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Fuzzy Logic-Based Evaluation of Physicochemical Water Quality Parameters in the Gökırmak River (Türkiye)

Gökırmak Nehri'nin (Türkiye) Fizikokimyasal Su Kalitesinin Bulanık Mantık ile Değerlendirilmesi

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ABSTRACT

Traditional water quality classification methods rely on fixed threshold values, which limits their ability to reflect the degree of deviation from these boundaries. This rigid approach often results in uncertainties when assessing the ecological status of rivers. Fuzzy logic, in contrast, provides a more flexible framework by incorporating gradual transitions between classes and accounting for the relative importance of parameters. In this study, a fuzzy logic-based classification system was developed to evaluate the water quality of the Gökırmak River (Türkiye) and was compared with the conventional water quality index defined by national standards. Ten physicochemical parameters (temperature, pH, dissolved oxygen, electrical conductivity, nitrate, nitrite, ammonium, phosphate, biochemical oxygen demand, and chemical oxygen demand) were monitored monthly at six stations for one year. The fuzzy logic model was constructed using triangular membership functions and a Mamdani inference system. Model performance was assessed by comparing fuzzy classification results with expert evaluations based on the Surface Water Regulation. The system achieved 90% agreement, calculated as the ratio of consistent classifications to the total number of cases, demonstrating that fuzzy logic can serve as a reliable tool in water quality assessment. The findings highlight that fuzzy logic-based approaches not only reduce classification uncertainties but also provide a decision support framework for sustainable water resource management. Further research should expand the dataset across longer time periods and incorporate retrospective records to improve generalizability.

Keywords: Decision support system, Environmental monitoring, Fuzzy logic, Water pollution, Water quality assessment

ÖZ

Geleneksel su kalitesi sınıflandırma yöntemleri sabit eşik değerlerine dayanmaktadır ve bu durum ölçüm değerlerinin bu sınırların ne kadar uzağında veya yakınında olduğunu yansıtamamaktadır. Bu katı yaklaşım, nehirlerin ekolojik durumunun değerlendirilmesinde belirsizliklere yol açmaktadır. Buna karşılık, bulanık mantık, sınıflar arasında kademeli geçişlere izin vererek ve parametrelerin göreli önemini dikkate alarak daha esnek bir değerlendirme çerçevesi sunmaktadır. Bu çalışmada, Türkiye'deki Gökırmak Nehri'nin su kalitesini değerlendirmek amacıyla bulanık mantık tabanlı bir sınıflandırma sistemi geliştirilmiş ve ulusal standartlarda tanımlanan klasik su kalite indeksi ile karşılaştırılmıştır. On farklı fizikokimyasal parametre (sıcaklık, pH, çözünmüş oksijen, elektriksel iletkenlik, nitrat, nitrit, amonyum, fosfat, biyokimyasal oksijen ihtiyacı ve kimyasal oksijen ihtiyacı) bir yıl boyunca altı istasyonda aylık olarak izlenmiştir. Bulanık mantık modeli üçgensel üyelik fonksiyonları ve Mamdani çıkarım sistemi ile oluşturulmuştur. Modelin performansı, Yüzey Suları Yönetmeliği'ne göre uzman değerlendirmeleri ile karşılaştırılarak test edilmiştir. Sistem, toplam sınıflandırmaların %90'ında uyum sağlamış olup bu oran, bulanık mantık yaklaşımının su kalitesi değerlendirmesinde güvenilir bir araç olduğunu göstermektedir. Bulgular, bulanık mantık tabanlı yöntemlerin sınıflandırma belirsizliklerini azaltmanın yanı sıra sürdürülebilir su kaynakları yönetimi için karar destek aracı sağlayabileceğini ortaya koymaktadır. Daha geniş veri setlerinin ve geçmiş yıllara ait kayıtların dahil edilmesi, yöntemin genellenebilirliğini artırmak için önerilmektedir.

Anahtar Kelimeler: Karar destek sistemi, Çevresel İzleme, Bulanık mantık, Su kirliliği, Su kalite değerlendirmesi

Introduction

Water pollution is among the most pressing environmental challenges of the 21st century, driven largely by population growth, industrialization, and intensive agricultural practices. Freshwater ecosystems, in particular, are increasingly exposed to anthropogenic pressures, threatening both ecological integrity and sustainable resource use (Abdullah et al., 2008). Accurate monitoring and classification of river water quality are therefore crucial for guiding environmental management and policy decisions.

The quality assessment of polluted waters provides important theoretical information not only for determining the effects of pollution elements in waters but also for the sustainability of limited water resources. Several pollution index techniques are employed in water quality assessment, and they define precise limits that show the amount and difference of water pollution at different levels. However, an uncertainty associated with risk appears in quality assessments due to the instability of each water pollutant. The presence of precise limits in uncertainty classification diagrams makes the employment of these diagrams challenging. Due to this uncertainty, environmental researchers have begun to work on advanced evaluation techniques by using fuzzy logic (Sönmez, 2011). Although the use of fuzzy logic, one of the artificial intelligence methods, in the field of water engineering is not very common, it is becoming increasingly widespread.

Traditional water quality assessment approaches, such as those outlined in national standards and international guidelines, are based on assigning water samples to discrete quality classes according to fixed threshold values. While these approaches are widely used, they present several limitations. First, they do not account for the degree of deviation from thresholds, thereby neglecting important nuances in water quality trends. Second, they assume that all measured parameters can be strictly categorized into a single class, which often fails to capture the inherent variability of natural systems (Icaga, 2007). These shortcomings can result in uncertainties and inconsistencies in decision-making.

In response to these challenges, researchers have increasingly turned to advanced computational techniques, particularly fuzzy logic, which provides a more flexible and robust framework for environmental assessment. Fuzzy logic introduces gradual transitions between classes and integrates multiple parameters with weighted significance, reducing uncertainty and improving interpretability (Liou & Lo 2005; Liou et al., 2003; Ludwig & Tulbure, 1996; Sadiq & Rodriguez, 2004; Shen et al., 2005; Wang & Zou, 2008). Recent applications have demonstrated its effectiveness in water quality evaluation across different contexts (Azzirgue et al., 2022; Dewanti & Abadi, 2019; Sönmez et al., 2013). Using fuzzy logic-based quality assessment indices instead of conventional indices will provide more objective results (Sönmez et al., 2018). However, the use of fuzzy logic in Türkiye's river systems remains limited, and no standardized fuzzy logic-based water quality index has been developed for national application.

The Gökırmak River, a major tributary of the Kızılırmak River, was selected as the case study for this research due to its ecological and socio-economic significance. Flowing through agricultural areas that are heavily used for rice cultivation, the river is subject to multiple pollution pressures, including nutrient enrichment, domestic discharges, and agricultural runoff (Dengiz et al., 2015). Despite its importance for regional agriculture and biodiversity, few studies have comprehensively evaluated its water quality using advanced computational approaches. This makes the Gökırmak River an appropriate and representative site for testing the applicability of fuzzy logic in Türkiye.

Against this background, the present study aims to evaluate the water quality of the Gökırmak River using a fuzzy logic-based classification system and to compare its performance with the conventional national classification method. The study contributes to the literature by (i) applying fuzzy logic to a river of high agricultural and ecological importance in Türkiye, (ii) providing a methodological framework for integrating multiple physicochemical parameters into a decision support system, and (iii) highlighting the potential for fuzzy logic to complement existing national water quality standards. By addressing these aspects, the research fills a gap in the application of artificial intelligence methods in water quality management in Türkiye and offers insights for future development of a standardized fuzzy logic-based water quality index.

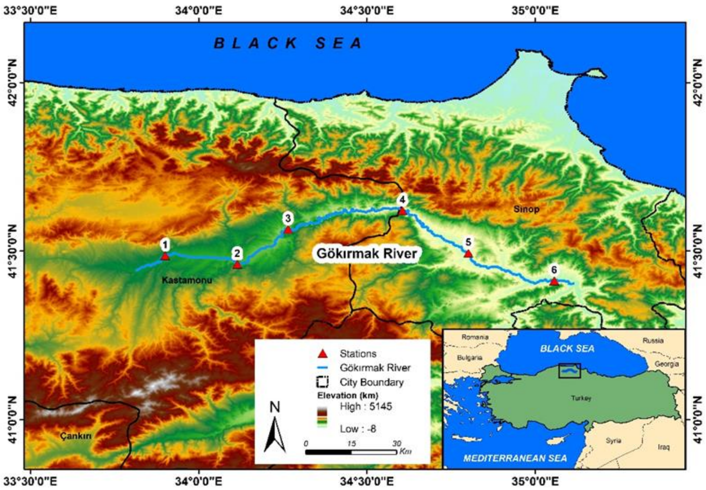
Methods

Study area

The Gökırmak River, depicted in Figure 1, originates from Ilgaz Mountain in Kastamonu province and serves as a significant tributary of the Kızılırmak River, the longest river fully inside Türkiye's borders. It extends 221 kilometers through Kastamonu, Taşköprü, Hanönü, Boyabat, and Durağan until converging with the Kızılırmak. The basin encompasses an area of roughly 7000 km² (Yildirim et al., 2013). The river basin region exhibits a semiarid climate and is predominantly agricultural, particularly for rice (Dengiz et al., 2015). The river is highly influenced by agricultural runoff, domestic discharges, and seasonal hydrological variability, making it a suitable case for water quality assessment. The geological structure of the basin includes sedimentary rocks and alluvial deposits, which contribute to variations in water chemistry. Average annual precipitation is evenly distributed across seasons, while maximum evaporation occurs in July (Tanatmış, 2004).

Figure 1.

Map showing the sampling stations along the Gökırmak River



Method

Water samples were collected monthly from six stations along the Gökırmak River between January 2020 and December 2021 (Figure 1). Stations were selected to represent upstream reference sites, agricultural zones, and downstream sections influenced by settlements. At each station, three replicate samples were taken at surface level (0–50 cm depth) to account for spatial variability. The geographic coordinates of the stations were recorded using a handheld GPS device. Field parameters (temperature, dissolved oxygen, pH, electrical conductivity) were measured in situ using a multiparameter probe (Hach Lange HQ40D). Nutrient and organic pollution parameters (nitrate, nitrite, ammonium, phosphate, biochemical oxygen demand [BOD], and chemical oxygen demand [COD]) were analyzed spectrophotometrically using standard commercial kits in accordance with APHA (2017) protocols.

Ten physicochemical parameters were selected based on their regulatory significance in Türkiye's Surface Water Quality Regulation (YSY, 2012) and their widespread use in international water quality assessment studies. These parameters represent key categories of water quality: (i) general physical conditions (temperature, electrical conductivity), (ii) acid-base balance (pH), (iii) oxygen regime (dissolved oxygen, BOD, COD), and (iv) nutrient enrichment (nitrate, nitrite, ammonium, phosphate). Together, they provide a comprehensive assessment of river water quality and its ecological implications.

The classical classification of water quality was conducted using the "Quality Criteria of Intra-Continental Surface Water Resources According to Their Classes" defined in the Surface Water Regulation (YSY, 2012). The thresholds for each parameter are presented in Table 1.

Table 1.

Water Quality Classes of Intra-Continental Surface Water Resources as per the Surface Water Regulation (YSY, 2012)

Water Quality Parameters	Water Quality Classes I	II	III	IV
Temperature (°C)	≤ 25	≤ 25	≤ 30	> 30
pH	6.5-8.5	6.5-8.5	6.0-9.0	outside 6.0-9.0
Electrical Conductivity (µS/cm)	< 400	400-1000	1001-3000	> 3000
Dissolved Oxygen (mg O_2/L)	> 8	6-8	3-6	< 3
Chemical Oxygen Demand (COD) (mg/L)	< 25	25-50	50-70	> 70
Biochemical Oxygen Demand (BOD) (mg/L)	< 4	4-8	8-20	> 20
Ammonium (mg NH_4^+-N/L)	< 0.2	0.2-1	1-2	> 2
Nitrite (mg NO_2^--N/L)	< 0.002	0.002-0.01	0.01-0.05	> 0.05
Nitrate (mg NO_3^--N/L)	< 5	5-10	10-20	> 20
Phosphorus (mg P/L)	< 0.03	0.03-0.16	0.16-0.65	> 0.65

Fuzzy logic generally includes the stages of fuzzification, fuzzy inference and clarification (defuzzification). The fuzzification module transforms the observed real information into a fuzzy form using membership functions determined in accordance with the problem characteristics. The fuzzy inference mechanism assesses the control rules stored in the fuzzy rule base. As a consequence of the fuzzy inference, one or a few fuzzy output sets are obtained, which is later clarified to obtain the control action of the membership functions. Clarification is the process of converting fuzzy outputs into numbers. It is not possible to use the outputs of fuzzy systems directly in applications. In this case, the fuzzy outputs need to be clarified. The clarification process is considered to be the exact opposite of the fuzzification process (Zadeh, 1988) (Figure 2).

Figure 2.

The flowchart of the Fuzzy Logic Inference System developed to assess the water quality classification along the Gökırmak River

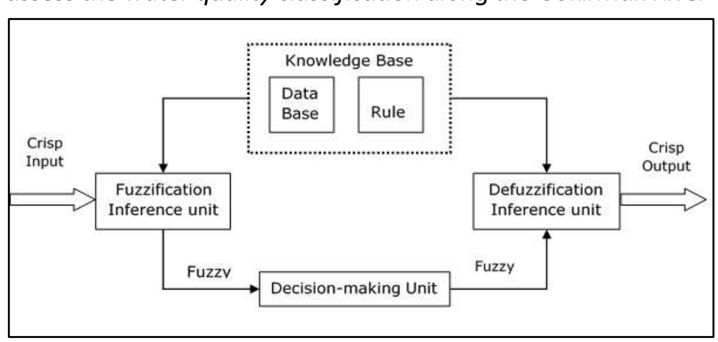
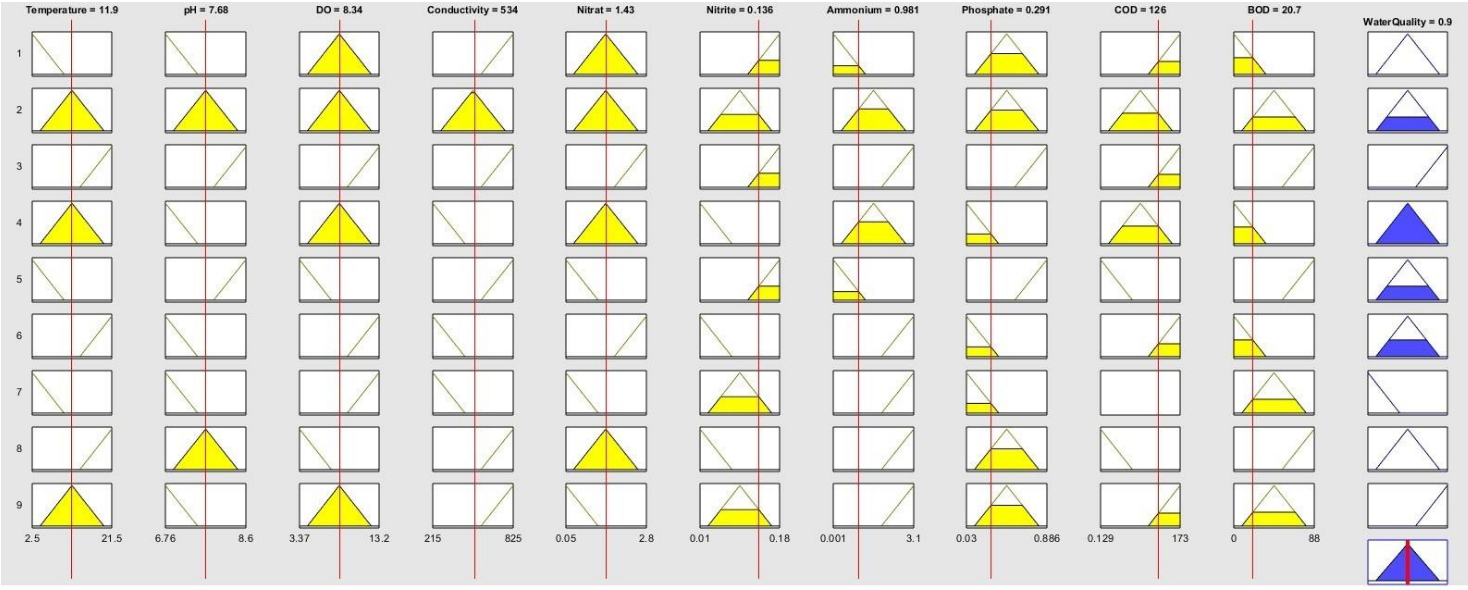


Figure 3.

Triangular membership functions developed to assess the water quality classification along the Gökırmak River



The fuzzy logic model was designed following standard steps of fuzzification, fuzzy inference, and defuzzification (Zadeh, 1988; Ross, 2004). The Mamdani inference system was chosen due to its widespread application in environmental studies and its ability to handle nonlinear and uncertain data with interpretability (Dewanti & Abadi, 2019; Sönmez et al., 2013). Triangular membership functions were applied to represent parameter categories (Classes I–IV), as they provide a simple yet effective structure for modeling gradual transitions between thresholds (Figure 3). The rule base was constructed by translating the classical classification scheme into fuzzy "if–then" rules.

While creating the fuzzy logic model in this study, the classical classification given in Table 1, which separates water quality into four classes, was taken into account. The fuzzy model consists of six steps (Akkaptan, 2012; Ross, 2004; Sivanandam et al., 2007; Sönmez et al., 2013, 2018);

1. Determining the quality classes of physicochemical parameters using the measured values with classical classification and collecting them in four groups.
2. Assigning fuzzy model membership names as the equivalent of classical quality classification.
3. Creating the membership functions of the input and output values in a triangular or trapezoidal structure and determining the limit values.
4. Creating the rule base using the quality classes of the input values.
5. Using the fuzzy logic algorithm with the Mamdani approach and then determining the fuzzy inference outputs of the groups with the membership function degrees of the parameters.
6. Defuzzifying the four different fuzzy inference outputs to determine the quality index ranging from 0 to 1.

It consists of refinement steps to determine the quality index of the four different fuzzy result outputs. All fuzzy logic analyses were performed using MATLAB R2014b with the Fuzzy Logic Toolbox.

Model performance was evaluated by comparing fuzzy logic outputs with expert classifications based on the Surface Water Regulation. Agreement was quantified using an accuracy metric defined as:

$$\text{Accuracy} = \frac{\text{Number of matching classifications}}{\text{Total classifications}} \times 100$$

The fuzzy logic system achieved 90% agreement across all stations and months, indicating that the method provides reliable results in classifying water quality.

Results and Discussion

Water quality classification of 10 physicochemical water parameters, determined at six stations along the Gökırmak River, was carried out using both the classical classification system and the fuzzy logic approach. The classical classification results are summarized in Table 2. According to the Surface Water Regulation (YSY, 2012), parameters such as temperature, pH, dissolved oxygen, and nitrate generally corresponded to Class I, while others (electrical conductivity, BOD, COD, ammonium, and phosphorus) were in Class II and nitrite was in Class III, reflecting moderate pollution pressures in certain sections of the river.

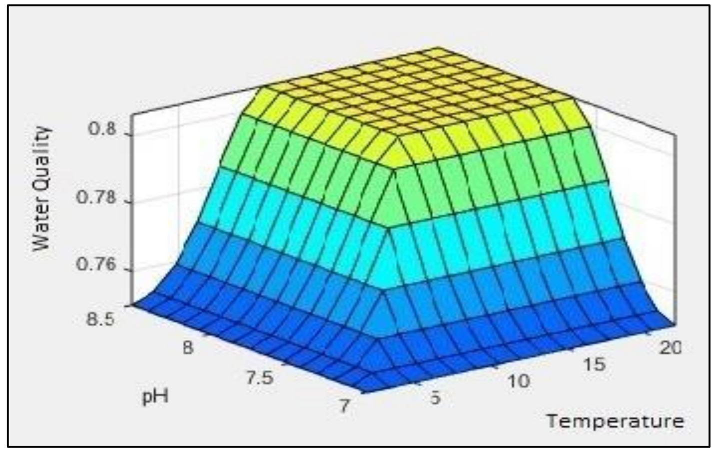
Table 2.
Water quality classes of physicochemical parameters determined in the study according to the classical classification

Parameter	Water Quality			
	I	II	III	IV
Temperature (°C)	X			
pH	X			
Conductivity (µS/cm)		X		
Dissolved Oxygen (mg O_2/L)	X			
COD (mg/L)		X		
BOD (mg/L)		X		
Ammonium (mg NH_4^+-N/L)		X		
Nitrite (mg NO_2^--N/L)			X	
Nitrate (mg NO_3^--N/L)	X			
Phosphorus (mg P/L)		X		

Some physicochemical properties of water included in the water quality standards have been reformatted with measured data, fuzzy logic terms and rule base connections created according to the decision support system structure. In order to create fuzzy sets of inputs and outputs, the classification scale of water quality parameters specified in the Surface Water Regulation was used to define triangular membership functions for each parameter (1st, 2nd, 3rd and 4th Class) (Figure 3). The fuzzy logic-based system provided classifications that showed 90% agreement with expert evaluations based on the national regulation. This high level of consistency demonstrates the capacity of fuzzy logic to serve as a reliable decision-support tool in water quality assessment. The most significant variables affecting water quality were determined to be temperature and pH between samples in the data set. This relationship is displayed in Figure 4. The discrepancies observed in approximately 10% of cases were largely associated with parameter values that were close to class boundaries (e.g., dissolved oxygen around 6 mg/L or COD near 50 mg/L). Unlike the rigid threshold structure of the classical approach, the fuzzy system allows for gradual transitions and reflects uncertainty in borderline cases, thereby offering a more flexible and realistic evaluation of water quality.

Today, many innovative index methods are used to determine water quality in rivers (Said et al., 2004). In the study of case study of Ocampo-Duque et al. (2006) on water quality assessment in rivers, several water quality parameters (dissolved oxygen, biological oxygen demand, organic matter content, microbiological parameters, etc.) were measured in the Ebo River in Spain, then quality classes were evaluated with different water quality indices including the fuzzy inference system. As a result, they reported that the expert opinions and reports specified for this region were in line with the fuzzy inference system.

Figure 4.
3D surface view of the relationships between inputs (temperature and pH) and output (water quality class)



In a study conducted by Sönmez et al. (2013) on water quality assessment in the Karasu River based on heavy metal pollution, it was revealed that the fuzzy logic approach is a suitable tool for evaluating water pollution. Similarly, in a water quality assessment study conducted in the Germeçtepe Dam Lake based on 10 water quality parameters, it was determined that the decision support system created to determine quality classes yields 90% success (Atea et al., 2018).

In a study (Dewanti & Abadi, 2019) aiming to develop a fuzzy logic system to classify the water quality status in the Gajahwong River, 11 parameters, including temperature, pH, dissolved oxygen, BOD, COD, free chlorine, nitrate, nitrite, oil, fat, lead and Escherichia coli were used to classify the water quality status in water samples taken from 3 different stations between 2007 and 2017. These 11 parameters, which were included as inputs to the fuzzy inference system, were exited through the system by being categorized as normal, lightly polluted, moderately polluted and heavily polluted. According to the results obtained, it was observed that the Mamdani Centroid and the Mamdani LOM methods were 90.90% and 96.97% compatible with the decision support system, respectively. Ultimately, they stated that fuzzy logic methods are suitable approaches for developing river water classification models.

Chanapathi and Thatikonda (2019) aimed to develop a Mamdani type fuzzy-based regional water quality index by examining ten different water quality, and used classifications from six countries in various geographical regions to assess the quality of surface water. It was reported that the presented model, despite its various geographical origins, resembles water quality models used in India, Malaysia and the United States and can help self-assess regional water quality on a global scale.

In another work carried out in Morocco on the quality assessment of groundwater, Azzirgue et al. (2022) compared a traditional and a fuzzy-based water quality index. Twelve physicochemical and bacteriological parameters taken from nine different wells for two years were included in the model and compared. According to their results, they concluded that the classical and fuzzy-based quality assessment indices supported each other and that the fuzzy-based model they proposed could be used confidently in water quality assessment.

A fuzzy logic framework was designed in Malaysia to evaluate river water quality by integrating six input variables into a single outcome. This system illustrated how fuzzy logic can streamline complex datasets, making them easier for decision-makers to interpret (Abdullah et al., 2008). In Indonesia, a fuzzy logic-based assessment of the Tanjung Karang watershed helped to measure the impact of agricultural practices on water quality. The capacity of the model to merge heterogeneous datasets proved essential in promoting sustainable farming methods (Gharibi et al., 2012). In Poland, fuzzy logic was applied to assess ecological status by combining biological and chemical indicators, showing its efficiency in reflecting intricate ecosystem interactions (Trach et al., 2022). Similarly, fuzzy logic techniques were employed to monitor the Ganges River, incorporating parameters like biochemical oxygen demand and phosphate levels. The study's results provided critical insights for policymakers aiming to improve river health (Raman et al., 2009).

Research on Italy's Sele River compared traditional binary assessment tools with fuzzy logic approaches. Results revealed that fuzzy logic delivered a more refined understanding of water quality and enhanced the accuracy of monitoring and sampling strategies (Scannapieco et al., 2012). In Nigeria, fuzzy logic was used to assess the Ikare community's water resources, offering a comparison with the conventional Water Quality Index. Findings showed that fuzzy logic better captured the variability of water parameters, underlining its usefulness in diverse environmental applications (Oladipo et al., 2021). Li et al. (2023) proposed a dual-input fuzzy control model for ammonia nitrogen management, which resulted in more than 95% savings in both water and energy consumption. These results highlight fuzzy logic's potential in sustainable aquaculture management. Likewise, de Oliveira et al. (2014) introduced the Fuzzy Raw Water Quality Index (IQABF) to evaluate raw water treatability. Compared with deterministic indices, IQABF was more restrictive yet consistent, proving effective in handling uncertainty and supporting treatment processes.

The utilization of fuzzy logic has also advanced environmental monitoring by predicting complex parameters such as sea surface temperature and heavy metal contamination. Kale (2020) constructed a fuzzy logic model to forecast sea surface temperature (SST) in the Çanakkale Strait, Türkiye, emphasizing its strong capacity to simulate complex environmental systems with high reliability. Later, Sonmez et al. (2018) explored the challenges of modeling heavy metal pollution in aquatic ecosystems, known for their nonlinear characteristics. Their work reinforced the accuracy and robustness of fuzzy logic, suggesting its broad potential in water quality management.

Taken together, these international studies highlight the adaptability of fuzzy logic to different environmental conditions, reinforcing its role in improving water quality monitoring and management while supporting sustainable resource use (Gharibi et al., 2012).

Sönmez and Taştan (2024) emphasized that fuzzy-based methods present a practical alternative to classical logic in water quality evaluation. Their study concluded that fuzzy approaches allow comparison of different indices and models across water bodies, offering a more rational and dependable option than traditional techniques.

Kale (2024) noted that fuzzy logic models provide an advanced pathway for water quality assessment by offering greater precision and flexibility. They represent a resilient approach capable of addressing the inherent variability and uncertainties in environmental datasets. Their ability to adapt across contexts and integrate with complementary tools makes them valuable for sustainable management. As environmental monitoring gains urgency, continued development of fuzzy logic methodologies will enhance their effectiveness, ensuring more reliable monitoring and management strategies in the future.

The findings are in line with above-mentioned studies that have applied fuzzy logic to river and reservoir systems. These parallels confirm that the fuzzy logic approach used in this study is robust and applicable in diverse hydrological contexts. It also confirms that the fuzzy logic-based approach used in this study is not only consistent with international applications but also contributes to the ongoing discussion on developing standardized and integrated water quality assessment frameworks, particularly for rivers in Türkiye.

The current model has certain limitations. Membership functions were statically defined and may require recalibration for other regions or under different hydrological conditions. Furthermore, the rule base was constructed according to national classification thresholds and expert judgment, which introduces subjectivity. Expanding the dataset with longer-term monitoring and incorporating additional indicators, such as microbiological parameters, would improve the robustness and transferability of the model.

Conclusion and Recommendations

This study evaluated the water quality of the Gökırmak River using a fuzzy logic-based classification system and compared the results with the conventional method defined in Türkiye's Surface Water Regulation. The fuzzy approach, which incorporated ten physicochemical parameters from six stations, achieved 90% agreement with expert assessments. These results confirm that fuzzy logic provides a reliable and flexible alternative to rigid threshold-based classifications, particularly in cases where parameter values are near class boundaries.

The main contribution of this work is the demonstration that fuzzy logic can reduce uncertainties inherent in classical water quality indices and offer a more realistic decision-support framework for environmental management. Unlike traditional methods, the fuzzy system considers gradual transitions and relative importance of parameters, thus improving the robustness of water quality assessments.

Nevertheless, the model has some limitations. Membership functions were statically defined and may require recalibration for different rivers or changing environmental conditions. In addition, the rule base was constructed according to regulatory thresholds and expert judgment, which introduces a degree of subjectivity. Future studies should address these limitations by expanding the dataset to longer time periods, including microbiological and ecological parameters, and testing alternative fuzzy structures such as adaptive neuro-fuzzy inference systems (ANFIS).

From a broader perspective, the findings highlight the potential of fuzzy logic to support the development of a standardized water quality index for rivers in Türkiye. Such an index would contribute to more accurate environmental monitoring, more effective policy-making, and ultimately to the sustainable and rational use of national water resources.

Evaluation of water quality in environmental management provides important information to decision-making mechanisms in terms of producing accurate policies. It provides a scientific basis, especially for the preservation of water resources and their sustainable and rational use. A correct monitoring and evaluation policy is essential to ensure the sustainability of water resources. These monitoring activities should be carried out routinely and inventory records should be made based on healthy and accurate data. It has been demonstrated in this paper that mathematical methods based on artificial intelligence such as fuzzy logic can be used for this purpose, however, they ought to be further developed and disseminated. Redefinition of quality classes by evaluating comprehensive data extending to years and more research are needed.

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