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Review

Groundwater Quality Studies in the Kingdom of Saudi Arabia: Prevalent Research and Management Dimensions

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Abstract: Groundwater is a valuable resource because it is widely used for drinking, and for domestic, agricultural, and industrial purposes. Globally, Saudi Arabia is known to be one of the driest regions with scarce water resources. The shallow groundwater near the major cities in the Kingdom of Saudi Arabia is becoming polluted because of industrial effluent discharge, use of fertilizers in agriculture and domestic sewerage in the region. This review tries to focus on groundwater quality problems due to anthropogenic or geogenic sources in the region of Saudi Arabia. In this paper, we focus on different water-quality variables, for groundwater quality evaluation and aquifer vulnerability assessment due to pollutants/contaminants present in groundwater. The current study gives a holistic understanding of different groundwater quality problems and therefore identifies the gaps of the previous studies and identifies the viewpoints of the future research dimensions. We describe the different groundwater quality problems related to toxicities of the fluoride, nitrate, and heavy metals and radionuclides in Saudi Arabia. A majority of the groundwater pollutants are of natural origin, but there is significant wastewater effluent discharge in the region that is also responsible for contamination of aquifers with heavy metals.

Keywords: water quality; groundwater; geochemical; geospatial techniques

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1. Introduction

The increased utilization of groundwater resources throughout the globe has caused deterioration in the quality of water and has also raised the level of contamination [1]. Groundwater is one of the most important sources of water supply to meet the demand for drinking and irrigation in the Kingdom of Saudi Arabia (KSA). In the past three decades, groundwater exploitation in KSA has increased, reaching to an extent of 17 billion m^3/year [2]. In KSA, 80% of water-supply demand is met through groundwater [3]. The net annual groundwater recharge is very low compared to the rate of withdrawal [4]. The declining groundwater levels also impact its quality. The deep aquifers in the sedimentary formations in the Arabian shield, which consist of a thick sequence of palaeozoic to recent sedimentary succession, have developed secondary porosities, overlying the fractured Precambrian basement that forms a major source of groundwater in the region [5]. However, the shallow aquifers mainly restricted to the valleys also constitute a major source of water in Arabian shields and coastal regions [6]. The climate of the region is dominantly arid to semi-arid, and the groundwater resources are under extreme stress because of high temperatures, low and erratic rainfall, and high evapotranspiration [7,8]. The groundwater resources were predominantly used in agriculture during 1970s. But due to the rapid increase in urbanization, growth in the industrial sector and the population, the groundwater resources in an already water-stressed region has become a concern both in quantity and quality [9]. The groundwater quality deteriorates because of either the anthropogenic sources or the natural/geogenic sources [10]. However, the study region experiences the groundwater quality issues mainly because of prevailing climatic and geological conditions. The groundwater quality depends upon the interaction of water with soils and sediments, flow path, rock types and predominant geochemical conditions such as dissolution, redox condition, precipitation, leaching, ion exchange, etc. [11]. Water quality evaluation is critically important from a public health point of view and for its holistic management and efficient utilization under the increasing impact of climate change. In desertic aquifers, the climate and the hydrochemistry of groundwater are controlled by various factors such as topography, soil chemistry and interaction of water with aquifer minerals along with internal mixing of chemically different groundwater along flow paths in the subsurface [12,13]. The genetic nature of groundwater is determined by hydrogeochemical processes such as weathering of aquifer minerals and the retention time of water in the subsurface [12,14]. In the absence of surface water resources, the groundwater is the only source for potable water supply in these desertic regions, thus the quality assurance for potable water supply becomes more critical [7,15,16]. Due to the severe climate conditions in arid and semi-arid regions, groundwater salinization is a common problem. Due to a high evaporation rate as a result of extreme temperature, the soil also develops salinity in these regions [17,18]. The annual rate of evaporation is 2500 mm in the coastal areas to more than 4500 mm inland areas and thus develops a highly alkaline condition, which in turn affects the quality of the groundwater [7,15,16]. The residence time of groundwater ranges in months for shallow aquifers, whereas it can be more than a million years for deeper aquifers [3,19]. Due to the hidden nature of groundwater because of inaccessibility, slow flow rate and huge volume [20,21] once contaminated it is difficult for groundwater to recover from any perturbations.

Over the years, water quality studies have evolved from using conventional techniques such as graphical methods/scatter plots to modern techniques such as geographical information systems (GIS), fuzzy modelling and machine-learning methods [22–25]. The conventional graphical methods utilized the ionic ratios, scatter plots between different ionic species to understand the geochemical mechanisms [26]. With the advancement of computing technology, techniques involving geostatistical modelling and multivariate statistics, geographical information systems, analytical hierarchical process (AHP) and machine-learning algorithms such as random forest modelling, artificial neural networks, etc. have been utilized to better understand the spatial variability and to characterize and visualize groundwater quality for effective supervision of groundwater resources.

We evaluated several studies conducted in different regions of KSA for evaluation of groundwater quality. However, several approaches were used to assess the hydro–geochemical properties of groundwater and to determine its suitability for drinking and agriculture [26–29]. The current review also evaluates different contaminants of health concern and gives an overview of the valleys in KSA impacted due to several groundwater contaminants, which would be helpful to give insights for holistic assessment of groundwater quality of the region.

2. Study Area

Saudi Arabia is located in the center of the great trade winds, desert that extends across northern Africa into Asia. In the country, the hot, dry climate is a result of the Red Sea and the adjoining mountain series in As Shifa, Hejaz and Asir. Rainfall is meager and occasional, ranging from a minimum annual mean of less than 2 cm in the north to a maximum of about 30 cm along the southern crest of the Asir range in the southwest (Figure 1). The region gets an average annual rainfall of 7–13 cm [7]. The Arabian Desert, as well as the related semidesert and scrub lands, covers more than 70% of the Arabian Peninsula. The climatic conditions are severe, with modest rainfall and a high rate of evapotranspiration [5]. Because of limited surface-water availability, the nonrenewable groundwater resources found in deep-seated sedimentary aquifers are used to meet more than 80% of the water demand. The groundwater stress in the region is one of the largest in the world based on the aquifer's groundwater footprint.

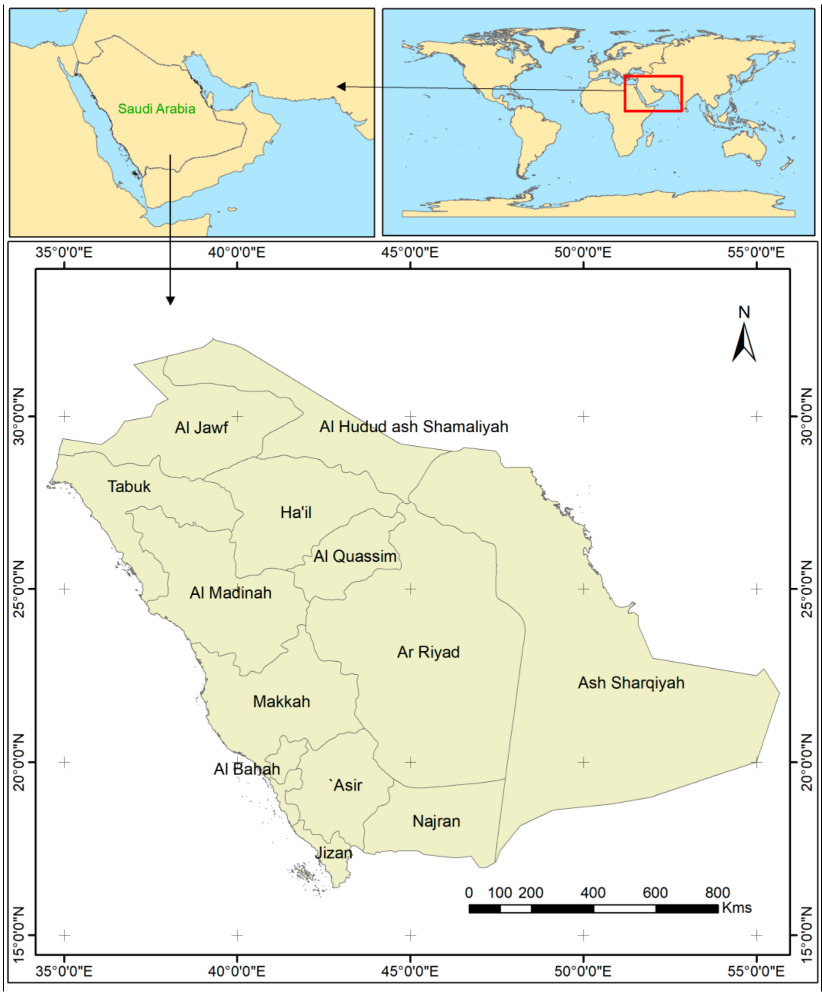

Figure 1. Study area.

3. Geology

Saudi Arabia is underlain by tightly folded, regionally metamorphosed volcanic-clastic and epi-clastic rocks, and many mafic-to-felsic plutons of the late Proterozoic age. It is called an 'Arabian Shield–Nubian Shield' and is just exposed in a major part of the area concealed by the sedimentary rock that dips gently toward the east (Table 1). As sedimentary cover, Palaeozoic sandstones, comprising the Cambrian–Ordovician Wajid sandstone, are found on the southeastern range overlying Proterozoic rocks. Due to volcanic activity that occurred during Precambrian, volcano-clastics and subordinate flow rocks, complex and inter-layered with volcanically delivered and epi-clastic sedimentary rocks, were formed. The younger rocks of Tertiary and Quaternary formation due to basalt-flows and gabbro-dikes are found in the area and are associated with the Red Sea rifting. The basalt is part of a large area of flow rocks and volcanic cones resulting from volcanic activity, whereas the gabbro dikes intruded into tension fractures [30,31]. Overlying the bedrock are unconsolidated Quaternary deposits that include alluvium, conglomerate from the Red Sea escarpment, terrace gravels, coastal-plain silt and eolian sand. Following the uplift of the area and the opening of the Red Sea, these developed during a time of active erosion, resulting in the development of a Wadi system draining to the east and west, as well as the erosional retreat of the Red Sea escarpment.

Table 1. Lithologic Sequence and Major Aquifers in Saudi Arabia [32].

	Lithologic Sequence	Principal Aquifers	Secondary Aquifers
1	Quaternary and Tertiary		Alluvium
2	Pliocene and Miocene Clastic Rocks	Neogene	Basalt
3	Eocene Carbonate to Upper Cretaceous Rocks	Damman Ummer Radhuma	Aruma
4	Middle and Lower Cretaceous Clastic Rocks	Wasia Biyadh	Sakaka
5	Lower and Upper Jurassic Cretaceous Carboante		Buwaib, Yamama, Sulay, Arab, Juballa. Hanifah
6	Middle and Lower Jurassic Clastic and Carbonate Rocks		Dhruma
7	Jurassic, Triasic and Permian Clastic Rocks	Minjur/Dhrumma	Jilh Jauf
8	Lower Paleozoic Clastic Rocks	Tabuk, Wajid, Saq	

4. Hydrogeology

The natural groundwater systems consist of aquifers of both the oldest and the youngest geologic ages. The oldest one is Precambrian crystalline rocks and the youngest is Recent alluvium deposits and eolian sands. The productive aquifer occurs within the sedimentary strata and porous volcanic rocks overlying the Precambrian basement. The lithologic sequence can be split up into eight major aquifers based on previous studies [33] as shown in Table 1. The distinction between primary and secondary aquifers is based on their hydrologic properties and areal extent. The permeability and yields of primary aquifers are higher than those of secondary aquifers, and primary aquifers have more water storage [34,35]. The layer primarily consists of sandstone, limestone and dolomites, which have a large areal extent and higher storage capacity. The sedimentary section consists of sandstone interspersed with less permeable strata, which act as confining beds [32]. The primary sandstone aquifers are widely distributed in the southeastern region and locally possess excellent water-bearing properties. Water-bearing sandstone and limestone beds of the Mesozoic age, such as Wajid and the Minjur/Dhruma aquifer in the southeastern part of the Asir and Najran province, are aquifers with good potential yield. The secondary aquifers have less water storage and lower yields [34]. These aquifers are present throughout the region and act as minor sources of water. Some aquifers are hydraulically connected with underlying primary aquifers and provide large potential yields. The majority of groundwater is stored in the primary deep aquifers and provides a dependable supply in the central and northern provinces of Saudi Arabia. The reserves for this deep-seated groundwater are estimated to be 1919 BCM. The amount of water stored in these deep aquifers in the Saq, Tabuk, and Wajid in Saudi Arabia is huge; however, because of quality-related issues the water is not suitable for consumption.

5. Groundwater Studies in Saudi Arabia

The main natural processes that influence the groundwater chemistry in semi-arid/arid regions are evaporation/crystallization caused by extreme temperatures and aquifer mineral interaction by processes such as dissolution, redox condition, precipitation, leaching, ion exchange, etc. [11,36,37]. Due to lesser rainfall and a high rate of evapotranspiration, the rate of groundwater recharge is insignificant [38], resulting in salinization of groundwater [39]. However, the hydrogeochemical processes controlling the chemical characteristics of groundwater chemistry can be substantially distorted by anthropogenic activities such as excessive withdrawal of groundwater, increased urbanization and industrial activities, use of fertilizers and pesticides in agriculture, dumping of untreated wastewater and sewage discharge, and leakage of septic tanks and landfills. Regardless of the anthropogenic contaminants, the groundwater may also contain elevated levels of contaminants that are of natural origin or geogenic in nature. A total of 27 studies conducted in past 5 years were considered in the current review to develop understanding of problems associated with groundwater quality in the region of Saudi Arabia. The details of the studies considered are given in Table 2.

Table 2. Assessments of groundwater-quality studies (all the studies considered in the current review are field cum laboratory studies).

	Author	Study Area	Groundwater Oriented- Purpose of Study	Method
1	Abdel-Satar et al. [40]	Hail	"Suitability of groundwater for irrigation uses"	SAR, RSC, Na%
2	El Alfy et al. [41]	Dhurma	"Hydrogeochemical processes affecting groundwater pollution"	Saturation Indices (SI), Cluster Analysis, Factor Analysis
3	Alabdulaaly et al. [42]	13 regions in Saudi Arabia	"Hydrogeochemical processes affecting groundwater pollution"	Graphical Methods for Hydrogeochemical processes
4	Al-Ahmadi [43]	Wadi Sayyah	"Hydrogeochemical processes, suitability of groundwater for irrigation uses and drinking"	SAR, RSC, Na%, PI, Piper and USSL diagram
5	Loni et al. [36]	Al Asyah	"Hydrogeochemical processes, fluoride and nitrate pollution"	Principal Component Analysis (PCA), Piper, Gibbs Diagram
6	Alabdula'aly [44]	Saudi Arabia	"Radon concentration in water"	Direct Measurements
7	Zaidi et al. [45]	Biyadh and Wasia	"Drinking water suitability, hydrogeochemistry, salinity and nitrate hazard"	SAR, RSC, Na%, PI, Piper diagram, CAI, SI
8	AlSuhaimi et al. [46]	Odqus County	"Drinking water suitability, hydrogeochemistry"	SAR and Wilcox, Piper,
9	Faraj et al. [47]	Hail	"Radium pollution, salinity, nitrate"	Piper, Durov, PCA
10	Al-Ahmadi and El-Fiky [48]	Wadi Marwani	"Hydrogeochemical processes, drinking and irrigation water quality"	Piper, Schoeller, Wilcox
11	Al-Barakah et al. [49]	Zamzam, Makkah	"Microbial assessment, hydrogeochemistry"	WQI, SI, Piper, Schoeller, and Durov diagrams, Wilcox
12	Alfaifi [27]	Rabigh area	"Hydrogeochemistry, high salinity, nitrate, Fe, Cr, Mn"	Durov, Piper, PCA
13	Alharbi et al. [50]	Wadi Al Hamad, Madinah	"Hydrogeochemistry, drinking and agricultural water quality"	bivariate plots, Piper Diagram and Gibbs plot, USSL plot, SAR, RSC, and Kelly's index, PCA, SI
14	Almadani et al. [51]	Alwadeen area	"Fluoride and nitrate pollution"	SI, Piper
15	Al-Omran et al. [25]	Al-Kharj	"Geostatistics, drinking water quality"	Piper, Gibbs, (SAR), Kelly's ratio (KR), residual sodium carbonate (RSC), and magnesium hazard (MH)
16	Ghrefat et al. [52]	Gulf of Aqaba	"Hydrogeochemistry, pollution assessment"	Statistical Analysis
17	Ghrefat et al. [53]	Midyan Basin	"Hydrogeochemistry, pollution assessment, drinking water quality"	SI, Piper
18	Aly et al. [1]	Hafar Albatin	"Hydrogeochemistry, drinking water quality"	WQI, USSL diagram, Durov, Piper, Schoeller, SAR, Kelly, SI
19	Al-Hobaib et al. [54]	Mahd Adh Dhahab	"Hydrogeochemistry, drinking water quality"	Direct Measurments, Statistics
20	Zaidi et al. [37]	Qassim and Riyadh province	"Irrigation, domestic, hydrogeochemistry"	Piper, PCA
21	Al-Omran et al. [2]	Al-Kharj	"GIS, C, spatial variability of water quality parameters"	USSL, Gibbs, WQI, Durov, Piper, Gibbs, Scholler (SAR), Kelly's ratio (KR), RSC
22	Zaidi et al. [55]	Hail, Al Jawf and Tabuk	"Irrigation water quality"	Chadha's classification and the chloro-alkaline indices, SAR, RSC, Mg Hazard, SI, USSL
23	Salman et al. [56]	Tabuk-Madina	"Geostatistics, spatial variability of water quality parameters"	Piper and Durov plot, PCA
24	Mallick et al. [26]	Asir	"Hydrogeochemistry"	PCA, SI, GIS
25	Haider et al. [22]	Buraydah, Qassim	"Iron, total dissolved solids (TDS) and radium (Ra) have been used to assess the quality of groundwater wells based on their human health"	GWQI, Fuzzy
26	Saleem et al. [57]	Wadi Ranyah	"Hydrogeochemistry, drinking water quality"	Cluster, Piper, USSL
27	Mallick et al. [58]	Asir	"Hydrogeochemistry, Assessments of groundwater quality studies"	NCBI, WQI, IWQI, Hydro-geochemical process, GIS

6. Groundwater Contamination

In groundwater, the metal comportment is complex and is related to the aquifer environment and the bio-geochemical process. The occurrence of metals in surface water and groundwater may be due to the dissolution of rock minerals that contain metals in the soil, aquifer materials or anthropogenic/industrial activities such as fuels, mining, smelting of ores and improper disposal of industrial waste [59]. The wastewater is over-laden with raised amounts of trace constituents, which are the main sources of groundwater pollution [60]. Heavy metals are produced through industries related to pesticides, batteries, alloys, electroplating, textiles and also from mining industries. Mining pursuits in Saudi Arabia have increased during the past few years and had adverse environmental impacts on the surrounding environment, specifically in soil and water resources. Al-Hobaib et al. [54] studied the effect of mining in the Mahd Adh Dhahab gold mine on water resources. Of all the metals, approximately 66% are of major concern for the health of human beings because of environmental exposure or due to occupational exposure. These elements are essential for humans as they are essential micronutrients and are part of dietary intake; however, if ingested or consumed beyond permissible limits, they may induce chronic toxicity and adverse health implications. Several of these metals may induce nervous dysfunction that can be carcinogenic and can affect several important organs of humans. The spatio–temporal variations of these heavy metals in water would be essential for monitoring and efficient management of water quality. The heavy metals are naturally occurring in groundwater; however, increased anthropogenic activities might impact the occurrence of these heavy metals in the surrounding environment. The impact of these metals on human health can be assessed by several health indices that depend on ingestion through drinking and eating or inhalation. Heavy metals are naturally present in sediment/rock and are rendered bioavailable due to the process of weathering of parent materials at levels that are regarded as trace (<1000 mg kg^{-1}) and rarely toxic [61,62]. Due to geogenic or anthropogenic influence, the sediments may accumulate one or more of the heavy metals above defined background values high enough to cause risks to health of humans, phytoplanktons and zooplanktons, and ecosystems [63]. The heavy metals present in the sediment become contaminants because their rates of production might exceed the natural rate of generation due to anthropogenic influences; the sludge or waste in several industries concentrate these metals and eventually have high concentration at discharged locations, and due to the redox conditions, the metal may become more bioavailable, thus resulting in biomagnification in plants or animals. The vast expansion in the industrial and mining sector and their related activities has escalated groundwater and surface water contamination and has also negatively impacted the flora and fauna of the region [64]. The awkward neutralization of lead (Pb) batteries and black-gold goods pollutes groundwater because of the redirected level of Pb, Cu, and Fe in groundwater [54]. The endemic and seasonal changes in concentration levels indicate contamination from point sources [65,66]. Apart from these heavy metals, the presence of cations and anions in water also determines its suitability for agricultural applications. Thus, an assessment of the chemical composition and overall quality of water for irrigation is also vital for evaluating salinization of soil. The extent of worsening impacts on soils depends on soil type, soil chemical composition, plant uptake, and nature and content of salts present in irrigation water, fluctuation of water table, etc. The drinking-water quality standards in Saudi Arabia are given in Table 3.

Table 3. SASO [67], Saudi Arabia, drinking water standards and the acceptable range of various physical parameters.

Water Quality Variables	Range of Permissible Standards (Desired) [67]
pH	6.5–8.5
TDS (mg/L)	1000
Ca (mg/L)	200
Na (mg/L)	200
K (mg/L)	-
Mg (mg/L)	150
HCO_3 (mg/L)	-
Cl (mg/L)	250
SO_4 (mg/L)	250
NO_3 (mg/L)	50
F (mg/L)	0.5–1.5

The common issues related to groundwater contamination in KSA are discussed below.

6.1. Groundwater Salinity

Groundwater salinity can affect plant/crop growth and development by affecting processes such as osmotic pressure, excessive nutrient intake, ion toxicity and/or nutritional disorders. Salinity in irrigation water has a direct effect on plant metabolism, potentially reducing soil productivity by toughening it and altering its porousness and ventilation efficiency. Chloride is required for plant growth in low concentrations and is harmful in high concentrations; plant photosynthesis can be harmed, and photosynthesis can be interrupted by chloride levels. Several researchers have studied the salinity in groundwater and its suitability for irrigation in regions of Hail; Wadi Sayyah; Al Asyah; Biyadh and Wasia; and Odqus County [36,40,43,45,46].

6.2. Fluoride Contamination

The presence of fluoride above the WHO permissible limits of 1.5 mg/L can cause severe health implications. These health implications could be aggravated due to the extreme climatic conditions in arid/semi-arid regions that create a favorable geochemical condition for fluoride mobilization in groundwater and also because the consumption of such contaminated water may be high in arid regions compared to temperate regions. Fluoride deficiency in the diet causes dental caries and osteoporosis, but chronic excess intake, caused by drinking groundwater with more fluoride than the WHO guideline, can cause severe dental and skeletal fluorosis. Fluoride is essential for tooth enamel and bone formations in humans. However, fluoride is added or consumed in the form of tablets, mouthwash and toothpaste. In some regions around the world, fluoride is included in table salt or drinking water to resist dental caries that are frequently observed in an affected population. The amount required by the human body is usually 0.5 to 1 mg/L [68]. However, intake of elevated fluoride can have more serious effects on the skeletal system of human body. Skeletal fluorosis in the form of bone deformation may be observed when drinking water contains 3–6 mg/L of fluoride. Crippling effects can be observed in the skeletal system by the intake of water having fluoride above 10 mg/L. Children less than eight years of age when exposed to disproportionate quantities of fluoride have an increased likelihood of developing corrosion in tooth enamel, giving it a brownish appearance [69]. Fluorosis at a more severe stage causes bilateral lameness and stiffness of gait [70]. The mechanism for fluoride in groundwater involves dissolution of fluoride-bearing minerals, such as fluorite (CaF_2), muscovite, hornblende, biotite, tremolite, villianmite, fluorapatite and some micas weathered from silicates, and sedimentary and igneous rocks, especially shale [71–73]. High bicarbonate, sodium and pH all favor the release to groundwater of fluoride from aquifer sediments [14,74,75]. Fluorite has been source of fluoride in groundwater, particularly in granitic terrain [76–78]. It has been observed that high-fluoride ground waters are associated with low Ca, high bicarbonate and are supersaturated with mineral phases such as calcite and dolomite, and undersaturated with fluorite [13,15,16,79]. The undersaturation of fluorite leads to dissolution of minerals and thus enriches groundwater with fluoride [80]. Apart from the natural fluoride mineral occurrences, fluoride concentrations in groundwater may get enhanced through the use of phosphatic fertilizers that can seep into the groundwater via irrigation return flows [81].

The saturation indexes (SI) of fluorite and calcite can give important insight in terms of the mechanism, which can be calculated [82] as given below:

$$Fluorite : SI_f = \log\left(a_{Ca} \times a_f^2\right) - \log\left(IAP_{fluorite}\right) \quad (1)$$

$$Calcite : SI_c = \log(a_{Ca} \times a_{CO3}) - \log(IAP_{calcite}) \quad (2)$$

where a is the activity (or mole concentration) term and IAP is the ion activity product. The log IAP values for fluorite and calcite at 25–50 °C are 10.02–9.91 and 8.46–8.67, respectively [83]. SI values less than zero for a particular mineral (fluorite) suggest that this fluorite mineral will dissolve in the aqueous medium, thus raising the concentration of fluoride in groundwater because the water is undersaturated with respect to the mineral.

Conversely, if the *SI* value is greater than zero for a mineral, the mineral will precipitate because the groundwater is oversaturated with respect to the mineral and therefore incapable of dissolving more of the mineral. It was observed in a study by Alabdulaaly et al. [42] that not too many wells exceeded the maximum contaminant limit of 4.0 mg/L defined by USEPA; however, it was still prominent in the Qassim area with as much as 3.7% of total samples exceeding the 4 mg/L limits of fluoride limits. The Hail region in KSA had almost 22% of wells exceeding the limits of 2 mg/L, whereas the maximum percentage of wells exceeding the WHO limit of 1.5 mg/L was observed in the Hadwad Shamalyah (85%) region. The possible source of fluoride in groundwater is the dissolution of silicate minerals composing the aquifer matrix in Wadi Marwani [48]. Arid climatic conditions and rock–water interaction with fluoride-bearing mineral agricultural practices involving use of fluoride-containing phosphate fertilizers result in a high concentration of fluoride in groundwater of the Rabigh region of western Saudi Arabia [27].

6.3. Radionuclide Pollution

Radon (222) is notably found in groundwater across several regions in the world. Radon has been linked to health issues causing stomach and lung cancer [84]. The radon concentration in groundwater of KSA has been studied by several researchers [85–88]. Alabdula'aly [44] studied 1025 groundwater samples spread across 13 different cities in KSA and found that regions such as Najran, Qassim, Tabuk, and Hail had radon levels above or equal to 11.1 Bq/L in almost 47.8–58% of samples. However, the levels of radon were prominent in the regions of Madina Al Munnawarah, Jizan, and Hadwed Shamalyah with almost 20–30% of samples having high radon concentration, and in regions such as the Makkah Al Mukarramah, Asir, Eastern Province, Riyadh, Al Baha, Al Jouf the severity was low with only 4–17% samples showing radon levels of 11.1 Bq/L. The high levels of radon were confined to shallow aquifers compared to deeper ones; the reason could be the existence of faults, pumping stress, seasonal fluctuations or dilution of the aquifer [84,89].

The radium isotopes 226 and 228 have been also studied in the Saq aquifers by Faraj et al. [47]. These are, again, alpha emitters and pose a health risk causing bone cancers and cancers arising from the red bone marrow, especially Alliukimia [90]. Of the total 54 groundwater samples collected in the Hail region by Faraj et al. [47], 11% of the samples showed high levels of radioactivity above the WHO guidelines. The presence of uranium-bearing minerals such as uraninite (UO_2), monazite, apatite and zircon ($ZrSiO_4$) has been confirmed in the Saq sandstone. Faraj et al. [47] observed high concentrations of uranium in the unconfined aquifers; however, the uranium content was low in the confined aquifers. The uranium disintegrates to form the Ra isotope under oxidizing conditions in groundwater. The ^{228}Ra activity above the WHO recommended levels of 2.7 pCi/L was observed in almost 98% of groundwater samples. The ^{228}Ra activity concentration in the groundwater was found to be related to aquifer lithology, where the contamination corresponds to the presence of monazite in fine-grained sand, which showed medium-high thorium activity. In some of the confined areas, the Hanader Shale is known to contain radioactive monazite, zircon, rutile and thorite with a high gamma-ray signal.

6.4. Mercury

The maximum mercury concentration of 9.99 mg/L was detected in the region of Mahd Adh Dhahab, which is almost 100 times more than the permissible limits of WHO for mercury in groundwater [54]. The existence of mercury in the mineralization zones along with its use in mining/extraction procedures of gold has been attributed to the presence of mercury in groundwater of the region. Mercury normally occurs in many forms of Hg^{2+} and shows a strong affinity towards organic matter and sulfides. Organic mercury compounds, i.e., methyl mercury complexes, are highly toxic and are used a few in agriculture. The mercury compounds are poisonous, and have severe impacts on the renal system and cause neurological disorders. The consumption of mercury has also been linked to irritation, inflammation, swelling of salivary glands, slackening of gums and continuous saliva discharge. A study carried out in Al-Madinah Al-Munawarah, Ref. [60] Saudi Arabia, found mercury concentrations ranging from 0.0001–0.0007 mg/L, which was well below the WHO standards. Mercury was also found in groundwater near Jeddah city [30] with a concentration ranging from 10–430 µg/L. The concentration of mercury in surface sediments near a waste disposal site in Al-Musk ranges from 1.70 to 2.63 mg/kg [91]. The effluent discharge in open areas and surface-water bodies has developed most of the heavy-metal pollution in KSA. Hg occurs in concentrations slightly higher than the allowed values in the water downstream of El-Madina that drains from the gold mine. The mercury concentration in water near EL-Madina was found to be as high as 9.99 ppm, which is 100 times more than the allowable values in drinking water. The relatively high concentration can be due to the occurrence of mercury in the mineralization zones and/or its use in the gold extraction process [54].

6.5. Lead (Pb)

Lead is a very toxic element and can accrue in the bones or skeletons of humans [92]. The enhanced levels of lead in the human body can result in irreversible impairment to the nervous system and may cause high blood pressure, impairment with hearing and also affect the reproductive system in males. The symptoms that might develop in females are reduced progression, annoyances, digestive complications, and muscle and joint pain [93]. Significant exposure to lead remains in many developing countries where unregulated mining and informal activities such as lead acid battery recycling, pipe manufacturing and use of paints are still in use. Pb is a health threat in developing countries as most do not have clear regulations or enforcement, and thus it remains one of the top environmental health problems today. Soil Pb contamination is spatially variable, and children can ingest harmful amounts by playing in Pb-laden soil or house dust. Pb is highly toxic, especially to developing children ages 6–12 years [94]. Pb toxicity has been well-established, and blood lead levels (BLL) as low as 10 µg/dL, the current WHO standard, in children are associated with impaired cognitive function, decreased intelligence quotient (IQ), and behavior difficulties. At high levels, Pb can cause coma, convulsions and death. Without further action, over the coming decades large numbers of young children may be exposed to lead in amounts that could impair their ability to learn and to reach their full potential. Lead concentrations in about 43.3% of the samples was higher than the permissible limits cited by SASO [67] and WHO [95] for drinking water in the Hail region of Saudi Arabia [40].

7. Pollution in Some Cities of Saudi Arabia

The Kingdom of Saudi Arabia relies on three sources of water to meet the demand of population, namely groundwater, surface water bodies and water from the sea. A limited population gets access to an adequate supply of water from surface and groundwater resources, which are scarce in the region. Desalinization of sea water is used to meet the demands of people in or nearby coastal areas and therefore a majority of the population depends on unsustainable resources that were revived previously [96].

Jeddah, a densely populated city with a population of 300,000 depends on groundwater sources that are inadequate to meet the per capita demand of the population, which is growing at the rate of 2.35% a year. Thus, the alternative source is desalinated water, which is meeting the demands of the city. The per capita demand in Jeddah city is 200 L of water per day, out of which 80 percent of the water consumed is rejected as wastewater. Jeddah faces a severe problem of sewage management as most of the area (70%) doesn't have a proper channel for sewage transport and therefore the sewage is collected in tankers or in subsurface pools from which they are transferred to different dumping grounds by tankers or trucks. The important sources of contamination in Jeddah are (i) untreated sewage water within the city, (ii) contaminants of oil refineries and desalination plants. These contaminant sources in fact concentrate the sludge or contaminants and thus are acting as severe polluters for the water resources in the city. The contaminants such as nitrogen and phosphorus, high chemical oxygen demand, household sewage and oil refinery refuse are common in beach frontlines [30]. The Hail province showed high concentrations of lead and fluoride that were found to be exceeding the limits of WHO standards [40,42]. In the Hail region, out of the total 54 groundwater samples collected by Faraj et al. [47], 11% of the samples showed high levels of radioactivity above the WHO guidelines; 98% of the water samples exhibited 228 Ra activity concentration above the WHO recommended guideline value of 2.7 pCi/L. The Dhurma aquifer had 42.6 percent of groundwater samples that met drinking water standards [41]. Al-Ahmadi [43] reported that the groundwater in the Wadi Sayyah could be used for drinking in most areas and is ideal for irrigation in others. The evaporate minerals gypsum and anhydrite are the main sources of sulfate in groundwater. It may also be caused by pyrite oxidation. Its concentration ranges from 118.40 to 1755.20 mg/L in this region. The nitrate concentration in this area's groundwater sample varies greatly, ranging from 11.70 to 450.20 mg/L with a mean of 56.97 mg/L. The concentration of nitrate in drinking water exceeds the WHO limits (50 mg/L) in 43% of the groundwater samples collected for this report. In Al Asyah, the TDS values of the samples range from 7349 to 2704 mg/L with an average of 4214.82 mg/L and are well beyond the maximum permissible limits of 500 mg/L in drinking water recommended by the WHO [68]. Fluoride concentration in the groundwater showed variation from 1.21 to 1.97 mg/L. Nitrate concentration in Al Asyah ranges from 5 to 185 mg/L.

Alabdula'aly [44] studied radon concentration in cities of Saudi Arabia and found that regions such as Najran, Qassim, Tabuk and Hail had radon levels above or equal to 11.1 Bq/L. The radon levels were significant in Madina Al Munnawarah, Jizan, Hadwed Shamalyah, and in the cities of Makkah Al Mukarramah, Asir, Eastern Province, Riyadh, Al Baha, Al Jouf the severity was low for radon levels in groundwater. In Biyadh and Wasia, nitrate values were high due to agriculture fertilizer use; fluoride was also found to be high in a few samples in the region [45]. In Odqus county, pH, nitrate and fluoride in all samples were below the local drinking water guideline: SASO (Saudi Standards, Metrology and Quality Organization) values, although a small fraction of samples (7.14%), were above the recommended TDS (total dissolved solid) content [46]. The nitrate concentration in the Wadi Marwani was within the range of 9.6–86.0 mg/L nitrate. High nitrate content was recorded for only two wells and was 86 and 51.4 mg/L, respectively. These two wells were identified as being likely contaminated by point source pollution [48]. According to a study by Al-Barakah et al. [49], in Zamzam the water quality index (WQI) revealed that 94% of the samples were excellent for drinking, while the remaining were unsuitable due to total coliform group contamination. The levels of nitrate content of only a small proportion (roughly 2%) of the water tested were higher than recommended limits [49]. The electrical conductivity values showed a very wide variation ranging from 619 to 20,900 µS/cm in the Rabigh region, whereas nitrate values in the region ranged from 0.55 to 226 mg/L [27]. Fluoride and nitrate pollution was observed in the Alwadeen area by Almadani et al. [51]. When using these ground waters for irrigation, high salinity is a major issue. The main reasons for the groundwater's deterioration in the Al-Kharj region are the large agriculture investment companies overexploiting groundwater [25]. Geochemical analyses of the groundwater samples from Midyan Basin reveal the concentration of fluoride between 0.98 and 2.1 mg/L [53]. In the Hafar Albatin area, Aly et al. [1] found that 14% of the water was in the poor water class, 39% was very poor water, and 47% was water unfit for human consumption. The high WQI values obtained for this study area were due to high pH values, TDS, Mg^{2+}, Cl^{-}, HCO_3^{-}, total hardness and nitrate.

The TDS content of the samples in the Qassim and Riyadh province ranged from 1015 to 18,970 mg/L. With a mean value of 1.76 mg/L, fluoride levels in the collected water samples surpassed the maximum allowable limit of 1.5 mg/L [37]. For irrigation purposes in Hail, Al Jawf, and Tabuk, groundwater samples were categorized as safe (less than 10) in terms of sodium adsorption ratio (SAR) values, strong (less than 1.25) in terms of residual sodium carbonate (RSC) values, and safe to moderate (between 0 and 3) in terms of Mg hazard. The average fluoride concentrations for Hail, Al Jawf, and Tabuk were 1.6, 1.7, and 1.7 mg/L, which are higher than the maximum permissible limit of 1.5 mg/L [37].

According to Salman et al. [56], nitrate concentrations decrease in the northern part of the Tabuk–Madina region, while the southern side is characterized by high concentrations, reaching the maximum permissible limit (45 mg/L) in the eastern side of the Al-Ula area. The main sources of the nitrate in the groundwater are inorganic fertilizers, human waste and sewage sludge. In the Buraydah, Qassim province, the GWPI was found to be high in 33% of the wells, while the pollution in the remaining wells was rated as medium. Similarly, 50 percent of groundwater wells had poor or very low water quality, necessitating extensive treatment. The groundwater quality index indicates that the water quality of the region belongs to the medium category [22].

The investigations in Makkah Al-Mukaramah corroborated the traces of microbial contamination in the stream water. According to Khdary and Gassim [97], selenium, barium, arsenic copper, chromium, mercury, cadmium cobalt and lead were found in water samples from different wells in the Makkah Al Mukarramah area. The groundwater samples collected from Rabigh also showed tainting of water because of coliform microorganisms [98].

8. Policies and Legislation

Saudi Arabia has commenced the desalination of seawater to meet a part of the demand for domestic purposes. There is a lot of stress on available water resources, and in such critical conditions new groundwater laws and legislation are required to implement conservation policies to save this precious resource, especially in arid and semi-arid regions [99].

Recently, the Ministry of Environment, Water, and Agriculture has framed the guidelines to provide safe water to the community. The water laws have been revised and reformulated to augment institutional ability and have ensured the sustainability of water, safeguarding and improving its resources. The Government of KSA has formulated access to clean and safe water for domestic purposes and adequate supply for agriculture. It has stressed public–private partnership for development of water resources, ensuring effective governance. The water supply is to be ensured to all stakeholders at reasonable prices with set standards of SASO. The diversification of agricultural crops has also been suggested, along with use of treated wastewater for agriculture. The new regulations prohibited draining rainwater, groundwater, agricultural drainage water or water produced from construction sites into the public drainage network, which have been primarily the sources of groundwater contamination. The national water strategy has recommended the use of triple-treated water after ensuring its safety, free of contaminants for use in sectors other than drinking and domestic uses. Reduction in random disposal can drive diversion of waste from landfills through reuse, recycling or recovery of materials or energy.

Current practices involve non-segregation of municipal waste at the source, thus limiting the use of this waste for recycling and leading to large biodegradable waste in landfills that could rather be used for preparing compost. According to a report, 90% of municipal waste is disposed of into landfills and only 10% is used for recycling. The environmental impact assessment of the landfills is not conducted, and most of them lack leachate treatment, resulting in groundwater pollution. Thus, monitoring pollution through anthropogenic activities and waste management, and adopting measures to reduce water pollution is required.

Overall, it can be stated that the new water policy of KSA relies on augmenting management of traditional water reserves, curtailing municipal and industrial demand, increasing wastewater compliance and reuse limiting the agricultural demand, monitoring, and preventing pollution of this precious resource.

9. Conclusions

The groundwater matrix is found to be complex and heterogeneous in most regions around the world. Therefore, a lot of ambiguity is common in groundwater quality studies in the region. The perturbations caused by anthropogenic influences are difficult to quantify using conventional approaches, and therefore it requires robust modelling techniques to quantify these changes. Social development is full of uncertainties, making groundwater quality research also uncertain. Advancements in groundwater quality research in Saudi Arabia are not very comprehensive, and it is found that a few pockets or aquifers have been the focus more than others. The approach also is not holistic in nature, and thus integrative studies involving all the stakeholders are required. We sketched out quite a few recommendations, so that an integrated management could be taken up by researchers in Saudi Arabia.

1. Groundwater quality safeguards necessitate more consideration from both nongovernmental and government organizations involving the stakeholders and the users. Implementing policy measures to safeguard groundwater quality and supervision are critical to stop the deteriorating condition of the aquifers. A step-by-step technical procedure for groundwater quality management would be a good start to implement the control on degrading water quality. It is observed that in several cities of Saudi Arabia there is no check and balance on sewage treatment and effluent. Many of the cities are discharging the sewage in open pits that would be a threat to confined aquifers. Once these confined aquifers, which serve as major sources of water, get contaminated it would be difficult to restore such aquifers.
2. There should be adequate policies on water pricing. It is observed that cities such as Jeddah are receiving water for their daily needs from desalination plants. However, for an oil economy such as Saudi Arabia it would not be a great deal to implement water pricing, but certainly it would be feasible to have a check on consumption of water with a lesser amount of waste. Awareness should be taken up with the communities to educate them for efficient and effective groundwater management.
3. The agencies responsible for water management, either governmental or nongovernmental, should have a collaborative approach. Involvement of researchers and organizations from the international community would also be beneficial to inculcate the practices of groundwater quality and quantity management. International collaboration is even more important and meaningful for Saudi Arabia.
4. Real-time groundwater quality monitoring stations would be an efficient way to have a control on the deteriorating situation of groundwater quality. Currently, there are few researchers focusing on groundwater quality issues and these studies are scattered and do not seem to be systematic. The monitoring stations seems to be inadequate to develop a holistic understanding of the current scenario of groundwater in the region of Saudi Arabia. Groundwater monitoring systems need to be enhanced and augmented to preserve groundwater quality.
5. Real-time decision support systems should be developed to visualize the changing scenarios in cities that are vulnerable to groundwater resources. The policymakers would be able to make informed decisions based on these decision support systems. To improve and implement the decision support system, a uniform information management system should be developed that should be updated on a monthly basis. The information about contaminants, water characteristics hydrogeological conditions and long-term monitoring should be made public.
6. Water demand could be reduced through a policy of diversification in farming practices, and water-intensive crops should not be encouraged. Agricultural water management should be encouraged using modern irrigation methods along with estimating the crop water demand. Water pricing for excessive use should be levied on those using water above the crop water requirements.
7. The use of cutting-edge technologies such as remote sensing and GIS database management should be encouraged along with high-quality research.

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