hydropower reservoirs in the basin because large amounts of silt and suspended solids in river flows are trapped in the reservoirs (Kummu et al. 2007). BOD_5 and COD concentrations decrease because of seasonal variation in the stream (Dou et al. 2012). Thus, regulation of river water by hydropower dams and discharges from the basin is an important factor affecting pollutant concentrations in the stream.

3.3. Relationship Between Water Flow and Pollutant Concentration

Fig. 5 shows the statistical relationship during the dry season between the water-flow variable Qd in rivers of the Son La hydropower reservoir basin and the pollutant concentrations of nine parameters, with the correlation coefficient (r) determined. Qd had a positive correlation coefficient ($r > 0$) with five surface-water-quality parameters: NH_4^+ at S1, S2, and S4; NO_3^- at S1 and S2; PO_4^{3-} at S1; and total Fe at S1, S2, S3, and S4. For NH_4^+ and total Fe at S1, S2, and S4 and NO_3^- at S1 and S4, the correlation coefficient (r) with Qd ranged from 0.5 to 1 (strong correlation); for PO_4^{3-} at S1, S2, and S4, the correlation coefficient (r) with Qd was < 0.29 (weak correlation). Qd had a negative correlation coefficient ($r < 0$) with four surface-water parameters: TSS at S1, S2, and S4; BOD_5 at S1, S2, S3, and S4; COD at S1, S2, and S4; and NO_2^- at S1, S2, and S3. Thus, during the dry season, as water flow increased, the concentrations of NH_4^+ , total Fe, NO_3^- , and PO_4^{3-} increased, whereas the concentrations of TSS, BOD_5 , COD, and NO_2^- decreased.

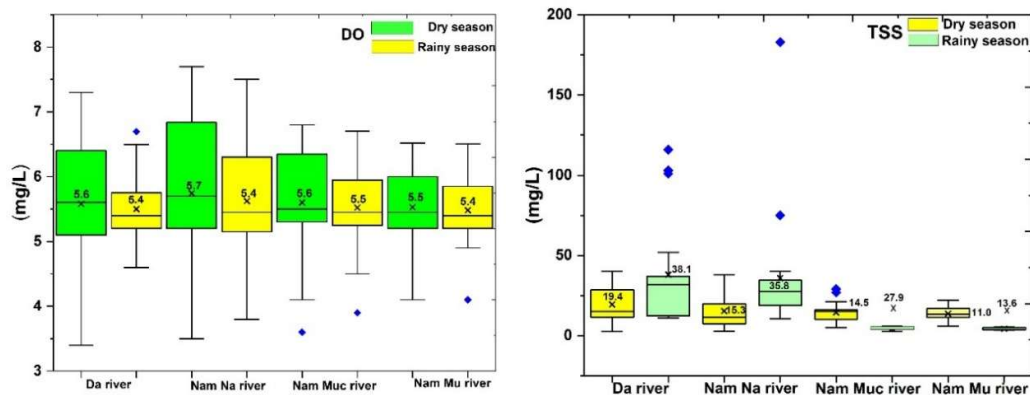


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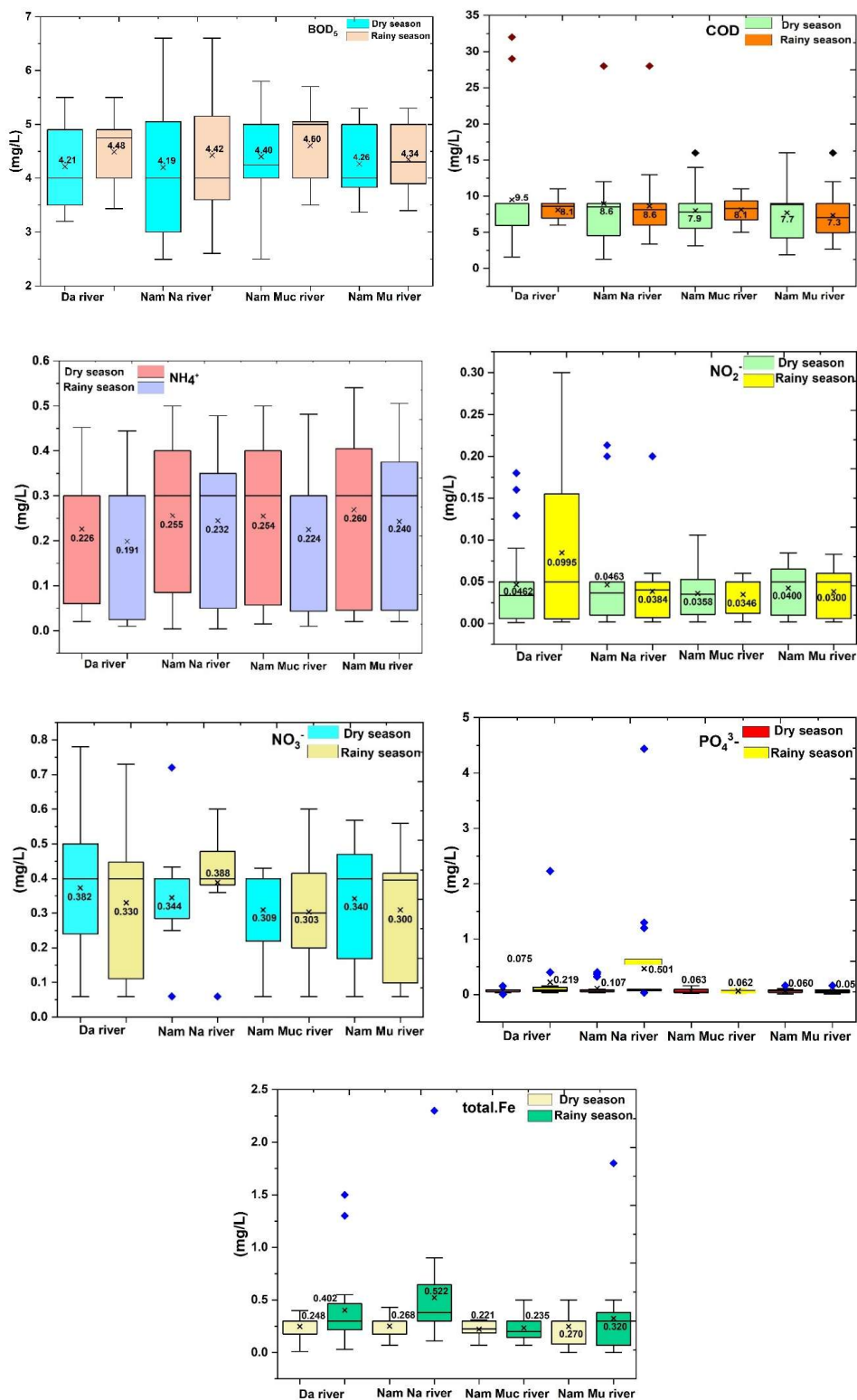


Fig. 4: Changes in DO, TSS, BOD₅, COD, NH₄⁺, NO₂⁻, NO₃⁻, PO₄³⁻, and total Fe concentrations in river flows during the dry and rainy seasons from 2014 to 2024.

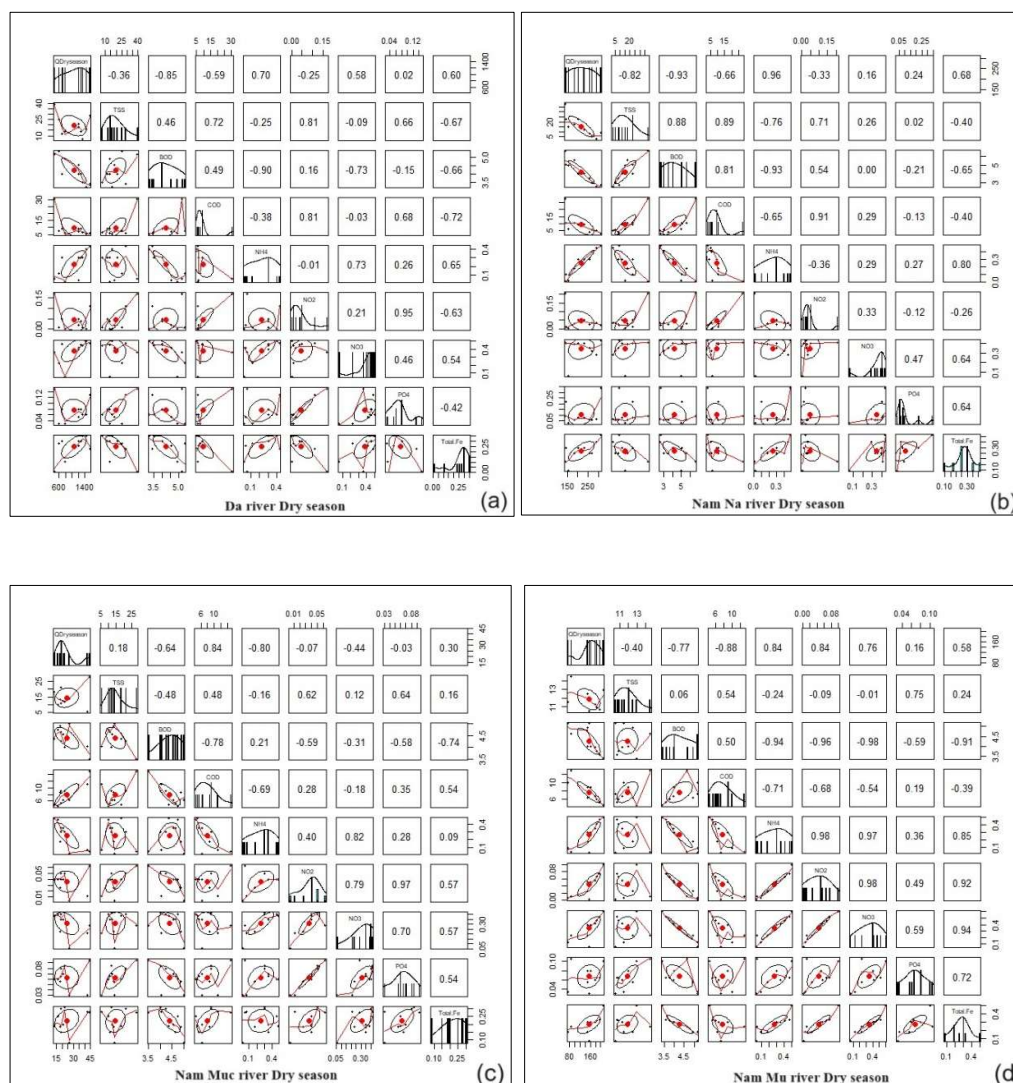


Fig. 5: Correlation between flow rate and dry-season stream pollutant concentration in the Da River (a), Nam Na River (b), Nam Muc River (c), and Nam Mu River (d) during 2014–2024.

Fig. 6 shows the statistical relationship during the rainy season between the water-flow variable Q_r and the concentrations of nine pollutants. Correlations (r) between river water flow and surface-water-pollutant concentrations during the rainy season differed among the Da River (S1), Nam Na River (S2), Nam Muc River (S3), and Nam Mu River (S4). Q_r had a positive correlation coefficient ($r > 0$) with NH_4^+ , NO_2^- , NO_3^- , and PO_4^{3-} at S1, S2, and S4; total Fe at S3 and S4; and TSS at S1 and S4. During the rainy season, Q_r had a negative correlation coefficient ($r < 0$) with BOD_5 and COD at S1, S2, S3, and S4.

This result is consistent with previous studies showing that the operation of artificial dams changes the natural river-flow regime, such as by reducing flow during the

rainy season and increasing flow during the dry season (Li et al. 2017). Dam operation affects the annual flow rate; concentrations of dissolved NO_3^- , NH_4^+ , and PO_4^{3-} downstream increase, while the concentration of suspended solids (TSS) decreases (Stow et al. 2001, Stanley 2002, Haque et al. 2018). Increased biomass decomposition in the upstream reservoir may reduce downstream BOD_5 and COD concentrations (Le et al. 2014). Total Fe concentration increases under low-flow conditions and decreases during flood periods (Heikkinen 1990). Thus, water accumulation associated with dams on river flows is an important factor influencing the correlation between flow rate and pollutant concentrations during the dry and flood seasons in the Son La hydropower reservoir basin.

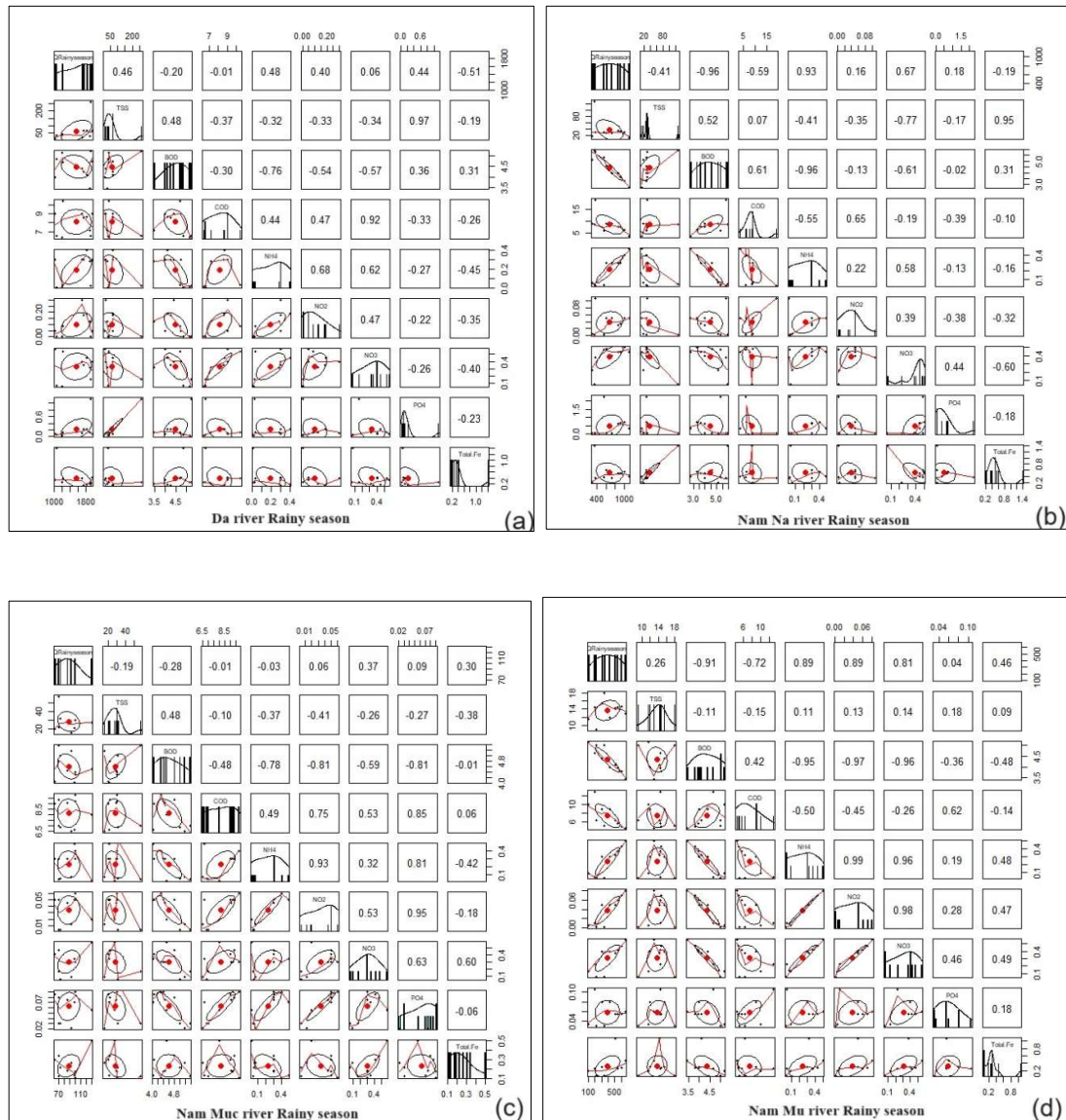


Fig. 6: Correlation between flow rate and rainy-season stream pollutant concentration in the Da River (a), Nam Na River (b), Nam Muc River (c), and Nam Mu River (d) during 2014–2024.

3.4. Pollutant Load of River System

The pollutant load of the river system of the Son La hydropower reservoir fluctuated from 2014 to 2024. During 2014–2024, the pollutant loads of the four rivers entering the reservoir (S1, S2, S3, and S4) ranged from 11,581,848 to 9,714,484 tonnes year⁻¹. The lowest and highest pollutant loads were obtained in 2017 and 2022, respectively. The pollutant load of the river system during the rainy season was significantly higher than that during the dry season ($p < 0.001$), mainly because of higher water flow in the rainy season. The rainy-season pollutant load accounted for

63.1%–92.4% (average: 77.2%) of the yearly pollutant load. During the rainy season, the pollutant load in the inflow ranged from 1,037,197 to 8,976,742 tonnes year⁻¹ (average: 2,762,709 tonnes year⁻¹), significantly higher than that during the dry season (372,913–1,098,830 tonnes year⁻¹; average: 640,894 tonnes year⁻¹) ($p < 0.01$).

Pollutant loads of the component parameters (TSS, BOD₅, COD, NH₄⁺, NO₂⁻, NO₃⁻, PO₄³⁻, and total Fe) also fluctuated greatly by season and year during 2014–2024. The average pollutant loads (tonnes year⁻¹) were in the following order: TSS (318,191) > COD (62,308) > BOD₅ (34,359) >

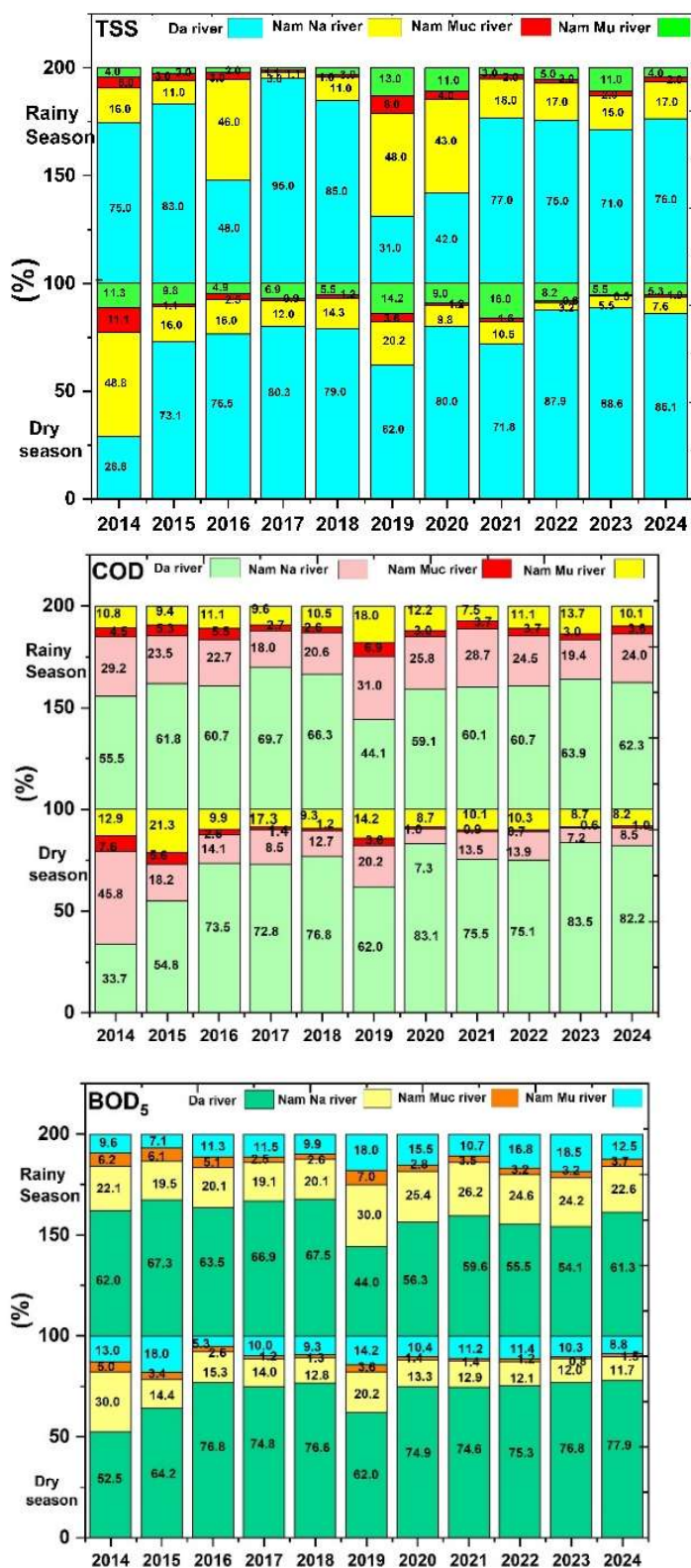


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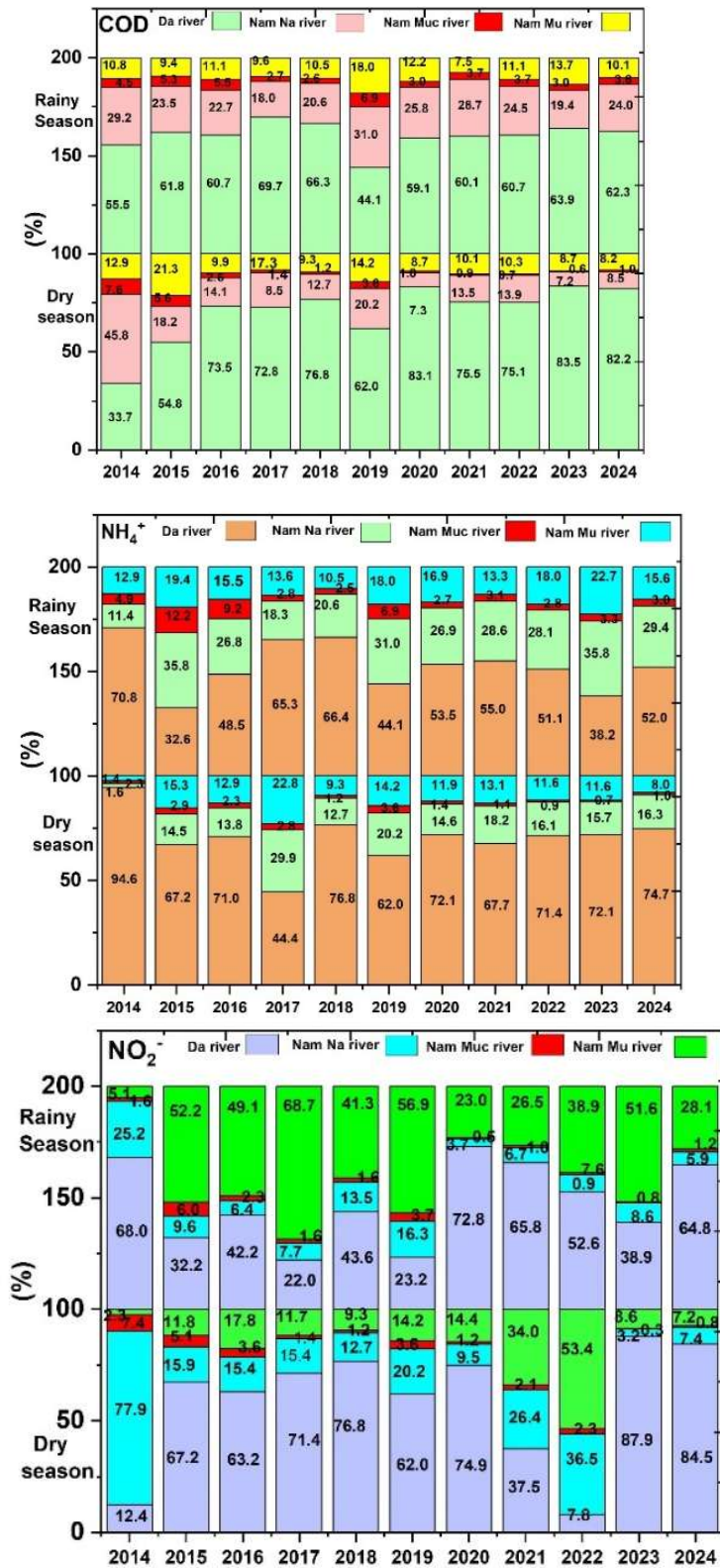


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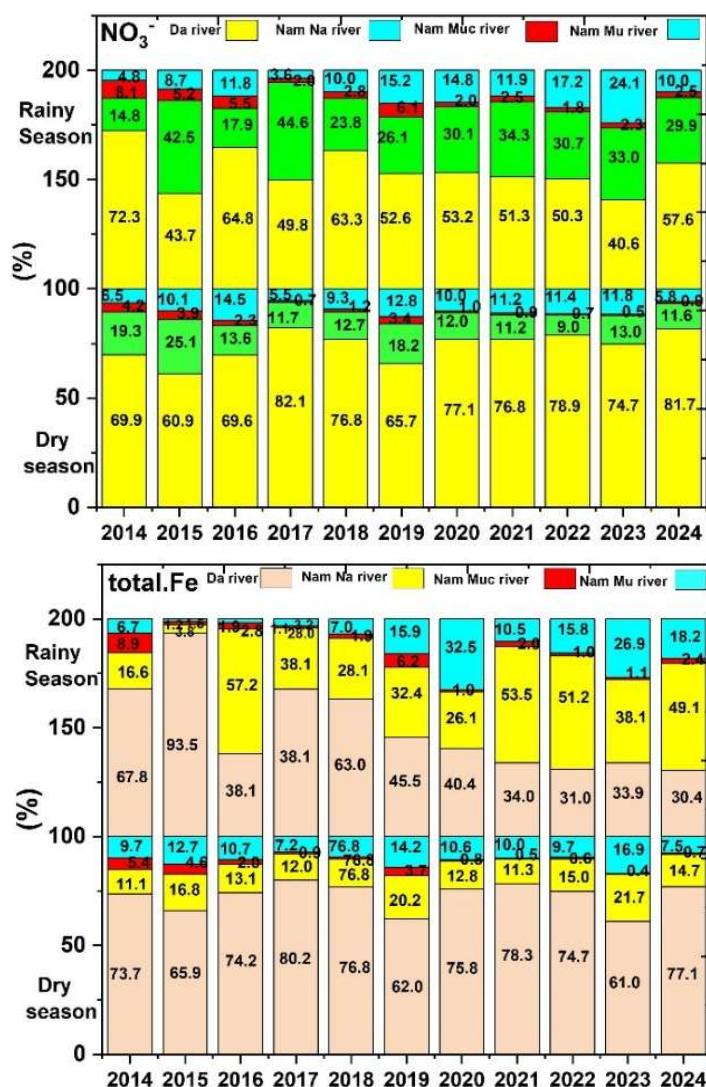


Fig. 7: Pollutant-load ratio during the dry and rainy seasons in river flows of the Son La hydropower reservoir basin during 2014–2024.

NO_3^- (3,061) > Fe (2,924) > NH_4^+ (2,107) > PO_4^{3-} (1,776) > NO_2^- (725). Fig. 7 shows that 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. Cultivation on sloping land in the Son La hydropower reservoir basin increases soil erosion and runoff, carrying dissolved solids with rainwater. This may contribute to increased total suspended solids (TSS) pollution loads 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 between the dry and rainy seasons, indicating that these two parameters have high pollution loads following basin flow (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). 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 nonpoint 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). 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 Son La hydropower reservoir in Northwest Vietnam.

Total pollutant load showed a strong negative correlation with water flow for TSS ($r = -0.81$, $p < 0.001$), BOD₅ ($r = -0.82$, $p < 0.001$), COD ($r = -0.79$, $p < 0.001$), NH₄⁺ ($r = -0.73$, $p < 0.001$), NO₃⁻ ($r = -0.77$, $p < 0.001$), PO₄³⁻ ($r = -0.75$, $p < 0.001$), and total Fe ($r = -0.78$, $p < 0.001$). Total pollutant load also showed a strong negative correlation with water flow for NO₂⁻ ($r = -0.67$, $p < 0.001$).

Fig. 7 shows that the Da River has a large water flow and correspondingly transports the highest pollution load to the reservoir compared with the three smaller rivers, namely the Nam Na, Nam Muc, and Nam Mu Rivers. This is because the Da River serves as a primary water source for agriculture in 25 provinces and cities and provides drinking water for more than 30 million people in urban and rural areas. The basin has significant economic and historical value (Le et al. 2019). The pollution load in the Son La hydropower reservoir basin may also depend primarily on flow regulation between the dry and rainy seasons by hydropower plants in the basin (Do et al. 2019, Do et al. 2020). At the same time, contaminant discharges to rivers increase with human population growth and activities in agricultural, residential, and livestock sectors, facilitating the detection of river contamination (Suhardono et al. 2025). Camargo Hinostroza et al. (2025) reported that total nitrogen values exceeded the limits established in the ECA in 82% of the data, pH in 13%, and phosphorus in 1%. For 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, in the ICA-PE evaluation of the dry and wet seasons. These findings highlight the importance of effective water resource management in the transboundary river basin of Northwestern Vietnam.

4. CONCLUSIONS

This study provides a comprehensive assessment of 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 (NO₂⁻) 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 (NH₄⁺), and other nutrients showed increasing trends, while total suspended solids (TSS), BOD₅, 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. Quantification of pollutant

loads revealed an average annual transport of 3,403,604 tonnes, characterized by marked seasonal variability. The rainy season was the dominant period for pollutant transport, accounting for 63.1%–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 BOD₅ (8%). Statistical analysis confirmed a strong correlation between seasonal discharge and pollutant concentrations, highlighting the impact of dam operations and land-use activities, particularly agriculture and cage aquaculture, on the reservoir's water chemistry. These findings have important implications for management of the Da River system, which serves as a vital source of domestic and agricultural water for millions of people in northern Vietnam. Effective watershed management should prioritize nonpoint source pollution control and account for the cumulative effects of the reservoir cascade. Future research should focus on self-purification mechanisms within these reservoirs and the development of integrated monitoring across the entire river system to safeguard regional water security.

5. ACKNOWLEDGEMENT

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