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Evaluating the suitability of different parameters for qualitative analysis of groundwater based on analytical hierarchy process

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ABSTRACT

Many parameters and indicators exist for the qualitative assessment of groundwater, but their importance differs according to the plain and aquifer; therefore, evaluating the appropriate parameters for quality analysis of different areas is essential. As the main objective, the most important parameters for assessment of the quality of groundwater was selected and ranked in present study using the analytical hierarchy process. The study was carried out in the Tajan plain in northern Iran. To achieve the objectives of the research, initial information was collected, a research hierarchy was formed, and a group of experts was set up. Questionnaires were distributed to the experts and the results were recorded using Expert Choice software. The decisions from the experts were combined and the final weight of each parameter was calculated to allow selection of the most important parameters. Six graphs were plotted; five ranked the criteria, anions, cations, physical factors, and microbial factors and one ranked all parameters. At the end, the quality parameters were categorized based on their final weight from most important to least important and the six parameters of highest priority (sulfate, iron, nitrate, EC, calcium, TDS) were chosen as indicators of groundwater quality in Tajan plain. It is noteworthy that the weight of each indicator parameter was higher than the average weight of all parameters.

Keywords: Quality parameters; AHP; Ranking; Groundwater; Tajan plain

1. Introduction

The increase in population in many developing countries has increased demand for water. This increase threatens the quantity and quality of both surface water and groundwater resources. Groundwater pollution has become a serious threat and is caused by intensive human activities such as solid-waste arising out of municipal and industrial sites [1] and also the changing environments in many countries, especially in communities where groundwater is used for drinking. All Caspian countries, including northern Iran, primarily use groundwater for the

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drinking supply in coastal zones [2]. The rapid depletion of groundwater supplies as a consequence of population growth and industrialization threatens the quality of many aquifers in Iran [3]. In this study, the most important parameters for evaluation of the quality of drinking groundwater were selected and ranked using analytical hierarchy process. The study was carried out in Tajan plain in northern Iran.

Groundwater quality assessment is the basis of groundwater pollution control and remediation [4]. Understanding the chemical composition of groundwater is necessary to evaluate its quality for different objectives. The definition of water quality strongly depends on the desired use of the water; different uses require different criteria of water quality [5].

Research usually focuses on some quality factors as indicators; if these factors are not properly selected, they may not be appropriate indicators, especially for sampling and laboratory analysis. This means that valuable time and financial resources are wasted on results that may not be reliable. Statistics show that there are more than 60 methods for water quality assessment; every method has its advantages and disadvantages and it is difficult to decide which method is the best. The most commonly used method is the water quality index [6,7].

Because different natural and man-made factors affect the quality of groundwater in different geographical regions, using one set of parameters to assess water resource quality in all areas is inadvisable. It is better to select parameters for a specific area using a method that can weight and rank parameters; such a method can help researchers to prioritize the most appropriate quality parameters, analysis of these parameters will be an accurate indicator of water quality in a particular region.

In this study, the multi-criteria decision-making (MCDM) approach has been used to weigh and prioritize, and select the most appropriate water quality parameters to assess the quality of drinking wells in the Tajan plain. Given the complexity of the decision process, the focus of MCDM approaches is to enhance the ability to make sound decisions for water resources management, in particular for river basin planning [8], hydropower operation [9], groundwater planning [10], and irrigation [11]. MCDM finds the best options among the feasible alternatives in the presence of multiple, usually conflicting, decision criteria.

The analytical hierarchy process (AHP) was founded by Professor T.L. Saaty in the early 1970s [12]. This method plays an important role in selecting alternatives. AHP is a widely used method for the practical solution to MCDM problems [13]. This method has been widely studied and many essays have been published focusing on that [14] and is known as a powerful and effective MCDM method for ranking and prioritizing because of its scientific method of determining weights [15]. This technique uses expertise and informed knowledge without the need for specific data [16].

2. Materials and methods

AHP was used to weight, rank, and select the most appropriate parameters to define the quality of groundwater in the Tajan plain. This method is based on expert judgments and pairwise comparisons of parameters. The following steps were performed to achieve the objectives.

2.1. Collection of initial information about the study area

Initial studies were performed to collect preliminary information about the study area. Tajan plain is geographically located in the Tajan basin in the northern Alborz range [17]. Tajan river basin is a predominantly calcareous basin that drains into the Caspian Sea [18]. The Tajan River is a major river in the Caspian Sea water basin [19], which is located in the province of Mazandaran, Iran. Tajan plain lies between 3979233–4076712 N latitude and 673657–705004 E longitude. The basin has an area of 4,372.33 km^2 and includes the Tajan plain at 631.1 km^2 located in the highlands of the Tajan basin. Fig. 1 shows that the Tajan plain is situated in the most northern region of the basin.

2.2. Forming the hierarchy of the research

The AHP begins with decomposition or structuring of the problem into a hierarchy [20]. The steps of the AHP began with formulating the main goal, identifying relevant factors, hierarchy formation, and assessment [21]. In this technique, the problem is studied hierarchically at different levels by performing pairwise comparisons to derive the relative importance of the variables at each level of the hierarchy [22].

The research hierarchy in the present study comprised three main levels: main goal, criteria, and sub-criteria. The sub-criteria level is based on the basic quality parameters of the research, the criteria level is based on the four groups in which the parameters were classified. Fig. 2 shows the research hierarchy.

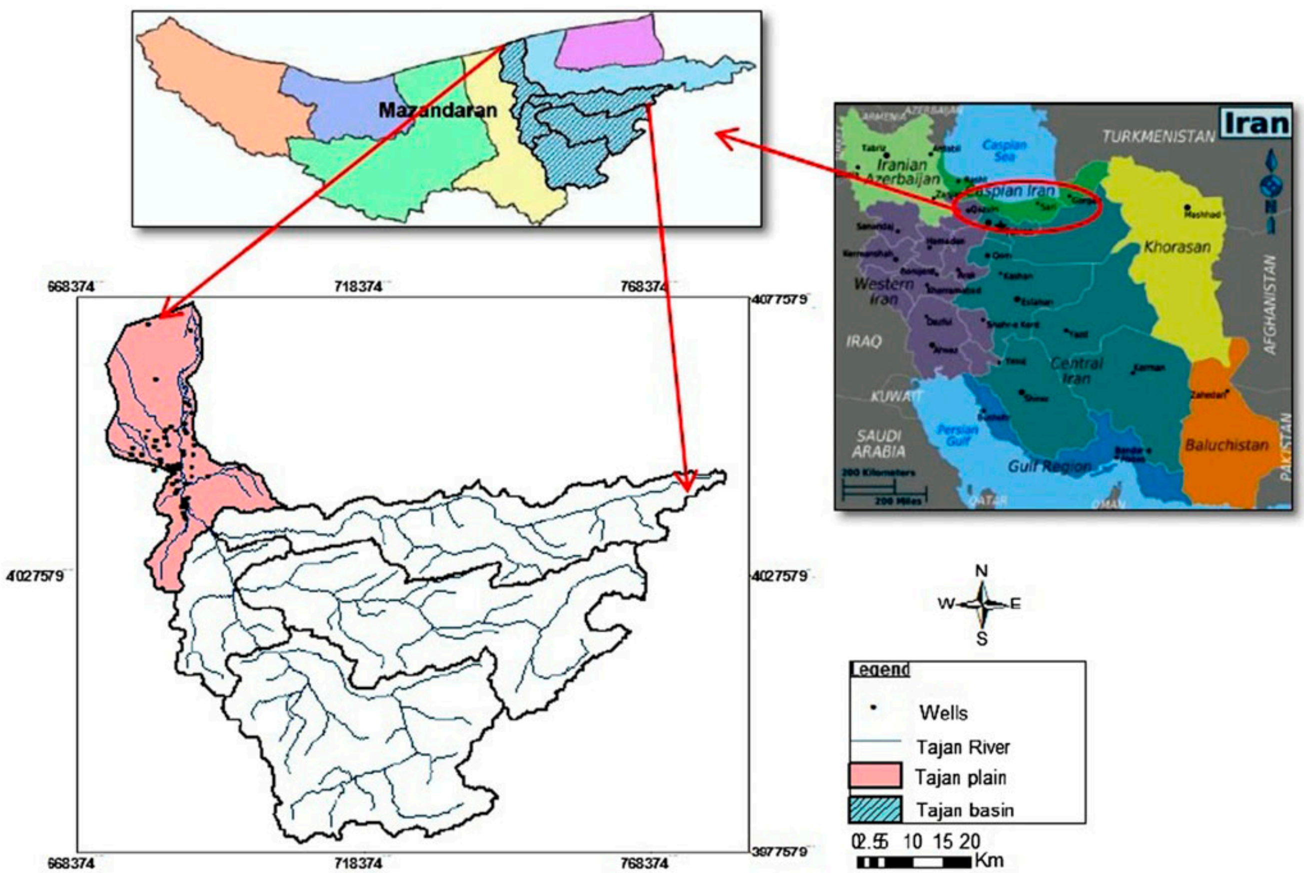


Fig. 1. Geographic location of Tajan plain (Source: LAR consulting engineers [26]).

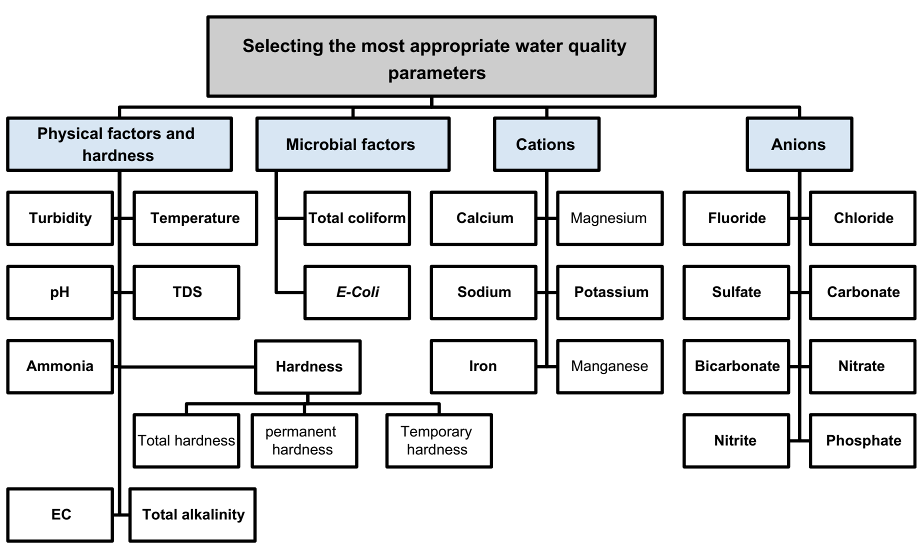


Fig. 2. The hierarchy of the research.

2.3. Formation of expert group

The basis of the AHP is expert opinion; thus, a group of experts were selected to rate the quality parameters. Each expert in the present study showed expertise in groundwater quality science and was familiar with the characteristics of the study area. Twenty experts were chosen to form the group.

2.4. Specialized questionnaires for expert group

A questionnaire was designed in the form of paired comparison tables and all experts were asked to compare the parameters. The experts compared alternatives using a criterion and assigned a numerical value to their relative weights; a scale of numbers from 1 (Indicates the equal preference of two criteria) to 9 (Indicates the full preference of one criterion over the other) was used [23].

2.5. Analyzing the results of questionnaire using Expert Choice Software

Expert Choice 11 software was used to facilitate the calculation and increase the accuracy of the results. After collecting the questionnaires, the results of the paired comparisons from each expert were entered into the program. The input was in the form of paired comparison tables. Expert Choice allows pairwise comparison and extracts priorities more accurately than other methods; this program reflects the opinions of the experts and provides more accurate results [24].

2.6. Correcting inconsistency in opinions and calculating the weights and priorities of parameters

One advantage of the AHP is that it allows checking of the consistency of the expert opinions to determine the importance factor of the criteria. The inconsistency ratio should be less than 0.1 (negligible and acceptable) in AHP. The closer the inconsistency ratio to zero shows the greater consistency [25]. After completing the scoring tables, all factors were entered into the program and inconsistencies in opinions were removed. The tables of paired comparisons were then analyzed to calculate the weight of each parameter and the results from each expert were ranked.

2.7. Combining opinions and calculating final weight of each parameter

At this stage, the results of the expert's ratings were combined, the final weight of each parameter was calculated, and final prioritizing was completed. The rankings were plotted for all criteria and sub-criteria.

2.8. Selecting the most appropriate and important parameters

After the ranking and determining the final weight of each parameter, the most appropriate and important water quality parameters were selected according to the priorities. The parameter with the highest weight is the most important indicator of the groundwater pollution in Tajan plain and that with the lowest weight is the least important parameter.

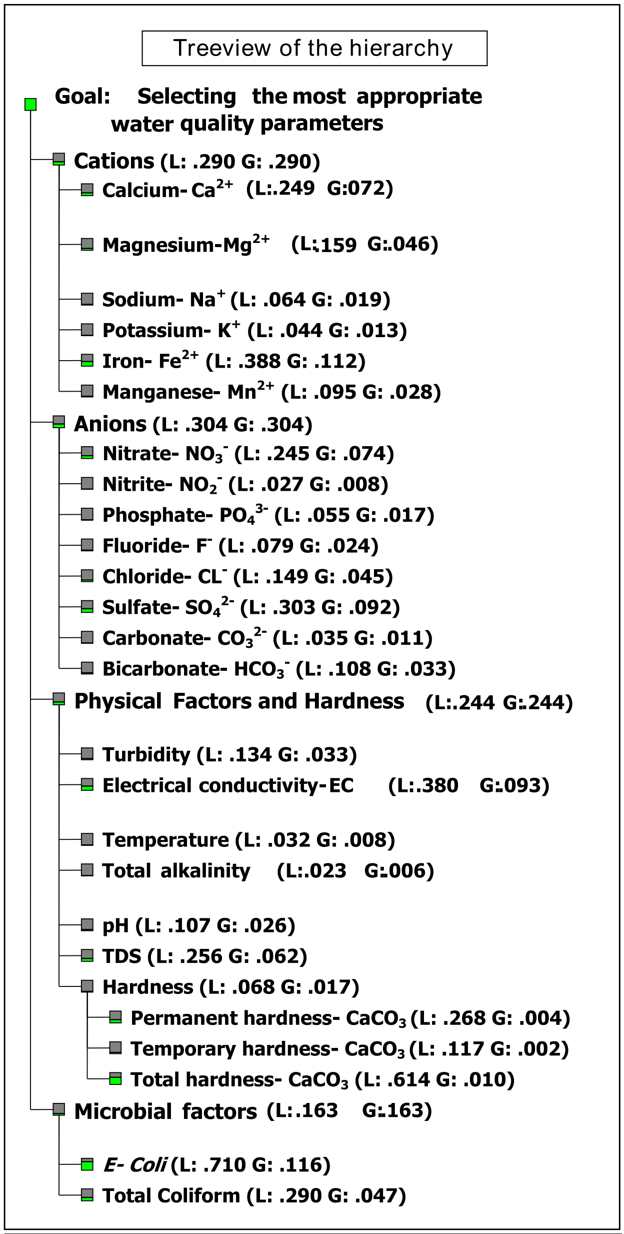
3. Results and discussion

After recording the research hierarchy into the software and completing the paired comparisons tables for all criteria and sub-criteria, the following results were obtained. Fig. 3 shows the research hierarchy after weighting. After all the syntheses were carried out and all the scores applied, two factors for determining the weights appeared in the hierarchy (Fig. 3).

The first factor is the local priority of parameters as denoted by the letter *L* in front of each parameter. *L* represents the weight of each parameter in comparison with the others at the same level. The sum of the local priorities at each level equals one, as can be seen for the sum of *L* scores for cations, anions, microbial parameters, physical parameters, and hardness. The second factor is the global priority as denoted by the letter *G* in front of each parameter. *G* represents the weight of each parameter in comparison with all other parameters in the study. It is observed in the hierarchy that the sum of the global priorities of all the criteria equals one; this is also true for all sub-criteria (quality parameters).

The rankings of the parameters can be understood upon careful consideration of the hierarchical structure. However, all weightings and rankings are shown more detailed in Figs. 4–9. The sign of "combined" at the top right of each graph shows that the weights and the graphs are the results of collective group opinion. The symbol at the lower left of the graph is the degree of inconsistency, which is less than 0.1 for all graphs, which is negligible and acceptable for the AHP method.

Fig. 4 is the graph of the four quality ranking groups (criteria) of the present study: anions, cations, physical parameters, and hardness, and microbial factors. Combining the ratings of expert opinion shows

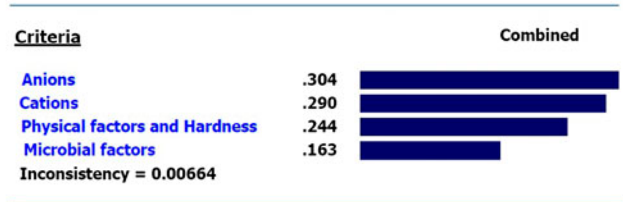


L represents the weight of each parameter in comparison with the others at the same level.

G represents the weight of each parameter in comparison with all other parameters.

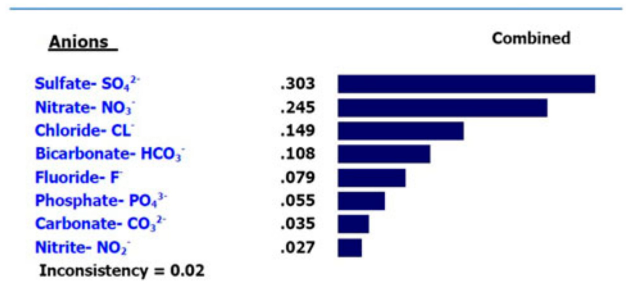
Fig. 3. Research hierarchy after weighting by Expert Choice Program.

that anions produced a score that was slightly superior to the other factors, which makes them the most important parameters for the quality of groundwater in Tajan plain. The weight of the anions was 0.304 and for the cations was 0.290. The physical parameters and hardness (0.244), and microbial factors (0.163) hold, respectively, lower positions of importance (Fig. 4).



- The value before each chart shows the weight of relative factor (criteria) in comparison with the others
- The sign of “combined” is the indication of collective group opinion
- Inconsistency: less than 0.1 is negligible and acceptable in the AHP method

Fig. 4. Ranking graph of the criteria.



- The value before each chart shows the weight of relative parameter (sub-criteria) in comparison with the others

Fig. 5. Ranking graph of anions.

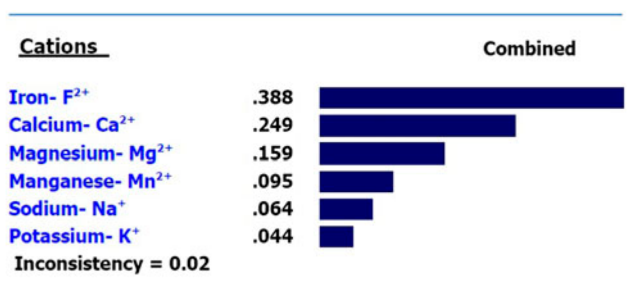


Fig. 6. Ranking graph of cations.

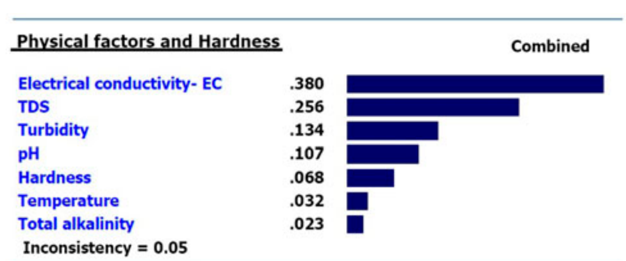


Fig. 7. Ranking graph of physical factors.

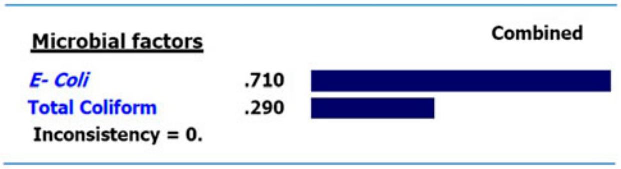


Fig. 8. Ranking graph of microbial factors.

The ranking of the anions is shown in Fig. 5. Sulfate, with a weight of 0.303, is the most important anion for groundwater contamination in the study area and should have first priority for study in qualitative research. This means, that according to expert opinion, sulfate, with a higher frequency and in the largest number of wells, has exceeded standard limits, which makes it the most important anion. The weights of nitrate (0.245) and chloride (0.149) are the second and third priorities, respectively. Fluoride (0.079), phosphate (0.055), carbonate (0.035), and nitrite (0.027) form the lowest respective priorities. The inconsistency rate is 0.02, which is less than 0.1 and means that the opinions were not inconsistent (Fig. 5).

Fig. 6 shows the ranking of cations. As seen, iron ion, with a weight of 0.388, is the most important cation in Tajan groundwater wells and the most appropriate cation for analysis of pollution of groundwater. This means that, if sampling and laboratory analysis of water is done, iron ions should be the first priority and should carry higher weight in quality analysis. Calcium (0.249) and manganese (0.159) are ranked second and third for the study area. Manganese (0.095), sodium (0.064), and potassium (0.44), respectively, comprise the lower ranks. The inconsistency rating is 0.02, which is similar to that for anions (Fig. 6).

Fig. 7 shows that electrical conductivity (EC) has the highest weight (0.380). This means that, according to expert opinion, EC is the most appropriate physical parameter for analysis of the quality of groundwater in Tajan plain. Total dissolved solids (TDS) are the next most important parameter (0.256). The results and weights demonstrate that these parameters exceeded the standard limits more frequently in the drinking water of the area and have created more problems. The total alkalinity (0.023) and temperature (0.032) are the least important physical parameters.

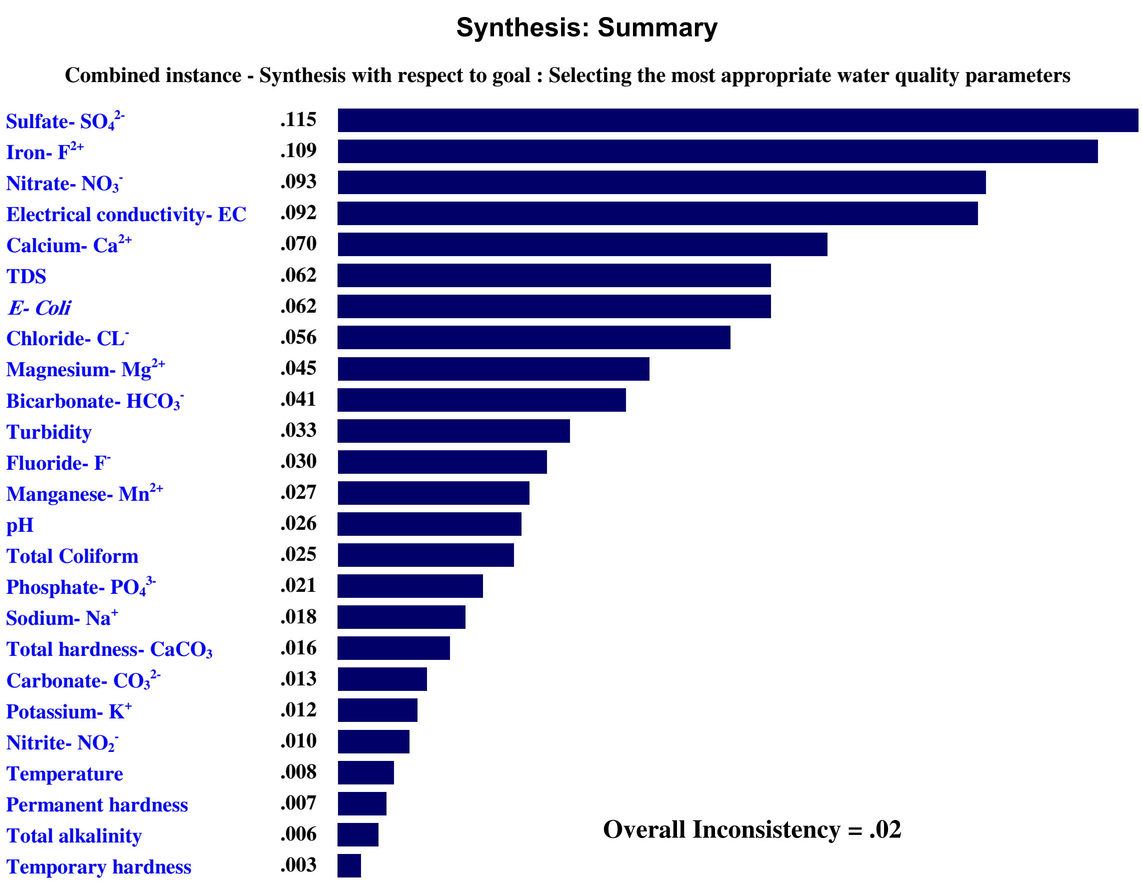


Fig. 9. Ranking graph of all the quality parameters of the study.

Table 1
The priority groups of the quality parameters

Priority group	Parameters	Final weight	Priority of the parameters
First priority group	Sulfate	0.115	1
	Iron	0.109	2
	Nitrate	0.093	3
	EC	0.092	4
	Calcium	0.070	5
	TDS	0.062	6
Second priority group	*E. coli*	0.062	7
	Chloride	0.056	8
	Magnesium	0.045	9
	Bicarbonate	0.041	10
	Turbidity	0.033	11
	Fluoride	0.030	12
Third priority group	Manganese	0.027	13
	pH	0.026	14
	Total coliform	0.025	15
	Phosphate	0.021	16
	Sodium	0.018	17
	Total hardness	0.016	18
Fourth priority group	Carbonate	0.013	19
	Potassium	0.012	20
	Nitrite	0.010	21
	Temperature	0.008	22
	Permanent hardness	0.007	23
	Total alkalinity	0.006	24
	Temporary hardness	0.003	25
Total weight	–	1	–

Turbidity (0.134), pH (0.107), and hardness (0.068), respectively, are in the medium priority range (Fig. 7).

It is clear from Fig. 8 that *Escherichia coli* with a weight of 0.71 is a more important index for microbial contamination than total coliform. This means that microbial contaminations observed in the drinking wells of Tajan plain are more related to the fecal type than other coli forms (Fig. 8).

The synthesis of all weighting results is shown in Fig. 9. In this graph, all parameters are ranked independently based on final weight, and the weightings of all parameters were sorted by priority. The overall inconsistency was 0.02, which shows a high degree of homogeneity in the opinions and synthesis (Fig. 9).

During selection of the most appropriate quality parameter for the study area, one proviso was determined by the expert group: the weight of each selected parameter should not be less than the average weight. For this purpose, the average weights of the parameters were calculated using Eq. (1) to be 0.04:

$$W = \frac{\sum_{i=1}^{n} W_i}{N} = \frac{1}{25} = 0.04 \quad (1)$$

where W is the average weight of all the parameters, W_i is the final weight of each parameter, and N is the number of parameters.

After calculating the average weight, the parameters were categorized from most important to least important in four priority groups based on the final weights (Table 1). Finally, the parameters of the first priority group were selected as indicators. Note that in Fig. 9 and Table 1, the weights of these six parameters (sulfate, iron, nitrate, EC, calcium, and TDS) were higher than the average weight (0.04). These parameters were determined to be the water quality index parameters for Tajan basin.

4. Conclusions

Three main results were obtained from this study. First, the weighting of each parameter determines its importance ratio; second, the parameters were prioritized and third, the most important parameters were selected according to weight.

The importance of all quality parameters in a study area was not the same. For example, expert opinion stated that microbial agents are rarely observed in wells in Tajan plain; thus, despite the importance of this factor, it is not a priority for analysis. Also, despite the importance of nitrate, sulfate was the most serious factor in this plain. This shows that the pollution load is not the same for every factor and each parameter should be considered in the analysis according to its importance ratio.

Similar research can be applied to other study areas for ground and surface water resources. For qualitative research, researchers typically use several parameters as indicators; therefore, it is better that selection be done in a logical way according to the characteristics and background of contamination in study area. It was concluded in the present study that a MCDM approach, especially the AHP method, is a reasonable method for calculation of weights, prioritization, and selection of the most appropriate parameters. This method saves time and cost of during sampling and laboratory analysis. The results of the present research can form the input of other qualitative research in the study area.

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