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Development of New Water Quality Model Using Fuzzy Logic System for Malaysia

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Abstract: Proper assessment of water quality status in a river system based on limited observations is an essential task for meeting the goals of environmental management. Various classification methods have been used for estimating the changing status and usability of surface water in River basin. 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 methologies like water quality index (WQI) when describing integrated water quality conditions with respect to various chemical constituents, biological aspects, nutrients, and aesthetic qualities. In recent years, the fuzzy logic based methods have demonstrated to be appropriated to address uncertainty and subjectivity in environmental issues. In the present 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 status of river water quality by comparing the output generated by fuzzy with that of conventional methods. The model is based on observations made from Semenyih River in West Malaysia. The findings clearly indicate that the fuzzy inference system (FIS) may successfully harmonize inherent discrepancies and interpret complex conditions. This river water quality model can be extended to determine the non-regulated contaminants in water.

Keywords: Water quality determinant, non-regulated contaminants, water management, water quality index, environmental monitoring, fuzzy inference system.

INTRODUCTION

Environmental protection and water quality management has become an important issue in public policies throughout the world. More than governments are concerned about the quality of their environmental resources because of the complexity of water quality data sets [1]. Many countries have introduced a scheme for river water quality monitoring and assessment, examining separate stretches of fresh water in terms of their chemical, biological and nutrient constituents and overall aesthetic condition. General indices are used as comprehensive evaluation instruments to help assess conditions at the earliest stage to clarify monitoring priorities for regulatory agencies dealing with pollution abatement problems [2].

Water quality indices are computed for classification of water wherein the integration of parametric information on water quality data and the expert's knowledge base on their importance & weights are considered. Considerable uncertainties are involved in the process of defining water quality for designated uses. One of the most effective ways to communicate information on environmental trends in general and river water quality in particular to policy makers and the public at large is with indices [3].

Traditional reports on water quality tend to be too technical and detailed, presenting monitoring data on individual substances, without providing a whole and interpreted picture of water quality. To resolve this gap, various water quality indices have been developed to integrate water quality variables worldwide. Most of these indices are based on the water quality index (WQI) developed by the U.S. national Sanitation Foundation [4]. Malaysian Department of Environment (DOE) has followed their own interim national water quality standards (INWQS) for evaluating water quality of the river for intended purposes. Environmental protection agencies define comprehensive sets of determinants to monitor water quality. In order to protect the ecological status, as declared in the Water Framework Directive [5] not only environmental concentrations of chemicals in rivers are being used to assess water quality, but also their effects on trophic chains. The Catalan Water Agency (Catalonia, Spain) uses 150 chemical indicators to survey the condition of water [6].

One of the difficult tasks facing environmental managers is how to transfer their interpretation of complex environmental data into information that is understandable and useful to technical and policy individuals as well as the general public. This is particularly important in reporting the state of the environment. Internationally, there have been a number

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of attempts to produce a method that meaningfully integrates the data sets and converts them into information [7]. In modeling complex environmental problems, researchers often fail to make precise statements about inputs and outcomes, but fuzzy logic could be applied to the development of environment indices in a manner that solves several common problems, including the incompatibility of observations and the need for implicit value judgements [8]. Conventional water quality regulations contain quality classes which use crisp sets (crisp sets means classical sets express two level in classical mathematic, instead of multiple level among two level [0,1]) and the limits between different classes have inherent imprecision [9].

In Malaysia, the classification of rivers by the Department of Environment (DOE) is based on a water quality index (WQI). A water quality index relates a group of water quality determinants to common scale and combines them into a single number in accordance with a chosen method or model of computation. The WQI was established based on the results of an opinion poll of a panel of experts who determined the choice of determinants and weights assigned to each chosen water quality determinants. DOE-WQI consists of six determinants: dissolved oxygen (0.22), biological oxygen demand (0.19), chemical oxygen demand (0.16), ammonical nitrogen (0.15), suspended solid (0.16) and pH (0.12). In parentheses are given the weight factors according to the importance of parameters. WQI system is to assess water quality trends for management purposes even though it is not meant specially as an absolute measure of the degree of pollution or the actual water quality [10]. DOE-WQI was originally designed to include six determinants designed for making an integrated assessment of water quality conditions in order to meet utilization goals. The methods which contain upper and lower limits have two ambiguities. Firstly, the traditional water quality evaluation methods use discrete form. This classification technique may cause a rough and imprecise approach for data, as in this approach, a parameter being close or far from the limit has equal importance for evaluation of concentration [11]. The most critical deficiency of this index is the lack of dealing with uncertainty and subjectivity present in this complex environmental issue. In this regard, some alternative methodologies have emerged from artificial intelligence. Fuzzy logic is being tested with actual environmental issues. The scientific community and general public has long recognized the need for developing a uniform method for measuring the water pollution abatement program results. Fuzzy logic can be considered as a language that allows one to translate sophisticated statements from natural language into a mathematical formalism [12]. Fuzzy logic can deal with highly variable, linguistic, vague and uncertain data or knowledge and, therefore has the ability to allow a logical, reliable and transparent information stream from data collection to data usage in environmental applications. The Fuzzy logic has been used to assess water quality by developing a water quality index based on fuzzy reasoning [13]. The basic architecture of a fuzzy inference system was shown in Fig. (**1**).

Rule-based models often deal with the linguistic descriptions. The linguistic aspect could be based on two different approaches in river water quality management: (1) expert knowledge and or (2) actual water quality data are available in a linguistic format. In this study, linguistic variables were based on actual water quality data. Fuzzy logic provides a framework to model uncertainty, the human way of thinking, reasoning, and the perception process. Fuzzy systems were first introduced by Zadeh (1965). The fuzzy logic can be used for mapping inputs to appropriate outputs. Fig. (**2**) shows an input-output map for the water quality classification problem.

In this study, the fuzzy logic formalism has been used to access River water quality by developing a water quality index based on fuzzy reasoning. Comparison has been done over conventional method (DOE-WQI). River water quality fuzzy model based on six input and one output was used to evaluate the Semenyih River quality in Malaysia.

In this methodology, membership functions of the quality determinants and fuzzy rule bases were defined and then the fuzzy logic toolbox of MATLAB7 package was used. The method was applied to the 1997-2004 observations of quality determinants of the Sememyih river basin based on Mamdani fuzzy inference system. The Fuzzy model was developed with physicochemical determinants of their weight assigned and significance ratings curve to evaluate the Semenyih river quality [14].

MATERIALS AND METHODS

Fuzzy Inference System

Fuzzy inference is the process of formulating the mapping from a given input determinant to an output determinant using fuzzy logic reasoning. Decisions can be made on basis

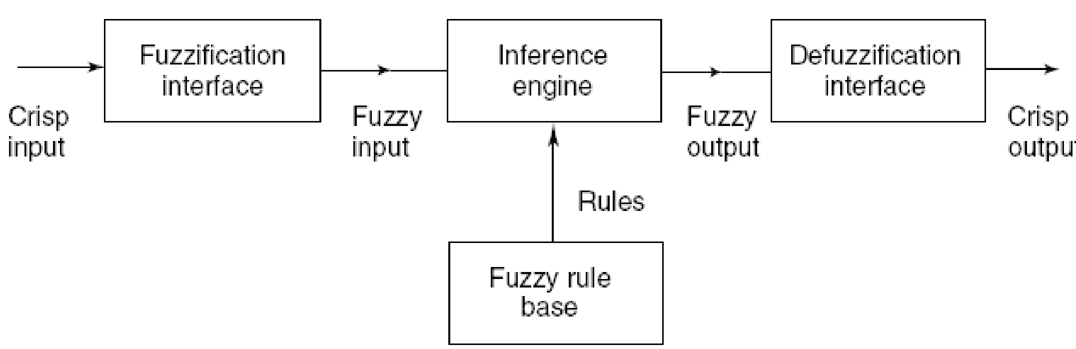

Fig. (1). Basic architecture of a fuzzy inference system.

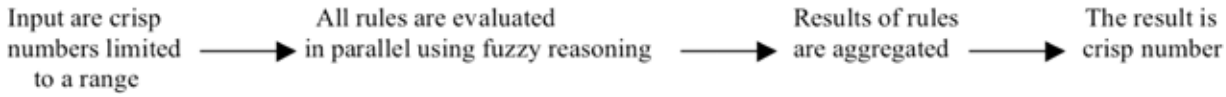

Fig. (2). Input–output mapping for the river water quality modeling.

of mapping, or patterns discerned. The fuzzy inference process involves three crucial steps: membership functions, fuzzy set operations, and inference rules.

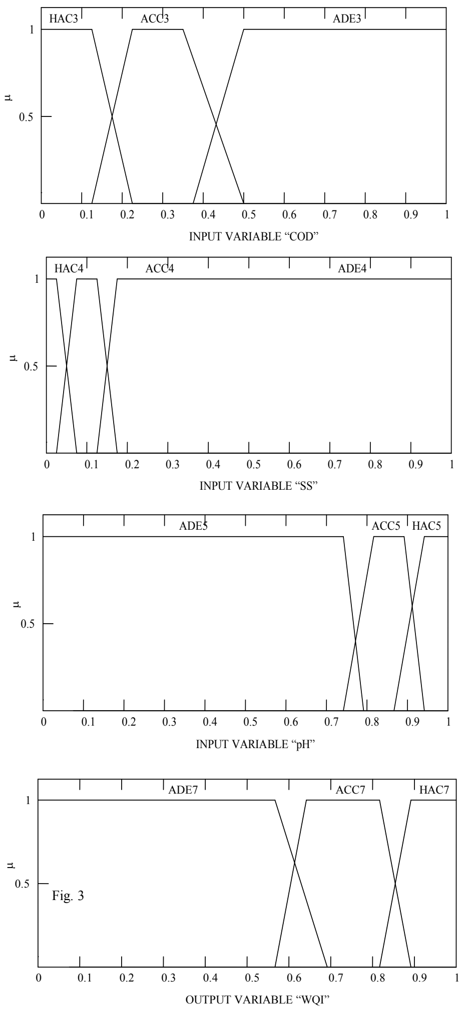

Fig. (3). Membership function defined for water quality classification.

A membership function is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. The input space is called the universe of discourse. The output-axis is called the membership value μ. If X is the universe of discourse and its elements are denoted by x, then a fuzzy set A is defined as a set of ordered pairs.

$$A = \{x, \mu_A(x) \mid x \in X\} \tag{1}$$

where μA(x) is the membership function of x in A. A membership function is an arbitrary curve whose shape is defined by convenience. The standard fuzzy set operations are: union (OR), intersection (AND) and additive complement (NOT). They manage the essence of fuzzy logic. If two fuzzy sets A and B are defined on the universe X, for a given element x belonging to X, the following operations can be carried out:

(Intersection, AND) $\mu_{A\cap B}(x) = \min(\mu_A(x), \mu_B(x))$ (2)

(Union, OR) $\mu_{A\cap B}(x) = \max(\mu_A(x), \mu_B(x))$ (3)

(Additive complement, NOT) $\mu_{\overline{A}}(x) = 1-\mu_A(x)$ (4)

The third concept is the inference rule. An if–then rule has the form: "If x is A then z is C", where A and C are linguistic values defined by fuzzy sets in the universes of discourse X and Z, respectively. The if–part is called the antecedent, while the then–part is called the consequent. The antecedent and the consequent of a rule can have multiple parts. Fuzzy logic comprises, usually, fuzzification, evaluation of inference rules, and defuzzification of fuzzy output results. Fuzzification is process to define inputs and outputs as well as their respective membership function that transform the numerical value of a variable into a membership grade to a fuzzy set. After the inputs are fuzzified, the degree to which each part of the antecedent is satisfied for each rule. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number is then applied to the output function. The input to the fuzzy operator is two or more membership values from fuzzified input variables. The output is a single truth value. The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. Implication is implemented for each rule. Because decisions are based on the testing of all of the rules in an FIS, the rules must be combined in some manner in order to make a decision. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. Finally, the input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. As much as fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variable is generally a single number. However, the aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the fuzzy set.

Fuzzy Model in River Quality Assessment

A fuzzy model for river water quality assessment has been developed. Different shapes of membership functions can be used, depending upon the type of application [14]. The right prediction of the fuzzy model depends on the number of fuzzy sets used in the mapping process, since it facilitates more continuity to the universe of discourse. However, in this research, each of the six input quality determinants have been divided into three categories, and trapezoidal membership functions were assigned as shown in Fig. (**3**). It has chosen ADE (adequate), ACC (acceptable), HAC (highly acceptable) fuzzy sets for inputs determinants, and for the output determinant. Trapezoidal membership func-

Table 1. Parameters for Membership Functions in the Fuzzy Inference System

Determinant	Units	Adequate ADE				Acceptable ACC				Highly Acceptable HAC				Range
		a	b	c	d	a	b	c	d	a	b	c	d	
DO	mg/L	.13	-0.13	.36	.50	.36	.48	.76	.87	.79	.85	1.07	1.13	0-1
BOD	mg/L	-.45	-.05	.13	.20	.13	.23	.42	.50	.36	.52	1.07	1.47	0-1
COD	mg/L	-.45	-.05	.13	.23	.13	.21	.35	.50	.38	.50	1.02	1.02	0-1
SS	mg/L	-.04	-.03	.04	.07	.04	.06	.13	.16	.13	.15	1.12	1.52	0-1
pH	mg/L	0	0	.77	.78	.75	.81	.90	.92	.88	.94	1.01	1.04	0-1
NH_3-N	mg/L	0	0	.083	.089	.06	.12	.14	.41	.33	.48	1.01	1.01	0-1
FWQ		0	0	.56	.66	.58	.65	.82	.86	.78	.86	1.05	1.07	0-1

tions were derived from the parameters given in Table **1**. Three fuzzy sets to split the input and output have been considered suitable for scope of this study. The amount of overlap, the width and the shape of fuzzy sets should be considered by an expert for each input variable. Ranges for fuzzy sets were based on interim national quality standards (INWQS) for Malaysia [15]. Malaysian rivers are classified in the interim national water quality standards (INWQS) for Malaysia based on water quality criteria and standards for several beneficial uses [15, 16]. Ranges and parameters of quality determinants in the fuzzy inference system was given in Table **1**. Six quality determinants have been selected to evaluate water quality by means of an aggregated index called FWQ index. In the fuzzy algorithm, the Mamdani approach is used. Fuzzy inference of the determinants are determined using grades of membership functions of the parameters. Defuzzificate the fuzzy inferences of the determinants to achieve an index number between 0-100 intervals using centroid methods which is the most prevalent and physically appealing of all available methods [17]. A selected sets of six water quality determinants and 86 rules has been used. In water quality assessment, expressions as the following are frequently used by the experts: "if the levels of organic matter in a river are ADE, and the levels or dissolved oxygen are HAC, then the expected water quality is ACC. In fuzzy description, it could be pronouns as follows:

Rule 1. If BOD5 is ADE, and DO is HAC then WQ is ACC. In the same way, other rules can be enunciated. Robustness of the system depends on the number and quality of the rules.

STUDY AREA

The Semenyih River, which is one of the tributaries of the Langat Rivers, flows southwards towards districts of Hulu Langat and Sepang. Semenyih River has been adversely impacted by urban and industrial wastes since the early 1990s. Semenyih basin lies between longitude 101 47.450" E to 101 53.034"E and latitude 02 53.021" N to 04.572" N. The average annual rainfall in the area is about 3000 mm. Currently, more than 1 million people intake a drinking water from Semenyih River. Water quality in the Semenyih is monitored by Department of Environment (DOE). Three sampling stations are located in the basin SP9, SP10, SP11. In 1997-2004, the Department of Environment initialized observations of water quality determinants in the three sampling stations of the Semenyih River, periodically. The observed determinants in the basin are dissolved oxygen (0.22), biological oxygen demand (0.19), chemical oxygen demand (0.16), ammonical nitrogen (0.15), suspended solid (0.16), and pH (0.12). In parentheses are given the weight factors according to the importance of determinants.

RESULT AND DISSCUSION

The water quality for the Semenyih River has been assessed with the FWQ index. Collected data sets from Department of Environment (DOE) of Malaysia was used to assess water quality between 1997-2004. The calculated FWQ index results according to fuzzy inference system (FIS) are given in Fig. (**4**). On the other hand, comparison has been done between FWQ and the reputed WQI index.

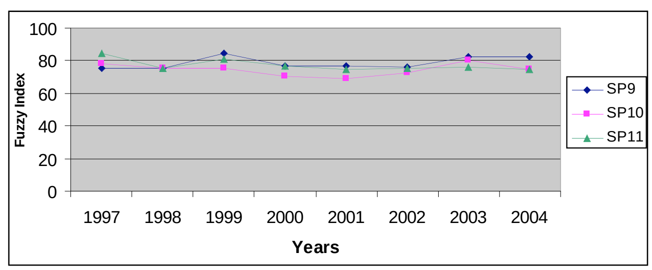

Fig. (4). Results for the fuzzy water quality index in Semenyih River.

Evaluation of the Semenyih River Water Status with FWQ Index

Fuzzy water quality index (FWQ) has been developed for assessment of water status in Semenyih river. Fuzzy water quality assessment results were compared to present DOE-WQI with respect to aquatic life, water supply, and irrigation. The observations have been taken for fuzzy model testing from 1997 to 2004 is shown in Fig. (**5**). In the fuzzy model, DO, BOD, and COD led to high values for FWQ indices, indicating a relative good condition, mainly affected by total suspended solid values and ammonia. FWQ index are acceptable in 1997, 1999, 2003, and 2004. But fuzzy score is adequate in 1998, 2000, 2001, and 2002. It is meant that water quality is adequate in these years but rest of years

(1997, 1999, 2003, 2004) has acceptable fuzzy output numeric score which means the water quality status is acceptable in those years. It can be observed in Fig. (**4**). As can be seen in the Fig. (**4**), SP9, SP10, and SP11 exhibit an acceptable water quality in different years due to different water quality status.

Fish and other aquatic animals need oxygen to breathe. Fish are put under stress when dissolved oxygen falls below 5 mg/L, and fish kills can result if dissolved oxygen falls below 2 mg/L. Cold water can hold more dissolved oxygen than warm water. The DOE-INWQS rating scale considers dissolved oxygen levels from 0 to 5 mg/L as adequate from 5 to 7 as acceptabl*e*, and above 7 as highly acceptable. The dissolved oxygen in the Semenyih River is acceptable on the basis of the fuzzy model results.

Biological oxygen demand (BOD) is a measure of the organic material, both natural (for example, decaying plant and animal material) or human (petroleum products and organic chemicals). BOD in the Semenyih is dominated by naturally occurring organic material (NOM). NOM can react with chlorine in water treatment plants to form harmful disinfectant by-products in drinking water. DOE-INWQS rating scale designates TOC levels of 0 to 3mg/L as highly acceptable, 4 to 5mg/L as acceptable and above 6mg/L as adequate. Overall BOD in the Semenyih River is acceptable on basis of fuzzy results. Semenyih River monitoring indicates that TOC is typically in an adequate range. The local water treatment plants closely monitor TOC to control the levels of disinfection by-products and to ensure safe drinking water for the community.

Chemical oxygen demand (COD) is a measure of chemical waste and often be correlated with BOD in water. The organic carbon is oxidized to carbon dioxide by chemical oxidation in water. DOE-INWQS rating scale designates COD levels of 1 to 10mg/L as highly acceptable, 10 to 25mg/L as acceptable and above 25 mg/L as adequate. COD is acceptable in the Semenyih River on the bases of fuzzy scores.

Total suspended solids (TSS) is a measure of the material that is suspended in the water. Semenyih River monitoring indicates that TSS is in the range for a highly acceptable rating in the fall, but gets an acceptable to adequate rating in the summer. Most TSS in the Semenyih River is sediment from runoff and bank erosion. The DOE-INWQS rating scale designates 0 to 50 mg/L TSS as Low (rated as highly acceptable), 50 to 100 as Medium (rated as acceptable), and 150 to >300 as High (rated as adequate). Based on adequate fuzzy model results, the TSS levels in the Semenyih River are in the adequate range.

pH is expressed on a logarithmic scale from 1 to 14, which is used to describes the acidity or alkalinity of water. A pH of 7 is neutral, values below 7 are acidic, and values above 7 are said to be basic or alkaline. Fish do best in waters with a pH between 6.5 and 8.4. Fish are harmed if pH becomes too acidic (falls below 4.8) or too alkaline (goes above 9.2). The DOE-INWQS rating scale designates a pH between 6.5 and 8.4 as highly acceptable and between 6 and 9 as acceptable, and below 6.5 and above 9 as adequate. The pH of the Semenyih River is very stable on basis of fuzzy scores (due in part to the dissolved carbonate minerals in the water).

The DOE-INWQS rating scale designates 0 to 0.1 mg/L ammonia as Low (rated as highly acceptable), 0.1 to 0.3mg/L as Medium (rated as acceptable), and 0.3 to >2.7 as High (rated as adequate). Based on fuzzy results the ammonia in the Semenyih River is the adequate range largely due to sewage deposal and urban runoff. Ammonia is a source of nitrogen (N), an important nutrient for plants and algae but at higher temperatures (32°C) or higher pH (10.2), converts from NH_4 to NH_3, a gas which is harmful to fish and aquatic life. Ammonia is excreted by animals and is produced during the decomposition of plants and animals. Ammonia is an ingredient in many fertilizers and is also present in sewage, storm water runoff, certain industrial wastewaters, and runoff from animal feedlots. At the temperature and pH range typical of most rivers, ammonia exists predominantly in the ionized form (NH_4^+). As pH and temperature increase, the ionized ammonia changes to un-ionized ammonia gas (NH_3). If sufficient dissolved oxygen (DO) is present, ammonia can easily be broken down by nitrifying bacteria to form nitrite and nitrate.

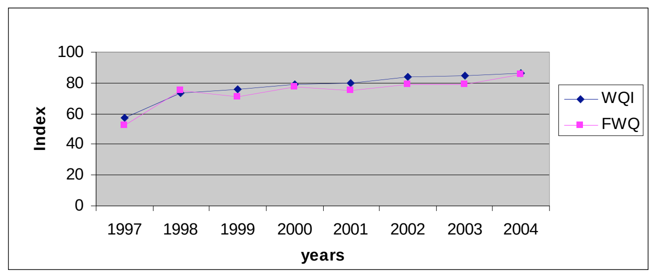

Fig. (5). Results of testing for FWQ and WQI in the Semenyih River.

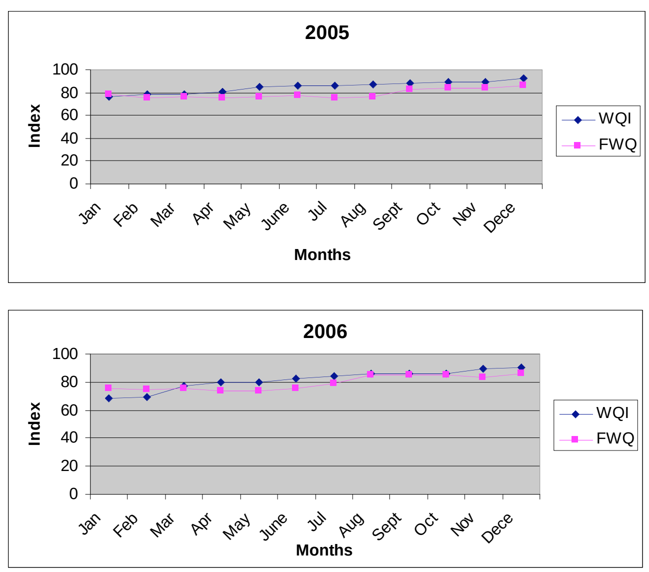

Fig. (6). Validation Results for water quality indices in the Semenyih river.

An analysis of variance (ANOVA) over the FWQ results has shown that there are significant ($p>0.05$) differences between years assessed. On the other hand, ANOVA shows that there are significant differences between sampling sites. The SP9 exhibits a good water quality, while SP10 shows adequate score. Differences between SP9 and the other sampling sites are due to the fact that this sampling sites does not have any industrial activities. The SP10 and SP11 have small scale industries and small residential areas. FWQ index indicated the load exerted on the Semenyih River basin taking into account both natural and anthropogenic factors. The most important advantage of the fuzzy methodology is that the inference system is built with words. Fuzzy model has been validated with the two years independent sets of data. The validation results have been shown in Fig. (**6**). In the Fig. (**6**), the FWQ index is compared to the WQI index, which is used by Department of Environment (DOE) for river water classification.

Model Validation

Validation or confirmation that the model is sound and effective for the purpose for which it was intended. FWQ does not aim at describing the variation of the concentration of a single pollutant or the alternation of a physical parameter. It is purpose is estimate about the status of water quality generated by physiochemical determinants. The Fuzzy model has been validated with the two years of independent sets of data. The Validation results are shown in Fig. (**6**). FWQ results revealed that the overall quality of Semenyih River belonged to the acceptable class. FWQ qualitative outputs agree with the real conditions reported by DOE-WQI.

CONCLUSIONS

In this study, a robust decision-making tool for water management in the form of the fuzzy water quality (FWQ) index is presented. The flexibility of the Fuzzy logic to develop classification model with a simple framework, construct with natural language, should be recommended in the development of similar environmental indices in which highly subjective information must be correlated. In this study, one index value was obtained to express the classification of river in order to make water quality assessment more understandable especially in public consideration. It has been demonstrated that computing with linguistic terms within fuzzy inference system (FIS) improves the tolerance for imprecise data. We have been assessed water quality in the Semenyih River with physicochemical determinants. Fuzzy model has demonstrated that water quality is below sustainable expected results in the Semenyih River. This new index is believed to assist decision makers in reporting the state of water quality, investigation of spatial and temporal changes. The authors believe that the fuzzy logic concepts, if used logically, could be an effective tool for some of the environmental policy issues. More stringent methodologies and reliable results are then required to convince managers and policy makers to apply fuzzy model in practice.

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