Vietnam Journal of Agricultural Sciences

ISSN 2588-1299

VJAS 2024; 7(4): 2280-2293
https://doi.org/10.31817/vjas.2024.7.4.03

Spatial Assessment of Pollutant Loads in the Ma River Basin, Song Ma District, Son La Province

Ngo Thanh Son, Nong Huu Duong*

Faculty of Natural Resources and Environment, Vietnam National University of Agriculture, Hanoi 12400, Vietnam

Abstract

This study evaluated the impact of pollution sources on the Ma River Basin in Son La Province, Vietnam, using data from local reports, statistical yearbooks, and scholarly literature. Through spatial analysis and statistical methods, the study mapped the distribution of pollutants across sub-basins in Song Ma district and assessed the pressure of each pollution source on water quality. The findings revealed that livestock raising and domestic activities were the major contributors to water pollution in the cluster 1 of sub-basins, while land-use activities were major threats to the surface water in the cluster 2 of sub-basins. The study recommended implementing centralized wastewater treatment systems in priority areas, promoting sustainable land management practices, and supporting environmentally friendly agricultural and livestock farming methods. These interventions are crucial for achieving sustainable development goals related to clean water and sanitation. The findings underscore the importance of integrated river basin management strategies to mitigate water pollution and ensure the long-term health and sustainability of the Ma River Basin.

Keywords

Pollution sources, pollutant load mapping, Ma river basin

Introduction

Water pollution threatens ecosystems and poses long-term environmental challenges. Among the United Nation's 17 Sustainable Development Goals (SDGs), Goal 6 (SDG6) aims to provide access to clean water sanitation, especially in areas with difficult conditions (Milan, 2017; Herrera, 2019). Achieving this requires improving water quality and reducing pollution from chemicals and untreated wastewater. SDG6 also emphasizes protecting and restoring natural water sources and implementing integrated resource management (Howard, 2021). Therefore, assessing the pressure of discharges on surface water sources is crucial to help localities better control

Received: May 29, 2024
Accepted: December 16, 2024

Correspondence to
nhduong@vnua.edu.vn

ORCID
Nong Huu Duong
https://orcid.org/0000-0001-9867-5249

pollutants and implement timely interventions, making an important contribution to ensuring the sustainable development goals of each country and community

Rivers are vital for economic, cultural, social, and ecological reasons and are the foundation to water security. In Vietnam, rapid population growth, urban development, and land-use changes, coupled with the adverse impacts of climate change, have intensified challenges to water resource management (Huong & Son, 2020; Bui *et al.*, 2019; Tri *et al.*, 2019). Pollution from both point sources (PS) and non-point sources (NPS) are the primary causes of water-related issues such as river pollution, aquatic ecosystem degradation, and eutrophication (Xiang *et al.*, 2017). Changes in land use often complicate non-point source pollution, as the mechanisms of pollution generation and transport vary with different land management and land use practices (Son&Loc, 2024). Agricultural pollutants, primarily from fertilizers and pesticides, are transported to water bodies through surface runoff and groundwater flow, which are influenced by climatic factors, topography, and soil characteristics such as soil type and moisture (Fan *et al.*, 2021). The extensive use of agricultural chemicals results in significant amounts of nutrients and pesticides entering water bodies, which negatively impacts both the environment and community health (Me *et al.*, 2018).

Watershed-based management is often prioritized in water resource management and when addressing pollution because watersheds reflect the natural movement of water flow, offering insight into processes such as land degradation, nutrient transport, and human impacts (Dourojeanni, 2001; Kemper *et al.*, 2007). Unlike administrative boundaries, watersheds encompass multiple geographic regions and natural systems allowing for more comprehensive and sustainable solutions to water-related challenges. Since water pollution transcends political borders, this approach fosters collaboration among governments, non-governmental organizations, and local communities to address shared issues (Bach *et al.*, 2011).

The Ma River is a transboundary river system shared by Vietnam and Laos and is one of Vietnam's nine major river systems. Within Vietnam, the Ma River basin covers an area of 17,653 km^2 spanning the provinces of Dien Bien, Son La, Hoa Binh, Thanh Hoa, and Nghe An (Nguyen, 2024). The basin is divided into eight planning sub-regions: Upper Ma River, Middle Ma River, Southern Ma River - Northern Chu River, Northern Ma River, Buoi River Basin, Am River Basin, Upper Chu River, and Southern Chu River. The terrain in this region varies from gentle to steep slopes with the mountainous areas in the Northwest having slopes ranging from 20^o to 35^o. The upper Ma River basin experiences a tropical monsoon climate with an average annual rainfall of 1900 mm, 80% of which occurs between May and October. According to the 2020 annual report from the Ministry of Natural Resources and Environment (MONRE), the basin has been significantly impacted by land use changes, land degradation, and nutrient depletion over the past 30 years, primarily due to widespread deforestation, agricultural expansion, and inadequate conservation practices. Additionally, water pollution has become increasingly severe as the discharge of untreated or poorly treated wastewater has caused many water sources to fall below acceptable quality standards for domestic water use.

In 2019, the Vietnam Environment Administration (VEA) issued guidelines for calculating the carrying capacity of river water sources (VEA, 2019). On January 8, 2024, the Deputy Prime Minister signed Decision No. 20/QD-TTg, approving the Overall Planning for the Ma River Basin for 2021 - 2030, with a vision towards 2050 (Government, 2024). This decision emphasizes the importance of assessing and managing pollution sources in watershed areas like the Ma River Basin to protect water resources and enhance the quality of life for local communities. In Vietnam, two studies by Ngo *et al*. (2020, 2024) successfully applied the VEA (2019) guidelines, along with statistical approaches, to map pollutant loads and identify major pollution sources at the sub-basin level in case studies conducted in Bac Giang and Lai

Chau provinces. These studies also highlighted the critical need for controlling both point source and non-point source pollution at the watershed scale. To identify the impact of pig farming on the total pollutant load in each sub-basin of Yen Dung district, Bac Giang province, Ngo *et al*. (2020) applied the Bayesian information criterion (BIC) to evaluate the significance of pig farming's contribution. In the later study, Ngo *et al*. (2024) applied multivariate analysis, including hierarchical cluster analysis (HCA), discriminant analysis (DA), and principal component analysis (PCA), on log-normalized data to identify spatial patterns in pollutant sources (COD, BOD, N-total, and P-total) across sub-basins. First, HCA and DA were used to group similar sub-basins and to evaluate how effectively pollutant variables distinguished these clusters. PCA was then employed to further reduce dimensionality by identifying the key pollutant sources, thereby highlighting the most influential parameters with minimal data loss. Building upon Ngo *et al*. (2024), our study aimed to assess pollution loads in the sub-basins of Song Ma District, Son La Province. This will contribute to better water resource management and support the achievement of Sustainable Development Goal 6 (SDG 6) on clean water and sanitation. By identifying the key pollution sources, the study highlighted the importance of "source control," as required by the Environmental Protection Law (2020) and the revised Water Resources Law (2023), which is essential for effective surface water quality management planning.

Materials and Methods

Study area

The study was conducted in Song Ma District, Son La Province **(Figure 1)**. Song Ma District is located 103 kilometers southwest of Son La City along National Highway 4G. Its geographical coordinates are 20°39'33" to 21°22' North latitude and 103°14'56" to 104°06'00" East longitude. The total natural area of the district is 163,955.7 hectares, comprised of 18 communes and one town. Song Ma District holds a crucial position in the socio-economic development and national defense of both the province and the country, with a 43.5-kilometer border shared with the Lao People's Democratic Republic.

Song Ma District has a rich network of rivers and streams. In addition to the Ma River, which flows through the district for 90 kilometers, there is a dense system of streams with a density of 0.75 to 1.27 km/km². However, their distribution is uneven. Major streams include Nam Cong, Nam Ty, and Nam Le, along with others like Nam Soi, Nam Man, and Nam Con. These streams have narrow cross-sections, steep gradients, and high flow rates, creating substantial hydropower potential. This provides a significant advantage for exploiting hydropower resources and developing small hydropower plants to serve the local population. Several hydropower projects have been constructed or are under construction, such as Nam Soi, Nam Cong III, Nam Cong IV, and Nam Cong V.

Surface water is the primary water source for production and daily activities for residents in the area. The district has a relatively abundant surface water supply, with the Ma River system and major streams like Nam Cong, Nam Ty, and Nam Le being particularly important. These water sources not only provide essential water supplies but also play a significant role in the hydrological regime and ecological environment. However, due to the steep, fragmented terrain and low vegetation cover, the area's water retention capacity is very limited. Consequently, surface water distribution is uneven across the territory, leading to severe water shortages in many areas, especially during the dry season in highland villages.

Data sources

The following data sources were used in the study:

- The 2020 land use map of Song Ma District.

- Spatial data, including the Digital Elevation Model (DEM) (SRTM 1 Arc-Second Global) with a 30-meter resolution, were downloaded from the United States Geological Survey (USGS) website to delineate sub-basins within Song Ma district using the QSWAT tool in QGIS software.

- Statistical data on the population of each commune and town in 2023.

- Statistical data on the number of livestock (buffalo, cattle, pigs, goats, poultry) in each commune in 2023.

- Pollutant coefficients for the major pollution sources were taken from the Guidelines for Calculating the Carrying Capacity of Rivers by the Vietnam Environment Administration, 2019 (**Tables 1, 2, 3**).

- The environmental status report of Song Ma District for 2023 (UBND, 2023a).

Calculating pollutant loads in the sub-basins

Figure 2 demonstrates the workflow for calculating pollutant loads in the sub-basins and can be specified in the following steps:

Sub-basin Delineation: The sub-basin delineation process for Song Ma District was conducted using a Digital Elevation Model (DEM) from the SRTM 1 Arc-Second Global dataset. The DEM was projected to the WGS 1984 UTM Zone 48N to ensure spatial consistency with the study area. The SAGA Fill Sinks tool (Wang & Liu, 2006) was applied to remove depressions and ensure accurate simulation of water flow across the terrain. The sub-basins were delineated in QGIS using the QSWAT tool, with an area threshold of 8000 hectares for upstream contributing areas. This threshold value, based on the average commune area, was selected to align with the scale correlation between sub-basin delineation and commune-level spatial analysis.

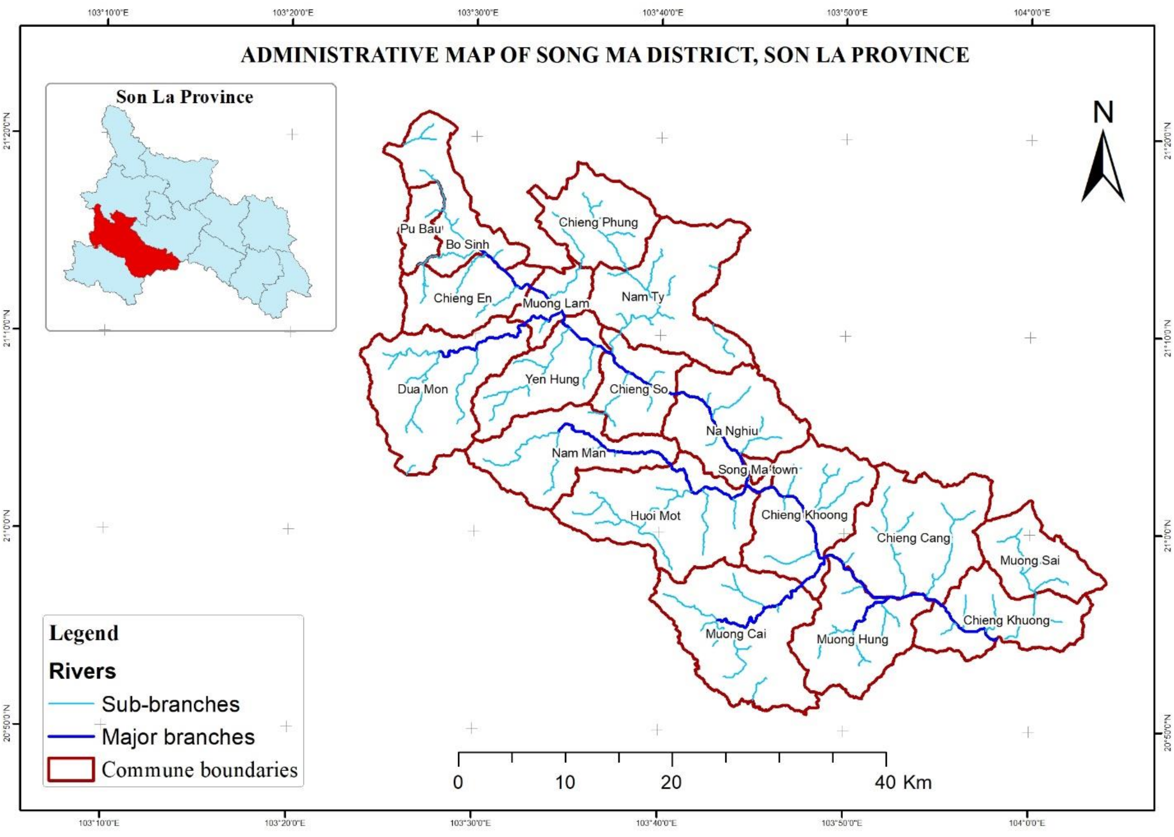

Figure 1. Study area

Table 1. Pollutant coefficients applied to domestic discharge

Domestic discharge	Unit	BOD	COD	T-N	T-P
Urban area	kg/person/year	18.07	34.13	3.3	0.93
Rural area	kg/person/year	14.45	27.30	2.64	0.74

Source: VEA (2019).

Table 2. Pollutant coefficients applied to livestock discharge

Livestock discharge	Average rearing time (month)	Unit	BOD	COD	T-N	T-P
Buffalo	12	kg/head/year	164	295	43.8	11.3
Cow	12	kg/head/year	164	295	43.8	11.3
Pig	6	kg/head/year	33	59	7.3	2.3
Horse	12	kg/head/year	146	263	95.3	16.4
Goat	6	kg/head/year	34	61	13.5	3.7
Poultry	3	kg/head/year	2	3	3.6	-

Source: VEA (2019).

Table 3. Pollutant coefficients from surface run-off of major land use types

Land use types	Unit	BOD	COD	T-N	T-P
Agriculture	kg/ha/year	16.8	30.2	17.9	1.1
Forestry	kg/ha/year	72.8	131.0	4.4	0.3
Specialized land	kg/ha/year	60.4	108.7	10.6	2.3
Urban	kg/ha/year	56.0	100.8	9.0	2.2
Aquaculture	kg/ha/year	90.0	162.0	12.6	-

Source: VEA (2019).

Spatial Data Integration: Statistical data at both the commune and district levels, including population figures, livestock numbers, and land use types, were spatially joined with the commune boundaries based on a common field (commune ID). Pollutant coefficients from VEA (2019) were applied to calculate the pollutant loads for each commune, including those from domestic activities, livestock, and land use practices. It should be noted that, due to the absence of geographic coordinates for discharges from households and livestock farms, these sources were considered as non-point source pollution.

Calculation of pollution loads at the commune level: Based on the statistical data and pollution coefficient **(Tables 1, 2, 3)**, four parameters, namely BOD, COD, total nitrogen, and total phosphorus loads, were calculated for the major pollution sources, namely domestic activities, livestock, and land use. For untreated domestic and livestock sources, the runoff coefficients were applied according to the percentage of urbanity suggested by the Japan Sewage Works Association (2008) in VEA (2019). In this study, the runoff coefficient of 0.4 was applied for Song Ma town with 5-10% of urbanity and 0.1 was applied for other communes with less than 5% of urbanity.

Calculation of pollutant loads at the sub-basin level: In the final step, the pollutant loads for each sub-basin were computed. Using the union tool in QGIS, the proportion of each commune's area falling within the sub-basins was determined. This enabled the estimation of the pollutant loads at the sub-basin level by aggregating the commune-level data accordingly.

Statistical approaches for analyzing pollution sources at the basin level

To analyze the pressure of pollution sources at the basin level, we adopted three interconnected statistical methods used in Ngo *et al*. (2024). First, hierarchical cluster analysis (HCA) was employed to group basins with similar pollution source characteristics. Next, discriminant analysis (DA) was applied to these clusters to identify and highlight the differences in pollution sources among the basin clusters, ensuring the clusters were distinct from each other. Finally, principal component analysis (PCA) was used to quantitatively assess the contribution of different pollution factors within each basin, providing a deeper understanding of which factors most influence the pollution in each cluster. Together, these methods offered a comprehensive approach where HCA grouped the basins, DA validated the differences between these clusters, and PCA helped quantify the influence of individual pollution factors, enabling more precise and effective management strategies.

Results and Discussion

Characteristics of pollution sources in Song Ma district

According to the Environmental Status Report No. 178/BC-UBND issued by the People's Committee of Song Ma District on February 24, 2023 (UBND, 2023a), there are no production facilities, businesses, or service establishments generating wastewater exceeding 50 m^3/day. Additionally, there are no industrial zones or clusters, resulting in negligible pollutant loads from this group. Furthermore, there is only one district general hospital in Song Ma District with a wastewater treatment system meeting 100% of the standards. Therefore, pollution sources in Song Ma District mainly come from land use activities, livestock farming, and domestic wastewater. These sources of pollution are summarized in **Table 5**.

From the statistical data on the characteristics of pollution sources and management measures, and based on the method of calculating pollutant loads for the specified sources outlined in the guidance document of the Vietnam Environment Administration in 2019, the total pollutant loads of Song Ma District for BOD, COD, total nitrogen, and total phosphorus for each source are presented in **Table 6**.

Table 4. Runoff coefficients for domestic and livestock discharges

Sources	Runoff coefficient (according to percentage of urbanity)			
	<5%	5% - 10%	>10% - 15%	>15%
Domestic and livestock discharges	0.1	0.4	0.7	0.9

Source: VEA (2019).

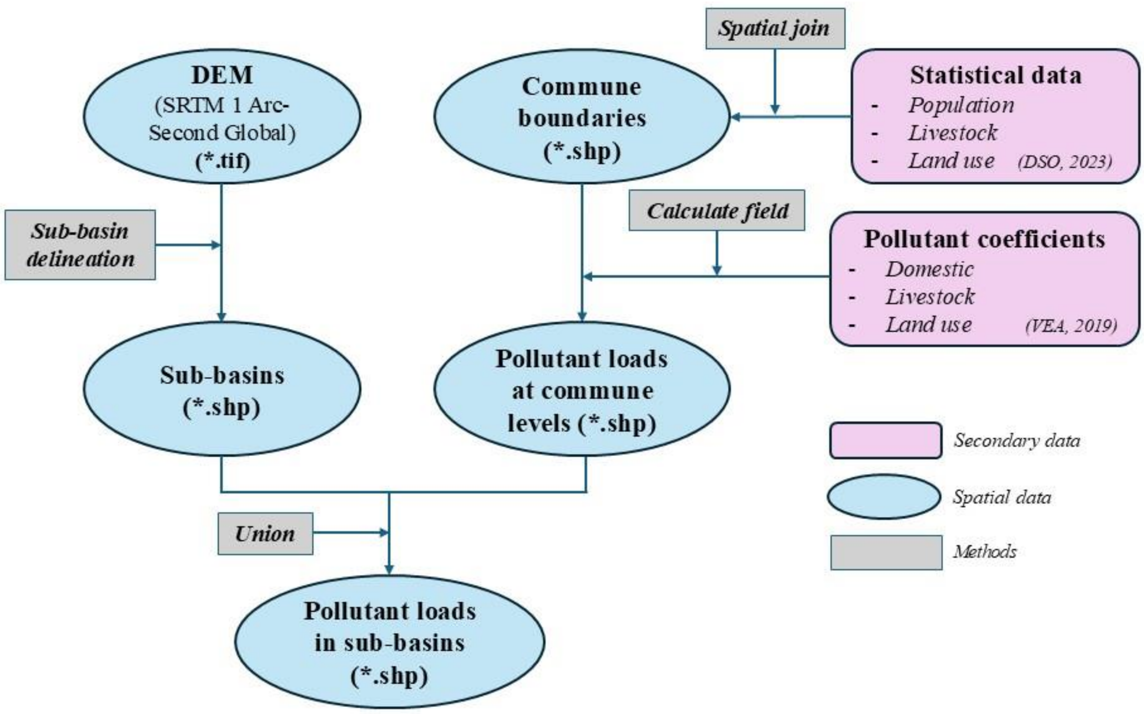

Figure 2. Workflow for calculating pollutant loads in the sub-basins

Table 5. Major pollution sources in Song Ma district

No	Pollution sources		Unit	Total
1	Land use	Agriculture land	*Ha*	34,241
2		Forest land	*Ha*	65,520
3		Specialized land	*Ha*	2,242
4		Aquaculture	*Ha*	287
5		Urban land	*Ha*	1,018
6	Livestock	Buffalo	*Head*	12,572
7		Cow	*Head*	56,784
8		Goat	*Head*	19,538
9		Pig	*Head*	86,302
10		Poultry	*Head*	1,104,011
11	Domestic	Population	*People*	160,866

Source: DSO (2023)

Table 6. Pollutant loads from major sources in Song Ma district

No	Pollution Source	Unit	BOD	COD	Total N	Total P
1	Land use	*Ton/year*	5,563.42	10,010.12	937.75	64.72
		%	79.10	78.29	56.78	34.02
2	Livestock	*Ton/year*	1,234.48	2,330.79	670.92	113.49
		%	17.55	18.23	40.62	59.65
3	Domestic	*Tons/year*	235.28	444.41	42.97	12.05
		%	3.35	3.48	2.60	6.33

The calculation results of the four environmental parameters from **Table 6** indicate that the pollutant load from land use activities accounted for the largest proportion, ranging from 34.02% to 79.1%, followed by livestock raising activities, ranging from 17.55% to 59.65%. Domestic pollution mainly came from residential households within the district and did not include other service activities (restaurants, hotels) due to their negligible contributions, ranging from 2.6% to 6.33% of the pollutant load. Therefore, if runoff from land use and livestock raising activities is not properly managed, it will exert significant pressure on the surface water quality locally and directly affect the Ma River.

Environmental monitoring results from the first round in 2022 in Song Ma District also showed that at four out of the four monitoring locations, the BOD values fluctuated between 6.7 mg L^{-1} and 8.0 mg L^{-1}, exceeding the National Technical Regulation on Surface Water Quality Standards (6 mg L^{-1}) by 1.1 to 1.3 times **(Figure 3)**.

Spatial distribution of pollution loads in the sub-basins

Song Ma District is divided into 10 sub-basins, labeled from SM1 to SM10 (**Figure 4**). Each sub-basin serves as a reservoir for pollutants from sources within its area before they enter the main river system, the Ma River.

The spatial distribution of the four parameters of pollutant loads in each sub-basin is presented in **Figure 5**. In these maps, darker colors indicate higher pollutant loads, while lighter colors correspond to lower pollutant loads in the sub-basins.

To illustrate the spatial differences in the distribution of various pollution sources, hierarchical cluster analysis (HCA) was employed with the input variables being BOD, COD, total nitrogen, and total phosphorus from land use, livestock, and domestic sources. The results in **Figure 6a** show that the 10 sub-basins could be divided into two statistically significant clusters with Euclidean distance values greater than 5. Cluster 1 included sub-basins SM1, SM5, and SM8, while Cluster 2 was comprised of the remaining sub-basins (SM2, SM3, SM4, SM6, SM7, SM9, and SM10) with similar characteristics in terms of pollutant impacts (**Table 7**, **Figure 6b**).

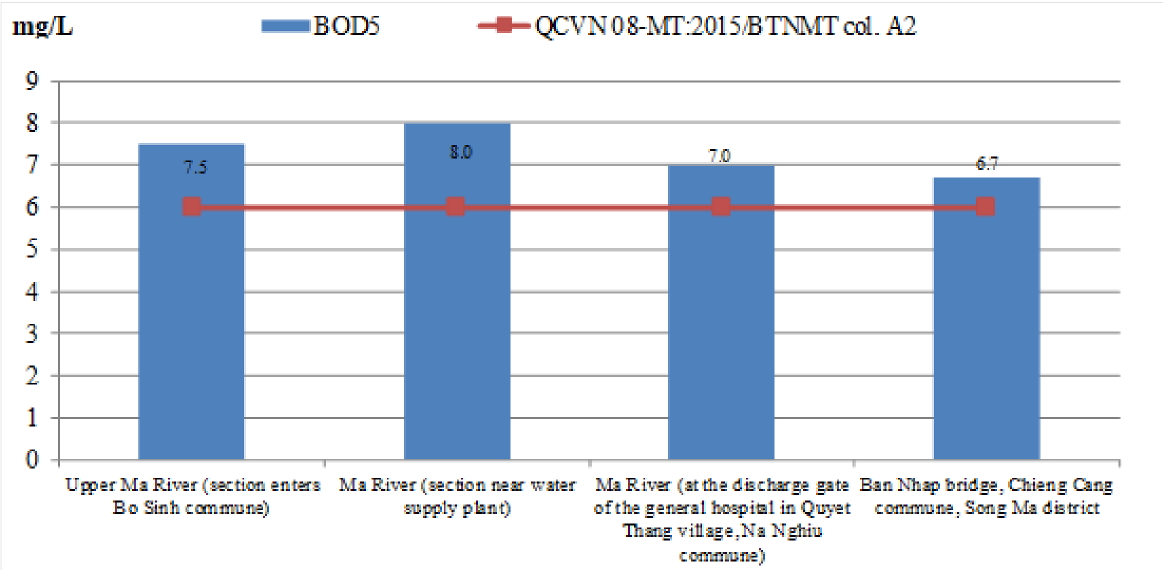

Figure 3. BOD5 in surface water environment of Song Ma district, first round 2022

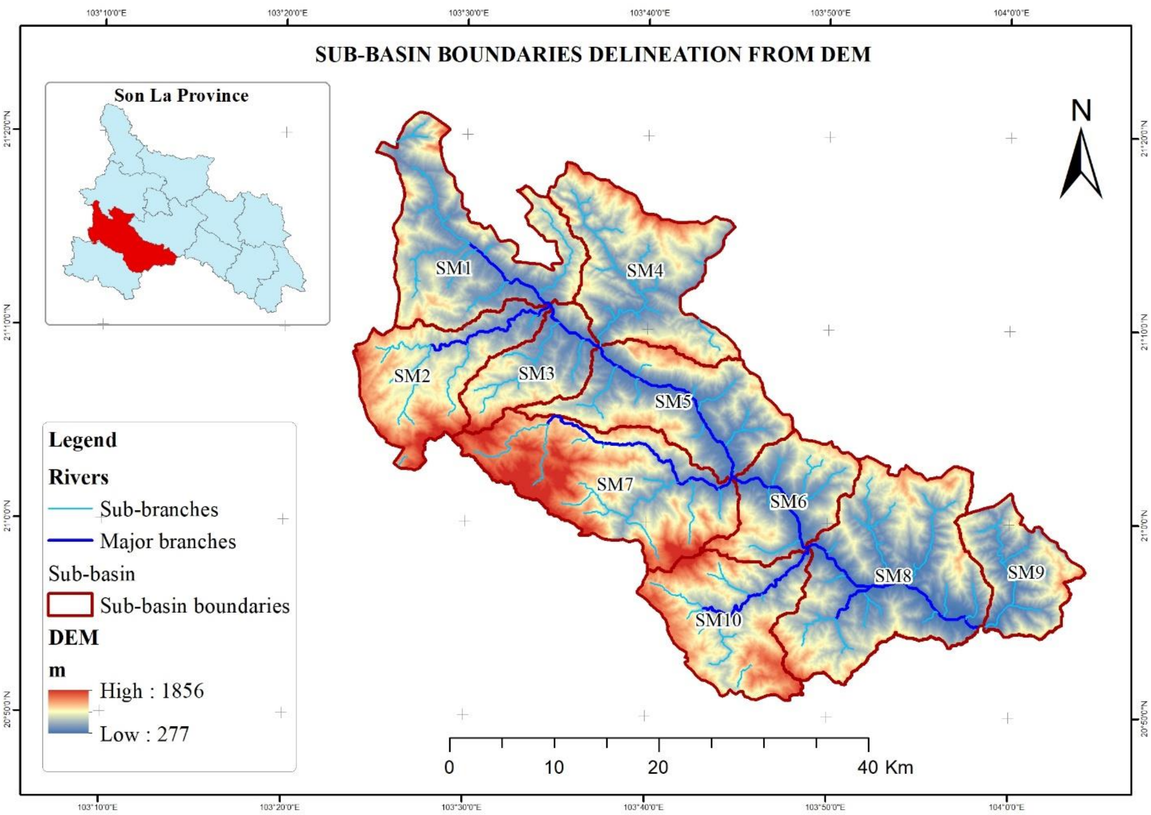

Figure 4. Sub-basin boundaries in Song Ma district

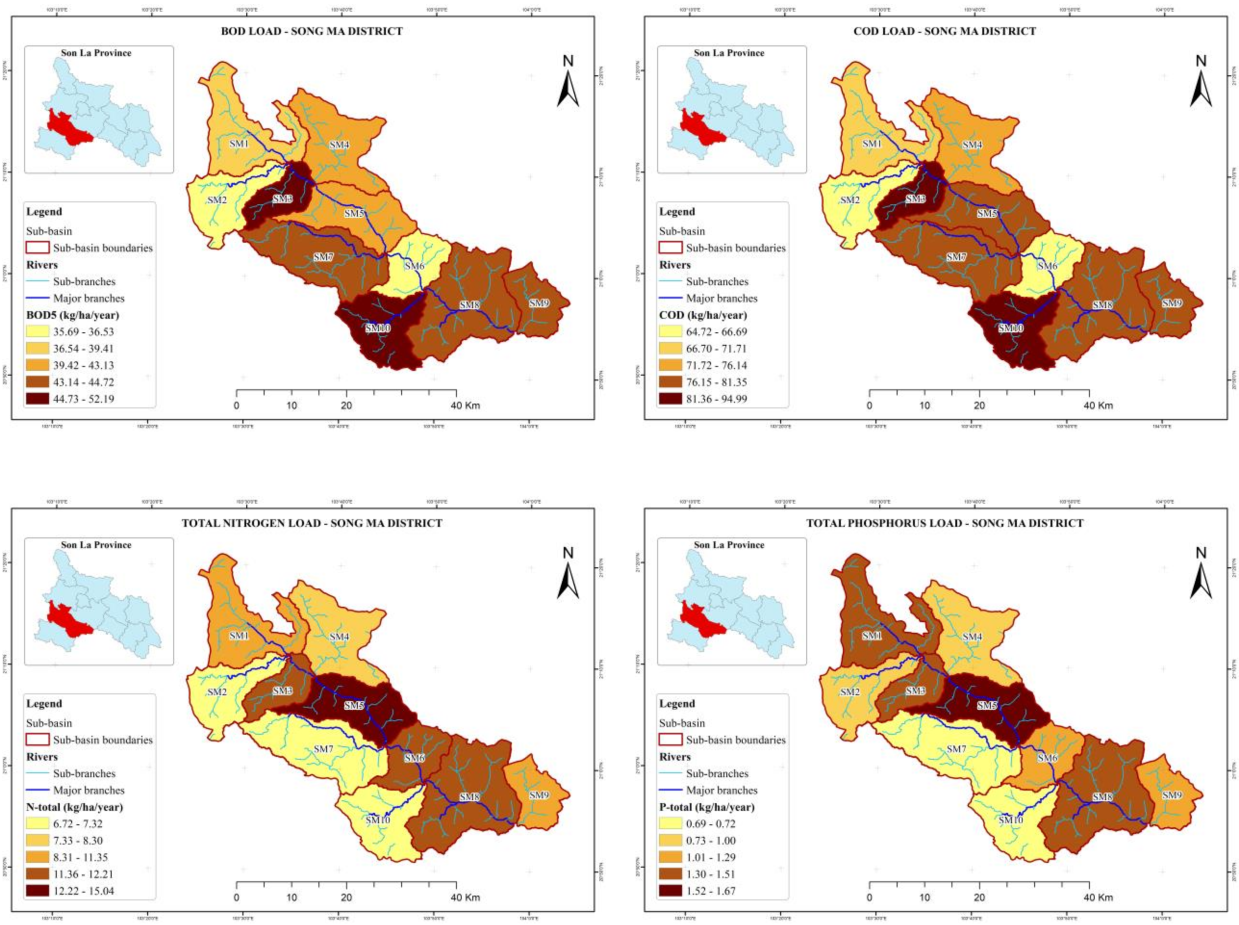

Figure 5. Distribution of pollutant loads across the sub-basins in Song Ma district

Table 7. Characteristics of pollution sources and pollutant loads in the sub-basins

Sub-basin codes	Area (ha)	Land use (kg/ha/year)				Livestock (kg/ha/year)				Domestic (kg/ha/year)			
		BOD	COD	Total N	Total P	BOD	COD	Total N	Total P	BOD	COD	Total N	Total P
SM1	19,679	27.53	49.53	6.13	0.43	10.36	19.31	4.95	0.89	1.52	2.87	0.28	0.08
SM2	14,069	27.21	48.96	3.95	0.27	7.41	13.74	3.17	0.61	1.07	2.02	0.20	0.05
SM3	8,427	39.86	71.71	6.50	0.44	10.98	20.73	5.47	1.00	1.35	2.55	0.25	0.07
SM4	18,343	34.19	61.51	4.67	0.32	6.56	12.45	3.42	0.62	1.15	2.17	0.21	0.06
SM5	17,028	31.09	55.94	7.55	0.52	9.04	17.73	6.94	0.99	2.99	5.65	0.55	0.15
SM6	10,792	27.55	49.56	6.83	0.48	7.00	13.40	4.70	0.69	1.98	3.74	0.36	0.10
SM7	22,622	39.91	71.82	4.67	0.32	4.11	7.55	1.92	0.33	0.70	1.32	0.13	0.04
SM8	27,507	34.02	61.20	6.69	0.46	9.02	17.07	4.86	0.84	1.63	3.08	0.30	0.08
SM9	9,336	33.89	60.98	6.09	0.43	8.96	16.72	4.49	0.78	1.53	2.89	0.28	0.08
SM10	15,224	45.59	82.04	4.75	0.33	3.89	7.33	2.10	0.36	0.69	1.30	0.13	0.04
Total	163,028	340.84	613.26	57.83	3.99	77.33	146.02	42.02	7.11	14.61	27.60	2.67	0.75
Total (SM1, 5, 8)	64,214	92.64	166.67	20.36	1.41	28.43	54.10	16.76	2.72	6.15	11.61	1.12	0.31
Percentage	39.39	27.18	27.18	35.21	35.26	36.76	37.05	39.88	38.24	42.05	42.05	42.05	42.07
Total (SM2, 3, 4, 6, 7, 9, 10)	98,813	248.20	446.58	37.47	2.58	48.91	91.92	25.27	4.39	8.47	16.00	1.55	0.43
Percentage	60.61	72.82	72.82	64.79	64.74	63.24	62.95	60.12	61.76	57.95	57.95	57.95	57.93

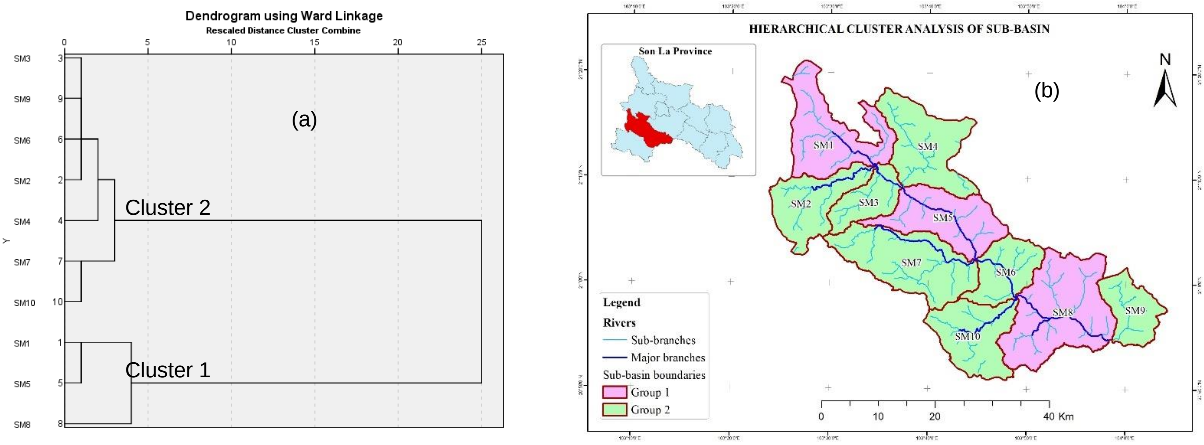

Figure 6. (a) Dendrogram using Ward Linkage; (b) Hierarchical cluster analysis of the sub-basins

Table 8. Test of differences in indicators between the sub-basin clusters

Pollution sources	Indicator (Standardized Z-score)	Wilks' Lambda	F	df1	df2	Sig.
Land use	BOD	.890	.993	1	8	.348
	COD	.890	.992	1	8	.348
	Total N	.291	19.460	1	8	.002*
	Total P	.286	19.981	1	8	.002*
Livestock	BOD	.204	31.207	1	8	.001*
	COD	.186	34.983	1	8	.000*
	Total N	.102	70.409	1	8	.000*
	Total P	.140	48.947	1	8	.000*
Domestic	BOD	.192	33.664	1	8	.000*
	COD	.192	33.665	1	8	.000*
	Total N	.192	33.666	1	8	.000*
	Total P	.192	33.598	1	8	.000*

The results of discriminant analysis (DA) in **Table 8** demonstrate that the variables with high F-values and low Wilks' Lambda values had significant differences between the two clusters of sub-basins. Except for BOD and COD from agricultural land use, all the other indicators showed significant differences (*Sig. < 0.05) between the two clusters of sub-basins.

Identification of significant pollution sources and their implications

To gain a deeper understanding of the pressure exerted by each pollution source on individual sub-basin clusters, the principal component analysis (PCA) method was employed. The results of the PCA analysis are presented in **Table 9**.

The PCA results in **Table 9** show that PC1 had an Eigenvalue of 9.603, explaining 80.027% of the variance. PC2 had an Eigenvalue of 1.804, explaining 15.037% of the variance. Together, these two PCs explained a total of 95.064% of the variance, indicating their significant role in describing the data. The inverse component matrix in **Table 10** reveals that the PC1, BOD, COD, total N, and total P parameters from domestic and livestock sources were the representative variables contributing primarily to the characteristics of PC1. For PC2, the BOD and COD parameters from land use activities were the representative variables reflecting the characteristics of PC2.

Table 9. Total variance of principal component analysis (PCA)

Component	Initial Eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	9.603	80.027	80.027	9.603	80.027	80.027	8.275	68.958	68.958
2	1.804	15.037	95.064	1.804	15.037	95.064	3.133	26.106	95.064
3	.537	4.472	99.536						
4	.049	.405	99.941						
5	.007	.054	99.995						
6	.000	.004	99.999						
7	.000	.001	100.000						

Extraction Method: Principal Component Analysis.

Table 10. Inverse component matrix

Pollution sources	Indicator (Standardized Z-score)	PC1	PC2
Land use	BOD	.162	.980*
	COD	.162	.980*
	Total N	.782	.611
	Total P	.783	.606
Livestock	BOD	.851*	.357
	COD	.869*	.345
	Total N	.970*	.233
	Total P	.925*	.294
Domestic	BOD	.965*	.145
	COD	.965*	.145
	Total N	.965*	.145
	Total P	.965*	.145

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
* Significant factors (varimax factor coefficients >0.85)

Figure 7 displays the score plot for the two principal components related to the two HCA-identified pollutant clusters. This factor scores plot revealed an association between pollutant sources and clusters, allowing for further distinction as follows:

Cluster 1 (red triangles), which consisted of sub-basins SM1, SM5, and SM8, is in lower terrain and evenly distributed on both sides of the Ma River. These sub-basins consistently receive significant pollutant loads from the territories of Bo Sinh, Pu Bau, and Chieng En in sub-basin SM1, Song Ma town, Chieng So commune, and Na Nghiu in sub-basin SM5, and Chieng Cang, Muong Hung, and part of Chieng Khuong commune in sub-basin SM8. As indicated by the above analysis, Cluster 1 was most affected by pollutants from livestock farming and domestic activities. Specifically, the number of livestock was 91,004 heads, accounting for 52% of the district's total livestock, and the number of poultry was 597,531 heads, accounting for 54% of the district's poultry. The total population of sub-basins SM1, SM5, and SM8 was 85,681 people, accounting for 53.2% of the district's population. However, the total area of these three sub-basins is only 64,213 hectares, equivalent to 39% of the natural area of Song Ma district. The 2023 environmental monitoring report for Song Ma district showed that four samples taken from surface water in Na Nghiu commune in sub-basin SM5 indicated signs of microbial contamination in the surface water. At all four monitoring locations, *E. coli* levels ranged from 40-90 mg L^{-1}, exceeding the limit by 2 to 4.5 times according to QCVN 08:2023/BTNMT - Table 1. The coliform parameter in ground water in Na Nghiu commune and Song Ma town in 2022 also exceeded the limit by 36.6 and 31.3 times, respectively, according to QCVN 09-MT:2015/BTNMT (UBND, 2023b). These findings imply that these sub-basins need to focus on controlling pollution sources from livestock raising and domestic use activities. Additionally, the total N and total P from land use activities also require attention due to their significant contributions to PC1, with varimax factor coefficients of 0.782 and 0.783, respectively.

Cluster 2 (black squares) included the remaining sub-basins distributed in higher terrain, with most of the area designated as forestry land. The total forestry land area in the Cluster 2 sub-basins is 44,386 hectares, accounting for 68% of the district's forestry land area. With steep slopes, these sub-basins will be vulnerable from soil erosion due to rainfall if adequate vegetation cover is not maintained. Furthermore, most of the hillside land in Song Ma district is used for cultivating corn and fruit trees (mainly longan and citrus). As a result, the amount of fertilizer and pesticides used annually is substantial. The impacts of nitrogen and phosphorus from land use activities on water source eutrophication were therefore considerable with varimax factor coefficients of 0.611 and 0.606, respectively. The 2023 environmental monitoring report for Song Ma district showed that the P-total parameter in agricultural land in Chieng So and Chieng Khuong communes exceeds the limit by 3.33 times according to TCVN 7374: 2004 (0.03 – 0.06 for degraded gray soil). Additionally, the DDTs parameter at both monitoring locations showed values of 0.0276 mg/kg and 0.037 mg/kg, respectively, exceeding the QCVN 15:2008/BTNMT limit (0.01 mg/kg dry soil) by 2.8 times and 3.7 times, respectively (UBND, 2023b). DDTs are highly persistent and toxic, and they degrade very slowly in the natural environment. These findings suggest that agrochemical usage should be cautious and carefully managed to ensure water quality is safe for humans and other organisms. With agricultural land covering 16,997 hectares, representing 50% of the district's agricultural land area, erosion control measures in hillside farming need to be implemented, such as planting leguminous strips, pasture strips, contour farming, agroforestry, etc.

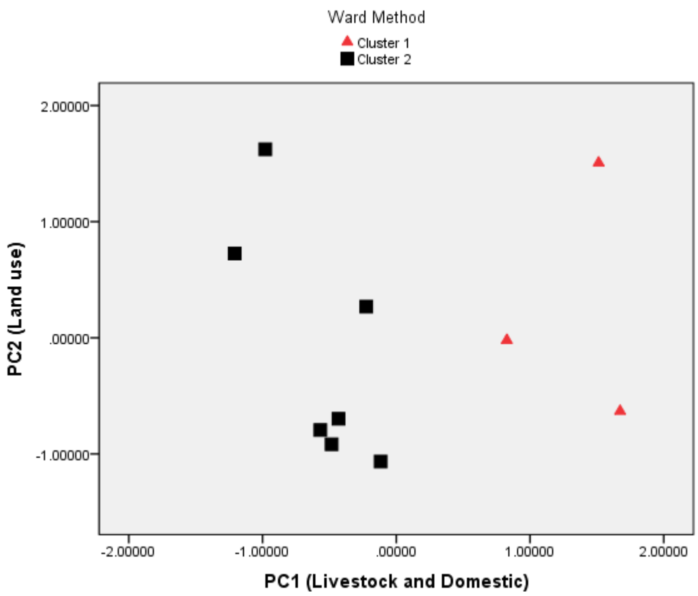

Figure 7. Scatter plot of principal component scores for the two clusters of sub-basins based on pollutant sources

Conclusions

Song Ma district was spatially divided into ten sub-basins, which were then grouped into two clusters of sub-basins with different characteristics of pollution sources. The findings highlighted that pollution from land use, livestock raising, and domestic activities were the primary contributors to the degradation of surface water quality, particularly in sub-basins SM1, SM5, and SM8, which had high livestock numbers and population densities. On the other hand, the remaining sub-basins, characterized by steep terrain and dominant agricultural activities, were affected by soil erosion and nutrient runoff, which further degraded water quality. Based on these findings, the study recommends the following measures: (1) develop a plan to control pollution from livestock farming and domestic activities in communes within sub-basins SM1, SM5, and SM8 through the construction of centralized wastewater treatment systems and the implementation of eco-friendly livestock farming models, (2) implement sustainable farming practices on sloping lands and enhance vegetation cover in the remaining sub-basins to reduce erosion and nutrient runoff into water sources, and (3) strengthen water quality monitoring and surveillance in sub-basins with high pollution risks to make informed management decisions. These solutions not only protect water resources but also contribute to the sustainable socio-economic development of the region, supporting the achievement of SDG6 of the 2030 Agenda for Sustainable Development on clean water and sanitation. Future studies should focus on the long-term effectiveness of proposed pollution control measures, assess the potential impact of agrochemical use on water quality, and explore advanced technologies for pollution monitoring and management to ensure sustainable water resource protection in the region. Finally, due to the lack of geographic coordinates for domestic and livestock pollution sources, our study used pollutant load calculations only for non-point sources based on VEA (2019) guidelines. This is important for readers to consider when interpreting the findings and for future studies to avoid potential misapplication of the VEA (2019) guidelines.

Acknowledgements

The authors would like to express our sincere gratitude to IFS, Sweden for generously sponsoring this research. The authors also extend thanks to the People's Committee of Song Ma district, the Department of Agriculture and Rural Development, the Department of Natural Resources and Environment, and all individuals involved for their valuable support and assistance to the research team.

References

Bach H., Clausen T., Trang D. T., Emerton L., Facon T., Hofer T., Lazarus K., Muziol C., Noble A. & Schill P. (2011). From local watershed management to integrated river basin management at national and transboundary levels. Mekong River Commission, Lao PDR.

Bui H. H., Ha N. H., Nguyen T. N. D., Nguyen A. T., Pham T. T. H., Kandasamy J. & Nguyen T. V. (2019). Integration of SWAT and QUAL2K for water quality modeling in a data scarce basin of Cau River basin in Vietnam. Ecohydrology & Hydrobiology. 19(2): 210-223.

Dourojeanni A. (2001). Water management at the river basin level: challenges in Latin America. ECLAC. 72: 1-72.

DSO (2023). Statistical Yearbook of Song Ma district 2023. District of Statistical Office (in Vietnamese).

Fan C., Chen K. H. & Huang Y. Z. (2021). Model-based carrying capacity investigation and its application to total maximum daily load (TMDL) establishment for river water quality management: A case study in Taiwan. Journal of cleaner production. 291: 125251.

Government (2024). Decision No 20/QĐ-TTG on approving the Master Plan for the Ma River Basin for the period 2021-2030, with a vision to 2050 (in Vietnamese).

Herrera V. (2019). Reconciling global aspirations and local realities: Challenges facing the Sustainable Development Goals for water and sanitation. World Development. 118: 106-117.

Huong H. L. & Son N. T. (2020). Response of streamflow and soil erosion to climate change and human activities in Nam Rom River Basin, Northwest of Vietnam. Environ. Nat. Resour. J. 18(4): 411-423.Howard G. (2021). The future of water and sanitation: global challenges and the need for greater ambition. AQUA - Water Infrastructure, Ecosystems and Society. 70(4): 438-448.

Kemper K., Blomquist W. & Dinar A. (2007). River basin management at the lowest appropriate level: when and why does it (not) work in practice? In: Integrated river basin management through decentralization. Springer: 3-15.

Me W., Hamilton D. P., McBride C. G., Abell J. M. & Hicks B. J. (2018). Modelling hydrology and water quality in a mixed land use catchment and eutrophic lake: Effects of nutrient load reductions and climate change. Environmental Modelling & Software. 109: 114-133.

Milan B. F. (2017). Clean water and sanitation for all: interactions with other sustainable development goals. Sustainable Water Resources Management. 3(4): 479-489.

Nguyen T. V. H. (2024). Integrated River Basin Planning for the Ma River Period 2021–2030, with a Vision to 2050. Institute of Strategy and Policy on Natural Resources and Environment (ISPONRE) (in Vietnamese).

Ngo T. A., Ngo P. L., Vo H. C., Nong H. D. & Nguyen T.H.G. (2020). Environmental pressure from pig farming to surface water quality management in Yen Dung District Bac Giang Province. VNU Journal of Science: Earth and Environmental Sciences. 36(1): 46-56.

Ngo T. A., See L., Leisz S., Tran N., Dinh T. & Nguyen T. (2024). Spatial assessment of pollutant loads for surface water quality management: a case study in Lai Chau city, Vietnam. IOP Conference Series: Earth and Environmental Science. IOP Publishing. 012012.

Son N. T. & Loc, N. D. (2024). Establishing Optimal Machine Learning Models for Monitoring Water Quality in Vietnam's Upper Ma River. Applied Environmental Research. 46(4). DOI: 10.35762/AER.2024053.

Tri D. Q., Linh N. T. M., Thai T. H. & Kandasamy J. (2019). Application of 1D–2D coupled modeling in water quality assessment: A case study in Ca Mau Peninsula, Vietnam. Physics and Chemistry of the Earth, Parts A/B/C. 113: 83-99.

UBND (2023a). Report No 178/BC-UBND on Environmental Status Report of Song Ma District in 2023 (in Vietnamese).

UBND (2023b). Report on the results of environmental mornitoring in Song Ma district, 2023 (in Vietnamese).

VEA (2019). Guidelines for Calculating the Carrying Capacity of Rivers, JICA Project on Strengthening Water Basin Environmental Management Capacity. Retrieved from https://openjicareport.jica.go.jp/pdf/12353678_04.pdf on October 2, 2024 (in Vietnamese)

Wang L. & Liu H. (2006). An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modelling. International Journal of Geographical Information Science. 20(2): 193-213.

Xiang C., Wang Y. & Liu H. (2017). A scientometrics review on nonpoint source pollution research. Ecological engineering. 99: 400-408.