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Evaluating groundwater quality using health risk assessment and irrigation indexes: Saveh Aquifer, Iran

Alireza Shahmirnoori, Maryam Hasani Zonoozi * and Mehrshad Samadi
Department of Civil Engineering, Iran University of Science and Technology (IUST), Narmak, Tehran 16846-13114, Iran
*Corresponding author. E-mail: mhzonoozi@iust.ac.ir

MHZ, 0000-0002-4392-6925; MS, 0000-0003-3867-0264

ABSTRACT

The aim of the study was to assess water quality in the Saveh aquifer for drinking, public health, and agricultural uses. The heavy metal pollution index (HPI), hazard index (HI) using non-carcinogenic health risk assessment, sodium percentage, sodium adsorption ratio (SAR), irrigation water quality index (IWQI), and a Piper diagram were used. The HPI exceeded 3,300, much higher than the WHO critical value, which is 100. The aquifer is severely contaminated with heavy metals and unsuitable for drinking. The heavy metal concentrations also caused the water to have cumulative HI $>$ 1 in 54 and 77% of sampling wells, respectively, for adults and children. For agriculture, both %NA and IWQI were stricter than SAR. Most of the aquifer was deemed suitable for irrigation using SAR, while %Na showed most parts unreliable, and IWQI represented almost all areas unsuitable for irrigation. The Piper diagram showed that the dominant water type was N–Cl, followed by Na–HCO_3 and Ca–HCO_3, indicating high aquifer salinity. Generally, the Saveh aquifer is saline and heavily polluted with heavy metals, so its use for drinking and/or irrigation carries many risks.

Key words: groundwater, heavy metals, irrigation water quality, pollution index, risk assessments

HIGHLIGHTS

- Evaluating water quality of Saveh aquifer in Iran for drinking, public health, and agricultural purposes.
- Using heavy metal pollution index, hazard index (HI), sodium percentage, sodium adsorption ratio, and irrigation water quality index (IWQI).
- Children and adults are at high non-carcinogenic risk via both drinking and dermal exposure.
- IWQI and %Na showed most areas of aquifer inappropriate for irrigation.

1. INTRODUCTION

Groundwater is a vital water resource used widely for drinking, irrigation, and industry. More than 1.5 billion people rely on groundwater for drinking worldwide (Ahmed *et al.* 2022; Najafzadeh *et al.* 2022). The health consequences of polluted groundwater are long term; exposure to water can cause many illnesses and 20% of cancer cases (Afshar *et al.* 2021; Chowdhury & Rahnuma 2023). The main sources of groundwater pollution are agricultural, industrial, and domestic runoff into land or water resources (Asif 2018; Rafiee 2020). Fast growth in population, agriculture, and industry has led to emerging pollution in water bodies and groundwater, including heavy metals, detergents, and pesticides, which are hazardous to public health (Amjad *et al.* 2013; Mbhele & Khuzwayo 2023). For this reason, many researchers are interested in evaluating groundwater quality. Studies in India report groundwater contamination due to industrialization and farming activities, and exposure to polluted groundwater can cause severe health consequences (Singh *et al.* 2018; Ahmed *et al.* 2022). It has been reported in China that heavy metals in groundwater can have both non-carcinogenic and carcinogenic health consequences for people (Tong *et al.* 2021). Studies of high fluoride and nitrate concentrations in groundwater and their impacts on health risks have demonstrated adverse effects on human health (Yang *et al.* 2022). Studies in Iran and Pakistan have also shown that high concentrations of heavy metals, nitrate, and/or fluoride are harmful to public health (Amjad *et al.* 2013; Yousefi *et al.* 2018).

Recent reports indicate that around 70% of groundwater is used for agriculture and irrigation in arid and semi-arid areas. Irrigation with low-quality groundwater can limit crop selection and reduce harvest efficiency and soil quality (Bouaroudj *et al.* 2019). Many studies have been conducted assessing irrigation water quality in countries including India, Algeria, Iran, and the United Arab Emirates (UAE). For example, research based on irrigation water quality index (IWQI) in southeast Iran showed that groundwater in more than 60% of the region is good to very good for agricultural irrigation. The UAE study indicated that groundwater quality in more than 95% of that region is unsuitable for agriculture (Abbasnia *et al.* 2018; Batarseh *et al.* 2021). Water-related issues threaten the earth's semi-arid and arid areas, including much of Iran. Combining such situations with public health and environmental problems has attracted attention to these issues worldwide.

The Saveh aquifer is among the most vital groundwater resources in the arid and semi-arid parts of Iran, and the supply of both agricultural and drinking water to about three million people depends on it. Relatively recently, the aquifer has been exposed extensively to agricultural drainage waters and municipal and industrial wastewater, so it would be valuable to investigate the effect of its pollution on public health. The main aim of this study was thus to evaluate the quality of the Saveh aquifer according to three general concepts: (1) heavy metal pollution based on (a) the heavy metal pollution index (HPI) and (b) non-carcinogenic health risks of oral intake and dermal contact; (2) irrigation water quality based on (a) sodium percentage (%Na), (b) sodium adsorption ratio (SAR), and (c) IWQI; and (3) hydrochemical groundwater types, based on the Piper diagram. The HPI and non-carcinogenic health risk indices were calculated using concentrations of 10 heavy metals detected in the aquifer, including lead (Pb), zinc (Zn), copper (Cu), cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As), manganese (Mn), aluminium (Al), and iron (Fe). Heavy metals are a group of metals and metalloids that are toxic even at μg/L levels and tend to accumulate in body tissue. Most heavy metals are considered to carry carcinogenic risks (Afzaal *et al.* 2022).

Irrigation water quality was assessed using parameters that play essential roles in it, including electrical sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), electrical conductivity (EC), chloride (Cl^-), and bicarbonate (HCO^3). The penetration rate of water into soil depends on many factors, but the most important are the water's salinity and SAR. The water available to the roots decreases when salts gather in the crop root area and can affect the crop adversely (Batarseh *et al.* 2021). A piper diagram was also used to evaluate the area's groundwater chemistry and determine its hydrochemical facies.

2. MATERIALS AND METHODS

2.1. Study area

The Saveh aquifer underlies the Saveh plain (Figure 1), which covers about 3,245 km^2 in central Iran (latitudes 34°:45′ to 35°:03′ N and longitudes 50°:08′ to 50°:50′ E). The provinces of Markazi and Qom, each with populations of about 3 million, lie on the aquifer's west and east, respectively. The area's average topographic level is between 1,100 and 1,120 m. The average annual rainfall and temperature on the plain are approximately 210 mm and 18 °C, respectively (AUT 2015). The study area and the wells sampled in the Saveh Aquifer are shown in Figure 1.

2.1.1. Pollution sources

The presence of gypsum and salt in the area reduces surface and groundwater resource quality significantly. About 55,000 and 250,000 tonnes of chemical and animal fertilizer are also used annually by farmers on the plain. Pesticide use, including Endosulfan, Dursban, and Metasystox, is also common, threatening groundwater quality. Kaveh Industrial Town, in the study area, is a significant industrial hub, and one of the largest, most vital industrial areas in Iran. A wide range of industries is active, including casting, pipe making, and metal container production. Such industries can be important in increasing the levels of heavy metals. There are 420 active factories in the area, with 246 livestock and 57 poultry units, and residues from them have polluted the aquifer over the years (AUT 2015).

2.1.2. Data

Information from 56 wells was used to analyse the groundwater quality. The parameters measured are presented with their minima and maxima in Table 1.

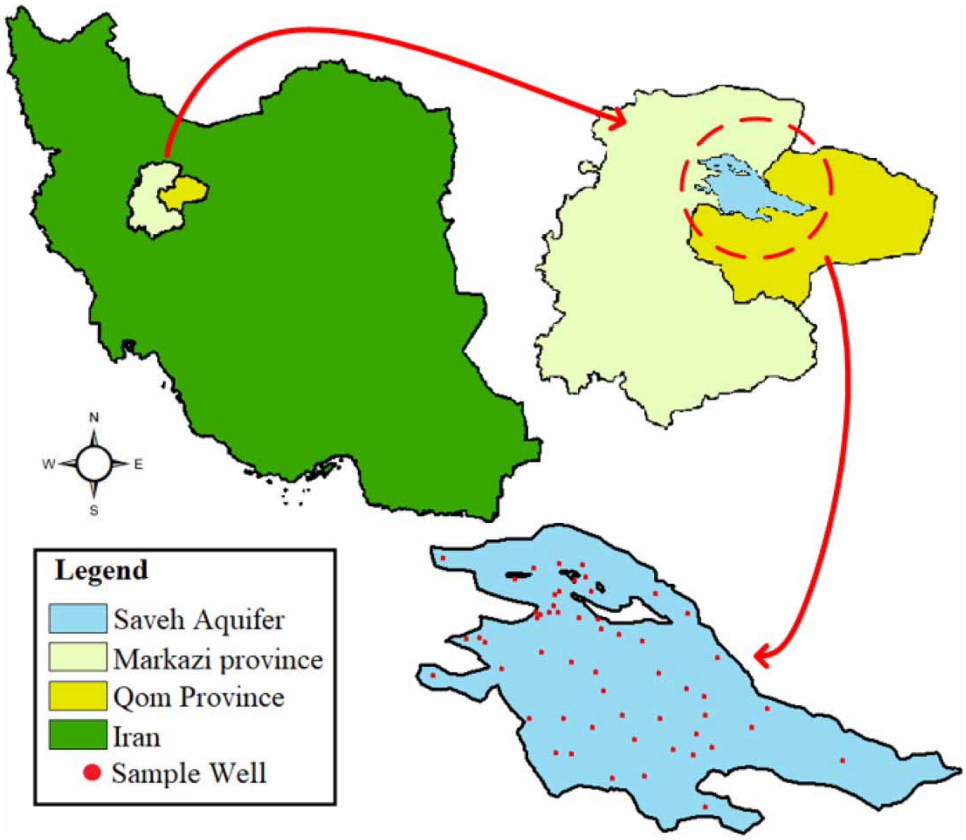

Figure 1 | The Saveh Aquifer (Iran) and sample well locations in the study area.

Table 1 | Parameter value ranges in the Saveh aquifer

Parameter	Unit	Min	Max
Na	mg/L	77.9	9,204
Ca	mg/L	23	870
Mg	mg/L	8	280
K	mg/L	1.9	47
EC	µS/cm	646.6	14,670
Cl	mg/L	130	500
HCO_3	mg/L	250	1,010
Pb	µg/L	5.2	192
Zn	µg/L	2.1	1,843
Cu	µg/L	1.3	264
Cd	µg/L	0.35	10.3
Cr	µg/L	5	2,919
Ni	µg/L	1.3	155
As	µg/L	1.1	61
Mn	µg/L	3	1,141
Al	µg/L	38	3,807
Fe	µg/L	10	10,624

2.2. Water quality assessment

2.2.1. Heavy metal contamination

2.2.1.1. Heavy metal pollution index. HPI is calculated using Equations (1)–(3) on the basis of the weights assigned to the parameters chosen i (W_i) (WHO 2017; Kumar *et al.* 2019), where W_i is the unit weighting of the ith heavy metal, calculated using Equation (2).

$$\mathrm{HPI} = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

$$W_i = \frac{1}{S_i} \tag{2}$$

$$Q_i = \sum_{i=1}^{n} \frac{|M_i - I_i|}{S_i - I_i} \times 100 \tag{3}$$

where n represents the number of heavy metals, Q_i is the heavy metal's sub-index, i, W_i is the weight per unit of the ith heavy metal, S_i (μg/L) is the maximum permissible concentration of the ith heavy metal in drinking water, M_i (μg/L) is the concentration of the ith heavy metal, and I_i (μg/L) is the maximum desirable concentration of the ith heavy metal. The values of I_i and S_i for each heavy metal in drinking water were defined using the WHO recommendations (2017).

HPI's critical limit is set at 100 to show that detrimental health effects are possible. An HPI value below 100 indicates a low level of heavy metal pollution (WHO 2017; Kumar *et al.* 2019). Table 3 shows the parameter values.

2.2.1.2. Human non-carcinogen health risk assessment. Human health risk assessment is a way to determine and predict the probability of negative impacts from environmental contaminants on public health (Singh *et al.* 2018; Tong *et al.* 2021). Two significant forms of heavy metal exposure to people were considered: oral intake (ingestion) and dermal absorption. The risks corresponding to these two forms of exposure were computed using the chronic daily intake ($\mathrm{CDI_{Ingestion}}$ and $\mathrm{CDI_{Dermal}}$), hazard quotient ($\mathrm{HQ_{Ingestion}}$ and $\mathrm{HQ_{Dermal}}$), and hazard index ($\mathrm{HI_{Ingestion}}$ and $\mathrm{HI_{Dermal}}$) equations. Equations (4) and (5), recommended by USEPA (2004), were applied to calculate the exposure amounts for direct ingestion ($\mathrm{ADD_{ingestion}}$) and dermal absorption ($\mathrm{ADD_{dermal}}$), respectively.

$$\mathrm{ADD_{ingestion}} = \frac{C_W \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \tag{4}$$

$$\mathrm{ADD_{dermal}} = \frac{C_W \times \mathrm{SA} \times K_p \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{CF}}{\mathrm{BW} \times \mathrm{AT}} \tag{5}$$

where $\mathrm{ADD_{ingestion}}$ is the average daily dose through ingestion (μg/kg/day), BW is the average body weight, AT is the average exposure time (for non-carcinogens), C_W is heavy metal concentration in groundwater (μg/L), IR is the rate of ingestion, EF is the exposure frequency, and ED is *ED* exposure duration. $\mathrm{ADD_{dermal}}$ is the average daily dose through dermal adsorption (μg/kg/day), SA is the exposed skin area, ET is the exposure time, and CF is the conversion factor (10^{-3}). The parameter values are presented in Table 2, and K_p and other values are presented in Table 3.

Non-carcinogenic risk is evaluated using Equations (6)–(8):

$$\mathrm{HQ_{ingestion}} = \frac{\mathrm{ADD_{ingestion}}}{\mathrm{RfD_{ingestion}}} \tag{6}$$

$$\mathrm{HQ_{dermal}} = \frac{\mathrm{ADD_{dermal}}}{\mathrm{RfD_{dermal}}} \tag{7}$$

$$\mathrm{HI} = \sum(\mathrm{HQ_{ingestion}} + \mathrm{HQ_{dermal}}) \tag{8}$$

Table 2 | Parameter values used in Equations (1) and (2) (Yousefi *et al.* 2018; Tong *et al.* 2021)

Parameter	Adults	Children
BW (kg)	78	15
ED (years)	70	12
EF (days/year)	365	365
IR (L/day)	2.5	1
AT (for non-carcinogens) = ED × 365	25,550	4,380
SA (cm^2)	16,600	12,000
ET (h/day)	0.4	0.4

Table 3 | Values of $RfD_{ingestion}$, RfD_{dermal}, and k_p (Kumar *et al.* 2019; Tong *et al.* 2021)

Heavy metal	$RfD_{ingestion}$ (μg/kg/day)	RfD_{dermal} (μg/kg/day)	Kp (cm/h)
Al	1,000	200	0.001
As	0.3	0.285	0.001
Cd	0.5	0.025	0.001
Cr	3	0.075	0.002
Cu	40	8	0.001
Fe	700	140	0.001
Mn	24	0.96	0.001
Ni	20	0.8	0.0002
Pb	1.4	0.42	0.0001
Zn	300	60	0.0006

where $HQ_{ingestion}$ represents the ingestion hazard quotient and HQ_{dermal} is the dermal hazard quotient. The ingestion and dermal reference doses (g/kg/d) are shown in Table 3 as $RfD_{ingestion}$ and RfD_{dermal}, respectively. HI is the hazard index (dimensionless) and is used to refer to the possible non-cancer risk of heavy metals. $HI > 1$ shows that a negative impact on public health is likely, while $HI < 1$ indicates no negative effects on public health (Kumar *et al.* 2019).

2.2.2. Irrigation water quality assessment

Low-quality irrigation water impacts crop efficiency and quality negatively, as well as the health of farmers who are in contact with it. The effects of using low-quality water vary depending on the contaminants. Irrigation water quality was assessed using three methods in this study: %Na, SAR, and IWQI.

2.2.2.1. Sodium percentage. If the sodium concentration in irrigation water is high, Na ions adhere to the clay particle surface, replacing Mg and Ca ions. Exchanging Na with Mg and Ca in water reduces soil permeability and ultimately decreases soil drainage so that water movement is limited in wet conditions, and the soil becomes harder when it is dry (Batarseh *et al.* 2021). The index (%Na) is calculated on the basis of the ratio of the cations in the water using Equation (9). Table 4 shows the water quality classification according to %Na.

Table 4 | Water quality classification according to %Na (Batarseh *et al.* 2021)

Range of %Na (meq/L)	Water quality
≤ 20	Excellent
$20 < Na \leq 40$	Good
$40 < Na \leq 60$	Permissible
$60 < Na \leq 80$	Doubtful
$80 < Na$	Unsuitable

$$\%Na = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \quad (9)$$

where the standard parameter unit for %Na is meq/L.

2.2.2.2. Sodium adsorption ratio. The SAR is highly significant in studying agricultural water quality. Irrigating land with water with high EC increases the potential for soil salinity and causes salt accumulation. This reduces the plants' osmotic activity and blocks water from reaching their branches and leaves (Bouaroudj *et al.* 2019; Batarseh *et al.* 2021). Equation (10) is used to compute SAR:

$$SAR = \sqrt{2} \times \frac{Na^+}{\sqrt{Ca^{2+} \ Mg^{2+}}} \quad (10)$$

where Na^+, Ca^{2+}, and Mg^{2+} denote sodium, calcium, and magnesium ion concentrations (meq/L) in water, respectively. SAR is measured in $(meq/L)^{1/2}$.

Water quality is divided into four categories using SAR: S_1 ($0 < SAR \leq 10$) excellent; S_2 ($10 < SAR \leq 18$) good; S_3 ($18 < SAR \leq 26$) suspicious; and S_4 ($SAR > 26$) poor.

2.2.2.3. Irrigation water quality index. Meireles *et al.* (2010) introduced IWQI to measure water quality for agriculture. It provides an obvious classification according to the influence of irrigation water on toxicity to plants and irrigated soil and has five classifications (Batarseh *et al.* 2021):

1. 100–85: No restriction.
2. 85–70: Low restriction.
3. 70–55: Moderate restriction.
4. 55–40: High restriction.
5. 40–0: Severe restriction.

Five parameters such as EC, SAR, Na^+, Cl^-, and HCO^{3-} are used to calculate IWQI using Equation (11):

$$IWQI = \sum_{1}^{n} q_i w_i \quad (11)$$

where w_i is the weight of each parameter; the values of w_i for EC, SAR, Na^+, Cl^-, and HCO^{3-} are 0.211, 0.189, 0.204, 0.194, and 0.202, respectively; n is the number of parameters used ($n = 5$), and q_i is the value of the ith water quality parameter and calculated using Equation (12) (Meireles *et al.* 2010; Abbasnia *et al.* 2018; Batarseh *et al.* 2021).

$$q_i = q_{imax} - \left[\frac{(x_{ij} - x_{inf}) \times q_{iamp}}{x_{iamp}} \right] \quad (12)$$

where x_{iamp} refers to the class amplitude to which the parameter belongs, x_{inf} is the lower limit of that class, x_{ij} shows the concentration of parameter i in well j, q_{iamp} is the class amplitude for q_i classes, and q_{imax} is the maximum amount of q_i for the class (Spandana *et al.* 2013; Batarseh *et al.* 2021). The proposed irrigation water quality parameter limits are presented in Table 5.

2.2.3. Water type

The Piper diagram is frequently used to determine groundwater hydrogeochemical facies (Gao *et al.* 2023) on the basis of cationic and anionic concentrations (Piper 1944). The piper plot in this study was drawn using AqQA software version 1.5.0.

Table 5 | Irrigation water quality parameter limits (Spandana *et al.* 2013; Batarseh *et al.* 2021)

q_i	HCO_3^- (meq/L)	Cl^- (meq/L)	EC (µS/cm)	SAR (meq/L) $^{1/2}$	Na^+ (meq/L)
85–100	1–1.5	<4	200–750	< 3	2–3
60–85	1.5–4.5	4–7	750–1,000	3–6	3–6
35–60	4.5–8.5	7–10	1,500–3,000	6–12	6–9
0–35	<1 or >8.5	>10	<200 or >3,000	>12	<2 or >9

3. RESULTS AND DISCUSSION

3.1. Heavy metal contamination

3.1.1. Pollution assessment based on HPI

The HPI results, based on WHO (2017), indicate that the Saveh aquifer is highly polluted with heavy metals and unsuitable for use as drinking water. The HPI was 3372, very much higher than 100 (Table 6). Among the heavy metals, Cr – with concentrations between 5 and 2,919 µg/L – had the most effect on HPI. The concentration range for Cr consistently exceeded both the maximum permitted (S_i) and maximum desirable (I_i) concentrations of 5 and 3 µg/l, respectively.

Table 6 | Heavy metal HPIs for the Saveh aquifer, based on WHO (2017) drinking water guidelines

Heavy metals	Concentration range (µg/L)	Maximum concentration in drinking water (S_i) (µg/L)	Maximum desirable concentration (I_i) (µg/L)	Sub-index (Q_i)	Unit weight W_i (1/S_i)	$W_i \times Q_i$	HPI
Pb	5.2–192	10	15	−602.57	0.1,000	−60.26	3,372.70
Zn	2.1–1,843	5,000	3,000	145.32	0.0002	0.03	
Cu	1.3–264	3,000	50	0.47	0.0003	0.00	
Cd	0.35–10.3	100	500	−124.37	0.0100	−1.24	
Cr	5–2,919	5	3	6,338.13	0.2000	1,267.63	
Ni	1.3–155	70	0	12.60	0.0143	0.18	
As	1.1–61	50	10	10.11	0.0200	0.20	
Mn	3–1,141	1,000	2,000	−186.74	0.0010	−0.19	
Al	38–3,807	100	200	−297.25	0.0100	−2.97	
Fe	10–10,624	1,000	100	66.98	0.0010	0.07	
Sum					0.3568	1,203.44	

Kaveh Industrial Town appears to be the main factor behind the high levels of Cr in the study area. The industries present are probably responsible for the significant increase in heavy metal concentrations, particularly Cr. Figure 2(a) shows the industrial area, and Figure 2(b) shows the Cr concentrations in different parts of it. The concentration of Cr exceeds 5 µg/L in nearly all regions, but the most pollution is seen around the industrial areas.

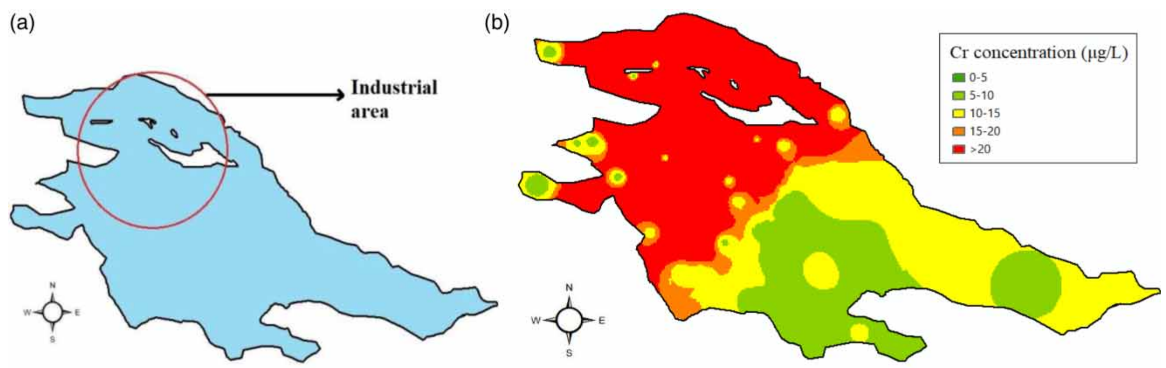

Figure 2 | Area where most factories are (a) and Cr concentration across the study area (b).

3.1.2. Non-carcinogen health risk assessment

The non-carcinogen health risk assessment associated with heavy metals was calculated using the United States Environmental Protection Agency approach (USEPA 2004). Ingestion and dermal exposure were considered, as they are the two main exposure forms to heavy metals. Table 7 shows the health risks for a random well in the study area. The results, for both children and adults, show that Cr, As, and Pb pose higher risks for both ingestion and dermal exposure than the others determined.

Table 7 | HI results for a random well in the study area

	Adults		Children		HI	
Heavy metal	HQ (ingestion)	HQ (dermal)	HQ (ingestion)	HQ (dermal)	HI (adults)	HI (children)
Pb	2.172	0.004	3.243	0.011	2.176	3.254
Zn	0.017	0.000	0.025	0.001	0.017	0.026
Cu	0.047	0.001	0.070	0.004	0.048	0.073
Cd	0.378	0.039	0.564	0.116	0.418	0.681
Cr	3.735	1.560	5.576	4.602	5.295	10.178
Ni	0.003	0.000	0.004	0.000	0.003	0.004
As	3.014	0.017	4.499	0.049	3.030	4.548
Mn	0.177	0.012	0.368	0.044	0.190	0.410
Al	0.016	0.000	0.033	0.001	0.020	0.030
Fe	0.032	0.000	0.067	0.002	0.030	0.070
					$\sum = 11.37$	$\sum = 19.40$

The HI values for Cr, As, and Pb were 5.295, 3.03, and 2.176 for adults and 10.187, 4.548, and 3.254 for children, respectively. As noted and based on the USEPA criteria for risk assessment, the permissible limit for non-carcinogenic risk is $HI \leq 1$. If the value exceeds 1, the potential for negative public health risk is relatively high (USEPA 2004). The details showed that ingestion had far more influence on HI than the dermal route. For example, Cr had an HI of 5.295 for adults, comprising $HQ_{ingestion}$ and HQ_{dermal} of 3.735 and 1.56, respectively ($HQ_{ingestion} > HQ_{dermal}$). The HI values for the other heavy metals taken from the aquifer were all less than 1.

Maps of the spatial distribution of cumulative HI for adults and children, respectively, and calculated for each well are shown in Figure 3(a) and 3(b). The maps were prepared using inverse distance weighting interpolation. For the non-carcinogenic risk, the cumulative HI values were changed from 0.42 to 44 – average 4.47 – for adults and from 0.89 to 80.75 – average 8.13 – for children. The ranges obtained arise from the difference in heavy metal concentrations in different wells. The differences in the values obtained for adults and children were based on coefficients – e.g., body weight, average exposure time – that differ between the groups to calculate HI. For adults, in 30 samples (54% of wells), the high heavy metal concentrations caused $HI > 1$, but results were even worse for children, as 43 samples (77%) had $HI > 1$.

The results show that both adults and children are heavily exposed to the non-carcinogenic consequences of heavy metal contamination by the ingestion and dermal routes, particularly from Cr, Pb, and As. Also, as can be seen, the southern regions exhibit lower levels of risk for adults, while nearly all areas are deemed hazardous for children.

3.2. Evaluation of irrigation water quality

3.2.1. Sodium percentage

The %Na index is used to assess groundwater for irrigation purposes and can show both sodicity issues and soil permeability (Batarseh *et al.* 2021). The results (Table 8 and Figure 4) show that none of the groundwater samples were in the range of 0–20%, and only five were within the 20–40% span. In other words, none of the groundwater was classified as excellent quality, and only 9% of the groundwater samples were good. For 21.5% of the sample wells, groundwater quality was estimated to be acceptable (40–60%), mainly in the southern part of the aquifer.

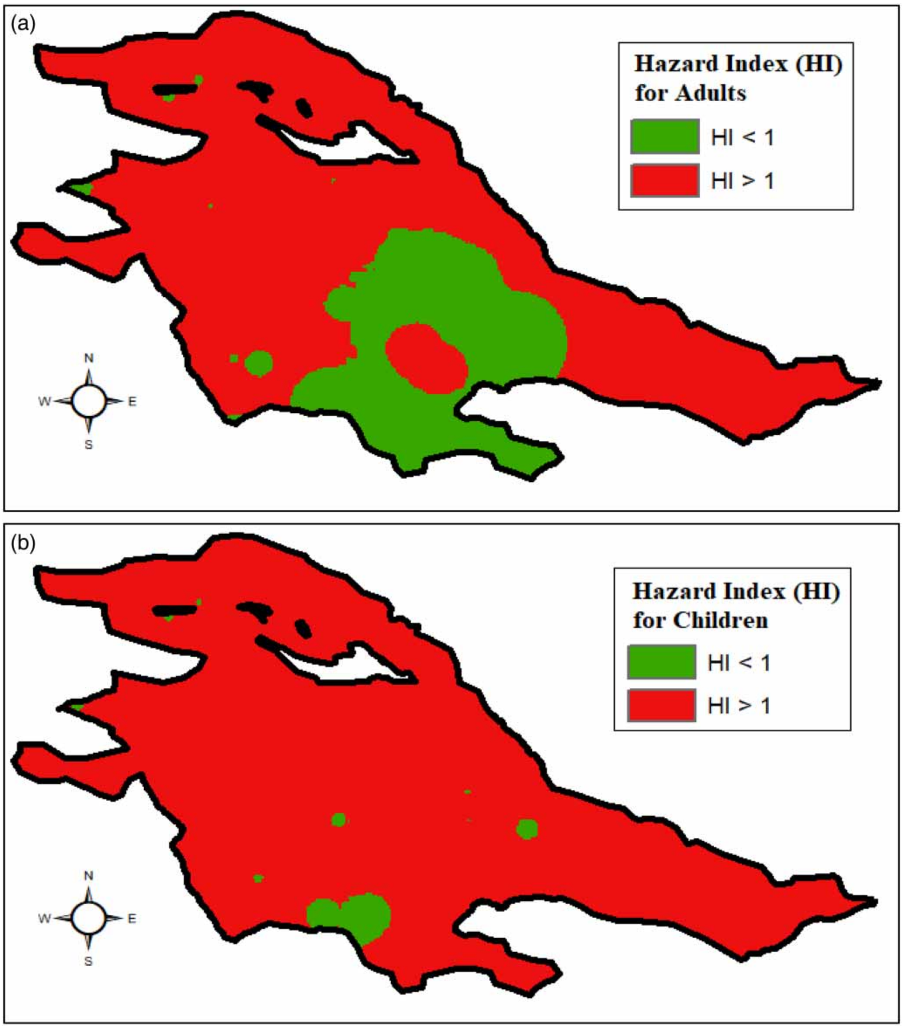

Figure 3 | Spatial distribution of cumulative HI for (a) adults and (b) children.

Most wells (23, 41%) had doubtful water quality (60–80%), while the remaining 28.5% had water of poor quality. Most of the latter are in the northern parts of the aquifer. The %Na for each well sampled is shown in Table 8.

3.2.2. Sodium adsorption ratio

The SAR index offers four quality categories: excellent, good, doubtful, and poor. Of those sampled, 23 wells (41%) were in the SAR range of 0–10 SAR, i.e., excellent. These areas – dark green in Figure 5 – are mainly in the south. A further nine wells (16%) reported SAR between 10 and 18, indicating good quality (light green in Figure 5), mainly in the centre and east of the aquifer. The SAR in 12 (22%) wells was between 18 and 26, classified as doubtful quality, and in the remaining 12 (22%) of those sampled, the SAR exceeded 26, indicating poor quality.

SAR was generally more optimistic than %Na, suggesting that most of the Saveh aquifer is suitable for irrigation. The indices showed the aquifer's northern and central regions as being less suitable than the other regions. The SAR for each well sampled is shown in Table 8.

3.2.3. Irrigation water quality index

As seen in Figure 6, none of the wells sampled in the study region yielded water with IWQI in the 85–100 range, i.e., good quality with no restrictions for irrigation, and only two (3%) were in the 70–85 range, which represents low restrictions. There were five wells (9%) in the 55–70 range (moderate restriction) and six wells (11%) in the 40–55 range (high restrictions for irrigation). The remaining 43 wells (77%) were all in the 0–40 range, indicating a need for severe restrictions on irrigation use.

Table 8 | Values of %Na, SAR, and IWQI for each well sampled in the Saveh aquifer

Well	%Na (meq/L)	SAR (meq/L)$^{1/2}$	IWQI	Well	%Na (meq/L)	SAR (meq/L)$^{1/2}$	IWQI	Well	%Na (meq/L)	SAR (meq/L)$^{1/2}$	IWQI
1	92.82	75.81	31.58	20	79.34	19.90	22.33	39	66.10	8.45	34.31
2	94.98	92.95	22.86	21	87.29	24.79	30.29	40	74.24	15.71	26.14
3	97.30	159.66	19.24	22	74.91	16.74	26.27	41	35.34	3.15	57.77
4	96.07	134.56	17.98	23	78.65	21.84	25.22	42	44.41	18.77	20.06
5	94.28	111.51	16.33	24	95.97	127.46	15.19	43	59.12	7.09	35.95
6	69.52	14.80	25.51	25	95.52	94.14	22.49	44	81.91	21.04	25.53
7	96.42	115.54	25.63	26	59.04	7.15	53.14	45	58.17	7.26	34.04
8	82.35	25.76	25.87	27	38.86	3.24	55.24	46	72.78	11.85	29.31
9	96.76	144.38	14.76	28	51.48	4.95	39.05	47	81.24	21.69	36.69
10	59.51	4.40	66.36	29	30.09	11.04	31.34	48	73.65	20.12	20.21
11	60.04	4.86	47.57	30	50.58	4.10	48.73	49	37.55	19.05	23.57
12	53.78	4.66	43.04	31	78.21	18.29	27.97	50	70.64	7.79	38.01
13	51.43	5.19	38.12	32	51.13	3.52	60.25	51	76.47	16.63	25.29
14	30.84	2.08	68.77	33	64.99	7.72	40.23	52	67.48	11.40	30.62
15	89.97	69.42	36.26	34	66.81	6.73	41.85	53	61.10	6.27	31.73
16	42.12	2.93	72.43	35	50.44	12.73	22.11	54	60.51	8.25	36.34
17	66.24	19.80	29.29	36	62.33	3.13	74.47	55	71.47	13.34	28.47
18	96.60	150.78	16.14	37	74.94	22.45	32.60	56	61.14	6.41	39.26
19	96.38	130.53	23.49	38	66.13	7.18	39.24	Average	69.24	34.13	34.33

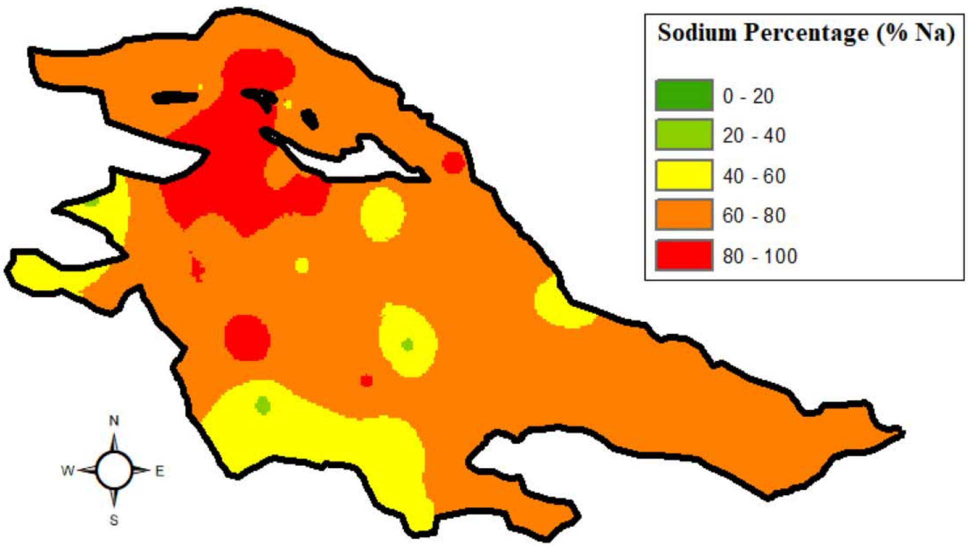

Figure 4 | %Na spatial distribution in the Saveh aquifer.

The average IWQI value for the Saveh aquifer was about 34, revealing a need for severe restrictions on agricultural use, with almost all areas unsuitable for irrigation. This could be because IWQI includes more qualitative parameters than %Na and SAR. For instance, EC, which indicates the salinity level, can show that the water is unsuitable for use in agriculture. The range of EC in the study area is 646–14,670 μS/cm, which is generally relatively high for agricultural purposes. The water quality standard for agricultural irrigation in Iran recommends a maximum EC of 3,000 μS/cm (DOE 2016). The IWQI for each well sampled is shown in Table 8. Groundwater quality classification in the study area using IWQI is indicated in Table 9.

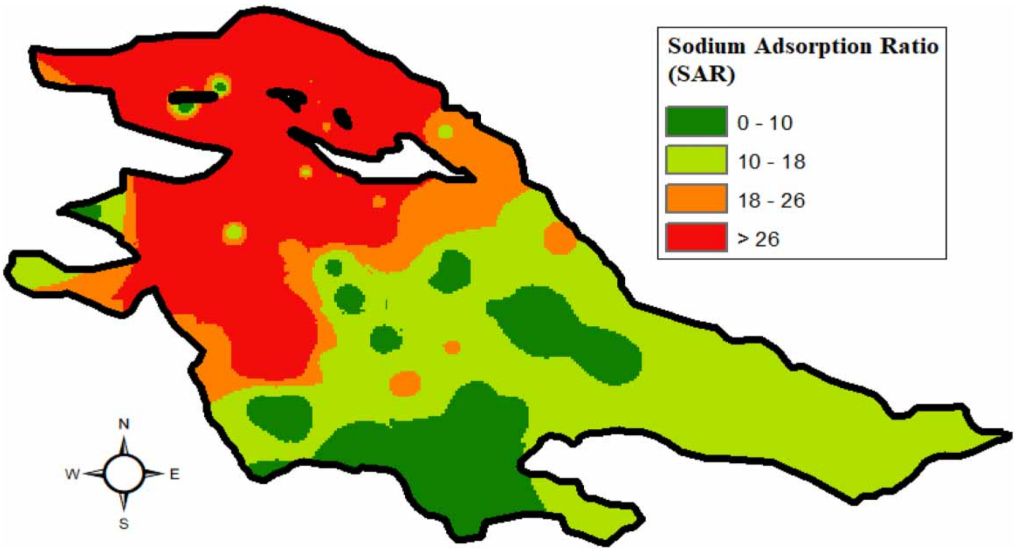

Figure 5 | SAR spatial distribution in the Saveh Aquifer.

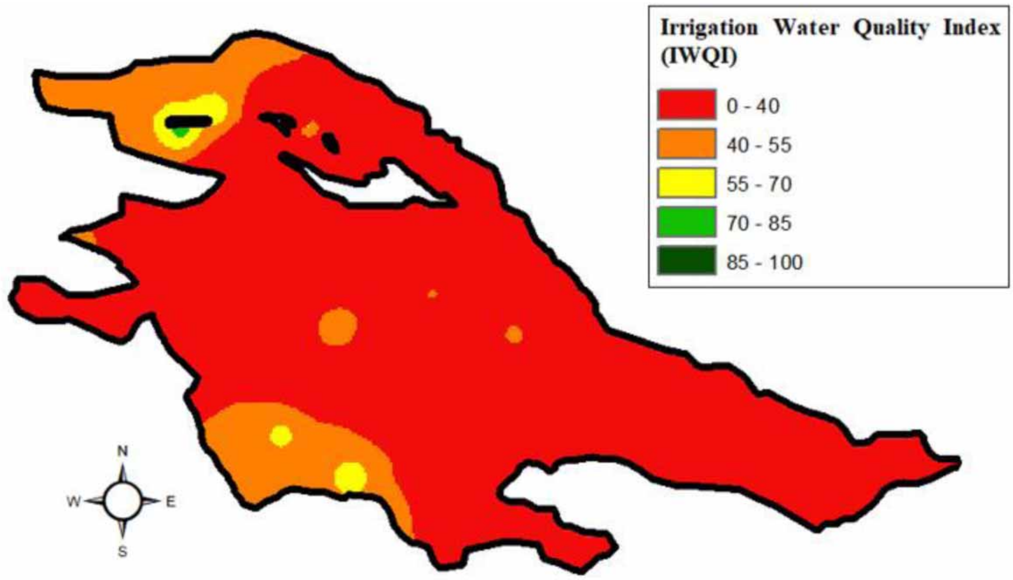

Figure 6 | IWQI spatial distribution in the Saveh aquifer.

3.3. Water type in the study area

A Piper plot (Figure 7) was used to evaluate the area's groundwater facies. It was drawn using AqQA software. As can be seen, the predominant water type in the area was sodium chloride (Na–Cl), found in 40 water samples (71.4%), which is consistent with an earlier study by Fakharian & Narany (2016). Some 15 (26.8%) and 1 (1.8%) of water samples were of the sodium bicarbonate ($Na–HCO_3$) and calcium bicarbonate ($Ca–HCO_3$) types, respectively. According to Parvaiz *et al.* 2021, water reported as of Na–Cl type on a Piper plot is highly saline.

The Piper diagram results are consistent with those obtained by IWQI and %Na, with respect to water salinity and its suitability for agricultural purposes. The predominance of Na–Cl type waters in the study area demonstrates the effect of evaporation as a major factor influencing the aquifer's water quality. Saveh is in the central plain of Iran, an arid and semi-arid area with high evaporation rates.

Table 9 | Groundwater quality classification for the Saveh aquifer based on IWQI, and suggestions for irrigated plants and soil

IWQI	Proportion of wells (%)	Suggestions (Abbasnia *et al.* 2018; Batarseh *et al.* 2021)	
		Plants	Soil
0–40 (severe restriction)	77	Just those that tolerate high salt.	Typically, avoid using water in this range for irrigation.
40–55 (high restriction)	11	Suitable for vegetation with normal to high salt resistance. Unique salinity control methods are required, except for water with low HCO_3, Cl, and Na concentrations.	This range can be used in areas with high permeability soils and without compact layers.
55–70 (moderate restriction)	9	Plants that can withstand moderate salt concentrations.	It can be used in areas with moderate to high soil permeability. Moderate leaching of salts can be useful to avoid soil degradation.
70–85 (low restriction)	3	Avoid irrigating salt-sensitive plants.	Soil with a light texture and average permeability can be irrigated. Soil leaching is suggested to avoid soil sodicity.
85–100 (no restriction)	0	Most plants can be irrigated; there is no toxicity risk.	Groundwater can be used for all types of soil, with low risk of salinity and/or sodicity issues

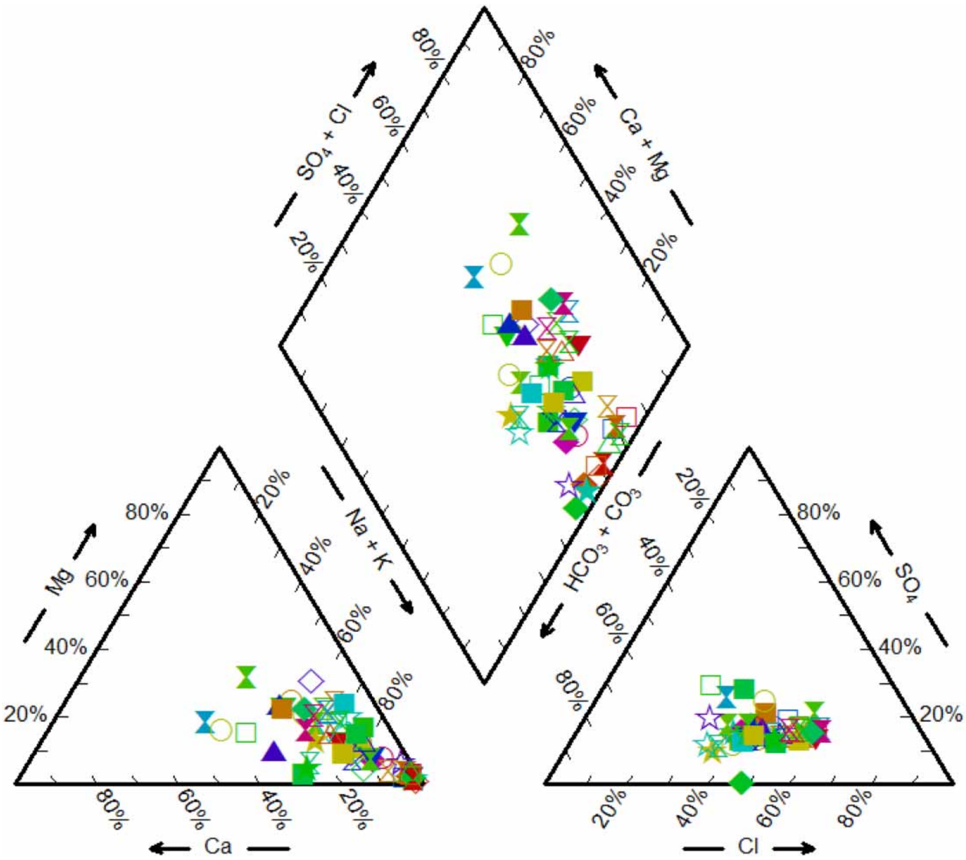

Figure 7 | Piper diagram reporting groundwater type.

4. CONCLUSIONS

In this study, the Saveh aquifer in central Iran was assessed in terms of heavy metal contamination (HPI and non-carcinogenic human health risk), suitability for agricultural irrigation (%Na, SAR, and IWQI), and water chemistry (Piper plot). HPI, used to assess heavy metal contamination of the aquifer for use as drinking water, exceeded 3,370, much higher than the maximum (100) recommended by WHO. The main cause was the high Cr concentrations found in most wells, probably attributable to the presence of many factories in the study area, including some operating in casting, pipe making, and metal container production.

The public health study, based on the non-carcinogenic health risk, demonstrated that both children and adults are at high risk through both drinking and dermal exposure. The cumulative HI values were changed from 0.42 to 44 (average 4.47) for adults and from 0.89 to 8,075 (average 8.13) for children. The variations observed resulted from varying heavy metal concentrations in wells in the research area. Discrepancies in the data for adults and children stemmed from distinct coefficients, such as body weight, average exposure duration, and so on, which were employed for each group in calculating HI. Southern areas were less dangerous for adults, but almost all were hazardous for children.

In the irrigation survey, %NA and IWQI were stricter than SAR in assessing water quality. SAR indicated that most of the Saveh aquifer is suitable for irrigation. %Na indicated, however, that most, particularly in the north, are not reliable. The strictest index, IWQI, showed almost all areas unsuitable for irrigation. According to the Piper plot, the dominant groundwater type was Na–Cl, followed by Na–HCO_3 and Ca–HCO_3. The results, indicating high water salinity, were consistent with those of IWQI and %Na.

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AUTHORS' CONTRIBUTIONS

Maryam Hasani Zonoozi supervised the study and planned and designed the research; Alireza Shahmirnoori and Mehrshad Samadi prepared the first draft of the manuscript; all authors contributed to the interpretation of the results and in writing, reading, and approving the final version of the manuscript, as well.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abbasnia, A., Radfard, M., Mahvi, A. H., Nabizadeh, R., Yousefi, M., Soleimani, H. & Alimohammadi, M. 2018 Groundwater quality assessment for irrigation purposes based on irrigation water quality index and its zoning with GIS in the villages of Chabahar, Sistan and Baluchistan, Iran. *Data in Brief* **19**, 623–631. https://doi.org/10.1016/j.dib.2018.05.061.

Afshar, A., Khosravi, M. & Molajou, A. 2021 Assessing adaptability of cyclic and non-cyclic approach to conjunctive use of groundwater and surface water for sustainable management plans under climate change. *Water Resources Management* **35**(11), 3463–3479. https://doi.org/10.1007/s11269-021-02887-3.

Afzaal, M., Hameed, S., Liaqat, I., Ali Khan, A. A., abdul Manan, H., Shahid, R. & Altaf, M. 2022 Heavy metals contamination in water, sediments and fish of freshwater ecosystems in Pakistan. *Water Practice & Technology* **17**(5), 1253–1272. https://doi.org/10.2166/wpt.2022.039.

Ahmed, S., Akhtar, N., Rahman, A., Mondal, N. C., Khurshid, S., Sarah, S., Ali Khan, M. M. & Kamboj, V. 2022 Evaluating groundwater pollution with emphasizing heavy metal hotspots in an urbanized alluvium watershed of Yamuna River, Northern India. *Environmental Nanotechnology, Monitoring & Management* **18**, 100744. https://doi.org/10.1016/j.enmm.2022.100744.

Amjad, H., Hashmi, I., Rehman, M. S. U., Awan, M. A., Ghaffar, S. & Khan, Z. 2013 Cancer and non-cancer risk assessment of trihalomethanes in urban drinking water supplies of Pakistan. *Ecotoxicology and Environmental Safety* **91**, 25–31. https://doi.org/10.1016/j.ecoenv.2013.01.008.

Asif, M. A. 2018 A theoretical study of the size effect of carbon nanotubes on the removal of water chemical contaminants. *Journal of Research in Science, Engineering and Technology* **6**(04), 21–27.

AUT 2015 Prevention, control and reduction of aquifer pollution studies in Saveh plain (in Persian), Amirkabir University of Technology, Tehran, Iran.

Batarseh, M., Imreizeeq, E., Tilev, S., Al Alaween, M., Suleiman, W., Al Remeithi, A. M., Al Tamimi, M. K. & AL Alawneh, M. 2021 Assessment of groundwater quality for irrigation in the arid regions using irrigation water quality index (IWQI) and GIS-Zoning maps: Case study from Abu Dhabi Emirate, UAE. *Groundwater for Sustainable Development* **14**, 100611. https://doi.org/10.1016/j.gsd.2021.100611.

Bouaroudj, S., Menad, A., Bounamous, A., Ali-Khodja, H., Gherib, A., Weigel, D. E. & Chenchouni, H. 2019 Assessment of water quality at the largest dam in Algeria (Beni Haroun Dam) and effects of irrigation on soil characteristics of agricultural lands. *Chemosphere* **219**, 76–88. https://doi.org/10.1016/j.chemosphere.2018.11.193.

Chowdhury, A. & Rahnuma, M. 2023 Groundwater contaminant transport modeling using MODFLOW and MT3DMS: A case study in Rajshahi City. *Water Practice and Technology* **18**(5), 1255–1272. https://doi.org/10.2166/wpt.2023.076.

DOE, Department of Environment (Iran) 2016 Iran's Water Quality Standard (in Persian), Tehran, Iran.

Fakharian, K. & Narany, T. S. 2016 Multidisciplinary approach to evaluate groundwater salinity in Saveh Plain, Iran. *Environmental Earth Sciences* **75**(7), 1–11. https://doi.org/10.1007/s12665-015-5104-1.

Gao, W., Zhang, J., Zhang, W., Sun, D., Guo, J., Zhao, S., Zeng, Y. & Liu, X. 2023 Hydrochemical characteristics and driving factors of travertine deposition in Huanglong, Sichuan, SW, China. *Water Science and Technology* **87**(5), 1232–1249. https://doi.org/10.2166/wst.2023.048.

Kumar, V., Parihar, R. D., Sharma, A., Bakshi, P., Sidhu, G. P. S., Bali, A. S., Karaouzas, I., Bhardwaj, R., Thukral, A. K., Gyasi-Agyei, Y. & Rodrigo-Comino, J. 2019 Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. *Chemosphere* **236**, 124364. https://doi.org/10.1016/j.chemosphere.2019.124364.

Mbhele, T. P. & Khuzwayo, S. 2023 Dimensions of supply risks in the supply of water: A case of Zet district municipality. *International Journal of Innovative Research and Scientific Studies* **6**(2), 399–417. https://doi.org/10.53894/ijirss.v6i2.1491.

Meireles, A. C. M., Andrade, E. M. d., Chaves, L. C. G., Frischkorn, H. & Crisostomo, L. A. 2010 A new proposal of the classification of irrigation water. *Revista Ciência Agronômica* **41**(3), 349–357. https://doi.org/10.1590/S1806-66902010000300005.

Najafzadeh, M., Homaei, F. & Mohamadi, S. 2022 Reliability evaluation of groundwater quality index using data-driven models. *Environmental Science and Pollution Research.* **29**, 8174–8190. https://doi.org/10.1007/s11356-021-16158-6.

Parvaiz, A., Khattak, J. A., Hussain, I., Masood, N., Javed, T. & Farooqi, A. 2021 Salinity enrichment, sources and its contribution to elevated groundwater arsenic and fluoride levels in Rachna Doab, Punjab Pakistan: Stable isotope (δ2H and δ18O) approach as an evidence. *Environmental Pollution* **268**, 115710. https://doi.org/10.1016/j.envpol.2020.115710.

Piper, A. M. 1944 A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union* **25**(6), 914–928.

Rafiee, P. 2020 Comparison coagulant performance of chloroferric and polyelectrolyte (LT25) in removing organic materials turbidity in raw water resources of Ardabil treatment plant. *Journal of Research in Science, Engineering and Technology* **8**(1), 7–13. https://doi.org/10.24200/jrset.vol8iss1pp7-13.

Singh, U. K., Ramanathan, A. L. & Subramanian, V. 2018 Groundwater chemistry and human health risk assessment in the mining region of East Singhbhum, Jharkhand, India. *Chemosphere* **204**, 501–513. https://doi.org/10.1016/j.chemosphere.2018.04.060.

Spandana, M. P., Suresh, K. R. & Prathima, B. 2013 Developing an irrigation water quality index for Vrishabavathi command area. *International Journal of Engineering Research & Technology* **2**, 821–830.

Tong, S., Li, H., Tudi, M., Yuan, X. & Yang, L. 2021 Comparison of characteristics, water quality and health risk assessment of trace elements in surface water and groundwater in China. *Ecotoxicology and Environmental Safety* **219**, 112283. https://doi.org/10.1016/j.ecoenv.2021.112283.

USEPA. 2004 Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment) Final. In, edited by Office of Superfund Remediation and Technology Innovation U.S. Environmental Protection Agency.

WHO, World Health Organization 2017 Guidelines for Drinking-Water Quality: First Addendum to the Fourth Edition, Geneva, Switzerland.

Yang, F., Jia, C., Yang, X., Yang, H. & Chang, W. 2022 Probabilistic potential health risk quantification, hydrochemistry, driving forces of groundwater nitrate and fluoride in a typical irrigation district, Northern China. *Journal of Environmental Management* **323**, 116171. https://doi.org/10.1016/j.jenvman.2022.116171.

Yousefi, M., Ghoochani, M. & Mahvi, A. H. 2018 Health risk assessment to fluoride in drinking water of rural residents living in the Poldasht city, Northwest of Iran. *Ecotoxicology and Environmental Safety* **148**, 426–430. https://doi.org/10.1016/j.ecoenv.2017.10.057.

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