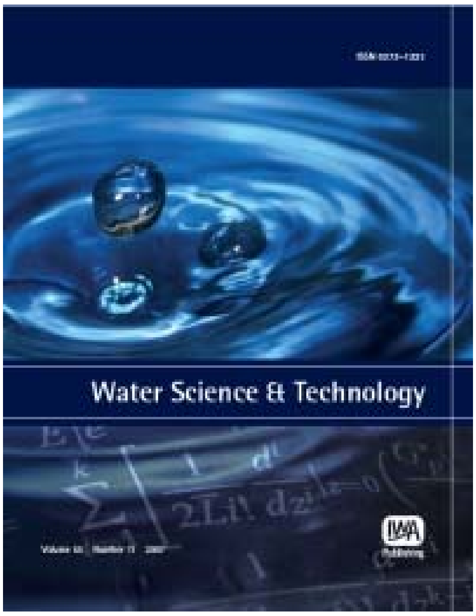
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Water quality assessment in an arid region using a water quality index

M. Nemati Varnosfaderany, N. Mirghaffary, E. Ebrahimi and A. Soffianian

ABSTRACT

Water quality of the Zayandehrud River, located in an arid region of central part of Iran, was assessed using National Sanitation Foundation Water Quality Index (NSF WQI) calculated by four aggregation methods. Water samples were collected monthly (July 2006 to June 2007) from eight stations in the middle of the river. The parameters required for the NSF WQI calculations including saturation percent of dissolved oxygen, biochemical oxygen demand, fecal coliforms, pH, nitrate, total phosphate, temperature deviation, total dissolved solids and turbidity were measured. According to WQI_m which appeared to be more adapted to environmental conditions of the Zayandehrud River, the studied section of the river was considered as "reasonable" to "polluted" water quality. All of the calculated water quality indices showed the lowest values in August. In addition to BOD_5 and fecal coliform amounts which were generally high, nitrate and total phosphate concentrations were also considerably increased due to agriculture practices in August. Generally, BOD_5 and fecal coliforms are the main water quality subindices that reflect the effect of anthropogenic activities on the water quality of this river.

Key words | aggregation method, NSF WQI, water quality, Zayandehrud River

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INTRODUCTION

The evaluation of temporal and spatial water quality trends is an important task for river management. One evaluation approach is to develop water quality indices of multiple parameters, providing a simple and comprehensible tool to manage of the quality of a given water body and its possible applications. Water quality index (WQI) attempts to provide a mechanism for presenting a cumulatively derived numerical expression defining a certain level of water quality (Hallock 2002).

The WQI approach has many variations concerning the selected parameters and aggregation methods. Some comparative studies have been reported in the literature (Landwehr & Deininger 1976; Ott 1978; Smith 1990). The assessment of river water quality by water quality indices has been developed in different countries such as India (Bhargava 1983), Poland (Dojlido *et al.* 1994), Dalmatia (Štambuk-Giljanović 1999), Thailand (Bordalo *et al.* 2001), Zimbabwe (Jonnalagadda & Mehere 2001), Taiwan (Liou *et al.* 2004), South-America (Debels *et al.* 2005), Malaysia (Azrina *et al.* 2006), Portugal and Spain (Bordalo *et al.* 2006), Canada (Lumb *et al.* 2006), Mexico (Sedeño-Díaz & López-López 2007) and Nepal (Kannel *et al.* 2007).

Nagels *et al.* (2001) indicated that most of the efforts to obtain water quality indices have made limited success and have not been widely adopted. Smith (1990) argued that a major reason for this could be due to the fact that most indices are involved aggregation of scores for individual water quality variables, resulting in "hiding" of valuable information compared to the raw water quality data. Furthermore, a low score for one variable that is a severe limitation for water use may be masked when aggregated with relatively high scores for other variables.

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Different aggregation methods are available for calculation of water quality index. Liou *et al.* (2004) discussed various types of aggregation methods and presented some examples of their application. The National Sanitation Foundation Water Quality Index (NSF WQI) is one of the first water quality indices (Brown *et al.* 1970) that aggregate nine water quality parameters through weighted arithmetic mean function (Equation 1). McClelland (1974) used weighted geometric mean function (Equation 2) and found that it is more sensitive than the weighted arithmetic mean function to show changes in the individual variables.

The unweighted harmonic square mean formula (Equation 3), an aggregation method of sub index results, has been also suggested as an improvement over the both weighted arithmetic and weighted geometric mean formulas (Dojlido *et al.* 1994). Minimum operator (Equation 4) is another aggregation function which avoids eclipsing entirely (Ott 1978; Smith 1990).

$$\mathrm{WQI_a} = \sum_{i=1}^{n} \mathrm{SI}_i W_i \tag{1}$$

$$\mathrm{WQI_m} = \prod_{i=1}^{n} \mathrm{SI}_i W_i \tag{2}$$

$$\mathrm{WQI_{har}} = \sqrt{\frac{n}{\sum_{i=1}^{n} 1/\mathrm{SI}_i^2}} \tag{3}$$

$$\mathrm{WQI_{min}} = \mathrm{Minimum}(\mathrm{SI}_1, \mathrm{SI}_2, \mathrm{SI}_3, \ldots) \tag{4}$$

Where WQI is water quality index, n is number of parameters, SI_i is sub index I, and W_i is weight given to sub index i.

Iran is situated in the dry belt of the world, and water supply for various consumptions is an important challenge for national and local authorities. Furthermore, increase of population, industrial development and agricultural activities around the main rivers, such as the Zayandehrud River, have caused the degradation of water quality. The water quality monitoring programs in Iran are mainly based on determination of some physical and chemical parameters. Use of water quality index has still not been in general use as a tool for assessment and management of the river ecosystems. The purpose of this study is to determine the water quality of the Zayandehrud River based on NSF WQI using four aggregation methods.

MATERIALS AND METHODS

Study area

The Zayandehrud basin is located in an arid region of the central part of Iran, with geographical coordinates between 50° 24′ to 53° 24′ E and 31° 11′ to 33° 42′ N (Figure 1). The area of the basin is about 42,000 km^2, with an altitude ranging from 1,466 to 3,974 m and average annual rainfall of 130 mm (Salemi *et al.* 2000). The Zayandehrud River emanates from Chadegan dam and after a distance of 350 km, discharges to the international Gavkhooni's wetland. Its flow regime depends not only on climatic conditions, but also is affected by hydroelectric power generation as well as irrigation needs through the dam. Major land uses in the catchment basin include agriculture and urban development. Eight stations (S_1 to S_8) were selected in the middle of the Zayandehrud River, from Baghbahadoran to Zyar along 132 km of river course, where human activities are intensified (Figure 1). The first station was located above Baghbahadoran City, where the water quality is acceptable for producing drinking water and is pumped to the Isfahan water treatment plant (Pourmoghadas 2002). The common characteristics of stations 1 to 6 are the presence of cobbles and pebbles, and sometimes sand and gravel; the two downstream stations have muddy type sediments. Water samples at each site were collected monthly from July 2006 to June 2007.

Sampling strategy

At each site, water samples were collected from the top 30-cm of the water column at the middle of the river using an acid-washed plastic bucket, rinsed with water of the site. Water samples were stored in the bottles (for chemical analysis) and sterile glass flasks (for bacteriological analysis), cooled, transported to the laboratory and processed within 12 h of collection. The flow rate data of the eight hydrometric stations were obtained from the Isfahan regional water organization.

Analytical procedures

A total of nine parameters required for the NSF WQI calculations were measured monthly. Analytical methods were chosen from *Standard Methods (1992)*, method

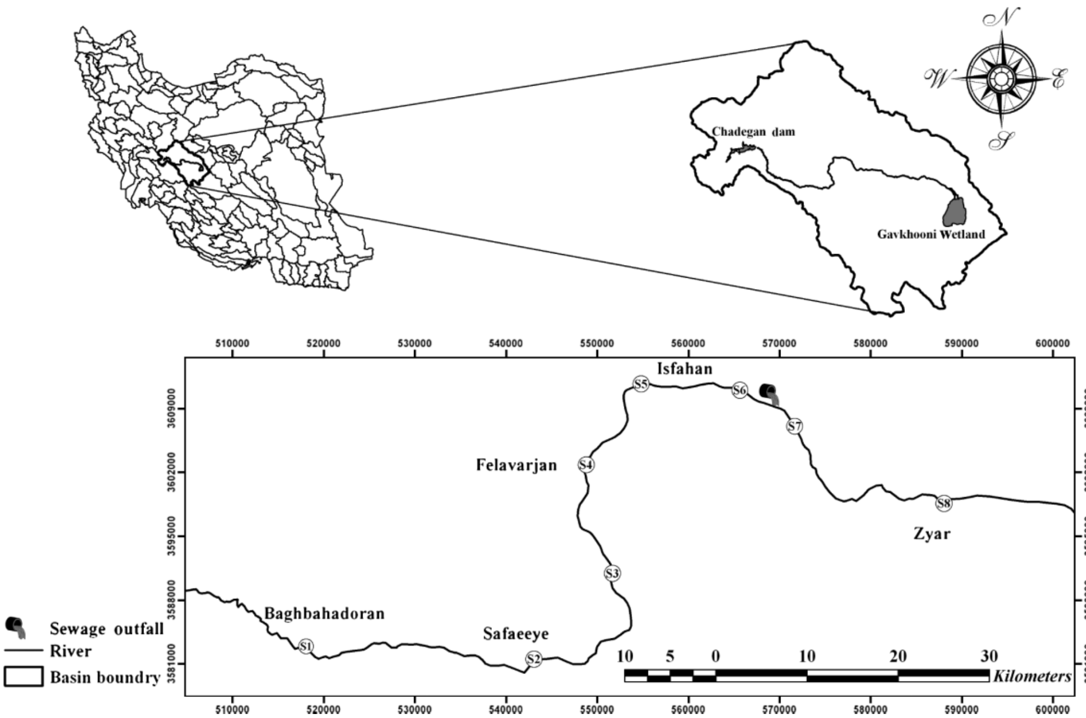

Figure 1 | Map of the Zayandehrud basin with sampling stations along the river.

numbers are cited in parentheses. The parameters include; 5-day biological oxygen demand (BOD_5) (5210 A), saturation percent of dissolved oxygen (%DO) (4500-O G, field measured with WTW Oxi230), fecal coliforms (9221 E), nitrates (4500-NO_3^- D), pH (4500-H^+B, field measured with Testo meter 251), total phosphorus (4500-P E, by presulfate digestion),: total dissolved solids (2510-A, field measured with Jenway meter 4200, by an empirical factor), temperature (2550-B, field measured) and turbidity (2130 B, field measured with DRT-15 in NTU units).

Data analysis

All chemical and bacteriological analyses were performed in duplicate and the means were subjected to statistical analysis. The measured individual parameters were compared to standard curves in order to generate subindices. The NSF WQI was calculated monthly in each station with four aggregation methods namely WQI_a, WQI_m, WQI_{har} and WQI_{min} (Equations (1) to (4) respectively). Temporal and spatial variations of the river water quality were investigated by calculated indices.

Normality of data was tested using the Kolmogorov-Smirnov test. Fecal coliform data were log-transformed in order to stabilize the variance. One-way analysis of variance (ANOVA) followed by Duncan multiple comparison tests were conducted to determine the significant differences between of water quality indices among sites and flow periods. Stepwise regression analysis was used to denote the main factors that determine variation of WQI (Zar 1999). All statistical analyses were performed using the SPSS software (version 10). The water quality map was generated with Surfer 6.01 software and kriging was used as an interpolating method.

RESULTS

Flow regime

Due to low rainfall in the studied region and water use for irrigation (mostly rice and wheat), the main factor that affects the flow regime of Zayandehrud River is the cultivation season. In the winter season (December to

February), the agricultural activities are limited and therefore the lowest discharge occurred. The influx water from Chadegan dam to Zayandehrud River increases at the late of the February, corresponding to the beginning of the agricultural activities in this region. Figure 2 represents the monthly flow rate during the water sampling. Water consumption for agricultural use could be estimated from standard deviations that are presented with bars on each monthly mean flow (Figure 2). The most water use was shown to be during April to August months. On the other hand, the high water use in October was due to fall cultivation (mostly wheat) in the eastern part of Isfahan province (S_7 and S_8). Generally, the flow regime of the Zayandehrud River is classified into a high flow period (March to November) and a low flow period (December to February).

Water quality parameters

Spatial variation of water quality parameters with regard to the high flow period (HFP) and the low flow period (LFP) are shown in Figure 3. Surface water temperature increased steadily from upstream to downstream (Figure 3A), and ranged between 4°C and 31°C in the HFP and 0°C to 12.5°C in the LFP ($p < 0.01$). Oxygen saturation decreased sharply at two downstream stations (S_7 and S_8) and had significant differences ($p < 0.01$) with six upstream stations (S_1 to S_6) at both periods of flow (Figure 3B).

Nitrate steadily increased from upstream to downstream of the river (Figure 3C), but significant differences only were found between S_1 and S_8 ($p < 0.01$) on both periods of flow. Nitrate values during the LFP were significantly lower than the HFP ($p < 0.01$). Maximum nitrate content of the river occurred in August ($29.55 \pm 4.27\,mg\,L^{-1}$) and September ($26.33 \pm 3.76\,mg\,L^{-1}$). Phosphate increased significantly ($p < 0.01$) at two downstream stations (S_7 and S_8) during the LFP (Figure 3D). Maximum phosphate content of the river was measured in July ($1.13 \pm 0.03\,mg\,L^{-1}$) and August ($1.12 \pm 0.02\,mg\,L^{-1}$).

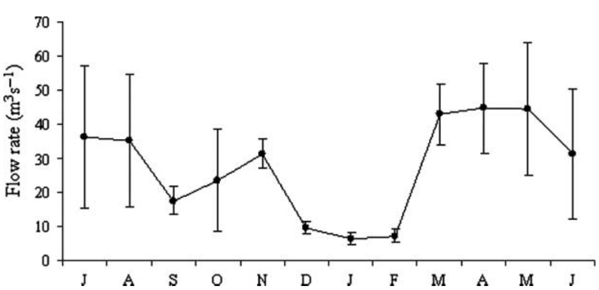

Figure 2 | Monthly means of flow rates in the Zayandehrud River. The bar denotes ± SD.

The variations of BOD_5 means did not follow a clear spatial trend at the two periods of flow (Figure 3E). However, the range of measured values varied from 1.8 to $32.4\,mg\,L^{-1}$ in the HFP ($18.20 \pm 0.88\,mg\,L^{-1}$) and 13.8 to $25.2\,mg\,L^{-1}$ in the LFP ($20.08 \pm 0.52\,mg\,L^{-1}$). The pH values varied between 7.37 to 8.38 in the LFP and 6.9 to 8.33 in the HFP (Figure 3F), indicating no significant differences. However, the pH values at two downstream stations (S_7 and S_8) were statistically lower than six upstream stations during the HFP ($p < 0.01$).

The total dissolved solids showed a steady increase from upstream to downstream of the river (Figure 3G), ranging from 73.9 to $212\,mg\,L^{-1}$ in the HFP and 137 to $306\,mg\,L^{-1}$ in the LFP. Significant differences were found between the two periods ($p < 0.01$). Water transparency increased significantly at five upstream stations (S_1 to S_5) during the LFP, when turbidity averaged 3.28 ± 0.29 NTU against 5.61 ± 0.32 NTU in the HFP (Figure 3H). Highest values of turbidity were in August (9.61 ± 1.01 NTU).

Fecal coliforms steadily increased from S_1 to S_6 (Figure 3I), but increased sharply at S_7 (average $30{,}750 \pm 3{,}921.8$ MPN Coli $100\,ml^{-1}$) and decreased at S_8 ($10{,}469.17 \pm 1{,}864.36$ MPN Coli $100\,ml^{-1}$). Two downstream stations (S_7 and S_8) had significant differences with six upstream stations at the two periods ($p < 0.01$). No significant differences were found between the periods of flow in terms of fecal coliforms.

Water quality index

The spatial and temporal variations of the NSF WQI calculated with the four aggregation method (Equations 1–4) for Zayandehrud River are represented in Figures 4 and 5. Annual mean of calculated water quality indices at each sampling station along the river showed a steady decline to downstream (Figure 4). At two downstream stations (S_7 and S_8), this decline was statistically significant ($p < 0.01$). Overall, spatial trends of four calculated water

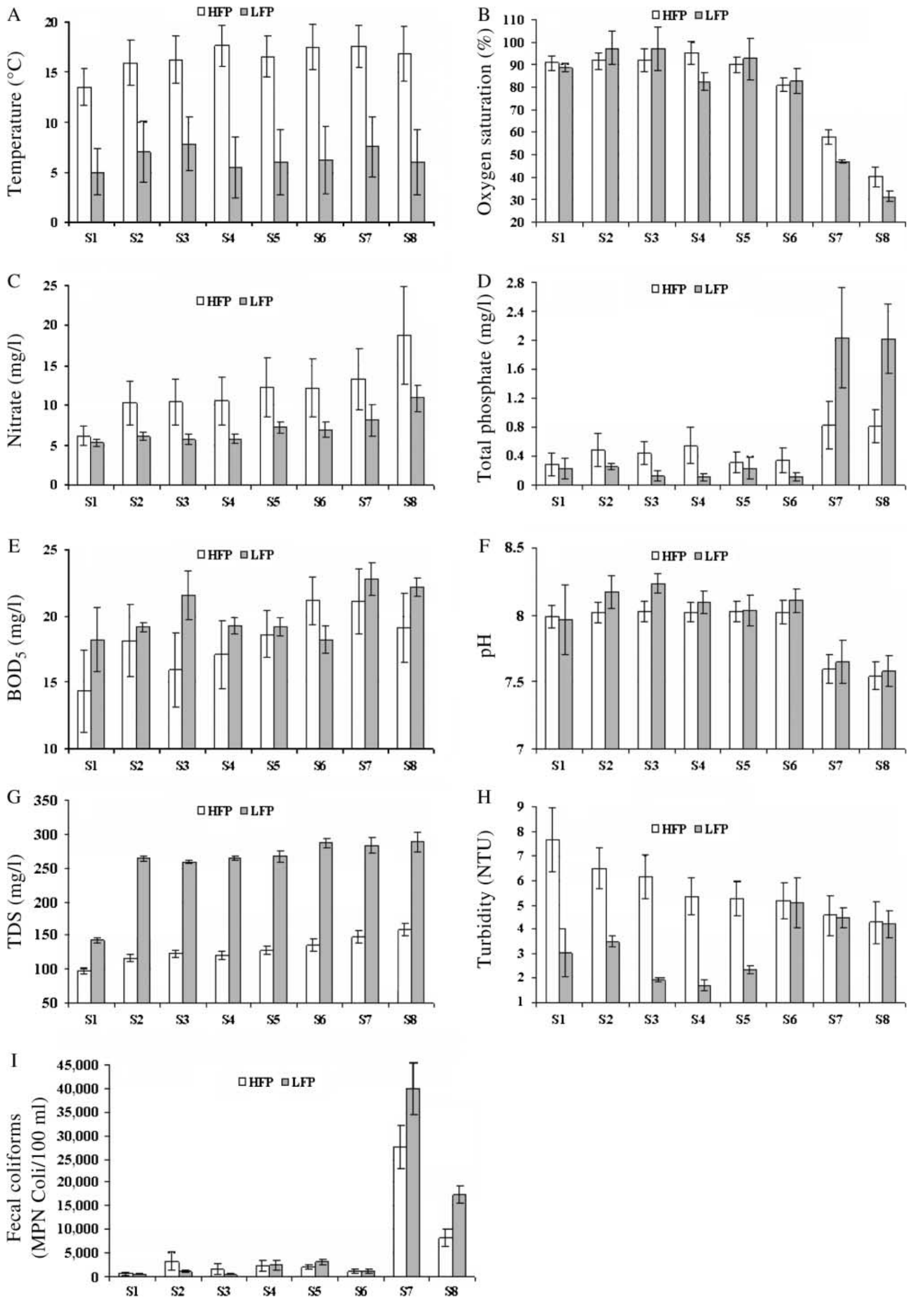

Figure 3 | Spatial variations of water quality variables in the Zayandehrud River at high flow (HFP) and low flow period (LFP). (A) Temperature, (B) Oxygen saturation, (C) Nitrate, (D) Total phosphate, (E) BOD_5, (F) pH, (G) TDS, (H) Turbidity, (I) Fecal coliforms. The bar denotes ± SE.

quality indices at six upstream stations (S_1 to S_6) were similar. However, at two downstream stations (S_7 and S_8), WQI_a and WQI_m showed reverse trends in compare to WQI_{har} and WQI_{min}. The annual mean of WQI_a and WQI_m at S_7 were greater than S_8, while those of WQI_{har} and WQI_{min} at S_8 were greater than that of S_7.

At each station, the range of calculated water quality indices are in order of: WQI_a (42.9 to 74), WQI_m (27.2 to

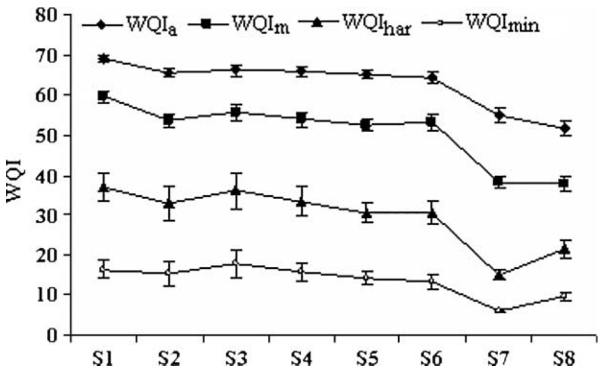

Figure 4 | Annual means of calculated indices at each sampling station along the Zayandehrud River. The bar denotes ± SE.

64.9), WQI_{har} (5.6 to 68.8) and WQI_{min} (2 to 41) and statistically different ($p < 0.01$). The minimum monthly means of calculated indices for all sampling stations were in August. Also, WQI_{har} and WQI_{min} indicated the deterioration of water quality in July and April (Figure 5). In the fall season, the water quality was better than in other seasons. All of the calculated water quality indices showed no significant differences between the two periods of flow.

According to the adapted definition (Table 1), it should be stressed that none of the single calculated indices were considered excellent (WQI > 91). WQI_a mainly placed (85.4%) the water quality of the Zayandehrud River in the class of "reasonable", while according to WQI_m, 59.4% of samples were considered "reasonable" and 40.6% "polluted". Based on WQI_{har}, 45.9% of data were considered as "polluted" and 47.9% as "badly polluted". For WQI_{min}, 90.7% of data were considered as "badly polluted".

From stepwise regression, it was found that oxygen saturation was the parameter that played the most crucial role for variations of WQI_a and WQI_m ($R^2 = 0.65$ and 0.62, respectively, $p < 0.001$). Whereas, in WQI_{har} and WQI_{min}, BOD_5 was the main factor of variations ($R^2 = 0.35$ and 0.31, respectively, $p < 0.001$).

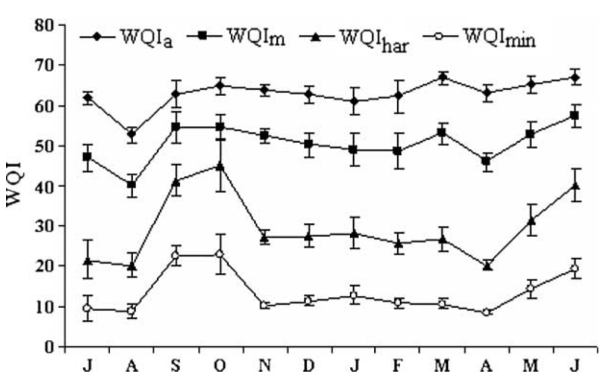

Figure 5 | Monthly means of calculated indices along the Zayandehrud River. The bar denotes ± SE.

DISCUSSION

Water quality parameters

Great decrease in annual means of oxygen saturation (40–60%) and pH (approximately 0.5 unit) as well as the increase of total phosphate and fecal coliforms (Figure 3) at two downstream stations (S_7 and S_8) could be due to discharge of urban sewage from the Isfahan wastewater treatment plant to the river at 3 km above the S_7. In general, urban wastewater has a neutral or slightly acidic pH. It causes an eutrophication process in the receiving water body due to an excessive input of organic material and plant nutrients (Hammer 1986). It should be mentioned that the amount of fecal coliforms in the majority of the sampling stations is so high that water use is not permitted even for recreation contact. Steady increase of TDS and nitrate along the river reflect the cumulative effects of point and non point pollution sources which through effluent, drained and runoff water enter the river. The high nitrate level at HFP (Figure 3C) corresponds to the cultivation season and use of fertilizers in this region.

In all the samples, BOD_5 values were higher than that of the standard limit ($5\,mg\,L^{-1}$) for unpolluted rivers (Hammer 1986). High BOD_5 content in the Zayandehrud River without clear spatial trend reveals the extent of organic pollution and a failure of self-purification in this river. Turbidity of water (Figure 3H) at five upstream stations (S_1 to S_5) is related to flow rate and turbulence of the water. At three downstream stations (S_6 to S_8), the turbidity is affected by aquatic vegetation as well as the muddy substrate of the river.

Water quality index

The NSF WQI is a general water quality index. In some cases, it may be necessary to adapt the water quality indices to local conditions. For example, water of Zayandehrud

Table 1 | Class ratings in percentage for water quality indices values in the Zayandehrud River*

	WQI_a				WQI_m		WQI_{har}			WQI_{min}	
	Polluted 21–40	**Reasonable 41–70**	**Good 71–90**	**Excellent 91–100**	**Reasonable 41–70**	**Good 71–90**	**Badly polluted 0–20**	**Polluted 21–40**	**Reasonable 41–70**	**Badly polluted 0–20**	**Polluted 21–40**
S1	41.7	58.3			91.7	8.3	16.6	41.7	41.7	91.7	8.3
S2		100			75.0	25.0	8.3	58.3	33.3	83.4	16.6
S3		100			83.4	16.6	16.6	41.7	41.7	75.0	25.0
S4	8.3	91.7			66.7	33.3	8.3	66.7	25.0	83.4	16.6
S5		100			83.4	16.6		66.7	33.3	100	
S6		100			75.0	25.0		66.7	33.3	91.7	8.3
S7		66.7	33.3			100			100	100	
S8		66.7	33.3			100		25.0	75.0	100	
Total mean	6.3	85.4	8.3		59.4	40.6	6.24	45.8	47.9	90.6	9.4

*Rating scales according to House & Ellis (1987) and Bordalo *et al.* (2006).

River is alkaline with an average pH $>$ 8. While, it is about 7.5 (Figure 3F) at two downstream stations (S_7 and S_8), resulting in slightly higher subindex scores compared with the upstream part of the river. Nevertheless, because of its negligible impact on the calculated indices, the pH curve was not modified.

As shown in Figure 4, spatial trends of water quality indices in the Zayandehrud River are similar. However, the calculated water quality indices by four aggregation methods reveal their specifications at two downstream stations (S_7 and S_8) as well as on the range of variability between stations. High values of fecal coliforms at S_7 (Figure 3I) caused lower values in WQI_{har} in comparison with S_8, indicating a poor self-purification of the river between these two stations. In contrast to WQI_a and WQI_m, WQI_{har} (Equation 4) do not has a weighting factor and, is very sensitive to low values of subindices such as fecal coliforms in this situation. On the other hand, the range of variability between stations is in order of: $WQI_{har} > WQI_m > WQI_a > WQI_{min}$.

The values of WQI_{min} were obtained from BOD_5 (61%), fecal coliforms (37%) and nitrate (2%) subindices, respectively. All of the calculated water quality indices showed the lowest values in August (Figure 5). In addition to BOD_5 and fecal coliforms amounts which were generally high, nitrate and total phosphate concentrations were considerably increased in August due to agricultural activities. Better water quality in the Zayandehrud River during the fall season is due to the relatively high flow rate (an average of 24.2 $m^3 s^{-1}$) coincident with a decrease of agricultural activities in the region. It should be noted that the cultivation pattern and consequently the irrigation needs are different in the upstream and downstream of the basin.

The effect of aggregation methods on NSF WQI calculation is more distinct when classification of water quality is taken into account. In this study, the water of the Zayandehrud River according to different aggregation methods (Equations 1–4), has different quality classes (Table 1) as the water quality varies from "reasonable" (85.4%) to "badly polluted" (90.7%). Thus, the selection of an aggregation method is an essential step to survey and describe the state of a given water body.

Although WQI_{min} does not present an eclipsing problem, it is not suitable as an aggregation function, because it fails to give a composite picture of water quality (Swamee & Tyagi 2000). In this regard, whereas only 25.5% data of subindices (mainly BOD_5 and fecal coliforms) in the Zyandeh Rud River are lower than 40 scores, but WQI_{min} means at all of the stations are 20 scores (Figure 4). Swamee & Tyagi (2000) indicated that the aggregation formula in WQI_{har} suffers from ambiguity. In fact, although the water is of acceptable quality, the harmonic aggregation formula classifies it as unacceptable. A distinctive example of this ambiguity for WQI_{har} is observed in November for the

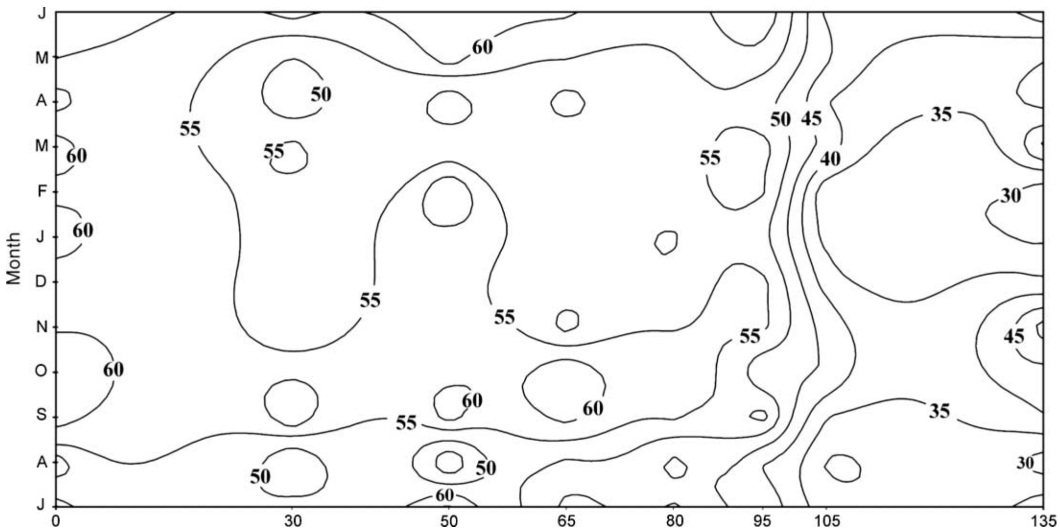

Figure 6 | Mapping of WQI_m along the Zayandehrud River. Distance (km) is from first station.

Zayandehrud River (Figure 5), while, 59.7% of subindices data score higher than 70 and, only 16.7% of subindices data including BOD_5 and fecal coliforms score lower than 30. The average of WQI_{har} of the river is 28.1.

Swamee & Tyagi (2000) have also confirmed that weighted geometric mean aggregation formula (WQI_m) for subindices that are low with smaller weight (near-zero) may be having an eclipsing problem. In the present study, BOD_5 and fecal coliforms subindices which have frequently low scores, were taken relative high weights of 0.11 and 0.16 in NSF WQI, respectively. Therefore, the evaluation of the water quality of Zayandehrud River using WQI_m (Figure 6) seems to be more reliable, because the effect of an eclipsing problem is negligible. However, it should be useful to consider the subindices that score lower than 50 and/or at least take into account the WQI_{min} for determination of pollution sources and interpretation of obtained data.

CONCLUSIONS

The assessment of the water quality of Zayandehrud River using NSF water quality index reaffirmed the importance and complexity of selecting aggregation methods for experts and decision makers. According to WQI_m which appeared to be more adapted to environmental conditions of the Zayandehrud River, the studied section of the river is considered as "reasonable" to "polluted" water quality. Generally, BOD_5 and fecal coliforms are the main water quality subindices that reflect the effect of anthropogenic activities on the water quality of this river. In summer, increase of nitrate and total phosphate due to use of fertilizers in farmlands within the basin contributes to the more decrease of the water quality index. It seems that the calculated WQI only based on physico-chemical parameters could not reflect the real water quality of the river ecosystem. Thus, the use of biological indices specially those based on benthic macroinvertebrates is also necessary for a comprehensive assessment of water quality.

From the river conservation point of view, based on calculated water quality indices, an integrated pollution abatement program must be focused on organic and microbial pollution control. Moreover, preventive actions will be necessary to minimize agricultural non point pollution sources. Finally, a regular monitoring program of water quality is needed to survey the whole river and verify its restoration.

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