Surface Water Quality Analysis using Fuzzy Logic Approach: A Case of Inter-provincial Irrigation Network in Vietnam

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Abstract. Water quality assessment plays an essential role in sustainable management and development of river systems. However, this process is highly complicated that requires professional expertise. The fuzzy water quality index (FWQI) based on fuzzy logic is computational method categorizing water quality into various categories for different water uses. In this study, a method based on fuzzy inference systems (FIS) to assess water quality in the Nhue River, an inter-provincial irrigation network in Northern Vietnam, using fuzzy logic is proposed. Nine fuzzy variables namely dissolved oxygen (DO), biological oxygen demand (BOD\textsubscript{5}), chemical oxygen demand (COD), pH, ammonium (NH\textsubscript{4}\textsuperscript{+}), phosphates (PO\textsubscript{4}\textsuperscript{3−}), total suspended solids (TSS), turbidity, and total coliform (Tco) on the potable quality of the river water are employed for the quality assessment. The fuzzy inference system is composed by 3250 rules with a score from 0 to 100 and five verbal categories. The FWQI was validated by comparison with Vietnam national water quality index. The result of the study clearly shows that the Fuzzy Inference System (FIS) approach was a practical, simple and useful tool to assess surface water quality in river as well as irrigation networks.

1. Introduction
Surface water is a natural resource playing an important role to sustain aquatic life, ecological integrity, and as an input for various human activities. The increasing population, urbanization, industrialization, and agricultural developments along river basins have increased the levels of water pollution worldwide. To deal with this problem, assessing water quality through frequent monitoring is among the highest priorities in resources protection policy of developing countries, including Vietnam. This process has been usually measured by physical and chemical parameters and through the comparison of results of monitoring programs with the existing water quality regulations or standards. However, regulations on surface water quality which contain upper and lower limits have two ambiguities [1]. Firstly, the traditional water quality evaluation methods use discrete form, this leads to a parameter being close or far from the limit has equal impact for evaluation of concentration. Secondly, all selected water quality parameters may not be included in a single class. These established various quality classes in one sampling location may constitute confusion for quality definition of a sampling location [2]. Moreover, water quality monitoring involves the determination of various water quality parameters, the use of individual water quality variable to describe water quality is not easily understandable by common people. Nowadays, various classification methods have been used for estimating the changing status and usability of surface water in river basins. However, a discrepancy frequently arises from the lack of a clear distinction between each water utilization mode, the uncertainty in the quality criteria of water
employed and vagueness or fuzziness embedded in the decision making output values. Owing to inherent imprecision, difficulties always exist in some conventional methodologies like water quality index (WQI) when describing integrated water quality conditions with respect to various chemical constituents, biological aspects, nutrients, and aesthetic qualities [3]. Some advanced methods, like fuzzy logic systems, artificial neural networks, and radial basis functions, have been helpful in enhancing the precision of prediction [4]. Recent studies focused on the evaluation of surface water quality using fuzzy logic. The fuzzy logic based methods have demonstrated to be appropriated to address uncertainty and subjectivity in environmental issues. In this study, a methodology based on fuzzy inference systems (FIS) to assess water quality is proposed. This paper presents a comparative study using fuzzy logic technique to assess water quality of the Nhue River in comparison with output generated by national water quality index.

2. Materials and methods

2.1. Study area

The Nhue River in Vietnam is the main source of irrigation water for suburban agricultural land and fish farm [5]. Wastewater from the industrial plants located along these rivers has been discharged, which has degraded the water quality of the rivers.

![Figure 1. Location map of study area and water quality sample sites in the Nhue River.](image)

The Nhue River takes its source from the Red River at the Lien Mac 1 Gate to the north west of Ha Noi (figure 1). It runs through a number of districts and finally runs into the Day River in Phu Ly city, Ha Nam province. In fact, the Nhue River is the receiving source of Ha Noi’s wastewater from the Ha Noi river system, including To Lich, Lu, Set, Kim Ngoo rivers. These inner rivers discharge into the Nhue River at Thanh Liet Gate with the flow of about 300,000 - 350,000 m³ per day. Although the Nhue river water now has the sign of pollution, it is still the water supply of many agricultural and aquatic activities in the watershed. On the other hand, the decrease of the Nhue river water quality also negatively impacts on the underground water used for the daily activities of the local people.
This paper presents a comparative study using fuzzy logic technique to assess status of water quality of Nhue River by comparing the output generated by Vietnam national water quality index. In order to assess the proposed fuzzy water quality index of the Nhue River, water samples were taken in October 2019 at 11 sites (figure 1). All measurements were conducted according to standard methods. Samples were collected from well mixed section of river 30 cm below the water surface using weighed bottles. Sample containers were labelled properly. After sampling they were transported to laboratory of Thuyloi University to analyse.

2.2. The national water quality index (WQI)
In Vietnam, to assess and determine the level of pollution of surface water in the river, scientists usually select and apply WQI water quality assessment method according to Decision No. 879/QĐ-TCMT July 1, 2011 of the Vietnam Environment Administration on promulgating a manual to calculate water quality index to assess the pollution level of surface water resources. WQI index was calculated for pH, temperature, dissolved oxygen (DO), biological oxygen demand (BOD₅), chemical oxygen demand (COD), ammonium (NH₄⁺), phosphates (PO₄³⁻), total suspended solids (TSS), turbidity, and total coliform (Tco) by the following formula as follows:

$$WQI_{ij} = \frac{q_i - q_{i+1}}{BP_{i+1} - BP_i} \left( BP_{i+1} - C_p \right) + q_{i+1}$$

where BPᵢ is the lower limit concentration of the observed parameter values corresponding to the level i; BPᵢ₊₁ is the upper limit concentration of the observed parameter values corresponding to the i + 1 level; qi: WQI value at level i given in the table corresponding to BPᵢ value; qi₊₁ is WQI value at i + 1 in the table corresponding to BPᵢ₊₁ value; C_p is the value of the monitoring parameter is taken into account.

The range of the final WQI will fall between 0 and 100, in which, a parameter is considered excellent if its WQI-value fall between 91 and 100, and will be considered bad if its WQI-value falls between 26 and 50.

2.3. Selection of fuzzy variables
In this study, 9 water quality parameters were selected based on their importance and availability, covering physicochemical and biological characteristics of surface water. The selected parameters are dissolved oxygen (DO), biological oxygen demand (BOD₅), chemical oxygen demand (COD), pH, ammonium (NH₄⁺), phosphates (PO₄³⁻), total suspended solids (TSS), turbidity, and total coliform (Tco). The selection criteria for each parameter are as follows:

1- Dissolved oxygen (DO) is one of the critical parameters for aquatic life support and the most frequently measured parameter in monitoring studies [6]. This parameter represents the amount of oxygen that is available to aquatic organisms for metabolism/respiration and assimilation of food.

2- Biological oxygen demand (BOD) is an important parameter for representing the overall water quality of rivers. The presence of a higher level of BOD in surface water can accelerate bacterial growth; in turn, the reduced oxygen levels in water can harm aquatic life.

3- Chemical oxygen demand (COD): similar to BOD, COD is also a parameter for representing the overall water quality of rivers.

4- pH is an important parameter in representing the quality of water, which can affect aquatic life, cause corrosion, and create a bitter taste in water and extreme values may lead to organoleptic consequences.

5- Ammonium (NH₄⁺) is an important parameter that serves as an indicator of organic pollution, and is a source of nitrogen present in water column that permits the aquatic biota to cover their nutritive needs of nitrogen. Normally the presence of nitrate may not affect aquatic life; however, an excess of nitrogen can cause adverse health and ecological effects. It also simulates the growth of plants and algae in water, which in turn can affect the life of fish and aquatic insects. Ammonia is excreted by animals and is produced during decomposition of plants and animals. Ammonia is an component in many fertilizers and is also present in sewage, storm water runoff, certain industrial wastewaters, and runoff from animal feedlots.
6. **Phosphates** ($PO_4^{3-}$) is generated from natural decomposition of rocks and minerals, storm water runoff, agricultural runoff, erosion and sedimentation, atmospheric deposition, direct input by animals/wildlife. Excessive phosphates input has been shown to be the main cause of eutrophication following the widespread occurrence of blue-green algal blooms in some fresh waters. Some blue-green algae can at times produce toxins, which are harmful to humans, pets, and farm animals. Some species of blue-green algae produce chemicals that are harmful to both animals and humans.

7. **Total suspended solids (TSS):** The presence of TSS may cause algal growth; therefore, it may be an indicator of eutrophication. It also reduces the penetration of light into water, which may affect the aquatic life in the water.

8. **Turbidity:** Turbidity will affect the acceptability of water to the end user and may affect its utility in commercial applications.

9. **Total coliform bacteria:** ($Tco$) by colony-forming unit (CFU) are an indicator organism, the presence of these bacteria is confirmed that the water has been contaminated with human or other animal farms.

### 2.4. Fuzzy inference system (FIS)

The fuzzy inference system (FIS) is the process of formulating the mapping from a given input to an output using fuzzy logic. The architecture of the FIS consists of four main parts including fuzzifier, rules, inference engine, and defuzzifier (figure 2).

![Architecture of fuzzy inference system](image)

*Figure 2. Architecture of fuzzy inference system*

In a fuzzy logic system, initially a crisp set of input data are gathered and they are converted to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms and membership functions. This step is known as fuzzification. Afterwards, an inference is made based on a set of rules. Lastly, the resulting fuzzy output is mapped to a crisp output using the membership functions, in the defuzzification step. The main components in the FIS are the membership functions of the input and output parameters, fuzzy set operations, and fuzzy rules.

The formulation of membership functions was given in the section on the development of membership functions. Intersection (AND), union (OR), and complement (NOT) are commonly used fuzzy set operators. In this study, the intersection (AND) operator was used. The proposed fuzzy inference system implemented utilizing Mamdani-type inference which is the most commonly used method, and is based on the set of IF-THEN rules consisting of both antecedent and consequent parameters. In this study, the centroid of area method (CENTROID) was selected for defuzzification.

Nine parameters (DO, BODs, COD, pH, NH$_4^+$, PO$_4^{3-}$, TSS, turbidity, total coliform) were arranged in 5 groups (figure 3). Group 1 contains DO and BODs, since they are the chemical parameters of water quality. Similarly, the Group 2 is composed of pH and COD. Group 3 consists of NH$_4^+$, and PO$_4^{3-}$ which are the parameters giving the nutrient information of water. Group 4 comprises TSS, and Turbidity, since they are the physical parameter of water quality. Group 5 contains only total coliform which is the biological parameter determining the water quality.
Figure 3. Flow diagram of the process used to create the new Index

2.5. Determination of membership functions (MFs)
Fuzzy sets are characterized in terms of membership functions, with a mapping domain of interest in the interval [0, 1]. Suppose x is an element that belongs to domain X, then Fuzzy Set A is characterized by the mapping of MFs corresponding to Equation (2):

\[ \mu_A(x) : X \rightarrow [0,1] \]  (2)

Where \( \mu \) = degree of membership function
In this study, triangular and trapezoidal MFs are used to calculate the WQI because these are computationally efficient and simple to use. The parameters and their ranges of various classes are defined based on water quality classes of Vietnam. For input fuzzy sets “Class I”, “Class II”, “Class III”, “Class IV”, “Class V” were chosen to represent the water quality parameters in linguistic form, as shown in table 1. The nine membership functions were assigned as shown in figures 4-12.

Table 1. The parameters for fuzzy memberships have been divided into five classes.

| Parameter | Range of membership functions | Corresponding class | Assigned as shown in |
|-----------|--------------------------------|---------------------|----------------------|
| 1. DO (mg/l) | [0-11] | I: \( \geq 6.0 \)
               |     | II: 5.0-6.5
               |     | III: 3.5-5.5
               |     | IV: 2.0-4.0
               |     | V: < 2.0 | Figure 4 |
| 2. BODs (mg/l) | [0-50] | I: \( \leq 4.0 \)
               |     | II: 3.0-7.0
               |     | III: 6.0-19.0
               |     | IV: 15-30.0
               |     | V: > 25 | Figure 5 |
| 3. pH | [0-15] | I: 6.5-7.5
               |     | II: 7.5-8.5
               |     | III: 8.0-9.5
               |     | IV: 9.0-10.5
               |     | V: > 10.0 | Figure 6 |
Note: Class I can be used for water supply after conventional treatment and useful for sensitive aquatic species; Class II can be used for water supply, but extensive treatment is required and useful for tolerant aquatic species and livestock drinking; Class III can be used only for irrigation; Class IV can be used only for water navigation; and Class V is not useful for the aforementioned utilities.
2.6. Determination of membership function for output
To construct membership functions for output (figure 13), “excellent”, “good”, “fair”, “bad”, and “poor” fuzzy sets are considered; their ranges are 91-100, 76-90, 51-75, 26-50, and 0-25, respectively, which were used for the FWQI and Vietnam WQI models.

2.7. Fuzzy rules determination
This study utilizes the linguistic model of fuzzy inference, in which the input parameter sets are known as predecessors, which are handled using linguistic IF/THEN rules to produce a yield set, known as consequents. The set of fuzzy rules with linguistic terms characterizes the dynamic behavior of the fuzzy system, and the fuzzy rules were constructed based on the status, and classes assigned to the quality parameters used to classify the water quality. The number of rules in the model varies according to the possible combinations of all possible states of each parameter.

In the first step, there are 125 inference rules were developed, for example: If DO is Class I, and BOD5 is Class I, then the output of Group 1 is Excellent. In the same way, other rules can be enunciated.

In the second step, the FWQI was developed from the fuzzy inference rules that were applied to groups 1 to 5 as input. Each input parameter has five membership functions, including “excellent”, “good”, “fair”, “bad”, and “poor”, so the number of possible combinations for the FWQI model is 3125 rules. In water quality assessment, subsequent expressions are often utilized by specialists: Rule 1: If Gr01 to Gr05 are excellent, then FWQI is excellent; Rule 763: if Gr01 to Gr05 are good, then FWQI is good; Rule 1836: if Gr01 is fair, Gr02 to Gr05 is poor, then FWQI is poor; Rule 2426: if Gr01 is bad, Gr02 is poor, Gr03 to Gr05 is bad, then FWQI is bad; Rule 3046: if Gr01 and Gr02 are poor, Gr03 and Gr04 are bad, and Gr05 are poor, then FWQI is poor. Similarly all other rules can be formed.

2.8. Mathematical analyses
The fuzzy water quality index for the Nhue River was carried out by using the Fuzzy Logic Design Toolbox of MATLAB V. R2018a.

3. Results and discussion
The water quality for the Nhue River has been assessed with the FWQI index. The calculated FWQI indices according to fuzzy inference system (FIS) are given in figure 14. In addition, comparison has been done between FWQI and the Vietnam national WQI index, and the results are shown in figure 15. In most cases water quality is satisfactory. The new index almost gave lower values than the WQI.
Figure 14. Results of the fuzzy water quality index of 9 sampling sites in October 2019.

Figure 15. Comparison of fuzzy logic (FWQI) and national WQI.

In the figure 15, the FWQI index is compared with Vietnam national WQI index, which is used by Vietnam Environment Administration for river water classification. FWQI results have shown status of water quality in the Nhue River as adequate in 11 sampling sites. It is therefore evident that the use of fuzzy logic for development of a water quality index is effective, since the results obtained in this study were in line with those provided by the index currently used by the Vietnam environmental agency. The results obtained by the new system were more rigorous, due to the fact that the collection of initial data are assessed by the basic rule, in contrast to the WQI, which employs a formula. The Nhue River is a Class “bad” (ranging from 26-50), and Class “poor” (ranging from 0-25) river according to the FWQI model as well as the Vietnam national WQI model. In which the Class “bad” can be used only for water navigation; and Class “poor” is not suitable for any uses. Although the Nhue river water has the sign of pollution, it is still the water supply of many agricultural and aquatic activities in the watershed.

4. Conclusions
This research has developed a new index named the fuzzy logic water quality index that offers an easy illustration of the wide and compound parameters (physicochemical and biological) that rule the general quality of river water. The new index provides a simple representation of the extensive and complex variables that govern the overall quality of surface water. Based on expert opinions and national experiences, nine water quality parameters including dissolved oxygen (DO), biological oxygen demand (BOD₅), chemical oxygen demand (COD), pH, ammonium (NH₄⁺), phosphates (PO₄³⁻), total suspended solids (TSS), turbidity, and total coliform (Tco) were considered as the significant indicator parameters of FWQI to assess the quality of surface water sources. Fuzzy model has demonstrated that water quality
has high sustainability with the expected results in the Nhue River. The authors believe that fuzzy logic concepts could be an effective tool for some of the environmental policy matters. Model based on FIS can be used for future determination of surface water quality, and to be believed to assist decision makers in reporting the state of the water quality.

5. References

[1] Sona M and Gayathri S M 2016 Development of New Water Quality Index Using Fuzzy Logic: A Case Study of Rivers in Calicut International Journal of Advanced Research in Management, Architecture, Technology and Engineering 2(10) 7.

[2] Antara S, Naman U, and Varun V 2014 Use of Fuzzy Logic in Determining Quality of Water International Journal of Scientific & Engineering Research 5(9) 252-259.

[3] Chang N B, Chen H W, and Ning S K 2001 Identification of river water quality using the Fuzzy Synthetic Evaluation approach Journal of Environmental Management 63(3) 293-305.

[4] Chanapathi T and Thatikonda S 2019 Fuzzy-Based Regional Water Quality Index for Surface Water Quality Assessment Journal of Hazardous, Toxic, and Radioactive Waste 23(4) 11.

[5] Huong N T L, Kanayama M, Higashi T, Chinh L V, Ha D T, and Dao C A 2014 Assessment of the water quality of the Nhue River in Vietnam and its suitability for irrigation water Journal of the Faculty of Agriculture, Kyushu University 59(1) 143-147.

[6] Jacinto Elías Sedeño-Díaz and Eugenia López-López 2016 Fuzzy Logic as a Tool for the Assessment of Water Quality for Reservoirs: A Regional Perspective (Lerma River Basin, Mexico) ed Rashed, Mohamed Nageeb (London: IntechOpen) chapter 2, pp. 155-174.

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