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Research article

Suitability of treated wastewater for irrigation and its impact on groundwater resources in arid coastal regions: Insights for water resources sustainability

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ABSTRACT

Water scarcity threatens agriculture and food security in arid regions like Saudi Arabia. The nation produces significant quantities of municipal wastewater, which, with adequate treatment, could serve as an alternative water source for irrigation, thereby reducing reliance on fossil and non-renewable groundwater. This study assessed the appropriateness of using treated wastewater (TWW) for irrigation in a dry coastal agricultural region in Eastern Saudi Arabia and its impact on groundwater resources. Field investigations were conducted in Qatif to collect water samples and field measurements. A multi-criteria approach was applied to evaluate the TWW's suitability for irrigation, including complying with Saudi Standards, the Irrigation Water Quality Index (IWQI), the National Sanitation Foundation water quality index (NSFWQI), and the individual irrigation indices. In addition, the impact of TWW on groundwater was assessed through hydrogeological and isotope approaches. The results indicate that the use of TWW in the study area complied with the Saudi reuse guidelines except for nitrate, aluminum, and molybdenum. However, irrigation water quality indices classify TWW as having limitations that necessitate the use for salt-tolerant crops on permeable and well-drained soils. Stable isotopic analysis (δ^2H, δ^{18}O) revealed that long-term irrigation with TWW affected the shallow aquifer, while deep aquifers were minimally impacted due to the presence of aquitard layer. The application of TWW irrigation has successfully maintained groundwater sustainability in the study area, as evidenced by increased groundwater levels up to 2.3 m. Although TWW contributes to crop productivity, long term agricultural sustainability could be enhanced by improving effluent quality, regulating irrigation practices, implementing buffer zones, and monitoring shallow groundwater. An integrated

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approach that combines advanced wastewater treatment methods, community involvement, regulatory oversight, and targeted monitoring is recommended to be implemented.

1. Introduction

Globally groundwater supplies around 36% of drinking water and 43% of agricultural water[1]. However, its quality increasingly threatened due to excessive extraction, pollution, and the effects of climate change [1–3]. It estimates that untreated wastewater discharge, agricultural runoff, and industrial pollution pollute almost 20% of the world's groundwater aquifers [1]. Trace metals, pesticides, chlorides, nitrates, and microbes are among other major pollutants contaminated fresh groundwater [4]. Groundwater contamination threatens global health and food production, especially in arid places like Saudi Arabia. Therefore. Maintaining groundwater quality and water security requires sustainable wastewater reuse and agricultural activities.

Water and food security challenges are more intense in arid regions due to the limited renewable freshwater resources, influencing crop yield and urban development (Folberth et al., 2020). Saudi Arabia serves as a good example of a dry country that faces significant water shortages owing to its minimal precipitation, intense desert environment, and high evapotranspiration rate [5]. These conditions have resulted in a significant reliance on non-renewable fossil groundwater and desalinated seawater to meet municipality and agricultural demands [6]. However, Unsustainable groundwater abstraction was beyond natural recharge rates, resulting in aquifer depletion and seawater intrusion in coastal regions [7,8]. To address the water security issue, unconventional water sources such as treated wastewater have been utilized to substitute the groundwater abstraction and reduce water scarcity and stress in many regions around the word[9].

The use of treated municipal wastewater effluent has the potential to significantly replace freshwater in the agriculture sector and conserving the limited freshwater resources [10]. The use of TWW irrigation has been applied by numerous countries to conserve freshwater resources, such as Jordan, The UAE, Tunisia, Mexico and Togo ([11]; Tampo, Alfa-Sika Mande et al., 2022). Treating wastewater to irrigate 10% of Jordan's crops replaces up to 75% of Jordan's vital freshwater [12]. The UAE utilized secondary and tertiary treated wastewater in parks, farms, and landscaping [13]. Through replacing TWW for groundwater extractions, this approach can dramatically reduce pressure on vulnerable coastal aquifers [8]. The use of TWW also contributed improve the soil fertility as TWW contains macro and micronutrient such as N, P, K, Fe, Zn, Cu and Mn [14,15]. High nutrient concentration contained by TWW typically has positive correlation with crop yield (H. jie [16]). Consequently, the utilization of TWW can reduce fertilizer applications and increase crop productivity as revealed by numerous studies ([17,18]; J. feng [19]). However, concerns about wastewater quality pose a significant barrier to further agricultural reuse ([20]; Mu'azu et al., 2020). Insufficiently treated effluent comprising excessive salts, sodium, trace elements, or pathogens presents significant risks of soil salinization, phytotoxicity, and crop contamination [11]. Sustainable, safe wastewater reuse in water-stressed areas requires integrated supervision and management of wastewater treatment, effluent quality, irrigation, and crop selection. Saudi Arabia has tight effluent quality criteria for agricultural reuse based on treatment level and irrigation type [21]. However, treated wastewater often exceeds electrical conductivity, sodium adsorption ratio, chloride, and other restrictions [22]. There are few investigations on treated wastewater's effects on underlying aquifers [23]. As Saudi Arabia expands treated wastewater irrigation, knowing these water quality challenges is crucial to protecting soil productivity, crop yields, and groundwater.

Furthermore, Saudi Arabia generates significant amounts of wastewater due to its dense cities [24]. The effluent, when properly treated, could provide an alternative water resource to help reduce unsustainable groundwater abstraction for agriculture. Recognizing this possibility, Saudi Arabia has significantly invested in sewage treatment facilities over the last three decades (Mu'azu et al., 2020)). The volume of wastewater treated at the secondary level increased from 0.11 billion m^3 in 2000 to 1.4 billion m^3 in 2016 [24]). The country's strategic plans promote the reuse of this treated effluent, notably the National Water Strategy 2018–2030, which targets 70% reuse of municipal wastewater by 2030 (Mu'azu et al., 2020). Agriculture is the primary beneficiary of treated wastewater in Saudi Arabia, accounting for roughly 22% of effluent reuse [25]. The application of treated wastewater for crop irrigation increased from eighty-seven million m^3 in 2000 to around 422 million m^3 by 2022 [26,24]. Such application can significantly relieve stress on vulnerable coastal aquifers by substituting treated wastewater for groundwater extractions. In dry regions with sandy aquifers, wastewater irrigation delivers nutrients that improve soil fertility and crop production[20]. However, concerns about wastewater quality pose a significant barrier to more comprehensive agricultural reuse [26]. Untreated effluent containing high salts, sodium, trace elements, or pathogens offers significant risks of soil salinization, phytotoxicity, and crop contamination [27].

The current research has developed to evaluate two hypotheses. Firstly, the used treated wastewater for irrigation in the studied region is suitable for irrigation and meets the Saudi water quality standards. Secondly the use of treated wastewater for irrigation could serve as alternative to the fresh groundwater abstraction from deep and fossil aquifer, thus, contributing to stabilize water level and preventing the depletion of these critical water sources. The main goal of the current research is to conduct comprehensive evaluation of the suitability of TWW for irrigation in an arid coastal region in Eastern Saudi Arabia, utilizing standard water quality indicators that are widely used to assess the water quality for irrigation purposes ([2]; Eid et al., 2023; Ibrahim et al., 2023 [3]; Osta et al., 2022). The specific objectives are to 1) analyze physical, chemical, and microbial water quality parameters of treated wastewater and groundwater; (ii) evaluate irrigation water quality using a multi-criteria approach; (iii) determine stable isotopic compositions to fingerprint wastewater and groundwater sources; and (iv) delineate groundwater aquifer impacted by treated wastewater recharge using mixing models. The results offer new insights on improving the quality of treated wastewater, regulating irrigation practices, and monitoring groundwater to enhance the sustainability of utilizing wastewater for agricultural purposes.

2. Background of treated wastewater use for irrigation in Saudi Arabia

Recycling TWW for agricultural irrigation is a significant freshwater conservation approach in desert environments such as Saudi Arabia. The country generates substantial quantities of municipal wastewater, which has the potential to supplement the limited freshwater supplies with proper treatment and appropriate reuse [25]. Over the last decades, Saudi Arabia has consistently and gradually progressed in wastewater treatment and subsequent reuse. According to the Ministry of Environment, Water, and Agriculture, the total volume of treated wastewater produced in Saudi Arabia in 2022 was 1.93 billion m^3. As shown in Fig. 1, 22% (422 million m^3) of this volume was reused for agricultural irrigation (MEWA, 2022). The percentage of treated wastewater reused for irrigation increased from 16% in 2017 to 22% in 2022, demonstrating increased wastewater reuse adoption. However, there is still tremendous potential to expand the use of treated wastewater in agriculture [28].

Several significant aspects influence the application of treated wastewater in Saudi agriculture. These elements encompass the escalating scarcity of water resources, an increase in wastewater production, governmental efforts to optimize water reuse, and the willingness of farmers to adopt wastewater irrigation practices (Mu'azu et al., 2020). Several key government policies have been implemented to support the practice of TWW reuse. These policies include the National Water Strategy, the National Environmental Strategy, and the wastewater reuse regulations published by the Ministry of Environment, Water and Agriculture [21]. The utilization of TWW is subject to strict quality standards and guidelines in order to safeguard public health. The regulations delineate the requisite level of treatment based on the specific method of crop irrigation. To allow for the free watering of crops that are consumed raw, it is necessary to implement tertiary treatment methods that adhere to rigorous microbiological requirements. According to the ministry guidelines [21]), secondary treatment is deemed sufficient for the restricted irrigation of animal feed, industrial crops, and landscaping areas with limited human contact.

3. Methods and materials

3.1. Study area

The study area is in eastern Saudi Arabia, on the edge of the Arabian Gulf, with geographic coordinates 26°35′38.82"N–26°29′2.38"N, 49°57′1.79"E−50°4′18.94"E (Fig. 2). The region includes Anak city and the southern part of Qatif city (Fig. 1). The terrain in the area is typically higher in the west and lower in the east, with elevations reaching up to 12 m. The landscape primarily consists of a flat coastal plain with a dome structure in the western part. The Eastern Province in Saudi Arabia is characterized by its arid climate and limited water resources, making it highly susceptible to the adverse effects of climate change. Over recent decades, the region has experienced a population annual growth of approximately 2.5% from 2010 to 2022 and rapid urbanization, leading to a deterioration in water quality in the province [29]. Notably, the Eastern Province undergoes a hot desert climate with high temperatures during the summer months and relatively mild winters. The months of June, July, and August have the highest average temperatures, reaching 36 °C [7,30]. During the summer, the maximum temperatures can exceed 47 °C. In contrast, temperatures in the winter months of December, January, and February typically range between 15 and 18 °C.

An analysis of precipitation data from the period of 1980–2019 (obtained from https://od.data.gov.sa/) reveals that Eastern Saudi Arabia consistently experiences limited rainfall, characterized by an annual rate ranging from 13 mm to 221 mm, with an average of 97 mm. The region has an arid climatic condition, with a notable increase in precipitation during the winter season (November to March). These months have the highest average monthly rainfall, reaching 19 mm in March. The summer months from June to September are usually dry, with minimal precipitation.

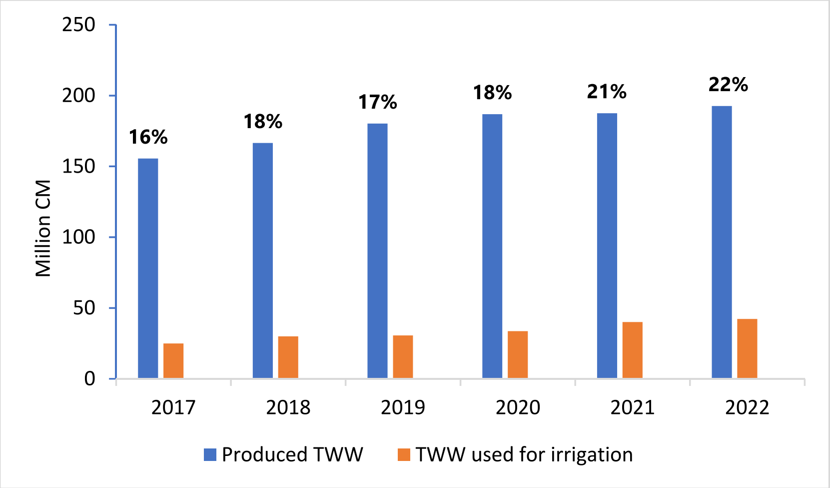

Fig. 1. Trends in treated wastewater production and utilization for irrigation in Saudi Arabia, 2017–2022 (MEWA, 2022).

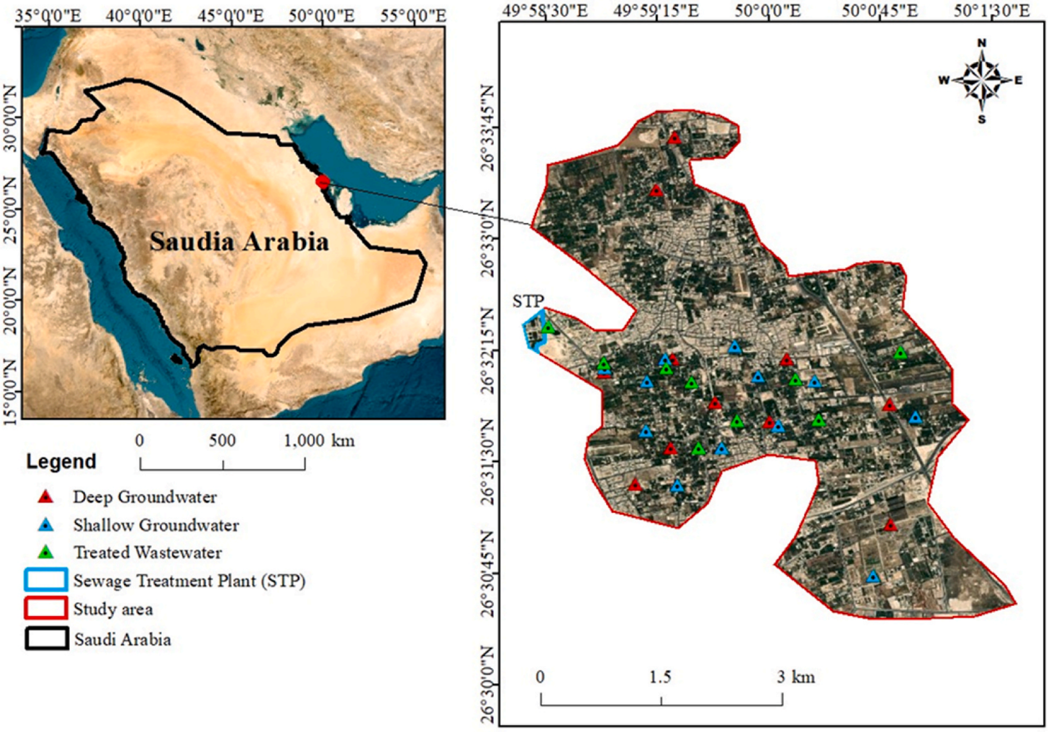

Fig. 2. Study area map showing the location of water samples and sewage treatment plant.

Geologically, the study area underlain by Phanerozoic sediments of the Arabian Platform and comprised by several formations, involving Wasia, Aruma, Umm Er Radhuma (UER), Rus, Dammam, Neogene and Quaternary deposit as shown by Fig. 3 [31]. Khobar, Alat and Neogene aquifers are the main aquifer that supply water demand in the study area [32]. Both Khobar and Alat aquifer are located within Dammam Formation and separated by Alat marl aquitard, thus they are commonly referred to as Dammam aquifer. The Khobar aquifer was developed in the lower section of Dammam Formation, which is comprised by karstified and fissured dolomitic limestone, with average depth of 130 m [7]. Alat aquifer was formed in the dolomitic limestone section of Dammam Formation. The depth of this aquifer varies from a few to over 100 m, with an average depth of 25 m [32]. Meanwhile, Neogene aquifer is unconfined

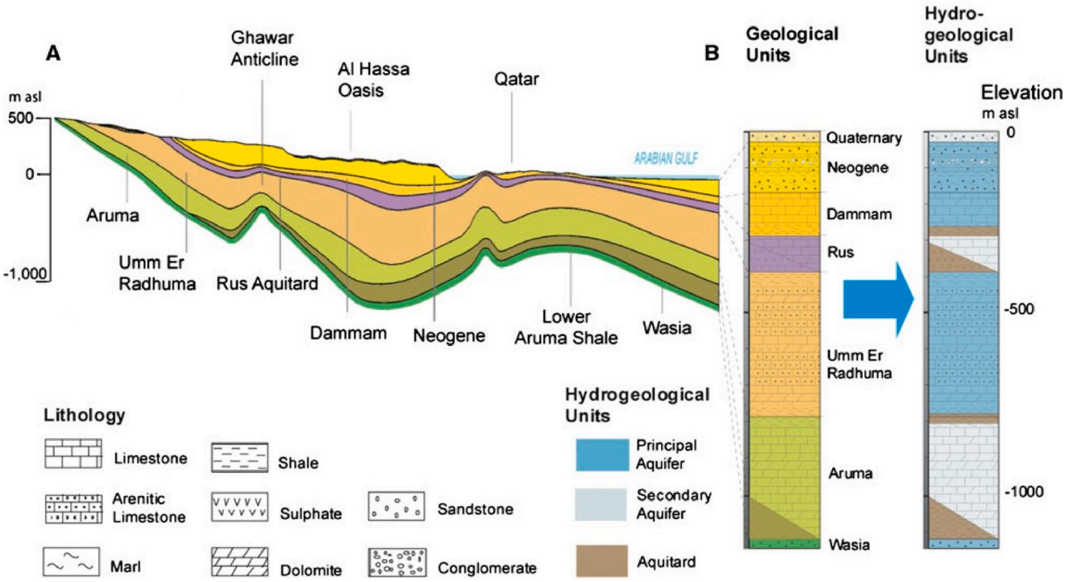

Fig. 3. (A) The cross section of geological setting and (B) geological and hydrogeological units in the study area[31].

and shallow aquifer, with maximum depth of 12 m [33].

3.2. Water sampling and field investigation

Water sampling and field measurements were conducted to investigate the suitability of treated wastewater for irrigation and its impact on groundwater quality. Water sampling has been performed in accordance with the procedures and protocols specified in united state environmental protection agency (USEPA) guidelines [34]. A total of 33 water samples were obtained, including 9 treated wastewater samples from irrigation supply channels, 12 shallow groundwater samples ($<$2 m depth), and 12 deep groundwater samples ($>$70 m depth). In addition, two shallow groundwater samples were collected from agricultural areas that were not irrigated with treated wastewater to serve as a baseline. The water samples have been collected from the groundwater well after pumping for more than 10 min and remove any stagnant water. The field physical and chemical parameters of water including pH, dissolved oxygen (DO), electrical conductivity (EC), temperature, turbidity, and oxidation-reduction potential (ORP/Eh) were directly assessed at the sampling sites. Multiparameter probe (model: HI9829) equipped by GPS manufactured by Hanna Instruments and has accuracy of ±0.02 pH, ±1.0 mV ORP, ±1 μS/cm EC, ±0.3 FNU turbidity, ±1.5% of reading DO, ±0.15 °C temperature was utilized to obtain the in-situ measurements. The real-time field data offers crucial foundational insights about the physical and chemical properties of the irrigated water. The water samples were collected using One-liter high-density polyethylene containers and subsequently transferred to the KFUPM laboratory for ions composition and isotope analysis(^{2}H and ^{18}O).

3.3. Experimental analysis

The ion composition (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, HCO_3^-, Br^-, NO_3^-, SO_4^{2-}) of all water samples was analyzed in the environmental laboratory at KFUPM. The titration method was used to measure the concentration of HCO_3^-, with a pH of 4.5, employing an Automated Titrator & Multi-Parameter Analyzer (manufactured by MANTECH (MANTECH Company©, Guelph, Canada)[35]. The gravimetric method was used to determine the concentration of total dissolved solids (TDS). The concentrations of the major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (Cl^-, Br^-, NO_3^-, SO_4^{2-}) were determined using a Dionex ICS Thermo Fischer 1100 Ion Chromatograph (manufactured by Thermo Fisher Scientific with detection limit of 0.05 ppm) and based on the reference method of EPA 9056A [36]. A test was performed to determine the accuracy of the analytical results through an assessment of the ionic balance. According to the requirements established by [37], an acceptable balance fell within a range of ±10%. The stable isotopes of oxygen and hydrogen of all water samples were analyzed in the Stable Isotope Laboratory of the College of Petroleum Engineering and Geosciences at KFUPM. The evaluation of 1.8 L sample injections was conducted utilizing cavity ringdown spectroscopy with the utilization of a Picarro L2130i water isotope analyzer. The isotope values for d18O and d2H (dD) are expressed as a deviation in parts per thousand (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) global reference standard. The calibration of instruments is performed using water reference materials provided by IAEA, USGS, and NBS. To address the influence of established instrumental memory effects, a total of five injections were performed for each sample and laboratory working standard. The reported value was determined by calculating the average of the fourth and fifth injections. The analytical precision for oxygen was ±0.08‰, whereas for hydrogen it was ±0.41‰, as determined through the replication of the lab working standard and the duplication of two blind samples [38].

3.4. Water quality evaluation for irrigation uses

Comprehensive water quality assessment methodologies were used to evaluate the suitability of the treated wastewater and deep groundwater for irrigation use. The irrigation water quality was assessed using Saudi standards for unrestricted irrigation with TWW [21], and common indices including the Irrigation Water Quality Index (IWQI), and National Sanitation Foundation Water Quality measure (NSFWQI). These aggregated indices combine various parameters to produce an integrated evaluation of irrigation appropriateness. Individual indices were also calculated to assess specific hazards, such as the Potential Salinity (PS) index for salinity risk, the Sodium Absorption Ratio (SAR) for sodium hazard, the Residual Sodium Carbonate (RSC) for bicarbonate toxicity, the Permeability Index (PI) for infiltration risks, and the Magnesium Absorption Ratio (MAR) for phytotoxicity potential. The combination of aggregated indices and individual hazard indices provides a multifaceted picture of irrigation water quality. The integrated irrigation water quality evaluation approach aids in evaluating the sustainability of wastewater irrigation practices and developing management measures to limit salinity, sodicity, and other dangers that effect soil productivity and crop health.

3.4.1. Irrigation water quality index (IWQI)

The Irrigation Water Quality Index (IWQI) is a comprehensive model used to measure irrigation water quality based on particular water quality indicators. Electrical conductivity (EC), Sodium Adsorption Ratio (SAR), sodium ion concentration (Na+), chloride ion concentration (Cl-), and bicarbonate ion concentration (HCO3-) are the five water quality parameters used to calculate IWQI [39,40]. All concentration units for these parameters were changed from milligrams per liter [mg/L] to milliequivalents per liter [meq/L] for analytical purposes.

Eg.1 was used to calculate the quality rating values, denoted by qi ([41]). Following that, the sub-index for each parameter (EC, Na, HCO3, Cl, and SAR) was calculated by multiplying the corresponding qi values by the associated weight values. The assigned weight (w_i) is 0.211, 0.204,0.202, 0.194, 0.189 for the quality parameters EC, Na^+, HCO_3^-, Cl^-, SAR, respectively ([41,42]). The quality rating value (qi) for each quality parameter was computed based on observed data and the limiting values for each class (see Table A1 in appendix A). Furthermore, in order to bypass the constraints of the suggested index, the maximum observed values of each quality indicator were chosen as the upper limit for Class 4.

$$q_i = q_{max} - \left(\frac{\left(x_{ij} + x_{inf}\right) \times q_{imap}}{x_{amp}} \right) \tag{1}$$

Noted that $q_{\max}$ is the maximum of the related q_i class, parameter observed values x_{ij}, $x_{\inf}$ is the class's lower limit for the observed parameter, the class amplitude for qi classes is represented by q_{imap} (qi upper limit-qi lower limit), x_{amp} is the observed parameter's class amplitude.

Finally, the IWQI was calculated using Eq. (2).

$$\text{IWQI} = \sum_{1}^{n} q_i \times w_i \tag{2}$$

Where, 'n' denotes the number of parameters (5) in this equation, and 'w_i' is the weight of each parameter.

3.4.2. National Sanitation Foundation Water Quality index (NSFWQI)

The second metric used to evaluate the overall quality of tested treated wastewater and groundwater is the National Sanitation Foundation Water Quality measure (NSFWQI). It is a comprehensive water quality assessment index developed by (Brown et al., 1970) and supported by National Sanitation Foundation. It encompasses both physicochemical and microbiological parameters of water (dissolved oxygen, fecal coliform, pH, biochemical oxygen demand, temperature change, total phosphate, nitrate, turbidity, and total solids). The NSFWQI scales from 0 to 100, with higher scores indicating better water quality ([43]). The NSFWQI index has been adopted by many scholars worldwide to assess the water quality for irrigation ([44–47]). As indicated in Eq. (3), it is determined by adding the products of relative weights (w_i) and individual quality ratings (q_i) for each parameter (i).

$$\text{NSFWQI} = \sum_{1}^{n} w_i \times q_i \tag{3}$$

3.4.3. Irrigation indices

3.4.3.1. Potential salinity (PS).

Potential salinity (PS) is an important criterion for determining the feasibility of water for irrigation. It determines the total dissolved salt content or salinity of the water [48]. Higher potential salinity indicates poor water quality due to salt ion buildup, which may damage crops and deteriorate soil structure over time [49]. Potential salinity values are classified as excellent (<5 meq/L), good (5–10 meq/L), and allowed (more than 10 meq/L) for irrigation [50]. The potential salinity of water is equal to the sum of the chloride ion concentration and half of the sulfate ion concentration (Eq. (4)) [48]. Monitoring potential salinity enables assessment of soluble salt hazard and classification of irrigation water sources for salinization prevention [51].

$$\text{PS} = \text{Cl}^- + \frac{1}{2}\,\text{SO}_4^{2-} \tag{4}$$

3.4.3.2. Sodium adsorption ratio (SAR).

The SAR is used to assesses the sodium hazard caused by irrigation water based on the relative amount of sodium ions to calcium and magnesium ions[52]. It is an essential criterion for determining the appropriateness of water for irrigation and the potential for sodium accumulation issues that may damage soil structure [48]. SAR values are classified as excellent (<10) to good (10–20), permissible (20–40), and unsuitable (>40) irrigation water quality [53]. Higher SAR indicates a higher ratio of sodium relative to divalent cations, which might result in reduced soil permeability and infiltration capability [51]. The SAR is computed as the ratio of sodium ion concentration to the square root of half the calcium and magnesium ion concentrations as shown in Eq. (5) [52]. Monitoring SAR allows for the classification of irrigation water in terms of sodium hazard and the adoption of appropriate management measures [48].

$$\text{SAR} = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \tag{5}$$

3.4.3.3. Sodium percentage (Na%).

Sodium percentage (Na%) quantifies the proportion of sodium ions in irrigation water compared to total cations [48]. It indicates the sodium threat associated with the application of water for irrigation [51]. Irrigation water quality is classified as excellent (20%), good (20–40%), permissible (40–60%), or unsuitable (>60%) based on sodium percentage values [53]. Higher sodium percentages indicate an increased sodium proportion in the cation composition, which might cause soil aggregate dispersion and issues with soil structure [49]. The sodium percentage is derived by dividing the sodium ion concentration by the total cation concentration (Ca2+, Mg2+, Na+, K+) and multiplying by 100 (Eq. (6)) [48]. Assessing sodium percentage allows for sodium danger evaluation and irrigation water source appropriateness classification to prevent soil degradation[52].

$$\text{Na\%} = \frac{\text{Na}^+ + \text{K}^+}{\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+ + \text{Na}^+} \text{ x } 100 \tag{6}$$

3.4.3.4. Kelly's ratio (KR). Kelly's ratio (KR) is an irrigation index used to assess the balance of sodium and divalent cations in irrigation water, particularly calcium and magnesium [54]. It is used to determine to determine if the water is suitable for irrigation based on the potential sodium risk [49]. Kelly's ratio values are categorized into four classes as excellent (<1) or good (1–2), permissible (2–3), or unsuitable (>3) irrigation water [55]. Higher KR indicates an imbalance with proportionally higher sodium relative to divalent cations, which can cause issues with soil dispersion and permeability [56]. Kelly's ratio is determined as the ratio of sodium ion concentration divided by divalent cation concentration (calcium + magnesium) (Eq. (7)) [54]. Assessing Kelly's ratio allows irrigation water to be classified in terms of sodium hazard and relevant amendments or techniques to be chosen [48].

$$\mathrm{KR} = \mathrm{Na}^{+}\frac{\mathrm{Na}^{+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}} \tag{7}$$

3.4.3.5. Residual sodium carbonate (RSC). The RSC quantifies the excess carbonate and bicarbonate in irrigation water in relation to calcium and magnesium ions [52]. It shows the potential for sodium accumulation and associated soil structural issues when using water for irrigation [55]. For irrigation suitability, RSC values are classed as safe (<1.25 meq/L), marginal (1.25–2.5 meq/L), and hazardous (>2.5 meq/L) [57]. Higher RSC indicates an imbalance with higher carbonates compared to divalent cations, which increases sodium adsorption and dispersion in soils [56]. RSC is determined as the difference between carbonate + bicarbonate and calcium + magnesium ion concentrations (Eq. (8)) [52]. Evaluating RSC enables the assessment of excess carbonate hazard and the classification of irrigation water sources to minimize sodicity issues [48].

$$\mathrm{RSC} = \mathrm{CO_3} + \mathrm{HCO_3}/\mathrm{Mg} + \mathrm{Ca} \tag{8}$$

3.4.3.6. Permeability index (PI). The permeability index (PI) evaluates water's suitability for long-term irrigation based on the risk of permeability degradation and infiltration rate decrease in soil [50]. It accounts for the amounts of sodium, calcium, magnesium, and bicarbonate in water [55]. In terms of irrigation suitability, permeability index values are classed as class I (>75%), class II (25–75%), and class III (25%). Given the relative concentration of sodium and bicarbonate ions, lower PI suggests a higher risk of permeability degradation [48]. The permeability index is computed using the concentration of sodium, calcium, magnesium, and bicarbonate ions (Eq. (9)) [50]. The PI index can be used to estimate the potential for structural degradation of soils caused by irrigation water and to determine appropriate management techniques [56].

$$\mathrm{PI} = \frac{Na^{+} + \sqrt{HCO3^{-}}}{Ca^{2+} + Mg^{2+} + Na^{+}}\ \mathrm{x}\ 100 \tag{9}$$

3.4.3.7. Magnesium adsorption ratio (MAR). The magnesium adsorption ratio (MAR) assesses irrigation water's sodicity risk based on the percentage of magnesium compared to calcium and sodium ions [55]. It indicates that magnesium serves to offset sodium

Table 1
Physical and chemical characteristics of the TWW against Saudi standards.

Parameter	Minimum	Maximum	Average	Saudi standards MPL	% Exceeding MPL
pH	6.9	7.5	7.2	6–8.4	0
EC μS/cm	3447.1	3894.6	3595.9	3000	100
Turbidity (NTU)	0.4	1.3	1.1	5	0
TDS (mg/L)	1467.0	1708.0	1579.8	2500	0
NO_3(mg/L)	50.2	56.1	52.5	10	100
BOD (mg/L)	<2	2.0	2.0	10	0
Fecal Coliform (CFU/100 ml)	<1	52.0	37.3	2.2	88
Boron (B) (mg/L)	0.177	0.374	0.316	0.75	0
Lithum (Li) (mg/L)	0.047	0.068	0.057	2.8	0
Aluminum (Al) (mg/L)	1.737	8.618	4.260	5	33
Cobalt (Co) (mg/L)	0.001	0.003	0.002	0.05	0
Vanadium (V) (mg/L)	0.013	0.031	0.024	0.1	0
Manganese (Mn) (mg/L)	0.011	0.034	0.021	0.2	0
Nickel (Ni) (mg/L)	0.002	0.004	0.003	0.2	0
Copper (Cu) (mg/L)	0.021	0.064	0.041	0.4	0
Zinc (Zn) (mg/L)	0.047	0.122	0.081	4	0
Arsenic (As) (mg/L)	0.002	0.008	0.005	0.1	0
Iron (Fe) (mg/L)	1.836	4.846	3.968	5	0
Chromium (Cr) (mg/L)	0.001	0.003	0.002	0.1	0
Lead (Pb)(mg/L)	0.000	0.000	0.000	0.1	0
Mercury (Hg) (mg/L)	0.000	0.000	0.000	0.001	0
Molybdenum (Mo) (mg/L)	0.003	0.016	0.009	0.01	55
Cadmium (Cd) (mg/L)	0.000	0.000	0.000	0.01	0
Beryllium (Be) (mg/L)	0.000	0.000	0.000	0.1	0

adsorption and dispersion in soil [56]. MAR values above 50% indicate suitable irrigation water, 25–50% indicates marginal quality, and less than 25% indicates unsuitable irrigation water [58,59]. Lower MAR indicates a higher sodium concentration, which may damage soil structure [52]. The sodium, calcium, and magnesium ion concentrations are used to compute the magnesium adsorption ratio as shown in Eq. (10) [50]. The assessment of MAR allows for the evaluation of magnesium deficit and associated sodium hazard in irrigation water in order to prevent permeability degradation [48].

$$\text{MAR} = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \text{ x } 100 \tag{10}$$

4. Results and discussion

4.1. Quality assessment of irrigated water

4.1.1. Physical and chemical properties of TWW

The TWW samples were assessed for 24 essential irrigation quality parameters, including physical and chemical properties, heavy metals, and microbiological characteristics, to determine their suitability for irrigation. The results were compared with Saudi standards and presented in Table 1. The data indicate that the concentrations of 20 out of the 24 key parameters were below the Saudi standards for the reuse of TWW in unrestricted irrigation [21]. These parameters include EC, Turbidity, TDS, BOD, Boron (B), Lithium (Li), Cobalt (Co), Vanadium (V), Manganese (Mn), Nickel (Ni), Copper (Cu), Zinc (Zn), Arsenic (As), Iron (Fe), Chromium (Cr), Lead (Pb), Mercury (Hg), Cadmium (Cd), and Beryllium (Be). However, the tested TWW samples exceeded the Saudi standards for NO_3, Fecal Coliform, Aluminum (Al), and Molybdenum (Mo), with exceedance percentages of 100%, 88%, 33%, and 55%, respectively. The TWW's nutrient overloading, microbial health concerns, and heavy metal excesses indicate the need for continuous monitoring to maintain the water quality and reduce the adverse effects on crops, soil, and fresh groundwater resources.

4.1.2. The Irrigation Water Quality Index (IWQI)

The Irrigation Water Quality Index (IWQI) is widely recognized as a robust and efficient index model for evaluating the overall quality of irrigated water. Consequently, it holds significant value for decision-makers in the realm of policy development (([39,60]; M'nassri et al., 2022; [61])). The present index classifies the quality of irrigation water into five categories according to its possible impact on soil and plant toxicity. The categories are no restriction (IWQI = 85–100), low restriction (IWQI = 70–85), moderate restriction (IWQI = 55–70), high restriction (IWQI = 40–55), and severe limitation (IWQI = 0–40) (class (see Table A2 in appendix A) [39,61]. Higher values of IWQI indicate higher quality irrigation water with less usage limitations. The IWQI for treated TWW and groundwater samples was estimated using five parameters: electrical conductivity (EC), sodium (Na), chloride (Cl), bicarbonate

Table 2
Sub-index ($q_i x w_i$) of the water parameters (EC, Na, HCO3, Cl, and SAR) and the overall irrigation water quality index (IWQI) ([39]).

Water Source	Sample ID	EC	Na	HCO3	Cl	SAR	IWQI
		$q_i x w_i$	$q_i x w_i$	$q_i x w_i$	$q_i x w_i$	$q_i x w_i$	
Treated Wastewater	TW-1	6.9	0.2	18.5	3.7	6.2	36
	TW-2	6.7	2.0	18.4	3.7	7.7	39
	TW-3	6.6	1.9	18.9	3.5	7.7	39
	TW-4	6.7	2.3	19.5	3.6	7.8	40
	TW-5	7.8	2.4	19.2	3.5	7.9	41
	TW-6	6.7	2.2	18.8	3.6	7.6	39
	TW-7	7.1	1.8	17.1	3.7	7.2	37
	TW-8	7.1	1.8	20.5	3.6	7.2	40
	TW-9	6.0	0.5	20.3	2.7	6.6	36
	Min	**6.0**	**0.2**	**17.1**	**2.7**	**6.2**	**36**
	Max	**7.8**	**2.4**	**20.5**	**3.7**	**7.9**	**41**
	Average	**6.8**	**1.7**	**19.0**	**3.5**	**7.3**	**38**
Groundwater	DG-1	2.8	3.5	15.5	4.9	9.6	36
	DG-2	3.5	3.9	15.3	4.9	9.9	37
	DG-3	6.4	6.0	15.4	6.2	11.2	45
	DG-4	5.3	5.3	15.2	5.8	10.8	42
	DG-5	4.1	5.0	15.3	5.6	10.7	41
	DG-6	3.4	4.4	15.3	5.1	10.2	38
	DG-7	2.1	3.1	15.4	4.5	9.3	34
	DG-8	6.0	6.0	15.3	6.2	11.3	45
	DG-9	4.0	4.3	15.2	5.5	10.4	40
	DG-10	0.1	2.0	15.9	3.9	8.6	31
	DG-11	0.3	3.3	15.9	4.2	9.8	33
	DG-12	5.3	3.1	15.6	4.3	9.5	38
	Min	**0.1**	**2.0**	**15.2**	**3.9**	**8.6**	**31**
	Max	**6.4**	**6.0**	**15.9**	**6.2**	**11.3**	**45**
	Average	**3.6**	**4.2**	**15.4**	**5.1**	**10.1**	**38**

(HCO3), and sodium adsorption ratio (SAR), as reported in previous studies ([39,60]).

The result of IWQI for both TWW and groundwater samples is illustrated in Table 2. The IWQI values range from 31 to 45 for the groundwater samples, while the TWW samples displayed a range of 36–41. According to established thresholds for the Irrigation Water Quality Index (IWQI), 42% of tested groundwater samples were categorized as having high restriction (IWQI 40–55). This classification suggests that the water is suitable for plants with moderate to high salt tolerance, particularly for soil with good permeability and leaching capability. On the other hand, 58% of the groundwater samples exhibited a severe restriction range (IWQI 0–40), hence imposing limitations on its utilization to only accommodate plants with high salt tolerance. In comparison, 66% of the TWW samples had IWQI values less than 40, indicating suitable only for salt tolerant crops and soils. The remaining 34% of TWW samples (IWQI 40–55) were classed as high restriction, limiting utilization to moderate-high salt tolerance plants with controlled leaching. The lower IWQI readings for TWW are most likely due to increased sodium and chloride levels compared to groundwater. Although some of the treated wastewater was in the high restriction class, the majority of samples still had severe restrictions that need careful irrigation control.

Notably, the minimum, maximum, and average values for each sub-index (Table 2) indicate that Electrical Conductivity (EC), Sodium (Na) and Chloride (Cl) are the major sub-indices that contribute to lowering the overall Irrigation Water Quality Index (IWQI) for both TWW and groundwater samples. The sub-index values of Sodium (Na) and Chloride (Cl) are found to be the lowest in the TWW samples. The Na sub-index has a range of values from 0.2 to 2.4, with a mean value of 1.7. Likewise, the Cl sub-index has a range of values between 2.7 and 3.7, with an average of 3.5. The low sub-index values seen in this context are indicative of elevated levels of Sodium and Chloride. As a result, it can be observed that the Na and Cl sub-indices play a crucial role in lowering the Irrigation Water Quality Index (IWQI) of treated wastewater. For the tested groundwater, the sub-indices for Electrical Conductivity (EC) and Sodium (Na) display the lowest values. The EC sub-index has a range of 0.1–6.4, with an average of 3.6, while the Na sub-index has a range of 2.0–6.0, with an average of 4.2. These low sub-index values suggest strong electrical conductivity and salt concentrations. As a result, the EC and Na sub-indices are the most important contributors in lowering the overall Irrigation Water Quality Index (IWQI) for groundwater.

4.1.3. Water quality index (NSFWQI)

The NSFWQI was used to evaluate the quality of TWW and deep groundwater and the results are illustrated in Fig. 4. Through integrating several water quality parameters (DO, Fecal Coliform, pH, BOD, NO_3^-, PO_4^{3-},T, Turbidity, and TDS)[62,63], this index generates a comprehensive, standardized score that reflects the quality of the irrigation water. Fig. 4 depicts the NSFWQI results, which reveal substantial variations in quality between the two types of water sources. The NSFWQI for the TWW samples varied from 45.02 (TW-9) to 47.84, with an average value of 46.25. According to the NSFWQI standards, the investigated TWW classified within in the "bad water quality" category. In contrast, deep groundwater samples had higher NSFWQI values, ranging from 52.1 to 53.04, with an average of 52.61. These values indicate deep groundwater as medium water quality. The comparison highlights the finding that the TWW shows higher levels of pollution comparing to the deep groundwater, hence emphasizing the necessity for implementing more stringent treatment procedures to ensure the safety of the wastewater prior to its utilization. The present result is consistent with the earlier investigation conducted by [64], whereby they employed the NSFWQI as a means to evaluate the water quality within the Ganga River system located in Uttarakhand, India.

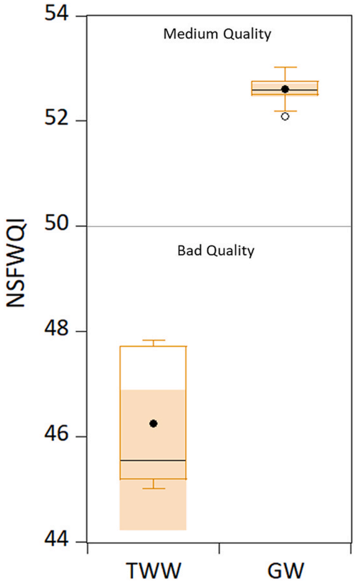

Fig. 4. NSFWQI for the irrigated treated wastewater (TWW) and groundwater.

4.2. Potential hazards of irrigation water on crops and soil

4.2.1. Salinity hazard

Electrical conductivity (EC) value was utilized to evaluate salinity hazard in this study. According to the classification of the United States' Salinity Laboratory, all samples from TWW and deep groundwater are classified in the unsuitable classes (Fig. 5). All samples are categorized as very high salinity class. However, the range of salinity of deep groundwater is higher than TWW. Therefore, it can be concluded that TWW is the better option as a source for irrigation than deep groundwater in terms of salinity.

4.2.2. Sodium hazard

The sodium hazard was analyzed by sodium adsorption ratio (SAR), sodium percentage (Na%), and Kelly's ratio (KR). SAR is usually associated with sodium or alkali hazard that can bring adverse effects on soil structure and aggregates. Based on our measurement, the SAR values in TWW and deep groundwater ranged from 10.48 to 12.55 and 6.44–9.61, respectively (Fig. 5). These results indicate that 100% of TWW and deep groundwater samples classified as good and excellent for irrigation, respectively. The second parameter to evaluate sodium hazard is Na% which in large quantity can reduce soil permeability. According to Na% analysis, all TWW samples had value above 50, thus indicating unsuitable for irrigation. On the other hand, 42% of water samples from deep groundwater are considered as good to permissible, while the rest of samples (58%) are categorized as unsuitable for irrigation (Fig. 5).

The value of Kelly's ratio (KR) can be associated with magnesium level, the increase of which can cause soil to harden and affect the crop yield. Based on KR values, the whole samples collected from TWW can be categorized as marginally suitable (Fig. 5). The KR value of deep groundwater had a range from 0.93 to 1.26 with 42% and 58% of samples are in suitable and marginally class, respectively.

The USDA's Wilcox diagram was used to assess the quality of water for irrigation obtained from TWW or groundwater and the results shown in Fig. 6 [52,65]. The Wilcox diagram classifies water samples into sixteen different categories, with C1S1 class suitable for irrigation and C4S4 class unsuitable. In this study, none of the tested water samples plotted in the irrigation suitability class C1S1. All TWW samples were classified as S2C4, indicating medium sodium and high salinity risks. Eighty percent of deep groundwater samples were classed as S2C4, suggesting medium sodium and moderate salinity hazards. However, 20% of deep groundwater samples were classified as S1C4, indicating low sodium but high salinity risk [7,66].

4.2.3. Carbonate hazard

The hazardous effect of carbonate was determined by the residual sodium carbonate (RSC) and permeability index (PI). According to the value of RSC, all water samples taken from the two different sources are regarded as safe for irrigation since their range is lower than 1.25 meq/L as shown in Fig. 5. The PI values of TWW and deep groundwater samples ranged from 64.19 to 67.84% and 55.61–60.46%, respectively (Fig. 5). These values indicate that all irrigation water samples are in good category.

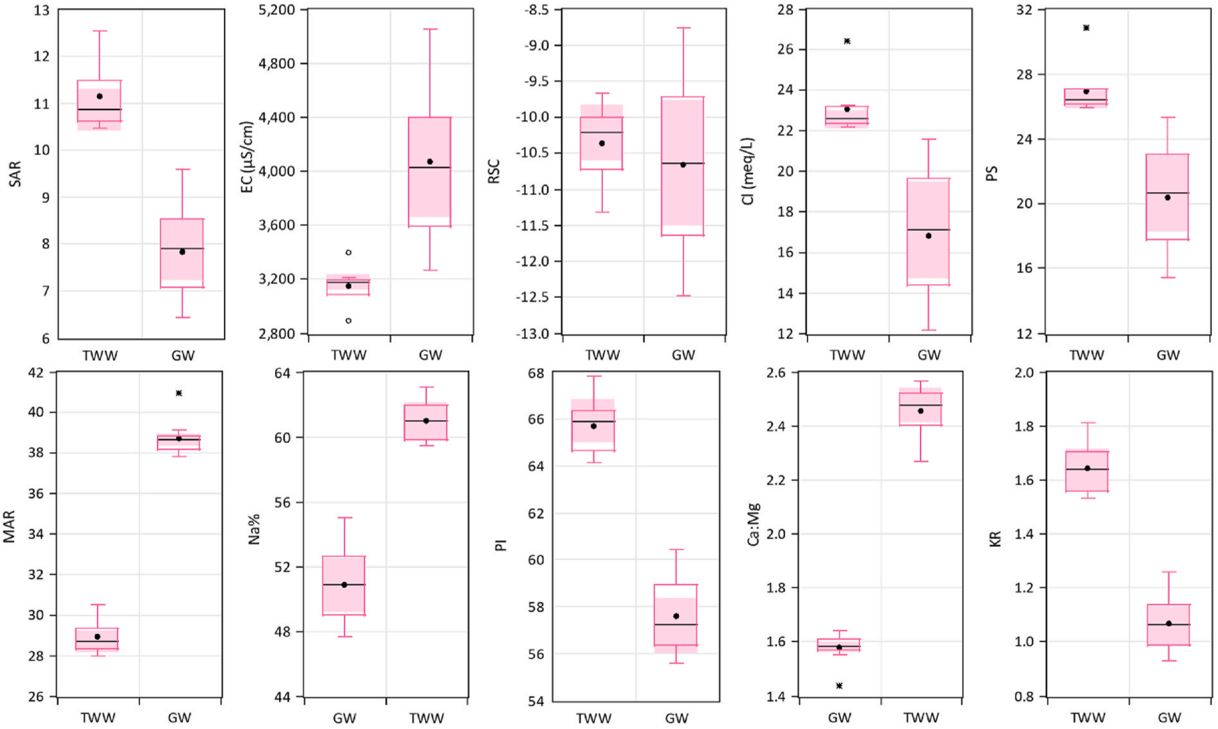

Fig. 5. The range of irrigation indices ten irrigation indices for the tested treated wastewater (TWW) and groundwater (GW).

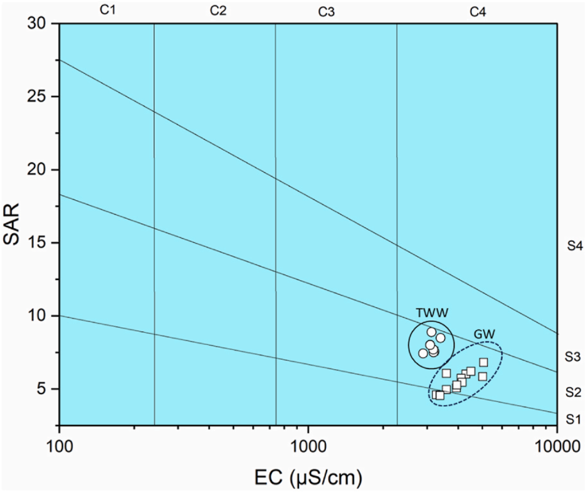

Fig. 6. Wilcox diagram illustrating the suitability for irrigation of the tested Treated Wastewater (TWW)(circle) and Groundwater (GW)(Square).

4.2.4. Magnesium hazard

In this study, magnesium hazard was investigated from magnesium adsorption ratio (MAR) and calcium to magnesium ratio (Ca/Mg). The results showed that all TWW and GW samples have value of MAR below 50, representing their suitability for irrigation purposes (Fig. 5). Furthermore, the values of Ca/Mg for all TWW and GW samples confirm their suitability for irrigation with no Magnesium Hazard on the crops and soil (Fig. 5).

4.2.5. Chloride hazard

The chloride hazard of all irrigation water sources was determined from the potential salinity (PS) and chloride content. Based on range of PS values, the use of all water sources from treated wastewater and deep groundwater for irrigation can be categorized as permissible to unsatisfactory (Fig. 5). Similar with PS, in general, Cl concentration above 10 meq/L could cause adverse effects on crops, therefore it should be used with restriction. Hence, based on Cl values, all irrigation water sources should be used with restriction since their concentrations are above 10 (Fig. 5).

4.3. Impact of treated wastewater (TWW) irrigation on groundwater

The impact of TWW used for irrigation in the study area on groundwater has been investigated via hydrogeological and isotope approaches. The water level of the deep aquifer (Dammam Aquifer) that historically used for irrigation and now substituted by TWW, has been mapped in the TWW-irrigated zones to illustrate the impact on groundwater quantity. As shown in the water level map of

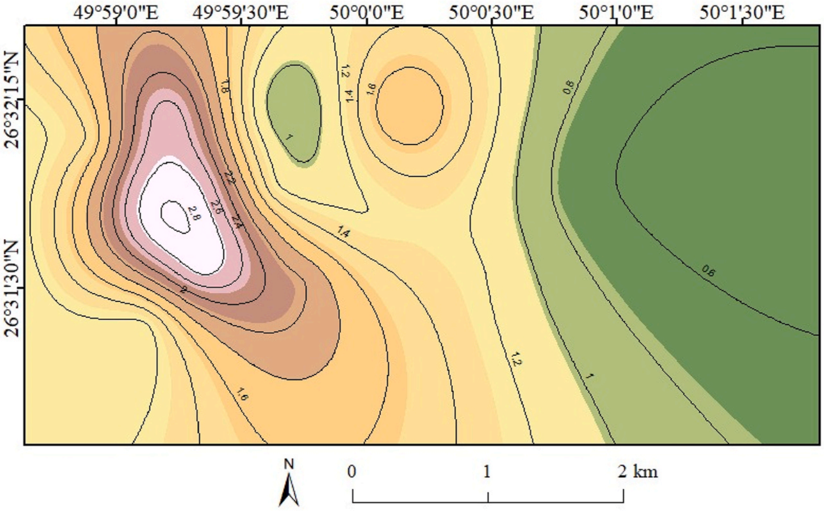

Fig. 7. Water level map of the deep aquifer (Dammam aquifer) showing significant level rise.

Dammam aquifer in Fig. 7, the water level has been increased to 2.8 m (above mean sea level) in the middle part of the study area, compared to the peripheral regions where the level is around 0.5 m. Such an increase in water level implies that the utilization of TWW has resulted in about 2.3 m reduction in groundwater abstraction. The positive influence has successfully safeguarded the non-renewable groundwater resources in the research area, thus alleviating the adverse consequences of excessive groundwater extraction.

The isotopic composition of a water source can provide a critical tool in hydrogeology for tracing and identifying water from different origins [67,68]. The isotopes of Hydrogen (δ^2H) and oxygen (δ^{18}O) are stable and resistant to biological changes, which makes them effective tracers [69]. In the current study, the isotopic composition of TWW, shallow groundwater, and deep groundwater were analyzed and compared to identify the impact of TWW irrigation on the groundwater resources (Table 3). The TWW showed δ^2H values ranging from −16.23 to −17.87 ‰ and δ^{18}O values ranging from −2.32 to −2.51 ‰. The values indicate a relatively narrow range for both isotopes, suggesting a consistent source or process influencing the isotopic composition. The isotopically heavier composition of the treated wastewater is expected, as it reflects enrichment from human activities such as water use and wastewater inputs.

The shallow groundwater has δ^2H values ranging from −20.58 to −26.82 ‰ and δ^{18}O values from −2.27 to −3.62 ‰. These ranges are broader than those observed for the TWW, indicating a greater degree of variability in the processes influencing the isotopic composition. This could be due to a variety of factors, including mixing with other water sources, fractionation due to evaporation and condensation, and interaction with geological materials. The deep groundwater has the most negative δ^2H and δ^{18}O values, ranging from −25.00 to −31.07 ‰ and −3.53 to −4.29 ‰, respectively. These values suggest that the deep groundwater is likely influenced by different processes than the shallow groundwater and treated wastewater. The more negative values may be due to a higher degree of fractionation, which could occur if the water has been in the ground for a longer period and has had more time to interact with geological materials.

The isotopic distinction between TWW and groundwater is significant and serves as an indication of their interactions. Isotopic compositions of shallow groundwater samples in TWW-irrigated areas closely align with TWW, indicating possible mixing process. Nevertheless, this pattern is not present in deep groundwater, suggesting that the influence of TWW on deep aquifer is negligible. The usefulness of isotope analysis for tracking TWW recharge is demonstrated by the clear isotopic distinction between TWW and groundwater by many researchers [69,70]. As seen in Fig. 8, shallow groundwater samples plot in the range between TWW and deep groundwater, with heavier isotopic compositions trending toward TWW values. It demonstrates the possibility of mixing with TWW used for irrigation in the research region. Deep groundwater, on the other hand, has more depleted isotope values, indicating a longer residence time and more contact with geologic materials. The finding could imply that TWW irrigation has no impact on deep aquifers.

Table 3

Isotope composition of TWW and groundwater, and fraction of TWW (FTWW).

Water Source	Sample ID	δ^2H [‰]	δ^{18}O [‰]	Fraction of treated wastewater (FTWW)	irrigation zone	Impacted Zone
Treated Wastewater	TW-1	−16.41	−2.33			
	TW-2	−16.60	−2.38			
	TW-3	−16.54	−2.35			
	TW-4	−16.44	−2.37			
	TW-5	−16.42	−2.33			
	TW-6	−16.23	−2.32			
	TW-7	−16.68	−2.35			
	TW-8	−16.66	−2.40			
	TW-9	−17.87	−2.51			
Shallow Groundwater	SG-1	−26.29	−3.62	<0.1	Non-TWW irrigation	No mixing
	SG-2	−22.42	−3.00	0.5	TWW irrigation	Intermediate Mixing
	SG-3	−21.85	−2.78	0.7	TWW irrigation	TWW-Dominated
	SG-4	−22.15	−2.89	0.6	TWW irrigation	Intermediate Mixing
	SG-5	−21.61	−2.79	0.7	TWW irrigation	TWW-Dominated
	SG-6	−21.19	−2.76	0.7	TWW irrigation	TWW-Dominated
	SG-7	−23.98	−3.16	0.4	TWW irrigation	Intermediate Mixing
	SG-8	−26.82	−3.51	0.2	TWW irrigation	low mixing
	SG-9	−22.54	−2.92	0.6	TWW irrigation	Intermediate Mixing
	SG-10	−26.73	−3.56	0.2	TWW irrigation	low mixing
	SG-11	−20.58	−2.64	0.8	TWW irrigation	TWW-Dominated
	SG-12	−21.04	−2.27	1.0	TWW irrigation	TWW-Dominated
Deep Groundwater	DG-1	−27.91	−3.86	<0.1	TWW irrigation	No mixing
	DG-2	−28.41	−3.89	<0.1	TWW irrigation	No mixing
	DG-3	−29.80	−4.04	<0.1	TWW irrigation	No mixing
	DG-4	−29.44	−4.01	<0.1	TWW irrigation	No mixing
	DG-5	−27.97	−3.83	<0.1	TWW irrigation	No mixing
	DG-6	−27.92	−3.84	<0.1	TWW irrigation	No mixing
	DG-7	−27.25	−3.71	<0.1	Non-TWW irrigation	No mixing
	DG-8	−29.30	−3.96	<0.1	TWW irrigation	No mixing
	DG-9	−28.50	−3.86	<0.1	TWW irrigation	No mixing
	DG-10	−25.00	−3.53	<0.1	Non-TWW irrigation	No mixing
	DG-11	−26.25	−3.78	<0.1	Non-TWW irrigation	No mixing
	DG-12	−31.07	−4.29	<0.1	Non-TWW irrigation	No mixing

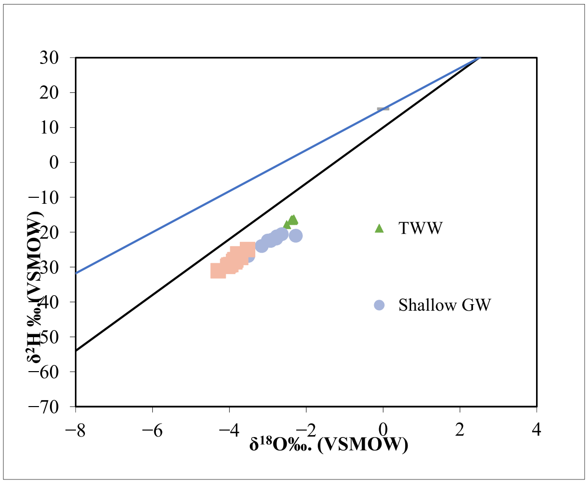

Fig. 8. Illustration of the isotopes of TWW and shallow and deep groundwater in comparison with local and global meteoric water lines.

Furthermore, the isotope mixing models have been used to evaluate the effect of treated wastewater (TWW) on groundwater and delineate groundwater zones impacted by TWW recharge ([71,72]). The models used δ^{18}O isotopic signatures of TWW (−2.5‰) and shallow groundwater from non-TWW-irrigated areas (−3.7‰), deep groundwater from non-TWW-irrigated areas (−3.87‰) as end-members to estimate the fraction of treated wastewater (FTWW) in groundwater samples (Table 3). The results of the mixing model showed that shallow groundwater samples collected from zones irrigated with TWW (SG-2 – SG-12) have elevated FTWW values, suggesting substantial mixing with TWW. In contrast, all tested deep groundwater samples in the TWW-Irrigated area consistently exhibit values of FTWW less than 0.1, suggesting that the deep aquifer remains protected from the influence of TWW. The aquitard layer that separates the shallow and deep aquifer plays a major role to protect the deep aquifer from recharge with irrigated TWW. The impacted zone of shallow groundwater has been classified based on FTWW values, with 30% of the shallow groundwater wells having high FTWW values (0.7–1.0), 40% having intermediate values (0.4–0.6), and 30% having low FTWW values (0.2). These findings highlight the importance of isotope mixing models for delineating groundwater zones impacted by TWW recharge and quantifying the degree of TWW influence. The spatial distribution of the FTWW in the study area was mapped as shown in Fig. 9. The map reveals that the shallow groundwater wells in the eastern part of the TWW-Irrigated area display high values of FTWW indicating more recharge of TWW. The higher values of the FTWW in the eastern part of the study area toward the coastal zone is mainly due to the decreasing the depth of water level eastward and the occurrence of the wells close to heavy irrigation zone and drainage canal. In addition, the wells located in the northern part also display medium to high values of FTWW. The water depth in this region is higher than the eastern part, however, increasing the values of FTWW mostly reflect heavy irrigation and close to drainage canals. Moreover, the groundwater

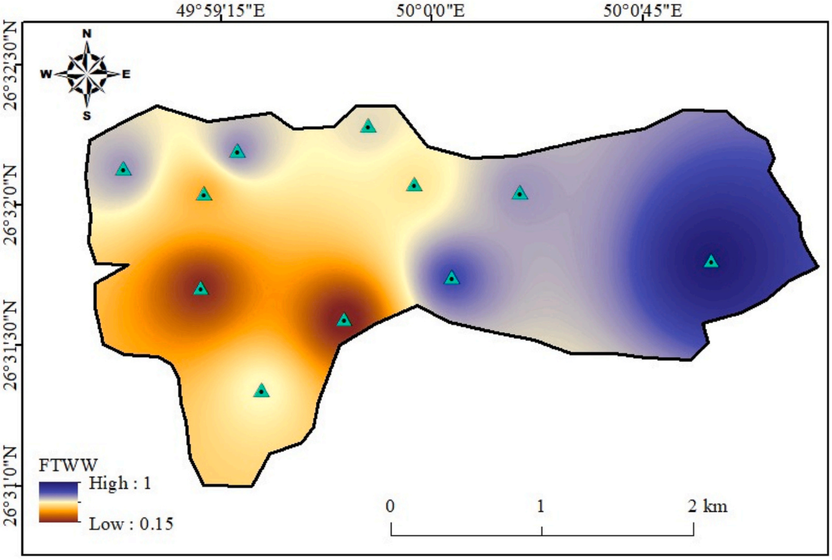

Fig. 9. Spatial map of the FTWW illustrates the rate of recharge of shallow groundwater by irrigation TWW.

wells in the Northwestern part of the TWW-irrigated area are less affected by TWW. However, long term irrigation by TWW could increase the rate of recharge of shallow aquifer with TWW.

4.4. Implications for groundwater sustainability

Using TWW for irrigating crops in arid regions is a crucial measure in advancing the sustainability of water resource management, especially in countries where groundwater sources are under stress [9,73]. Through complementing irrigation with TWW, the extraction rates from the fossil aquifers can be directly decreased [73]. In Jordan, for example, TWW fulfills more than 20% of the irrigation requirements, resulting in a substantial decrease in freshwater consumption [74]. Such conservation measures help reduce the risk of overuse, such as the depletion of aquifers and associated geohazards including land subsidence and the intrusion of seawater. These risks pose a threat to the long-term availability and quality of groundwater resources [7,32]. The findings from research conducted in the United Arab Emirates indicate that substituting 31% of groundwater utilized for agricultural purposes with treated wastewater (TWW) resulted in an average increase of 3.5 m in aquifer water levels [39]. They demonstrate the efficacy of this approach in relieving strain on depleted aquifers. Our current research demonstrates that utilizing a portion of TWW for irrigation in the agricultural areas of Al-Qatif Governorate has effectively improved the sustainability of groundwater resources. This practice has resulted in a notable increase of around 2.3 m in the groundwater level.

The conducted stable isotopic analysis (^{2}H, ^{18}O) in this work offers conclusive proof that irrigation with TWW has no noticeable effect on the deep aquifers of the region. The isotopic compositions of all deep groundwater samples showed no evidence of interaction with TWW irrigation. It is particularly evident in the deep aquifers, such as the Alat and Al-Khobar aquifers, which are accessed by municipal supply wells at depths exceeding 70 m and are effectively protected from potential surface contamination by low permeability aquitards (clay and marl of Dammam formation) that separate shallow and deep aquifer systems[7,32,75]. Consequently, the study conclusively demonstrates that long-term use of TWW for irrigation has no effect on the quality or integrity of the vital groundwater resources in deep aquifers. In contrast to deep aquifer, the study's isotopic tracing has clearly delineated a mixing zone in the shallow aquifer in regions irrigated with TWW. Several recent studies using a range of techniques have demonstrated shallow aquifer impacted from TWW irrigation, aligning with the findings of this research. A review by Mora et al. [73] concluded that TWW irrigation extensively affects shallow groundwater quality through leaching of salts, nutrients, and emerging contaminants. Research in Australia combining environmental isotopes with contaminant analysis showed clear evidence of TWW recharge into a shallow aquifer from irrigation areas [76]. Similarly, a study downstream of a wastewater treatment plant in Jordan revealed via water quality analysis that TWW irrigation loading had degraded shallow groundwater through increased salinity, nitrate, and metal concentrations [20]. It is crucial to implement measures to manage both the spatial extent and the hydrochemical effects of the mixing zone in the shallow aquifer. More regulated irrigation practices, such as limiting application rates and enhancing irrigation efficiency, could mitigate deep drainage losses [27]. Moreover, further optimization of wastewater treatment processes is essential to decrease the contaminant load in TWW before its reuse [77]. The establishment of buffer zones around irrigation fields can also help prevent the lateral subsurface spread of mixed water [78]. These strategies, coupled with improved water quality monitoring, can effectively manage the mixing zone created by TWW irrigation. With prudent management, the environmental and economic benefits of TWW reuse can be maintained while safeguarding shallow groundwater resources [79].

The study showed that TWW could sustain agricultural productivity in water-stressed coastal regions. However, a long-term management strategy is needed to maximize its potential [25,26]. The approach could involve implementing the most recent treatment methods to improve effluent quality and reduce health and environmental hazards from TWW reuse [13,28]. Effective regulatory frameworks and governance structures are needed for developing treatment standards, monitoring impacts, and enforcing compliance.

Furthermore, engaging stakeholders, such as farmers, by demonstrating the benefits and offering educational programs can also help TWW irrigation systems succeed [20,80]. Incorporating treated wastewater in water resource management to meet national goals can enhance sustainability, self-sufficiency, and climate resilience [81]. It is advisable that a cooperative management model that incorporates modern wastewater treatment and community participation could make treated municipal effluent a key option for food and water security in agriculturally dependent desert regions. The dynamic nature of shallow aquifer systems, especially as amended by TWW irrigation, requires careful and targeted monitoring. These programs should track conventional and emerging contaminants that may be harmful [82]. Groundwater in production wells in the TWW-irrigated field can be monitored for plumes and changes in patterns using isotopic and geochemical tracers [83]. Monitoring results can help create adaptive management strategies that rapidly address water quality issues and safeguard both the environment and public health. The findings of this study highlight the importance of implementing stringent regulatory standards that are customized to the unique environmental conditions and agricultural practices in different regions. The regulations should be based on scientific principles and consider the specific hydrogeological conditions of each site [84]. To ensure that TWW meets strict sustainable irrigation criteria, wastewater treatment operations may need upgrading with advanced treatment technologies that can remove salts, nutrients, and micropollutants to protect soil, plants, and groundwater [85].

The current work has important theoretical and practical implications for managing treated wastewater irrigation to ensure groundwater sustainability. On a theoretical level, the study highlights the need for an integrated method that combines water quality assessment, environmental tracers, and hydrogeological analysis to comprehensive evaluation of the impact on the fresh groundwater resources. The results demonstrate the intricate relationship between treated wastewater and various aquifer units, emphasizing the need to consider local geological conditions. On a practical level, the study underlines the need for continuous water quality monitoring, groundwater modeling, economic analysis, public participation, and adaptive policy. To facilitate adoption, the findings recommend strategic strategies for optimizing treated wastewater usage, such as regulated irrigation rates, treatment process upgrades, buffer zones, and conjunctive use programs. The integrated techniques, analytic tools, and management strategies described can provide a platform for evidence-based planning and regulation of sustainable treated wastewater reuse systems in water-scarce areas across the globe. The study recommends expanding, well-managed irrigation using treated wastewater to enhance groundwater sustainability while reducing environmental and health hazards. Moreover, the research on using treated wastewater for irrigation to promote groundwater sustainability has several positive long-term effects on environmental conservation and public health. The research shows that substituting some groundwater with treated wastewater could potentially preserve overused aquifers while maintaining the quality of deep groundwater, supporting the wider adoption of sustainable wastewater reuse initiatives. It will enhance long-term groundwater resource security, decreasing dependence on limited fossil aquifers. Advancements in science-based methods for monitoring, modeling, and regulating these systems can help reduce environmental concerns. The study emphasizes the need to include stakeholders and create flexible regulations to promote effective governance for sustainable water reuse. Increasing public awareness of the advantages of using treated wastewater and the real health hazards, as opposed to perceived ones, will result in enhanced public approval in the long run. Acceptance is crucial for increasing the use of treated wastewater to improve water and food security. The study's integrated assessment technique may be used as a model methodology in the field to thoroughly evaluate the effects of irrigation water sources. The conclusion of this project will promote the sustainable use of treated wastewater globally, leading to environmental benefits and improved climate resilience.

5. Conclusions and recommendations

The current study focused on TWW used for irrigation in the arid coastal agricultural region in Eastern Saudi Arabia to substitute for non-renewable groundwater resources. It evaluates the TWW for irrigation compared with deep groundwater and its impact on groundwater quantity and quality. The Saudi standards, IWQI, NSFWQI, and individual irrigation indices were utilized for irrigated water suitability assessment based on irrigated water's physical, chemical, and microbiological properties and heavy metal concentration. The stable isotopes (δ^2H, δ^{18}O) data was used to delineate the impact of TWW on the shallow and deep groundwater. The key conclusions of the current research can be summarized as follows.

- The tested TWW meets Saudi standards for unrestricted irrigation, except for EC, NO3, Fecal Coliform, Aluminum (Al), and Molybdenum (Mo), with exceedance percentages of 100%, 100%, 88%, 33%, and 55%, respectively.
- Despite the overall suitability of TWW for irrigation, exceedances of some parameters highlight the need for advanced treatment to enhance water quality.
- The results of the IWQI indicator showed that tested TWW is suitable for salt-tolerant crops, with a large portion requiring careful management due to severe restriction level.
- The NSFWQI results showed that the quality of TWW lower than deep groundwater, highlighting the necessity of quality improvement efforts.
- The salinity and sodium hazard indices show that the TWW is slightly better for irrigation than deep groundwater.
- The isotopic investigation, employing δ^2H and δ^{18}O isotopes, clearly shown that TWW has a considerable impact on the shallow groundwater, especially in the vicinity of irrigation sites and drainage canals. However, there is no noticeable effect on the deeper aquifer due to the presence of impermeable layers.
- The use of TWW in irrigation has resulted in a measurable rise in groundwater levels, indicating its significance in conserving limited non-renewable water resources.

The current study acknowledges some limitations that are recommended for future study including the seasonal variation and presence of emerging contaminant such as Per- and polyfluoroalkyl substances (PFAS) and Pharmaceuticals and personal care products (PPCPs). The research recommends continuous monitoring of conventional and emerging pollutants, especially in shallow aquifers, to protect the environment and public health. It is also recommended that adaptive management strategies be developed to address water quality issues effectively. Advanced treatment technologies should be used to remove excess salts, nutrients, and micropollutants from TWW and ensure sustainable irrigation and soil, plants, and groundwater protection.

Furthermore, future studies should focus on various areas to enhance the long-term usage of treated wastewater for irrigation. Longitudinal studies are required to investigate the long-term effects of TWW on soil composition, agricultural production, and aquifer integrity. It will provide essential data on the long-term feasibility of TWW irrigation. Additionally, the scope of water quality assessments should be widened to capture a larger range of pollutants, particularly targeting pharmaceutical residues, personal care byproducts, and PFAS compounds. Conducting pilot-scale tests to evaluate the effectiveness and cost-benefit ratio of modern TWW treatment methods is also crucial. Emphasis should be placed on assessing their appropriateness for arid environment, where the limited availability of water is a notable issue to achieving sustainable development. Finally, developing a more cooperative strategy for managing water resources is essential. Engaging the scientific community, policy makers, farmers, and community people in active discourse may help ensure that decisions are well-informed and that important water resources are managed responsibly.

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CRediT authorship contribution statement

Mohammed Benaafi: Methodology, Investigation, Project administration, Writing – original draft, Conceptualization, Data curation, Funding acquisition. **Arya Pradipta:** Writing – original draft, Visualization, Software, Formal analysis, Data curation. **Bassam Tawabini:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization, Resources, Supervision. **Ahmed M. Al-Areeq:** Writing – original draft, Visualization, Investigation, Data curation. **Abdullah Bafaqeer:** Writing – original draft, Methodology, Formal analysis. **John D. Humphrey:** Writing – review & editing, Resources, Methodology, Conceptualization. **Mazen K. Nazal:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Isam H. Aljundi:** Project administration, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] UN-Water, United Nations World Water Development Report 2022: groundwater: making the invisible visible 19 (2022) 225.

[2] M.H. Al-Mashreki, M.H. Eid, O. Saeed, A. Székács, P. Szűcs, M. Gad, M.R. Abukhadra, A.A. AlHammadi, M.S. Alrakhami, M.A. Alshabibi, Integration of geochemical modeling, multivariate analysis, and irrigation indices for assessing groundwater quality in the Al-Jawf basin, Yemen, Water 15 (8) (2023) 1496.

[3] M. Masoud, M. El Osta, A. Alqarawy, S. Elsayed, M. Gad, Evaluation of groundwater quality for agricultural under different conditions using water quality indices, partial least squares regression models, and GIS approaches, Appl. Water Sci. 12 (10) (2022) 244.

[4] M. El Osta, M. Masoud, A. Alqarawy, S. Elsayed, M. Gad, Groundwater suitability for drinking and irrigation using water quality indices and multivariate modeling in makkah Al-Mukarramah province, Saudi Arabia, Water 14 (3) (2022) 483.

[5] M. Alotaibi, N.S. Alhajeri, F.M. Al-Fadhli, S. Al Jabri, M. Gabr, Impact of climate change on crop irrigation requirements in arid regions, Water Resour. Manag. 37 (5) (2023) 1965–1984.

[6] S. Chowdhury, M. Al-Zahrani, Characterizing water resources and trends of sector wise water consumptions in Saudi Arabia, Journal of King Saud University-Engineering Sciences 27 (1) (2015) 68–82.

[7] M. Benaafi, B. Tawabini, S.I. Abba, J.D. Humphrey, A.M. Al-Areeq, S.A. Alhulaibi, A.G. Usman, I.H. Aljundi, Integrated hydrogeological, hydrochemical, and isotopic assessment of seawater intrusion into coastal aquifers in Al-Qatif area, eastern Saudi Arabia, Molecules 27 (20) (2022) 6841.

[8] A.R. Kacimov, M.M. Sherif, J.S. Perret, A. Al-Mushikhi, Control of sea-water intrusion by salt-water pumping: coast of Oman, Hydrogeol. J. 17 (3) (2009) 541–558.

[9] S. Ofori, A. Puškáčová, I. Růžičková, J. Wanner, Treated wastewater reuse for irrigation: pros and cons, Sci. Total Environ. 760 (2021) 144026.

[10] F. Pedrero, S.R. Grattan, A. Ben-Gal, G.A. Vivaldi, Opportunities for expanding the use of wastewaters for irrigation of olives, Agric. Water Manag. 241 (2020) 106333.

[11] M. Qadir, A. Bahri, T. Sato, E. Al-Karadsheh, Wastewater production, treatment, and irrigation in Middle East and North Africa, Irrigat. Drain. Syst. 24 (2010) 37–51.

[12] M. Abu-Madi, R. Al-Sa'ed, Towards sustainable wastewater reuse in the Middle East and North Africa, Consilience 2 (2009) 1–20.

[13] R.M. Abdelrahman, S.E. Khamis, Z.E. Rizk, Public attitude toward expanding the reuse of treated wastewater in the United Arab Emirates, Environ. Dev. Sustain. 22 (8) (2020) 7887–7908.

[14] S. Mishra, R. Kumar, M. Kumar, Use of treated sewage or wastewater as an irrigation water for agricultural purposes- Environmental, health, and economic impacts, Total Environment Research Themes 6 (2023), https://doi.org/10.1016/j.totert.2023.100051.

[15] M.J. Mohammad, N. Mazahreh, Changes in soil fertility parameters in response to irrigation of forage crops with secondary treated wastewater, Commun. Soil Sci. Plant Anal. 34 (9–10) (2003), https://doi.org/10.1081/CSS-120020444.

[16] H. jie Wang, J. Wang, X. Yu, Wastewater irrigation and crop yield: a meta-analysis, J. Integr. Agric. 21 (4) (2022), https://doi.org/10.1016/S2095-3119(21)63853-4.

[17] F.M. Kiziloglu, M. Turan, U. Sahin, Y. Kuslu, A. Dursun, Effects of untreated and treated wastewater irrigation on some chemical properties of cauliflower (Brassica olerecea L. var. botrytis) and red cabbage (Brassica olerecea L. var. rubra) grown on calcareous soil in Turkey, Agric. Water Manag. 95 (6) (2008), https://doi.org/10.1016/j.agwat.2008.01.008.

[18] S. Rezapour, A. Nouri, H.M. Jalil, S.A. Hawkins, S.B. Lukas, Influence of treated wastewater irrigation on soil nutritional-chemical attributes using soil quality index, Sustainability 13 (4) (2021), https://doi.org/10.3390/su13041952.

[19] J. feng Wang, G. xu Wang, H. Wanyan, Treated wastewater irrigation effect on soil, crop and environment: wastewater recycling in the loess area of China, J. Environ. Sci. 19 (9) (2007), https://doi.org/10.1016/S1001-0742(07)60178-8.

[20] G.A. Al-Nakshabandi, M.M. Saqqar, M.R. Shatanawi, M. Fayyad, H. Al-Horani, Some environmental problems associated with the use of treated wastewater for irrigation in Jordan, Agric. Water Manag. 34 (1) (1997) 81–94.

[21] Ministry of Environment, Water Agriculture, Executive regulations of law of treated sewage water and its reuse thereof. Saudi Arabia. https://www.mewa.gov.sa/en/InformationCenter/DocsCenter/RulesLibrary/Docs/Executive%20Regulations%20of%20Law%20of%20Treated%20Sewage%20Water%20and%20its%20Reuse%20Thereof.pdf.

[22] A.A. Aljaloud, Reuse of wastewater for irrigation in Saudi Arabia and its effect on soil and plant, 19th World Congress of Soil Science, Soil Solutions for a Changing World (2010) 1–6.
[23] A. Singh, A review of wastewater irrigation: environmental implications, Resour. Conserv. Recycl. 168 (2021) 105454.
[24] Ministry of Environment ,Water and Agriculture, Statistical Yearbook. Saudi Arabia (2022) 256.
[25] O.K.M. Ouda, Treated wastewater use in Saudi Arabia: challenges and initiatives, Int. J. Water Resour. Dev. 32 (5) (2016) 799–809.
[26] N. Ungureanu, V. Vlăduţ, G. Voicu, Water scarcity and wastewater reuse in crop irrigation, Sustainability 12 (21) (2020) 9055.
[27] M. Qadir, P. Drechsel, B.J. Cisneros, Y. Kim, A. Pramanik, P. Mehta, O. Olaniyan, Global and regional potential of wastewater as a water, nutrient and energy source, Nat. Resour. Forum 44 (1) (2020) 40–51.
[28] H.M. Alahdal, S. AlYahya, F. Ameen, H. Sonbol, M.N. Alomary, A review on Saudi Arabian wastewater treatment facilities and available disinfection methods: implications to SARS-CoV-2 control, J. King Saud Univ. Sci. 33 (7) (2021) 101574.
[29] General Authority for Statistics. Saudi Arabia, Population Summary Report, 2022. *Retrieved from*, https://portal.saudicensus.sa/static-assets/media/content/20230531_GASTAT_Population_Report.pdf?crafterSite=gastat-portal.
[30] A. Al-Shaibani, Economic potential of brines of Sabkha Jayb Uwayyid, eastern Saudi Arabia, Arabian J. Geosci. 6 (7) (2013) 2607–2618.
[31] I. Engelhardt, R. Rausch, B. Keim, M. Al-Saud, C. Schüth, Surface and subsurface conceptual model of an arid environment with respect to mid-and late Holocene climate changes, Environ. Earth Sci. 69 (2013) 537–555.
[32] M. Benaafi, S.I. Abba, B. Tawabini, I. Abdulazeez, B. Salhi, J. Usman, I.H. Aljundi, Integrated clustering analysis for delineating seawater intrusion and heavy metals in Arabian Gulf Coastal groundwater of Saudi Arabia, Heliyon 9 (9) (2023) e19784, https://doi.org/10.1016/j.heliyon.2023.e19784.
[33] C.H.V. Ebert, Water resources and land use in the Qatif Oasis of Saudi Arabia, Geogr. Rev. 55 (4) (1965), https://doi.org/10.2307/212411.
[34] USEPA, Groundwater sampling guidelines, Environment Protection Authority, April 36 (2000).
[35] I.S.O. Iso, 9963-1: 1994 Water Quality—Determination of Alkalinity—Part 1: Determination of Total and Composite Alkalinity, International Organization for Standarization, Geneva, Switzerland, 1994.
[36] USEPA, Method 9056A: Determination of Inorganic Anions by Ion Chromatography, US EPA, Cincinnati, 2007.
[37] A. Hounslow, Water Quality Data: Analysis and Interpretation, CRC press, 2018.
[38] D. Penna, B. Stenni, M. Šanda, S. Wrede, T.A. Bogaard, M. Michelini, B.M.C. Fischer, A. Gobbi, N. Mantese, G. Zuecco, Evaluation of between-sample memory effects in the analysis of δ 2 H and δ 18 O of water samples measured by laser spectroscopes, Hydrol. Earth Syst. Sci. 16 (10) (2012) 3925–3933.
[39] M. Batarseh, E. Imreizeeq, S. Tilev, M. Al Alaween, W. Suleiman, A.M. Al Remeithi, M.K. Al Tamimi, M. Al Alawneh, 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 (2021) 100611.
[40] S. Mukate, V. Wagh, D. Panaskar, J.A. Jacobs, A. Sawant, Development of new integrated water quality index (IWQI) model to evaluate the drinking suitability of water, Ecol. Indicat. 101 (2019) 348–354.
[41] A.C.M. Meireles, E. M. de Andrade, L.C.G. Chaves, H. Frischkorn, L.A. Crisostomo, A new proposal of the classification of irrigation water, Rev. Cienc. Agron. 41 (2010) 349–357.
[42] S. Zahedi, Modification of expected conflicts between drinking water quality index and irrigation water quality index in water quality ranking of shared extraction wells using multi criteria decision making techniques, Ecol. Indicat. 83 (2017) 368–379.
[43] R.M. Brown, N.I. McClelland, R.A. Deininger, M.F. O'Connor, A Water Quality Index—Crashing the Psychological Barrier, Indicators of Environmental Quality: Proceedings of a Symposium Held during the AAAS Meeting in Philadelphia, Pennsylvania, 1972, pp. 173–182. *December 26–31, 1971*.
[44] A. Hamlat, A. Guidoum, I. Koulala, Status and trends of water quality in the Tafna catchment: a comparative study using water quality indices, Journal of Water Reuse and Desalination 7 (2) (2017) 228–245.
[45] H.S. Jahin, A.S. Abuzaid, A.D. Abdellatif, Using multivariate analysis to develop irrigation water quality index for surface water in Kafr El-Sheikh Governorate, Egypt, Environ. Technol. Innovat. 17 (2020) 100532.
[46] F. Misaghi, F. Delgosha, M. Razzaghmanesh, B. Myers, Introducing a water quality index for assessing water for irrigation purposes: a case study of the Ghezel Ozan River, Sci. Total Environ. 589 (2017) 107–116.
[47] L. Tampo, S.L. Alfa-Sika Mande, A.O. Adekanmbi, G. Boguido, K.V. Akpataku, M. Ayah, I. Tchakala, M.D.T. Gnazou, L.M. Bawa, G. Djaneye-Boundjou, E. H. Alhassan, Treated wastewater suitability for reuse in comparison to groundwater and surface water in a peri-urban area: implications for water quality management, Sci. Total Environ. 815 (2022), https://doi.org/10.1016/j.scitotenv.2021.152780.
[48] R.S. Ayers, D.W. Westcot, Water Quality for Agriculture, vol. 29, Food and Agriculture Organization of the United Nations Rome, 1985.
[49] K.K. Tanji, N.C. Kielen, Agricultural Drainage Water Management in Arid and Semi-arid Areas, vol. 61, FAO, Rome, 2002.
[50] L.D. Doneen, Notes on water quality in agriculture, in: Department of Water Science and Engineering, University of California, Davis, 1964.
[51] J.D. Rhoades, A. Kandiah, A.M. Mashali, The Use of Saline Waters for Crop Production-FAO Irrigation and Drainage Paper 48, FAO, Rome, 1992, p. 133.
[52] L.A. Richards, Diagnosis and Improvement of Saline and Alkali Soils, US Government Printing Office, 1954, Issue 60.
[53] A. Tiri, L. Belkhiri, M. Asma, L. Mouni, Water Chemistry. *Suitability and Assessment of Surface Water for Irrigation Purpose*, 2020.
[54] W. Kelly, Alkali Soils-Their Formation Properties and Reclamation, Third, Reinhold Publication, 1951.
[55] M. Kumar, K. Kumari, A.L. Ramanathan, R. Saxena, A comparative evaluation of groundwater suitability for irrigation and drinking purposes in two intensively cultivated districts of Punjab, India, Environ. Geol. 53 (2007) 553–574.
[56] O.P. Choudhary, B.S. Ghuman, N. Thuy, R.J. Buresh, Effects of long-term use of sodic water irrigation, amendments and crop residues on soil properties and crop yields in rice–wheat cropping system in a calcareous soil, Field Crops Res. 121 (3) (2011) 363–372.
[57] A. Saleh, F. Al-Ruwaih, M. Shehata, Hydrogeochemical processes operating within the main aquifers of Kuwait, J. Arid Environ. 42 (3) (1999) 195–209.
[58] R. Ayyandurai, S. Venkateswaran, D. Karunanidhi, Hydrogeochemical assessment of groundwater quality and suitability for irrigation in the coastal part of Cuddalore district, Tamil Nadu, India, Mar. Pollut. Bull. 174 (2022) 113258.
[59] M. Benaafi, S.I. Abba, I.H. Aljundi, Effects of seawater intrusion on the groundwater quality of multi-layered aquifers in eastern Saudi Arabia, Molecules 28 (7) (2023) 3173.
[60] M.H.D. Al-Kubaisi, N.Z. Al-Salmani, O.J. Mohammad, A.M. Fayyadh, O.H. Orabi, Evaluation of irrigation water quality index (IWQI) for Habbaniya lake in Anbar Governorate, Iraq, IOP Conf. Ser. Earth Environ. Sci. 1080 (1) (2022) 012019.
[61] D.H.F. Muniz, J.V. Malaquias, J.E.F.W. Lima, E.C. Oliveira-Filho, Proposal of an irrigation water quality index (IWQI) for regional use in the Federal District, Brazil, Environ. Monit. Assess. 192 (9) (2020) 607.
[62] T. Abbasi, S.A. Abbasi, Water Quality Indices, Elsevier, 2012.
[63] R.M. Brown, N.I. McClelland, R.A. Deininger, R.G. Tozer, A water quality index-do we dare, Water Sewage Works 117 (10) (1970).
[64] G. Matta, A. Nayak, A. Kumar, P. Kumar, Water quality assessment using NSFWQI, OIP and multivariate techniques of Ganga River system, Uttarakhand, India, Appl. Water Sci. 10 (2020) 1–12.
[65] Lv Wilcox, *Classification and Use of Irrigation Waters* (Issue 969), US Department of Agriculture, 1955.
[66] M. Benaafi, S.I. Abba, I.H. Aljundi, Effects of seawater intrusion on the groundwater quality of multi-layered aquifers in eastern Saudi Arabia, Molecules 28 (7) (2023) 3173.
[67] E. Heiderscheidt, A. Tesfamariam, H. Marttila, H. Postila, S. Zilio, P.M. Rossi, Stable water isotopes as a tool for assessing groundwater infiltration in sewage networks in cold climate conditions, J. Environ. Manag. 302 (2022) 114107.
[68] C. Kendall, J.J. McDonnell, Isotope Tracers in Catchment Hydrology, Elsevier, 2012.
[69] I.D. Clark, P. Fritz, Environmental Isotopes in Hydrogeology, CRC press, 2013.
[70] I. Negev, J. Guttman, W. Kloppmann, The use of stable water isotopes as tracers in soil aquifer treatment (SAT) and in regional water systems, Water 9 (2) (2017) 73.

[71] E.-H. Koh, E. Lee, K.-K. Lee, D.-C. Moon, Integrated application of a Bayesian mixing model, numerical model, and environmental tracers to characterize groundwater recharge sources in a mountainous area, Sci. Total Environ. 853 (2022) 158619.
[72] J.E. Solder, K.R. Beisner, Critical evaluation of stable isotope mixing end-members for estimating groundwater recharge sources: case study from the South Rim of the Grand Canyon, Arizona, USA, Hydrogeol. J. 28 (5) (2020) 1575–1591.
[73] A. Mora, J.A. Torres-Martínez, M.V. Capparelli, A. Zabala, J. Mahlknecht, Effects of wastewater irrigation on groundwater quality: an overview, Current Opinion in Environmental Science & Health 25 (2022) 100322.
[74] G. Carr, R.B. Potter, S. Nortcliff, Water reuse for irrigation in Jordan: perceptions of water quality among farmers, Agric. Water Manag. 98 (5) (2011) 847–854.
[75] R.H. Al-Sadeq, Environmental Assessment of Groundwater Condition in Tarout Island, Eastern Province of Saudi Arabia, Master Thesis, King Fahd Univ. Petrol. Miner. Dhahran (2011) 172.
[76] W. McCance, O.A.H. Jones, D.I. Cendón, M. Edwards, A. Surapaneni, S. Chadalavada, S. Wang, M. Currell, Combining environmental isotopes with Contaminants of Emerging Concern (CECs) to characterise wastewater derived impacts on groundwater quality, Water Res. 182 (2020) 116036.
[77] M. Lewoyehu, Comprehensive review on synthesis and application of activated carbon from agricultural residues for the remediation of venomous pollutants in wastewater, J. Anal. Appl. Pyrol. 159 (2021) 105279.
[78] D.L. Correll, Principles of planning and establishment of buffer zones, Ecol. Eng. 24 (5) (2005) 433–439.
[79] S.B. Megdal, A.K. Gerlak, R.G. Varady, L. Huang, Groundwater governance in the United States: common priorities and challenges, Groundwater 53 (5) (2015) 677–684.
[80] F. Pedrero, I. Kalavrouziotis, J.J. Alarcón, P. Koukoulakis, T. Asano, Use of treated municipal wastewater in irrigated agriculture-Review of some practices in Spain and Greece, Agric. Water Manag. 97 (9) (2010) 1233–1241, https://doi.org/10.1016/j.agwat.2010.03.003.
[81] K. Schacht, Y. Chen, J. Tarchitzky, B. Marschner, The use of treated wastewater for irrigation as a component of integrated water resources management: reducing environmental implications on soil and groundwater by evaluating site-specific soil sensitivities, Integrated Water Resources Management: Concept, Research and Implementation (2016) 459–470.
[82] D.J. Lapworth, N. Baran, M.E. Stuart, R.S. Ward, Emerging organic contaminants in groundwater: a review of sources, fate and occurrence, Environ. Pollut. 163 (2012) 287–303.
[83] Q. Xia, J. He, B. Li, B. He, J. Huang, M. Guo, D. Luo, Hydrochemical evolution characteristics and genesis of groundwater under long-term infiltration (2007—2018) of reclaimed water in Chaobai River, Beijing, Water Res. 226 (2022) 119222.
[84] UN-Water, The United Nations World Water Development Report 2018: Nature-Based Solutions for Water, 2018.
[85] S. Mishra, V. Singh, L. Cheng, A. Hussain, B. Ormeci, Nitrogen removal from wastewater: a comprehensive review of biological nitrogen removal processes, critical operation parameters and bioreactor design, J. Environ. Chem. Eng. 10 (3) (2022) 107387.