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MINISTRY OF EDUCATION AND TRAINING

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SURFACE WATER QUALITY MANAGEMENT IN THE CONTEXT OF SOCIO-ECONOMIC DEVELOPMENT IN THE HIGHLANDS OF VIETNAM – A CASE STUDY IN BA RIVER BASIN OF GIA LAI PROVINCE

By

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Under the supervision of

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A dissertation submitted to Doctoral Training Program in Sustainable Urban Development, Faculty of Engineering, Vietnamese-German University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Ho Chi Minh City, 10/2025

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Nguyen Tuan Anh

ABSTRACT

Population growth and urbanization in the context of socio-economic development in river basins may lead to deterioration of surface water. The Ba River Basin is facing water pollution due to wastewater from agricultural and urban areas. Therefore, the study focuses on evaluating spatial and temporal variations in river water quality based on physicochemical characteristics and pesticide parameters in 2022–2023. Then, this study also evaluates the carrying capacity of pollution load in river water, which reveals how much pollutants river water can receive. Research on simple water treatment processes and optimization of operating parameters provides the model of river water for decentralized domestic water treatment systems in small-scale urban areas. People's willingness to participate in environmental protection programs in the Ba River Basin is also modelled to identify important factors that help enhance community participation in solutions to protect the river water environment.

The results indicated that the water quality has been deteriorating due to anthropogenic activities such as intensive agricultural activities, domestic wastewater, and industrial activities. The concentrations of the parameters were higher in the rainy season than in the dry season due to diffuse sources in agricultural and urban areas. Notably, low concentrations of the pesticides chlorpyrifos (ethyl) (0.0074 – 0.0076 µg/L) and deltamethrin (0.004 – 0.0218 µg/L) were detected during the rainy season at several locations in Ayun commune, Cau Phu Thien, and An Khe bus station. The hierarchical cluster analysis and WQI results classified the water quality in the areas of Ben Mong Bridge (Ayun Pa town), An Khe Bridge, and An Khê bus station as having a medium-to-high pollution level. In addition, the results from the carrying capacity calculation revealed that Ba River cannot receive more pollution load, except the total suspended solid load.

In addition, studying the laboratory water treatment system and optimizing the coagulation-flocculation process showed that it is suitable for treating Ba River water with effective removal of DOC and turbidity in river water. Response surface methodology (RSM) was applied to design the experiments, analyze the results, and optimize the variables. The quadratic regression models of PACl, PFS and aluminium

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are statistically significant at the 95% confidence level ($p < 0.05$), and the p values of Lack of Fit are not significant ($p > 0.05$). The coagulants PACl and PFS were more effective than alum in both DOC and turbidity removal. In addition, willingness to participate (WP) in community-based water management depends on many factors, such as community consciousness, awareness, beliefs, and demographic characteristics. The results showed that the regression model explained 67.9% of the variation in WP levels ($R2 = 0.679$, $p < 0.001$). Sense of community (SC) variables and perceptions of current water resource management (PW) are the most significant factors affecting community willingness to participate. Training campaigns and awareness-raising campaigns need to be integrated into regular community activities to increase the level of community willingness to participate in water resource protection.

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LIST OF ABBREVIATIONS

BOD_5	Biochemical oxygen demand
CCD	Central composite design
COD	Chemical oxygen demand
DO	Dissolved oxygen
HCA	Hierarchical cluster analysis
NH_4-N	Ammonium-nitrogen
NO_2-N	Nitrite-nitrogen
NO_3-N	Nitrate-nitrogen
PO_4-P	Phosphate
QCVN	Vietnam National Technical Regulation
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
PCA	Principle component analysis
OCPs	Organochlorine pesticides
PACl	Polyaluminum chloride
PFS	Poly ferric sulphate
Alum	Aluminium sulfate
TC	Total carbon
TOC	Total organic carbon
TN	Total nitrogen
TP	Total phosphorus
Tur	Turbidity
TSS	Total suspended solid
Mn	Mangan
Fe	Ferric
Cu	Copper
AS	Arsenic
Cr^{6+}	Chromium (VI)

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CHAPTER 1: INTRODUCTION

1.1. Rationale

Protecting water sources is a top priority because water plays a vital role in human and animal life. However, rapid socio-economic development in developing countries can significantly cause water pollution problems [1]. Waste from both natural and human activities can pollute water sources. Natural sources such as weathering or soil erosion are common [2], while human activities are often related to different activities in land use types. The relationship between land use types and water quality has been evaluated in previous studies [3], [4], [5]. Specifically, in urban areas, the primary sources of pollution are industrial and domestic wastewater [3], [4], and agricultural areas can be the main source of water pollution in rural areas [5]. Due to the simultaneous impact of activities on urban land, agricultural land, and other land uses on water quality parameters, determining their relationships is complex and uncertain [3]. Wastewater discharges from urban activities and intensive agricultural practices are significant sources of organic pollution to surface waters [6]. Agricultural activities may be associated with concentrations of nutrients, pesticide residues, and other pollutants that enter river waters through surface runoff or irrigation, leading to the degradation of river water quality [7], [8]. Heavy metals can be released into aquatic environments due to human activities, such as industrial, agricultural, and domestic and commercial wastewater [9], [10]. In addition, seasonal variations in rainfall, surface runoff, and groundwater flow can significantly impact river flows, leading to seasonal variations in pollutant concentrations in river waters [11]. Under certain climatic conditions in some previous studies, it was found that the temperature in the dry season is usually higher than in the rainy season, and the water flow may be low, resulting in less disturbance and dilution [11], [12]. Meanwhile, the dissolved oxygen concentration and turbidity are usually higher in the rainy season due to high dilution [11]. In addition, point sources have a significant impact on water quality in the dry season, while dispersed sources may be the primary source of river water pollution in the rainy season due to runoff [13].

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Vietnam has a dense river system with a total annual surface water flow of 830-840 billion m^3. However, about 63% of the total water source flows into Vietnam from neighboring countries, which is an unsustainable factor in ensuring water resources in the future [14]. Therefore, Vietnam faces the risk of water scarcity and water crisis due to the lack of fair sharing and rational use of water resources in trans-boundary rivers by upstream countries, posing a threat to sustainable socioeconomic development and food security. At the same time, the demand for water for production and human lives is increasing due to the rapid socio-economic development process. The pressure of population growth and the rapid urbanization process in recent years have caused many negative impacts on the quality and reserves of water resources in the river basins. In 2018, according to the Vietnam National Environmental Status Report 2018 with the topic "Water Environment of River Basins", the WQI values were calculated for seven major river basins based on monitoring data from 2014-2018, including Mekong, Dong Nai, Vu Gia - Thu Bon, Ma, Hong - Thai, Nhue - Day, and Cau River Basin. The report showed that the percentage of average water quality index accounted for the largest proportion in these river basins, from about 50% - 63% (WQI was calculated according to Decision No. 879/QD-TCMT dated July 1st, 2011 of the Director General of the General Department of Environment on the promulgation of the Handbook for calculating water quality index). The trend of surface water quality in these river basins tends to be increasingly polluted [14].

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According to the Gia Lai environmental status report for 2015-2020, the water quality in Ba River, which is located in Vietnam's Central Highlands, has deteriorated because of waste sources from domestic, industrial, and agricultural activities along the riverbank [15]. Waste from agricultural activities contributes to surface water pollution. The development of large livestock farms in districts and towns such as An Khe, Mang Yang, Phu Thien and Ia Pa in recent years can also affect local environmental issues, especially surface or groundwater water quality because the waste and wastewater from those farms have not been appropriately treated. In addition, domestic wastewater also contributes to deteriorating water quality in some residential areas [15].

In general, the current status of the Ba River basin is that some areas are showing signs of pollution. Therefore, it is necessary to evaluate the spatial and temporal variation of water quality by employing a combination of the WQI approach and statistical analysis, assessing pollution load, and testing appropriate surface water treatment technology. However, few comprehensive studies on surface water quality have been conducted in the Ba River basin, especially in the upstream and midstream areas flowing through Gia Lai province. At the same time, lack of domestic water supply is an urgent issue in residential areas living along the Ba River. Therefore, simple domestic water treatment technology suitable for the Central Highlands needs to be tested to provide technological options in the near future. From the results, the proposed solutions help effectively manage water quality and move towards the sustainable use of surface water in the Ba River area, particularly the Central Highlands, in general.

1.2. Research question and objectives

Research question: What is a holistic approach to managing river water quality in flowing rivers in the context of soci-economic development in small and medium-scale urban areas?

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Research aim: To develop and propose a holistic, integrated strategy for sustainable river water quality management in the Ba River Basin, Gia Lai Province, Vietnam, that balances socio-economic development pressures in small and medium-scale urban areas with effective pollution control, while significantly contributing to the goal of ensuring sufficient and safe domestic water supply.

Objective 1: To assess the current status of surface water quality and identify which factors could affect water quality in Ba River Basin pass through Gia Lai Province – Vietnam.

Objective 2: To assess the pollution load on Ba River

Objective 3: To test simple water treatment processes for treating Ba river water

Objective 4: To propose an approach to managing river water flowing to small and medium-scale urban areas towards sustainable water management.

1.3. Objects and scope of the study

Surface water quality and pollution sources in the Ba River basin in Gia Lai province.

The study will be carried out in the Ba River basin in Gia Lai province, and pollution sources may impact water quality on the main Ba River stream. The duration of the project is from January 2022 to June 2024.

The study focuses on assessing physico-chemical and pesticide parameters in river water. Moreover, the domestic water treatment system only considers DOC and Turbidity removal through the optimization of operational conditions (pH levels and Coagulant Dosages).

1.4. Research contents

Content 1: To evaluate the spatio-temporal variations of surface water quality based on physical-chemical parameters and pesticide analysis.

Content 2: To calculate water quality index (WQI) in Ba river Basin.

Content 3: To identify which factors could affect water quality in Ba river Basin

Content 4: To calculate the current carrying capacity of pollution load on Ba river.

Content 5: To research and optimize the operational conditions in coagulation – flocculation process for river water treatment

Content 6: To propose an approach to managing river water flowing to small and medium-scale urban areas towards sustainable water supply and management.

1.5. The novelty and contributions of the study

The study presents pioneering contributions to the field of surface water quality management in the Ba River Basin, Gia Lai Province, Vietnam.

- Conducting the first comprehensive study on pesticide residues in the Ba River Basin, providing new insights into agriculture chemical pollution sources.

- Applying a new application of Principal Component Analysis (PCA) to determine weights for the Water Quality Index (WQI), enhancing the accuracy of water quality assessment.
- Evaluating the effectiveness of a new coagulant, Polyferric Sulfate (PFS), for treating river water to ensure safe domestic water supply, marking an innovative step in water treatment technology.
- Developing a simple and effective water treatment method tailored for small residential areas and villages, addressing practical needs in underserved regions.
- Investigating the key factors influencing local communities' willingness to participate in river water quality protection, offering a socio-economic perspective on sustainable management.

1.6. Scientific and socio-economic significance

1.6.1. Scientific significance

Assessing the spatial and temporal variation of water quality, sources and pathways of pollution, the pollutant load in the highland river basin, and the treatment efficiency. The contents studied are highly scientific and will be reference materials for subsequent studies. Also, these results help to enrich the knowledge base on integrated river basin management.

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1.6.2. Socio-economic significance

Water resource management is an urgent issue in the context of increasingly scarce water resources. The study assesses the overall quality of water and surface water resources at the river basin scale. The results are a basis for proposing solutions toward sustainable water water quality management, which significantly contribute to protecting water resources to supply safety water for human activities, especially in local socio-economic development activities towards sustainable development.

CHAPTER 2: LITERATURE REVIEW

2.1. Research literature

Water pollution has become a significant issue in various regions worldwide [1]. As surface water is one of the primary sources of water for communities, therefore preserving its quality is critical for home use. Both natural and human activities can influence the condition of river water supplies [16]. Land use practices can influence river water quality by altering its physicochemical characteristics, either positively or negatively. Activities like deforestation, improper handling of livestock waste, and farming can introduce the influx of sediments, nutrients, organic materials, heavy metals, and pathogens into waterways via surface runoff or irrigation systems [5], [17]. Population expansion and rapid urbanization have put more strain on ecosystems and aquatic environments. To support the growing population, industrial activities have expanded, frequently causing the discharge of sewage and pollutants into the ecosystem [18], [19]. Those contaminants can degrade the quality of water in rivers. Additionally, climatic factors such as temperature and rainfall differ across regions and seasons, leading to fluctuations in river water quality over time and across different areas [11], [12]. Moreover, extreme weather events like droughts and floods influence river systems by altering stream flow and reducing their ability to dilute pollutants, as well as the amount of substances that enter rivers [20], [21].

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2.1.1 Primary factors influencing the quality of river water in rural and urban regions

In general, water resources are affected by both natural and anthropogenic factors. Primary factors affecting water quality in river basins include land use types, urbanization, weather patterns, basin topography, climate change, and extreme weather events [7], [12], [22], [23], [24]. Figure 2.1 illustrates the main factors that can affect water quality.

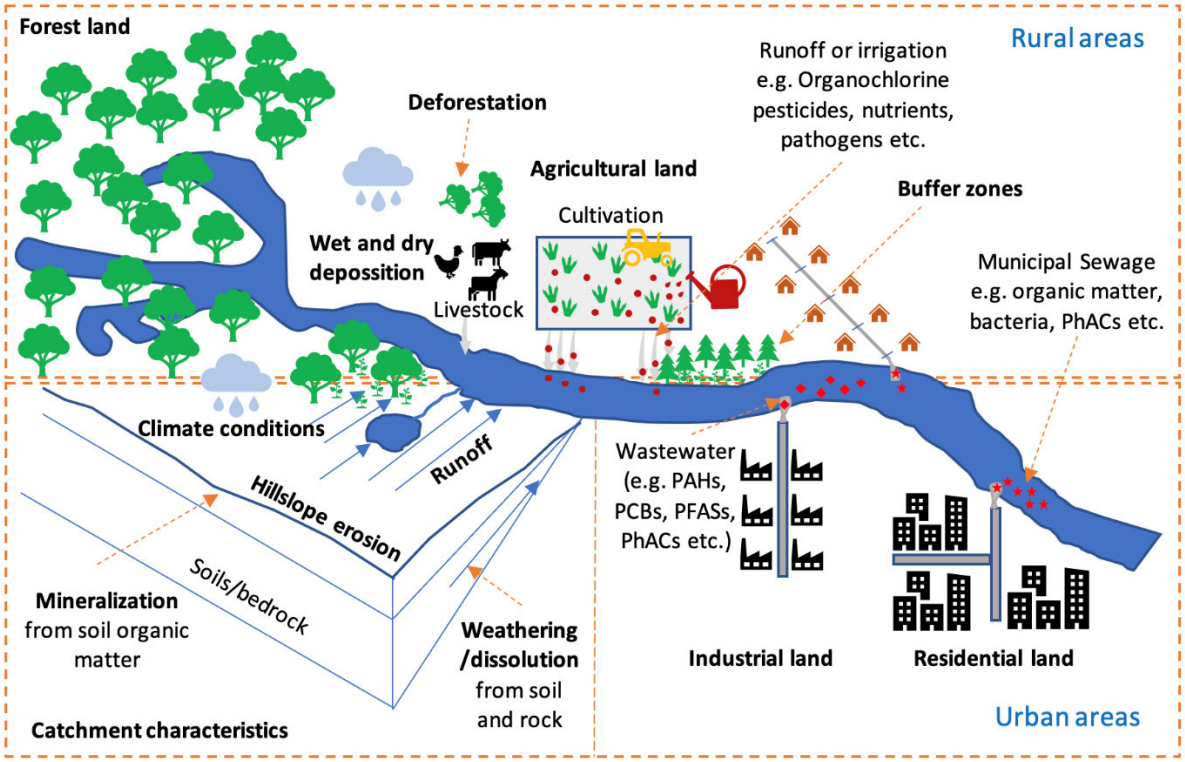

Figure 2.1. Primary factors influencing the quality of river water [25].

❖ *Water quality and land use*

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Recent studies have shown that land use plays a significant role in influencing changes in water quality [7], [8], [17], [26], [27], [28]. Based on an analysis examining the relationship between various land use types and water quality index, residential land was positively correlated with the nutrient parameters such as PO_4^-P and NO_3^-N, suspended particles, and organic contaminants such as COD and BOD_5 in the Medlock River, UK [26]. This aligns with the results observed in the Mitidja Watershed region of Algeria. A regression analysis indicated that settlement areas could serve as strong predictors of water quality parameters such as COD, BOD_5, PO_4^-P, NH_4-N, and SS, all of which exhibited positive correlations with residential land. In the Hooghly River (India), the findings showed that the increased concentration of PCBs was caused by port and industrial activities along the river [27]. The levels of PAHs at the industrial zone sampling site were markedly higher compared to those at the other two locations [28].

Table 2.1. The relationship between land use/land cover and water quality.

Water quality parameters	Wood/ Forest areas	Vegetation/ Urban green areas	settlement areas/ urban land	Commercial/ Industrial areas	Agriculture areas	References
DO	+	+		-		[26]
		+	-		-	[3]
	+				+	[29]
Conductivity	-	-	+	+		[26]
					+	[29]
	-		+			[30]
NO_3^-N		-	+			[26]
		-	+		+	[3]
					+	[31]
	-		+			[30]
PO_4^-P		-	+			[26]
		-	+		+	[3]
TSS			+			[26]
		-	+		+	[3]
	-		+			[30]
COD		-	+		+	[3]
			+	+		[32]
			+	+		[19]
BOD_5		-	+		+	[3]
			+	+		[19]
PAHs				+		[28] [33]
PCBs				+		[27]
OCPs					+	
OCPs		-			+	[34]
Pesticides*					+	[35]

(-): Negative correlation; (+): Positive correlation.

* Pyrimethanil, Butachlor, Fenpropimorph, Cadusafos, Pendimethalin, Malathion.

In many river basins, previous studies have identified agricultural activities as a major contributor to water pollution [3], [7], [8], [11], [12]. The deterioration of water quality can be linked to agricultural activities due to the large quantities of nutrients, pesticide residues, and other organic contaminants that are carried into rivers via irrigation or surface runoff. According to the findings of the Spearman Rank correlation

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analysis, nitrate and phosphorus concentrations are strongly positively correlated with the proportion of intensification activities on agricultural land [8]. This aligns with the PCA findings from the case study carried out in Indonesia's Opak Sub-Watershed. In the third and fifth principal components, a significant relationship was observed between the proportion of agricultural land used for cultivation and livestock activities and the concentrations of nitrate, nitrite, ammonia, and dissolved oxygen. When fertilizers are applied, phosphate and nitrate may be released by irrigation or runoff, increasing the amount of nutrients [7]. Agricultural land exhibited a positive relationship with both dissolved oxygen and conductivity levels at the buffer scale in Setikhola, Nepal [29]. Finally, research has shown a connection between agricultural land and the presence of OCPs and other pesticide. The relationship between different land uses and pesticide residues has yet to be examined in the case studies [27], [34], [35]. However, the relationship between water quality parameters and agricultural land might be unclear because of the combined influences of other land use types, including urban areas, agricultural land, and forests [3].

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The majority of research indicates that forest land has a crucial impact on minimizing pollution and decreasing soil erosion [36], [37]. The research on the relationship between land use areas and water quality in the Medlock River case study in the United Kingdom found that urban green spaces and forest land were positively correlated with dissolved oxygen (DO) levels, while demonstrating an inverse relationship with nutrient and conductivity [26]. Similarly, in the Setikhola watershed (Nepal), there was a significant correlation between the land cover of forests and the DO levels [29]. Furthermore, another case study in Chao and Bai Rivers (China) used remote sensing, multiple linear regression, and redundancy analysis to assess how the landscape in buffer zone affects the water quality. The findings indicated that landscape elements within the buffer zone significantly affect variations in river water quality. Specifically, the landscape within the 100-meter buffer zones has the most substantial impact on the quality of river water. Although there was a strong and positive association between TN, and NO_3^- and agricultural land and grassland in buffer zone, and a negative relationship between water quality indicators and forest land was also reported in this study [31]. Similarly, the case study of the Guadalupe Dam Watershed

in Mexico indicated that forest area in buffer zones had a beneficial influence on the protection of water quality [30]. Recent studies have shown that a buffer zone can enhance water quality [30], [38]. As a result, it is essential to carry out measures to protect and rehabilitate the buffer zone when carrying out river water management strategies. Previous research has shown that agricultural and built-up areas are the main contributors to the degradation of water quality, whereas vegetation, forests, and grasslands can improve river water quality [11], [12], [13].

❖ *Water quality and Urbanization*

Population expansion and rapid urbanization have impacted multiple facets of human existence [1]. In response to population growth, the neeed for fossil fuels in manufacturing processes has increased, leading to a considerable rise in PAHs levels released into water environment [28]. Domestic chemicals, degradation byproducts, carpets, firefighting foams, and sewage sludge disposal may discharge PFASs into the environment, potentially contaminating water bodies under certain conditions [39]. In their study on the effects of urbanization on the quality of river water, Kim et al. (2016) used linear regression to examine the connections between the proportion of impervious surfaces and various water quality parameters. The findings revealed that a higher percentage of impervious surface was positively associated with several parameters including COD, BOD_5, TOC, and TP [22]. In addition, the findings revealed a positive correlation between the population and five parameters including COD, BOD_5, TSS, fecal coliforms, and toxicity. This is due to the higher demand for producing and consuming goods and services, which leads to an increase in waste and wastewater generation [19]. The levels of nutrients including NH4-N, PO4-P, TN, TP, and microbial load (fecal indicators and pathogens) were significantly higher in highly urbanized areas compared to those in areas with medium and low levels of urbanization [40]. The study conducted in Suzhou (China) similarly found that water quality was poorest in highly urbanized regions [41].

❖ *Seasonal variation in water quality*

Seasonal variations in precipitation, streamflow, and groundwater flow can significantly affect river flows, leading to seasonal variations in pollutant

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concentrations in the stream. Under certain climatic conditions, some previous studies have found that dry season temperatures are typically higher than wet season temperatures and water flows can be lower, resulting in less turbulence and dilution [11], [12]. Dissolved oxygen and turbidity levels are higher in the rainy season due to increased dilution [11]. Point sources of water pollution significantly affect water quality in the dry season. In contrast, non-point sources become the primary cause to river pollution because of increased runoff in the rainy season [13]. These effects can be intensified by favorable topographic and geological features, such as steeper slopes, well-drained soils, and sparse vegetation, which facilitate surface runoff into the river [42], [43], [44].

❖ *Water quality and extreme weather events, climate change.*

Recent research on the impacts of climate change on river water quality has highlighted sediment transport and nutrient loading [45], [46], [47], [48]. An analysis of water quality data from droughts in 1976, 1991, and 2003 revealed that water quality degradation was associated with rising temperatures and reduced flows. During these droughts, eutrophication was also observed in the Rhine River, Switzerland [24]. Rising water temperatures in certain European rivers have been observed to reduce DO levels and lower the pH of the river water [24], [49]. Furthermore, increasing nutrient concentrations in water during droughts may be associated with reduced dilution capability of river water due to low runoff [21]. Additionally, it is essential to regulate point source pollution during droughts, as low water flows and high temperatures can lead to a significant deterioration in river water quality [49]. Floods can increase flow volume, leading to the introduction of excessive inorganic or organic materials and sediment into river water. A study conducted on the Muar River (Malaysia) during flood events utilized Water Quality Index (WQI) calculations and Pearson correlation analysis, revealing that elevated suspended solids levels contribute to rising NO3-N levels and decreasing pH values [23]. Climate-related factors, including extreme river flows and water temperature, can significantly impact the quality of surface water [24].

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❖ *Atmospheric deposition*

Nutrients, persistent organic pollutants and heavy metals from the atmosphere can enter water environment via both wet and dry deposition processes [42], [50]. Atmospheric precipitation serves as a major pathway for transporting PCBs, pesticides, and other persistent organic contaminants into water bodies [27], [34]. Through this process, air pollution could affect river water quality. Notably, heavy metals, including cadmium and lead, can release into surface water systems via atmospheric deposition [51]. Surface runoff, which facilitates the transport of pollutants to river water, showed a strong correlation with the concentrations present in atmospheric deposition [52].

❖ *Catchment topography, geology, and hydrology*

The chemical characteristics of the rocks and soils could affect the level of salt and nutrient sources in catchments. Both soil sorption capacity and rock and soil erodibility may have an effect on the mobilization of elements in catchments. Subsurface and surface runoff carrying nitrogen, phosphorus, and salts may flow into water environment, and such processes are dependent on the capacity of the soils' drainage [42]. Phosphorus concentration has a strong correlation to soil texture, with clayey soils, for instance, exhibiting greater erodibility [53]. Sedimentary and igneous rocks are primary origins of phosphorus, released via weathering processes and hydrologic transport [43].

Landscape configuration greatly impacts how pollutants are transported to water bodies through surface water, subsurface and groundwater [16]. A waterbody's characteristics can also influence the movement and reduction of contaminants within a catchment. Liu et al. (2021) examined how natural characteristics of catchments and human activities (such as land use) influence water quality. Their multi-model analysis revealed that catchment elevation has a significant negative correlation with NH_4 and dissolved organic nitrogen, while dissolved organic phosphorus has a negative correlation with slope [43]. Additionally, the presence of lakes, wetlands, and dams can result in reduced levels of sediments, nutrients, and salts in downstream river sections, which may explain the low phosphorus levels observed in the case study [53].

2.1.2. Surface water pollution problems in river basins

❖ *Organic pollution and Nutrients*

Organic matter and nutrients come from both natural and anthropogenic activities, but the primary sources of organic contamination in surface water are human activities, particularly urban wastewater discharge and intensive farming[6]. The BOD_5 parameter serves as a key indicator of organic pollution, while parameters like total nitrogen (TN), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), and ammonium nitrogen (NH_4-N), total phosphorus (TP), represent nutrients in water. Furthermore, these concentrations can vary spatially between upstream and downstream sections of the river basin, as well as seasonally or in response to climate change and extreme weather events such as droughts and floods [12], [20].

Persistent organic pollutants (POPs) are organic compounds that resist breakdown through chemical, biological, and photolytic processes [54]. They can be divided into two categories: deliberately manufactured and unintentionally generated compounds. The deliberately produced compounds consist of industrial chemicals such as polybrominated diphenyl ethers (PBDEs), hexabromocyclododecanes (HBCDs), polychlorinated biphenyls (PCBs), perfluoroalkyl substances (PFAS), perfluorooctane sulfonic acid (PFOS), short-chain chlorinated paraffins (SCCPs), hexachlorocyclohexanes (HCHs), and hexachlorobenzenes (HCBs), as well as organochlorine pesticides like dieldrin, aldrin, endrin, chlordane, heptachlor, mirex, dichlorodiphenyl trichloroethanes (DDT), and toxaphene. In contrast, the accidentally produced compounds include polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans [55]. Additionally, Some persistent organic contaminants, including PAHs, DDTs, and PCBs, are part of the organochlorine compounds and are categorized as endocrine-disrupting chemicals (EDCs). These can contaminate the soil, water, or air, potentially causing long-term harm to human and animal health. However, toxicity data and research on certain emerging contaminants remain insufficient [56]. Organochlorine pesticides have also been detected in rivers and occasionally exceed allowable values, indicating potential risks to human health and ecosystems [34], [57]. In conclusion, POPs threaten ecosystems and human health because of their toxic

properties, persistence in the environment, widespread emissions, and ability to bioaccumulate. These pollutants are found in surface waters, where their concentrations are often higher than in other water sources like seawater and groundwater [58].

❖ *Heavy metal pollution*

Heavy metals can be introduced into water environments through waste from industrial and agricultural activities, and residential areas. Additionally, natural sources such as leaching and weathering can contribute to heavy metal contamination, though these sources are typically less significant [9], [10]. The primary sources of heavy metal pollution are industrial wastewater and domestic sewage. Wastewater from industries such as metal manufacturing, paints, pigments, varnishes, pulp and paper, tanneries, distilleries, rubber production, thermal power plants, steel plants, and mining operations can release heavy metals like arsenic (As), zinc (Zn), lead (Pb), copper (Cu), cadmium (Cd), nickel (Ni), mercury (Hg), and chromium (Cr) into water bodies [59].

❖ *Pesticide pollution*

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The unchecked and overuse of fertilizers has enduring impacts on surface and groundwater, particularly in upstream areas of river basins, where farming activities can lead to pollution. Residual chemicals from fertilizers can be introduced into water sources via surface runoff or underground flow [5]. The movement of these chemicals into surface water is influenced by several factors, including their current usage, proximity to water sources, weather conditions, and the physicochemical properties of the pesticide's active ingredient [16].

2.1.3. Some typical methods for assessing surface water quality

A typical method for evaluating water quality involves comparing it to established standards or use a single-factor evaluation. Surface water quality standards are often employed to compare the analytical results of each water quality parameter. This method is simple and convenient to apply, but it tends to produce cautious or conservative evaluation results [60]. The water quality index (WQI) convert water quality dataset into a single figure that represents and categorizes the water quality in rivers. This approach helps evaluate pollution levels in various sections of both urban

and rural rivers [61], [62], [63]. In recent years, multivariate statistical methods, such as Pearson or Spearman correlation analysis, multivariable linear regression, factor analysis (FA), principal component analysis (PCA), and cluster analysis (CA) have been used to assess variations and interpret datasets of water quality [64], [65]. Additionally, machine learning algorithms (ML), including artificial neural networks (ANN), decision trees (DT), support vector machines (SVM), k-nearest neighbors (KNN), naive Bayes, and random forests (RF), are utilized to analyze complex datasets of water quality and uncover potential patterns [66]. Despite its potential, the use of ML for analyzing the primary factors impacting river water quality remains limited due to these complex techniques and lack of data.

❖ **Water quality index**

The Water Quality Index (WQI) concept was initially introduced by Horton in 1965 [67], and Brown et al. (1970) later employed the Delphi method to propose the WQI for the US National Sanitation Fund [68]. However, this method lacks objectivity due to reliance on expert panels for parameter ratings. To improve the final WQI calculation, several other indexes have been developed, such as the British Columbia Water Quality Index, the Oregon Water Quality Index, and the Canadian Council of Ministers of the Environment Water Quality Index [69], [70], [71]. In a comprehensive review of 30 water quality indices, Sutadian et al. (2016) categorized them into three types: fixed, open, and mixed systems [72]. Fixed water quality indices (WQIs) utilize a consistent set of parameters to compute the final index, often leading to issues of inflexibility. In contrast, open WQI systems allow for varying parameters across different cases, which can complicate comparisons between study areas. The mixed system integrates both basic and additional parameters. Principal Component Analysis (PCA) is recognized as an effective method for analyzing pollution sources or selecting appropriate parameters for WQI calculations [64], [73], [74]. PCA provides an objective method for determining the weights of each parameter, leading to more trustworthy outcomes [74], [75]. Choosing an appropriate method and relevant water quality parameters is crucial for determining the final WQI that accurately represents the current state of water quality [72]. Therefore, this study adopts an open system approach

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and employs PCA for parameter selection to calculate the final water quality index (WQI).

Moreover, the biodegradability index was calculated by dividing BOD_5 by COD. A BOD_5/COD ratio of 0.4 showed strong degradability, a ratio between 0.2 and 0.4 suggested moderate degradability, and a ratio below 0.2 signified low degradability. [76], [77]. A high biodegradability index indicates the presence of more degradable matter in the river, but it does not specify the sources or affecting factors [77]. Heavy Metal Pollution Indexes are utilized to evaluate water quality by calculating the weighted arithmetic sum of heavy metal concentrations in water quality parameters. Additionally, the Heavy Metal Evaluation Index (HEI) is employed to assess the concentrations of heavy metals and trace elements. The HEI is classified into three levels: high heavy metal (>20), medium heavy metal (10–20), and low heavy metal (<10) [78], [79]. This method, however, cannot pinpoint the origins of pollution or the primary factors influencing water quality, as its results solely reflect the extent of pollution in the river water quality.

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❖ **Statistical analysis**

Numerous research have used statistical techniques to understand complex dataset of water quality [75], [80], [81]. Pearson's or Spearman's correlation analysis is widely applied to measure the degree of dependence between variables. Water quality parameters are assessed for correlation based on coefficient values (from +1 to -1). A value of zero indicates no relationship, while +1 and -1 signify a perfect correlation, with significance at $p < 0.05$. Correlation coefficients greater than 0.7 indicate strong relationships, while values from 0.5 to 0.7 suggest moderate relationships. Recent studies have applied this method to analyze both positive and negative correlations between water quality parameters [11], [62], [75], [77]. Multiple linear regression has been used to develop models that help find key factors influencing water quality parameters [3]. Cluster analysis (CA) groups objects according to their similarities or differences. The Euclidean distance measures how comparable two samples are, where the "distance" represents the "difference" between the two values. The distance is measured by the total of squares from the analysis of variance, and a dendrogram is

created to visually represent the clustering [11], [75], [82]. Principal component analysis (PCA) is utilized to reduce the quantity of variables while preserving the same level of explained variance using fewer variables (principle components). PCA seeks to highlight the relationships between variables based on underlying, unquantified components. Before performing PCA, the data was screened for suitability using the Kaiser-Meyer-Olkin (KMO > 0.5) and Bartlett's sphericity tests ($p < 0.05$) [11], [82]. PCA was employed to find the main parameters of water quality and pollution sources. The primary parameters within each principal component aid in predicting sources of pollution and contributing factors [11], [12].

2.1.4 Surface water treatment technologies

Surface water is the primary source of water supply in cities. The water demand is increasing, while the quality of surface water is degrading due to the influx of wastewater into river basins [83]. The choice of water treatment technology depends on the chemical, physical, and biological properties of the raw water source. Lai (2004) mentioned four processes of water treatment technology for surface water [84]. Surface water often changes its properties seasonally, so the application of a preliminary treatment process to stabilize the water entering the treatment system, such as using screens to remove large solids, raw water tanks (equalization ponds) to help decrease the concentration of large suspended solids and regulate the water entering the system. If the input water source has low turbidity, the treatment processes need to perform the disinfection step (chlorination), or add a slow filter tank before disinfection and then distribute for the population. For surface water sources with high turbidity, the process of Coagulation - Flocculation - Sedimentation - Filtration - Disinfection is often chosen to ensure that the output water meets the standards and regulations [84].

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Surface water treatment encompasses a range of processes implemented in conventional water treatment facilities, including coagulation-flocculation, sedimentation, rapid sand filtration, and disinfection, alongside advanced techniques such as membrane filtration and advanced oxidation processes. Among these, coagulation-flocculation, followed by sand filtration, sedimentation, and flotation, is widely recognized as the most prevalent and cost-effective approach for removing

natural organic matter (NOM) and particulate matter [85]. The coagulation-flocculation process, a well-established and operationally straightforward method, is employed to eliminate suspended solids, colloidal particles, and dissolved organic compounds from water. Coagulation involves the destabilization and neutralization of charged particles, colloids, or dissolved organic compounds, promoting their aggregation into larger flocs through flocculation, which facilitates their sedimentation. Optimization of the coagulation-flocculation process enhances the removal efficiency of NOM and supports the stable performance of water treatment systems. Additionally, chemical costs represent a substantial portion of the operational and maintenance expenses in water treatment facilities. Reducing chemical usage can significantly lower these costs, thereby improving the overall efficiency of water treatment operations [86].

Coagulation-flocculation process is a common treatment method in water treatment technology. To effectively remove organic substances in the coagulation-flocculation process, important factors such as coagulant dosage, optimal pH level as well as mixing time and intensity need to be considered [87]. There are many types of coagulants used in the coagulation process such as poly aluminium chloride (PACl), polyferric sulfate (PFS), alum ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$). The choice of coagulants in water treatment depends on several factors such as raw water characteristics, removal performances, cost and availability of coagulants [88], [89]. Then, the sedimentation process is an important step to remove suspended solids from the water. There are many ways to classify the sedimentation stage in water treatment according to the working mode (intermittent sedimentation tank, continuous sedimentation tank) or according to the direction of water flow (horizontal sedimentation, vertical sedimentation and centrifugal sedimentation). The filtration process cleans water by separating suspended solids, flocculent bodies and microorganisms through layers of filter materials. There are usually two filtration technologies including rapid filtration (water velocity passes through the material layer at a speed of about $1.5x10^{-3}$ m/s) and slow filtration (water velocity passes through the material layer at a speed of about $0.03x10^{-3}$ m/s to $0.15x10^{-3}$ m/s) [90].

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In summary, to improve the efficiency of suspended solids, organic matter and some metals, coagulation – flocculation methods are often applied because of their simplicity and economy. However, due to the seasonal characteristics of river water and receiving wastewater, parameters such as turbidity, COD and BOD will change significantly. Pre-sedimentation can be used to reduce turbidity in case of high turbidity, especially in the rainy season [91]. Therefore, these traditional technologies are often applied in rural areas because of their ease of operation and low cost.

2.2. Research literature in Vietnam

Surface water is a primary water source for communities, making the preservation of its quality crucial for meeting people's daily needs. However, the 2018 National Environmental Status Assessment Report used the WQI to evaluate water quality in 7 major river basins in the 2014-2018 period, including the Mekong, Dong Nai, Vu Gia - Thu Bon, Ma, Hong - Thai, Nhue - Day, and Cau river basins. The report revealed that the proportion of water quality reaching the medium level accounted for the largest proportion in these river basins, from about 50% - 63% (WQI value from 51 - 75/100). Surface water quality in these river basins tends to be increasingly polluted [14].

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Agricultural activities taking place along rivers can significantly impact changes in river water quality [25]. Specifically, waste from aquaculture areas and agricultural runoff are the main pollutants in some areas of the Hau River in An Giang and Can Tho provinces [92]. Similarly, in the Dong Nai River, waste from agricultural activities is the main cause of pollution of some indicators of nitrate, turbidity, BOD, COD [93]. Research on the Gieng and Dinh rivers (Binh Thuan province) showed that the concentration of pollutants tends to increase because the water flowing through Ham Tan district and La Gi town has many point sources of discharge, especially from livestock farms [94]. In addition, some pesticides such as chlorine-based pesticides (OCPs) were also detected in the Dong Nai River due to farming activities along the river [95]. Several herbicides such as glyphosate and glufosinate have been detected in the Red River basin, and studies have also found correlations between these substances and ammonium (NH_4^+), which suggests that both nitrogen-containing fertilizers and

herbicides has been used in areas near the banks of the Red River [96]. Waste from domestic activities in residential and urban areas directly impacts the river if not properly treated. For example, a study assessing the pollution level in three inner-city rivers of Hanoi city concluded that river sections flowing through urban and residential areas are often affected by untreated domestic wastewater [97]. Some endocrine disruptors such as nonylphenol triethoxylate and nonylphenol diethoxylate have also been found in the Saigon - Dong Nai river water, especially near the water intake points of the state water treatment for Ho Chi Minh City such as Phu Cuong Bridge, Hoa Phu because of the presence of waste sources from domestic activities of Thu Dau Mot city [98]. However, the presence of waste sources simultaneously affects river water quality, making it difficult to separate the contribution of waste sources to river water pollution

However, the presence of different waste sources simultaneously affecting river water quality will make it difficult to separate their contribution of each source in river water pollution [25]. The study was conducted in the middle area of the Saigon - Dong Nai river system affected by waste sources from industrial parks in Di An and Thuan An cities, some industrial parks in Ho Chi Minh City have degraded surface water. Water quality is only average, and most parameters exceed the allowable threshold of QCVN 08:2023/BTNMT [99].

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In the Central Highlands region, there are four major river basins including the Se San River basin, the Ba River basin, the Serepok River basin and the Dong Nai River basin [100]. Research in the Se San River basin on the relationship between land use policy and water quality during the period from 2000 to 2018. The results showed that the conversion of poor forests to rubber plantations (from 2010 to 2015), and increased agricultural activities and urbanization (from 2005 to 2009) in the basin increased the total nitrogen, total phosphorus and sediment concentrations. Research on water quality in the downstream of the Ba River basin (in Phu Yen province), the study was conducted at 9 sampling locations, carried out in 3 phases in 2016 with 11 parameters including pH, DO, TSS, EC, BOD_5, COD, NO_3-N , NH_4-N , PO_4^{3-} , total coliform (TC) and total dissolved iron (Fe). The study used the comparison method (QCVN 08-MT: 2015/BTNMT) and calculated the WQI index, the results showed that water quality is

getting worse, especially at the points receiving wastewater from industrial, agricultural and coastal urban activities [101]. Another study assessing the water quality of WQI in the upstream of the Ba River basin was conducted at 10 locations. The authors used the comparison method with standards and WQI index to assess the current status of surface water quality of the main river branch of the Ba River basin. The study concluded that 7 out of 10 monitoring locations had good water quality indexes. Water quality at 2 locations, Le Bac Bridge and Quy Duc Bridge, was heavily polluted. A study conducted in 2020 in the Ba River basin (in Gia Lai province) assessed the carrying capacity and concluded that the Ba River basin was not capable of receiving additional discharge sources for the parameters COD, BOD, TSS, and PO_4^{3-} [102]. In general, water quality in the Ba River basin is at a moderate level of pollution, with only a few locations polluted with Fe, NO_2-N, NH_4-N, especially in the downstream of the Ba River basin (Phu Yen province) [101].

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CHAPTER 3: RESEARCH METHODOLOGY

3.1. Study area

The Ba River basin spans approximately 13,900 km² and is located in Vietnam's Central Highlands provinces. The main river stretches 388 km, originating from Ngoc Ro peak at an altitude of 1,549 meters in the Truong Son mountain range. It flows through the provinces of Gia Lai, Dak Lak, and Phu Yen before emptying into the East Sea. The basin, shaped like an "L" in the upper and lower sections, narrows in the middle, with a river network density of 0.22 km/km², an average elevation of 400 meters, and a slope of 10.9%. Annually, the basin receives around 1,740 mm of rainfall, resulting in a total flow of 10 billion m³ of water. The Ba River basin in Gia Lai province includes several irrigation and hydroelectric reservoirs, such as An Khe-Kanak Hydroelectric Lake, Ayun Ha Lake, Dak Srong Lake, and others like Krong H'nang Lake, Song Hinh Lake, Dong Cam Irrigation Dam, and Ba Ha Lake in Phu Yen province. The river flows in a northwest-southeast direction from upstream to An Khe, then changes to a north-south direction until Ayun Pa. From Ayun Pa to the Hinh River mouth, it flows northwest-southeast again, then heads west-east, emptying into the East Sea at the Da Rang River mouth. The Ayun River, the largest tributary of the Ba River, originates from Kong Qua Bon peak (elevation 1,710 meters) in Mang Yang district and runs through Mang Yang, Chu Se, and Ayun Pa districts before joining the Ba River at Cheo Reo. The Ayun River's main course is 175 km long with a basin area of 2,950 km², and it is home to the Ayun Lower Irrigation Project.

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According to the assessment report on the current environmental status of Gia Lai province, the water quality of Ba River is deteriorating due to the discharge of wastewater from factories along the riverbanks during the dry season, and diffuse sources during the rainy season. During the rainy season, TSS and nutrient contents are often high due to surface runoff, rainwater overflows into surface water sources [103]. In addition, domestic wastewater also contributes to reducing water quality in some residential areas such as An Khe, Ayun Pa, Phu Thien and Phu Tuc towns. Because domestic wastewater is almost only discharged through preliminary treatment facilities and directly into surrounding rivers and streams. Waste from agricultural activities also

contributes to surface water pollution via runoff or irrigation activities. The main factors are uncontrolled amounts of chemical fertilizers, pesticides, and livestock waste. In recent years, the development of large livestock farms such as those in districts/towns such as An Khe, Phu Thien and Ia Pa has the potential to affect local environmental issues, especially the Ba River basin, when waste treatment systems are improper to handle waste.

3.2. Research approach

The study applied qualitative and quantitative methods to carry out the expected main contents. First, the fluctuations in water quality and the influencing factors were evaluated through the application of experimental analysis and statistical methods. Next, the study employed the method of secondary data collection to calculate the pollution load of Ba River water. The combination of experimental analysis method and RSM approach aims to optimize the operational factors in the river water treatment process. At the same time, statistical processing methods are applied to detect the main factors influencing the willingness of people to participate in solutions to protect river water quality. From the above results, management and technical solutions will be proposed to protect water quality on the Ba River basin.

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3.3. Research methodology

3.3.1. Data collection

3.3.1.1. Secondary data collection.

The study gathered documents and reports on water quality, the socio-economic context, meteorological and hydrological data, along with other materials concerning the Ba River. These datasets were obtained from the Department of Natural Resources and Environment, the Department of Agriculture and Rural Development of Gia Lai Province, the Statistics Office, and other relevant agencies.

3.3.1.2. Primary data collection

Questionnaire. A questionnaire survey method was used to gather information from local residents regarding their willingness to participate, sense of community, dependence on river water, perceptions of current water management, and land possession. With a population of approximately 607,273 people (around 151,818

households) and A 10% error margin [104], the study aims to sample around 100 households, calculated using equation 2.1.

$$n = \frac{N}{1+Ne^2} = 100 \qquad (2.1)$$

whereas: N = 151 818 ; e=0,1 (10%)

Water sampling. Water samples were collected from 17 locations in March 2022 (dry season), August 2022 (rainy season), and January 2023 (early-dry season) along the main stream of the Ba River Basin (Fig. 3.1 and Table 3.1). Sampling was carried out on the same day during each campaign, under normal weather conditions, with no rainfall in the three days prior, ensuring that water quality was not temporarily affected. Samples were taken from a depth of 0.5 meters below the surface. The water was preserved in 2-liter polyethylene plastic bottles to maintain its physical, chemical, and microbiological integrity for analysis. Additionally, 2-liter brown glass containers were used for pesticide testing. Both types of bottles were stored at 2–3°C in cool boxes and transported to the laboratory for further analysis.

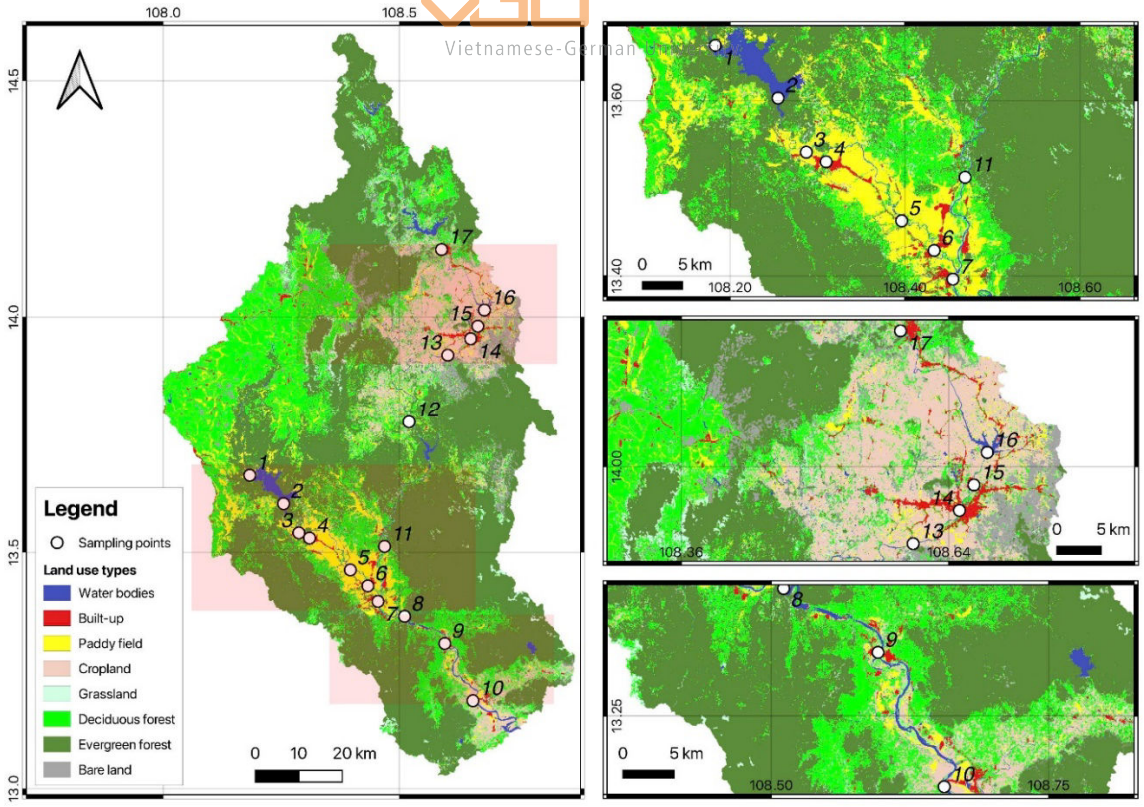

Figure. 3.1. The location and land use map of Ba River Basin (Gia Lai Province – the Highlands of Vietnam) and the sampling locations in 2020.

Table 3.1. The description of land use in the water sampling locations.

Or.	Sampling Locations	Latitude	Longitude	Description
1	Ayun commune	13°41'47.7"N	108°10'16.6"E	Rural area with intensive agriculture activities (perennial plants and rice crops).
2	Ayun Ha Lake	13°34'58.5"N	108°15'25.1"E	Rural area with agriculture activities.
3	Plei Tang Bridge	13°32'34.3"N	108°17'06.0"E	Rural area with residential areas, and annual rice crops.
4	Phu Thien Bridge	13°32'44.9"N	108°18'49.6"E	Suburban area with residential areas, intensive agriculture activities (annual and rice crops), and sand mining.
5	Chroh Ponan Commune	13°27'38.0"N	108°23'49.0"E	Rural area with intensive agriculture activities (rice crops) and sand mining.
6	Quy Duc Bridge	13°25'44.4"N	108°25'59.9"E	Urban area with medium-density residential areas, industrial and agriculture activities.
7	Ben Mong Bridge	13°23'45.9"N	108°27'12.5"E	Urban area with residential areas, entertainment activities and rice crops.
8	Dak Srong Dam	13°20'56.3"N	108°31'11.7"E	Rural area with agriculture activities (crops and livestock) and forest areas.
9	Le Bac Bridge	13°18'20.9"N	108°35'52.8"E	Rural area with dominant perennial crops (coffee, pepper) and annual crops (tobacco).
10	Phu Can Bridge	13°11'07.9"N	108°39'18.4"E	Urban area with residential areas, industrial and agriculture activities.
11	Ia Kdam Bridge	13°30'45.3"N	108°28'07.6"E	Rural area with agriculture activities (crops and livestock) and forest areas.
12	Yang Trung Bridge	13°46'37.0"N	108°31'13.8"E	Urban area with residential areas and agriculture activities.

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13	Tu Luong Bridge	13°55'08.0"N	108°36'09.9"E	Rural area with agriculture activities (crops and livestock).
14	Ba River Bridge	13°57'15.6"N	108°39'04.9"E	Urban area with medium density residential areas, industrial activities.
15	An Khe bus station	13°58'49.9"N	108°39'57.0"E	Urban area with residential areas and rice crops.
16	An Khe Dam	14°00'56.8"N	108°41'29.2"E	Rural area with agriculture activities (crops and livestock) and forest areas.
17	Kbang Bridge	14°08'12.4"N	108°35'54.1"E	Rural areas with residential areas, and forest areas.

3.3.2. Data analysis

3.3.2.1. Analytical methods for physico-chemical parameters in water samples

To regulate surface water quality, the Vietnam Ministry of Natural Resources and Environment (MONRE) incorporated guidelines into the Vietnam Environmental Protection Law and related legal frameworks. MONRE established the National Technical Regulation on Surface Water Quality (QCVN 08-MT/2015/BTNMT), which classifies surface water quality into four categories based on its usage and protection goals. The water quality of the Ba River was assessed against Class A2 of QCVN 08-MT/2015/BTNMT, which applies to raw water intended for domestic water treatment facilities.

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The study analyzed various physicochemical parameters, including pH, total suspended solids (TSS), turbidity (Tur), dissolved oxygen (DO), chemical oxygen demand (COD), biological oxygen demand (BOD_5), total carbon (TC), total nitrogen (TN), total organic carbon (TOC), ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), total phosphorus (TP), and heavy metals (Mn, Fe). On-site measurements of pH, DO, and turbidity were taken using multiparameter meters HI98194 and HI98703 (Hanna Instruments, Portugal). TSS was determined by weighing filters before and after drying the residue, following the standard method for water and wastewater analysis (SMEWW 2540D). TP was measured using the ascorbic acid method (SMEWW

4500P.B&E), where samples were decomposed with persulfate in acid to convert all phosphates to orthophosphate, and absorbance was recorded at 880 nm using a UV-vis spectrophotometer (UV-1800, Shimadzu, Japan). Nitrite (NO_2^-) and nitrate (NO_3^-) were analyzed via colorimetric and cadmium reduction methods at a wavelength of 543 nm (SMEWW 4500). Specifically, nitrite was measured by reacting sulfanilamide with N-(1-naphthyl)-ethylenediamine dihydrochloride to produce a red-violet azo compound at pH 2.0-2.5. Nitrate was determined by comparing nitrite concentrations before and after reduction using cadmium. COD was estimated through the closed reflux method, digesting samples with $K_2Cr_2O_7$ in an acidic medium for two hours at 150°C, followed by titration with ferrous ammonium sulfate (SMEWW 5220C). BOD_5 was measured by comparing initial and final DO values over a five-day period (SMEWW 5210B). TOC, TC, and TN were analyzed using a TOC Analyzer (TOC-L, Shimadzu, Japan). Cr^{6+} was quantified by reacting it with diphenylcarbazide in an acidic solution, measuring the resulting complex at 540 nm (SMEWW 3500). Heavy metals such as Mn, Fe, As, and Cu were analyzed using an atomic absorption spectrophotometer (AAS, Analytik Jena, ContrAA300, Germany). Samples were acidified to a pH below 2 and boiled to break down organic compounds, then filtered and atomized using an air-acetylene flame for electrothermal ionization at wavelengths of 279.5 nm for Mn, 248.3 nm for Fe, and 324.7 nm for Cu. Arsenic (As) was analyzed using Hydride-AAS, employing N_2 gas for thermal decomposition of AsH_3 at 193.7 nm. Standard chemicals for metal analysis, with concentrations of 1,000 µg/mL in 5% HNO_3, were purchased from Agilent, United States.

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All experiments were carried out in triplicate, with a blank and a quality control sample included for each analysis. The average values were subsequently calculated. The measurement range for each piece of equipment used, along with the method detection limit (MDL), is detailed in Table 3.2.

Table 3.2. Analytical methods for water parameters.

Or.	Parameters	Description	Units	Analytical methods/ Equipements	MDL
1	pH	pH value	pH unit	Multiparameter meters HI98194	0-14
2	DO	Dissolved oxygen	mg/L	Multiparameter meters HI98194	0-50 mg/L
3	Tur	Turbidity	NTU	Hanna Instruments HI98703	0 – 1000 NTU
4	COD	Chemical oxygen demand	mgO_2/L	SMEWW 5220C:2023	3.0 – 400 mg/L
5	TSS	Total suspended solids	mg/L	SMEWW 2540D:2023	2.06 – <200 mg/L
6	BOD_5	Biochemical oxygen demand	mgO_2/L	SMEWW 5210B:2023	1.0 – 300 mg/L
7	TOC	Total organic carbon	mg/L	TOC Analyzer	4.0 – 30,000 µg/L
8	TC	Total carbon	mg/L	TOC Analyzer	4.0 – <30,000 µg/L
9	TN	Total nitrogen	mg/L	TOC Analyzer	4.0 – <30,000 µg/L
10	NH_4-N	Ammonium	mg/L	SMEWW 4500-NH_3.B&F:2023	0.01 – 0.6 mg/L
11	NO_3-N	Nitrate	mg/L	SMEWW 4500-NO_3^-.E:2023	0.01 – 1.0 mg/L
12	NO_2^--N	Nitrite	mg/L	SMEWW 4500.NO_2^-.B:2023	0.004 – 1.0 mg/L

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13	TP	Total phosphorus	mg/L	SMEWW 4500-P.B&E: 2023	0.03 – 2.0 mg/L
14	Mn	Manganese	mg/L	SMEWW 3111.B:2023	0.03 – 10 mg/L
15	Fe	Iron	mg/L	SMEWW 3111.B:2023	0.02 – 10 mg/L
16	Cu	Copper	mg/L	SMEWW 3111.B:2023	0.03 – 10 mg/L
17	AS	Arsenic	mg/L	SMEWW 3111.B:2023	0.0008 – 2.0 mg/L
18	Cr^{6+}	Chromium (VI)	mg/L	SMEWW 3500-Cr B:2023	0.003 – 1.0 mg/L

3.3.2.2. Pesticide residue in water samples

The selected pesticides for analysis include Dimethoate, Chlorpyrifos (-ethyl), Quinalphos, Profenofos, Cyhalothrin, Cypermethrin, Deltamethrin, Aldrin, Isoprothiolane, DDT-p.p', and DDT-o,p'. All pesticide standards were obtained from Sigma-Aldrich Pte Ltd. (United States), each with a chromatographic purity exceeding 99.0%. Water samples were extracted using liquid-liquid extraction and silica gel cleanup methods, as outlined in EPA guidelines (US EPA Method 3520C and US EPA Method 3630C). A total of 1.6 liters of unfiltered water was shaken and extracted with 500 mL of methylene chloride under neutral conditions for three replicates. The solvent was then purified by eluting with hexane through a silica gel column topped with sodium sulfate. The concentration of the target compounds was enriched through evaporation using a nitrogen gas blowing system at 40°C, prior to injecting 1 µL into the gas chromatography system.

Eleven pesticide compounds were analyzed using the gas chromatography-tandem mass spectrometry system, specifically the GCMS-TQ8050 Triple Quadrupole GC-MS (Shimadzu, Japan). The chromatographic separation was carried out on an SH-Rxi-5Sil MS column (30 x 0.25 mm, 0.25 µm, Shimadzu, USA). Standard curves for

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the 11 target pesticide compounds were established, achieving a correlation coefficient of linear regression (r^2) greater than 0.99. Following the methodology described by Lynch et al., standard substances were spiked into the water samples to determine the method detection limit (MDL), limit of quantitation (LOQ), and standard deviation (SD) for each compound [105]. Details regarding system setup, quality assurance, and quality control are provided in Tables 3.3 and 3.4.

Table 3.3. Information on MS/MS condition in the analysis of target pesticides.

Pesticide name	m/z	CE	Ret. Time (minute)
Dimethoate	125.00 > 79.00	8	13.4
Chlorpyrifos (-ethyl)	313.90 > 257.90	14	20.21
Aldrin	254.90 > 220.00	20	20.21
Quinalphos	146.00 > 118.10	10	22.56
Isoprothiolane	204.00 > 118.00	8	24.57
Profenofos	336.90 > 266.90	14	24.76
DDT o,p	235.00 > 165.10	22	26.2
DDT p,p	235.00 > 165.10	22	26.96
Cyhalothrin	207.90 > 180.90	8	29.79
Cypermethrin	163.00 > 127.00	5	31.43
Deltamethrin	252.80 > 92.90	16	33.26

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Table 3.4. Information on quality assurance, and quality control in the analysis of target pesticides using GC-MS/MS.

Pesticide name	SD	MDL (µg/L)	LOQ (µg/L)
Dimethoate	0.00036	0.001	0.004
Chlorpyrifos (-ethyl)	0.00072	0.002	0.007
Aldrin	0.00036	0.001	0.004
Quinalphos	0.00036	0.001	0.004

Isoprothiolane	0.00108	0.003	0.011
Profenofos	0.00036	0.001	0.004
DDT o,p	0.00036	0.001	0.004
DDT p,p	0.00072	0.002	0.007
Cyhalothrin	0.00036	0.001	0.004
Cypermethrin	0.00108	0.003	0.011
Deltamethrin	0.00108	0.003	0.011

3.3.3. Data analysis

To assess the extent to which one variable or parameter depends on others, Spearman's correlation analysis was utilized in this study. The correlation coefficient values range from +1 to -1, with a value of zero indicating no relationship between the variables. Values of +1 and -1 represent a perfect correlation at significant levels of $p < 0.05$, $p < 0.01$, and $p < 0.001$. In general, Spearman's correlation coefficients of $r > 0.7$ are deemed strong correlations, while r values between 0.5 and 0.7 are considered moderate correlations. Additionally, one-way analysis of variance (ANOVA) was used to assess the statistical significance of the physicochemical parameters in relation to both temporal (seasonal) and spatial (sampling location) variations, consistent with methodologies employed in previous studies [106], [107]. Hierarchical cluster analysis (HCA) was employed to group sampling sites into categories or clusters based on their similarities or differences. Typically, the Euclidean distance is used to assess the comparability of two sites, with "distance" reflecting the "difference" in their analytical values. The water sample sites were classified according to physicochemical parameters using HCA, applying the Ward method of association and the squared Euclidean distance as a measure of similarity. The distance between two groups was calculated by summing the squares of the analysis of variance, resulting in a dendrogram that visually represents the clustering processes [11], [75], [82]. This study utilized principal component analysis (PCA) to identify appropriate parameters and their weights for calculating the final water quality index (WQI). PCA helps reduce the number of variables (parameters) while maintaining the same level of variance with fewer variables (principal components). Additionally, PCA seeks to elucidate the relationships between observations and underlying factors that are not directly

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observable. A linear combination is used to transform the original variables (X) into a smaller set of new principal components (PCs) [64], [73], [74] as in Eq. 3.1.

$$Z_{ij} = a_{i1}x_{1j} + a_{i2}x_{2j} + \ldots + a_{im}x_{mj} \quad \text{(Eq. 3.1)}$$

where z is the component score, a is the component loading, x is the measured value of a variable, i is the component number, j is the sample number, and m is the total number of variables.

To verify the suitability of an existing water quality dataset, Kaiser-Meyer-Olkin (KMO) and Bartlett's tests were conducted before performing PCA, and a KMO value of 0.5 or more was required to do PCA. For the output results, the higher the eigenvalues, the higher the significance of the principal components. The eigenvalues of the principal components (≥1.0) were considered to be significant [75].

Principal component analysis was used to calculate the factor loadings for each variable, indicating the extent to which each variable contributes to the overall information of the factor [75]. The sum of squared loadings for each variable, known as communality values, was used to calculate the weight of each variable [74], [108]. Sub-index values were then calculated using linear functions, based on the regulated limits in QCVN 08:2015-MT/BTNMT - National Technical Regulations on Surface Water Quality [109]. Two common methods for calculating the final water quality index (WQI) are the additive (arithmetic) and multiplicative (geometric) approaches. While the additive method is easy to apply, it has the drawback of causing an issue known as "eclipsing." Therefore, this study utilized the multiplicative method (Eq. 3.2) to compute the final WQI values. These results were then compared to the VN-WQI approach during the rainy season to highlight the advantages of this method.

$$WQI = \prod_{i=1}^{n} {q_i}^{w_i} \quad \text{(Eq. 3.2)}$$

Where WQI is the final water quality value, q_i is the sub-index value of parameter i, w_i is the weight of parameter i, and n is the number of selected parameters.

All statistical processes were performed using R Language version 4.2.2. Microsoft Excel 2013 was also used for the data preparation and WQI calculation. QGIS software (version 3.22) was used to illustrate the figure of the study area.

3.3.4. Pollution load and carrying capacity in Ba River

The method outlined in Vietnam's Circular 76/2017/TT-BTNMT for assessing the maximum carrying capacity of rivers like the Ba River offers a standardized, cost-effective approach for regulatory compliance, relying on simple dilution equations and basic field data to determine pollution thresholds, making it ideal for data-scarce regions and rapid assessments; however, it oversimplifies dynamic processes, and lacks predictive power for future scenarios. As complex models such as MIKE and SWAT demand significant data, expertise, and computational resources, the method in Vietnam's Circular can be impractical for quick regulatory checks in Vietnam with optimal resources, which are suitable for the Ba River Basin.

The maximum carrying capacity is the threshold of contaminants at which the river water can no longer self-purify or becomes a dead water body. Therefore, calculating the maximum carrying capacity in Ba River provides a clear overview of whether river water can receive more pollution load or not. The calculations of carrying capacity applied the methods in The Vietnam Circular 76/2017/TT-BTNMT, regulations on assessment of wastewater reception capacity, pollution carrying capacity of rivers and lakes.

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To estimate and evaluate the carrying capacity, the equation 3.3 were applied.

$$L_{re} = (L_{max} - L_{avail} - L_{dis}) \times F_s \qquad \text{(Eq. 3.3)}$$

Whereas L_{re}: The maximum carrying capacity; L_{max}: The maximum pollution load; L_{avail}: The available pollution load in the river; L_{dis}: Pollution load of wasewater F_s: safety coefficients.

The equation 3.4 was used to calculate the maximum pollution load

$$L_{max} = (Q_{rw.min} + Q_{ww.\max}) \times C_{thr} \times 86.4 \qquad \text{(Eq. 3.4)}$$

Whereas L_{max}: The maximum pollution load; $Q_{rw.min}$: The minimun water flow $Q_{ww.max}$: The maximum wastewater discharge C_{thr}: Allowable values in National regulation; 86.4 is the unit conversion factor (m^3/s) x (mg/L) → kg/ngày.

Then, the available pollution load in the river was calculated according to the equation 3.5.

$$L_{avail} = Q_{rw.min} \times C_p \times 86.4 \quad \text{(Eq. 3.5)}$$

Whereas L_{avail}: The available pollution load in the river; $Q_{rw.min}$: The minimun water flow; C_p: the maximum concentration before receiving wastewater; 86.4 is the unit conversion factor (m^3/s) x (mg/L) → kg/ngày.

Finally, pollution load in wastewater was calculated based on the maximum pollutant concentration in wastewater and The maximum wastewater discharge (the equation 3.6).

$$L_{dis} = Q_{ww.max} \times C_{w.max} \times 86.4 \quad \text{(Eq. 3.6)}$$

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Whereas L_t: pollution load of wasewater $C_{w.max}$: the maximum pollutant concentration in wastewater; $Q_{ww.max}$: The maximum wastewater discharge; 86.4 is the unit conversion factor (m^3/s) x (mg/L) → kg/ngày. The components $Q_{rw.min}$,$Q_{ww.\max}$, and C_p, $C_{w.max}$ were collected in Gia Lai DONRE, and C_{thr} was taken from the vietnamese regulation on surface water QCVN 08:2023/BTNMT. River water quality datasets were applied in the period 2020 – 2023, wastewater from industrial and domestic activities were in 2023. This study applied the calculation method of Vietnamese Circular 76/2017/TT-BTNM.

3.3.5. Empirical analysis

River water samples were collected from the Ba River Basin in Vietnam's Highlands, a key water source for various uses, including drinking and irrigation in agricultural regions with ethnic minorities. The samples were kept at 5°C for analysis and experimentation, with approximately 50 liters collected each time. The water's properties are presented in Table 3.5.

Table 3.5 Characteristics of raw water from Ba river.

Paramters	**Turbidity (NTU)**	**UV_{254} (cm^{-1})**	**DOC (mg/L)**	**SUVA ($m^{-1}mg^{-1}L$)**	**pH**
Range	11.2-11.8	0.116-0.119	3.83-3.91	3.03-3.04	6.95-7.04

DOC: Dissolved organic carbon; SUVA: Specific ultraviolet absorbance.

The Response Surface Methodology (RSM) approach was applied to forecast and optimize the conditions of the coagulation-flocculation process for treating surface water from the Ba River Basin in Vietnam's Highlands. Water samples from the river were tested for pH, turbidity, dissolved organic carbon (DOC), and UV_{254} parameters. The conditions of experiments are designed by a central composite design (CCD). The jar-test method was employed to modify the pH levels and coagulant dosage according to the design of CCD. The treated water was then analyzed for turbidity levels and DOC, which served as input data for the RSM analysis.

Polyaluminium Cloride ($[Al_2(OH)_nCl_{6-n}]_m$, and Al_2O_3 31%) sourced from Pursuit Industries PVT. Ltd., India, and Polyferric Sulfate ($[Fe_2(OH)_n(SO_4)_{3-n/2}]_m$, and Fe_2SO_3 10%) supplied by Nittetsu Mining Co., Ltd, Japan, were used in this study. Aluminum sulfate ($Al_2(SO_4)_3.16H_2O$, and Al_2O_3 15%) was obtained from from South Basic Chemicals JSC, Vietnam. The pH was adjusted using 0.1M NaOH or 0.1M HCl prior to adding the coagulants. The coagulation process was performed via jar tests in 1-liter cylindrical beakers at 25°C ± 1. To promote interaction among destabilized particles formed in the initial stage, mixing was conducted rapidly at 250 RPM for 1 minute, followed by a slower mixing phase at 30 RPM for 10 minutes. The water was then left to settle for 60 minutes. The levels of pH were tested with a pH meter of Horiba (F-54 BW, Japan), and the DOC levels were determined using a TOC Analyzer of Shimazu (TOC-VCPH, Japan) with Standard Method 5310B (the High-Temperature Combustion Method). The levels of turbidity were analyzed by a Turbidimeter of HANNA (HI98703-02, USA) using Standard Method 2130B (the Nephelometric Method). In addition, To measure UV_{254} parameter, a UV-vis spectrophotometer of Shimadzu (UV-1800, Japan) was used, and SUVA was determined by the DOC/ UV_{254}.

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The Response Surface Methodology (RSM) with central composite design (CCD) was employed to optimize dissolved organic carbon (DOC) and turbidity elimination in raw water. The study considered pH and coagulant dosage as the key input variables, while the elimination efficiencies of DOC and turbidity served as the response variables. The pH range was established between 4.9 and 9.1, and coagulant dosages varied from 17.6 to 102.4 mg/L for PFS, PAC, and alum, as outlined in Table 3.6. The high (+1) and low (-1) ranges of pH were based on the optimal coagulation-flocculation range in surface water treatment [110], [111], [112] and the typical dosage used for treating Ba River water.

Table 3.6 Experimental ranges and factors applying CCD.

Factor	Coded factor levels				
	Lowest	**Low**	**Center**	**High**	**Highest**
	-1.414 (-α)	-1	0	+1	+1.414 (-α)
pH	4.9	5.5	7	8.5	9.1
Coagulant dose (mg/L)	17.6	30	60	90	102.4

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The circumscribed Box-Wilson central composite design (CCD) generated a total of 13 experimental trials. As depicted in Figure 3.2, the design consists of four factorial (cube) points, four axial points, and five center point replications [111]. The total number of experimental runs (N) is calculated using Equation 3.7, which accounts for 2k factorial points, 2k axial points, and N_0 center points, with k representing the number of input variables (in this case, k = 2)

The circumscribed Box-Wilson central composite design (CCD) resulted in 13 experimental runs. Figure 3.2 illustrates the four cube or factorial points, four axial points, and five center points [112]. Equation 3.7 shows how to calculate the total number of experimental runs (N), which includes the four factorial points (2^k), four

axial points (2k), and five replicated center points (N_0), where k represents the number of independent variables (k = 2).

$$N = 2^k + 2k + N_0 = 4 + 4 + 5 = 13 \qquad \text{(Eq. 3.7)}$$

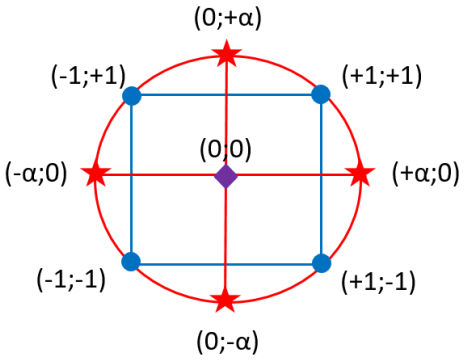

Figure. 3.2 CCD for two factors.

After conducting 13 experimental trials, a second-order polynomial model was applied to describe the linkage between the outcome variables (DOC and turbidity) and the experimental factors (pH and coagulant dosage), as presented in Equation 3.8.

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$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \varepsilon \qquad \text{(Eq. 3.8)}$$

Where Y denotes the predicted values for turbidity and DOC removal, k refers to the number of variables considered, and x_1 and x_2 correspond to pH and coagulant dosage, respectively; β_0 denotes the intercept term, while β_1 and β_2 represent the coefficients of the linear terms; β_{11} β_{22} indicate the second-order (quadratic) coefficients, whereas β_{12} represents the coefficient for the interaction between variables.

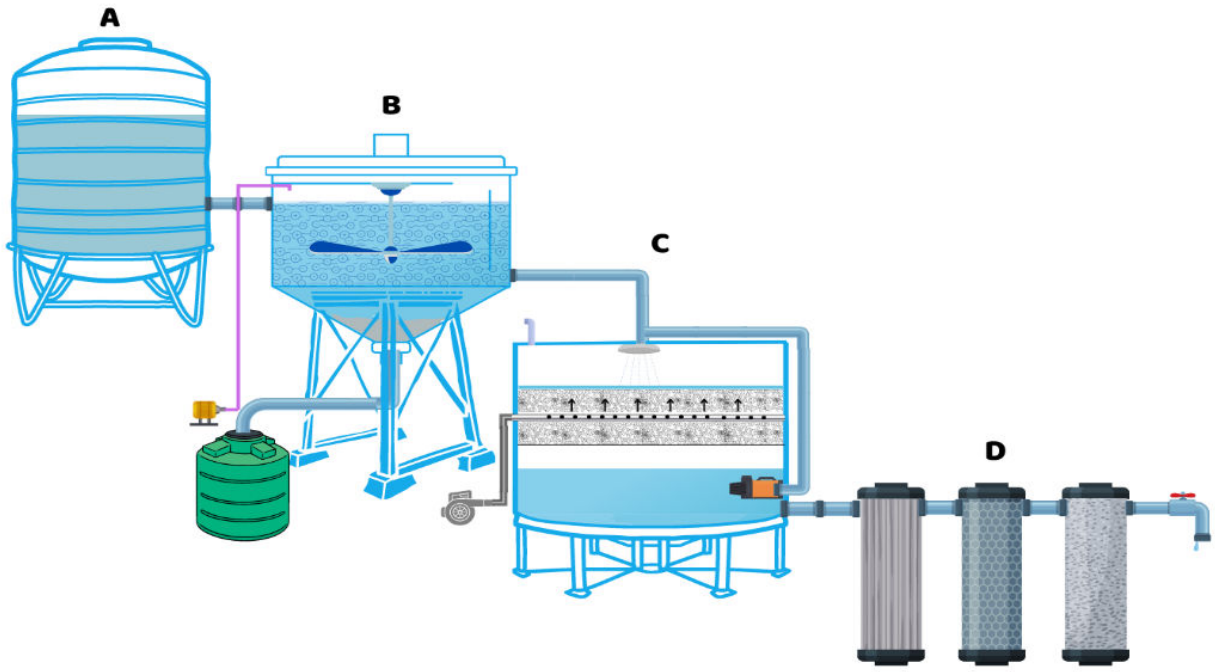

Figure. 3.3 The lab-scale river water treatment system (**A**) input tank, (**B**) coagulation - flocculation reaction tank, (**C**), Aeration tank, (**D**) Filter unit (1 micron polypropylene filter column, activated carbon, and cation ions-exchange).

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The household water treatment system comprises three main elements: coagulation, aeration, and pre-filter units, incorporating a 1-micron filter column of polypropylene, activated carbon, and cation exchange, as illustrated in Figure 3.3. In the coagulation/flocculation tank, which has a total volume of 10 liters, the sample water was mixed using a motor powered by 24V DC at 40 rpm (Autotrol Corporation, USA). The treated water was then transferred to the aeration tank, equipped with a 220V AC circular pump (HG-350, 9W, China) and a 220V AC aerator (ACO-001, 18W, China) to eliminate iron and aluminum residues over a period of 30 minutes. After aeration, the water passed through a filtration unit (Karofi, USA) containing a 1-micron filter of polypropylene, a column of AC and a column of cation ion-exchange.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1. The current status and the factors affecting water quality

4.1.1. The current status of water quality

The physicochemical properties of the river water are presented in Table 4.1 and Figures 4.1 – 4.4. The pH levels of all water samples were within the acceptable limits specified in QCVN 08-MT:2015/BTNMT by the Vietnam Ministry of Natural Resources and Environment (MONRE). A pH range of 6.5 – 9.0 is considered ideal for freshwater ecosystems [120]. Although there were statistically significant differences in pH levels across the sampling locations ($p<0.01$), no significant seasonal variations were observed.

Dissolved oxygen (DO) concentrations exhibited significant seasonal variations (***$p < 0.001$). During the dry season, DO levels at 11 out of 17 locations, and in the early-dry season at 16 out of 17 locations, fell below the guideline values specified in QCVN 08-MT:2015/BTNMT. During the dry season, runoff from farmland and domestic sewage from residential areas may lead to a decrease in DO levels due to the increased oxygen consumption by microbial activity as they break down organic matter [11]. In contrast, during the rainy season, DO levels exceeded the standard value of 5 mg/L at most locations, except for locations 4, 8, and 13, where intensive agricultural activities occur, and locations 14 and 15 in urban areas (An Khe Town). The observed seasonal variations in DO levels can be attributed to temperature and annual rainfall changes, leading to higher DO concentrations in the rainy season compared to the dry season [29], [75].

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Table 4.1. Physicochemical characteristics of Ba River water and spatio-temporal variations.

Parameters	QCVN 08-MT:2015	Unit	Range (Min - Max) from 17 samples each			p value	
			Dry season	Rainy season	Early-dry season	Seasonal	Spatial
pH	6-8.5	-	6.85 - 7.7	6.87 - 7.80	6.89 - 7.7	0.959	0.008**
DO	>5	mg/L	2.99 - 6.18	4.03-6.91	3.21-5.41	0.0004***	0.965
Turbidity	5[(a)]	NTU	1.28 - 16.6	15.5 - 135.4	7.5 - 28.5	<0.0001***	0.219
TSS	30	mg/L	20.1 - 93.7	29.2 - 115.7	12.9 - 41.7	0.0001***	0.969
COD	15	mg/L	15.4 - 55.5	20.7 - 59.5	14.43 - 45.05	0.0212*	0.0592
BOD_5	6	mg/L	7.2 - 23.3	11.7 - 35.48	7.2 - 23.5	0.0002***	0.151
TOC	4[(b)]	mg/L	4.756-12.035	2.167-24.079	1.856-10.515	0.002**	0.0452*
TC	-	mg/L	13.848-30.313	12.284-45.375	9.864-32.385	0.009**	0.303
TN	10[(c)]	mg/L	0.1592-1.84	0.243-1.173	0.205-1.785	0.166	0.0008***
NH_4^+-N	0.3	mg/L	0.011-0.475	0.019-0.453	0.012-0.509	0.278	0.0733
NO_3^--N	5	mg/L	0.01-0.36	0.012-0.296	0.01-0.1625	0.451	0.002**
NO_2^--N	0.05	mg/L	0.008-0.08	0.005-0.07	0.004-0.045	0.199	0.0194*
TP	0.4[(c)]	mg/L	0.03-0.133	0.069-0.655	0.035-0.89	0.0112*	0.146
Mn	0.2	mg/L	ND	0.0551-0.1796	ND-0.041	<0.0001***	0.252
Fe	1	mg/L	0.0953-1.2158	0.02-2.1242	0.1144-1.133	0.0213*	0.0147*

[(a)] WHO guideline value; [(b)]Column A1 – QCVN 08-MT:2015; [(c)] Nutrient criteria for surface water from the values (interquartile range) in use by Member States of the European Union (Poikane et al., 2019); *p< 0.05, Statistically significant difference at **p< 0.01, Statistically significant difference at ***p< 0.001. ND: Non-Detection.

Turbidity and total suspended solids (TSS) levels were found to have a significant correlation with the seasons (p<0.001). During the rainy season, turbidity and TSS values were highest among the seasons among the different seasons, ranging from 15.5 to 135.4 NTU and 29.2 to 115.7 mg/L, respectively. Specifically, locations

4, 5, 8, 9, 11, 13, and 16 often experience severe erosion due to surface runoff from intensive agricultural areas. In contrast, locations 6, 7, 10, 12, 14, and 15 (Ayun Pa, Krong Pa, and Ayun Pa Town) receive stormwater runoff from urban regions during the rainy season. During this time, the turbidity and TSS levels exceeded the threshold limits set by MONRE and WHO guidelines, as increased precipitation led to elevated surface runoff, causing erosion and soil transport [113]. Additionally, the river water during the rainy season was highly diluted and had increased discharge, contributing to elevated turbidity levels [11].

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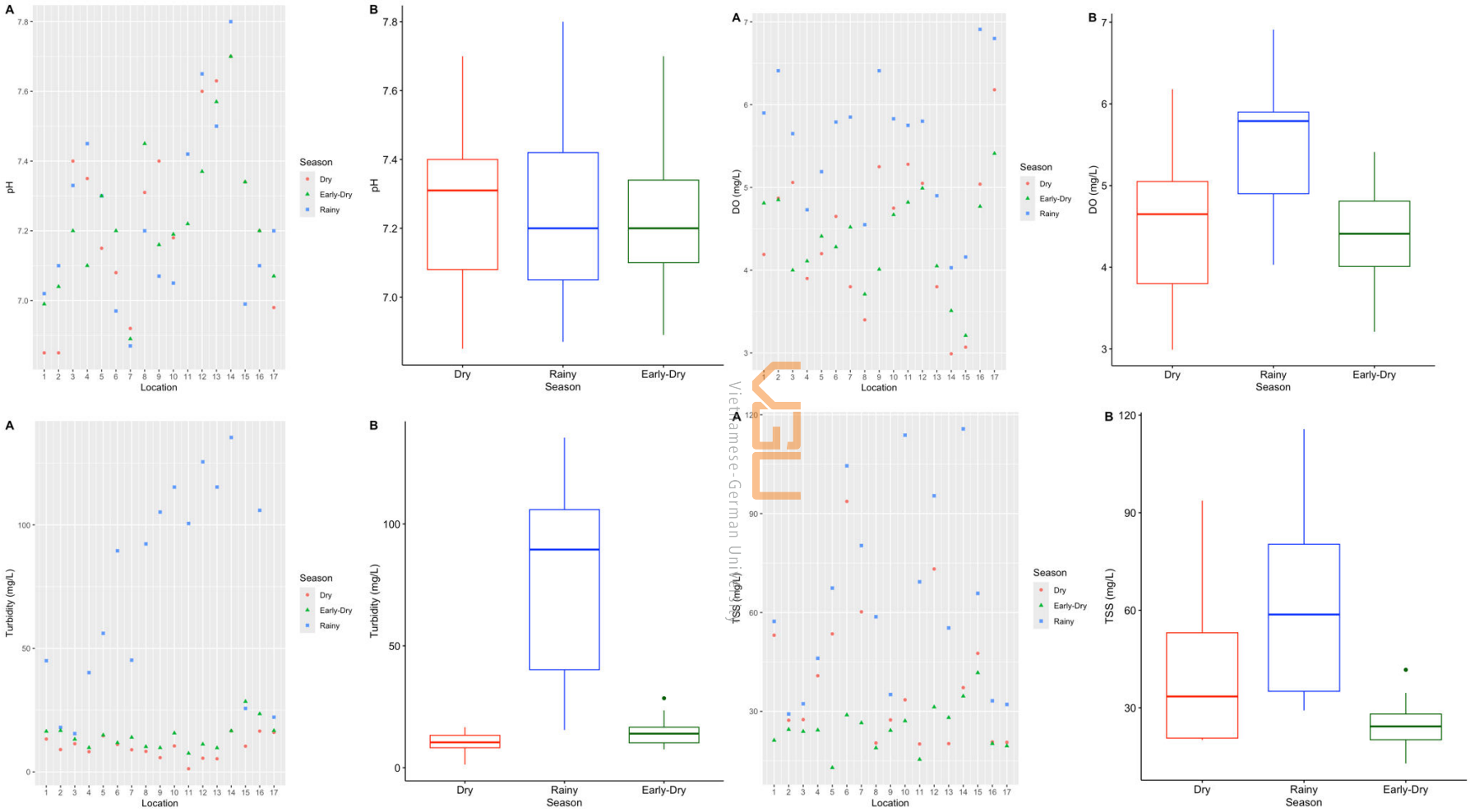

Figure 4.1. Seasonal and spatial variations of some basic parameters at sampling locations (A) spatial variations (B) Temporal variations.

The concentrations of chemical oxygen demand (COD) and biological oxygen demand (BOD_5) exhibited significant seasonal variations, with correlation coefficients of $p<0.05$ and $p<0.001$, respectively. Most COD and BOD_5 values exceeded the acceptable limits established by MONRE, which are 15 mg/L for COD and 6 mg/L for BOD_5. Notably, locations 7, 14, and 15, situated in urban areas, receive direct discharges of stormwater and sewage into the rivers, leading to elevated levels of COD and BOD_5. The introduction of domestic waste or wastewater into the natural environment can result in increased COD and BOD_5 concentrations through both direct (via sewage systems) and indirect pathways (such as surface or subsurface flow) [42]. Furthermore, agricultural activities along the rivers contribute to this issue, as organic matter can leach from cultivated soils during the rainy season due to runoff or irrigation practices [114], [115].

The concentrations of Total Organic Carbon (TOC) were found to be statistically significant both seasonalily ($p < 0.01$) and spatially ($p < 0.05$), while Total Carbon (TC) levels exhibited significant seasonal variations. In both the dry and rainy seasons, most TOC values exceeded the 4 mg/L limit set by the Vietnam Ministry of Health for drinking water (QCVN 01:2009/BYT). Seasonal climate conditions, such as rainfall, can significantly influence the organic matter content in river water due to soil erosion and runoff, which can raise organic carbon concentrations [116]. An expected rise in mean temperature and precipitation is also predicted to increase TOC levels [117]. A study in Brittany, France, observed that TOC fluxes rose in line with river flow rates. Additionally, the application of manure or slurry during the rainy season could contribute to the elevated TOC levels in rivers [118]. Spatially, agricultural runoff (from locations 2, 4, 5, and 8) and urban stormwater (from locations 6, 7, 14, and 15) cause an increase in TOC concentrations during the rainy season [119], while forested areas (locations 11, 16, and 17) contribute to a decrease in TOC levels [116].

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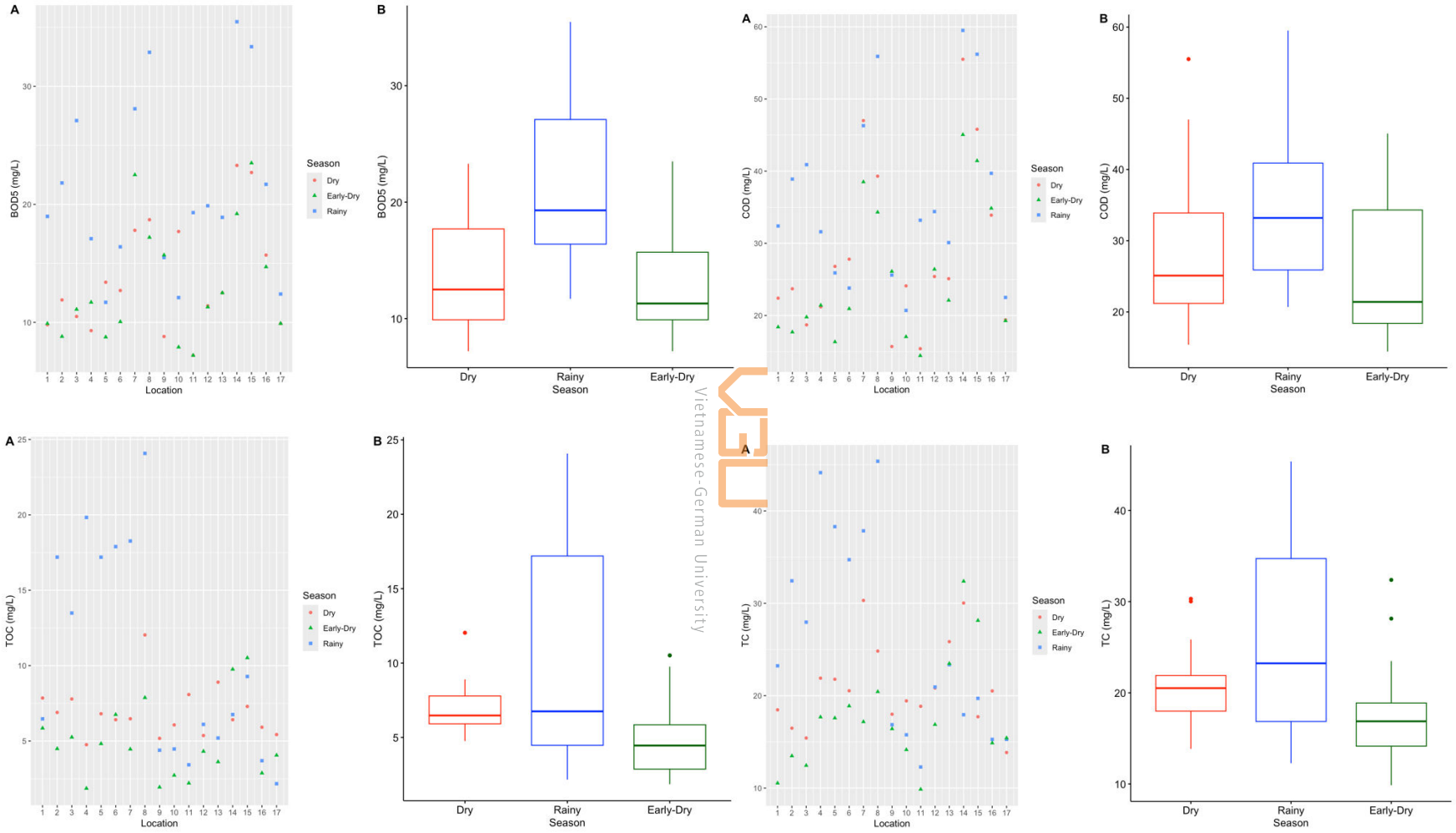

Figure 4.2. Seasonal and spatial variations of organic matter parameters at sampling locations (A) spatial variations (B) Temporal variations.

The levels of TN, NO_2^--N and NO_3^--N were found to have statistically significant spatial variations. Their concentrations were below the standard limits of MONRE but the values in locations 14 and 15 (urban areas) in the dry season, locations 7 and 15 (urban areas and rice cultivation) in the rainy season, and locations 7, 12, and 13 (urban areas and agriculture activities) in the early-dry season were relatively higher than the figures in the other locations. There were no significant seasonal and spatial variations in NH_4^+-N levels but these concentrations were above the standard threshold, such as at location 14 in the dry season, 15 in the rainy season, and 7, 12, and 15 in the early-dry season. The discharge of household wastewater from urban regions at these locations may primarily contribute to their heightened concentrations. Livestock manure, and agricultural runoff along the rivers in these locations can greatly contribute to the NH_4^+-N concentrations [12].

Total Phosphorus (TP) levels showed significant seasonal differences, with higher concentrations during the rainy season. For example, TP levels at locations 2 to 7, where rice farming occurs along the river, ranged from 0.323 to 0.655 mg/L. The increased use of fertilizers in crops, along with the application of animal manure and domestic wastewater from septic tanks, contributes to pollution in the river through runoff and subsurface flows during the rainy season [120].

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Iron concentrations showed significant seasonal and spatial variations ($p < 0.05$), while manganese levels exhibited significant seasonal differences ($p < 0.001$). Iron levels exceeded the MONRE standard at site 15 during the dry and early-dry seasons, and at sites 11, 12, and 14 during the rainy season. In contrast, manganese levels at all locations remained below 0.2 mg/L. The elevated iron levels at site 15 are likely due to domestic and industrial wastewater from the An Khe urban area, while the increased levels at sites 11, 12, and 14 during the rainy season can be attributed to runoff and wastewater. Manganese concentrations were higher during the rainy season than in the early-dry season, primarily due to diffuse sources through runoff. Both metals may originate from soil and rock erosion [121], domestic wastewater, and the excessive use of fertilizers in coffee and rice farming [122], [123]. Additionally, the Latosol (Oxisol)

soil in these locations, which contains high iron content, may release iron through surface runoff or agricultural irrigation [124].

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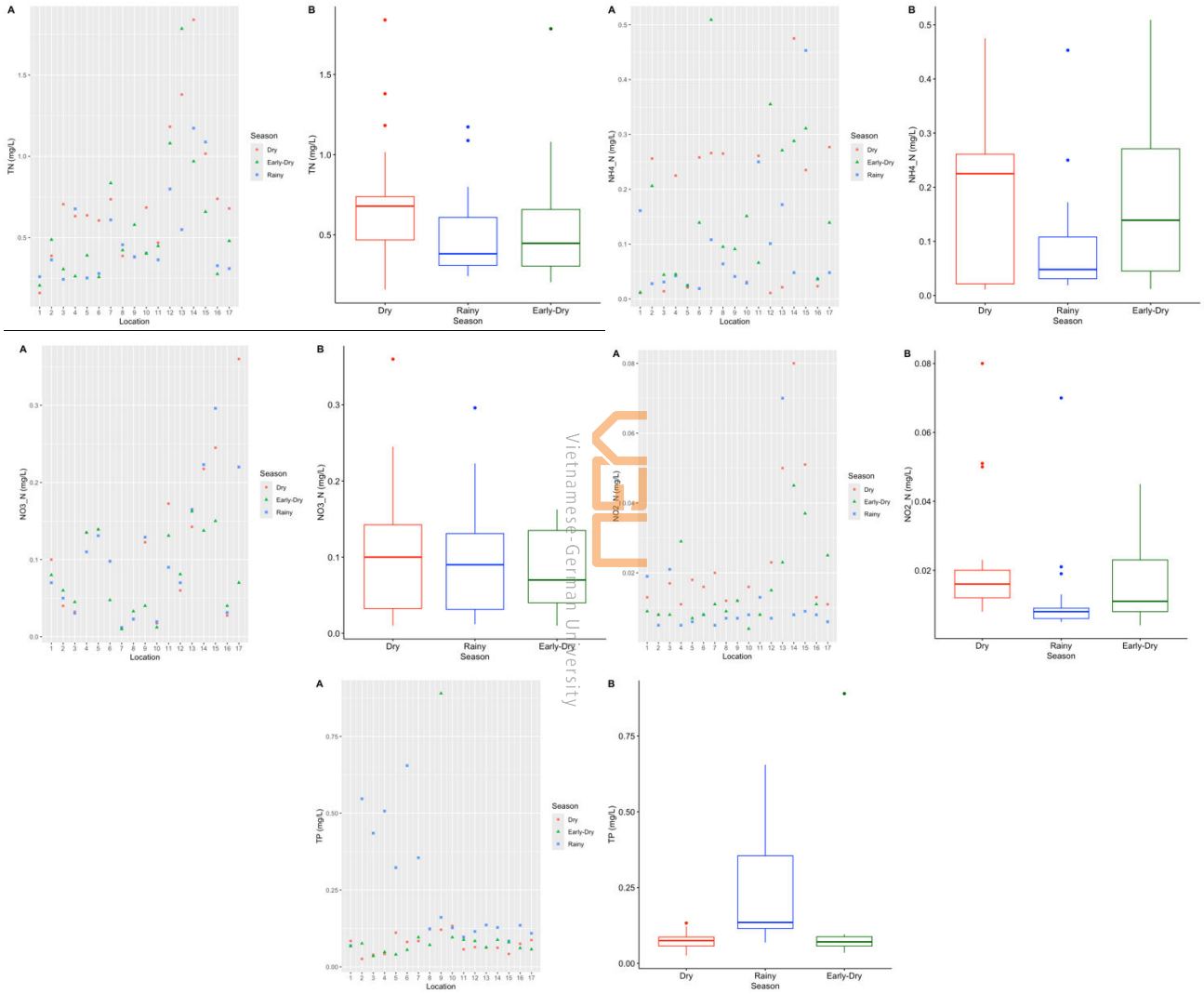

Figure 4.3. Seasonal and spatial variations of nutrient parameters at sampling locations (A) spatial variations (B) Temporal variations.

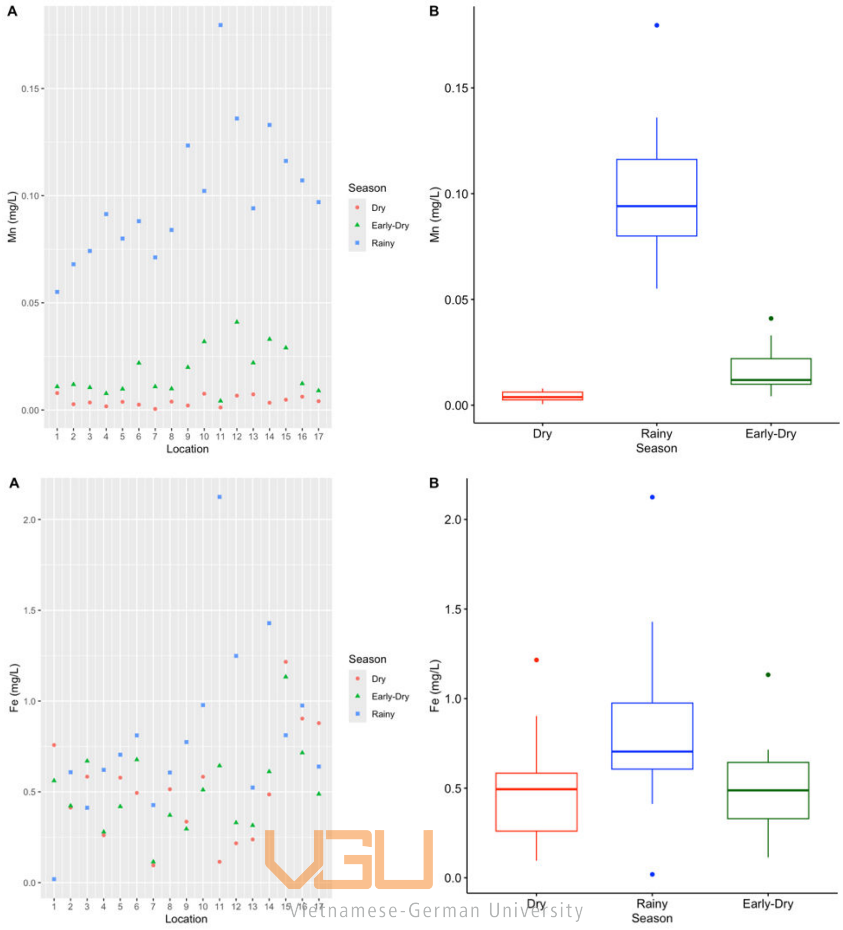

Figure 4.4. Seasonal and spatial variations of heavy metal paramters at sampling locations (A) spatial variations (B) Temporal variations.

When comparing the findings with the annual monitoring data from the Department of Natural Resources and Environment of Gia Lai province for the period 2020–2023 (Figures S2–S9 - Annex), the parameter ranges for pH, DO, TSS, COD, BOD_5, NO_2-N, NH_4 at locations 1, 7, 9, 12, 14, 15, and 17 showed similar trends. Seasonally, DO and TSS concentrations were generally higher during the rainy season. BOD_5 and COD levels fluctuated significantly during the rainy season, but higher concentrations were detected in locations 14 and 15 (An Khe) during the dry season, likely due to increased industrial and domestic waste. Similarly, NO_2-N and NH_4 concentrations from the province's annual monitoring data were higher during the dry season compared to the rainy season (Figures S7 and S8).

Figure 4.5 illustrates the results of the correlation analysis of the physicochemical parameters. The findings indicate a strong positive correlation between COD and BOD_5 ($r = 0.94$, $p < 0.001$), suggesting the presence of biodegradable organic matter in the water, which can consume oxygen and reduce DO levels. However, the relationship between BOD_5 and DO is less clear, showing a weak negative correlation ($r = -0.11$). This might be due to the characteristics of mountainous river basins, such as steep slopes (10.9%) and high elevations [29], which can lead to water disturbance and increased dissolved oxygen, causing DO levels to vary significantly (from 2.99 to 6.91) across study sites. Additionally, TOC levels are strongly positively correlated with TC values ($r = 0.73$, $p < 0.001$), as TOC is a common indicator of organic matter in natural water. Natural organic matter (NOM), produced from the decomposition of plants, animals, and microbes, consists of both hydrophobic and hydrophilic components, with hydrophobic acids making up about 50% of the TOC in water [125]. TN levels show a weak positive correlation with NH_4^+-N ($r = 0.39$, $p < 0.01$) and NO_2-N ($r = 0.37$, $p < 0.01$), but no significant correlation with NO_3^--N, suggesting that organic nitrogen may be a key contributor to TN concentrations [126]. Furthermore, turbidity levels have a strong positive correlation with Mn ($r = 0.82$, $p < 0.001$) and Fe ($r = 0.62$, $p < 0.001$), indicating that soil and rock erosion, along with runoff, are major sources of these metals. Mining activities and excessive fertilizer use also contribute to the increased concentrations of Fe and Mn in river water [121], [122].

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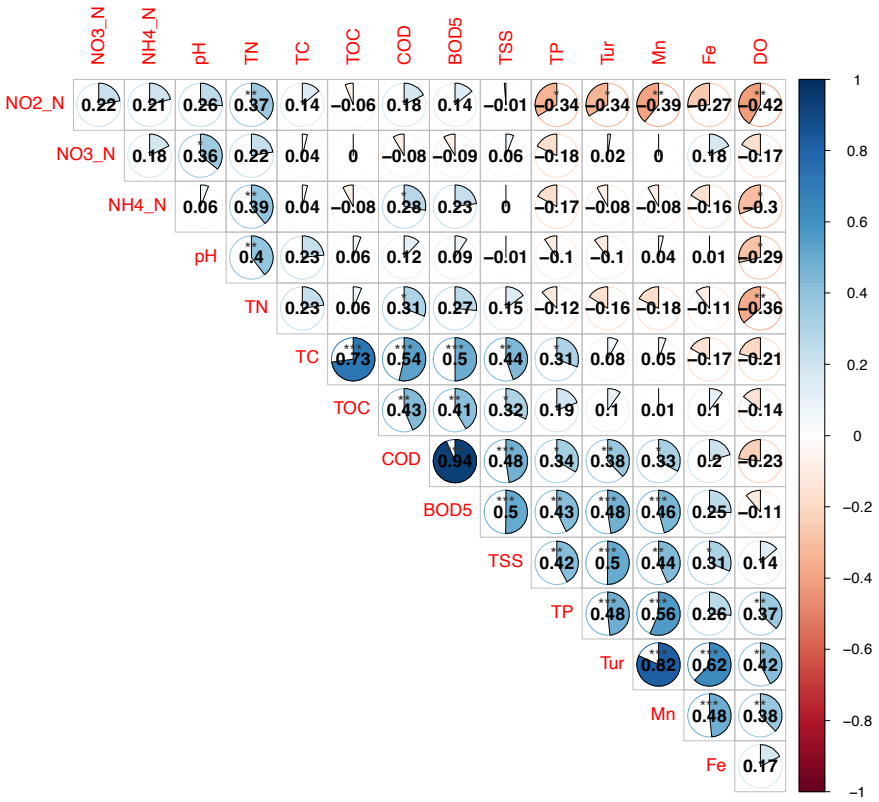

Figure 4.5 Spearman correlation coefficient values between the different water quality parameters.

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The colored gradient legends represent the coefficients of correlation r values from +1.0 (dark blue) to −1.0 (dark red). The color and proportion of the pie charts illustrate the coefficients.

Statistically significant difference at *p < 0.05. Statistically significant difference at **p < 0.01. Statistically significant difference at ***p < 0.001.

Agricultural activities dominate the Ba River Basin, making it essential to analyze pesticide residues in the river water to identify areas where preventive measures should be taken. Pesticide analyses were conducted during both the dry and rainy seasons, but only chlorpyrifos-ethyl and deltamethrin were detected in the rainy season. Chlorpyrifos-ethyl was found at concentrations of 7.4 ng/L at location 4 and 7.6 ng/L at location 15, while deltamethrin was detected at 21.8 ng/L at location 1 and 4.0 ng/L at location 4. However, these levels were below the Australian Drinking Water Guidelines (ADWG) limits for surface water [127].

A case study in the Jiménez River watershed, Costa Rica, was carried out during both the rainy and dry seasons. Three sites showed no signs of agricultural impact, while four sites were affected by nearby pineapple plantations. The study found that average chlorpyrifos concentrations ranged from 1 ng/L to 26 ng/L, with pesticide use in the pineapple fields identified as the primary contributing factor [128]. Chlorpyrifos-ethyl is one of the most commonly used insecticides in Vietnamese agriculture, especially for rice cultivation [129]. A study in the Mekong Delta, where farmers sprayed pesticides at typical concentrations, found much higher levels of chlorpyrifos-ethyl (4230–5250 ng/L) in water just after 1h application for rice crops, although levels dropped below detection within three days [130]. Rice is frequently grown in areas along the Ba River, and pesticide residues from these fields can enter the river through runoff or irrigation. Deltamethrin, a pyrethroid insecticide, has been commonly used for pest control in the Central Highlands and other parts of Vietnam since the 1990s. [131]. A study on the Chenab River in Pakistan discovered significantly higher levels of deltamethrin, with concentrations reaching up to 108 ng/L. The increased pesticide levels were primarily attributed to agricultural and commercial activities [132]. The water in the Ba River at locations 1 (a rural area) and 4 (suburban areas) was primarily influenced by plantation crops such as rice, coffee, and rubber. Table 4.2 provides the analytical results of pesticide residues in the Ba River.

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Table 4.2. Screening pesticide residues in mid dry and mid rainy seasons.

Pesticides (µg/L)	**Dry season**	**Rainy season**				**Standards**	
	All locations	**01**	**04**	**15**	**The other locations**	**ADWG (µg/L)**	**QCVN 08-MT :2015/ BTNMT**
Dimethoate	ND	ND	ND	ND	ND	7	
Chlorpyrifos	ND	ND	**0.0074± 0.00036**	**0.0076± 0.00025**	ND	10	
Quinalphos	ND	ND	ND	ND	ND	-	

Profenofos	ND	ND	ND	ND	ND	0.3	
Lambda-Cyhalothrin	ND	ND	ND	ND	ND		
Cypermethrin	ND	ND	ND	ND	ND	200	
Deltamethrin	ND	**0.0218± 0.00096**	**0.004± 0.0002**	ND	ND	40	
Aldrin	ND	ND	ND	ND	ND	0.3	0.1
Isoprothiolane	ND	ND	ND	ND	ND	-	
DDT-p.p'	ND	ND	ND	ND	ND	9	1
DDT-o,p'	ND	ND	ND	ND	ND	9	1

ND: None detection; ADWG: Australian Drinking Water Guideline [127].

4.1.2. Cluster analysis for the spatial grouping of the sampling locations

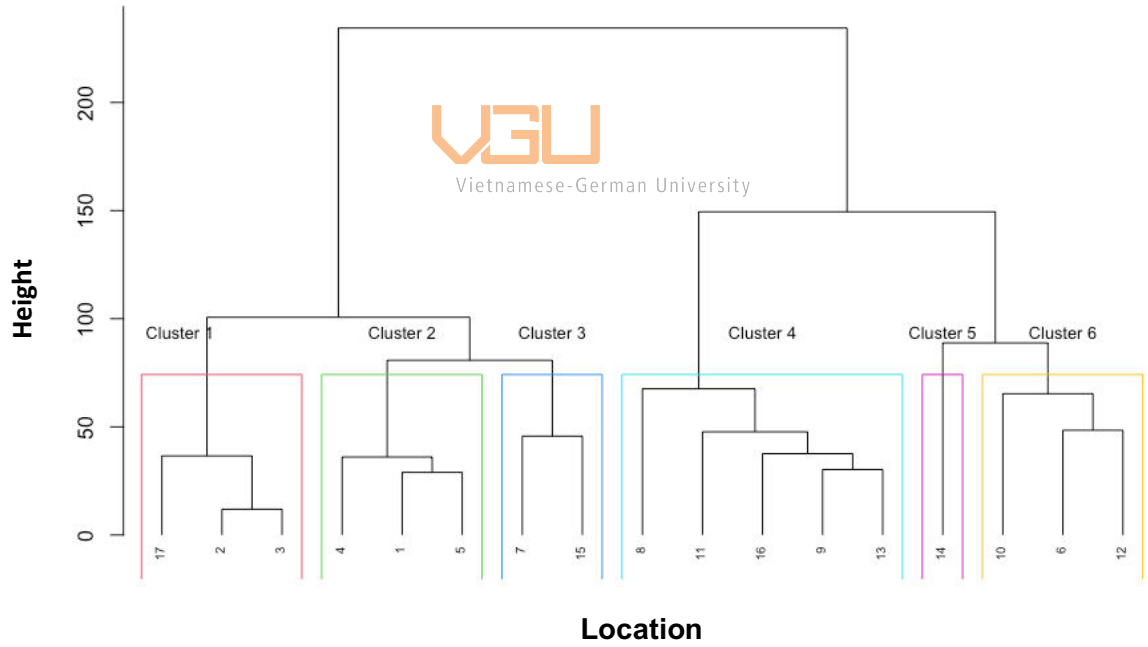

Figure 4.6. Clustering of sampling locations in Ba River Basin following the cluster analysis.

Hierarchical cluster analysis (HCA) was conducted using Euclidean distance and the Ward method to group the sampling locations based on similar physicochemical characteristics in the river water. Ward's minimum variance method was applied, with dissimilarities squared prior to performing the clustering. The resulting clusters, shown in Figure 4.6, reflect similar land use patterns and characteristics. Based on the

physicochemical data, the sampling locations were divided into six clusters. Cluster 1 (locations 2, 3, and 17) includes rural areas with small villages, agricultural activities, and forested regions, and is categorized as having low pollution levels. Cluster 2 (locations 1, 4, and 5) is considered to have a medium pollution level and includes suburban areas with residential zones, intensive agriculture, and sand mining. Cluster 3 (locations 7 and 15) is classified as highly polluted, with these sites being near urban areas, intensive farming, and industrial activities. Cluster 4 (locations 8, 9, 11, 13, and 16) features areas dominated by agricultural activities and is rated as having medium pollution. Locations 8 and 16 are hydrological dams, while locations 9, 11, and 13 are rural areas with small communities, agriculture (crops and livestock), and forested land. Cluster 5 (location 14) is an urban area with dense residential and industrial activities and is categorized as highly polluted. Cluster 6 (locations 6, 10, and 12) consists of urban regions with residential, industrial, and agricultural activities and is classified as having a moderate pollution level.

To validate the stability of clusters in hierarchical clustering analysis, the average Jaccard coefficient was used to evaluate the selected clusters. The stability of each cluster from the initial clustering was assessed based on the average Jaccard coefficient across all bootstrap iterations. Clusters with a stability value below 0.6 are considered unstable, while those with stability ratings of 0.85 or higher are classified as highly stable [133], [134]. The R package (pfc) was utilized to assess clustering stability for six clusters (K=6) using the resampling method (hclustCBI). This method serves as an interface for the hclust function, which performs agglomerative hierarchical clustering with the option for noise clusters, and involves 100 resampling runs for each scheme (B=100). The average Jaccard coefficients (γ) and the instability of the clusters (i) indicate that Cluster 1 (γ=0.81, i=0.19), Cluster 2 (γ=0.82, i=0.23), Cluster 3 (γ=0.74, i=0.31) and Cluster 5 (γ=0.78, i=0.3) and Cluster 6 (γ=0.74, i=0.44) are medium stable clusters, while it is noticeable that Cluster 4 (γ=0.56, i=0.49) is unstable. The instability of Cluster 4 may be attributed to significant variations in the physicochemical parameters of the river water at the sampling locations. These findings offer an overview of the monitoring sites and suggest a strategy for reducing the number of

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monitoring locations in the Ba River Basin. For Cluster 4, further research is required to determine which sites should be prioritized for monitoring. Hierarchical Cluster Analysis (HCA) is a valuable tool for classifying sampling locations based on water quality characteristics, aiding in the selection of monitoring sites within the Ba River Basin. This approach could result in cost savings for water quality monitoring and provide an effective method for managing river water quality. Similar strategies have been successfully implemented in water quality monitoring programs in previous research [75], [82], [135].

4.1.3. Water Quality Index (WQI)

4.1.3.1. Principal Component Analysis for defining weights

The KMO value for the current dataset was 0.65, and the Bartlett's test of sphericity yielded a result of 2,986.2 (p-value < 0.001), indicating that the dataset is appropriate for performing Principal Component Analysis (PCA). The PCA identified the first four principal components (PCs) with eigenvalues greater than one, collectively accounting for over 73% of the total variance in the dataset. Furthermore, this step assessed which water quality parameters significantly influenced the patterns of water quality in the Ba River basin. The loadings obtained from the PCA illustrate the relationships between the variables and the principal components.

The chosen parameters include pH, DO, Tur, COD, TSS, BOD_5, TOC, TN, NH_4^+-N, NO_2^--N, TP, and Fe (Table 4.3). TC parameter was not selected because of a strong correlation with the TOC, and Mn and NO_3^--N levels were also excluded due to being below the MONRE recommended thresholds. Following the PCA analysis, 12 principal components (PCs) were extracted, and the selection criteria included a cumulative contribution to overall variance of at least 60% and eigenvalues of the components of 1.0 or higher [101], [136]. The loadings for the first four PCs are presented in Table S2. For these four PCs, factor loadings greater than 0.35 (either positive or negative) were selected to calculate the weights and the final Water Quality Index (WQI).

Table 4.3. Squared loadings of PCs, communality and weights in WQI calculation.

Squared loadings	PC1	PC2	PC3	PC4	Communality	Contribution (%)	Weights
pH	0.073	0.000	0.083	0.367	0.523	14	0.14
DO	0.192	0.042	0.008	0.031	0.273	07	0.07
Tur	0.079	0.064	0.169	0.002	0.314	08	0.08
COD	0.017	0.308	0.011	0.013	0.350	09	0.09
BOD_5	0.000	0.311	0.010	0.009	0.330	09	0.09
TOC	0.026	0.105	0.204	0.067	0.402	11	0.11
TN	0.182	0.005	0.005	0.012	0.204	05	0.05
NH_4^+-N	0.130	0.005	0.007	0.365	0.506	13	0.13
NO_2^--N	0.167	0.000	0.006	0.036	0.209	06	0.06
TP	0.071	0.002	0.189	0.094	0.357	09	0.09
Fe	0.027	0.050	0.253	0.002	0.331	09	0.09
Total					**3.799**	**100**	**1.00**

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In this study, communality, defined as the sum of the squared loadings of the principal components (PCs) for each variable, was used to determine the weights. Variables with higher communality values made more significant contributions to the PCs [136]. The highest communality value was observed for pH (0.523), assigning it the greatest weight (0.14), while NO_2-N had the lowest communality value (0.209), giving it the smallest weight (0.06). The allocation of relative weights was based on each variable's percentage contribution to the total communality. Table 4.3 presents the squared loadings, communality values, and relative weights.

4.1.3.2. Determination of sub-index values

The method of calculating sub-index values based on standard guideline thresholds has been applied in numerous studies [72], [74]. A simple linear interpolation was used to calculate the sub-index values, as shown in Equation 4.1. The guideline values from QCVN 08:2015-MT/BTNMT were utilized to establish the linear equations presented in Table 4.4. For the DO parameter, the saturation level at 20°C and 760 mmHg air pressure is 9 mg/L, with algal synthesis in eutrophic waters occurring at

concentrations above 9 mg/L. The sub-index (y) was calculated as 100 for DO concentrations between 6 and 9 mg/L (Equations 4.2 and 4.3). Equations 4.4 and 4.5 were used to form the DO linear equation for concentrations between 9 and 12 mg/L. For pH, the sub-index equals 100 within the range of 6 to 8.5 (Class A1 and A2 – QCVN 08-MT:2015/BTNMT). However, the second sub-index for pH was set to 1 for values below 5.5 (Class B1) or above 9 (Class B2) [74].

$$y = a \times x + b \quad \text{(Eq. 4.1)}$$

$$100 = a \times (\text{limit of Class A1}) + b \quad \text{(Eq. 4.2)}$$

$$1 = a \times (\text{limit of Class B2}) + b \quad \text{(Eq. 4.3)}$$

$$100 = a + b \times 9 \quad \text{(Eq. 4.4)}$$

$$1 = a + b \times 12 \quad \text{(Eq. 4.5)}$$

Table 4.4. The limits and linear equations for each parameter.

Parameters	**Unit**	**Standard (QCVN 08-MT:2015)**				**Linear Equations (q_i)**
		A1	**A2**	**B1**	**B2**	
pH	-	6-8.5	6-8.5	5.5 – 9.0	5.5 – 9.0	(pH= 5.5-6) $y = 198x - 1088$ (pH=8.5-9) $y = -198x + 1783$
DO	mg/L	≥ 6	≥5	≥ 4	≥ 2	(DO= 2-6) $y = 24.75x - 48.5$ (DO = 9 – 12) $y = -33x + 397$
Tur[(a)]	mg/L	2-100				$y = -1.0102x + 102.0204$
COD	mg/L	10	15	30	50	$y = -2.475x + 124.75$
BOD_5	mg/L	4	6	15	25	$y = -4.7143x + 118.8571$
TOC[(b)]	mg/L	4 – 150				$y = -0.6781x + 102.7123$
TN[(c)]	mg/L	0.4 – 10				$y = -10.3125x + 104.125$
NH_4^+-N	mg/L	0.3	0.3	0.9	0.9	$y = -165x + 149.5$
NO_2^--N	mg/L	0.05	0.05	0.05	0.05	$> 0.05(q_i=1); \leq 0.05(q_i=100)$
TP[(d)]	mg/L	0.035-0.4				$y = -271.2329x + 109.4932$
Fe	mg/L	0.5	1	1.5	2.0	$y = -66x + 133$

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[a] Lower Limit (2mg/L – QCVN 01:2009/BYT – National technical regulation for drinking water quality); Upper Limit referenced at [12], [137].

[b] TOC value limits: 4 – 150 (bad quality of surface water. Decision 1460/QĐ-TCMT - VEA).

[c] [d] Nutrient criteria for surface waters under the European Water Framework Directive [138].

4.1.3.3. WQI calculation

The multiplicative aggregation function (Eq. 3.2) is one of the most widely used methods for calculating final water quality index (WQI) values [139], [140]. This approach was employed to assess WQI levels in the Ba River. The results indicated that water quality in the dry and early-dry seasons was better compared to the rainy season. Heavy rainfall contributed to runoff, causing erosion and the introduction of nutrients and pollutants into the river. As a result, concentrations of key water quality parameters, including turbidity, COD, BOD_5, TOC, TN, and TP, were higher during the rainy season compared to the other two seasons. Approximately 54.9% of WQI values fell within the "Excellent" and "Good" categories, while 21.6% were classified as "Moderate" and 23.5% as "Poor," as shown in Table 4.5.

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Table 4.5. Water quality index values in three seasons.

Location	Dry season	Rainy season	Early-dry season
1	86 – Good	79 – Good	90 – Good
2	90 – Good	49 – Poor	91 – Excellent
3	91 – Excellent	37 – Poor	88 – Good
4	89 – Good	52 – Medium	88 – Good
5	83 – Good	72 – Medium	92 – Excellent
6	86 – Good	48 – Poor	88 – Good
7	67 – Medium	42 – Poor	73 – Medium
8	72 – Medium	33 – Poor	78 – Good
9	92 – Excellent	58 – Medium	56 – Medium

10	82 – Good	60 – Medium	91 – Excellent
11	95 – Excellent	37 – Poor	93 – Excellent
12	89 – Good	51 – Medium	91 – Excellent
13	85 – Good	42 – Poor	86 – Good
14	37 – Poor	26 – Poor	67 – Medium
15	44 – Poor	41 – Poor	61 – Medium
16	80 – Good	49 – Poor	81 – Good
17	90 – Good	88 - Good	92 – Excellent

HCA clusters reveal that agricultural activities (fertilizer and pesticide use) and urban wastewater are primary pollution drivers. WQI quantifies this impact, showing that sites near urban centers (Ayun Pa, and An Khe bus station) and agricultural zones (Ayun commune, and Phu Thien) have lower WQI scores, indicating higher pollution. The presence of pesticides like chlorpyrifos and deltamethrin at specific locations (Ayun commune, Cau Phu Thien, An Khe bus station) during the rainy season is a key finding from HCA, corroborated by WQI's indication of degraded water quality at these sites.

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4.1.3.4. Comparing to VN_WQI in the rainy season

According to Decision 1460/QĐ-TCMT – VEA, at least three out of five parameter groups must be selected for the VN_WQI calculation. Therefore, heavy metals such as As, Cr^{6+}, and Cu (Group III), which were analyzed during the rainy season, were included in the WQI calculation alongside Group I (pH) and Group IV (DO, BOD_5, COD, TOC, NH_4^+-N, NO_3^--N, NO_2^--N). At all sampling sites, the concentrations of As, Cr^{6+}, and Cu remained below the MONRE guideline limits of <0.02 mg/L, <0.02 mg/L, and <0.2 mg/L, respectively. The results (Table 4.6) showed significant differences between the WQI and VN_WQI values in the rainy season, likely due to the different sets of parameters used in each calculation. The applied WQI provided a more accurate reflection of the actual water quality during the rainy season, as it allowed for flexibility in parameter selection through PCA. Among the parameters of the VN_WQI calculation, As, Cr^{6+}, Cu, and NO_3^--N levels were within acceptable limits, contributing to the higher WQI values. However, the parameters of TN, TP, Tur,

and Fe were used to calculate the applied WQI, varied significantly among the three seasons. Thus, the WQI using PCA better represented the actual water quality in the Ba River Basin. These findings align with previous research in another region of Vietnam [74].

Table 4.6. Comparisons of applied WQI and VN_WQI values in the rainy season.

Location	WQI	VN-WQI	Difference (-/+)
1	79 – Good	75 – Medium	4
2	49 – Poor	70 – Medium	-21
3	37 – Poor	68 – Medium	-31
4	52 – Medium	69 – Medium	-17
5	72 – Medium	74 – Medium	-2
6	48 – Poor	74 – Medium	-26
7	42 – Poor	66 – Medium	-24
8	33 – Poor	60 – Medium	-27
9	58 – Medium	82 – Good	-24
10	60 – Medium	83 – Good	-23
11	37 – Poor	79 – Good	-42
12	51 – Medium	75 – Medium	-24
13	42 – Poor	63 – Medium	-21
14	26 – Poor	65 – Medium	-39
15	41 – Poor	59 – Medium	-18
16	49 – Poor	79 – Good	-30
17	88 - Good	85 – Good	3

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4.2. Calculating pollution load and carrying capacity of the Ba River

Table 4.7 and Figure 4.7 shows water quality of Ba River in the period 2020 – 2023 that were used in the calculation of carrying capacity. Ba River was divided into four sections including section 1 (from Phu Thien District to Ayun Pa Town), section 2 (from Kbang District to An Khe Town), section 3 (from Dak Doa District to Ia Pa District), and section 4 (from Ayun Pa to Krong Pa)

Table 4.7 Water quality of Ba River in the period 2020 – 2023 (the results from the anual monitoring programs in Gia Lai Province).

Parameter / Location	TSS	COD	BOD_5	Nitrit	Amoni
River section 1					
L1					
2020	32.14	24.25	16.25	0.0655	0.6
2021	52.69	25	13.17	0.03	0.42
2022	66	32	20	0.02	0.15
2023	20	13	7	0.011	0.03
L7					
2020	38.28	27.17	18	0.065	0.541
2021	49.02	22	13.5	0.03	0.52
2022	48	26	16	0.02	0.2
2023	24	12	7	0.036	0.02
River section 2					
L14					
2020	32.14	24.25	16.25	0.0655	0.6
2021	41.79	27.5	17	0.05	0.43
2022	63	29	19	0.03	0.2
2023	20	13	6	0.175	0.13
L15					
2020	43	30	21	0.02	0.22
2021	56.32	29	15.33	0.04	0.64
2022	64	34	22	0.03	0.18
2023	27	19	8	0.01	0.02
L17					
2020	31.8	30	20	0.0317	0.6
2021	45.35	22.33	14.33	0.02	0.3371
2022	64	27	14	0.046	0.14
2023	14	11	6	0.012	0.15
River section 3					
L12					
2020	36.25	27	18	0	0.356
2021	42.94	24.33	11.83	0.02	0.4
2022	50	29	18	0.01	0.18
2023	22	14	8	0.029	0.06
River section 4					
L9					
2020	35.83	25.17	16.83	0.073	0.723
2021	51.48	22.5	13.67	0.02	0.47
2022	51	26	15	0.02	0.2
2023	26	16	8	0.013	0.03

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Point sources of pollution along Ba River were collected from Gia Lai DONRE including the water flow and water quality in Table 4.8.

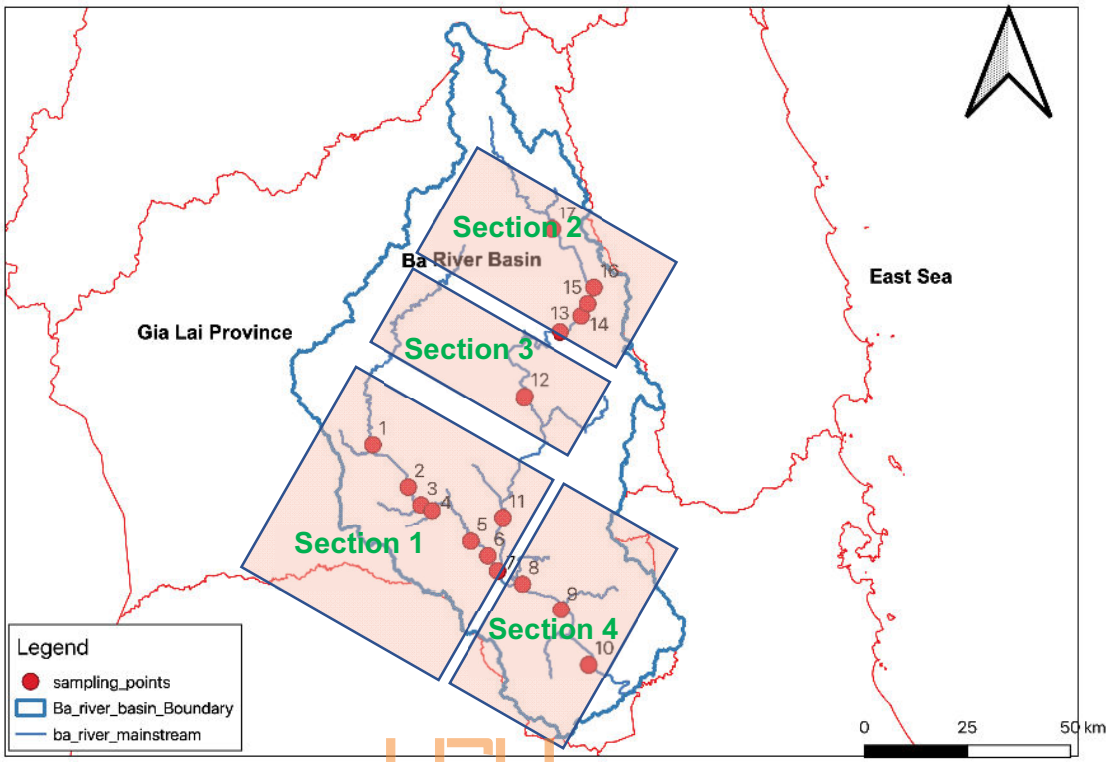

Figure 4.7 Four sections to calculating pollution load in Ba River Basin

Figure. 4.7 Four sections to calculating pollution load in Ba River Basin

Table 4.8. Point sources of pollution in Ba River.

Discharge Location	Field/sources	Flow (m^3/day)	BOD	COD	NO_2	NH_4	TSS
River Section 1							
AyunPa	Sugar production	3120	34,3	63,48	0,2665	1,49	62
Phu Thien	Domestic wastewater	220	33	41	0,22	1,22	45
Ayun Pa	Domestic wastewater	450	30	37	0,223	1,31	42,2
Total		3790					
River Section 2							
An Khe	Tapioca Starch production	1000,8	45	134	2,022	2,55	89
An Khe	Sugar production	4860	44	67,1	0,2	0,9	68,5
An Khe	Domestic wastewater	850	37	46,4	0,253	1,42	45,5
Total		6710,8					
River Section 3							
Ia Pa	Tapioca Starch production	1951,2	90	124	0,98	2,85	95
River Section 4							

Krong Pa	Tapioca Starch production	2500,8	32,29	79,67	0,721	1,29	71

Table 4.9 shows carrying capacity of pollution load in four sections of Ba River. The concentration of most parameters exceed the carrying capacity of pollution load, except TSS. River water in four sections can receive more TSS load 13,195 kg/day (Section 1), 3,584 kg/day (Section 2), and 6,481 kg/day (Section 3), 8,392 kg/day (Section 4),. While COD, BOD_5, NO_2, and NH_4 load values exceed maximun carrying capacity, and Ba river can get more NO_2 load in section 3 about 3 kg/day.

Table 4.9. Carrying capacity of pollution load in Ba River.

Parameter	$Q_{rw.min}$ (m3/s)	$Q_{ww.max}$ (m3/s)	C_{thr} (mg/L)	C_p (mg/L)	$C_{w.max}$ (mg/L)	L_{max} (kg/day)	L_{avail} (kg/day)	L_{dis} (kg/day)	L_{re} (kg/day)
Section 1 (Phu Thien – Ayun Pa)									
TSS	44.87	0.044	100	66	62	388,057	255,867	236	**13,195**
COD	44.87	0.044	15	32	63.48	58,209	124,057	241	**-6,609**
BOD_5	44.87	0.044	6	20	34.3	23,283	77,535	130	**-5,438**
NO_2	44.87	0.044	0.05	0.0655	0.2665	194	254	1	**-6**
NH_4	44.87	0.044	0.3	0.42	0.66	1,164	1,628	3	**-47**
Section 2 (Kbang – An Khe)									
TSS	11.5	0.078	100	64	89	100.034	63.590	600	**3.584**
COD	11.5	0.078	15	34	134	15.005	33.782	903	**-1.968**
BOD_5	11.5	0.078	6	22	45	6.002	21.859	303	**-1.616**
NO_2	11.5	0.078	0.05	0.175	40.44	50	174	273	**-40**
NH_4	11.5	0.078	0.3	0.64	5.82	300	636	39	**-38**
Section 3 (Dak Doa – Ia Pa)									
TSS	15	0.023	100	50	95	129,799	64,800	189	**6,481**
COD	15	0.023	15	29	124	19,470	37,584	246	**-1,836**
BOD_5	15	0.023	6	18	90	7,788	23,328	179	**-1,572**
NO_2	15	0.023	0.05	0.029	0.98	65	38	2	**3**
NH_4	15	0.023	0.3	0.4	2.85	389	518	6	**-13**
Section 4 (Ayun Pa – Krong Pa)									
TSS	20	0.029	100	51,48	71	173,051	88,957	178	**8,392**
COD	20	0.029	15	25.17	79.67	25,958	43,494	200	**-1,774**
BOD_5	20	0.029	6	16.83	32.29	10,383	29,082	81	**-1,878**
NO_2	20	0.029	0.05	0.073	0.721	87	126	2	**-4**
NH_4	20	0.029	0.3	0.72	1.29	519	1,244	3	**-73**

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4.3. Testing of surface water treatment technology

In the Ba River Basin, DOC and turbidity were selected as key parameters for water treatment testing due to their prominence as pollution indicators. HCA and WQI supported the results from water quality analysis, indicating organic contamination from urban wastewater and agricultural runoff. These parameters significantly affect water clarity and safety for domestic use, with DOC posing risks of harmful disinfection byproducts. Table 4.10 shows the result of the input water of the coagulation and flocculation experiment and the laboratory-scale water treatment system.

Table 4.10 Characteristics of raw water in Ba River.

Paramters	**Turbidity (NTU)**	**UV_{254} (cm^{-1})**	**DOC (mg/L)**	**SUVA ($m^{-1}mg^{-1}L$)**	**pH**
Range	11.2-11.8	0.116-0.119	3.83-3.91	3.03-3.04	6.95-7.04

Table 4.11 presents the experimental outcomes generated under the conditions of CCD. In general, the experiments demonstrated that the coagulation-flocculation process achieved high removal efficiency, with over 50% of dissolved organic carbon and over 90% of turbidity levels being removed from river water. These results highlighted the percentage reductions in DOC and turbidity, which were used as input data for the response surface methodology (RSM) models.

Table 4.11. Experimental setup and outcomes for the efficiency of DOC and turbidity removal.

Run	**pH (X_1)**	**Dosage (X_2)**	**PAC (% removal)**		**PFS (% removal)**		**Alum (% removal)**	
			DOC	**Turbidity**	**DOC**	**Turbidity**	**DOC**	**Turbidity**
1	5.5	30	31.88	87.13	45.99	80.35	23.16	82.52
2	8.5	30	52.96	89.39	41.11	76.43	28.33	86
3	5.5	90	19.23	83.39	36.99	39.57	22.62	82.52
4	8.5	90	36.92	88.26	24.55	70.26	30.82	84.26

5	4.9	60	16.92	82.96	41.47	48.87	20.05	83.48
6	9.1	60	41.57	87.22	35.71	74.61	27.69	85.22
7	7	17.6	43.44	92.17	38.02	83.48	23.14	85.13
8	7	102.4	23.21	85.65	26.61	60.78	30.85	79.74
9	7	60	47.81	86	52.39	85.3	36.58	87.65
10	7	60	44.58	87.22	44.58	87.74	35.42	86.35
11	7	60	44.65	87.04	43.73	87.83	38.28	85.57
12	7	60	46.35	86.09	47.12	84.78	38.38	86.96
13	7	60	48.28	86.09	45.99	87.39	35.76	86.09

4.3.1 Statistical evaluation and formulation of the regression model equation

Mathematical models describing DOC and turbidity elimination were established by examining the interactions between pH and coagulant dosage. These relationships were represented through second-order polynomial equations (Eq. 2.7). The resulting quadratic regression analysis provided specific equations for turbidity and DOC elimination, detailed in Equations 4.6 to 4.11.

$$Y_{DOC\ (PAC)} = -176{,}76 + 54{,}268X_1 + 0{,}628X_2 - 3{,}357X_1^2 - 0{,}006X_2^2 + 0{,}019X_1X_2 \quad \text{(Eq. 4.6)}$$

$$Y_{DOC\ (PFS)} = -52 + 23{,}166X_1 + 1{,}026X_2 - 1{,}626X_1^2 - 0{,}008X_2^2 - 0{,}042X_1X_2 \quad \text{(Eq. 4.7)}$$

$$Y_{DOC\ (Alum)} = -129{,}69 + 40{,}248X_1 + 0{,}568X_2 - 2{,}803X_1^2 - 0{,}005X_2^2 + 0{,}017X_1X_2 \quad \text{(Eq. 4.8)}$$

$$Y_{Tur\ (PAC)} = 78{,}322 + 4{,}509X_1 - 0{,}323X_2 - 0{,}306X_1^2 - 0{,}001X_2^2 + 0{,}015X_1X_2 \quad \text{(Eq. 4.9)}$$

$$Y_{Tur\ (PFS)} = -151{,}28 + 71{,}534X_1 - 0{,}7X_2 - 5{,}558X_1^2 - 0{,}008X_2^2 - 0{,}192X_1X_2 \quad \text{(Eq. 4.10)}$$

$$Y_{Tur\ (Alum)} = 51{,}261 + 7{,}311X_1 + 0{,}287X_2 - 0{,}435X_1^2 - 0{,}002X_2^2 - 0{,}01X_1X_2 \quad \text{(Eq. 4.11)}$$

Table 4.12. Actual and predicted elimination efficiencies.

Run	PFS (% removal)				PAC (% removal)				PFS (% removal)			
	DOC Act.	DOC Pre.	Tur. Act.	Tur. Pre.	DOC Act.	DOC Pre.	Tur. Act.	Tur. Pre.	DOC Act.	DOC Pre.	Tur. Act.	Tur. Pre.
1	45.99	42.81	80.35	77.43	31.88	30.38	87.13	87.79	23.16	21.96	82.52	83.38
2	41.11	40.23	76.43	75.92	52.96	50.48	89.39	89.77	28.33	26.49	86	86.17
3	36.99	36.17	39.57	40.36	19.23	17.75	83.39	82.96	22.62	23.66	82.52	81.91
4	24.55	26.02	70.26	73.46	36.92	34.46	88.26	87.56	30.82	31.22	84.26	82.96
5	41.47	43.95	48.87	50.43	16.92	18.21	82.96	82.79	20.05	20	83.48	83.21
6	35.71	34.94	74.61	72.77	41.57	44.24	87.22	87.44	27.69	28.54	85.22	85.92
7	38.02	40.54	83.48	85.96	43.44	45.44	92.17	91.42	23.14	25.12	85.13	84.31
8	26.61	25.8	60.78	58.01	23.21	25.18	85.65	86.44	30.85	29.67	79.74	81
9	52.39	46.76	85.3	86.61	47.81	46.33	86	86.49	36.58	36.88	87.65	86.52
10	44.58	46.76	87.74	86.61	44.58	46.33	87.22	86.49	35.42	36.88	86.35	86.52
11	43.73	46.76	87.83	86.61	44.65	46.33	87.04	86.49	38.28	36.88	85.57	86.52
12	47.12	46.76	84.78	86.61	46.35	46.33	86.09	86.49	38.38	36.88	86.96	86.52
13	45.99	46.76	87.39	86.61	48.28	46.33	86.09	86.49	35.76	36.88	86.09	86.52

Pre. : Predicted removal; Act. : Actual removal

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The predicted and experimental values for DOC and turbidity removal are shown in Table 4.12. The results indicated that the proposed quadratic polynomial models can be applied for prediction, showing a strong correlation between the predicted and experimental results. As seen in Table 4.12, the predicted values for DOC and turbidity elimination closely matched the experimental data. Figure 4.8 visualizes this relationship, with data points distributed along the 45° line, demonstrating good agreement between the actual and predicted values. Thus, the overall second-order models, represented by Equations 4.6 – 4.11, are both significant and reliable.

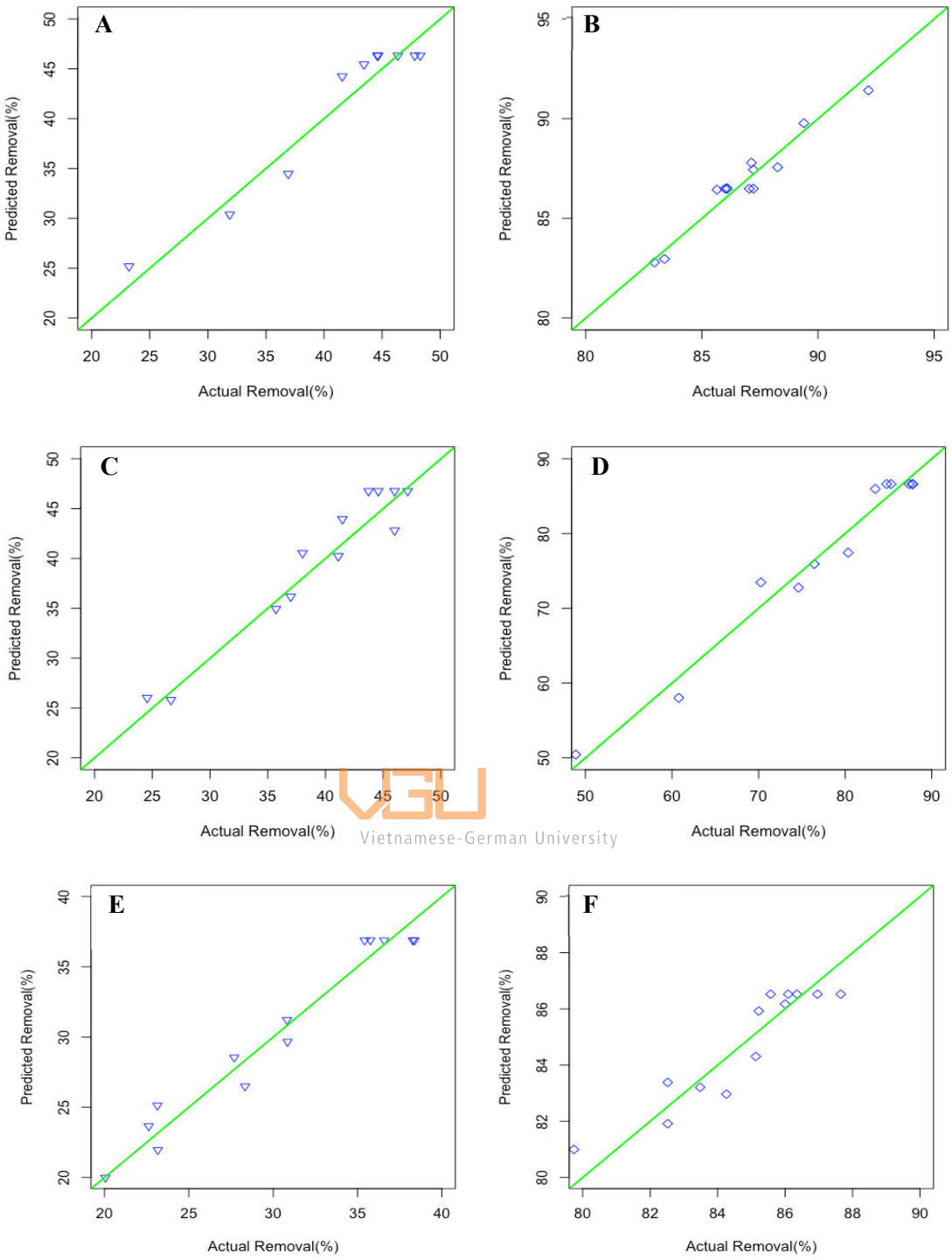

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Figure. 4.8 Actual and predicted elimination efficiencies: PAC, DOC (A) and turbidity (B); PFS, DOC (C) and Turbidity (D); Alum DOC (E) and turbidity (F)

Model validation was conducted by applying Fisher test for analyzing ANOVA, where the p-value was used to assess the significance of the F-statistic. According to Table 5, the quadratic models demonstrated statistical significance at the 95% confidence level, with p-value below 0.05. The F-test for lack of fit was applied to

evaluate the model-data agreement, and a p-value greater than 0.05 indicated a strong association between the predictors and the response variables [112], [141]. In this case, the p-values for the lack of fit in all models exceeded 0.05, indicating that the lack of fit was not statistically significant. Specifically, for PAC, these values were 0.118 for turbidity removal and 0.207 for DOC removal. In the cases of PFS and alum, the p-values for DOC removal were 0.559 and 0.242, while those for turbidity removal were 0.055 and 0.164, respectively.

A well-fitted model should have an R-squared (R^2) value of at least 0.80 to ensure accuracy [142]. The R^2 value helps determine how well a model fits the data, and the adjusted R^2 reveals the model's effectiveness in representing the models [143]. In terms of the PFS model, the R^2 value of 90.32% indicates that the DOC removal model accounts for most variations, with only 9.68% unexplained. The turbidity removal model, with an R^2 of 98.38%, leaves 1.62% unexplained. Likewise, DOC removal models achieved R^2 values of 97.31% for PAC and 96.05% for alum; for turbidity elimination, the corresponding values were 94.20% for PAC and 85.58% for alum.

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Table 4.13 ANOVA results.

		PAC				PFS				Alum				
DOC removal	**d.f**	**Sum of square**	**Mean square**	**F value**	**P value**	**d.f**	**Sum of square**	**Mean square**	**F value**	**P value**	**d.f**	**Sum of square**	**Mean square**	**F value**	**P value**
Regression Model	2	1088.08	544.04	84.268	<0.0001	2	298.39	149.19	14.15	0.003	2	93.70	46.852	16.556	0.002
Error	7	45.19	4.46			7	73.81	10.54			7	19.81	2.83		
Lack of fit	3	33.31	11.1	3.74	0.118	3	27.45	9.15	0.79	0.559	3	12.12	4.041	2.103	0.242
Pure error	4	11.88	2.97			4	46.35	11.59			4	7.69	1.921		
	R^2= 97.31%; $R^2_{adjusted}$= 95.38%					R^2= 90.32%; $R^2_{adjusted}$= 83.4%					R^2= 96.05%; $R^2_{adjusted}$= 93.23%				
Turbidity removal	**d.f**	**Sum of square**	**Mean square**	**F value**	**P value**	**d.f**	**Sum of square**	**Mean square**	**F value**	**P value**	**d.f**	**Sum of square**	**Mean square**	**F value**	**P value**
Regression Model	2	46.45	23.22	41.494	<0.0001	2	1280.0	640.0	93.82	<0.0001	2	18.332	9.166	7.788	0.017
Error	7	3.92	0.56			7	47.75	6.82			7	8.238	1.177		
Lack of fit	3	2.52	0.84	2.41	0.207	3	39.31	13.1	6.21	0.055	3	5.651	1.884	2.913	0.164
Pure error	4	1.4	0.35			4	8.44	2.11			4	2.587	0.647		
	R^2= 94.20%; $R^2_{adjusted}$= 90.06%					R^2= 98.38%; $R^2_{adjusted}$= 97.22%					R^2= 85.58%; $R^2_{adjusted}$= 75.29%				

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Table 4.14. Estimated regression coefficients and corresponding T- and P-values.

	DOC removal				Turbidity removal			
PAC	Coefficient	Standard error	T-value	P-value	Coefficient	Standard error	T-value	P-value
Constant	-176.76	24.607	-7.184	***<0.001***	78.322	7.245	10.8103	***<0.001***
pH	54.268	6.258	8.672	***<0.001***	4.509	1.843	2.448	***0.044***
Dosage	0.628	0.238	2.644	***0.033***	-0.323	0.07	-4.619	***0.002***
pH×Dosage	0.019	0.028	-0.667	0.526	0.015	0.008	1.744	0.125
pH×pH	-3.357	0.428	-7.841	***<0.001***	-0.306	0.126	-2.427	***0.046***
Dosage×Dosage	-0.006	0.001	-5.724	***<0.001***	-0.001	0.0003	4.307	***0.004***
PFS								
Constant	-52.473	31.446	-1.669	0.139	-151.28	25.294	-5.981	***<0.001***
pH	23.166	7.997	2.897	***0.023***	71.534	6.432	11.121	***<0.001***
Dosage	1.026	0.304	3.381	***0.012***	-0.7	0.244	-2.869	***0.024***
pH×Dosage	-0.042	0.036	-1.164	0.283	-0.192	0.029	6.626	***<0.001***
pH×pH	-1.626	0.547	-2.972	***0.021***	-5.558	0.44	-12.628	***<0.001***
Dosage×Dosage	-0.008	0.001	-5.521	***<0.001***	-0.008	0.001	-7.382	***<0.001***
Alum								
Constant	-129.69	16.291	-7.961	<0.001	51.261	10.506	4.879	***0.002***
pH	40.248	4.143	9.715	***<0.001***	7.311	2.672	2.736	***0.029***
Dosage	0.568	0.157	3.613	***0.009***	0.287	0.101	2.828	***0.025***
pH×Dosage	0.017	0.019	0.901	0.398	-0.01	0.012	-0.802	0.449
pH×pH	-2.801	0.283	-9.889	***<0.001***	-0.435	0.182	-2.38	***0.049***
Dosage×Dosage	-0.005	0	-7.439	***<0.001***	-0.002	0.0005	-4.708	***0.002***

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4.3.2. Optimization of dissolved organic carbon (DOC) reduction effectiveness

Table 4.13 illustrates the impact of interaction, linear, and quadratic terms on DOC models, where the significance of each regression coefficient is analyzed using Fisher's F-test. The p-value indicates the statistical significance of each factor and their interactions. A p-value below 0.05 denotes statistical significance, with lower values indicating a stronger effect. According to the analysis, significant statistical effects ($p < 0.05$) were observed for the linear variables (pH and dosage) and their quadratic terms (pH^2 and $dosage^2$), whereas the interaction effect between the two was statistically insignificant ($p > 0.05$) in all experiments using PAC, PFS, and alum. This indicates that the linear and quadratic influences of pH and dosage are key factors in DOC removal, consistent with the results of earlier studies using PAC and alum [112].

Figure 4.9 presents 3D response surface plots and 2D contour of the quadratic models for DOC elimination using the coagulants PFS, PAC and alum. The contour plots show that increasing the levels of pH enhances the removal of DOC with PAC, with the optimal range being at pH 7.5-8.5 and coagulant dosages of 20-50 mg/L, achieving an elimination efficiency of over 50%. In terms of alum, more than 36% DOC removal was achieved at pH 6.5-8 and dosages of 50-80 mg/L, while for PFS, over 45% removal occurred at a lower pH of 5-7.5 and dosages of 30-70 mg/L. PFS had a lower optimal pH range compared to the other coagulants, and PAC required the lowest dosage. The 3D plots also indicate that both overdosing and underdosing reduce removal efficiency. When dosages exceeded 80 mg/L, DOC removal efficiency decreased to under 40% for both PFS and PAC. In contrast, lower alum dosages led to a DOC elimination effectiveness of less than 30%.

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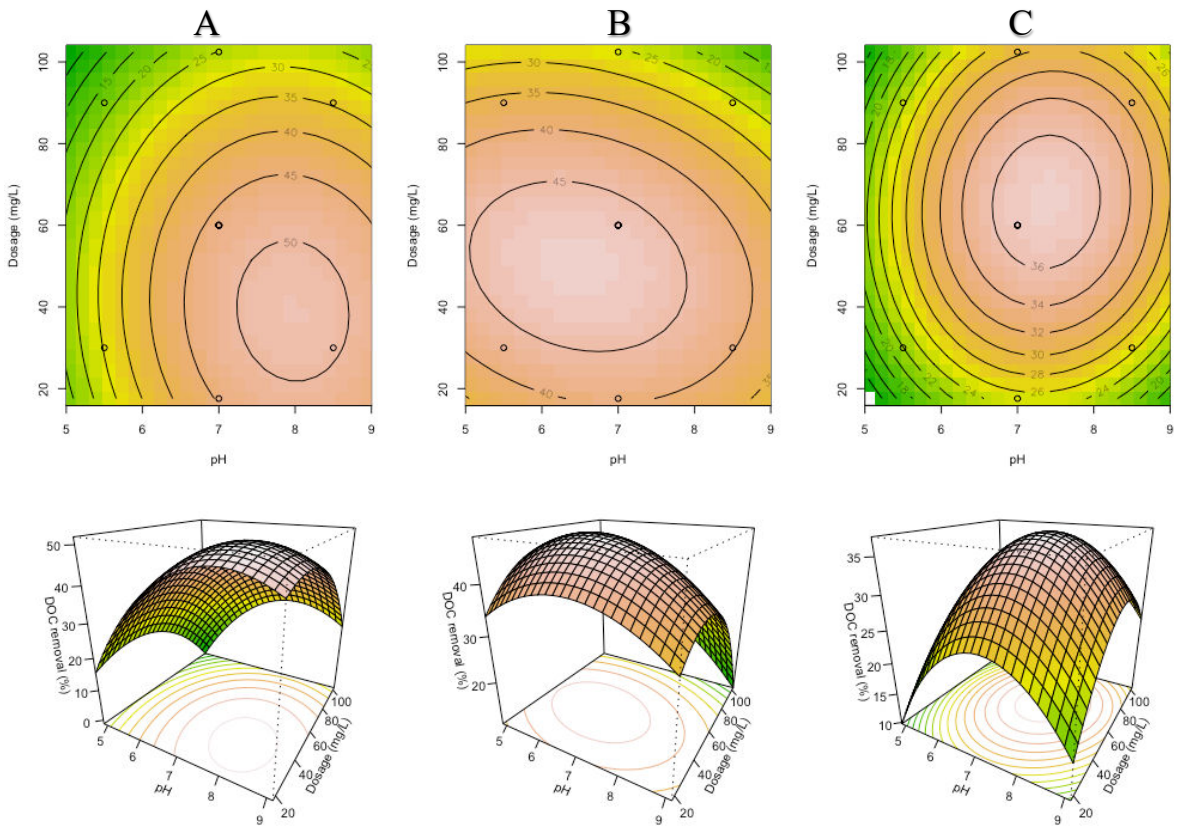

Figure. 4.9 2D contour and 3D surface plots for DOC removal using (**A**) PAC, (**B**) PFS, and (**C**) Alum.

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A high SUVA value suggests a prevalence of hydrophobic, high-molecular-weight organic materials, whereas a low SUVA value indicates mostly hydrophilic, low-molecular-weight organic molecules with lower charge density [125], [144]. Hydrophobic natural organic matter (NOM) was found to carry a significant negative charge due to ionized functional groups such as carboxylic and phenolic groups. Consequently, the hydrophobic component primarily affects the unique colloidal charge characteristics of water, with fractions that have a higher charge showing increased reactivity for removal [85]. As indicated in Table 4.10, SUVA levels exceeding 3 imply that the river water has a substantial presence of aquatic humic substances. Levels ranging from 2 to 4 indicate a blend of aquatic humics and other natural organic matter (NOM), featuring both hydrophobic and hydrophilic properties, along with a mix of high and low molecular weights [85]. This explains why the DOC removal efficiency reached 50% or more, as presented in Table 4.12. In another

study with lower SUVA values (1.27 to 1.33 L mg−1 m−1), the optimum DOC removal efficiency was reported to be lower, around 35% [112]. The hydrophobic portion of natural organic matter is generally eliminated more efficiently by coagulation compared to the hydrophilic portion

Humic substances (HS), the primary component of dissolved organic carbon in natural waters, are divided into less soluble humic acids (HAs) and more soluble fulvic acids (FAs). The elimination of NOM occurs through multiple mechanisms, such as adsorption, entrapment, charge neutralization, and complexation with coagulant metal ions, resulting in the formation of insoluble particulate aggregates. Charge neutralization serves as the primary mechanism for NOM removal, and the optimal coagulant dose for water with high molecular weight NOM is generally low. However, this optimal dose significantly increases when the NOM consists of low molecular weight (LMM) or non-humic compounds, as the removal process is believed to involve adsorption onto the surfaces of metal hydroxides [85].

PFS and PAC can generate the most advantageous hydrolysis and polymeric species for effective coagulation process. The prehydrolysis of $AlCl_3$ can increase the amount of Al_{13} ($AlO_4Al_{12}(OH)_{24}^{7+}$), which is regarded as the most effective aluminum species for contaminant elimination. The polymeric species (Feb) formed during PFS coagulation also play a key role in removing contaminants via mechanisms such as charge neutralization, adsorption, and interparticle bridging. This results in better DOC elimination performance relative to traditional coagulants like ferric sulfate and alum. As shown in Fig. 4.8, PAC and PFS require smaller dosages to achieve higher DOC removal, with optimal dosages ranging from 30-70 mg/L for PFS and 20-50 mg/L for PAC, whereas alum requires a dosage range of 50-80 mg/L.

Al-based coagulants are more effective at removing unsaturated, larger compounds [145], [146], while Fe-based coagulants are better suited for eliminating smaller, saturated compounds with shorter carbon chains [146]. As shown in Fig. 4, PAC outperformed both PFS and alum in DOC removal, primarily due to the ability to remove high-molecular-

weight NOM, such as humic acids, through charge neutralization [85]. Additionally, PFS showed better DOC removal than alum, as the phenolic functional groups in fulvic compounds (like lignin-like substances) act as binding sites for Fe^{3+} at neutral pH, forming $[Fe(OPh)_6]^{3-}$ complexes that facilitate floc formation [147].

4.3.3 Optimization of turbidity removal efficiency

Table 4.14 illustrates that, aside from the interaction effects in the models of alum and PAC, the pH and dosage variables exhibited statistically significant impacts in both their linear and quadratic forms ($p < 0.05$). This indicates that pH and dosage are crucial factors in the removal process of turbidity, which has also been confirmed in previous studies on coagulation [110], [112]. The PFS model demonstrated a significant interaction effect ($p < 0.05$), highlighting that turbidity removal was mainly influenced by a combination of linear, quadratic, and interactive factors.

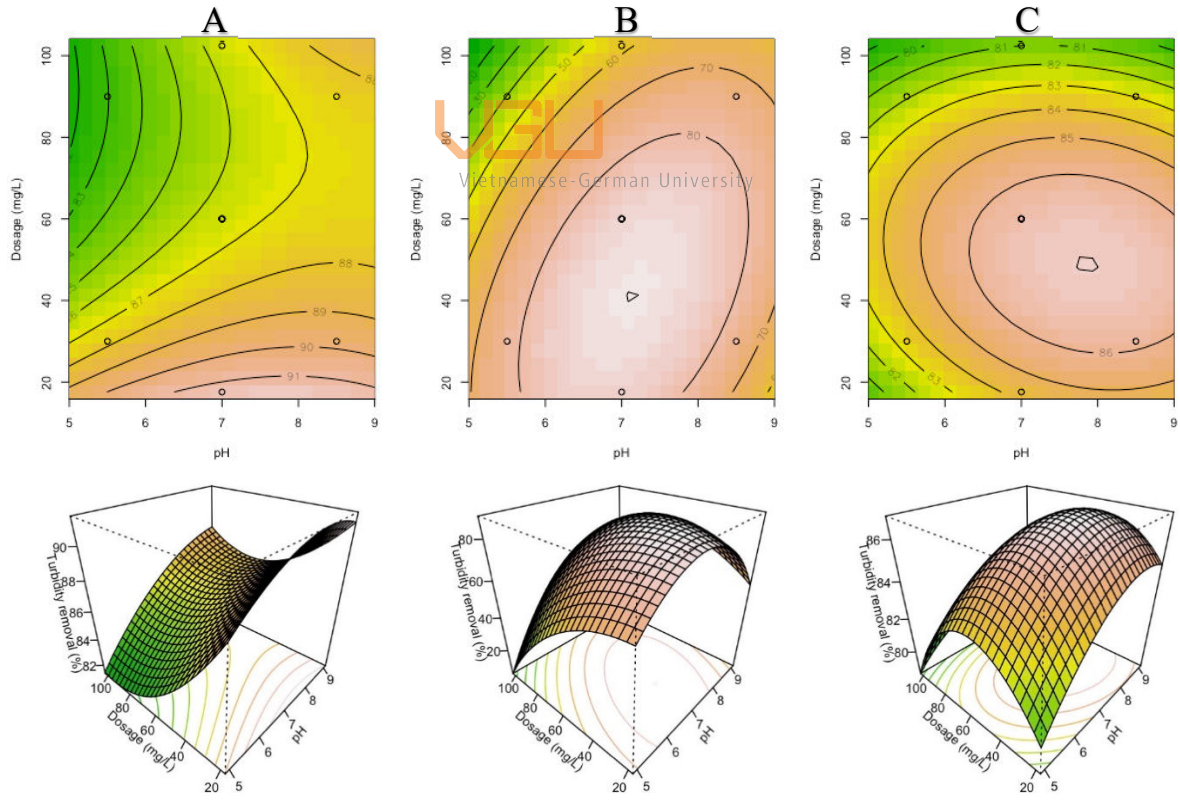

Figure 4.10 2D and 3D plots for turbidity removal using (**A**)PAC, (**B**) PFS, and (**C**) alum.

The plots of 2D and 3D in Figures 4.10 A, B, and C depict the quadratic models for turbidity elimination. When PAC was used at a dosage below 20 mg/L, an elimination effectiveness greater than 91% was achieved within pH levels ranging from 6.5 to 9. Increased alum dosage and pH values led to improved turbidity removal, with optimal conditions occurring at approximately 50 mg/L (alum) and 7.9 (pH). For PFS, a turbidity elimination effectiveness above 80% was achieved over a wider pH range of 6.5-8.5 and 80 mg/L dosage, with the optimal conditions near a pH of 7.0 and 40 mg/L coagulant dosage. Previous studies have confirmed that charge neutralization and sweep flocculation are the primary mechanisms for turbidity removal [110], [112]. Sweep flocculation, most efficient at pH levels from 7.0 to 8.5, requires higher coagulant dosages due to the need for substantial coagulant quantities to overcome the widely dispersed particles [110]. This explains the higher alum dosage needed for optimal turbidity removal. PFS and PAC outperformed alum by generating polymeric species (Al_b or Fe_b), which are larger size and carry more positive charges [85]. PAC achieved high removal efficiency with a small amount because of the presence of highly stable, positively charged species such as ($AlO_4Al_{12}(OH)_{24}^{7+}$, Al^{13}). Previous studies have also shown PAC's better performance in turbidity elimination compared to PFS [112], [148], likely resulting from an elevated zeta potential during charge neutralization [148]. However, PFS demonstrated superior turbidity removal compared to conventional coagulants like ferric sulfate and aluminum sulfate in various water environments [149], [150].

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4.3.4. Optimal conditions for the simultaneous elimination of DOC and turbidity

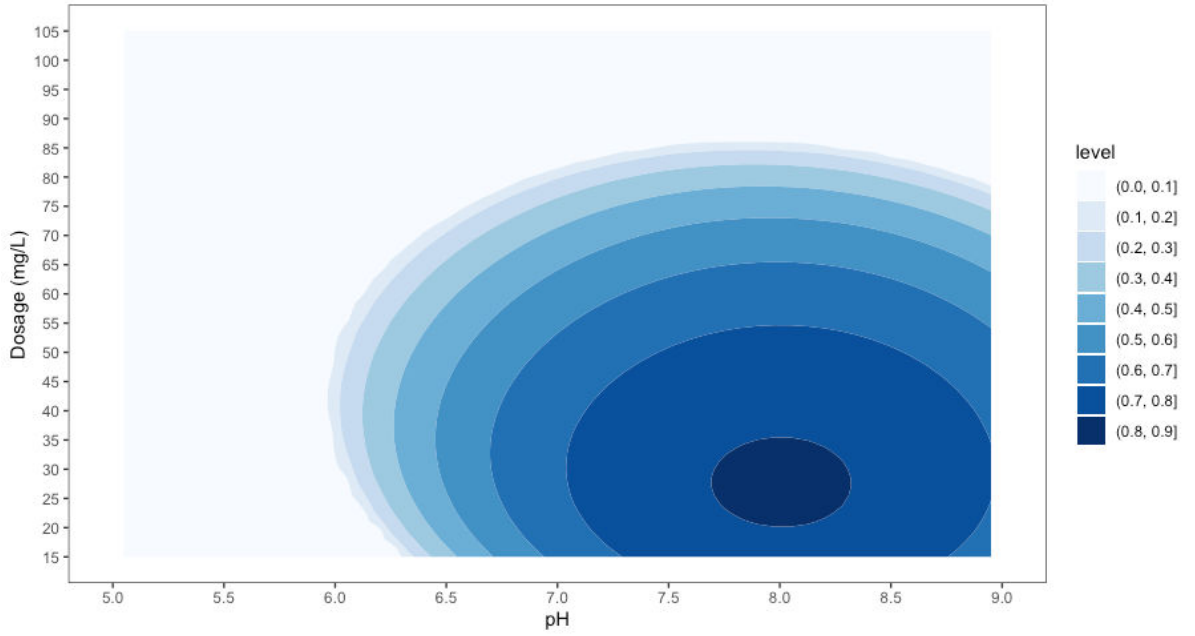

Figure 4.11 Illustrating the efficiency of DOC and turbidity elimination using PACl.

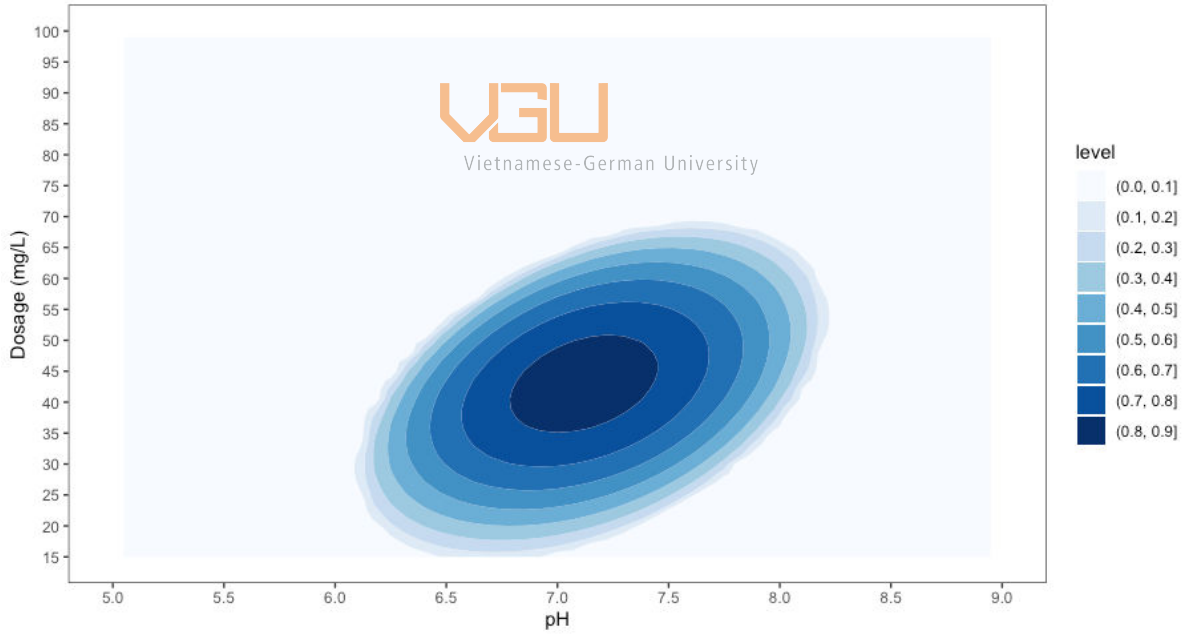

Figure 4.12 Illustrating the efficiency of DOC and turbidity elimination using PFS.

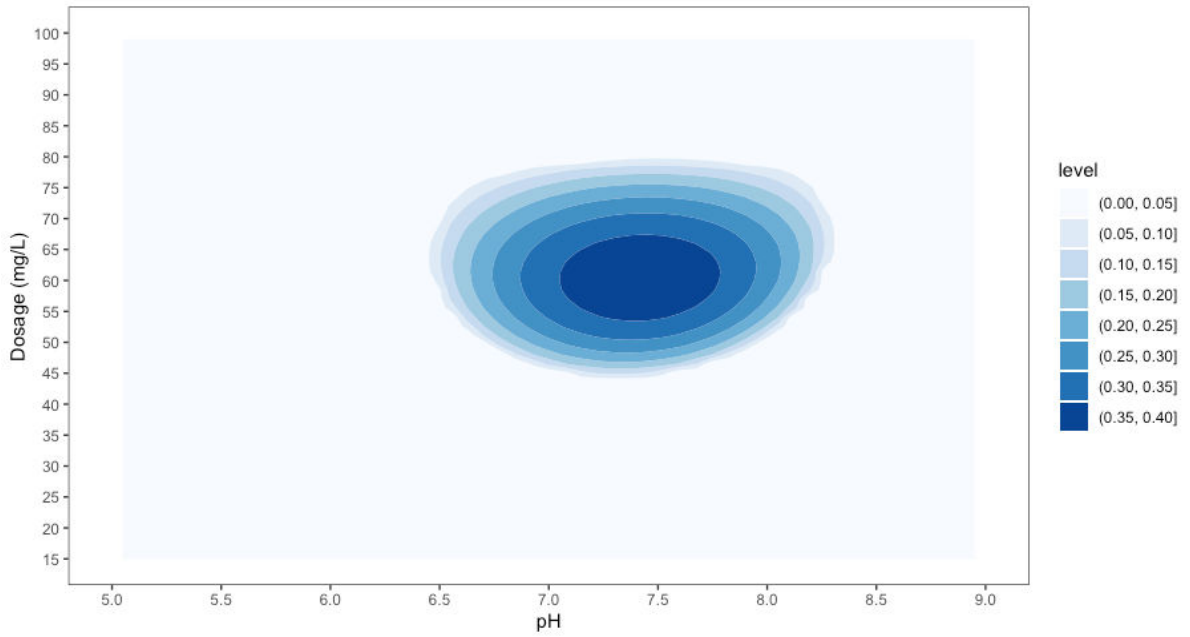

Figure 4.13 Illustrating the efficiency of DOC and turbidity elimination using alum.

The desire function approach allows for the elimination optimization of both turbidity and DOC [151]. The desirability function was employed to convert each response function. This method converts individual response functions into desirability functions and uses their geometric mean to compute the overall response desirability, which is then optimized within the target area [152].

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For this study, target thresholds of 85% turbidity and 35% DOC elimination, the optimal levels are illustrated in Figures 11, 12, and 13. The dark blue areas represent the optimal regions for both pH and dosage, achieving the desired levels for DOC and turbidity elimination. Specifically, the removal of 48.3% DOC and 92% turbidity was obtained at 15 mg/L (PAC) and 7.98 (pH). Similarly, the elimination of 47.5% of DOC and 90% of turbidity levels was achieved with 43.5 mg/L (PFS) at 7.08 (pH). In contrast, lower removal efficiencies of 37.2% DOC and 86.7% turbidity were found with 60 mg/L (alum) at 7.45 (pH). These results align with previous studies [85], [144], [153]. For instance, the optimal pH for PAC precipitation in water at 25°C was around pH levels ranging from 7.0 to 8.3 [144]. Furthermore, the ideal pH for PAC coagulation is approximately 7.0, probably because of PAC hydrolysis precipitation in alkaline environment [153]. The optimal pH

range for iron-based coagulation is between 4.5 and 7, while aluminum-based coagulants reach their highest efficiency for NOM removal at pH levels between 5.5 and 7.7 [111].

Table 4.15. Assessment and evaluation of optimal parameters.

	Experiment conditions		Responses	
	Dosage (mg/L)	pH	DOC (%)	Turbidity (%)
PFS				
Experiment	43.5	7.08	45.97	88.72
Prediction	43.5	7.08	47.5	90
Error (%)			1.53	1.28
PAC				
Experiment	15	7.98	47.78	91.08
Prediction	15	7.98	48.3	92
Error (%)			0.52	0.92
Alum				
Experiment	60	7.45	36.98	86.01
Prediction	60	7.45	37.2	86.70
Error (%)			0.22	0.69

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To validate the model-predicted outcomes, further experiments were conducted using the optimal levels of pH and coagulants. The findings are presented in Table 4.15. The experimental outcomes closely matched the model predictions, with errors below 1% for PAC and alum, and marginally higher for PFS at 1.53% (DOC) and 1.28% (turbidity), as shown in Table 4.15. This demonstrates that the RSM method is highly effective for optimizing the coagulation process. This method offers flexibility to adapt to varying treatment goals.

4.3.5. Applying optimal treatment conditions in domestic water treatment systems

The laboratory-scale water treatment system employed PFS and PAC coagulants in the coagulation process. A comparison was made between the turbidity and DOC

elimination efficiencies of both coagulants to assess their effectiveness in this process. The findings indicated that PFS achieved elimination efficiencies of turbidity (87.12%) and DOC (98.9%), remaining DOC level (0.501 mg/L) and turbidity level (0.15 NTU). The system utilizing PAC achieved elimination efficiencies of 86.19% for DOC and 98.33% for turbidity, with concentrations of 0.537 mg/L for DOC and 0.19 NTU for turbidity (Table 4.16). These results align with the high adsorption efficiency of AC, achieving the turbidity levels below the guideline limits set by Vietnamese standards for domestic water (< 2 NTU). In relation to this, Kim et al. (2022) found that a full-scale system achieved an additional 15% to 23% DOC elimination through granular activated carbon filtration [154]. Therefore, combining the coagulation unit with aeration and a pre-filter system (which includes a 1-micron polyethylene filter column, activated carbon, and cation ion exchange) under optimal coagulation conditions identified through RSM can effectively treat river water for domestic use, as illustrated in Fig. 2.6

Table 4.16. The effectiveness of removing DOC and turbidity.

PFS	**Raw water**	**After the treatment processes**							
		Coagulation		***Aeration***		***AC filtration***		***Cation/anion***	
			%		%		%		%
DOC *(mg/L)*	3,89	2,125	45,37	1,687	11.26	0,608	27.74	0,501	2,75
Turbidity *(NTU)*	11,5	1,36	88,17	0,79	5.22	0,2	5.13	0,15	0.43

PACl	**Raw water**	**After the treatment processes**							
		Coagulation		***Aeration***		***AC filtration***		***Cation/anion***	
			%		%		%		%
DOC *(mg/L)*	3,89	2,021	48,05	1,762	6.65	0,628	29.15	0,537	2.34
Turbidity *(NTU)*	11,5	1,12	90,26	0,84	2.43	0,26	5.04	0,19	0.6

4.4. Assessing the willingness of people to engage in protecting water quality

The willingness to participate of residents plays in a key role in the success of community-based water quality protection programs. Therefore, considering important factors affecting people's willingness to participate will help to develop more practical and effective water quality protection programs in river basins. This study conducted a survey on people's willingness to participate, and established a regression model to examine the importance of factors of people's willingness to participate.

4.4.1 Descriptive analysis

Table 4.17 shows that the survey included 46% male and 54% female respondents. Regarding education, 55% (n = 55) of participants had not completed secondary school, while 45% (n = 45) had achieved the levels of high school or higher education. Over one-third (34%) of adults aged 18–30 joined in the sampling campaing, while about two-thirds (66%) of those above 31 agreed to complete the questionnaire. Agriculture famer is the predominant occupation in the Ba River, accounting for 58% (n = 58) of participants, while business, office, freelance jobs, and manual labor made up 42% (n = 42) of the surveyed locals.

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Table 4.17 Descriptive characteristics of respondents.

Characteristic (n=100)		**Percentage of samples (%)**	**Urban (n=44)**	**Rural (n=56)**
Gender	Male	46	47.7	44.6
	Female	54	52.3	55.4
Education levels	No formal education	0	0	0
	Primary	11	11.4	10.7
	Secondary	44	45.5	42.9
	Highschool	36	40.9	32.1
	College/graduate	9	2.3	14.3

Age	18-30	34	31.8	35.7
	31-40	42	38.6	44.6
	41-50	22	27.3	17.9
	51-60	2	2.3	1.8
	>60	0	0	0
Occupation	Officer	10	4.5	14.3
	Business	20	25	16.1
	Agriculture	58	52.3	62.5
	Worker	1	2.3	0
	Freelance	11	15.9	7.1

4.4.2 The multivariate regression model for assessing participation willingness

The consistency and reliability of scaled variables within the model. The variables, including WP, SC, DW, and PW, were assessed using a Likert scale. Cronbach's alpha (α) was used to measure the internal consistency of these variables, with alpha values needing to be at least 0.7 for reliability [155]. The alpha values for WP, SC, DW, and PW are 0.77, 0.81, 0.81, and 0.77, respectively, as presented in Table 4.18. Since all these values exceed 0.7, this indicates a high level of internal consistency in the scaled data.

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Table 4.18. Descriptive statistics and internal reliability.

Variable	Code	Items	Mean (Std. Dev)	Cronbach's Alpha α (std. α)
Willingness to participate	WP	3	4.18 (0.30)	0.77 (0.77)
Sense of community	SC	18	4.09 (0.42)	0.81 (0.81)
Dependence on river water	DW	3	3.94 (0.53)	0.81 (0.8)

Perceptions of current water resource management	PW	3	2.79 (0.49)	0.77 (0.76)
The lelvel of income	IN	1	3.2 (0.77)	-
Gender	GE	1	-	-
Education	ED	1	3.34 (0.81)	-
Place of residence	PR	1	-	-

The response variable in this study is WP, whereas the independent variables encompass SC, DW, PW, IN, GE, ED, and PR. Multiple linear regression analysis revealed that the initial model can interpret 59.6% of the variation in WP levels ($R^2 = 0.596$, $p < 0.001$). As shown in Figure 4.14, Cook's distances were used to identify outliers, assessing the influence of individual data points on the regression line. The analysis identified seven datapoints that are outliers including 37, 46, 65, 66, 67, 68, and 88 with Cook's Distances ranging from 0.048 to 0.155. These outliers were removed to prevent significant impact on the model. After their removal, the model's explanatory power improved, with the final model showing an R^2 of 0.679 ($p < 0.001$).

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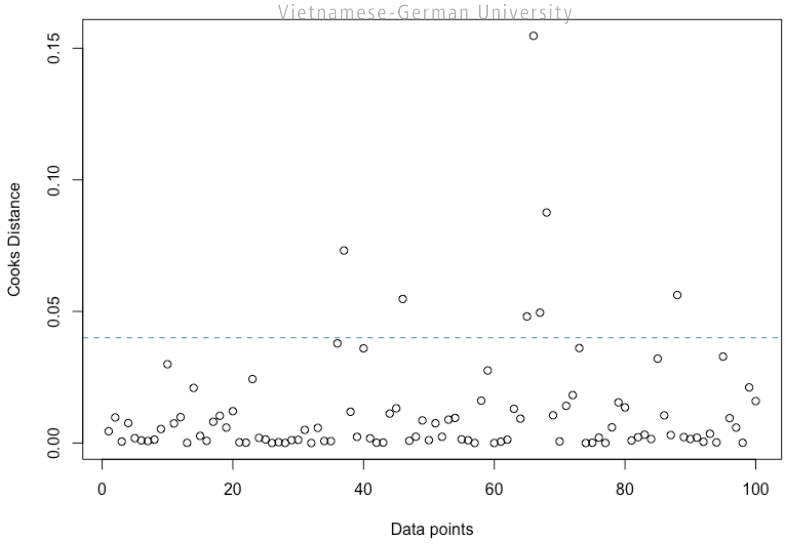

Figure 4.14 Cook's distance of residuals

The variables SC and PW showed high statistical significance with p-values less than 0.001, while DW and IN had p-values of 0.018 and 0.012, respectively ($p < 0.05$). For PR,

the p-value was 0.008, which is below the 0.01 threshold. Conversely, gender and education did not show statistical significance, with p-values exceeding 0.05. Notably, SC had the largest impact on WP, with a coefficient of 0.45, indicating that a 1% increase in sense of community corresponds to a 0.45% rise in willingness to participate. Additionally, increases in DW, PW, and IN were also associated with higher levels of WP. Details of the regression model are shown in Table 4.19 and equation (4.12).

$$WP = 0.262 + 0.45 \times SC + 0.139 \times DW + 0.292 \times PW + 0.103 \times IN + 0.07 \times GE + 0.037 \times ED + 0.138 \times PR \quad (4.12)$$

Table 4.19. The outcomes of the regression analysis.

	Estimate	Standard error	t-value	p-value
Intercept	0.262	0.357	10.734	0.465
SC	0.45	0.1	4.484	<0.001***
DW	0.139	0.058	2.415	0.018*
PW	0.292	0.064	4.559	<0.001***
IN	0.103	0.04	2.566	0.012*
GE	0.07	0.05	1.388	0.169
ED	0.037	0.039	0.952	0.344
PR	0.138	0.051	2.701	0.008**

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Significant levels: '***' 0.001 '**' 0.01 '*' 0.05

The regression output, including residuals and fitted values, is visualized in Figure 4.15. The residuals generally fall both above and below zero. A linear correlation is anticipated between the independent variables and the dependent variable (WP).

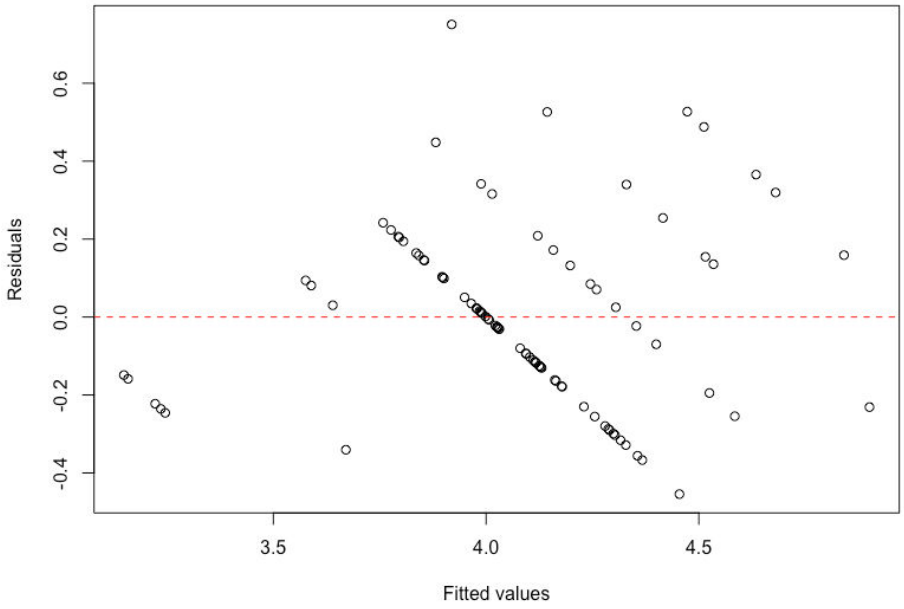
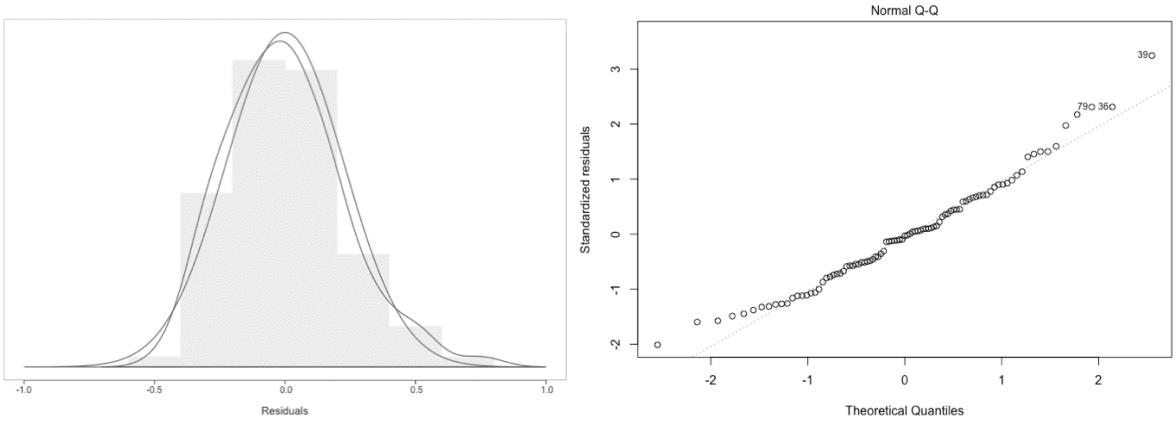


Figure 4.15 The graphical representation of the regression residuals.

The normality of the model was assessed using a histogram and normal QQ-plot of the residuals. Figures 4.16 (A) and (B) indicate that the residuals follow a normal distribution. Additionally, The residuals were found to be normally distributed based on the Shapiro-Wilk test, as evidenced by a W statistic of 0.974 and a p-value of 0.062, which exceeds the 0.05 significance level. As the p-value is above the 0.05 threshold, This suggests conformity of the residuals to a normal distribution pattern.



(A) (B)

Figure 4.16 (A) Histogram of residuals (B) normal QQ-plot.

To assess multicollinearity, the tolerance and variance inflation factor (VIF) values were calculated and analyzed. Table 4.20 indicates that the tolerance values for the variables exceed 0.1, while the VIF values remain below 10. This indicates the absence of multicollinearity between the variables. Additionally, The binary variables exhibit low to moderate levels of correlation, as illustrated in Figure 4.17.

Table 4.20. Tolerance and variance inflation factors.

Variable	Tolerance	VIF
SC	0.678	1.476
DW	0.538	1.859
PW	0.738	1.355
IN	0.666	1.501
GE	0.946	1.057
ED	0.682	1.467
PR	0.922	1.084

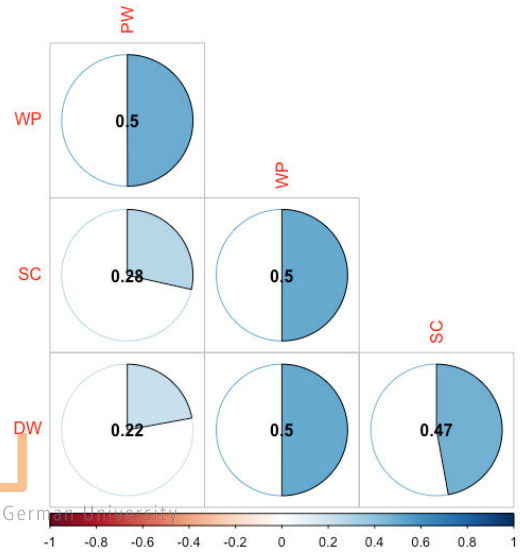


Figure 4.17 Correlation of variables.

4.4.3 Discussion on factors affecting willingness to participate

SC and PW significantly impact the model of engagement willingness. SC encompasses personal relationships and community social traits, which can be grouped into historical ties, trust, a sense of belonging, and and cohesiveness within existing living environments [156]. This finding aligns with previous research [156], [157]. The Ba River Basin is predominantly composed of rural and small, medium urban areas, with around half of the population belonging to ethnic minorities. While ED has a limited impact on the model, lower education levels may result in a lack of perception regarding water management issues. Thus, raising public awareness and improving attitudes are crucial for

encouraging community participation in water resource management [158]. Furthermore, DW directly impacts WP, as most individuals recognize the vital role of water in their daily existence. Involvement as a user was acknowledged as an economic factor that grants individuals the right to access water resources [159]. The study also examined income levels, considering both average monthly earnings and the extent of land ownership. Utilizing river water for agricultural purposes may contribute to higher income, thereby serving as a key determinant of their engagement willingness.

The place of residence (urban or rural) can influence the cognitive perspectives of inhabitants, leading to different perceptions and views on water-related issues [160]. Some studies indicated a significant disparity in participation rates for supporting tourism development between urban and rural populations [160], [161]. In the Ba River Basin, certain minority ethnic groups, such as the Banah and Jrai, reside along the main river and have limited access to education and information compared to urban residents. In contrast, those living in urban areas benefit from formal education and a variety of information sources, which can enhance their understanding and awareness of water issues. While the education variable (ED) did not show any statistical difference in the regression model, the importance of formal education in influencing willingness to participate is undeniable [173].

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The Banah and Jrai ethnic minority groups living along the Ba River have less access to education and information than urban dwellers. Urban populations, however, benefit from formal education and diverse information sources, enhancing their awareness and knowledge of water-related issues. While the ED variables were not statistically significant in the model, the importance of formal education in fostering willingness to participate remains clear [162].

A regulatory framework has been set up to assist organizations and stakeholders in exploring and protecting water sources. Despite this, the implementation of initiatives or programs has been ineffective, leading to minimal impact on altering local behaviors. To address this, authorities should adopt diverse strategies to enhance public perceptions.

Beyond formal education and awareness campaigns, community involvement in all project stages is essential. This engagement provides local communities with the skills and expertise required to maintain the project [163].

The regression model was effectively adopted to the Ba River Basin in the Highlands of Vietnam, where ethnic minorities reside along the Ba river. The outcomes present a practical model for other watershed regions in Vietnam and in countries with similar population profiles. In many of these areas, minority populations often face economic hardships, limited education, and insufficient access to information. Despite these challenges, greater emphasis should be placed on fostering sense of community and community engagement in water management programs in such regions.

4.5. River watershed management and governance in Vietnam

Vietnam has enacted the laws on water resources, environmental protection, and irrigation, which govern issues related to river basins. The Water Resources Law addresses the administration, extraction, and utilization of water resources, while the Environmental Protection Law focuses on safeguarding water environments and controlling contamination in river watersheds. The Irrigation Law deals with managing and utilizing irrigation systems and operating hydroelectric reservoirs for irrigation purposes [164]. Despite these regulations, there are still gaps in legal documents concerning water environmental protection that have not been adequately revised or developed [165]. Practical implementation faces challenges due to limited resources, such as funding and personnel, particularly in rural and small urban areas. Additionally, water environmental protection has not been sufficiently prioritized in related plans, such as urban development planning [164].

The Vietnamese government has assigned MONRE as the lead authority responsible for the integrated management and sustainable governance of river basins and freshwater resources. MONRE is responsible for directing, monitoring, and coordinating the implementation of policies, legal frameworks, strategies, plans, and programs aimed at protecting and utilizing water resources, preventing their degradation and overexploitation,

and facilitating the restoration of aquatic ecosystems within river basins. The MARD handles issues concerning irrigation systems, flood and storm mitigation, rural water supply, hydraulic infrastructure, dike construction and maintenance, as well as the development of the aquaculture and fisheries sectors. The MOC is responsible for urban water supply and drainage systems, while MOH monitors drinking water quality. The MT manages waterway transport, and the MOIT oversees hydroelectric dams. Additionally, the MPS is empowered to monitor, conduct investigations, and enforce penalties against individuals or entities that pose risks to the water environment.

Given the involvement of many agencies, organizations, and stakeholders in managing water resources, implementing IWRM is challenging. The sources of river water are utilized for multiple purposes including drinking water, irrigation, and hydroelectric production, with key stakeholders including companies, MONRE, MARD, and MOIT. This can lead to inconsistent management and conflicts in practical situations. In 2020, the Environmental Protection Law first regulated community involvement, including gathering and providing information on environmental protection and assessing businesses' environmental performance in local areas. However, both internal and external factors could hinder effective community involvement, with willingness to participate being a key element of water management programs. Figure 18 illustrates water governance and institutional framework.

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The Ba River Basin remains largely unaffected by major urban centers, with small to medium scale towns and agricultural activities dominating the region. Domestic and agricultural waste and wastewater are often discharged directly into rivers, significantly impacting water quality variations [7], [25]. Human activities in buffer zones can also substantially affect river water quality [19], [31], [166]. Thus, community participation is crucial for safeguarding the quality of river water via sustainable land use, maintaining vegetation cover, and protecting riverbank buffer zones.

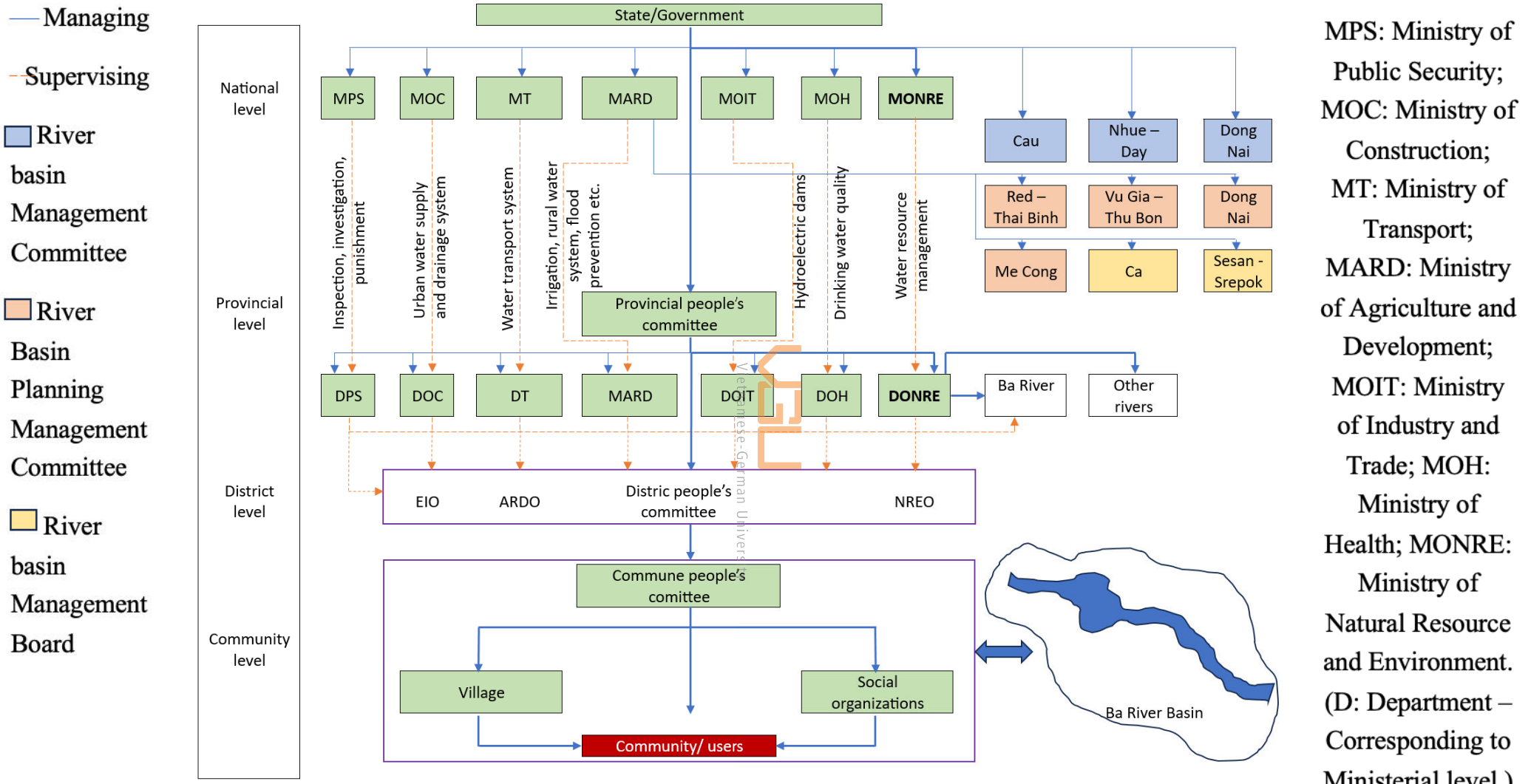

Figure 4.18 Vietnam's river water management and institutional framework.

4.6. Solutions for water quality management in Ba River Basin and the approach to managing river water quality in small scale urban areas

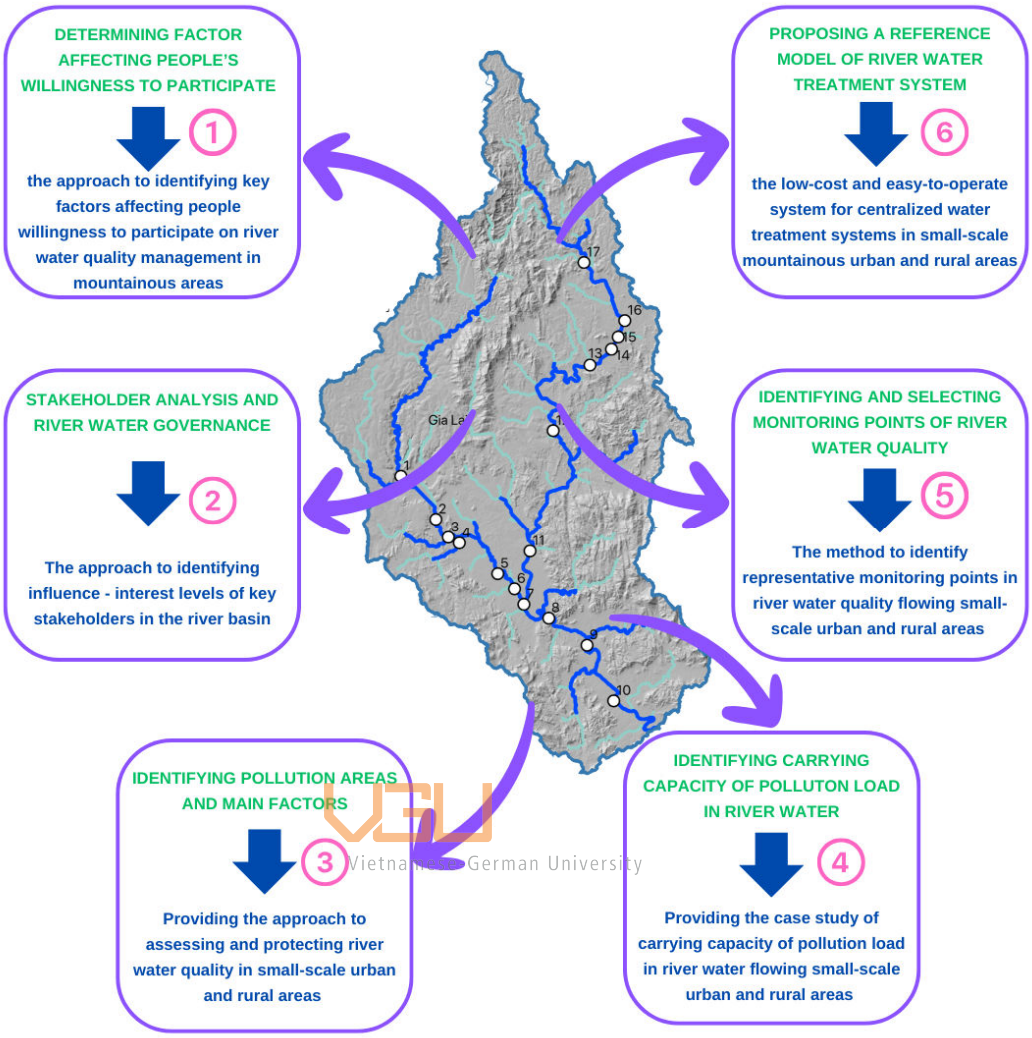

Figure 4.19 The contribution to managing river water quality in the Ba River Basin.

River basin management should focus on the relationships between land use and land cover, water movement and storage, and water quality [167]. Therefore, it is necessary to have comprehensive water resources planning to effectively manage these activities and ensure sustainable water supply for socio-economic development in localities. Currently, some river basins in Vietnam, including Ma, Huong, Dong Nai, and Cuu Long, have had their comprehensive water resources planning approved by the Ministry of Natural Resources and Environment. The planning aims to ensure water security in the river basin, allocate water resources reasonably, manage water quantity, protect water quality towards sustainable use of water resources for socio-economic development and ensure national security and defense. Figure 4.19 shows some contributions to managing river water in the Ba River Basin

Strengthening community participation in river basin protection activities, programs and planning. When people living in a river basin are aware of their essential role in that river basin, planning and implementation of activities will be effective. At the same time, the community realizes that their actions impact the river basin and participates in protecting and restoring the river basin for the benefit of the community as a whole and future generations. Community participation is necessary in all stages of river basin protection and restoration programs. For instance, communities actively contributed ideas during meetings and executed programs, resulting in better alignment with local needs like waste management and reforestation in the Cirasea Sub-Watershed [168]. involving locals in joint management has led to better conservation outcomes, supporting the integration of training and awareness-raising to strengthen community dependence on and stewardship of water resources [169]. In the Ba River Basin, a sense of community and dependence on water resources are the two most important factors when considering people's willingness to participate in protecting the water environment of the Ba River. Therefore, it is necessary to strengthen the sense of community through community activities. At the same time, training activities, awareness raising, and people's participation should be integrated into the implementation stages of activities, programs, or projects to protect and restore the river basin. In general, community engagement can take many forms but is designed to {1} Build community consensus on a vision for the future of the river basin {2} Develop strategies to address the issues most important to the river basin {3} Maintain community involvement in the process of developing and implementing river basin activities, programs, and plans.

Enhancing stakeholder engagement and cooperation. Stakeholders in the river basin include parties that have interests or are affected by the results of the river basin water resources planning or planning. The purpose of cooperation and stakeholder participation is to balance interests, and achieve consensus among stakeholders including the community. The review emphasizes that participation enables active interactions for knowledge sharing and problem-solving on issues like pollution and water allocation, reducing power imbalances and building trust [170]. The main stakeholders in the Ba River basin are represented by their level of influence and level of interest. The component "Influence" is the impact of the stakeholder on river water quality management, while the level of interest "Interest" is the interests related to water quality protection and management. Figure 4.20 shows the level of influence and level of interest divided into Low - Medium - High levels.

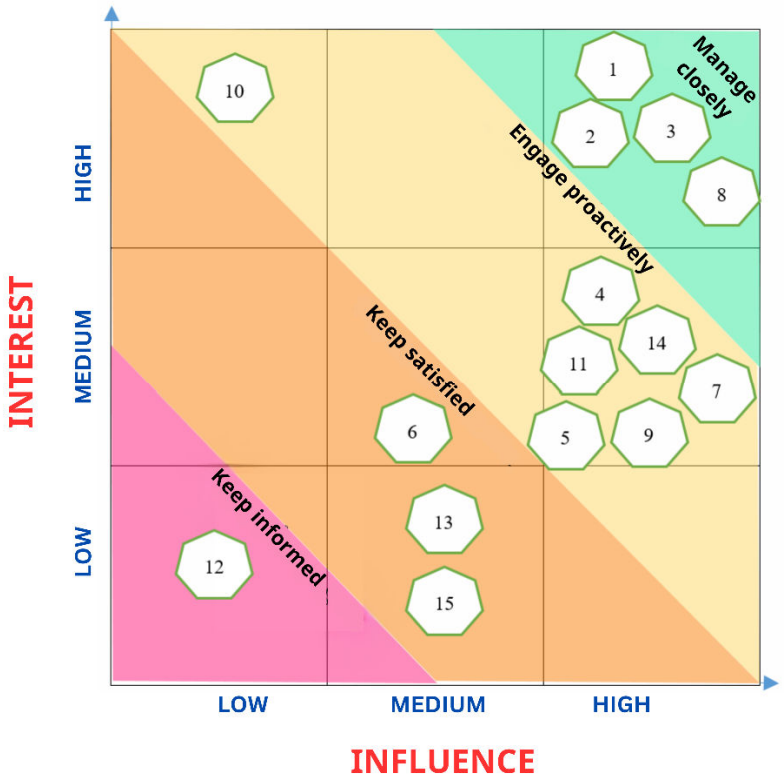

Figure 4.20 Interest – Influence Matrix on water quality management.

[**1**] Government agencies (Ministry of Agriculture and Development, MOH: Ministry of Health, MONRE: Ministry of Natural Resource and Environment etc.) [**2**] Provincial People's Committee [**3**] Department of Natural Resources and Environment [**4**] Department of Agriculture and Rural Development [**5**] Department of Industry and Trade [**6**] Other relevant departments and agencies [**7**] Environmental Police Department [**8**] District People's Committee [**9**] District level Departments [**10**] Experts and Professionals [**11**] Companies/Businesses [**12**] Media agency [**13**] Social organizations, non-governmental organizations [**14**] Commune People's Committee [**15**] Community.

Key stakeholders include Government agencies (Ministry of Natural Resources and Environment, Ministry of Agriculture and Rural Development etc.), Provincial People's Committees, Department of Natural Resources and Environment, and District People's Committees.

This is a group with a high level of interest - influence because these agencies enact related regulations that greatly impact the management of water quality of the Ba River. Next is the proactive consultation group, which consists of stakeholders who mainly participate in the implementation process, carry out related activities and influence the management of water quality in the Ba River basin. The group with an average level of interest - high influence includes the Department of Agriculture and

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Rural Development, Department of Industry and Trade, Provincial Environmental Police Department, relevant departments at the district level, Companies/enterprises, and Commune People's Committees. Experts or professionals with high interest and low to medium influence because experts usually only conduct independent research and provide opinions or solutions that are very valuable to water quality management. For the group that maintains interest with medium interest – medium to low influence is the media.

Monitoring pollution areas and main factors affecting river water quality. River water at locations 7,14, and 15 were classified as high-level pollution areas. Also, locations 1,4 and 5 have potential pesticide contamination. In addition, concentrations of physicochemical parameters in the rainy season were higher than in the dry season due to diffuse sources in agricultural and urban areas. Therefore, the authority should focus on controlling diffuse pollution in the whole basin, especially in urban areas (locations 7,14, and 15) and rural areas (locations 1,4, and 5) in the Ba River Basin.

Controlling pollution load discharging into Ba river water. BOD_5, COD, NO_2, NH_4 load in Ba river water exceed the maximum pollution load. River water can only receive more TSS load. This revealed that the authority should focus on the implementation of actions that prevent the deterioration of river water quality.

Applying statistical analysis to selecting monitoring locations for annual water quality monitoring programs in Ba River Basin. The hierarchical cluster analysis method can be used to classify water quality monitoring locations based on data on water quality parameters of the Ba River. This approach can help select and optimize the number of water quality monitoring locations in the Ba River basin while ensuring representativeness. The monitoring locations in the current surface water monitoring program of Gia Lai province change every year, and there are only a few fixed locations such as locations 7,9,12,14,15,17, corresponding to the clusters in the HCA analysis, including clusters 3 (7 and 15), cluster 4 (9, and 13), cluster 5 (14), and cluster 6 (12). However, clusters 1 and 2 are not included in the annual surface water monitoring locations of Gia Lai province. In cluster 2 (Location 1), Ayun Ha Lake has an automatic monitoring station and Ayun Ha water supply plant. Therefore, it is necessary to consider adding 1 monitoring location in cluster 1 (Location 17, 2, and 3) to ensure representativeness in the surface water monitoring program of the province. At the same time, at locations 1, 4, and 5, low concentrations of chlorpyrifos (-ethyl) and deltamethrin pesticides were detected, so further research is needed to monitor pesticide indicators and preventive measures. This approach to selecting surface water

monitoring locations has been successfully applied to water quality monitoring programs in previous studies [75], [82], [135].

Application of response surface method (RSM) to optimize domestic water treatment processes. Proposing a simple traditional technology for domestic water treatment suitable for the conditions of Ba river basin. Figure 2.6 Laboratory-scale river water treatment system including inlet tank, coagulation-flocculation reactor tank, aeration-aeration tank, and filter (1-micron filter column, activated carbon and cation exchange) can be a reference water treatment system in evaluating treatment technology options for concentrated residential clusters living in Ba river basin.

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CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The results from the research topic "Research on water quality assessment, pollution load and water resource management solutions in the Ba river basin in Gia Lai province", the following main results were obtained:

- Concentrations of physicochemical parameters in the rainy season were higher than in the dry season due to diffuse sources in agricultural and urban areas. Low concentrations of chlorpyrifos (-ethyl) and deltamethrin pesticides were detected in the rainy season at some river locations in Ayun commune, Phu Thien bridge, and An Khe bus station. Therefore, the authority should focus on controlling diffuse pollution in the whole basin, especially in urban areas (locations 7,14, and 15) and rural areas (locations 1,4, and 5).

- The results from hierarchical cluster analysis (HCA) and WQI water quality index show that water quality in Ben Mong bridge area (Ayun Pa town), An Khe bridge, An Khe bus station are classified as moderate to high pollution level. HCA can help select and optimize the number of water quality monitoring locations in the Ba River basin while ensuring representativeness.

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- The results from the carrying capacity calculation revealed that Ba river water could not receive more pollution load, except the total suspended solid load.

- The coagulation-flocculation process can effectively treat DOC concentration and turbidity in surface water under optimal conditions based on the results of the response surface methodology. At the same time, the laboratory-scale treatment system effectively removed DOC and turbidity from Ba River water into domestic water. This system is suitable for decentralized domestic water treatment systems.
- Willingness to participate (WP) in community-based water management depends on many factors, such as community sense, awareness, beliefs and demographic characteristics. The results showed that the regression model explained 67.9% of the variation in community willingness to participate ($R^2 = 0.679$, $p < 0.001$). Sense of community and awareness of water resources management were the most influential factors in community willingness to participate.

5.2. Recommendations

The results of this study give the case study of applying statistical methods in assessing the variation in river water quality, caculating carrying capacity of pollution, optimizing water treatment processes, establishing the model of people' willingness to participate. The approach is suitable for both agricultural and urban river basins. Also, the findings provide some suggestions, including the selection of annual monitoring stations and the flexible approach to assessing the water quality index. Further research should focus on the application of machine learning and artificial intelligence to assess and predict river water quality.

The contents of water quality management of the Ba River basin should be effectively integrated into current local planning, such as Gia Lai province planning, land use planning and other specialized planning. At the same time, it is necessary to conduct a comprehensive study of activities in the Ba River basin, especially considering the relationship between land use and river water quality to implement Gia Lai province's water resources planning in the coming period to replace the current water resources planning to 2025. In addtion, climate change could affect both the quantity and quality of river water, so its effects should be considered in related plans towards sustainable water resources management

Stakeholder engagement and cooperation should be enhanced and implemented through annual seminars, forums, and conferences. This helps to propose and conduct new ideas or initiatives for river water protection. The local authority should be a key and active stakeholder, and it is necessary for connecting related stakeholders in the Ba river Basin.

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1. Anh, N. T., Can, L. D., Nhan, N. T., Schmalz, B., & Luu, T. L. (2023). Influences of key factors on river water quality in urban and rural areas: A review. Case Studies in Chemical and Environmental Engineering, 8, 100424. https://doi.org/10.1016/j.cscee.2023.100424 ***(Q1, Citescore: 9.2 – SCOPUS)***
2. Anh, N. T., & Luu, T. L. (2024). A Review About the Occurrence and Effectiveness of Conventional and Advanced Treatment Technologies of Persistent Organic Pollutants in Surface Water. Reviews of Environmental Contamination and Toxicology, 262(1), 11. https://doi.org/10.1007/s44169-024-00062-4 ***(Q1, Impact factor: 6.1 – Web of Science)***
3. Anh, N. T., Nhan, N. T., Tri, D. V., Britta, S., & Luu, T. L. (2024). Evaluating the spatiotemporal variation of Ba River water quality in the agricultural and urban watershed in the highland of Vietnam. Water Environment Research, 96(8), e11100. https://doi.org/10.1002/wer.11100 ***(Q2, Impact factor: 2.5 – Web of Science)***
4. Anh, N. T., Can, L. D., Schmalz, B., & Luu, T. L. (2025). Key factors affecting people's willingness to participate in water resource protection in the agricultural Ba River Basin – in the highlands of Vietnam. *Journal of Water and Climate Change*, *16*(4), 1225–1237. https://doi.org/10.2166/wcc.2025.103 ***(Q2, Impact factor: 2.7 – Web of Science)***
5. Anh, N. T., Dan, N. H., Schmalz, B., & Luu, T. L. (2025). Coagulation/floculation as a key unit in the decentralized surface water treatment systems in upland rural areas of Vietnam: Results from a lab scale to a pilot scale

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system. *Process Safety and Environmental Protection*, *194*, 1194–1205. https://doi.org/10.1016/j.psep.2024.12.058 ***(Q1, Impact factor: 6.9 – Web of Science***

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ANNEX

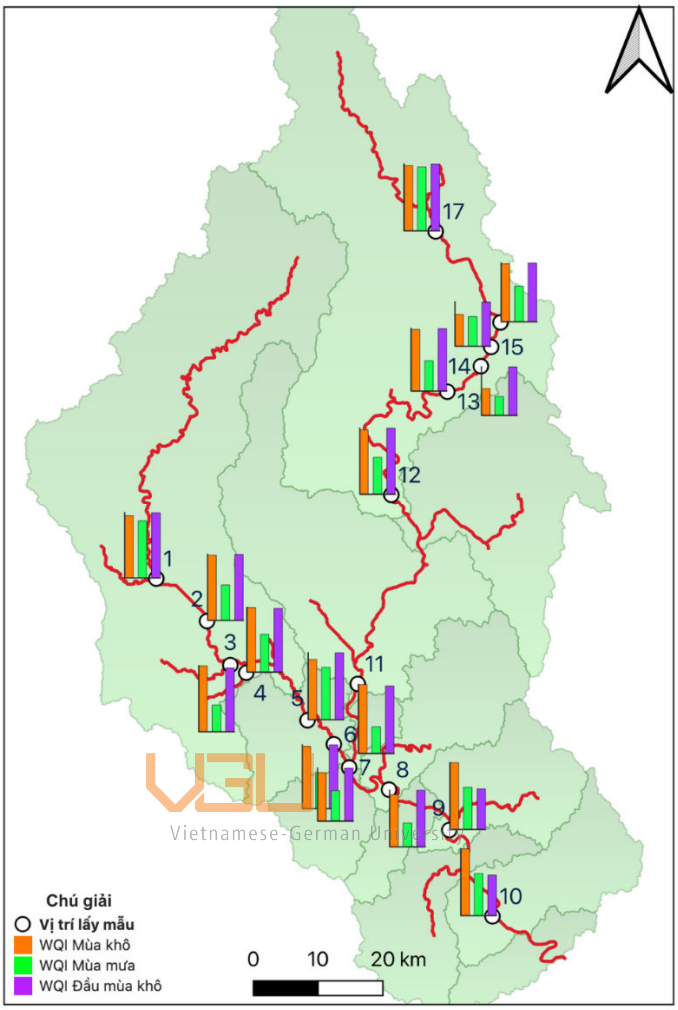

Figure S1. Comparison of water quality values between different seasons on Ba River

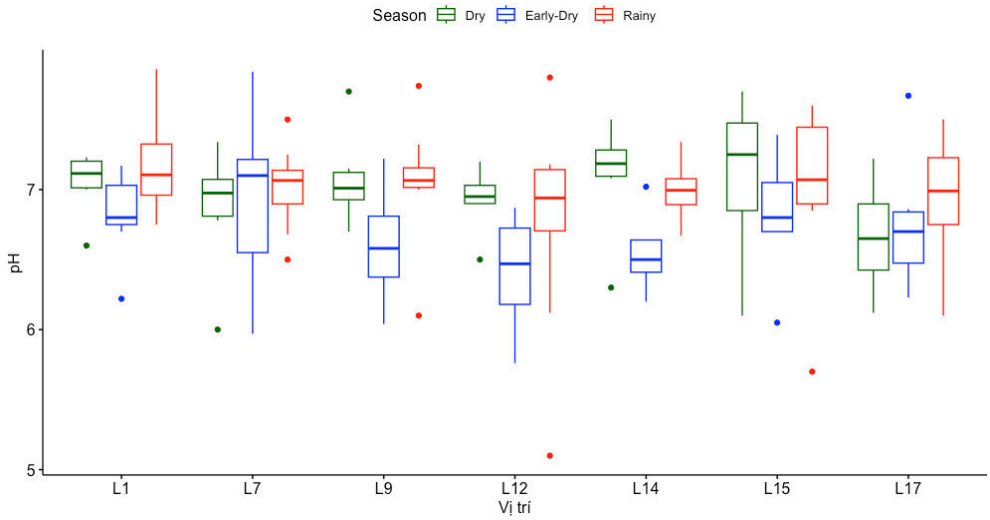

Figure S2. pH levels according to annual monitoring data of Gia Lai province in the period 2020-2023.

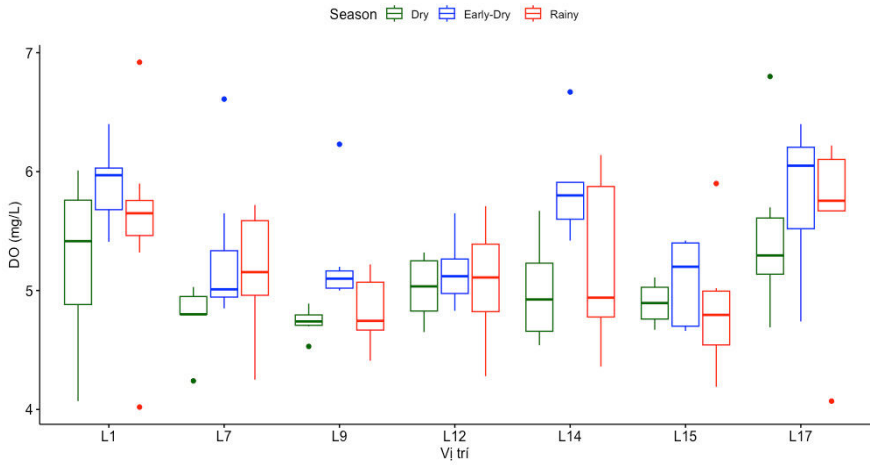

Figure S3. DO levels according to annual monitoring data of Gia Lai province in the period 2020-2023.

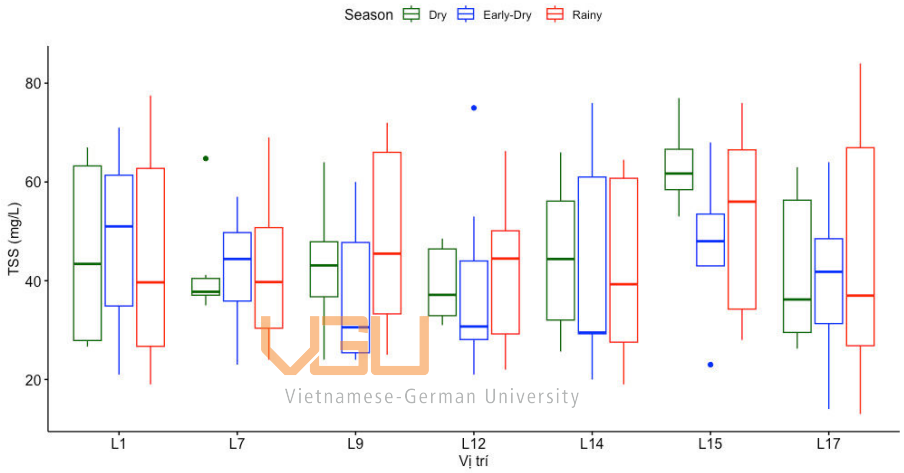

Figure S4. TSS levels according to annual monitoring data of Gia Lai province in the period 2020-2023

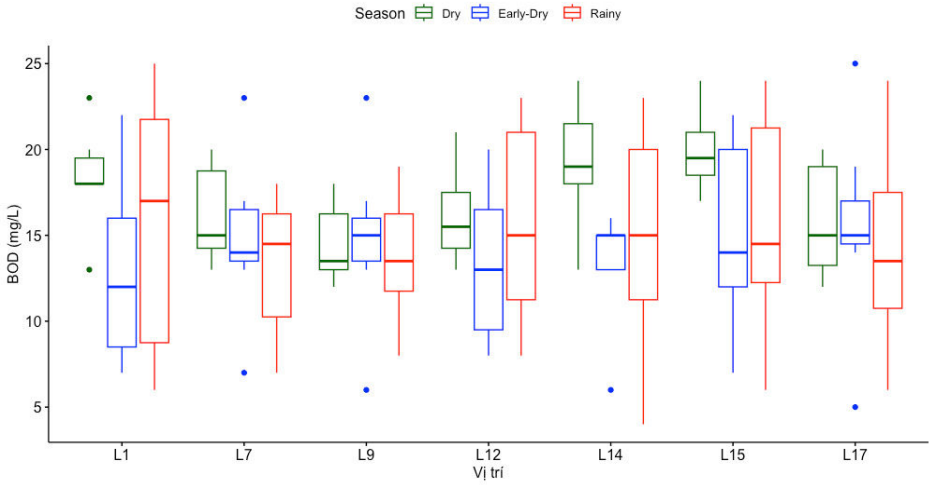

Figure S5. BOD_5 levels according to annual monitoring data of Gia Lai province in the period 2020-2023.

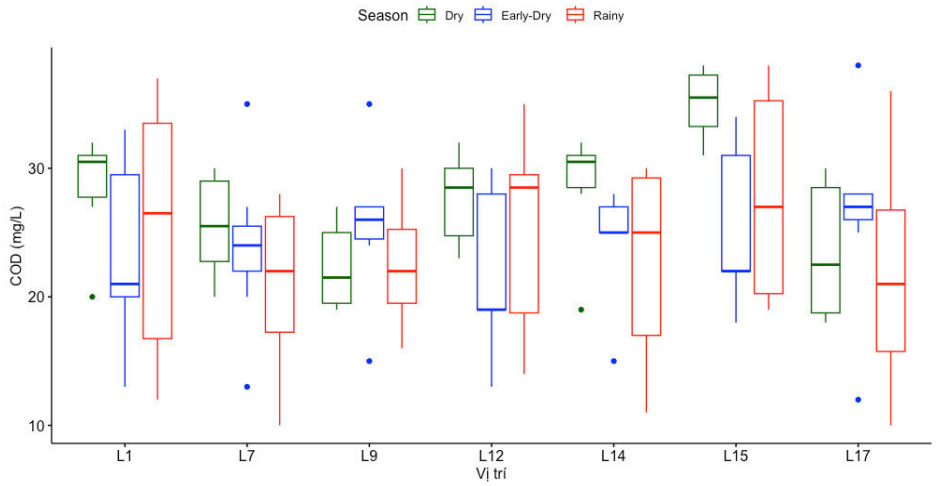

Figure S6. COD levels according to annual monitoring data of Gia Lai province in the period 2020-2023.

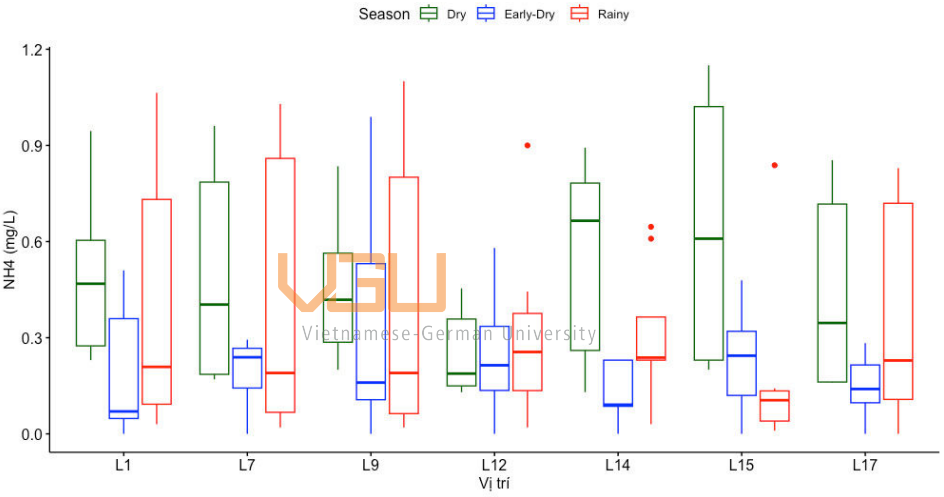

Figure S7. NH_4-N levels according to annual monitoring data of Gia Lai province in the period 2020-2023.

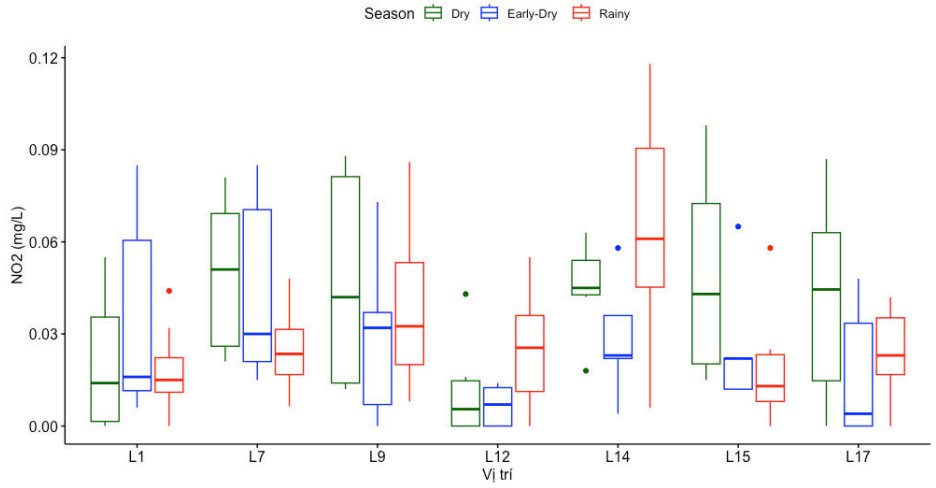

Figure S8. NO_2-N levels according to annual monitoring data of Gia Lai province in the period 2020-2023

Table S1. Seasonal water quality analysis results.

Season	Location	pH	DO	Turbidity	COD	TSS	BOD5	TOC	TC	TN	NH4_N	NO3_N	NO2_N	TP	Mn	Fe
Dry	1	6,85	4,19	13,3	22,4	53,1	9,8	7,85	18,47	0,1592	0,011	0,1	0,013	0,084	0,0079	0,7579
Dry	2	6,85	4,87	9,03	23,7	27,3	11,9	6,89	16,484	0,3878	0,256	0,04	0,008	0,026	0,0027	0,4135
Dry	3	7,4	5,06	11,4	18,7	27,5	10,5	7,79	15,42	0,7051	0,0141	0,0325	0,017	0,039	0,0035	0,5837
Dry	4	7,35	3,9	8,18	21,2	40,8	9,3	4,76	21,9	0,6316	0,225	0,135	0,011	0,042	0,0017	0,2609
Dry	5	7,15	4,2	14,6	26,8	53,5	13,4	6,81	21,781	0,6366	0,021	0,139	0,018	0,111	0,0038	0,5783
Dry	6	7,08	4,65	11,1	27,8	93,7	12,7	6,41	20,532	0,605	0,258	0,0975	0,016	0,081	0,0025	0,4942
Dry	7	6,92	3,8	8,97	47	60,2	17,8	6,47	30,313	0,7356	0,266	0,01	0,02	0,084	0,0005	0,0953
Dry	8	7,31	3,4	8,31	39,3	20,4	18,7	12,04	24,83	0,3871	0,265	0,0225	0,012	0,122	0,0039	0,5146
Dry	9	7,4	5,25	5,76	15,7	27,4	8,8	5,18	17,994	0,3788	0,041	0,1225	0,012	0,121	0,0021	0,3359
Dry	10	7,18	4,75	10,5	24,1	33,5	17,7	6,07	19,441	0,6848	0,031	0,0175	0,016	0,133	0,0076	0,5831
Dry	11	7,42	5,28	1,28	15,4	20,1	7,2	8,08	18,8532	0,4683	0,261	0,1725	0,008	0,057	0,0012	0,1149
Dry	12	7,6	5,05	5,54	25,4	73,2	11,4	5,36	20,832	1,182	0,011	0,06	0,023	0,064	0,0067	0,2164
Dry	13	7,63	3,8	5,31	25,1	20,2	12,5	8,90	25,851	1,38	0,0214	0,1425	0,05	0,063	0,0073	0,2378
Dry	14	7,7	2,99	16,6	55,5	37,2	23,3	6,41	30,03	1,84	0,475	0,2175	0,08	0,062	0,0034	0,4858
Dry	15	7,34	3,07	10,4	45,8	47,6	22,7	7,29	17,723	1,016	0,235	0,245	0,051	0,042	0,0048	1,2158
Dry	16	7,2	5,04	16,5	33,9	20,7	15,7	5,91	20,513	0,7384	0,0233	0,0275	0,013	0,075	0,0062	0,9033
Dry	17	6,98	6,18	16	19,4	20,6	9,9	5,43	13,848	0,679	0,277	0,36	0,011	0,087	0,0041	0,8784
Rainy	1	7,02	5,9	45	32,4	57,3	19,0	6,47	23,235	0,259	0,161	0,07	0,019	0,069	0,0551	0,0192
Rainy	2	7,1	6,41	18	38,9	29,2	21,8	17,20	32,43	0,3628	0,028	0,05	0,005	0,547	0,068	0,6081
Rainy	3	7,33	5,65	15,5	40,9	32,3	27,1	13,49	27,96	0,243	0,031	0,0305	0,021	0,435	0,0742	0,4123
Rainy	4	7,45	4,73	40,2	31,6	46,1	17,1	19,83	44,145	0,6763	0,042	0,11	0,005	0,507	0,0914	0,621
Rainy	5	7,3	5,19	56,1	25,9	67,4	11,7	17,19	38,295	0,2514	0,025	0,131	0,006	0,323	0,08	0,7044
Rainy	6	6,97	5,79	89,5	23,8	104,5	16,4	17,89	34,725	0,2787	0,019	0,098	0,008	0,655	0,0881	0,811
Rainy	7	6,87	5,85	45,23	46,3	80,3	28,1	18,27	37,845	0,6086	0,108	0,012	0,005	0,355	0,0712	0,4273
Rainy	8	7,2	4,55	92,3	55,9	58,7	32,9	24,08	45,375	0,4557	0,064	0,023	0,007	0,124	0,084	0,6065

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Rainy	9	7,07	6,41	105,2	25,6	35,1	15,5	4,39	16,86	0,3821	0,041	0,129	0,007	0,161	0,1234	0,774
Rainy	10	7,05	5,83	115,3	20,7	113,8	12,1	4,47	15,765	0,4043	0,029	0,0195	0,008	0,127	0,1022	0,978
Rainy	11	7,42	5,75	100,57	33,2	69,3	19,3	3,42	12,2835	0,3631	0,25	0,09	0,013	0,097	0,1796	2,1242
Rainy	12	7,65	5,8	125,52	34,4	95,4	19,9	6,10	20,94	0,7988	0,101	0,07	0,007	0,115	0,136	1,2487
Rainy	13	7,5	4,9	115,32	30,1	55,3	18,9	5,20	23,355	0,5489	0,172	0,165	0,07	0,136	0,0941	0,5235
Rainy	14	7,8	4,03	135,4	59,5	115,7	35,5	6,75	17,94	1,173	0,048	0,223	0,008	0,128	0,133	1,429
Rainy	15	6,99	4,16	25,7	56,2	65,8	33,4	9,28	19,71	1,088	0,453	0,296	0,009	0,084	0,1162	0,8117
Rainy	16	7,1	6,91	105,89	39,7	33,2	21,7	3,69	15,27	0,3268	0,036	0,0314	0,008	0,135	0,1071	0,9754
Rainy	17	7,2	6,8	22,15	22,5	32,1	12,4	2,17	15,27	0,3094	0,048	0,22	0,006	0,109	0,097	0,6391
Early-dry	1	6,99	4,81	16,4	18,4	21,2	9,9	5,85	10,5345	0,205	0,012	0,08	0,009	0,067	0,0109	0,5611
Early-dry	2	7,04	4,85	16,7	17,7	24,5	8,8	4,49	13,4805	0,487	0,206	0,06	0,008	0,076	0,0119	0,4231
Early-dry	3	7,2	4	13,2	19,8	23,9	11,1	5,25	12,4425	0,305	0,044	0,045	0,008	0,035	0,0105	0,6699
Early-dry	4	7,1	4,11	9,8	21,4	24,3	11,7	1,86	17,685	0,2617	0,045	0,135	0,029	0,048	0,0077	0,2791
Early-dry	5	7,3	4,41	14,9	16,3	12,9	8,8	4,82	17,58	0,39	0,024	0,139	0,007	0,04	0,0098	0,419
Early-dry	6	7,2	4,28	11,8	20,9	28,9	10,1	6,75	18,885	0,257	0,139	0,0475	0,008	0,055	0,0219	0,6771
Early-dry	7	6,89	4,52	13,97	38,5	26,5	22,5	4,46	17,175	0,835	0,509	0,01	0,011	0,096	0,0109	0,1144
Early-dry	8	7,45	3,71	10,2	34,3	18,9	17,2	7,87	20,43	0,4223	0,095	0,033	0,009	0,071	0,0099	0,3712
Early-dry	9	7,16	4,01	9,76	26,1	24,2	15,7	1,93	16,41	0,5788	0,091	0,04	0,012	0,89	0,0199	0,296
Early-dry	10	7,19	4,67	15,7	17,1	27,1	7,9	2,72	14,1495	0,4015	0,151	0,0122	0,004	0,096	0,0319	0,511
Early-dry	11	7,22	4,82	7,5	14,4	15,4	7,2	2,20	9,864	0,4477	0,066	0,131	0,008	0,088	0,0042	0,644
Early-dry	12	7,37	4,99	11,2	26,4	31,3	11,3	4,31	16,875	1,08	0,355	0,081	0,015	0,084	0,041	0,33
Early-dry	13	7,57	4,05	9,7	22,1	28,1	12,5	3,62	23,475	1,785	0,271	0,1625	0,023	0,063	0,022	0,3151
Early-dry	14	7,7	3,51	16,6	45,1	34,6	19,2	9,76	32,385	0,969	0,288	0,1375	0,045	0,088	0,033	0,6112
Early-dry	15	7,34	3,21	28,5	41,4	41,7	23,5	10,52	28,14	0,6584	0,311	0,15	0,037	0,08	0,029	1,133
Early-dry	16	7,2	4,77	23,5	34,9	20,2	14,7	2,87	14,8755	0,2754	0,037	0,04	0,011	0,061	0,0123	0,715
Early-dry	17	7,07	5,41	16,7	19,3	19,5	9,9	4,05	15,42	0,479	0,139	0,07	0,025	0,057	0,009	0,4882

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Table S2. The loadings of variables on the first PCs for the Ba River Basin dataset.

	Parameters	Comp.1	Comp.2	Comp.3	Comp.4
1	pH	-0.270	-0.011	0.287	-0.606
2	DO	0.438	0.205	0.092	0.177
3	Tur	0.282	-0.252	0.411	-0.040
4	COD	-0.132	-0.555	-0.104	0.116
5	TSS	0.191	-0.329	0.236	-0.021
6	BOD_5	-0.015	-0.557	-0.099	0.095
7	TOC	0.162	-0.324	-0.451	-0.259
8	TN	-0.426	-0.073	0.071	-0.111
9	NH_4-N	-0.360	-0.067	-0.083	0.604
10	NO_2-N	-0.409	-0.012	0.076	-0.191
11	TP	0.266	-0.044	-0.435	-0.307
12	Fe	0.163	-0.223	0.503	0.044
Eigenvalue		3.28	2.96	1.52	1.10
% Total variance		27.32	24.64	12.69	9.17
Cumulative % variance		27.32	51.95	64.64	73.81

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Table S3. Survey results of community willingness to participate on a Likert scale.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
PT001	4	4	4	4	4	4	3	3	4	4	4	4	4	5	4	4	4	4
PT002	5	5	4	5	5	4	4	4	4	4	4	4	5	4	4	4	4	4
PT003	4	5	4	4	5	4	3	3	4	4	4	4	4	4	4	4	4	5
PT004	4	3	3	4	4	3	4	3	3	4	3	5	4	4	4	4	3	3
PT005	4	4	4	5	4	4	3	4	3	4	3	4	4	4	4	5	4	5
PT006	5	5	4	5	5	4	4	3	4	5	4	4	5	4	4	5	4	4
PT007	4	5	5	4	4	3	5	3	4	5	5	3	5	4	5	4	4	4
PT008	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5
PT009	5	5	4	4	5	4	4	5	4	4	4	4	5	4	4	4	4	4
PT010	3	3	4	4	4	5	5	4	4	3	5	5	4	5	4	5	5	5
PT011	4	4	4	5	5	4	4	4	5	4	4	4	5	4	4	4	4	4
PT012	4	4	3	3	4	3	4	3	4	4	3	4	3	3	4	4	4	4
PT013	4	4	4	5	5	5	5	3	4	4	5	5	4	5	4	5	5	5
PT014	5	5	4	5	5	4	4	4	4	4	4	4	5	4	4	4	4	4
PT015	4	5	5	5	4	5	4	4	3	4	4	5	4	5	5	5	5	5
PT016	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4
PT017	5	5	5	5	5	5	5	5	4	5	4	4	5	4	4	5	4	5
PT018	5	5	4	5	5	5	4	4	4	4	4	5	5	5	4	5	5	5
PT019	5	5	5	5	5	4	5	4	5	5	5	4	5	4	5	4	4	4
PT020	4	4	4	5	4	5	5	4	4	4	5	5	4	5	4	5	5	5
AY021	5	5	4	4	5	3	3	3	3	4	4	4	5	4	4	4	4	4
AY022	5	5	5	4	5	4	3	3	4	5	3	4	5	4	5	4	4	4
AY023	4	4	4	4	4	3	4	3	3	4	4	4	4	4	4	4	3	3
AY024	4	4	5	3	4	4	3	4	3	4	3	4	4	4	5	4	3	3
AY025	5	5	4	4	5	4	4	3	3	4	4	4	5	4	4	4	4	4
AY026	5	4	4	5	5	3	4	3	4	4	4	4	5	4	4	4	3	3
AY027	4	4	4	4	4	4	3	4	3	4	3	4	4	4	4	4	4	3
AY028	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
AY029	4	4	5	4	4	3	4	3	3	4	4	3	5	3	5	3	3	3
AY030	5	5	5	3	4	4	4	3	4	3	4	3	4	4	4	4	3	3
AY031	4	4	5	4	4	5	5	3	5	4	5	5	4	5	5	5	5	5
AY032	5	5	5	4	5	4	4	3	4	5	4	4	5	4	5	4	4	4
AY033	4	4	4	5	4	3	4	3	3	4	4	3	4	3	4	3	3	3
AY034	4	4	5	4	4	4	3	3	3	4	3	4	4	4	5	4	4	4
AY035	4	4	5	4	4	4	3	4	3	4	3	4	4	4	5	4	4	4
KP036	5	5	5	4	5	4	5	5	5	5	4	4	5	4	5	4	5	5
KP037	5	5	4	5	5	5	4	4	4	4	4	5	5	5	4	5	5	5
KP038	5	5	5	5	5	4	4	4	4	4	4	4	5	4	5	4	4	4
KP039	5	5	4	5	5	4	4	4	3	5	4	4	5	4	4	4	4	5
KP040	5	5	4	4	5	3	4	3	4	4	4	4	5	4	4	4	4	4
KP041	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	5

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KP042	4	4	4	4	4	4	3	5	4	4	3	4	4	4	4	4	4	4
KP043	4	4	4	4	4	4	5	4	5	4	5	4	4	4	4	4	4	4
KP044	5	5	5	5	5	5	4	3	4	5	4	4	5	4	5	5	5	5
KP045	5	5	4	4	5	5	4	4	4	4	4	4	5	4	4	5	5	5
KP046	3	3	3	4	4	4	4	5	4	3	4	4	3	4	3	4	4	4
KP047	4	4	4	4	4	5	5	4	5	4	5	4	5	4	4	4	4	4
KP048	3	3	4	5	4	4	4	3	3	3	4	4	4	4	4	4	4	4
KP049	4	4	4	5	5	5	3	4	4	4	3	4	4	4	4	5	5	5
KP050	5	5	5	4	5	4	4	4	4	5	4	4	5	4	5	5	5	5
IP051	4	4	4	5	5	4	4	3	4	5	4	4	4	4	4	4	4	4
IP052	4	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4
IP053	3	3	4	5	4	5	5	4	4	4	5	5	3	5	4	5	5	5
IP054	4	5	4	5	4	4	5	4	4	5	5	4	4	4	4	4	4	4
IP055	5	5	4	4	5	4	4	4	5	5	4	4	5	4	4	4	4	4
IP056	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5
IP057	4	4	4	5	4	5	4	5	4	4	4	5	4	4	4	5	5	5
IP058	4	4	4	4	4	4	4	4	3	4	4	4	3	4	4	3	3	3
IP059	3	4	3	4	4	4	3	3	3	4	4	4	3	4	3	3	3	3
IP060	4	4	4	5	5	5	3	3	4	4	3	5	4	5	4	4	4	4
IP061	5	5	5	5	5	5	4	4	4	4	4	5	5	4	5	4	4	4
IP062	4	4	4	5	4	5	4	4	5	4	4	5	4	4	4	4	4	4
IP063	4	4	4	4	5	5	5	4	4	4	5	5	4	5	4	5	5	5
IP064	4	4	4	5	5	4	4	4	4	5	5	4	5	4	4	5	5	5
IP065	4	5	5	5	4	5	5	5	4	5	5	4	5	4	4	4	5	5
KC066	4	4	4	4	5	5	4	4	3	4	4	5	5	5	4	5	5	5
KC067	4	4	4	4	5	4	3	4	4	4	3	4	4	4	4	5	5	5
KC068	4	4	4	5	4	5	4	4	4	4	4	5	4	5	4	5	5	5
KC069	4	4	4	4	5	4	4	4	4	5	5	4	4	4	4	4	4	4
KC070	5	5	5	5	5	5	4	3	5	5	4	5	5	4	5	5	5	5
KC071	5	5	4	4	5	4	3	4	4	4	4	4	5	4	4	5	5	5
KC072	5	5	4	4	5	5	3	4	4	4	4	5	5	5	4	5	5	5
KC073	5	5	5	4	5	4	5	4	5	5	5	4	4	5	5	4	5	5
KC074	4	4	4	4	5	5	3	4	4	4	4	5	5	5	4	5	5	5
KC075	4	4	4	5	4	4	4	3	3	5	4	4	4	4	4	4	4	4
AK076	5	5	5	4	5	5	4	4	3	5	4	5	5	5	5	5	3	3
AK077	4	4	4	4	4	4	4	3	3	4	4	4	5	4	4	4	4	4
AK078	5	5	5	3	5	3	3	4	4	5	3	4	5	4	5	4	4	4
AK079	5	5	5	4	5	4	5	5	3	5	4	4	5	4	5	4	5	5
AK080	5	5	5	5	5	4	5	5	4	4	5	3	4	3	5	4	5	5
AK081	4	4	4	4	5	4	4	3	4	4	4	4	4	4	4	4	3	3
AK082	4	4	4	4	5	3	4	3	3	5	4	4	5	4	4	4	4	4
AK083	4	4	4	4	4	4	4	3	4	4	4	4	5	4	4	4	3	3
AK084	5	5	5	3	5	3	3	3	3	5	3	3	5	4	5	4	4	4

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AK085	4	4	4	4	5	4	4	3	4	4	4	4	4	4	4	4	3	3
AK086	5	5	5	4	5	5	3	4	4	5	4	4	5	4	5	4	4	4
AK087	4	5	5	3	5	4	3	3	4	4	4	4	5	4	5	4	4	4
AK088	5	5	5	4	5	4	4	4	4	5	4	4	5	4	5	4	5	5
AK089	5	5	5	4	5	4	4	4	4	5	4	4	5	4	5	4	5	5
AK090	4	4	4	5	5	4	4	3	3	4	4	4	4	4	4	4	4	4
KB091	4	4	4	4	5	4	3	4	3	5	3	4	5	4	4	4	4	4
KB092	4	4	4	4	4	4	4	3	4	4	4	4	5	4	4	4	4	4
KB093	5	5	5	4	5	5	3	4	4	5	3	5	5	5	5	5	5	5
KB094	4	4	4	4	5	4	4	3	4	4	4	4	4	5	4	5	5	4
KB095	5	5	5	4	5	4	3	4	4	5	4	4	5	5	5	5	5	4
DD096	4	4	4	4	5	4	3	3	4	4	4	4	4	4	4	4	4	4
DD097	5	5	5	5	5	5	3	4	4	5	4	5	5	4	5	4	4	4
DD098	4	4	4	4	4	4	4	4	4	4	4	4	4	5	4	5	5	5
DD099	3	3	3	3	4	4	4	4	3	4	4	4	4	4	5	4	3	3
DD100	4	3	4	3	4	4	3	3	4	4	4	4	4	4	4	3	3	3

Table S4. Summary of variable values on community willingness to participate.

Respondents	**WP**	**SC**	**DW**	**PW**	**IN**	**GE**	**ED**	**PR**
PT001	4,33	3,94	4,5	3,00	4	0	4	0
PT002	4,00	4,28	4	3,00	4	1	2	0
PT003	4,00	4,06	3,5	3,00	3	0	3	0
PT004	3,00	3,61	2,5	2,25	2	0	2	0
PT005	4,00	4,00	4	3,00	4	1	4	0
PT006	4,00	4,33	3,5	3,00	3	1	4	0
PT007	4,00	4,22	4	2,25	4	0	3	0
PT008	4,33	4,17	5	2,50	4	1	3	0
PT009	4,00	4,28	3,5	2,25	3	0	3	0
PT010	4,00	4,28	4,5	3,25	4	1	5	0
PT011	4,00	4,22	4	2,00	2	0	3	1
PT012	3,00	3,61	2,5	2,00	1	0	2	1
PT013	4,00	4,50	4	2,00	3	0	3	1
PT014	4,00	4,28	5	3,00	3	0	4	1
PT015	4,00	4,50	4,5	2,00	3	1	3	1
PT016	4,00	4,06	4	2,75	3	1	4	1
PT017	5,00	4,67	4,5	3,50	4	1	5	1
PT018	4,00	4,61	4	3,00	3	0	3	1
PT019	4,00	4,61	4	2,75	3	0	3	1
PT020	4,00	4,50	4,5	2,75	3	0	3	1
AY021	4,00	4,00	3	3,00	3	1	3	1
AY022	4,33	4,22	4,5	3,00	3	1	4	1
AY023	4,33	3,72	3,5	3,00	3	0	3	1

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AY024	4,00	3,78	3,5	2,75	3	0	3	1
AY025	4,00	4,11	3,5	3,00	3	1	4	1
AY026	4,00	4,00	3,5	2,75	3	1	3	1
AY027	3,67	3,78	3	2,75	2	0	3	1
AY028	4,00	4,00	3,5	3,00	3	1	3	1
AY029	3,67	3,72	3	2,75	2	0	2	1
AY030	3,67	3,83	3	2,50	2	0	3	1
AY031	4,67	4,56	4	3,00	4	1	4	1
AY032	4,00	4,33	3,5	2,25	3	1	3	1
AY033	4,00	3,61	3,5	2,75	3	0	4	1
AY034	4,00	3,89	3,5	2,75	4	0	4	1
AY035	4,00	3,94	4	2,75	4	0	4	1
KP036	5,00	4,67	4,5	3,00	4	1	4	0
KP037	4,00	4,61	4	3,25	5	0	2	0
KP038	4,00	4,39	4,5	3,00	4	0	3	0
KP039	4,00	4,33	4	2,00	3	1	3	0
KP040	4,67	4,11	3,5	3,00	3	0	3	0
KP041	4,00	4,11	4,5	2,50	4	0	2	0
KP042	4,00	3,94	4	3,00	4	0	4	0
KP043	4,00	4,17	4	2,75	4	0	3	0
KP044	4,00	4,61	4	2,75	4	1	3	0
KP045	4,67	4,44	4,5	3,75	3	0	4	0
KP046	4,67	3,72	4,5	3,25	4	1	4	0
KP047	4,00	4,28	4	2,25	4	0	2	1
KP048	4,00	3,78	4	2,25	3	1	3	1
KP049	4,33	4,22	4	4,00	4	0	4	1
KP050	4,33	4,56	4	2,25	4	1	3	1
IP051	4,00	4,11	4,5	3,00	3	1	3	0
IP052	4,00	4,06	4	2,25	3	1	3	0
IP053	4,00	4,33	4,5	3,25	2	0	3	0
IP054	4,00	4,28	3	2,75	3	1	3	0
IP055	4,00	4,33	4	2,75	4	0	4	0
IP056	4,33	4,17	4	3,50	3	1	4	0
IP057	4,00	4,39	4	3,00	2	0	3	0
IP058	3,33	3,72	3,5	2,75	3	0	3	0
IP059	3,00	3,44	3	2,25	2	1	2	0
IP060	4,00	4,11	4	3,00	3	0	3	0
IP061	4,00	4,50	3,5	2,75	3	1	3	0
IP062	4,00	4,22	4,5	2,75	3	1	4	0
IP063	4,67	4,50	4,5	3,25	3	1	3	0
IP064	4,67	4,44	4	4,50	5	1	5	0
IP065	5,00	4,61	4	3,75	4	0	3	0
KC066	4,00	4,39	4	4,25	3	1	5	1

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KC067	5,00	4,11	4	3,50	4	0	4	1
KC068	4,00	4,39	4	4,00	4	0	5	1
KC069	4,00	4,17	4	3,00	4	1	3	1
KC070	4,33	4,72	4	2,75	3	0	3	1
KC071	4,00	4,33	4,5	3,00	4	1	4	0
KC072	4,00	4,50	4	3,25	4	0	2	0
KC073	5,00	4,67	4,5	3,50	4	0	3	0
KC074	4,00	4,39	4	3,00	2	0	4	0
KC075	4,00	4,00	4	2,75	3	1	4	0
AK076	4,00	4,44	4	2,75	3	0	3	1
AK077	4,00	3,94	4	2,75	3	0	4	1
AK078	4,00	4,17	4	2,75	4	1	3	1
AK079	5,00	4,56	4,5	3,25	4	1	4	1
AK080	5,00	4,50	4,5	3,50	4	1	4	1
AK081	4,00	3,89	4	2,25	3	1	3	1
AK082	4,00	4,00	4,5	2,75	3	0	4	1
AK083	4,33	3,89	4,5	2,50	4	1	5	1
AK084	4,00	4,00	4	2,50	4	1	4	1
AK085	4,67	3,89	4	3,00	4	0	4	1
AK086	4,00	4,39	4,5	2,50	4	0	4	1
AK087	4,00	4,11	4,5	2,25	4	0	3	1
AK088	4,67	4,50	4,5	3,00	2	1	2	1
AK089	4,67	4,50	4,5	3,00	4	1	4	1
AK090	4,00	4,00	4	2,50	4	1	4	1
KB091	4,00	4,00	4	2,00	4	0	4	1
KB092	4,00	4,00	4,5	2,75	2	1	4	1
KB093	4,33	4,61	4,5	2,75	4	0	5	1
KB094	4,33	4,17	4,5	3,00	4	0	5	1
KB095	4,33	4,50	4,5	2,00	2	0	4	1
DD096	4,33	3,94	4	2,75	4	1	3	0
DD097	4,00	4,50	4,5	2,50	3	0	5	0
DD098	4,00	4,22	4	2,75	3	0	4	0
DD099	3,00	3,67	2,5	2,25	2	1	2	0
DD100	3,00	3,61	2,5	2,25	2	0	4	0

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Table S5. The cluster stability and instability with the average Jaccard coefficients

Clusters	AvgJaccard	Instability
1	0.81	0.19
2	0.82	0.23
3	0.74	0.31
4	0.56	0.49
5	0.78	0.30
6	0.74	0.44

SURVEY QUESTIONNAIRE

VIETNAMESE – GERMAN UNIVERSITY

TOPIC

ASSESSMENT OF FACTORS IMPACTING ON WATER QUALITY AND WILLINGNESS TO PARTICIPATE IN THE PROTECTION OF WATER RESOURCES ALONG BA RIVER BASIN

Dear Sir/Madam, For the purpose of studying about the use of surface water and the willingness to participate in the protection of surface water along the Ba River, Gia Lai province. The study was carried out to have a basis for proposing appropriate surface water management solutions. Therefore, we would like to ask for your opinions on the following issues.

This information sheet is only used for research purposes and personal information will be kept strictly confidential. Thank you very much!

Code:……
Survey date:…….

I. BASIC INFORMATION

Name (Optional): ……
Age (Optional): …….
Address:……..
Ethnic Minority: ……..

1. **Gender**
   ☐Male ☐Female
2. **How many people are your household:**…… people.
3. **What is your age group:**
   ☐ 18 – 30 ☐ 31 – 40
   ☐ 41 – 50 ☐ 51 – 60
   ☐ > 60
4. **What is your education level?**
   ☐ No formal education ☐ Primary level
   ☐ Secondary level ☐ High school level
   ☐ College level ☐ Graduation
   ☐ Post graduation
5. **What are the main sources of income:**
   ☐ Wages (officials) ☐ Business
   ☐ Agriculture activities ☐ Worker
   ☐ Freelance ☐ Others:
   ……..
6. **What is your group of average income (per households): (VND)**
   ☐ 1 – <5 million ☐ 5 – 15 million
   ☐ >15 million
7. **How many years are have you lived here ?**: …….years

II. AWARENESS OF THE IMPORTANCE AND MEASURES TO PROTECT SURFACE RESOURCES

8. **What water sources are your household taking?** (multiple answers)
   ☐ Tap water
   ☐ Groundwater → the depth of wells: ……..…m
   ☐ Public tap → How far from your house:……..…m
   ☐ Rainwater
   ☐ Surfacewater → How far from your house:…….m

☐ Bottled water
☐ Others: ……

9. Do you use surface water of Ba River?

☐ Yes ☐ No

If yes, what is surface water used for?

☐ Agricultural activities
☐ Domestic purpose
☐ Production activities
☐ Others:…….

10. In your opinion, the role of surface water in daily life?

☐ Totally unnecessary	☐ Unnecessary	☐ Normal	☐ Necessary	☐ Very necessary
1	2	3	4	5

11. What information source does the household understand about the importance of using and protecting surface water?

Information sources	Degree (Not propagated -> very often)				
☐ Media	1	2	3	4	5
☐ Training and propaganda campaings	1	2	3	4	5
☐ Self-study	1	2	3	4	5
☐ Unknown	1	2	3	4	5
☐ Others……	1	2	3	4	5

12. In your opinion, to what extent are the negative impacts of surface water unavailable?

☐ Strongly unaffect	☐ Unaffect	☐ Neutral	☐ Affect	☐ Strongly affect
1	2	3	4	5

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13. In your opinion, to what extent is the economic value or benefit of surface water?

☐ completely unprofitable	☐ little profitable	☐ Moderately profitable	☐ highly profitable	☐ Very highly profitable
1	2	3	4	5

14. In your opinion, what factors affect the quality and quantity of surface water along the Ba River?

☐ Agricultural activities (using fertilizers, pesticides, clearing forests for farming, etc.)
☐ Industrial activities (wastewater and waste from factories, industrial clusters)
☐ Domestic activities (domestic wastewater and wastes from residential areas)
☐ Mining activities
☐ Unknown
☐ Others ……..

15. In your opinion, to what extent do these factors affect the quality and quantity of water in the Ba River?

Agricultural activities	1	2	3	4	5
Industrial activities	1	2	3	4	5
Domestic activities	1	2	3	4	5
Mining activities	1	2	3	4	5
Other…….	1	2	3	4	5

Other…….	1	2	3	4	5

16. In your opinion, to what extent is it necessary to protect the surface water on the Ba River?

☐ Totally unnecessary	☐ Unnecessary	☐ Normal	☐ Necessary	☐ Very necessary
1	2	3	4	5

17. Are you willing to participate in water conservation activities (do not discharge wastewater and waste, do not exploit sand and soil in rivers, do not participate in cutting down watershed forests to keep water, use resources sparingly) water including living and irrigation….)

☐ Very unwilling	☐ unwilling	☐ Neutral	☐ willing	☐ Very willing
1	2	3	4	5

18. Do you own agricultural land along the Ba River?

☐ Yes ☐ No

If yes, what kind of tree are you growing?

☐ Perennial crops (Pepper, coffee, rubber …)

☐ Annual crops (vegetables…)

☐ Others …….

Thank you very much Mr/Ms!

Gia Lai, Date on……/...../2022

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THE SURVEY ON SENSE OF COMMUNITY

No.	Questions
1	Overall, I am very attracted to living in his neighborhood
2	I feel like i belong to this neighborhood
3	I visit with my neighbors in their homes
4	the friendships and associations i have with other people in my neighborhood mean a lot to me
5	given the opportunity, i would like to move out of this neighborhood
6	If the people in my neighborhood were planning something i'd think of it as something "we"
7	If i needed advice about something i could go to someone in my neighborhood
8	I think i agree with most people in my neighborhood about what is important in life
9	I believe my neighbors would help me in an emergency
10	I feel loyal to the people in my neighborhood
11	I borrow things and exchange favors with my neighbors
12	I would be willing to work together with others on something to improve my neighborhood
13	I plan to remain a resident of this neighborhood for a number of years
14	I like to think of myself as similar to the people who live in this neighborhood
15	I rarely have neighbors over to my house to visit
16	A feeling of fellowship runs deep between me and other people in this neighborhood
17	I regularly stop and talk with people in my neighborhood
18	Living in this neighborhood gives me a sense of community

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Figure S9: Some pictures of the presence of agricultural, and industrial activities along the Ba River

