Surface Water Contamination Risk Assessment Modeled by Fuzzy-WRASTIC

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ABSTRACT

This research provides a Fuzzy-WRASTIC new model for water resource contamination risk assessment in a GIS (Geographic Information System) environment. First, this method setting in a multi-criteria evaluation framework (MCE) reviewed and mapped the sub criteria of every above-mentioned criterion. Then, related sub-layers were phased by the observance of GIS environment standards. In the next step, first the sub-layers were combined together, next the modeling of pollution risk status was done by utilizing a fuzzy overlay method and applying the OR, AND, SUM, PRODUCT and GAMMA operators by using WLC (Weighted Linear Combination) method and providing weights in the WRASTIC model. The results provide the best combination of modeling and the percentages of its risk categories of low, medium, high and very high, which are respectively 1.8, 14.07, 51.43 and 32.7. More areas have severe risk due to the unbalanced arrangement and compact of land uses around the compact surface water resources.

KEYWORDS: environmental impacts, geographic information system (GIS), risk assessment, fuzzy logic
Introduction

Freshwater ecosystems provide vital resources for human beings and support high levels of biodiversity, yet they are severely threatened throughout the world (Martinuzzi et al., 2014). Freshwater resources are finite in space and time. In the face of growing water demand (Vorosmarty et al., 2000; Dessu et al., 2014), natural river flow is being challenged by land ownership (Pearce, 2004; Dessu et al., 2014), economic growth (Chong and Sunding, 2006; Dessu et al., 2014), advances in technology (Bittermann, 2008; Dessu et al., 2014), legislations (Ansink and Weikard, 2009; Dessu et al., 2014), political will and social barriers (Lueck, 1995; Mostert et al., 2007; Dessu et al., 2014). The majority of the freshwater resources have already been depleted and there is a reduction in global agricultural production with escalation in population and food demand (Misra, 2014). However, it is reduced due to the strong human dependence on fresh water, changes in land use, water course alterations, and the introduction of species leading to widespread water pollution, habitat degradation, and biodiversity loss (Malmqvist & Rundle, 2002; Dudgeon et al., 2006; Martinuzzi et al., 2014).

Several studies have been conducted on assessment of the factors causing changes in the quantity and quality of freshwater resources, some of which are mentioned here. Research results in southern Malawi reveal that anthropogenic activities have negatively affected low flow environmental flow requirements by increasing zero flow days in Rivirivi River Catchment (Chimtengo et al., 2014). Over the period of thirteen years from 1997 to 2009 in Malaysia, the results of efforts that included public participation, engineering and river works and strict statutory regulations by government had demonstrated success in improving the river water quality (Sulaiman et al., 2014). Hydrology and water resources usually involve a system of concepts, principles, and methods in order to deal with modes of reasoning which are approximate rather than exact. In other words, hydrology is hampered by uncertainties.
caused by nature (e.g., climate), limited data, and imprecise models (Bogardi et al., 2003). Fuzzy logic is used when uncertainty or imprecision exists (Shepard, 2006; Ocampo Duque, 2008).

Fuzzy theory has been developed for modeling complex systems in uncertain and imprecise environments (Ross, 2009; Ocampo Duque, 2008). The water quality assessment is a fuzzy concept with multiple indicators and classes (Wang et al., 2014). Introducing Fuzzy Comprehensive Evaluation Method is a way of assessing the water quality of the environment using the principle of fuzzy mathematics. It is a method to determine the water level by the membership degree, which is specified by the measured sample sequence and the standard sequence of levels (Ma et al., 2014). Fuzzy logic uses sets with unclear boundaries. Fuzzy logic can be used for mapping inputs to appropriate outputs. “The considerable risk of the aquatic ecosystem in the river due to the high number of wastewater discharges” is a clear example of an inherently fuzzy statement. Fuzzy logic offers a powerful framework to develop decision models for water management. (Ocampo Duque, 2008). Fuzzy logic has been applied to many areas in GIS such as fuzzy spatial analysis, fuzzy reason, and the representation of fuzzy boundaries (Kainz, 2008). Zimmerman (1996) discussed a variety of combination rules. Bonham-Carter (1994) discussed five operators, namely the fuzzy and fuzzy or, fuzzy algebraic product, fuzzy algebraic sum, and fuzzy gamma operator.

This study uses the five fuzzy operators for combining the fuzzy membership functions (Lee, 2007). This paper adopts a different approach and employs a spatial suitability model based on fuzzy set theory (Zadeh, 1965; Lewis et al., 2014). As compared to traditional overlay models, fuzzy logic better addresses data variability, imprecision, and ambiguity (Hall et al., 1992; Lewis et al., 2014). The environmental risk assessment (ERA) is the process by which hazards are identified, exposure is quantified, and dose response relationships are determined for risk characterization (Tristán et al., 2000; Rebelo et al., 2014) and covers
spatial and temporal scales according to chemodynamics, environmental mobility and ecosystem response (Schaeffer et al., 2009; Rebelo et al., 2014).

The hazard posed by a chemical is related to its use, its quantity and its partition into environmental media (Daginnus et al., 2011; Rebelo et al., 2014). The process of pollution risk assessment requires the assimilation of data that are spatially variable in nature, making geographical information systems (GIS) an ideal tool for such assessments (Foster & McDonald). Multi-criteria evaluation (MCE) methods linked with geographic information systems (GIS) can be used to make risk-based decisions (Chen et al., 2001). Spatial multi-criteria analysis (SMCA) proved to be a useful tool in decision-making where GIS plays a role in analyzing spatial data (Jamali et al., 2014). These methods can support the definition and development of quantitative methods aimed at modeling, analyzing and evaluating landscape quality. There are also recent literatures about real-life case studies of contemporary soft computing techniques without using GIS in water resources engineering such as “Predicting monthly stream flow using data-driven models coupled with data-preprocessing techniques” (Wu et al., 2009), “Long-term prediction of discharges in Manwan Reservoir using artificial neural network models” (Cheng et al., 2005), “Intelligent manipulation and calibration of parameters for hydrological models”, “Neural network and genetic programming for modeling coastal algal blooms” (Muttil & Chau, 2006), “An ontology-based knowledge management system for flow and water quality modeling” (Chau, 2007).

The decisions in water quality management are often made on the basis of uncertain information existing in many system components and their interactions. The random character of natural processes governing water resources, the estimation errors in parameters of water quality models, and the vagueness of planning objectives and constraints are all possible sources of uncertainty (Beck; Huang and Xia; Rehana and Mujumdar;
Susceptibility Analysis is a means to evaluate the potentiality for a public water system to draw contaminated water at concentrations posing a health risk to consumers. In order to conduct a Watershed Protection Survey or Vulnerability Analysis, it is helpful to prepare a WRASTIC map of the area in question (Williams, 2000). The aim of this study is the risk contamination assessment of surface water resources done by underlying WRASTIC method and utilizing fuzzy logic in GIS environment. In other words, it is possible to create the last basical risk map of the area as spatial by creating risk pollution maps and combinations of these layers. The presented model will provide various scenarios of risk assessment.

**Methodology**

According to studies conducted on population and area activities, as you can see in Figure 1, this research was done in parts of Tehran, Semnan, Mazandaran, Qom and Alborz provinces. The reason for selection of this range is the expansion and centralization of economical, social, industrial, and recreational activities on the margin of Tehran province. Therefore, taking into account all the conditions of Tehran province, it was chosen as the vast majority of studies. Tehran province, metropolis, capital was located in the north of Iran. Tehran catchment has the area of 2250 km\(^2\) and is surrounded by Alborz Mountains in the north and the Arad Mountains in the south (Dehghani et al., 2013).

**WRASTIC Method.** The susceptibility of surface water sources to contamination is evaluated in a similar manner to ground water sources by comparing the characteristics of the source area (sensitivity) to the characteristics of the contaminant (vulnerability). The sensitivity of surface water sources to contamination is determined by evaluating 1) the stream flow rate or area of reservoir; 2) the adequacy of construction and the physical integrity of intake structures; and 3) the WRASTIC Index calculated for the system or intake.
From the above-mentioned index, a WRASTIC model was used and developed in this research. WRASTIC is a model that is an acronym for wastewater discharges (W); recreational land use impacts (R); agricultural land use impacts (A); size of watershed (S); transportation avenues (T); industrial land use impacts (I); and amount of vegetative ground cover (C) (Yarrow et al., 2008; Williams, 2000) that was developed by Drinking Water Bureau of the New Mexico Environment Protection Agency to evaluate watershed susceptibility to surface water contamination in any hydrogeological setting based on major watershed characteristics and land uses. The method assigns a relative weight to each factor to determine the relative sensitivity of a given surface water supply to surface-derived contamination. The higher the WRASTIC Index, the more sensitive the water supply of contamination (Williams, 2000).

Clearly, seven criteria are analyzed in this method. In other words, first this method is conducted to score the criteria on the case study by using the multicriteria evaluation and then the amount of water resource pollution risk is calculated by summing these criteria based on related criteria. The method used in this research is developed by WRASTIC method according to Figure 2.

**Multi-Criteria Evaluations (MCE).** In multicriteria evaluation methods, it is frequently the case that several criteria will need to be evaluated to meet a specific objective (Voogd, 1983; Carver, 1991; Eastman, 2012). In this method, the possibility of analysis and the presence of all the existing information related to the options are based on various and multidimensional criteria. Multicriteria evaluation (MCE) is most commonly achieved by one of the following procedures: Boolean Overlay and Weighted Linear Combination. The first involves Boolean overlay whereby all criteria are reduced to logical statements of suitability and then are combined by means of one or more logical operators such as intersection (AND) and union (OR). The second is known as Weighted Linear Combination (WLC) wherein
continuous criteria (factors) are standardized to a common numeric range, and then they are combined by means of a weighted average. The result is a continuous mapping of suitability that may then be masked by one or more Boolean constraints to accommodate qualitative criteria and final threshold so as to yield a final decision (Eastman, 2012).

First the effective criteria layers are prepared in this method (MCE). Since various data of covered areas in the research are analyzed together, all data should be consistent and correspond together in terms of geometry and also comply with a unique Geographic Coordinate System. Both cell sizes of all entry and maps, also, must be equal. Furthermore, the given criteria are measured on different scales and parameters are exposed to standardization (normalization) in the next step. This means that the transformation process was performed on factors. Ultimately, these factors were combined with a weighted linear combination method after fuzzification.

Weighted Linear Combination Method (WLC). The weighted linear combination (WLC) technique is a decision rule for deriving composite maps in GIS environment. The method that has been used in this research is one of the most common decision models. This model is often used to analyze suitability/land use, site selection, issues related to the resource assessment. The primary reason for its popularity is that the method is very easy to implement within the GIS environment using map algebra operations and cartographic modeling (Tomlin, 1994; Berry, 1999; Malczewski, 2000).

\[ V(X_i) = \sum_j w_j v_j(x_i) = \sum_j w_j n_j \]

Where \( w_i \) is a normalized weight, such that \( \sum w_i = 1 \), \( v_j(x_i) \) is the value function for the j-th attribute, \( x_i = (x_{i1}, x_{i2}, \ldots, x_{in}) \), and \( n_j \) is the attribute transformed into the comparable scale. The weights represent the relative importance of the attributes. The most preferred alternative is selected by identifying the maximum value of \( V(x_i) \) for \( i = 1, 2, \ldots, m \). Given the decision
rule ($\mathcal{V}(x) = \sum w_j \eta_j$), the GIS/WLC method involves the following steps: (i) defining the set of attribute (objectives and associated attribute map layers); (ii) identifying the set of feasible alternatives; (iii) deriving commensurate attribute maps; (iv) defining the criterion weights (that is, a weight of “relative importance” is directly assigned to each attribute); (v) combining the commensurate attribute maps and weights using the multiplication and addition overlay operations to obtain the overall score for each cell (alternative); and (vi) ranking the alternatives according to the overall performance score (the cell with the highest score is the “best” cell). WLC can be operationalized using any GIS system having overlay capabilities. The overlay techniques allow the attribute map layers (input maps) to be aggregated in order to determine the composite map layer (output map) (Malczewski, 1998).

Two types of ranked or fuzzy criterion layers can be used in this method. As utilization of ranked layers, there will be weakness points why it is not possible to provide cell-based analyses and we can just obtain a polygon map with some classes of risk. In other words, selected areas in the output map cannot be sorted based on the degree of favorability. This method has limited decision-making power and provides fewer options to risk management. For this purpose, a method or model must be used to generate various management scenarios.

The aim of this research is to obtain a continuous set of values to show the possible risk of surface water resource contamination on the area. Fuzzy method can do it; therefore, fuzzy logic was used in order to uniform the factors. For this purpose, all the criteria layers were modeled by this logic.

**Fuzzy Modeling Method.** In this method, all factors are combined together in one step; it can use a purposeful pattern of integrating the maps. The idea of fuzzy logic considers spatial objects on the map such as the members of a set. In the fuzzy set theory, membership can take any value between 0 and 1 that reflects certain degrees of membership and there is no practical limit on the choice of fuzzy membership values (Hansen, 2005; Lee, 2007; Kabir, 2008).
et al., 2014; Ghosh et al., 2012). The Fuzzy Logic method creates more flexible compositions of weighted maps and can be easily implemented with GIS modeling language (Lee, 2007). Values are selected based on subjective judgment to show the membership degree of a set (Figure 1). Fuzzy membership functions can be classified from two aspects: Type and Shape. Types include an S-shaped (Sigmoidal), J-shaped (J-shaped), Linear and shapes include monotonically increasing, monotonically decreasing, and symmetric. Thus taking into account the User Defined, numbers of the membership functions can be detected. Shapes of membership functions are detected based on points named Inflection Points (Eastman, 2012). In this research, two types of functions were used: Increasing Linear and User Defined.

The Standardization method of linear functions is through using the minimum and maximum values as scaling points (Figures 3 and 4). Linear Scaling method can be shown as follows (Eastman, 2012):

\[
X_i = \frac{(R_i - R_{\text{min}})}{(R_{\text{max}} - R_{\text{min}})} \times \text{standardized range}
\]

Where is:

- \(X_i\): cell value after standardization;
- \(R_i\): cell value before standardization;
- \(R_{\text{min}}\): minimum value of factor;
- \(R_{\text{max}}\): maximum value of factor; Standardized_range: the range of standardization variations.

Generally, the ranges of standardization variations are as two types · to 1 (actual numerical scale) and · to 255 (byte scale). The higher score indicates a higher suitability of the cell for making decision. Furthermore, the zones with a zero score were considered as a constraint.

In the User Defined method, control points are defined by user which are generate very different shapes of this type of function. The fuzzy logic model can be used in generating factor maps, integrating them together and the values of their classes’
standardization. Five fuzzy operators named OR, AND, SUM, PRODUCT and GAMMA are used to combine a set of GIS data which are shown in table 1 (Lewis et al., 2014).

**The Indices of Fuzzy-WRASTIC.** As previously mentioned, one way to determine the sensitivity of surface water sources to contamination is using the WRASTIC Index. In this regard, fuzzy operation is done on them by respecting order and rating rate according to WRASTIC rating table by fuzzificating the parameters presented for WRASTIC model. These indices, which are the data that we used, are as follows:

- **Human and animal sewage:** wastewater is basically consumable water of communities that has been polluted as a result of various applications. Wastewater can be known as a combination of liquids and wastes that is carried by water from residential, administrative areas and commercial and industrial parts, and in some cases, it is mixed with ground water, surface water and floods. In order to obtain a final map of this criterion, first all of the existing uses on the area are identified including residential, service, educational, commercial and sanitary uses except the industrial activities (this use will be considered under the industrial activity criterion) and is considered as the human sewage producer factor. On the other hand, all of the animal production and breeding units were calculated for existing animal waste on the area.

- **Recreational and leisure activities:** In order to supply a fuzzy model of recreational activities affecting the sensitivity of water resources, first we must explain leisure-recreational activities and then provide a submodel for them. To do so, the presented locations in the Index Table are provided as leisure-recreational activity locations and a distance function was created on them. Leisure-recreational activities locations were classified as following:

  1. There are generally concentrated recreational activities: ancient sites, parks, museums, sport areas, stadiums and historical tombs and holy shrines.
More concentrated and less extensive recreational activities: camps and fishponds.

More extensive and less concentrated recreational activities: forests and gardens.

There are extensive recreational activities: lakes, rivers, wetlands, springs, caves and waterfalls.

- Agricultural activities: first for this criterion, all the existing agricultural activities were identified on the area and then were placed in five main classes based on the presented classification in the WRASTIC model and investigations were developed according to the conditions of the study area. Therefore this classification includes five classes: irrigated cultivation, gardens, dry land farming, tree planting and meadow, grassland and shrubbery.

- Industrial Activities: For this criterion, the all types of industries and factories and industrial complexes of the area were divided into 14 classes which are alimentary, textile, leathery, cellulosic, metallic, non-metallically mineral, chemical, pharmaceutical, electronic, agricultural, machine building, new (nano and biotechnology), oily, gaseous, petrochemical and recycling based on their pollution levels according to the regulations imposed by the Environmental Protection Agency. Then, these industries were placed in six classes based on the intensity of pollution, so sixth class means maximum amount of pollution. In order to do this classification, process criteria and production rate, area of industrial unit, the number of employees, needed raw materials and other parameters and finally guidelines of the EPA were used.

- The basin size: the desired study area was divided into 21 subbasins based on the classification of the watershed basins in the country. Finally, the area amount of the subbasins were placed in 5 standard classes after obtaining the area of existing basins for classifying and scoring in the final model.
• Roads and Transportation: For mapping the layer of the roads, different types of hierarchy paths were identified, including main roads, secondary ones, asphalt, etc. along with railway routes. Then, a distance function was applied to them; farther areas were considered more appropriate.

• Vegetation density: For this criterion, vegetation density of the study area is analyzed based on existing resources. Then, according to existing surveys and classification of WRASTIC model, three main classes were developed for this criterion according to the rate of density.

**Validation of Fuzzy-WRASTIC Model for Surface Water Risk Assessment.** The applied methodology of this paper aimed for a surface water risk assessment by using a Fuzzy-WRASTIC model. The validation of this model was done by using collected samples (Torabian et al., 2011) from Jajrood river. Two parameters (NO₃, Fecal Coliform (FC) and Total Coliform (TC)) were used to describe the level of pollution and the results of analyzing these parameters were compared with the results of the model.

**Nitrate.** A major inorganic nutrient that drives primary production in aquatic habitats is Nitrate (NO₃⁻); therefore nitrate analysis helps explain ecosystem dynamics. High nitrate concentrations increase productivity because algae require nitrate for growth. However, high concentrations may also lead to animal or fish kills, thus reducing system productivity. Nitrates and nitrites are jointly considered due to their conversion from one form to the other in the environment. High nitrate and nitrite levels are associated with sewage contamination (Ntengwe, 2006).

**Fecal and Total Coliform.** The bacteriological analysis includes the testing of fecal and total coliform populations in the water samples. Previously sterilized borosilicate glass bottles of about 500 ml capacities were used. The cap was removed just before sampling. The collected samples were immediately brought to the laboratory and analyzed within four
hours. All the precautionary measures were taken during transportation and storage of the sample to avoid contamination by other microbes and environmental factors (Sivaraja & Nagarajan, 2014).

Results and Discussion

Risk maps of this area were obtained based on multicriteria evaluation using the Fuzzy-WRASTIC model on the study area. The following results were obtained:

Results of the Study Area. Figure 7 indicates the effects of any specific criterion on the study area that standardized layers show continuous suitability degrees for any entry criterion. Lower obtained values in any criterion of Fuzzy-WRASTIC model indicate the area with less contamination risk. According to Figure 7a in basins 13, 19, 15 and 5, more density of residential areas leads to a concentration of human and animal sewage, finally raising the water resource contamination water risk of this area and lowering risk of basin 18 towards the other areas. Figure 7b represents the presence of leisure and recreational activities on the study area. The concentration of these activities in basins 5, 7, 9, 10, north of 19 and 13 is higher than in other areas. Consequently, the contamination risk of surface water resources increases. It considers the presence of leisure and recreational activities in south basins such as 18, 20, 14 and south parts of basins 19 and 16 where surface water resources are less affected. According to Figure 7c, agricultural activities are a greater threat to southern parts of basins 8, 16, and north parts of basins 13 and 19. Several existing industrial centers in close to the surface water resources are a serious threat to the adjacent ecosystems. According to Figure 7d, the contamination risk of surface water resources is high due to the effect of industrial activities in the entire study area. The margin of the study area is less vulnerable. In this area, it is observed that the higher the concentration of industrial units, the higher the pollution rate. Generally speaking, the highest concentration of industrial units was in 8, 16, 13, 16 and north parts of 14 and this situation is a more serious risk to the environment of the
area. For Figure 7e, the size of basin criterion is effective on the amount of pollution. The area of basins 9, 13 and 14 is higher than the other adjacent basins. For this reason, the possibility of different land use establishment including residential, recreational and industrial has been provided, consequently the possibility of contamination of surface water resources increases in this way. According to Figure 7f, contamination risk is high in terms of road and transportation criterion in basins 9, 10, 19, 13 and 15. As it is observed in Figure 7e, distribution of vegetation in the area is not uniform, so that the vegetation density of study area basins 5 and 8 has its minimum value and it will lead to a higher amount of risk for contamination of surface water resources according to the model applied in this study.

_Suitability._ Using the fuzzy operators, criterion layers are combined together which indicates membership of any layer (Figure 8). The “AND” operator selects the minimum value of the standardized suitability criteria, which gives emphasis to the most suitable criterion. The “PRODUCT” operator combines input criteria by cross multiplying the values of the standardized suitability criteria. This operator is more limiting than the “AND” operator since the product of multiple standardized criteria (with values less than one) is lower than the value of any standardized criterion. In this way, the “PRODUCT” overlay results in an output where the combination of multiple variables has a lower suitability value than that of the inputs by themselves, whereas the “AND” operator is affected by the values of the other criteria. The result of the “OR” operator outputs the maximum value of the standardized suitability criteria. Hence, the “OR” operator is notable since it only considers the highest membership of a single criterion while it ignores any criteria with low membership value. The “SUM” operator is an increasing linear combination function, where the combination of multiple input criteria is larger than any of the inputs by themselves. The output of “SUM” operator, unlike the output of “OR” operator is affected by the combination of criteria; however, only one criteria must have a high value for the overlaying
to display a high value. Both the ‘‘OR’’ and ‘‘SUM’’ operators give substantial weight to criteria with high suitability. In these scenarios, a single criterion with high membership presents the results despite the occurrence of other criteria with low memberships in the same area. The ‘‘GAMMA’’ operator, which combines both the fuzzy ‘‘PRODUCT’’ and the fuzzy ‘‘SUM’’, offers a way to balance multiple input criteria to represent the best suitability. This approach leads to enhancement of their weight to other entry layers by giving positive values to limiting factors. In this way, the ‘‘GAMMA’’ operator identifies the gradient of suitability rather than a surface with discrete and unreal cutoffs.

**Fuzzy Overlay Sensitivity.** As mentioned above, the ‘‘GAMMA’’ operator is a combination of two operators: the fuzzy-algebraic ‘‘PRODUCT’’ and fuzzy-algebraic ‘‘SUM’’. At low values of gamma, the ‘‘GAMMA’’ operator is closer to the fuzzy-algebraic ‘‘PRODUCT’’, leading to an output surface with values lower than any input. This is an ‘all or nothing’ scenario where all suitability criteria must have high values for a pixel to be suitable and if any of the criterion has low suitability, the entire pixel is classified as having low suitability. At high values of gamma, in the related formula, the ‘‘GAMMA’’ operator is dominated by the fuzzy-algebraic ‘‘SUM’’ and is cumulative in character; that is, favorable input values lead to an output that is larger than any of the inputs. This is an ‘either or’ scenario, that a pixel only needs one mapped criteria to be suitable for a pixel to be classified suitably. Adjusting the range of ‘‘GAMMA’’ to be either closer to the ‘‘PRODUCT’’ operator or closer to the ‘‘SUM’’ one enables the three suitability criteria to interact in converging or diverging ways. For this analysis, different values for ‘‘GAMMA’’ were tested on the standardized suitability criteria in order to generate a risk assessment map. At gamma values below 0.25, the generating raster map can have values lower than any one of the input criteria and it has taken the values larger than any of the input criteria for values more than 0.75.
Figure 9 indicates that fuzzy overlay with OR operator has the most suitable display among the operators due to better distribution of values.

For this purpose, the result map of this operator for contamination risk classification was used in the area. As a result, the overall risk of contamination in the area is categorized in four classes of low, medium, high and very high according to Table 2. According to this table, the largest area of the study area with frequency of 51.43% belongs to high risk class. As OR values tend to be higher, the higher frequency values of risk are increased and the standard deviation is decreased. Figure 8 shows the frequency of any risk class histogram (y-axis) in a divided basin (x-axis) and Figure 10 shows an average risk histogram (y-axis) in a divided basin (x-axis).

As it is clear in Figure 10, the greatest amount of risk is observable in basins 13 and 17 due to the higher density of waterways and their proximity with high-density residential and industrial areas. These areas place around the Capital, meaning Tehran; lack of suitable national, zonal and local planning in the past have been provided in high and inharmonious density of industrial and residential units in an irregular matrix. Also, this histogram represents a broad range of risk values in each basin well which means the presence and distribution of all types of seven indicators generate surface water contamination risk. All of the factors mentioned should be considered and an integrated management plan is needed in order to control risks in the area. This histogram can be used as a basis for managerial priorities in order to verify and decrease identified risks. Figure 8 shows the frequency of 4 risk classes: very high, high, medium and low. In almost all zones, there are classes with very high risk, which is consistent with the previous histogram. This correspondence is correct about other risk classes, which means high basic risk in the study area. Smaller columns in the histogram represent areas further from the capital.
Validation the FUZZY-WRASTIC Model. Validation was done to ensure that the model worked correctly and ensures that mistakes have not been made in running the model. For this purpose, data collected from some random points (Torabian et al., 2011) in the river and two parameters (NO₃, Fecal Coliform (FC) and Total Coliform (TC)) were chosen to validate the model. The results of the experiment on the samples indicate that these data correspond with the results of the model. Table 3 describes the collected data with their attributes.

Nitrate. Nitrate was selected as the first parameter to prove the accuracy of the Fuzzy-WRASTIC model and eight points were chosen for the analysis and sampling. As can be seen in Table 3, the level of nitrate in surface water increases with risk. Therefore there is a positively direct relationship between them.

Fecal and Total Coliform. This is the second parameter for sampling, analyzing and validating the model. The results showed that fecal and total coliforms populations in the water samples increase in high-risk areas.

Conclusions

Ecological conditions of surface water resources show a drastic reduction of available water resources and their increasing pollution. This matter indicates the importance of attention to risk assessment of surface water resource contamination. Therefore, regarding the conditions described above, a standard, quantitative, spatial, accurate model is needed in order to assess the status of water resource contamination. For this purpose, in this research a new method was created for risk modeling of the study area. The selection of a study range with a high density of different land uses has been applied in order to achieve more tangible and applicable results according to the new method. The area has very high social and environmental sensitivities due to its location near the capital, Tehran. In this research, a multicriteria evaluation method has been used based on the utilization of WRASTIC model
and fuzzy logic in the GIS environment. Unlike mathematical models, GIS has the ability of storing, analyzing and displaying spatially integrated reference data with spatial data. For this purpose, to obtain an overview of the probable risk level in the area, the GIS environment is the best space for providing and showing a composite model for analysis. In this method, a WRASTIC model was chosen by carrying out investigations to determine parameters affecting pollution of surface water sources. By various investigations, this model has considered seven main and effective criteria in the procedure of water resource contamination and the impact of each criterion was determined by weighting the criteria. For this reason, the model is appropriate to assess the possibility of surface water resource contamination risk.

Fuzzy modeling has a key role in the developed model of this research. Hence, achieving a continuous, standard and comparable set of values was provided by standardization of the various factor layers. The layers are basic for the modeling of surface water resource contamination risk possibility. In the next step, raster maps which represent the status of contamination risk were generated by applying different operators of OR, AND, SUM, PRODUCT and GAMMA. Utilizing the above mentioned operators in generating risk maps leads to the production of different scenarios for risk assessment. It could be said that no particular method or model has been developed to assess the risk of surface water contamination so far. The existing methods often survey or assess water contamination and follow the modeling of the whole or part of waterways by modeling the physical and chemical parameters of water. In existing methods, usually two-dimensional or three-dimensional modeling of quantitative and qualitative status of rivers is done by water sampling and testing the various factors of water entering the waterway and utilizing quantitative and mathematical models. These models do not consider activities adjacent to the waterway. The results of this models do not indicate water contamination risk in the study area.
The advantage of the method presented (compared with the other methods of surface water contamination) is to consider almost all of the factors affecting the water resource contamination of an area in order to do a risk assessment (and not a contamination evaluation). Moreover if the cell-based analysis is included, the possibility of making decisions is created for each point within an area.

In this regard, by mapping subcriteria and combining the layers with the WLC method, seven main criteria were generated (human and animal wastewater, agricultural, recreational, industrial activities, size of basin, roads and transportation and vegetation density). All input layers for each criterion were standardized by using linear and USER DEFINED functions and then seven information layers were provided by the WLC method.

The fuzzy maps with different methods of OR, AND, SUM, PRODUCT and GAMMA were combined. The SUM operator produced the results that were almost reverse of the other operators. The smallest value of fuzzy membership has been applied in the AND operator and resulted in the classification of the area into two parts: proper and improper. This operator is not recommended.

Since the amount of output in the PRODUCT operator is always less than or equal to the smallest amount of input of fuzzy membership, e.g. only in areas where they are obtained by other methods with high risk, calculated risk values were very high and most other areas displayed no risk. The operator is also inappropriate.

The amount of output in the SUM operator is always greater than or equal to the smallest amount of input fuzzy membership. The generated map by this operator is almost the reverse of the other operators. Field surveys show that the result is incorrect.

Low coefficient of gamma produced a result close to that of the PRODUCT operator. Most areas were calculated without risk and the areas with high risk also had very high or low risk compared with PRODUCT. Unexpectedly, a high coefficient of gamma, which must
be similar to SUM, generated a map similar to AND. Many areas were found to be risk-free and the others very high risk. The areas with middle or intermediate-risk were not obtained. Also, this operator is not recommended.

In the OR operator, output is controlled by the maximum value of input maps. The generated map has a balanced range of values across the entire area: low to very high. This operator is recommended for generating risk assessment maps.

The model was developed so that it could produce different spatial, numerical and graphical results. In addition to producing various types of histograms, different classes of area risk status maps can be produced.

In this research, the status of vulnerability or surface water contamination risk in this area is divided into four ranges: low, medium, high and very high. There are more zones of the area at high and very high risk classes because of an inappropriate land use matrix of the area. The main reason for increasing contamination risk of compressed waterways in the study areas is the unbalanced placement of industrial and residential uses together with a high and unplanned densities. This area is located around the capital.

The following conclusions and suggestions for further research have been obtained from the present study:

The method presented in this research is appropriate for contamination risk assessment of surface water resources and can be used as a standard defined method for all available watersheds in the world for management and qualitative protection of surface water resources.

Since the removal of the contamination of surface water resources is expensive, zoning can become a valuable tool for the administrators and officials to help them make necessary decisions to manage the mentioned basins. Areas with higher pollution potentiality for constructing industrial or agricultural centers which carry a high contamination risk will
not be appropriate in the study area and we must prevent site selection of new and polluting uses in this area.

In this research, the weights used for each of the model criteria are based on a WRASTIC index. It is recommended that weights of further criteria should be calculated by different decision making methods such as AHP, ANP, TOPSIS and fuzzy methods of these techniques.

This method should be developed by algorithms such as neural networks, genetic, ant colony, PSO (Particle Swarm Optimization), and other methods.

References


University of Vienna, Austria.


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**Table 4.** Status of Risk Contamination Classification

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Table 1. Types of Fuzzy Operators

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<thead>
<tr>
<th>Operator</th>
<th>Formula</th>
<th>Explanations</th>
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<td>AND</td>
<td>$\mu_{\text{combination}} = \text{MIN}(\mu_A, \mu_B, \ldots)$</td>
<td>Control of output map by the smallest amount of fuzzy membership</td>
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<tr>
<td>OR</td>
<td>$\mu_{\text{combination}} = \text{MAX}(\mu_A, \mu_B, \ldots)$</td>
<td>Control of output map by the largest amount of fuzzy membership</td>
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<td>PRODUCT</td>
<td>$\mu_{\text{combination}} = - \prod_{i=1}^{n} \mu_i$</td>
<td>(\gamma). Output value of any position is less than or equal to the smallest value of fuzzy membership at corresponding positions of entry maps. (\gamma). The impact of decreasing (\gamma) value between zero and one.</td>
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<td>SUM</td>
<td>$\mu_{\text{combination}} = 1 - (\prod_{i=1}^{n} (1 - \mu_i))$</td>
<td>(\gamma). Fuzzy membership value of output map at any position is always greater than or equal to the largest value of fuzzy membership value at corresponding positions of entry maps. (\gamma). The impact of increasing (\gamma) value between zero and one.</td>
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<td>GUMMA</td>
<td>$\mu_{\text{combination}} = (\text{FuzzySum})^\gamma \times (\text{FuzzyProduct})^\gamma$</td>
<td>(\gamma). The importance of Fuzzy Algebraic Sum method is greater, the selection of (\gamma) value next to one (\gamma). The importance of Fuzzy Algebraic Product</td>
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method is greater, the selection of $\gamma$ value next to zero
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Table 5. Status of Risk Contamination Classification in the Study Area

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**Figure 3.** Equation and diagram of increasing linear fuzzy membership function (Liu et al., 2014)

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**Figure 6.** Flowchart of research method

**Figure 7.** Surface water contamination risk assessment fuzzy-WRASTIC model criteria

- a) Human and animal wastewater
- b) Recreational and leisure activities
- c) Agricultural activities
- d) Industrial activities
- e) Size of basin
- f) Roads and transportation
- g) Vegetation density

**Figure 8.** Histogram representing frequency risk in basins

**Figure 9.** Submodel of recreational activity

**Figure 10.** Histogram representing average risk in basins

**Figure 11.** The risk of surface water contamination by fuzzy operators

- a) AND
- b) OR
- c) SUM
- d) PRODUCT
- e) GAMMA 0.25
- f) GAMMA 0.75

**Figure 12.** Classification of contamination surface waters risk in the study area
Fig 1. The location of study area

Fig 2. Fuzzy membership function diagram (Dombi, 1990)

Fig 3. Equation and diagram of increasing linear fuzzy membership function (Liu et al., 2014)
Fig 1. Equation and diagram of decreasing linear fuzzy membership function (Liu et al., 2014)

Fig 2. The relationship of fuzzy gamma operator to the other fuzzy functions

Fig 3. The flowchart of research method
Fig 7. Surface water contamination risk assessment fuzzy-WRASTIC model’s criteria

a) Human and animal wastewater  b) Recreational and leisure activities  c) Agricultural activities  
d) Industrial activities  e) the size of basin  f) Roads and transportation  g) Vegetation density

Fig 8. Histogram of representing frequency risk in basins
**Fig 9.** Sub-model of recreational activity

**Fig 10.** Histogram of representing average risk in basins

**Fig 11.** The risk of surface water contamination by fuzzy operators

a) AND  b) OR  c) SUM  d) PRODUCT  e) GAMMA 0.75  f) GAMMA 0.25

**Fig 12.** Classification of contamination surface waters risk in the study area