Chapter 9

Fuzzy Logic as a Tool for the Assessment of Water Quality for Reservoirs: A Regional Perspective (Lerma River Basin, Mexico)

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/64265

Abstract

The aim of this study is to propose a water quality index for reservoirs in a basin using fuzzy logic. Most of the water quality indices are designed for use in rivers and streams and based on expert opinion; however, when the water is dammed, the quality usually Is modified. Mexico is a country with many contrasts in quantity and quality of water. Management of water resources in the Lerma River is achieved with a system of artificial reservoirs where water is stored in order to meet human needs, such as public supply, industry, agriculture and recreation, among others. Monitoring of 11 reservoirs in the Río Lerma basin was performed to characterize the water quality. Using the water quality data, those indicators that do not represent redundancy were selected based on the concentration gradient that occurred in the different reservoirs. Thus, the proposed index uses eight indicators of water quality. The fuzzy inference system is composed by 633 rules with a score from 0 to 100 and seven verbal categories. The index was validated by comparison with other water quality index, and their use across the basin was tested by applying it in five additional water bodies.

Keywords: fuzzy inference system, physicochemical approach, reservoirs, water quality

1. Introduction

Water quality assessment traditionally has been measured by physical and chemical parameters and through the comparison of results of monitoring programs with the existing local guidelines. Only in some of these cases, the use of this methodology allows for a proper

identification of contamination causes and may be essential for checking legal compliance; however, it does not readily give a global behaviour of the water quality in a basin [1].

Water quality indices have been used to translate large data sets on water quality into a single value representing a certain level of water quality [2]. The common denominator for all water quality indices is its ability to combine data from monitoring programs by means of a simple quality vector [3].

The most common water quality constituents used in water quality indices include dissolved oxygen (DO), pH, temperature, faecal coliforms, turbidity, biochemical oxygen demand, chlorides, colour, nitrates, total phosphorus, and total solids [3, 4]. These parameters traditionally have been selected and qualified through the combined judgment of a panel of water quality experts within a region or country utilizing a set of questionnaires based on the Delphi system [5, 6].

Water quality indices are mainly used by water resource managers to communicate whether water is acceptable for its intended uses [3, 6–9], as well as to compare and identify trends between different watersheds or water bodies, and facilitate comparison among different sampling sites and/or events [1, 2, 10, 11].

In addition to water uses (public water supply, agricultural irrigation, industrial, navigation, recreation, etc.), which are qualified by water quality indices, the services provided by water bodies, such as maintenance of groundwater level, balance of atmospheric gasses, climate regulation, and reduction of soil erosion, are extremely important to human welfare; however, their importance has decreased and is not considered in the assessment tools. There is evidence that many human dominated ecosystems have become highly stressed and dysfunctional [12].

The evolution of water quality indices has been satisfactory in terms of water resources management because they were all developed for a specific set of goals such as rating the water use [13], communication tool, and decision-making managers [6], and they are based on criteria or standards (environmental benchmarks) that reflect the impairment of quality caused by the presence of pollutant/parameter considered in the water quality index (WQI).

Horton [14] is considered the pioneer in the design of water quality indices, and he proposed that various water quality characteristics could be integrated into an overall index. This first WQI was defined as a rating reflecting the composite influence on overall quality of a number of individual quality characteristics. After Horton, numerous indices have been developed that include different water quality characteristics, calculation methods, and different purposes. Dinius [6] proposed a geometric WQI qualifying until six water uses.

Numerous studies have used water quality indices to determine water quality in rivers [2, 3, 9, 15–20]. Recently, fuzzy theory has been used to design water quality indices and also to assess the water quality in rivers [21–25].

Few studies, much less at a regional level, have been conducted to assess the water quality in lakes or reservoirs in terms of a water quality index. In some cases, studies are available on trophic state development [26–29]. López [28] carried out a regional study in reservoirs of the Río Lerma basin, pointing out the existence of a trophic gradient from a regional perspective.

http://dx.doi.org/10.5772/64265

Sedeño-Díaz and López-López [30] applied a geometric WQI to 10 reservoirs of the Río Lerma basin, and Shuhaimi-Othman et al. [31] carried out a study of the water quality changes of Chini Lake. Fuzzy synthetic evaluation [32] and fuzzy theory [33, 34] have been utilized for diagnostic of trophic state in reservoirs. None of these WQI has been developed from a gradient of environmental conditions inside a hydrologic basin which allows to compare the different water bodies inside the same region.

Human population growth and changes in adjacent land use have increased the pollutant and nutrient inputs in the reservoirs, altering water quality and accelerating the eutrophication of reservoirs, lakes and watercourses. The Río Lerma basin with an extension of only 3% of the Mexican territory is the most important water system in the central plateau of Mexico. Likewise, urban areas, agricultural lands, and industrial centres located along its course are set to become one of the most densely populated and polluted regions in the country. This basin has experienced negative impacts due to human activities; it currently faces an imbalance between water demand and availability, primarily due to its natural water scarcity as well as uneven water quality distribution. The rapid urban and industrial growth among other economic and social factors has made this worse. Water needs have grown, water users are fiercely competing with each other and conflicts are emerging as a result. Hence, water quality has also deteriorated as urban and industrial effluents are often discharged without treatment. The Río Lerma basin is also considered as a centre for fish fauna endemism [2] and therefore is mandatory to take conservation measures.

To overcome the water availability problem, numerous reservoirs have been built to satisfy the needs of the population. Cotler-Ávalos [35] indicates that at present there are 552 reservoirs in the basin. Therefore, it is important to have simple and easy-to-use tools to assess the water quality of the reservoirs and facilitate interpretation and decision making, since they are the main source of water to meet the needs of the population in that region. In this study, a water quality index (WQI) based on fuzzy logic was designed to assess and to compare the environmental condition of several reservoirs of the Río Lerma basin, using a selection of eight water quality characteristics.

2. Background about fuzzy logic and fuzzy inference systems

The aim of this section is not to expose the full fuzzy logic theory (FL); however, it is important to give a brief introduction. FL was introduced in 1965 by [36], and it is a mathematical tool for dealing with uncertainty as it is able to measure linguistic concepts or subjective words that are fundamentally imprecise, ambiguous or fuzzy [21, 37].

We can ask what does a water quality index do with the FL. For several years, FL has been applied to design environmental indices because it solves complex situations such as ambiguity, subjective judgments, and interpretation of a complex set of multidimensional data [22, 37]. The results of a WQI are most often associated with different linguistic water quality categories (e.g. excellent, good, regular, or bad water quality). These linguistic variables use unclear boundaries, that is, these terms include a high degree of uncertainty. In addition,

considerable vagueness is involved in the allocation of a water quality score for multiple uses inclusive of a specific use [11]. FL can be considered as a language that allows us to translate the uncertainty of natural language into mathematical expressions [11]. Thus, FL has been considered as a useful tool for modelling water quality as it is an alternate approach to problems where the goals and boundaries are diffuse or imprecise [24, 38].

2.1. Fuzzy inference systems (FISs)

FISs are based on the fuzzy set theory, which maps input values to output values [23, 38]. The input is called *antecedent*, while the output is known as *consequent*. Maps are outlined in the membership functions.

A membership function is a curve whose shape is defined by convenience [11, 38], and that defines how each point in the antecedent is mapped to a membership value in a range of 0–1 [21]. In FIS, different shapes of membership functions can be used, such as Gaussian, bell, trapezoidal and triangular, among others. Trapezoidal and triangular membership functions have the advantage of being asymmetric [39], but the gradient of values of membership develops over the same slope value.

In concordance with [11, 38, 40, 41], a FIS consist of three main steps:

- Fuzzification, is the process which changes a crisp input data to a fuzzy number expressed in a membership function, that is, the transformation of a numerical value of any water quality variable into a membership grade to a fuzzy set.
- Evaluation of fuzzy decision through the system of linguistic *If-Then* rules which include the fuzzy operators to integrate the combined antecedents to the consequent.
- Defuzzification, is the process to obtain a representative value of a fuzzy set, that is, the final crisp value that integrates all attributes of the multiple antecedents. There are different methods of defuzzification, the most common are centroid, mean of maxima, and bisector; however, it is very important to select an appropriate defuzzification method.

These fundamental three steps are imperative to obtain a successful FIS.

In concordance with [38], there are at least six reasons to use models based on fuzzy rules and fuzzy sets: (a) they can be used to describe a large variety of nonlinear relations, (b) they tend to be simple, since they are based on a set of local simple models, (c) they can be interpreted verbally and this makes them analogous to artificial intelligence models, (d) they use information that other methods cannot include, (e) the fuzzy approach has a big advantage over other indices as they have the ability to expand and combine quantitative and qualitative data that express the water quality status, and finally, (f) FL can deal with and process missing data without compromising the final result.

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3. Methods

3.1. Study area

We studied 11 reservoirs with different water use (power generation, agriculture irrigation, drinking trough, recreational, and public supply) and different location within the Río Lerma basin (upper, middle, and lower reaches), all of them considered as hydrological priority systems by Mexican Environmental Authorities (**Figure 1**).

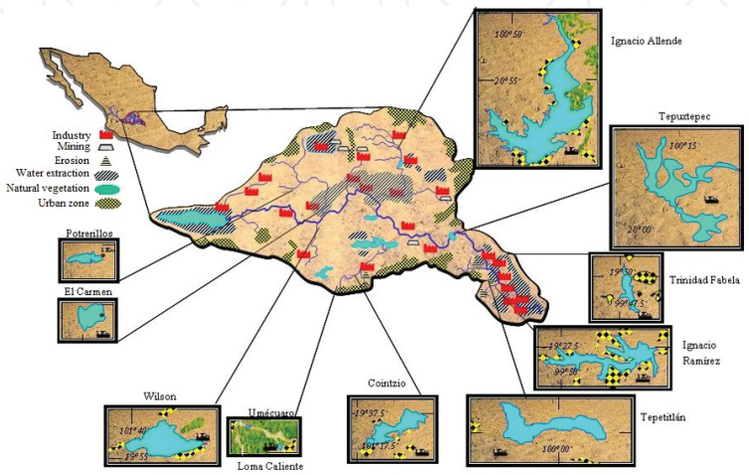

Figure 1. Río Lerma basin and location of reservoirs studied.

The upper Río Lerma includes the following reservoirs: Ignacio Ramírez (IR), Tepetitlán (TP), Trinidad Fabela (TF), and Tepuxtepec (TX). In the middle portion of Río Lerma are Ignacio Allende (IA), Potrerillos (PO), Umecuaro (U), Loma Caliente (LC), Carmen (CA), and Cointzio (CO), and finally, the reservoir studied in the lower Río Lerma was Wilson (W).

Some reservoirs are located in the headstreams of some Río Lerma tributaries (LC, U, TP, TF, PO), while others are close to urban or industrial centres (IA, CO, TX) or adjacent to agriculture and livestock areas (CA, W, IR). Nonetheless, they all sustain human influence of one kind or another.

3.2. Water quality variables

Water quality for each reservoir was characterized by means of 19 parameters, four times in an annual cycle to determine the spatial and temporal variation in one year: dissolved oxygen (mg/L), water temperature (T, °C), Secchi disk transparency (SDT, m), chlorophyll *a* (Chl *a*, μg/L), turbidity (Turb, NTF), and specific conductance (Cond, μS/cm) were measured *in situ* with a Hydrolab DataSonde Surveyor 4, while biochemical oxygen demand (BOD, mg/L), total nitrogen (TN, mg/L), nitrates (NO_3, mg/L), nitrites (NO_2, mg/L), ammonia (NH_4, mg/L), total phosphorus (TP, mg/L), ortho-phosphates (O-PO_4, mg/L), total suspended solids (TSS, mg/L), and colour (C, Pt-Co units) were determined through Hach techniques with a Hach spectrophotometer DR2500. Alkalinity (Alk, mg/L), hardness (H, mg/L), and chlorides (Cl, mg/L) were

determined by titration, and finally, total dissolved solids (TDS, mg/L) were measured with a TDS meter Hach model 44600.

A multivariate discriminants analysis (DA) was applied to water quality data to find trends and reservoirs sharing similar characteristics. Maximum, minimum, and median of all water quality parameters along 11 reservoirs were taken into account to select those parameters that should be incorporated in the FIS. Likewise, multiple regressions were carried out to find relationships among different parameters and to eliminate those with redundancy or without significance.

The range of values for each selected parameter was considered by taking into account the absolute lowest and the absolute highest values in all the reservoirs and is expressed along the x-axis in the membership function curve.

The membership functions were assigned using the Gaussian curve because is the shape that better reflects the semantic meaning of each parameter considering that increased or decreased water quality is not lineal.

Linguistic classification for each water quality parameter in the antecedent was considered only with three categories: Excellent, Medium, and Bad. In the case of water temperature, only two categories were used: Excellent and Not Excellent, since both low and high temperatures alter the physiology of organisms inhabiting the water of the reservoirs. The linguistic variables in the consequent output were considered as Unacceptable, Very Polluted, Contaminated, Regular Quality, Slightly Polluted, Good Quality, and Excellent.

Different defuzzification methods were tested (Bisector; Centroid; Large of Maximum, LOM; and Middle of Maximum, MOM) to select the best method.

In addition, the water quality index proposed by [6] was computed for all the reservoirs to obtain a reference value of water quality (benchmark).

3.3. Mathematical analyses

Statistical analyses were performed using the StatistiXL version 1.8. The Fuzzy Water Quality Index for the Río Lerma reservoirs was carried out using the Fuzzy Logic Design Toolbox of MATLAB V. R2013a.

4. Results

4.1. Water quality index as reference status

As a first approach, WQI proposed by [6] (WQI_{Dinius}) was computed for all the reservoirs to have a reference status of water quality. Mean values for each reservoir are show in **Table 1** and **Figure 14**. The maximum value of WQI was in LC, a reservoir located in a headstream of a tributary of Río Lerma. The lowest score of WQI was detected in TX, which is located downstream of an urban and industrial zone. These results are the benchmark to compare the new water quality index.

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Reservoir	LC	U	TF	TP	PO	W	CO	IR	CA	IA	TX
WQI	79.9	74.83	71.54	70.94	69.84	67.78	67.21	66.42	62.82	62.79	62.49

Table 1. Mean WQI_{Dinius} scores for all the reservoirs.

4.2. Selection of environmental variables

In order to select the environmental variables (water quality parameters) to be used in the setting of the new Fuzzy Water Quality Index for reservoirs of Río Lerma basin ($FWQI_{Lerma}$), a DA was performed with the purpose to detect groups of reservoirs sharing water quality characteristics. In this sense, DA scatter plot showed a significant formation of four groups (Wilk's Lambda = 15E-8, $p < 0.001$, **Figure 2**). Using box and whisker plots, we detect the environmental variables that typify the groups of reservoirs as follows:

Group I:Reservoirs (U, LC, and Pot) with SDT > 0.5 m (**Figure 3a**), and the lowest concentration of TSS (**Figure 3b**), turbidity (**Figure 3c**), colour (**Figure 3d**), conductivity (**Figure 3g**), and TDS (**Figure 3h**).

Group II:Reservoirs (Tepe and TF) with the lowest concentration of nutrients (nitrates and ortho-phosphates, **Figures 3g** and **3h**, respectively).

Group III:Reservoirs (Co and W) with the highest concentration of nitrates (**Figure 3g**), turbidity (**Figure 3c**), and colour (due the presence of clay, **Figure 3d**), and the lowest values of hardness (**Figure 3i**).

Group IV:It includes the reservoirs IR, Car, IA, and Tepu, which shows the highest concentration of hardness (**Figure 3i**), TSS (**Figure 3b**), ortho-phosphates (**Figure 3f**), biochemical oxygen demand (**Figure 3j**), and the lowest values of SDT (**Figure 3a**).

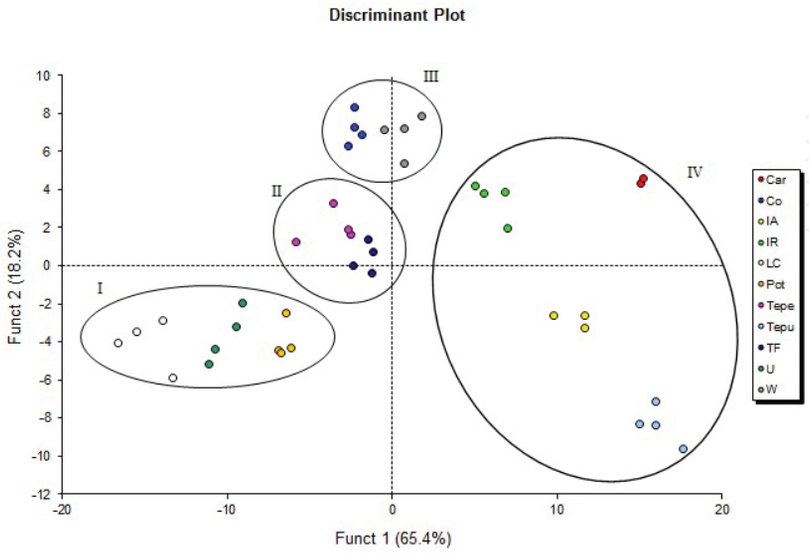

Figure 2. Scatter plot of the discriminant analysis of reservoirs based on their water quality attributes.

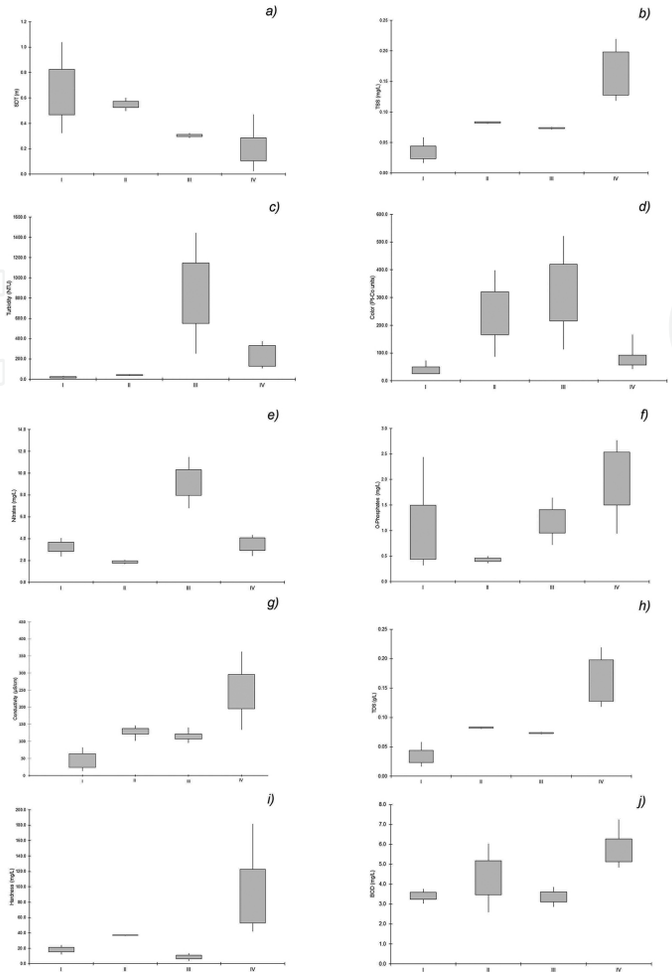

Figure 3. Box and whisker plots of physicochemical variables that characterize each group of reservoirs according to DA.

Based on these groups, five variables were selected: (a) Secchi disk transparency, (b) conductivity, (c) nitrates, (d) ortho-phosphates, and (e) colour, with the following justification:

Secchi disk transparency: This is an important physical parameter in lentic systems because it has a close relationship with turbidity (physical and biological), the total suspended solids and colloidal particles. In several cases, there is a direct relationship with chlorophyll *a* content and therefore, in such cases, can be an indicator of biological productivity for lentic systems.

In the Río Lerma basin, a relationship between SDT, turbidity, Chl *a*, and TSS data was determined for all the water bodies studied. The following expression summarizes the relationship among these parameters:

$$SDT = 1.83 - 0.00598 ln(Turbidity) - 0.27 ln(Chl\,a) - 0.101 ln(TSS) \qquad R^2 = 0.816$$

Thus, we can consider only SDT measure as a representative parameter of Chl *a*, turbidity, and TSS — the last two are parameters that characterize the reservoirs according to DA.

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The membership function for SDT was obtained considering the minimum (0.07 m) and maximum value (1.5 m) of transparency detected in all the reservoirs (**Figure 4**).

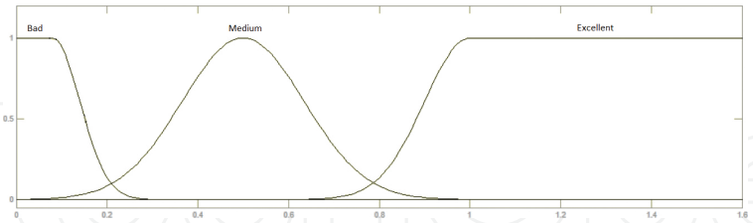

Figure 4. Membership function for SDT.

Conductivity: The specific conductance or conductivity represents the salinity of water. It is a measure of the ability of water to conduct electrical current; likewise, conductance qualitatively reflects the status of inorganic pollution and is a measure of total dissolved solids and ionised species in the water [16, 19]. An empirical relationship between total dissolved solids and conductivity can be derived for any stream. High levels of dissolved and suspended solids in the water systems increase the biological and chemical oxygen demand, which deplete the dissolved oxygen levels in the aquatic systems. The levels of TDS in a broad sense reflect the pollutant burden of the aquatic system [16], and include the carbonates and sulphates that are considered in hardness measurements. Therefore, conductivity is an important parameter to be considered in the $FWQI_{Lerma}$. The membership function was considered taking into account a range of values of conductivity from 0 to 700 μs/cm (**Figure 5**).

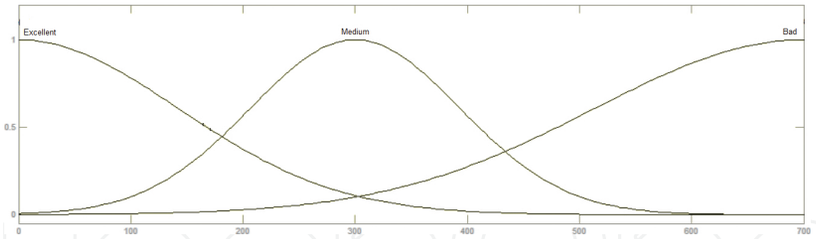

Figure 5. Membership function for conductivity.

Colour: Water colour is indicative of substances in solution or in colloidal suspension, but also is the result of interplay of light on suspended particulate materials together with such factors as bottom or sky reflection. Dissolved substances and particulate organic matter contribute to the colour and turbidity of natural waters. It is also indicative of algae blooms [7]. For the Río Lerma basin reservoirs, in addition to SDT, colour was considered as an important factor due the nature of the substrate, because colour varies according to the type of clays found in different regions of the basin independently of primary production due to algae. Reservoirs Co and W were those with the highest values of colour due to clays. The membership function of colour was determined considering a range of values from 0 to 700 Pt-Co units (**Figure 6**).

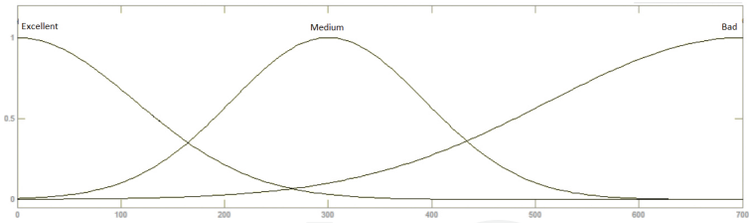

Figure 6. Membership function for colour.

Ortho-phosphates: They are the bioavailable chemical species of phosphorus for the aquatic organisms, which is the main reason for its consideration in this index. Still more than total phosphorus, this one can be in nonbioavailable dissolved inorganic forms for the organisms or in particulated form (like part of the aquatic organisms). Furthermore, ortho-phosphates are an indicator of the trophic state, as well as of municipal effluents and the agricultural runoff. The membership function was performed considering a range from 0 to 12 mg/L of ortho-phosphates (**Figure 7**).

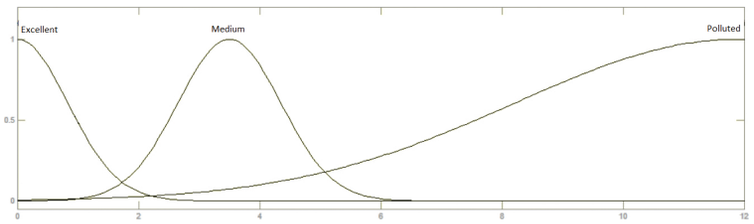

Figure 7. Membership function for ortho-phosphates.

Nitrates: The nitrates are a chemical species of the nitrogen bioavailable to be used by the aquatic biota, mainly by the primary producers. Nitrates are a source of nitrogen present in water column that permits the aquatic biota to cover their nutritive needs of nitrogen. Likewise, it is an indicator related to the trophic state in lentic systems. The membership function was performed considering a range of values from 0 to 40 mg/L, taking into account all the reservoirs (**Figure 8**).

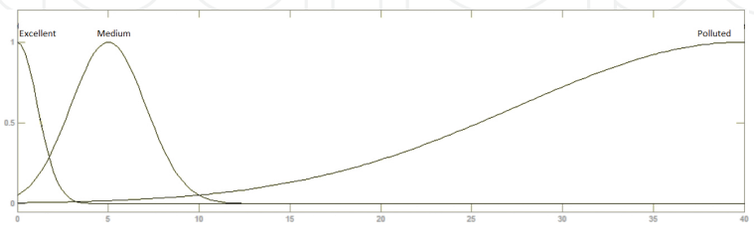

Figure 8. Membership function for nitrates.

Three additional variables were included in the $FWQI_{Lerma}$: dissolved oxygen, water temperature, and ammonia, taking into account the following:

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Dissolved oxygen is one of the critical parameters for aquatic life support and the most frequently measured parameter in monitoring studies. This parameter represents the amount of oxygen that is available to aquatic organisms for metabolism/respiration and assimilation of food [42]. DO is an indicator of photosynthetic activity and the deoxygenation and reaeration factors such as water currents, temperature, wave action, and other disturbances at the reservoir surface results in a greater passage of the oxygen into solution. Membership function was based on the percentage of saturation of DO, taking into account that temperature and altitude are the principal factors that affect the concentration of DO, and that 100% represents the better condition of DO (**Figure 9**).

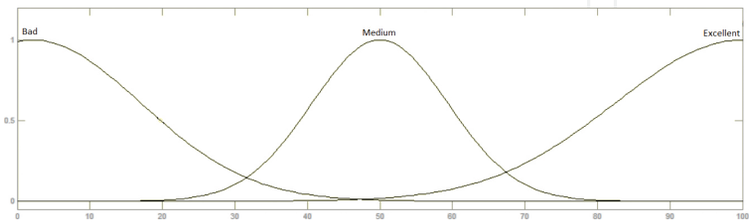

Figure 9. Membership function for DO.

Water temperature is an important parameter in water quality because it has a great relationship with the physiology of the aquatic organisms; in lentic systems, the temperature shows a gradient in the first metres of deep, and in certain reservoirs, a thermocline may occur. To determine a value of temperature, which represents an ideal value for the fish fauna and other aquatic organisms living in the Río Lerma basin, the mean value of temperature from 1975 through 1999 in the 17 monitoring stations (in all of the three portions of this basin) was considered as a satisfactory value; the data were taken from [2]. The 100% of membership (excellent) was adjusted on the mean value of water temperature in that period. Temperature values above or below the mean value were considered "Not Excellent" in a gradient of decrease or increase (**Figure 10**).

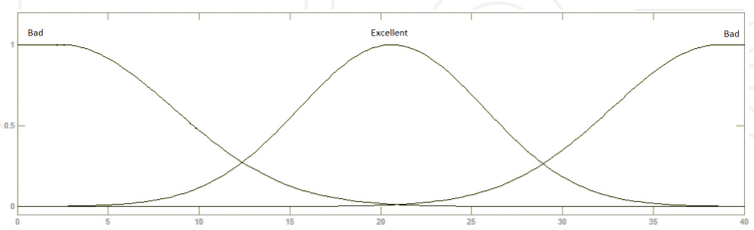

Figure 10. Membership function for water temperature.

Ammonia is considered because it is a chemical that participates in the cycle of nutrients (N) and is an indicator of organic pollution that is faster and easier to determine than the total and faecal coliforms. It is an indicator of faecal pollution and municipal wastewaters. 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. Furthermore, ammonia can be toxic depending on the temperature and pH. In this sense, ammonia can be an excellent water quality indicator of organic pollution, mainly of domestic wastewater. The membership function was considered with a range from 0 to 1.6 mg/L, which were the values observed through all the reservoirs (**Figure 11**).

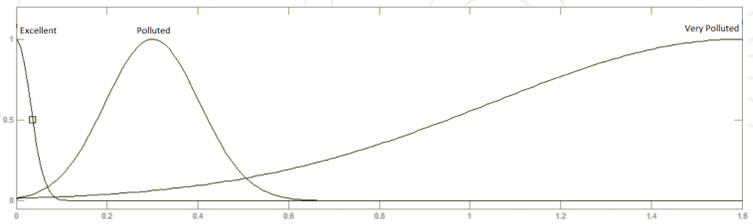

Figure 11. Membership function for ammonia.

4.3. Inference rules (*If-Then*)

Since eight water quality variables were used to perform the $FWQI_{Lerma}$, it was necessary to conform a system of *If-Then* rules. The effect of the different water quality variables cannot be isolated because all of them occur simultaneously in the water. Then, a single rule must incorporate all the variables, and so all the rules. Thus, the FIS for $FWQI_{Lerma}$ was composed by 633 *If-Then* rules considering the eight water quality variables as the antecedent and seven linguistic categories in the consequent output.

Examples of inference rules for each category of the consequent output are:

- If DO is bad, and NO_3 is excellent, and DS is medium, and Specific Cond is excellent, and O-PO4 is excellent, and Colour is excellent, and Ammonia is excellent, and Temp is not Excellent, then WQI is *Unacceptable*.
- *If* DO is medium, and NO_3 is medium, and DS is bad, and Specific Cond is bad, and O-PO_4 is bad, and Colour is bad, and Ammonia is bad, and Temp is excellent, *then* WQI is *Very Polluted*.
- *If* DO is excellent and NO_3 is bad, and DS is bad, and Specific Cond is medium, and O-PO_4 is medium, and Colour is bad, and Ammonia is bad, and Temp is Excellent, *then* WQI is *Contaminated*.
- *If* DO is excellent and NO_3 is excellent, and DS is bad, and Specific Cond is medium, and O-PO_4 is bad, and Colour is bad, and Ammonia is medium, and Temp is Not excellent, *then* WQI is *Regular Quality*.
- *If* DO is excellent and NO_3 is excellent, and DS is excellent, and Specific Cond is medium, and O-PO_4 is medium, and Colour is medium, and Ammonia is medium, and Temp is excellent, *then* WQI is *Slightly contaminated*.

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- *If* DO is excellent and NO_3 is excellent, and DS is excellent, and Specific Cond is excellent, and O-PO_4 is medium, and Colour is medium, and Ammonia is Good Quality, and Temp is excellent, *then* WQI is *Good Quality*.
- *If* DO is medium and NO_3 is excellent, and DS is excellent, and Specific Cond is excellent, and O-PO_4 is excellent, and Colour is excellent, and Ammonia is excellent, and Temp is excellent, *then* WQI is *Excellent*.

The consequent output is a crisp value as a result of defuzzification process, which is associated with the linguistic category in the consequent. Thus, the Input-Output map of the FIS for $FWQI_{Lerma}$ is depicted in **Figure 12**.

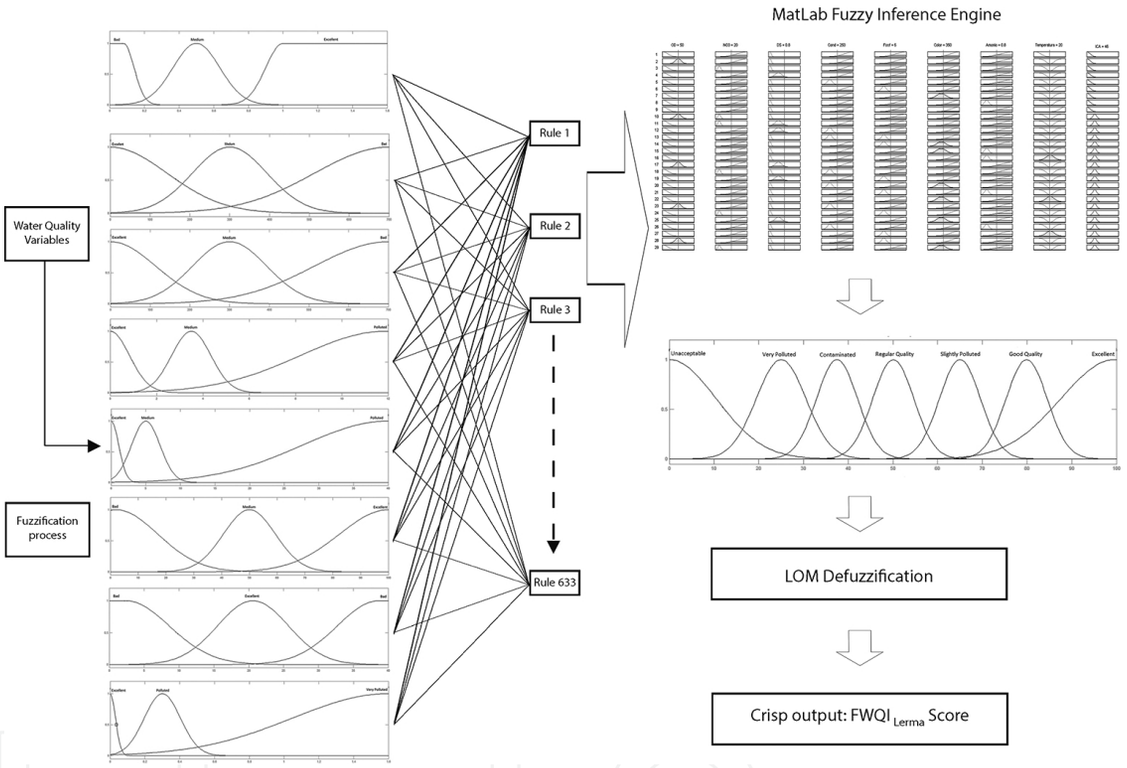

Figure 12. Map for fuzzy water quality index inference system.

4.4. Selection of defuzzification method

As indicated above, different methods of defuzzification were tested, for which ANOVA was performed between the $WQI_{Diniuis}$ results and the scores obtained for $FWQI_{Lerma}$ with the application of the following defuzzification methods: Bisector, Centroid, LOM, and MOM. In this case, the best method was selected based on the minimum statistical difference between WQI proposed by [6] (benchmark) and defuzzification results. **Figure 13** shows the box and whisker plot of the comparison between WQI_{Dinius} score and the scores of the different methods of defuzzification; LOM is the one with the smallest difference with WQI_{Dinius}; in fact, there is a total overlap. In this sense, LOM was selected as the method of defuzzification for $FWQI_{Lerma}$.

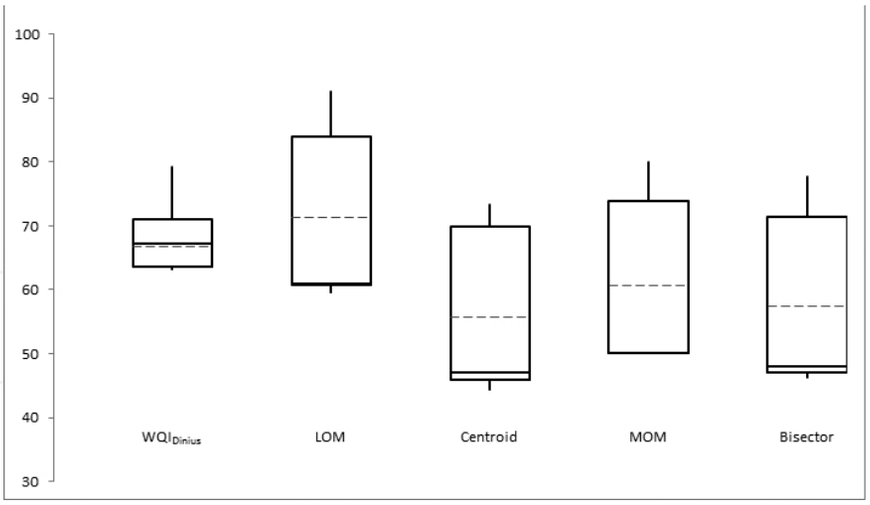

Figure 13. Box and whisker plot representing the results of ANOVA of the application of different defuzzification methods compared with the benchmark WQI_{Dinius}.

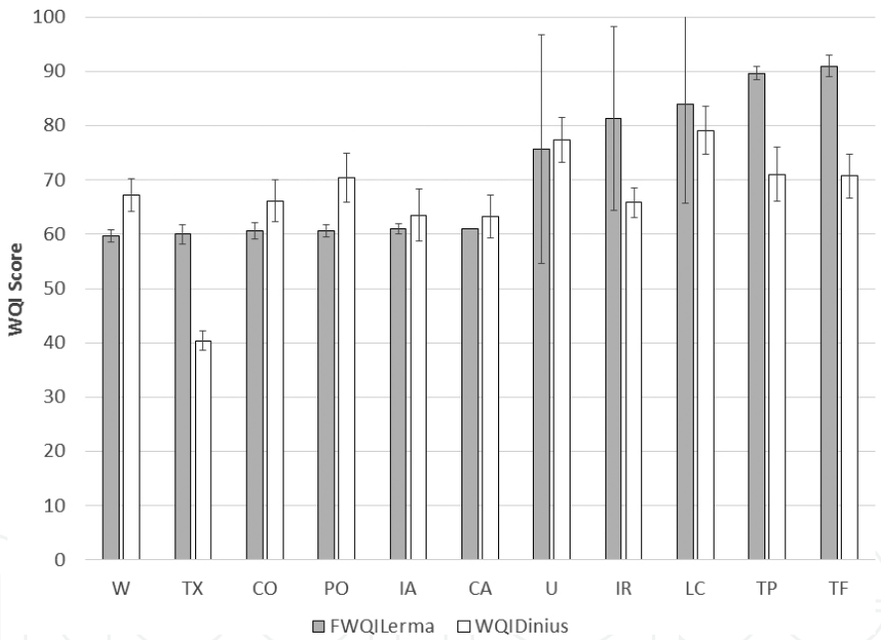

Figure 14. WQI scores (±SD) of Río Lerma reservoirs, considering results of WQI_{Dinius} and $FWQI_{Lerma}$.

Once the defuzzification method was selected, it is possible to compute the $FWQI_{Lerma}$ for all the reservoirs. **Figure 14** shows the WQI scores for WQI_{Dinius} and $FWQI_{Lerma}$. The best scores were obtained from LC, U, TP, and TF reservoirs, which are in headstreams.

4.5. Model validation

In order to identify the effectiveness of the $FWQI_{Lerma}$, a validation process was carried out using five new water bodies located in different sites into the Río Lerma basin. Thus, two water

http://dx.doi.org/10.5772/64265

bodies with an excellent water quality were selected: Nieves and Zacapu Lake; on the other hand, additional water bodies were selected with a regular water quality: Melchor Ocampo Reservoir, Pool Lake, and Solis Reservoir.

When the $FWQI_{Lerma}$ was applied to these water bodies, the first two showed a score of 86, and the other three obtained the score of 64, 64, and 62, respectively (**Figure 15**), showing that $FWQI_{Lerma}$ effectively reflects the water quality status in other water bodies of the same basin.

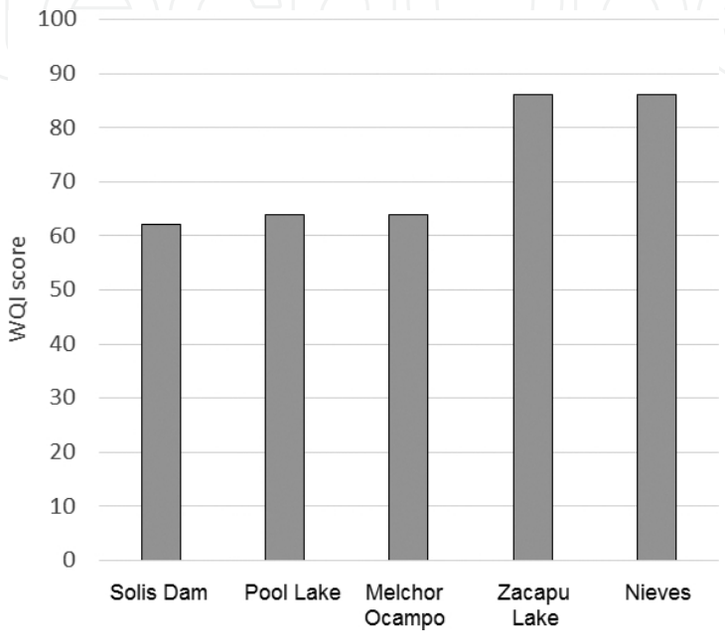

Figure 15. WQI scores for water bodies of validation.

5. Discussion

The WQI have been an excellent tool to assess water quality using physicochemical approach. Historically, water quality indices have been applied by environmental agencies to take decisions about water management and conservation and to advise the water quality status to the public. Both regional (ecoregions) and basin approaches have proven to be the most successful tools for the assessment of water resources. In this case, the new $FWQI_{Lerma}$ is focused in assessing reservoirs located in the same basin, considering different water uses, surrounding land use, and their position into the basin. Like other WQI, their scores are into the range of 0–100, with the superior limit indicating an excellent water quality. Unlike other WQI that use 15–18 water quality variables, $FWQI_{Lerma}$ only uses eight. This is the first WQI that includes SDT as an important parameter, making measurement easier and cost-effective. It is an important issue in a basin with a high number of reservoirs.

Fuzzy inference system has been used by other authors to design WQI for rivers [24, 38], but not in reservoirs or lakes. Liou and Lo [12] applied fuzzy set theory to evaluate trophic state

in some reservoirs in China using the three typical parameters: total phosphorous, Chl *a*, and SDT.

Bai et al. [11] and Mourhir et al. [23] proposed a river water quality index based on fuzzy logic, using six indicators and 15,625 and 86 rules, respectively. The fuzzy WQI proposed by [38] was set up with 27 water quality indicators (WQInd) and 96 fuzzy inference rules; while those proposed by [24] is composed of 9 variables and 3125 fuzzy rules. In this study, a multivariate analysis of discriminants and other statistic tools were employed to characterize the reservoirs and select the most important water quality variables; in this sense, $FWQI_{Lerma}$ was set up by eight water quality indicators and 633 inference rules.

While other authors have applied only one of the traditional methods of defuzzification: Centre of Gravity [21], Centroid [11, 21, 38], or MOM [41], this study analysed what could be the best defuzzification method, considering a benchmark. Thus, the best method for defuzzification was LOM. In this sense, comparison with other WQI as a benchmark was a process to know the range of water quality at which the reservoirs should be. In this study, we look for the match with the WQI_{Dinius}.

Ocampo-Duque et al. [38] compared their FWQI with some impact indicators such as biochemical responses in fish, which matched with FWQI spatial data. Semiromi et al. [21] compared their FWQI with other indices using a set of independent data. In this study, $FWQI_{Lerma}$ was compared to WQI_{Dinius} to verify the range of scores and to select the best method of defuzzification, which is a part of the validation process. On the other hand, a set of other reservoirs into the Río Lerma basin was used to evaluate the applicability of this index in other water bodies whose water quality data were not used in the setting, that is, its potential use at the regional or basin levels was tested.

Thus, $FWQI_{Lerma}$ scores were compatible with the water quality status assessed with the WQI_{Dinius}. This index showed that those reservoirs exposed to minimum impact (U, LC, TF, and TP) obtained the best scores, while those reservoirs closed to urban, industrial, or agricultural zones (W, TX, CO) displayed scores with a regular water quality.

6. Concluding remarks

- Water Quality Indices are important tools to assess the status of water bodies considering the integrated measure of physical and chemical indicators that contribute to decision making.
- In concordance with other authors, FL and FIS in this study resulted to be excellent tools to assess the water quality in water bodies.
- $FWQI_{Lerma}$ shows to be consistent with WQI_{Dinius}.
- $FWQI_{Lerma}$ proved to be an outstanding and robust tool to rate and take decisions about the water quality in reservoirs located in the Río Lerma basin since it reflected the water quality scores in the same range as other indices.

- This index is believed to be cheaper because it uses only eight parameters, among them DO and conductivity are measured in the field using a probe (a very common equipment for water quality monitoring), and SDT is recorded with a single Secchi disk.
- This index is one of the WQI specially configured to assess water quality in reservoirs.

Acknowledgements

Authors are thankful to Instituto Politécnico Nacional and CONACyT-SEMARNAT for financial support for the Project "Diagnóstico del estado trófico y calidad del agua de embalses de la cuenca del río Lerma, generación de un modelo regional. C01-0384." (Assessment of trophic state and water quality of reservoirs of the Río Lerma Basin, generating a regional model.). Likewise, authors would like to thank to Ing. Mali Carol Uspango Becerro by editing the figures.

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