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Assessment of water quality in groundwater resources of Iran using a modified drinking water quality index (DWQI)

Mohammad Reza Mohebbi[a], Reza Saeedi[b], Ahmad Montazeri[a], Kooshiar Azam Vaghefi[a], Sharareh Labbafi[a], Sogol Oktaie[c], Mehrnoosh Abtahi[c,*], Azita Mohagheghian[c]

[a] Water Quality Control Bureau, National Water and Wastewater Engineering Company, Tehran, Iran
[b] Department of Public Health, Faculty of Health, Safety and Environment, Shahid Beheshti University of Medical Sciences, Tehran, Iran
[c] Department of Environmental Health Engineering, School of Public Health and Institute for Environmental Research, Tehran University of Medical Sciences, P.O. Box 14155-6446, Tehran, Iran

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ABSTRACT

An innovative drinking water quality index (DWQI) based on the Canadian DWQI was developed as "modified DWQI" and applied for assessing the water quality in all of the groundwater resources that are used as the source of drinking water in urban areas of Iran in 2011. Assignment of weight factors for input parameters was the modification carried out in the DWQI. In development of the modified DWQI, twenty-three water quality parameters and relevant Iranian standards for drinking water quality were selected as input parameters and benchmarks, respectively. The modified DWQI is calculated for each sampling station over one year using three factors: the number of parameters that excurse benchmarks, the number of measurements in a dataset that excurse benchmarks and the magnitude of excursion from benchmarks in the violator measurements. The modified DWQI contains two sub-indices: health-based index as "modified HWQI" and acceptability index as "modified AWQI". The modified DWQI and its sub-indices scores range from 0 to 100 and classify water quality in five categories as poor, marginal, fair, good and excellent, respectively. The results of the case study revealed that the nationwide average scores of the modified DWQI, HWQI and AWQI in the groundwater resources were 85, 79 and 91, respectively and overall situation of water quality in the groundwater resources was described as good. According to the modified DWQI value, about 95% of the groundwater flowrates were in the good condition, also in 3 and 2% of the groundwater flowrates, water quality was determined to be fair and marginal, respectively. This study indicated that the modified DWQI and its sub-indices could describe the overall water quality of water bodies easily, reliably and correctly and have the potential suitability for extensive application all over the world.

1. Introduction

Traditional assessment of water quality in water resources consists of comparing the individual water quality parameters levels with their guideline or standard values based on allocated water use or uses. This type of assessment is simple and detailed, but not capable to provide a whole and interpreted picture of water quality especially for managers and decision-makers who require concise information about water bodies. To resolve this decision-making problem, several water quality indices have been developed to transform water quality parameter levels to an integrated indicator value. A water quality index (WQI) describes the general situation of water bodies by changing water quality parameters levels into a numerical score using mathematical tools (Boyacioglu, 2007; Icaga, 2007; Ocampo-Duque et al., 2006; Silvert, 2000).

Horton (1965) developed the first WQI by selecting and weighting water quality parameters and introducing an aggregation function. The WQI was then revised by the U.S. National Sanitation Foundation (NSF) using the Delphi technique. The NSF revised WQI (NSFWQI) has been used all over the world extensively. In the NSFWQI, the applied water quality parameters and their weight factors (in parentheses) include dissolved oxygen (0.17), fecal coliforms (0.16), pH (0.11), biochemical oxygen demand (0.11), nitrate (0.10), total phosphate (0.10), temperature change (0.10), turbidity (0.08), and total solids (0.07). For obtaining the NSFWQI, the measured water quality parameters levels are standardized using rating curves in the range of 0–100; so that a value of 100 represents the best condition, while zero indicates the worst status. The NSFWQI is then calculated by adding the multiplication of the respective weight factor by a standardized water quality value

* Corresponding author. Tel.: +98 21 88954914; fax: +98 21 88950188.
E-mail address: mehrabtahi@yahoo.com (M. Abtahi).

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of each parameter. The calculated NSFWQI value ranges from 0 to 100 and classifies water bodies as poor (0–25), fair (25–50), medium (50–70), good (70–90) or excellent (90–100) (Chang et al., 2001; Ott, 1978). Despite widespread application of the NSFWQI, this index has been criticized for its inflexible structure, inadequate input water quality parameters and subjective rating curves (Ocampo-Duque et al., 2006; Ramesh et al., 2010).

After introducing the NSFWQI, considerable advances on development of the composite indices have been made based on the NSFWQI using slightly modified concepts (Cude, 2001; Liou et al., 2004; Ocampo-Duque et al., 2007; Vasanthavigar et al., 2010). Among the introduced water quality indices, whichever categorizes water resources especially for utilization as community water supply resources is called drinking water quality index (DWQI). For example, Ramesh et al. (2010) developed a DWQI using twenty-two water quality parameters in an innovative manner, which can be categorized in four steps: parameter selection and classification, development of sub-indices, assignment of weight factors to the parameters and finally aggregation of DWQI. Although application of the DWQI was promising, this index had several disadvantages including complex and time consuming calculations, subjective rating curves and lack of flexibility in selection of water quality parameters and judgment criteria.

One of the successful attempts for development of an efficient DWQI was performed by the Canadian Council of Ministers of the Environment (CCME, 2001). Contrary to most of the previous water quality indices, the Canadian DWQI compares observed levels of water quality parameters to guideline or standard values as benchmarks instead of standardizing observations by subjective rating curves. The Canadian DWQI has several advantages including simple calculations and flexibility in selection of water quality parameters and benchmarks, but a critical drawback is observed in the DWQI. This disadvantage is the equal effect of different water quality parameters in the final score of the DWQI (Rickwood and Carr, 2009; Lumb et al., 2006; Ocampo-Duque et al., 2006).

The objective of this research was to develop a modified DWQI based on the Canadian DWQI to eliminate the model weak point. The modified DWQI was then used to evaluate water quality of groundwater resources of Iran that are utilized as the drinking water resources of urban areas.

2. Materials and methods

2.1. Development of the modified DWQI

In this study, the Canadian DWQI was revised by assigning weight factors for input water quality parameters and the introduced index was named “modified DWQI”. The modified DWQI is calculated only for water quality data collected over a predetermined period (typically one year), not for a single sampling dataset; therefore, the modified DWQI presents the long-term or steady status of water quality in water resources. The set of sampling stations is refined and only stations wherein a minimum of any four input water quality parameters are measured at least four times per year are selected for calculating the modified DWQI. The development process of the modified DWQI can be categorized in four steps as follows:

(a) *Selection of water quality parameters and benchmarks*: From a general point of view, drinking water quality parameters are classified in two groups; health-based parameters and acceptability parameters. According to this classification, two sub-indices were introduced for the modified DWQI; modified health-based water quality index (HWQI) that considers human health and modified acceptability water quality index (AWQI) that considers esthetic aspects of drinking water. Water quality parameters for inclusion in the modified DWQI were selected regarding two criteria: regular measurement (at least four times per year) in the groundwater resources and owning an Iranian drinking water quality standard as a benchmark. Based on the criteria, 23 parameters were selected for development of the modified DWQI (Table 1) and its sub-indices. Since all of the groundwater resources will be disinfected before use as drinking water, application of the Iranian drinking water quality standard of fecal coliforms (0 MPN/100 mL) is exceptionally stringent, hence a guideline value of 20 MPN/100 mL was used for fecal coliforms (recommended for water resources designated for public water supply) as benchmark.

(b) *Appropriation of weight factors for input parameters*: Significance of different water quality parameters on the overall suitability of water is not equal. Carcinogens and microbial and other health-based parameters are more important in comparison with acceptability parameters; this concept was considered in development of the modified DWQI by assignment of weight factors for input parameters. Weight factor states the relative importance and effect of the input parameters in the final score of the modified DWQI. Since the effectiveness of the modified DWQI depends on the assignment of proper weight factors for input parameters, this attempt was performed in contribution with water quality experts all over the country using the Delphi technique. The assigned weight factors of input parameters are given in Table 1.

(c) *Calculation of the modified DWQI*: The modified DWQI is calculated using three factors: scope factor (F_1), frequency factor (F_2) and amplitude factor (F_3). The scope factor is a function of the number of parameters that excurse benchmarks, the frequency factor is a function of the number of measurements in a dataset that excurse benchmarks and the amplitude factor is a function of the magnitude of excursion from benchmarks in the failed measurements. The F_1 and F_2 factors are calculated using equations presented below as Eqs. (1) and (2), respectively:

$$F_1 = \frac{\sum_{j=1}^{n} w_{q_j}}{\sum_{i=1}^{m} w_{q_i}}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n \tag{1}$$

$$F_2 = \frac{\sum_{j=1}^{n} (w_{q_j} \times N_{q_j})}{\sum_{i=1}^{m} (w_{q_i} \times N_{q_i})} \tag{2}$$

where w_{q_i} is the weight factor of an input parameter, w_{q_j} is the weight factor of a violator parameter, N_{q_i} is the number of input parameter measurements, N_{q_j} is the number of violator parameter measurements, m is the number of input parameters and n is the number of violator parameters.

For determination of the F_3 factor, first, the excursion amount of violator parameters and then the normalized sum of excursions (NSE) are calculated by Eqs. (3) and (4), respectively, as follows:

$$E_{q_j} = \sum_{N_{q_j}} \left(\frac{C_{q_j}}{SV_{q_j}} - 1 \right) \tag{3}$$

$$\mathrm{NSE} = \frac{\sum_{j=1}^{n} (w_{q_j} \times E_{q_j})}{\sum_{i=1}^{m} (w_{q_i} \times N_{q_i})} \tag{4}$$

where E_{q_j} is the excursion amount of a violator parameter, C_{q_j} is the concentration of the violator parameter and SV_{q_j} is the standard value of the violator parameter.