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Research paper

Spatiotemporal mapping of groundwater salinity in Al-Batinah, Oman

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ABSTRACT

The aim of this study is to analyze the spatiotemporal variation of groundwater salinity in Al-Batinah governorate, a Sultanate of Oman, and the strategies to manage and control this problem in an effective way. Around 58,000 water wells were investigated based on their operational status and type between 1990 and 2018. The groundwater salinity levels in the area were classified into five categories based on the electrical conductivity (EC). These categories include fresh water or excellent irrigation water, low salinity water, moderate salinity water, high salinity water, and very high salinity water. A salinity map was created to track the changes in groundwater salinity over time in the study area. The results show that water salinity increases over time due to the increase in urbanization and over-pumping of water from these wells. The increase in water salinity has a negative impact on the sustainability of the society and the economy, particularly on the agricultural sector and hence effective government measurements are required to reduce these negative effects.

1. Introduction

Groundwater is the primary source of water for billions of people around the world, and it influences sustainable socioeconomic development of every community (Sahour et al., 2020; Gašparović and Singh, 2020; Ferchichi et al., 2018; Gleeson et al., 2012). Over the past few decades, the sustainability of this natural resource has been threatened in many parts of the world due to its increasing demand and over-exploitation (Motevalli et al., 2019; Rawat et al., 2018a; Wada et al., 2010). Specifically, the groundwater quality and water flow patterns in the coastal aquifers have witnessed erratic changes due to excessive withdrawal and overexploitation leading to the encroachment by seawater intrusion to coastal aquifers and the increase in groundwater salinity (Shi et al., 2020; Argamasilla et al., 2017; Werner et al., 2013a; Bouchaou et al., 2009). Groundwater salinization is more significant in arid and semi-arid areas that have limited freshwater resources. Furthermore, the groundwater salinity in these areas is considered a major environmental issue that needs a special attention (Mosaffa et al., 2021; Choudri et al., 2015a). This phenomenon, which is a dynamic process and is either induced by humans or occurs naturally, has adverse economic consequences, affects the quality of drinking water and ecological health, and makes different negative impacts on crop growth and productivity, and, hence, it can lead to land degradation (Sahour et al., 2020; Abu-alnaeem et al., 2018; Gholami et al., 2017).

In arid and semi-arid areas, the availability of good quality water is extremely low in comparison to its utilization. Consequently, the demand for groundwater exceeds the supply quantities, which results in the utilization of saline groundwater in huge quantities with consequences of salinization and desertification (Mosaffa et al., 2021; Ferchichi et al., 2018). Furthermore, water salinity is a significant factor in soil salinity, which is considered one of the important reasons for desertification in arid and semi-arid areas (Al-Yahyai and Khan, 2015; Choudri et al., 2015a; Al-Belushi 2003). Hence, timely detection of groundwater salinity and the assessment and monitoring of its severity level and extent have become essential to mitigate the negative effects of this phenomenon. Mitigating the negative impact of groundwater salinity will help in conserving non-renewable land and water resources as well as in minimizing the losses to crops and environment (Estevez et al., 2019; Allbed and Kumar, 2013).

Salt water, since it is heavier, usually occurs as a wedge beneath fresh water (Abu-alnaeem et al., 2018; Song et al., 2018). Salt and fresh water mix in the diffusion zone or transition zone and hence water becomes more saline downwards and toward the sea. The presence of a transition zone illustrates the existence of a significant circulation of seawater into

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and out of the aquifer (Majeed and Muhammad, 2019; Song et al., 2018). The saline water is prevented from moving further inland because of the formation of a natural barrier due to a continuous movement of fresh water through the zone. The flow of fresh groundwater to the sea is maintained by limited pumping of water from wells achieved by recharge in the upper parts of the aquifers. The tradition zone holds a fairly constant position (Canedo-Arguelles et al., 2019; Jia et al., 2017). On the other hand, the groundwater level falls when excessive pumping alters this equilibrium, mainly near the coast where the flow of fresh water is reduced. The transition zone, in this case, will move inland and upwards. Therefore, the water pumped from wells near the coast progressively becomes more saline (Abu-alnaeem et al., 2018; Jia et al., 2017).

The groundwater salinization is a common significant environmental and socioeconomic problem, particularly in highly populated coastal areas (Abu-alnaeem et al., 2018; Maguette et al., 2017). The salinization problem can be attributed to natural factors and anthropic activities. The natural factors include, but not limited to, climate, hydrodynamic conditions, seawater intrusion, infiltration from surface saline water and wastewater, topographic relief, interaction of water with rocks, low annual precipitation, geology, upward intrusion of brines from deeper aquifers, impact of adjacent aquifers, and saline water up-coning caused by groundwater overexploitation. The anthropic activities include, but not limited to, intensive farming activities, large-scale irrigation, urban expansion, improper sewage disposal and septic tank leachate, overexploitation of groundwater, and unplanned industrialization (Abd-El-hamid et al., 2020; Mirzavand et al., 2020; Rawat et al., 2018b; Argamasilla et al., 2017; Mahlknecht et al., 2017; Tringali et al., 2017; Bodrud-Dozaa et al., 2016; Ledesma-Ruiz et al., 2015; Kaliraj et al., 2014; Werner et al., 2013b; Huang et al., 2013; Elgettafi et al., 2012; Carol et al., 2009).

Several studies have been conducted globally to investigate water salinity and seawater intrusion in different aquifer systems by utilizing different modeling approaches (Mosaffa et al., 2021; Abu-alnaeem et al., 2020; Maliqi et al., 2020; Ferchichi et al., 2018; Mahlknecht et al., 2017; Bodrud-Dozaa et al., 2016; Chitrakar and Sana, 2016; Chenini et al., 2015; Molla et al., 2015; Zghibi et al., 2014; Sherif et al., 2012; Park et al., 2012; Datta et al., 2009). Furthermore, the spatiotemporal development of salinity has been detected by using the geographic information system (GIS) (Mosaffa et al., 2021; Gašparović and Singh, 2020; Maliqi et al., 2020; Ferchichi et al., 2018; Abu-alnaeem et al., 2018; Arslan, 2012). Mosaffa et al. (2021) investigated the source of salinity in groundwater by using stable isotope tracers and the GIS in the Azarshahr and Shabestar-Sufyan aquifers located in the Urmia basin, northwest Iran. The use of isotope tracers was effective to observe the effect of basin geology and groundwater salinity. The study found that evaporation and dissolution of evaporation rocks in the study area were greatly effective in isotopic concentrations. Sahour et al. (2020) mapped the spatial distribution of groundwater salinity in the southern coastal aquifer of the Caspian Sea. They used the statistical and machine learning techniques by utilizing the available hydrogeology and hydrometeorology data. They considered different variables affecting the groundwater salinity (e.g., the distance from the sea, mean annual evaporation, the depth of the water table, mean annual precipitation, aquifer transmissivity, and elevation). They found that aquifer transmissivity was the most significant factor to affect the groundwater salinity in the study area. Park et al. (2012) investigated the seawater intrusion into a coastal aquifer system in Korea by using the groundwater modeling system and a multidimensional hydrodynamic dispersion model. They found that seawater intrusion could be reduced if saltwater extraction was carried out in a range of 30–50% of the groundwater pumping rate.

Different studies have been conducted to assess the groundwater and soil salinity in Oman in general and in Al-Batinah in particular. Most of these studies have focused on assessing the soil salinity rather than groundwater salinity. Al-Rahbi et al. (2019) investigated the salinity intrusion in Al-Batinah area by using the color aerial imaging with an Unmanned Aerial Vehicle. They found an adverse relationship between the soil EC and the distance from the seashore. In addition, they found that intensive pumping from a fresh groundwater zone and evaporation from a saline phreatic surface lead to a trough in the water table. No fresh groundwater recharge into the sea caused by the resistivity traverses perpendicular to the shoreline. Kacimov et al. (2005) considered different elements to study the seawater intrusion, such as the catchment sizes, water densities, incident freshwater level in mountains, intensities of fresh groundwater pumping, sea level, hydraulic conductivity, and evaporation rates. They found that pumping salt water from an intruded part of the aquifer could mitigate the seawater intrusion to fresh groundwater in Al-Batinah area. The higher solute concentration and density of seawater compared to fresh groundwater have been found to be the main reasons of seawater intrusion in coastal aquifers. This intrusion process is exacerbated due to the high extraction of fresh groundwater in over-pumped catchments. Furthermore, the seawater intrusion occurs due to the penetration of saline ‘tongue’ landward from an interface between the coastal aquifer and seawater (Kacimov et al., 2005). The fresh groundwater seeping to the sea from a higher elevation zone in the upper part of a coastal catchment stymies the tongue propagation.

Al-Belushi (2003) analyzed the factors of desertification in Al-Batinah, where the study was based, to classify the soil types in the area and investigate the characteristics of these soils to determine if some soil types speed up the process of desertification in the area. The study also took into consideration the mapping of the groundwater salinity for different catchment locations in the study area. The study found that groundwater in Al-Batinah governorate, particularly the areas near the coastal zone, was severely affected by the seawater intrusion. The study also concluded that the relationship between the soil salinity and water salinity in the study area was the result of irrigation practices. Bajjali (2003) analyzed the quality of groundwater for 20,000 wells in Oman by using GIS. He found that the most affected area was Al-Batinah governorate, particularly the coastal area, where the groundwater salinity ranged between 4000 and 35,000 mg/L (ppm). Al-Barwani and Helmi (2006) mapped the groundwater salinity levels by using the GIS and Autocad in the coastal area of Al-Batinah plain. The map was based on groundwater EC surveys conducted by the Ministry of Regional Municipalities and Water Resources between 1984 and 2005. The study concluded that the cultivated land was reduced by 7% between 2000 and 2005. The study also found that the salinity water moved 12 km toward inland in different parts of Al-Batinah governorate, particularly in Barka. The Ministry of Agriculture and Fisheries developed the Oman Salinity Strategy in 2012 to consider groundwater and soil salinization, socioeconomic impacts, and feasible managerial and institutional responses. The report discussed different strategies, policies, and management approaches to overcome salinity problems.

In Al-Batinah area, the groundwater salinity problem has increased due to limited supplies of fresh water and a tremendous increase in the use of saline groundwater in agriculture (MAF and ICBA, 2012). The agricultural sector is significant for food security objective in Oman. The area under cultivation in the area has decreased by about 1800 feddans (units of area) a year since 1997 (MAF and ICBA, 2012), which is of great concern for policymakers. The agricultural sector contributes to the economic growth through job creation, improvement in rural income, diversification of the national income; the sector is considered a strong barrier against rural migration (Naifer et al., 2011). The agricultural sector in the study area depends mainly on irrigation, and hence the availability of water, rather than the availability of suitable soils, is the main constraint in the expansion of the agricultural area under cultivation (Hussain et al., 2010). Groundwater is a primary natural water resource in this area. Therefore, its management is crucial for the agricultural sector, economic development, and the benefit of the future generation. However, the systematic over-abstraction of groundwater resources has many negative consequences, such as the groundwater salinization, collapse of traditional irrigation, and aquifer depletion in coastal areas. Currently, the country is increasingly dependent on non-conventional water sources, such as desalination and treated wastewater, to bridge the gap between the supply and demand (Abulibdeh and Zaidan, 2020; Al-Rahbi et al., 2019; Sana et al., 2013; Hussain et al., 2010).

The aim of this study is to analyze the spatiotemporal variation of groundwater salinity in Al-Batinah governorate, the Sultanate of Oman, and the ways to manage and control this problem in an effective way. Around 58,000 water wells were investigated based on their operational status and type between 1990 and 2018. The groundwater salinity levels will be examined based on the EC of the water. In addition, the study aims to study the appropriate measures that the authorities could encounter to mitigate this phenomenon to reduce the negative social and economic impact on the residents of the study area.

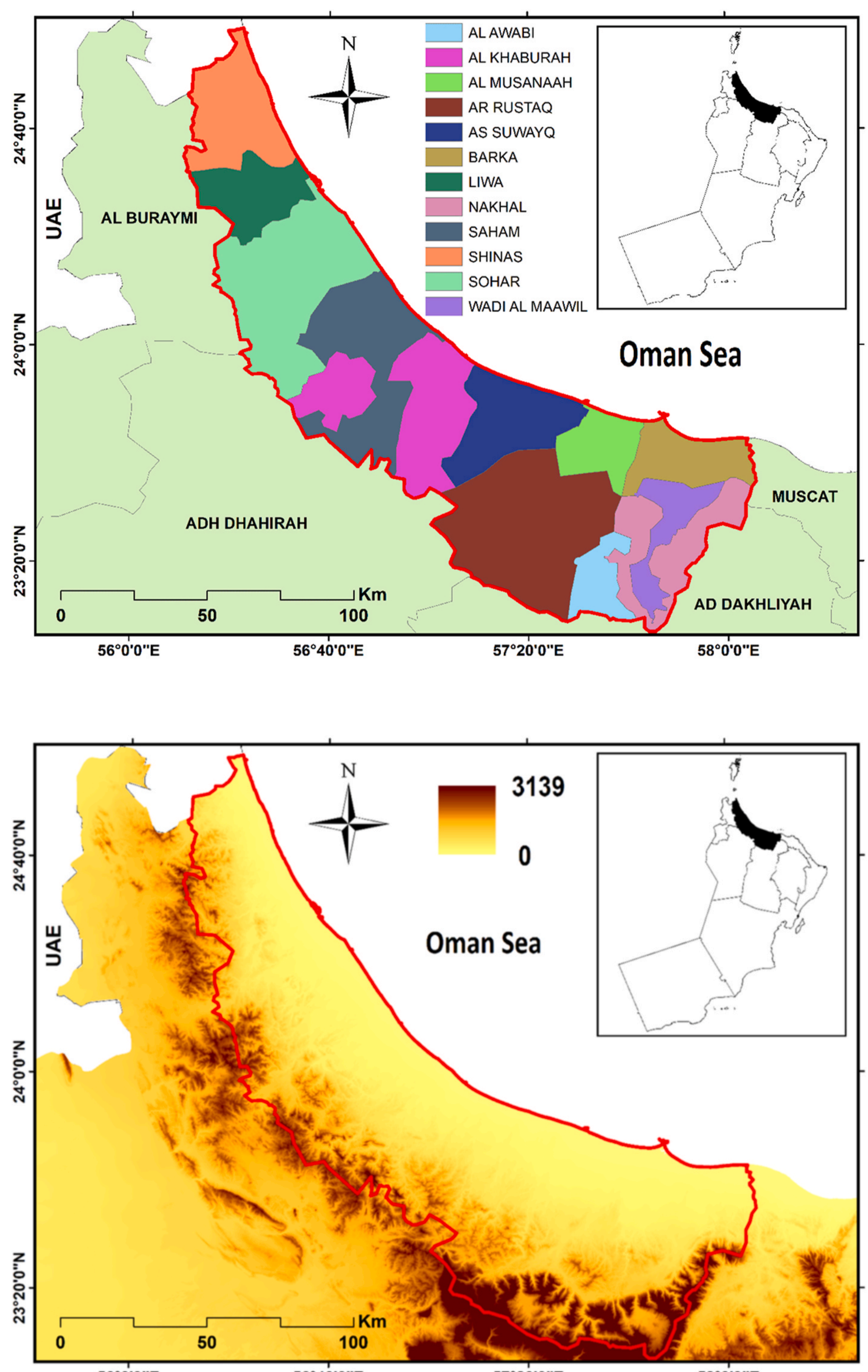


Fig. 1. (a) Al-Baitnah Governorate study area; (b) Digital Elevation Model (DEM) for Al-Batinah Governorate consists of mountains and alluvial planes, which form a setting for water storage.

2. Study area

2.1. Geographical setting

Al-Batinah plain extends in nearly 300 km northwest of the capital city Muscat and along the west shore of the Gulf of Oman. It is located at the foot of the Western Hajar Mountains in the northeastern part of the sultanate as shown in Fig. 1. It extends from the northwest to southeast trends in a crescent shape (Al-Hatrushi, 2014). This plain is the second most dense area in the country after the capital Muscat. It has witnessed a rapid increase in population growth and socioeconomic activities, such as intensive urbanization, coastal tourism projects, active ports, infrastructure development, agricultural development, and industrial activities (Al-Rahbi et al., 2019; Choudri et al., 2015b). This growth has resulted in elevating the pressure on natural resources and the subsequent increase in the demand for freshwater use, further leading to an extensive pumping of fresh groundwater. Furthermore, these activities have resulted in environmental challenges such as seawater intrusion, water and soil salinization, and desertification (Lawley et al., 2016; Choudri et al., 2016). Consequently, the subsequent lowering of the water table has led to the creation of an unbalanced situation between saline water and fresh water. This in turn causes seawater intrusion.

Al-Batinah plain is the most fertile area in the Sultanate of Oman and the largest agricultural area covering around 24% of the total cultivated area. This is the most concentrated farming area of Oman with about 52% of land under cultivation, which accounts for 65% of the Omani agricultural production of crops, such as vegetables, dates, and forage (Choudri et al., 2013, 2015a). Al-Batinah is one of the richest areas of fresh groundwater in the country. The plain is the main source of fresh water in this area and a favorable region for groundwater occurrence, which is crucial for agricultural economy of the country. Al-Batinah governorate accounts for 52% of the national agricultural water demand but provides 38% of the nation's renewable water resources (MAF and ICBA, 2012). Consequently, the local agricultural demand exceeds the supply by 58% leading to critical water shortage in the area (Al-Rahbi et al., 2019). Furthermore, the groundwater level in this area has witnessed a severe decline due to the industrial endeavors, urbanization, and the increase in irrigation resulting in the significant seawater intrusion (Al-Rahbi et al., 2019; MAF and ICBA, 2012). In the recent decades, the agricultural activities have increased manifold due to the availability of modern pumping facilities and resulting in the depletion of the fresh groundwater. Consequently, the increased groundwater salinity has adversely affected the agricultural sector in the area and the country (MAF and ICBA, 2012). Furthermore, the prolonged droughts have negatively affected the fresh groundwater level by increasing the extracted water from aquifers. The seawater intrusion and well depletion are other challenges for Al-Batinah's water resources as these processes increase the water salinity (Chitrakar and Sana, 2016; Al Ismaily and Probert, 1998).

The salinity problems in the study area are of the two following categories:

(i) Soil salinity in areas supplied by fresh water caused by improper irrigation management: This type of salinity can be reversed—unless the soil is significantly damaged—through improved drainage and better soil water management by using fresh water.
(ii) Groundwater salinity caused by the imbalance between abstracted fresh groundwater and what is naturally available: This imbalance allows the inflow of seawater into coastal aquifers. This results in salinizing the irrigated water sources. This type of salinization is difficult to reverse as the chemistry of the groundwater aquifer is frequently irreversibly changed. However, bringing the groundwater system back into balance can slow down the rate of seawater intrusion. In addition, this requires a reduction in fresh groundwater use in the affected areas.

2.2. Climate settings

According to Koppen-Geiger climate classification, the Sultanate of Oman is classified as Tropical and Subtropical Desert Climate (BWh). The country is characterized by two seasons: summer and winter. The summer that extends between April and October is scorching, while winter is characterized by warmth and low humidity. The air temperature varies depending on the location and altitude, with a mean annual temperature ranging between 32 °C and 38 °C and around 17.8 °C in the mountains. The precipitation is limited and erratic with an average annual rainfall of about 100 mm (Al-Rahbi et al., 2019; Al-Hatrushi, 2014; Kwarteng et al., 2009). Although the rainfall is scanty, it is the only source of natural water replenishment and is considered the main source for recharging the groundwater aquifers in the study area. The relative humidity is very high in the coastal areas throughout the year and reaches a maximum of 99% in summers. Furthermore, the evapotranspiration rate is around 1.29 m/year (Al-Rahbi et al., 2019; Al-Hatrushi et al., 2014).

2.3. Geological and hydrogeological settings

The Sultanate of Oman is located near the northeastern edge of the Arabian Plate. Hawassina bed formed the bed of ocean in the late Cretaceous period. In general, the country is divided into three geological provinces, namely, the Oman Mountains in the north, the low-lying Al Huqf in the central part, and the Dhofar Mountains in the southwest (Kwarteng et al., 2016; Al Hatrushi et al., 2014; Hanna, 1995). The geology of Al-Batinah coastal plain is coupled with the geology of the North Oman Mountains (see Fig. 2). These mountains are composed of tectonically emplaced Paleozoic and Mesozoic continental margin and Tethys deep-sea sediments along with a slab of Cretaceous oceanic crust and mantle, popularly known as Samail Ophiolites (Kwarteng et al., 2016; Robertson, 1990). Lithologically, the Northern Oman Mountains are composed of three consecutive main rock units in addition to Quaternary sediments (Kwarteng et al., 2016; Hanna 1995). The base rock units consist of the Autochthonous sequence, which are the oldest rocks exposed in the mountains and are composed of the Precambrian crystalline basement of the Arabian platform. In addition, these base rocks are composed of the Precambrian crystalline basement of the Arabian platform and the pre-Permian shelf carbonates known as the Hajar Super Group sequence. Overlying the autochthonous sequence is the allochthonous sequence, which consists of Samail Ophiolites, Hawasnah Complex, and metamorphic rocks sandwiched between them. Overlying the allochthonous sequence is the Late Tertiary and Quaternary deposits that include gravel terraces and fans in the alluvial plains, slopes, and aeolian deposits. The surface deposits along the coastline consist of a mixture of terrestrial and marine deposits including he raised beaches, alluvial gravel, coral terraces, and aeolian sands (Kwarteng et al., 2016).

Based on the geological setting and rock type, the Al-Batinah area can be divided into two major parts (Kwarteng et al., 2009, 2016; Al Hatrushi et al., 2014): (1) the mountains, which are composed of hard rocks, mainly igneous, overlain by ophiolite sediments with some sandstones and conglomerates underlain by several thrust sheets of pelagic sediments and tertiary limestone; and (2) the Al-Batinah plain, which has been formed over millions of years by the effect of natural processes such as weathering and rainfall. The rainfall on mountains is an important element that contributes to building up the plain by spreading sediments. Furthermore, the complex patterns of clay and gravel have been formed in valley channels. The plain is composed of coarse gravels and boulders with occasional cemented beds. Al-Batinah plain can be divided into two main zones: (1) the Piedmont zone, which consists of several alluvial terraces of fluvial origin of limited extent, and (2) the surface of the plain, which is composed of coarse sand and gravel along with alluvial terraces that elevate around 600 m above the sea level. Numerous valleys descending from mountains and meandering to

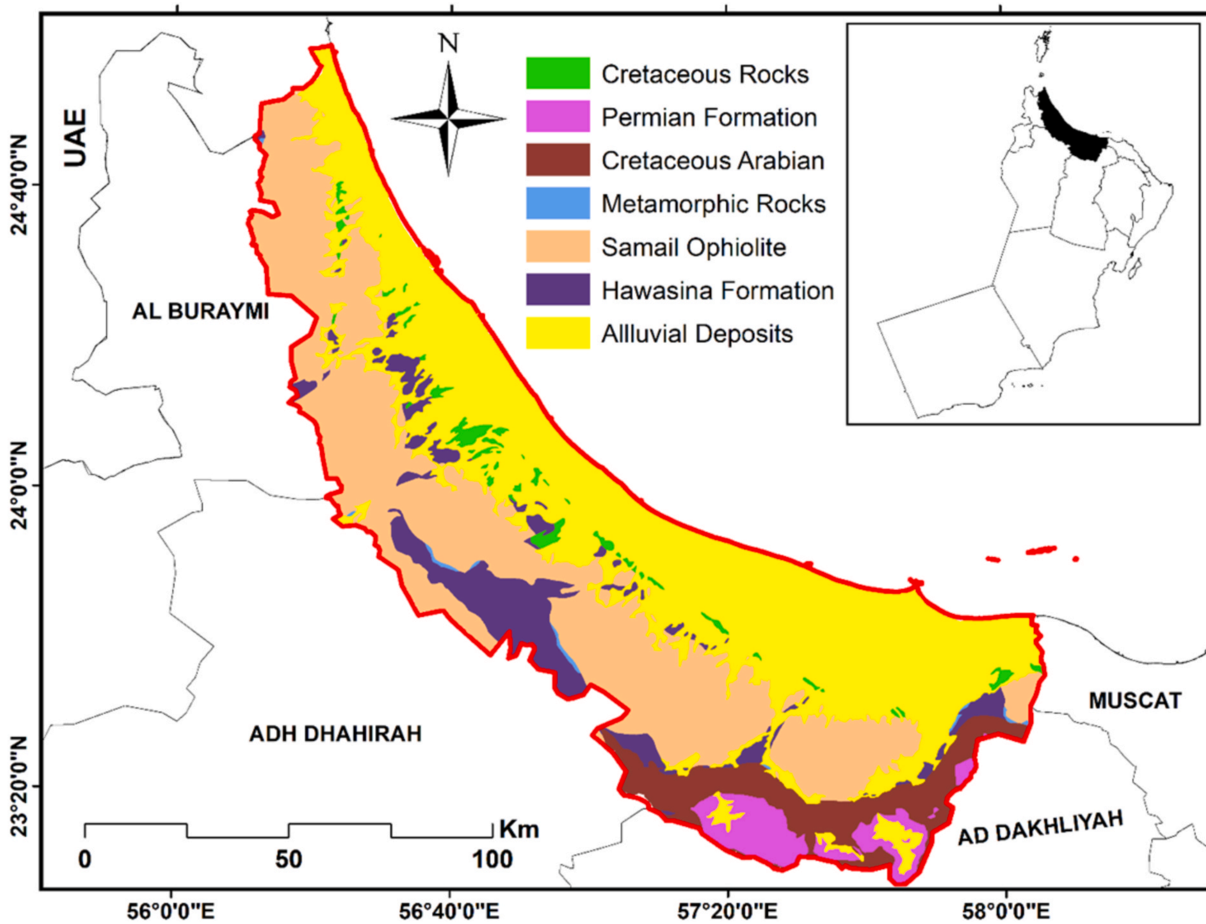


Fig. 2. Geological map of the study area.

drain in the Gulf of Oman have dissected the surface. The modern valley gravel acts as a major conduit to the upper catchment's reaches in Al-Batinah plain. Furthermore, these modern valley gravels, which reach 50 m in thickness, are the location of the major water-bearing formation. Second, the valley fans prevail at lower reaches forming the coastal plain. The coastal zone is less than 20 m above the sea level and the surface mainly consists of terrestrial and marine coarse to fine sands. Furthermore, the sand dunes and sabkhas exist near the coast. The coastal alluvium extends up to the depth of 600 m of poorly sorted silts, sands, and gravels.

The alluvial deposits become finer toward the interfluve area between the systems of braided channels as well as toward the coastal area. In the Northern Batinah coastal plain, the groundwater occurs in both the alluvium and the underlying Upper Fars formation, from where less than 1% of the current abstraction originates (Al-Hatrushi, 2016; Al-Hatrushi et al., 2014). On the other hand, groundwater occurs in alluvium aquifer in the Southern Al-Batinah coastal plain. Hydrogeologically, they are divided into three parts, namely, upper gravels, clayey gravels, and cemented gravels (Al-Barwani and Helmi, 2006). The upper gravel is comprised of low-lands or Piedmont Zone, which constitutes the main productive zone where thickness increases toward the sea. Hydraulically, this unit is affected by the cementation with calcium carbonate, grain size, and the degree of sorting. However, its storage and transmissivity are generally good. The transmissivity value ranges between 550 m^2/day in the southern part and 3000 m^2/day or greater in the northern part of the plain (Al-Barwani and Helmi, 2006). The high transmissivity in the northern part is due to the higher proportion of coarse materials caused by the narrowness of the coastal plain or greater aquifer thickness. The clayey gravels underline the upper gravels. This part is characterized by the appearance of brown and red marly gravels and clayey sands associated with decreasing well yields and average transmissivity of about 223 m^2/day. The cemented gravels are located at the bottom of the clayey gravel sequence. This part is characterized by the smallest specific capacities and biggest drawdowns, which make them markedly poor aquifer.

The groundwater quality in this area varies between mountainous and plain areas. The water quality near recharge sources, in mountainous areas, is good with the total dissolved solid (TDS) of less than 1500 mg/L (Chitrakar and Sana, 2016; McDonnell, 2016; Kwarteng et al., 2009; Al-Barwani and Helmi, 2006). While water quality in the plain and lowland areas decreases as groundwater dissolves many salts (calcium carbonate) during its way to the sea with higher TDS values in the range of 1500–6500 mg/L associated with larger settlements (Chitrakar and Sana, 2016). The alluvium forms a complex system of water-bearing formations in Al-Batinah region. The recharge to the alluvial system overall varies annually depending on precipitation patterns; however, it is estimated to average 396 MCM/year (McDonnell, 2016; Chitrakar and Sana, 2016). A single deep groundwater basin is formed from these deposits along the Al-Batinah plain containing relatively fresh groundwater inland where saline intrusion exists near the coast. The freshwater aquifer, in the coastal zone, is underlain by a saltwater wedge that now extends to several kilometers inland. The other relevant hydrological characteristics of the Northern Batinah alluvial aquifer include the hydraulic conductivity, which ranges from 0.3 m/day to 449 m/day, where the highest values are associated with uncemented sands and gravels and the lowest hydraulic conductivity is associated with cemented, clayey sands. The storage coefficient values of the Northern Al-Batinah alluvial aquifer range from 1×10^{-5} to 1×10^{-2}, while the transmissivity ranges from 0.9 m^2/day to 16,900 m^2/day (McDonnell, 2016).

3. Methodology

Table 1 summarizes the data sources that have been used to conduct this research. The road network data from the Oman National Center Statistical and information (NCSI) were used to rectify all data sources into one coordinate system, which is WGS 1984 UTM zone 40.

This study relied on several research approaches, either in data collection, analysis, or interpretation, as illustrated in Fig. 3.

The methodology can be divided into two main steps:

3.1. Step 1: collecting and analyzing salinity data

In early 1993, Oman stopped issuing permits for drilling water wells and immediately started having a comprehensive inventory of wells, including the location of the well, type of well, water quality, ownership, height, depth of water, and other important information. The total number of wells in the study area were 58,850, including 24,207 operational and 34,643 nonoperational wells. Only 2669 wells of the Ministry of Regional Municipalities and Water Resources (MRMWR) were used to conduct the salinity mapping in the study area for the periods 1990, 2000, 2010, and 2018. The degree of water salinity was analyzed based on the degree of EC. The unit that was used to define water salinity was micro-Siemens per centimeter [μS/cm]. The ministry measured the salinity several times a year for monitoring. For research, the average readings of salinity were used to map salinity in the study area. Each water well was defined by easting and northing coordinate system (WGS, 1984; Zone 40). The level of salinity was attached to the well as an attribute.

3.1.1. The inverse distance weighting (IDW) methods

The IDW is a widely used spatial deterministic interpolator, which gives more weight to closer points over space. The advantage of this approach is to estimate the cell values using the average values of the closest to the center of the cell whose value is to be estimated (Myers, 1994; Mitas and Mitasova, 1999). It is a widely accepted interpolation algorithm in the regions of plain topography, such as Al-Batinah plain, where the possible effect of topography on the accuracy of the interpolated surfaces is minimized. According to the IDW, the value of interpolated variable at any sampling point is computed in view of the weight of neighboring points. To compute the value at any un-sampled point (*n*) over space, a weight is assigned to each of the neighboring points with data. The weight (Wn) assigned to point *n* is simply computed, as:

$$W_n = \frac{1}{d_n^i} \tag{1}$$

where d is the Euclidean distance between points i and n.

Then, the value at any un-sampled point (Xi) is computed using the weights of all points with data, as:

$$X_i = \frac{w_1x_1 + w_2x_2 + w_3x_3 + w_4x_4 + w_5x_5 + w_6x_6\ldots.. + w_nx_n}{W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + \ldots + W_n} \tag{2}$$

where x is the value at the un-sampled point (i) and X_n is the value of the variable at point ***n***. ***Wn*** is the Euclidean distance between the point i and the point n. A comprehensive description of this interpolation algorithm is detailed in Hodam et al. (2017) and Madhloom et al. (2018).

3.1.2. Validation outputs

There are several statistical metrics that could be used to assess the accuracy of IDW outputs, including the bias, mean absolute error (MAE), root mean squares error (RMSE), % RMSE, and correlation coefficients (Kazemi et al., 2017; Bronowicka-;Mielniczuk et al., 2019). In this study, some of these metrics were deployed to assess the output of a cross-tabulation procedure. Specifically, we excluded 10% from the whole dataset (wells) and carried out the interpolation algorithm to the remaining data points (90%). Based on the interpolated surface using 90% of points, we extracted the values corresponding to the randomly selected sample (10%). We compared the observed data of this random sample with the predicted values by using IDW, % bias, coefficient of determination (R^2), and scatterplot diagrams (Fig. 4). Here, it is noteworthy to indicate that the sample (10% of all points) was selected by randomly using Hawth's Tools imbedded in ArcGIS software. Table 2 summarizes the accuracy metrics computed following the cross-validation procedure.

3.2. Step 2: collecting and analyzing urban and vegetation data

The remote sensing with the GIS is a popular technique for identifying built-up and green areas (Joseph et al., 2020; Abulibdeh, 2020; Hereher and Al-Awadhi, 2020; Abulibdeh et al., 2019a; Fadda et al., 2019; Al-Awadhi et al., 2017; Rajendran et al., 2016; Rawat and Kumar, 2015; As-Syakur et al., 2012; Vermeiren et al., 2012; Al-Awadhi, 2008; Xu, 2007). Four Landsat images were used to identify built-up and green areas for 1990, 2000, 2010, and 2018 with other ancillary sources, such as population settlements and census data. The pre-processing such as image geometric correction and enhancement has been done in ArcGIS (ArcMap) ver. 10.5 environment.

Several methods are used to extract the information from satellite images. It depends on the type of images, coverage areas, concertation of the object value in the image, and others. For this study, the built-up areas were extracted with the help of the Enhanced Built-Up and Bareness Index (EBBI) by using Equation (3). However, the information for 1990 was extracted by using the other supported data such as printed aerial photos and topographical maps.

$$\text{EBBI} = \frac{\text{Band } 5 - \text{Band } 4}{\sqrt[10]{\text{Band } 5 + \text{Band } 6}} \tag{3}$$

The remote sensing techniques have been used broadly to identify and extract the green area, especially when covering the large area with

Table 1
Summary of data sources.

Data Description	Year	Resolution & Scale	Bands	Data format	Source
Landsat 5 image TM	1990	30*30 M	7	Raster (tiff)	USA Geological Department
Landsat 7 image ETM+	2000	30*30 M	8	Raster (tiff)	USA Geological Department
Landsat 8 image OLI/TIRS	2010	30*30 M	9	Raster (tiff)	USA Geological Department
Landsat 8 image OLI/TIRS	2018	30*30 M	12	Raster (tiff)	USA Geological Department
IKONOS	2002	1*1 M	3 (RGB)	Raster (tiff)	SCTP
Arial photo	2012	1:20,000	3 (RGB)	Raster (tiff)	SCTP
Road network 2018	2018	1:20,000	–	Shapefile	NCSI
Population Settlements	2010	1:20,000	–	Shapefile	NCSI
Census data	1993 & 2010	–	–	Statistical data	NCSI
Water wells	1993	1:20,000	–	Shapefile	MRMWR
Salinity data	1990, 2000, 2010 and 2018	–	–	Shapefile & Statistical data	MRMWR
Tourism and topographic map	1990	1:20,000	–	Printed map	NSA

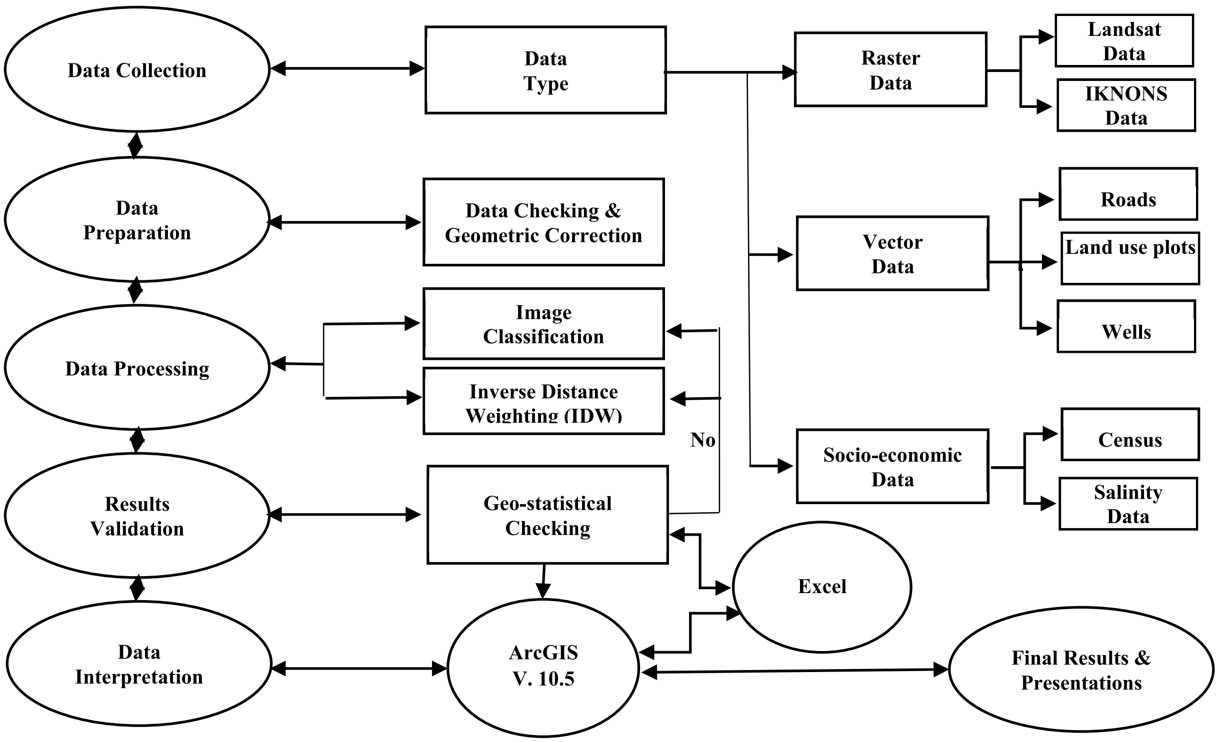


Fig. 3. Research methodology flowchart.

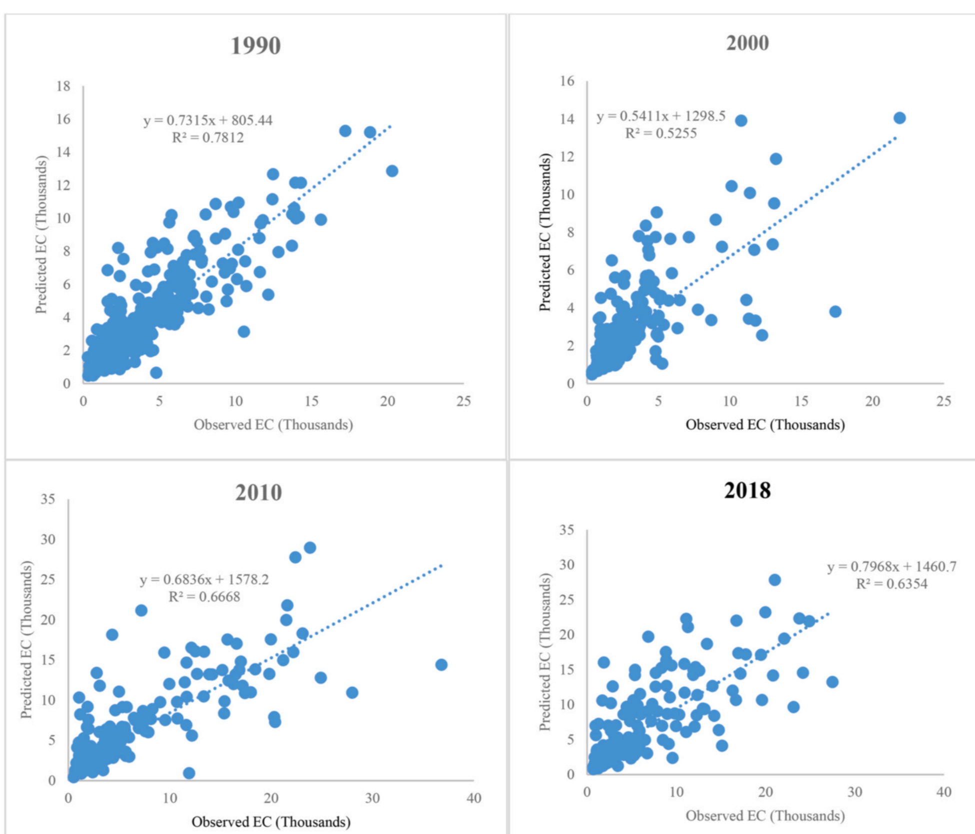


Fig. 4. Scatterplots show the association between the observed and predicated EC; predicted values were estimated by using the IDW interpolator. The results are presented for four different years.

Table 2
Accuracy assessment metrics applied to assess the performance of IDW in the study domain.

Year	Number of Samples	Average			%Bias	Overall Accuracy	R^2
		Observed	Predicted	BIAS			
1990	538	3206	3151	55	1.75	98.25	0.7812
2000	234	3006	2925	81	2.76	97,24	0.5255
2010	267	5145	5095	50	0.97	99.03	0.6668
2018	267	4866	5338	472	8.84	91.16	0.6354

healthy concertation. Many methods and approaches were used to identify the green area, such as supervised classification, unsupervised classification, NDVI, Artificial Neural Network (ANN). For, this study, NDVI was used. The main concept of NDVI is to calculate the difference between near-infrared (NIR) and red (RED) and then divide by their sum, as shown in Formula 4. The value index of NDVI ranges in (1) – (−1). The index near 1 means high concertation of green area, while near −1 means less concertation.

$$NDVI = \frac{NIR - R}{NIR + R} \quad (4)$$

4. Results and discussion

To add more insight to the analysis of groundwater salinity, this study examines the groundwater salinity based on the spatial distribution of the abstraction water wells and their operational status for the whole study area, as shown in Fig. 5a. The map shows that the majority of the wells are located along the cost in a thin strip of land. This increases the probability of seawater intrusion. The total number of wells in the study area is 58,850, of which 24,236 were in use in 1990. The number of the wells in use almost remained the same in 2018; however, the main difference is the salinity ratio. The water wells were classified into three categories based on their operational status, as shown in Fig. 5b. The majority of the water wells are agricultural wells and most of them are located along the coastal area. These wells are more vulnerable to salinity due to seawater intrusion and high consumption of water for agricultural purposes. As a result, many of these wells have been abandoned that negatively affects the agricultural sector in this area. The same applies to other types of wells.

The groundwater salinity levels were classified into five classes, ranging from low to high salinity (Table 3), based on EC and Fipps (1996) and Glover (1996) irrigation water classification. The five categories included: (1) fresh water or excellent irrigation water, which corresponds to EC of the soil in the root zone less than 2000 micro-Siemens per centimeter or (μS/cm); (2) low salinity water, which corresponds to EC of the soil in the root zone less between 2100 and 4000 μS/cm; (3) moderate salinity water, which corresponds to EC of the soil in the root zone between 4100 and 8000 μS/cm; (4) high salinity water, which corresponds to EC of the soil in the root zone between 8100 and 12,000 μS/cm; and (5) very high salinity water, which corresponds to EC of the soil in the root zone more than 12,000 μS/cm.

Table 3
Classes of salinity.

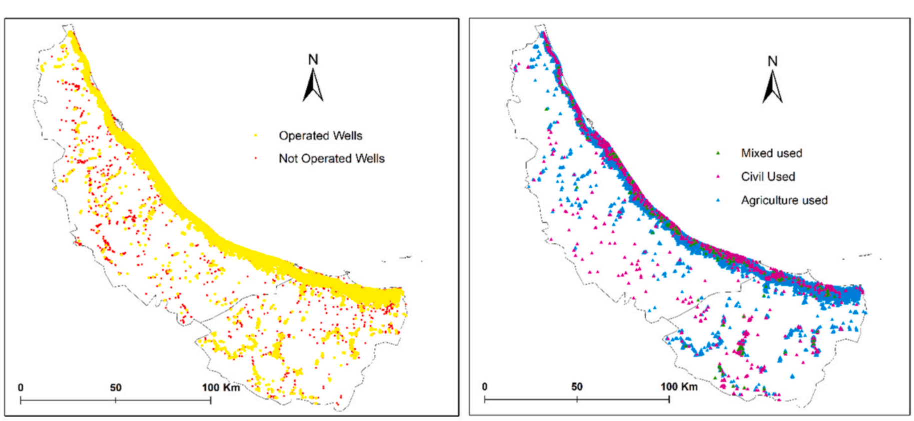
Fresh water	0–2000 μS/cm
Low salinity	2001–4000 μS/cm
Moderate salinity	4001–8000 μS/cm
High salinity	8001–12,000 μS/cm
Very high salinity	12,000+ μS/cm

The results of the statistical analysis of groundwater salinity in Al-Batinah area are shown in Table 4. The results show the increase in the salinization value over time in the study area. The maximum value of EC doubled over the study period. This indicates that salinity is spreading fast in the study area. Table 5 shows the total coverage area for each EC class in Al-Batinah over the study period. The table shows that water salinity is increasing and extending to more areas over time. The freshwater area decreased by 30% while very high salinity increased around nine folds. The spatial and temporal analysis reveals that groundwater salinity is rising over time in all the catchments in Al-Batinah area, particularly in the areas near the coastline, as shown in Fig. 6.

Table 6 shows the total number of wells in each salinity category.

Table 4
Statistical information of electrical conductivity (EC) classes (1990–2018) in the study area.

Statistical Indicator	1990	2000	2010	2018
Minimum	105	121.8	141	148
Maximum	32,800	53,400	60,700	61,190
Range	32,695	53278.2	60,559	61,042
Mean	3241.1	2931.9	4892.5	5210.9
Standard Deviation	3025.7	3238.3	6207.2	6166.6



(a) Operational status, 2018 (b) Type of well by water use

Fig. 5. Operational status and location of wells in the study area.

Table 5
Total coverage area (km^2) of each electrical conductivity (EC) class (1990–2018) in the study area.

EC Classes	Area Km^2				% Changed between 1990 and 2018
	1990	2000	2010	2018	
Fresh water	10816.56	9533.56	8005.88	7429.56	−31.3%
Low salinity	1746.6	2926.64	3288.4	3648.12	108.9%
Moderate salinity	510.76	559.24	1090.24	1173.36	129.7%
High salinity	99.76	148.36	485.76	494.72	395.9%
Very high salinity	48.56	54.44	351.96	476.48	881.2%
Total	13222.24	13222.24	13222.24	13222.24	

Table 6 clearly shows that there is an inverse relationship between the salinity category and the number of wells over time. The number of the used freshwater wells, for example, dropped by 68% over the study period, while very high salinity used wells increased by 1195%. Even the number of the low to moderately used wells has decreased to the expense of the high to very high salinity used wells. The same applies to the not used wells as the percentage of fresh to moderate wells has decreased to the expense of high to very high not used wells.

It is clear that water salinity is increasing rapidly over time in all water wells with different operational purposes, as shown in Table 7. In general, this implies a negative impact on economy, particularly on the agricultural sector. Most of the operated wells are for agricultural purposes and hence they are the most affected by the increase in water salinity.

Irrigating the plants with saline water results in a yield loss as plants differ significantly in the extent to tolerate salts in the soil. This loss depends on many factors, such as soil type and drainage, stage of growth

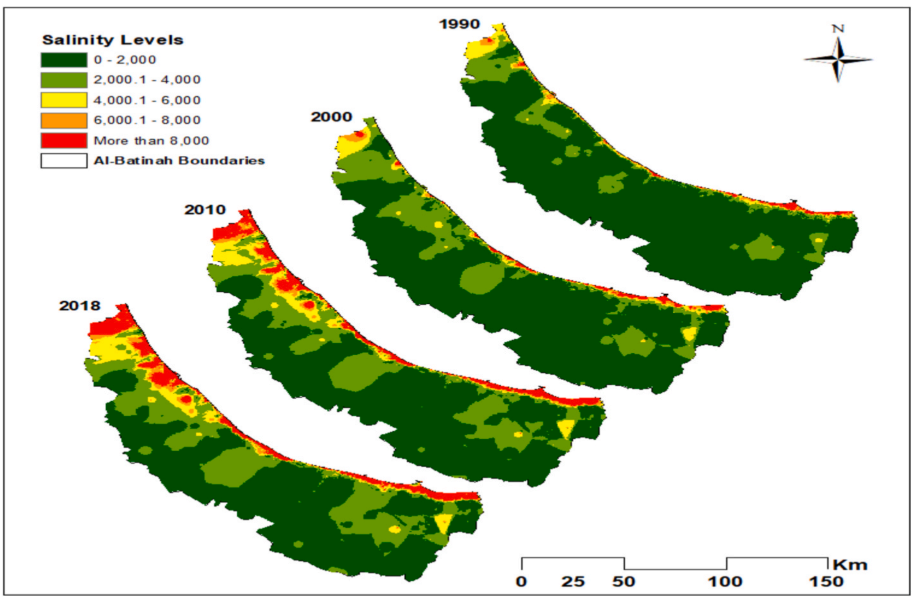


Fig. 6. Spatial and temporal growth of groundwater salinity in Al-Batinah area between 1990 and 2018.

Table 6
The total number of used and not used wells in each salinity category in 1990–2018.

Salinity Classes	1990			2018					
	Used	Not used	Total	Used	% difference from 1990	Not used	% difference from 1990	Total	% difference from 1990
Fresh Water	8984	11,490	20,474	2859	−68.2%	2990	−74%	5849	−71.4%
Low Salinity	7646	8990	16,636	4458	−41.7%	6289	−30%	10,747	−35.4%
Moderate Salinity	5609	9935	15,544	5285	−5.8%	7774	−92.2%	13,059	−16%
High Salinity	1422	3376	4798	4150	191.8%	6248	85.1%	10,398	116.7%
Very High Salinity	575	823	1398	7446	1195%	11,351	1279.2%	18,797	1244.6%
Total	24,236	34,614	58,850	24,198	−0.156%	34,652	0.11%	58,850	0%

Table 7
The total number of wells based on their operational purposes in each salinity category in 1990–2018.

Salinity Classes	1990					2018				
	Agriculture	Municipal	Mixed used	Not used	Total	Agriculture	Municipal	Mixed used	Not used	Total
Fresh Water	8230	677	77	11,490	20,474	2551	264	44	2990	5849
Low Salinity	7255	352	39	8990	16,636	4137	293	28	6289	10,747
Moderate Salinity	5317	278	14	9935	15,544	4958	302	25	7774	13,059
High Salinity	1366	54	2	3376	4798	3925	211	14	6248	10,398
Very High Salinity	561	12	2	823	1398	7137	286	23	11,351	18,797
Total	22,729	1373	134	34,614	58,850	22,708	1356	134	34,652	58,850

and varietal differences, frequency and timing of irrigation, climate, and the method of irrigation. The groundwater and soil salinity effects on crop yields are given in Table 8.

In terms of fresh water and non-saline soils, the yields of all crops are not affected as long as water and soil salinity are kept within the freshwater range. Since irrigation with fresh water could lead to accumulating water and soil salinity to a field over a season, good water and soil management are significant to maintain the soil and water quality. On the other hand, lower levels of water and soil salinity result in reducing the yields slightly or significantly, depending on the crop type and the severity of the water and soil salinity. These losses could be overcome by adopting water and soil management and agronomic practices that are appropriate for local conditions. Some of the mitigation strategies can be followed to reduce the negative effects of salinity on crop yields, including deep irrigation before sowing to migrate the salts from the soil, proper leveling of soil to prevent accumulation of salts in elevated areas, and mulching and applying organic matter to improve physical properties of soil. Other mitigation strategies could include increasing leaching, salt scraping and piling, selecting irrigation system with uniform application, and sowing on shoulders of ridges. In terms of moderate salinity, the crop selection based on salt tolerance is the most significant management decision in mitigating the salinity effect of yield crops. Different factors also play an important role in soil and water salinity mitigation, such as crop variety, local climate, soil type, management practices, and irrigation water quality. In high salinity situation, it is better to use the crops having much higher levels of tolerance than what is currently used. The diversification of production systems with high salinity crops is an important adaptation strategy to mitigate the adverse effects of salinity and to sustain farm productivity in high saline water and soil. Finally, in a very high salinity stage, introducing biosaline agricultural system is an approach to achieve production from saline land and using saline water resources. Therefore, growing non-conventional crops is no longer economical when water and soil are characterized by very high salinity.

5. Driving forces of salinity in the study area

The salinity problem in Al-Batinah area is significant and has been increasing over time. Utilizing saline water in agricultural practices is considered a common practice in that area (Al-Rahbi et al., 2019; MAF and ICBA, 2012). This practice elevates the problem of salinity over time. The primary cause of water salinization in the study area is groundwater overdraft. In Al-Batinah governorates, the groundwater use was about 54% higher than renewable supplies in 2010, where recharged water is 360 million cubic meters a year (Mcm), compared to 557 Mcm water abstraction (Ahmed and Askri, 2016; MAF and ICBA, 2012). Therefore, the underground water in storage has been used to meet the water demand, and hence it has resulted in reducing groundwater levels. The reduction in the groundwater level allows fresh water in the landward side of the irrigation coastal strip to be accelerated from the hills because of the increase in the groundwater gradient. However,

Table 8
The effects of groundwater and soil salinity on crop yields.

Salinity	Electrical Conductivity (μS/cm)	Effect on crop yields
Fresh water	0–2000	No significant effect on yield
Low salinity	2001–4000	Yields of sensitive crops maybe affected
Moderate salinity	4001–8000	Yields of many crops are affected
High salinity	8001–12,000	Only tolerant crops yield satisfactorily
Very high salinity	12,000+	Only a few very tolerant crops yield satisfactorily

Source: Adopted from MAF and ICBA, 2012.

the pumping process flattens or reverses the groundwater gradient to the sea and hence allows for seawater intrusion as pumping process reduces the outflow of groundwater that prevents the flowing of seawater into the aquifer (Al-Rahbi et al., 2019; Kacimov et al., 2005). In addition, the reduction in the thickness of fresh water reduces the pressure on the deeper seawater wedge and allows it to rise up into the aquifer. A primary way to stop the inflow of seawater is to reduce the withdrawal of groundwater, which in turn reduces further salinization of the farms using groundwater (Sana et al., 2013).

The groundwater salinity has also increased in this area due to climate characteristics and the area's proximity to the sea (Ahmed and Askri, 2016; Kacimov et al., 2005). The climatic conditions in this area are conducive to accumulation of salts in groundwater and on the surface and subsurface of the soil as salt cannot leach down completely. Therefore, the net water movement in the soil remains upward and is associated with the dissolved salts (Hussain et al., 2010). The groundwater evaporates and leaves these salts on the surface area or nearer the underneath. These conditions increase the probability of the development of groundwater and soil salinity. This process is always active particularly in dry seasons and hence gradually, but slowly, builds up the saline groundwater and soils.

Another factor that elevates the groundwater salinity in Al-Batinah is its nearness to the sea. The area is subject to saline seawater intrusion that increases the salinity of the groundwater. Furthermore, soil salinity increases due to soil formation from minerals high in salty water sprays, soluble salt content, and saline water floods. The salt content is naturally high in a significant part of Al-Batinah soils as these soils were built up from the deposited coastal materials. Salinity also accumulates when soil is left uncultivated for long periods since the net water movement becomes upward. The irrigation for crops diverts the water cycle and salt movement downward and hence it is useful to keep the soils under crop cover (Munns and Gilliham, 2015). However, in Al-Batinah area, water resources are very limited and hence the crop intensity cannot increase. This forces the farmers to keep their lands fallow for some part of the year, particularly during summers. Therefore, the accumulated salts in subsurface remain recycling and cannot leach very deep or be drained off. Humans activities induce the secondary type of salinity. These activities include cultural practices, sewage from residential areas, polluted effluents from industries into waterways and soils, and irrigation operations and crop sequences in agricultural fields. This type of salinity is pronounced in Al-Batinah area (Al-Rahbi et al., 2019; MAF and ICBA, 2012; Al-Mulla, 2010).

The urbanization is another driving force of groundwater salinity. Al-Batinah area has witnessed rapid urban transformation between 1990 and 2018, driven by population growth and economic development. The urbanization in this area has spread horizontally, as shown in Fig. 7. The urban area expanded by 138.4% between 1990 and 2000 to cover a total area of 87.33 km^2, as shown in Table 9; however, the rate of expansion retreated between 2000 and 2010 to reach 24.3%, whereas the urban area expanded to cover 108.6 km^2 by 2010. Between 2010 and 2018, Al-Batinah area witnessed a rapid increase in urbanization. The area of urbanization increased by 117.3% to cover 235.9 km^2 by 2018. Most urban expansion took place along the coastal strip where the land is fertile and groundwater wells are extensive. The urbanization has increased the probability of discharging treated water from wastewater treatment plants into the groundwater and the soil. Therefore, the urban development in this area has resulted in gradual but consistent increase in salt concentration of groundwater.

The expansion in urbanization in Al-Batinah area was on the expanse of the vegetation area, as shown in Table 9 and Fig. 8. Although between 1990 and 2010, the percentage of vegetation area increased in Al-Batinah area, the main increase was in the landscape vegetation as the percentage of the farms witnessed reduction due to urbanization and water salinization. After 2010, the green areas witnessed a rapid decline until 2018, as shown in Table. One reason for this phenomenon is that many farmers converted their farms to other types of use, mainly

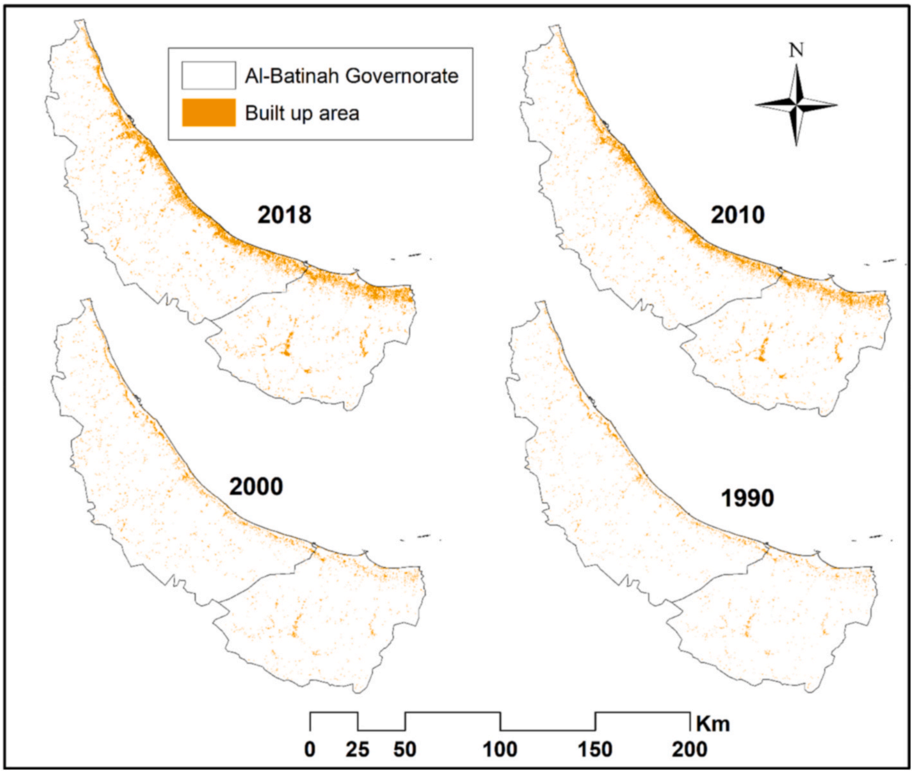


Fig. 7. Expansion of urbanization in Al-Batinah area between 1990 and 2018.

Table 9
Urban development in Al-Batinah Governorates.

Year	Built-up		Vegetation	
	Km^2	Change %	Km^2	Change %
1990	36.6	0	311.9	0
2000	87.3	138.4	407.0	30.5
2010	108.6	117.3	478.4	22.5
2018	235.9	117.3	478.4	−4.1

residential and commercial areas.

The agricultural production in the country increased steadily until 1990 and accelerated in 1997. The agricultural production increased from 0.68 million tons in 1985 to 0.7 and 1.23 million tons in 1990 and 1997, respectively (MAF and ICBA, 2012). However, this production decreased by 4.7% nationally in the subsequent years to an average of 1.17 million tons over the period 2006–2010. Al-Batinah governorates accounted for 80% of this reduction (MAF and ICBA, 2012). Water and soil salinization are significant contributors for the loss of cultivated land and productivity. In addition, the loss of the cultivated area was greater than that provided by new lands brought into production. The rising groundwater salinity in Al-Batinah area is a serious threat to the sustainable use of natural resources and economy of the area, particularly the agricultural sector. The expansion of the agricultural sector in Al-Batinah area accelerated the use of groundwater resources through over-pumping. This process resulted in disturbing the water balance and seawater intrusion.

The farms in the upstream areas were irrigated by the wells equipped with pumps and motors or by drilling of deep wells and heavy pumping. The aquifer became deficit since the withdrawals were higher than the recharge. Therefore, the salinization process became very active and persistent with no salt control at that time. In addition, the area witnessed the increasing number of Sebkha, which are poorly drained depression areas near the coastal areas where salt and water accumulate. Gradually, the salt content in these areas increased as the excessive water either evaporated or drained into the sea. As a result, the salt affected the agricultural areas and abandoning the farms became a permanent feature and ever-increasing phenomenon of the landscape in Al-Batinah plain. Therefore, agricultural practices, development, and sustainability in this area would not be possible as water and salinity emerged as an extreme problem.

6. Management strategies

Some measures were taken by the authorities to control and reduce the level of water salinity, such as the control of digging new wells and the rehabilitation of the older ones. Furthermore, the authorities constructed new recharge dams and developed incentives for modern irrigation system. However, a number of farms have been abandoned due to high salinity levels that were unendurable even to the most salt-tolerant crops. Furthermore, the groundwater salinity in Al-Batinah is irreversible due to the existence of depressions in aquifers. Therefore, it has become of paramount importance to develop and implement sufficient and effective groundwater reclamation policies and strategies to prevent any further salinization to sustain agricultural lands and natural ecosystems and manage and monitor groundwater salinity. The current situation requires the management techniques that ensure the sustainable use of saline water, help in conserving land and water resources, and minimize the loss to crops and soil health.

In agricultural and water sectors, the water shortage can result in social and economic difficulties and hence technical and policy changes are needed to avoid these hardships (Abulibdeh and Zaidan, 2020). Improving water management options is needed as a transition from focusing on augmenting supply. This necessity provides the direct service to concentrate on water management and regulation of services. Allocating water based on the principles of economic efficiency has an advantage of providing objective guidance and developing methods that have built-in flexibility to manage differences in water supply and demand. These changes require the development of plans that promote demand management; integrate water quantity and quality; enforce

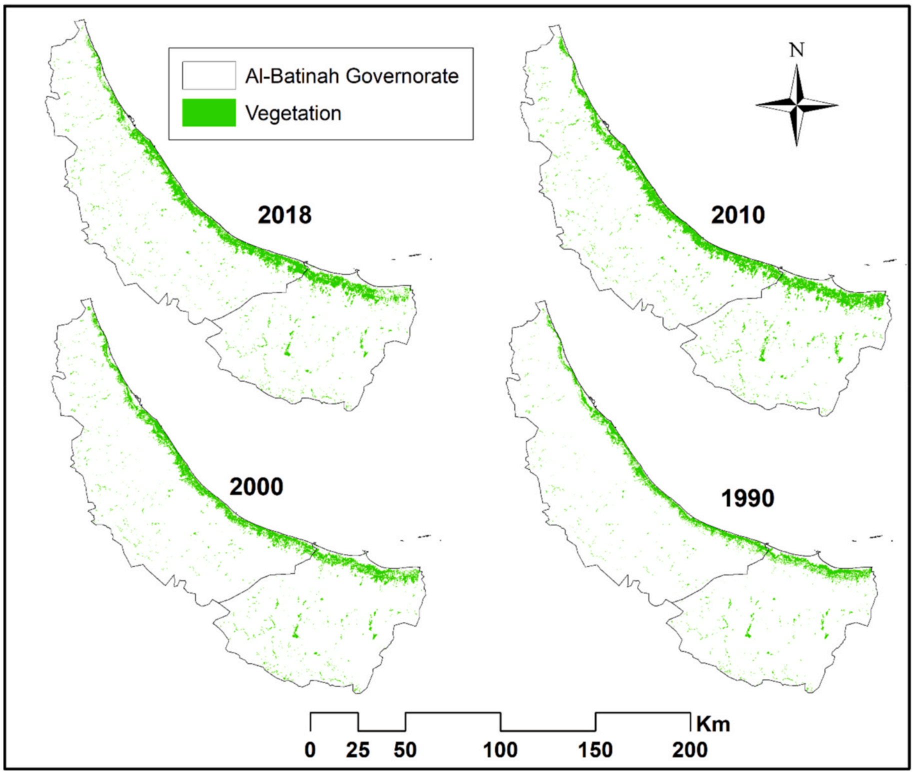


Fig. 8. Vegetation areas in Al-Batinah area between 1990 and 2018.

environmental regulations in better and stronger ways; decentralize responsibility for delivering water services; reform tariffs for water supply, irrigation, and sanitation; and strengthen government agencies.

Seawater intrusion and salinization of groundwater phenomena are inseparable and negatively affect agricultural lands in Al-Batinah area. This impact is difficult to be solved without introducing the measures to reduce and eliminate groundwater overdraft. Managing and mitigating salinity effects require addressing policies and regulations that align with water and environmental conservation. Furthermore, these policies and regulations should halt seawater intrusion by balancing water supply and demand, improve management of soil resources and water inputs, and adapt agronomy in the salinity-affected areas to produce higher yields. Many of the crops in Al-Batinah area are among low-value crops in response to concerns for food security in the country. Therefore, the agricultural sector consumes around 93% of all water use in the country. It is important to measure the needed water in terms of its spatiotemporal use and in what quantities it should be done routinely and accurately. Most of the input data can be defined by regular monitoring and evaluating the groundwater levels. This data can define the physical characteristics of the groundwater reservoir. The focus should be on those areas where the groundwater system is affected by the seawater intrusion. Furthermore, the soil profile should be determined in these areas to measure how much water and nutrients can be stored for plants' use and the portion of water that will likely drain from it to recharge the water table. Increasing the supply is an expensive approach in addition to its environmental challenges. The main source of water in the country is the desalinated water (Abulibdeh et al., 2019b). Constructing desalination plants to address agricultural water deficits is costly and economically not efficient. Furthermore, constructing dams takes many years and dams are environmentally challenging. Therefore, the better management of the water demand in the agricultural sector is considered the biggest payoff in view of the overwhelming share of agriculture in the excess water demand of this sector. The management objective is to mitigate and control seawater intrusion and not to prevent the process itself.

Another challenge is to manage groundwater extraction since most of the groundwater production is private, prevent exhausting the resource, and manage agricultural trade. To reduce agricultural water demand, one of the options is to shut down wells in areas that are negatively affected by salinization of soils and seawater intrusion. The farmers in the areas affected by seawater intrusion believe they have the access to groundwater by tradition, right, and very long-term usage. This ambiguous water right needs a solution that is socially equitable, efficient, and effective. However, wells and groundwater are owned by the country. The recently constructed wells on new lands are licensed and controlled by the government.

In addition, the government should subsidize most of the pumping equipment and initial capital investment in agricultural wells. To encourage the changes in behavior that leads to water conservation and reduction, price-based approaches can be used to conserve water and use tariffs to transmit information about water scarcity. The groundwater users must bear the production cost; however, groundwater is freely accessible by public. However, most of the agricultural users receive the subsidized electricity at flat rate tariffs. Consequently, groundwater is severely over-exploited and hence groundwater levels fall resulting in the marginalization of many small farmers, and those who can afford the larger pumps remain in the business. The volume of groundwater pumped can be constrained if measures such as price of the electricity is equivalent to the electricity production cost and thereafter by increasing the block tariff.

The improvement in agricultural extension services for delivering high quality technical support and advice that farmers need will eventually return a high value to economy. By overcoming the threats of dwindling farm productivity due to mismanagement of water and soil resources, the farmers should be able to produce competitively and remain in the business vis-à-vis the cheap imported food and agricultural products. Biosaline production system is an economically efficient approach in a short-to-medium-term to moderate high salinity areas of Al-Batinah, particularly in good quality groundwater areas to rejuvenate soils that have become salinized through poor management. The reduction in groundwater utilization will enable the agriculture to be sustained in this area and add important value to economy. These strategies carry considerable operational difficulties and should be finetuned considering the costs, opportunities, benefits, and socio-political risks. The investment in upgrading the on-farm irrigation efficiency, reuse of treated wastewater, and new recharge dams will not be sufficient to slow down the rate of seawater intrusion. Therefore, the overall utilization of groundwater has to be reduced.

The elements, such as the extreme freshwater deficit prevailing in the area and the extensive aridity of centuries, do not allow to get rid of salinity. One approach to mitigate and manage salinity in this area in an efficient and effective way is using appropriate hydrological, agronomic, cultural, and biological techniques. These techniques are evolving, particularly for the Al-Batinah area, and are adopted by farmers. Furthermore, the support of the adaptation of reliable management techniques requires initiating strong and wise policy decisions. Some techniques suggested to optimize the salt management and control with a minimum loss to deep percolation include leaching salt periodically, reliable estimation of leaching fraction, monitoring the salinity of the root zone and water distribution uniformity (Hussain et al., 2010).

7. Policy implications

Managing water services may include policies to shift the role of the government to regulator rather than water service-provider and make water service deliveries business-oriented. The authorities must develop a comprehensive water resources management policy to enable assessment, planning, and regulation of all water-using sectors. Different approaches to better manage and regulate water demand and supply are needed. These approaches may include shifting their policies of directly providing water supply services to private sector as services to be provided by private or independently owned utilities. Managing both the water services delivery and water resources need to be recognized in new legislative changes. Water resources management could include adopting water-friendly agricultural policy that aims to divert resources away from crops that produce low economic returns compared to the high value of water. Furthermore, this approach can adopt a virtual water policy.

Developing and implementing policies and strategies to manage water demand for the agricultural sector should be considered carefully in consideration of the reactions of farmers. One of the main issues that has been debated a lot is weather farmers should pay the price of water they consume. The farmers in areas that are negatively affected by seawater intrusion have free access to water. The seawater intrusion causes a loss of income and sometimes results in farms' abandonment. Therefore, there is a strong social, economic, and environmental debate in favor of water use regulation and pricing.

Implementing the regulation of licensing the new wells in the study area to prevent the construction of new illegal wells in the saline areas of Al-Batinah is significant in reducing water salinity. The suggestions have been made to stop agricultural practices and production in highly saline areas and to shift them to new areas of suitable soil and good quality groundwater. This can lead to significant increase in farm productivity and incomes. A water right can be allocated to each new farm where the use of this water would be monitored. Furthermore, each new farm should be equipped with water supply monitor, automated water demand soil sensors, and subsidized irrigation equipment. The conditional leases should also be proposed as an alternative to ownership so that new farms can maintain a commercial approach. In addition, rezoning of the farms for housing, commercial, or tourist facility development is an effective payoff for farmers in saline water coastal areas. The subsidies is a means that can aid farmers in the transition process over the short-term.

Food security is a major concern in the country and has driven the substantial government investment in irrigation systems. Furthermore, the food security concern has led to subsidies of inputs (electricity, irrigation technology, and pumps) and of outputs through price support mechanisms. This aims to increase food self-sufficiency on the national level in view of the geopolitical tension in the region. Therefore, agricultural policy reform has a potential to reduce the agricultural water demand. Progressive agricultural policies allow the country to increase the imports of lower-value staples and grow those crops more that have a comparative advantage to export. Furthermore, it is also useful to benefit from different approaches that have been taken by other neighboring countries or countries with similar climate, soil, and agricultural conditions.

8. Conclusion

The salinity in Al-Batinah is a serious problem, and it has a negative impact on food security and the economy because of its impact on the agricultural sector. Therefore, it has become of paramount importance to develop and implement sufficient and effective groundwater reclamation policies and strategies to prevent any further salinization to sustain agricultural lands and natural ecosystems and manage and monitor groundwater salinity. The current situation requires management techniques that can ensure the sustainable use of saline water, help in conserving land and water resources, and minimize the losses to crops and soil health. Different mitigation strategies and management techniques are more appropriate for this arid area. These techniques could include the application of organic matter that increases water-holding capacity of the soil and decrease evaporation, practice of mulching, the increased number of seedlings or higher seed rates of crops, precision in land leveling (to avoid over- and under-irrigation), breaking capillaries by plowing the fields during fallow periods (to reduce evaporation and accumulation of salts), adjusting irrigation scheduling/irrigation depth/irrigation frequencies to provide more irrigation water than mere crop requirements (appropriate leaching fractions), planting on the shoulders of ridges, and seed priming/pretreatment of seeds.

Declaration of competing interest

The authors declare no conflicts of interest.

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