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Climate change and management practices on spatiotemporal variations of ground water resource qualitys

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ABSTRACT

This study quantitatively assesses the impacts of drought and overexploitation on the quality of groundwater resources in Fars and Qazvin Provinces and accurately shows the critical points of degradation on relevant maps to identify targeted and evidence-based management strategies. In order to determine the spatial and temporal distribution of various water quality parameters including: total dissolved solids (TDS), sodium ion concentration (Na^+), sodium percentage (Na%), salinity (EC), acidity (pH), sodium absorption ratio (SAR), chloride ion concentration (Cl^-), sulfate ion concentration ($SO4^{2-}$), total hardness (TH), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) of groundwater in Fars and Qazvin provinces, data from all groundwater wells was collected and analyzed by the Regional Water Organization. Descriptive statistics, such as mean, median, standard deviation, minimum, maximum, and coefficient of variation, were calculated using SPSS software. The spatial continuity of the variables was described using GS+ software, and the best variogram model was selected based on the coefficient of determination (R^2) and the sum of squares of residuals (RSS). The most suitable interpolation method either kriging or inverse distance weighting (IDW) was determined using MAE, MBE, MSE, and MSDR statistics in GS+ and ArcGIS environment. Using the best model and interpolation method, spatial distribution maps were created for each parameter in each year across the entire province. The study also examined the impact of climate change on the drying process of lakes and playas. The results showed that the water quality in the entire province, especially in southern regions of Fars, the features is not in a good condition and the quality of water resources and consequently soil resources are facing serious problems. The temporal trend analysis also revealed that the water quality is deteriorating over time. This is likely due to mismanagement of water and soil resources, leading to the drying up of all lakes in a short period, as well as an increase in temperature and evapotranspiration, and a decrease in precipitation. A 13-year analysis of groundwater quality in Fars Province reveals a significant upward trend in key parameters, with mean EC and SAR increasing by 48% and 35%, respectively posing serious risks to soil and ecosystem health. The southern plains experienced degradation rates 3.5 times higher than the provincial average. Long-term climate data show a 16% decline in annual precipitation and a warming trend of 0.4 °C per decade, alongside a 59.5 mm/year rise in potential evapotranspiration. These combined pressures, along with mismanagement, have led to the complete desiccation of major lakes, including Bakhtegan, Tashk, and Maharloo, indicating a severe environmental shift.

Keywords: Geostatistic, Soil Quality, Water Quality, Water Resources, Water Salinity.

1. Introduction

Excessive water extraction has caused a decrease in the water table of wells, leading to limited groundwater resources. The drilling of wells and increased water extraction in the lake area, along with restricted water inflow to the lakes, has resulted in the drying up of lakes and wetlands in a short period of time. As a result of this water extraction, the quality of well water has generally decreased, with increased salinity and dissolved salts. Groundwater is crucial for agriculture in Iran, and particularly in Fars Province. However, the use of saline and poor-quality water, for irrigation has led to the salinization and destruction of soil resources. This process poses a threat to human life, as access to sufficient and healthy water is essential for life and development of civilizations. (Davamani et al., 2024).

Unfortunately, water is not distributed equally in all parts of the world, and Iran is considered one of the arid and semi-arid regions of the world in terms of climate. Given the importance of water in agriculture, it is crucial to pay close attention to irrigation practices. Agriculture is a vital sector in Fars Province, and the livelihoods of many people depends on it. However, due to population growth and inadequate management, the shortage and declining quality of water resources are becoming increasingly severe. The low quality of water has not only affected soil resources and the environment, but also highlights the need for proper irrigation practices and optimal management of water resources (Ndoye et al., 2023).

Soil salinity is a major issue caused by the accumulation of soluble salts in the root zone of plants, resulting in physical, chemical, and biological problems that reduces fertility and crop production. These effects include osmotic stress, specific ion toxicity, reduced soil fertility and biodiversity, soil instability, dust generation, migration, poverty, and environmental problems (El-Ramady, et al., 2024).

Pollution and overexploitation of groundwater resources are also significant challenges faced by many societies today (Taghizadeh Mehrjerdi et al., 2008). Studies have shown that there is a strong spatial dependence of groundwater salinity on the east coast of India, the areas with EC greater than three dS/m have increased from 37.8% in 1999 to 56.7% (Mini et al., 2015). In Mashhad city the groundwater quality was evaluated during both wet and dry periods and spatial dependence increased in the wet period and water quality decreased in the wet period (Rostami et al., 2014).

In studying the spatial variability of depth and quality characteristics of groundwater resources in a part of India, the best variogram model for groundwater depth was the spherical model and for water quality characteristics was the exponential model, and for assessing the risk of groundwater pollution, index kriging has been introduced as a useful interpolation method (Verma and Chakraborty, 2014). In assessing groundwater quality for the possibility of using it in pressurized irrigation in southwest Kerman, among the kriging and inverse distance weighting methods, the IDW method was preferred, and 35% of the area was suitable for sprinkler irrigation and 48% for drip irrigation (Azareh et al., 2014).

The use of the Kriging method in the Maragheh aquifer has been skillfully effective in interpolating spatial data gaps and has enabled a comprehensive understanding of the findings through predictive modeling, and spatio-temporal analysis has shown strong correlations between different environmental variables (Nourani et al., 2024).

In assessing groundwater quality using water quality indicators and geostatistical methods in the Tiaroye aquifer, Senegal, it was shown that most waters are classified as poor to very poor quality and a small percentage of them are considered acceptable for human consumption, stating that groundwater is globally unsuitable for long-term irrigation (Benam-Beltoungou et al., 2025).

While previous research has examined changes in groundwater quality across a single plain and over a period of time, this study provides the first comprehensive quantitative analysis, using advanced geostatistical techniques to spatially map the extent of quality degradation across Fars and Qazvin Provinces and precisely in different regions of the province, and examines these changes over time, thereby filling an important gap in data-driven water management for the region. Combining long-term climate data with accurate groundwater quality metrics, applying robust interpolation methods to produce annual spatial distribution maps, and identifying critical areas of degradation to inform targeted, evidence-based management strategies were important innovative aspects of this research. By linking environmental change to human pressures, this study provides a scalable framework for groundwater monitoring and policy development in vulnerable areas.

Therefore, it is crucial to determine the spatial and temporal variability of groundwater characteristics in order to protect production resources. Identifying the best geostatistical model and the best interpolation method is essential for effective management of water resources.

2. Materials and Methods

Fars Province, as one of the leading agricultural hubs of Iran, uses over 90 percent of its groundwater for irrigation, which has significantly reduced groundwater levels and exacerbated salinity. The region's arid to semi-arid climate exacerbates water shortages and limits natural recharge. These conditions have created serious challenges for groundwater quality (Golian et al., 2021).

The dataset used in this study was received from the Regional Water Organization. It should be noted that this study used 13 years of long-term data in all study points of Fars province. The data was measured by the Fars and Qazvin Regional Water Organization laboratory over a long period of time and has high accuracy due to its careful monitoring. The goal was to analyze a very large volume of data that had been continuously and over many years and at great expense. This analysis shows spatial and temporal changes in the quality of groundwater resources throughout Fars province. The result of the analysis, in addition to showing changes in the quality of water resources in different parts of the provinces, also shows changes in the quality of water resources over time. This goal could not be achieved by measuring the characteristics at a single point in time and at a number of specific points. Geostatistical methods were selected to generate spatial maps because of their robustness in modeling spatial dependence and variability in groundwater quality parameters. In this study, the combined use of geostatistics, taking into account climate variability indicators and management factors, has enabled a more comprehensive understanding of groundwater dynamics under combined climate and human pressures.

Therefore, the optimal and more sustainable management and utilization of groundwater resources in Fars and Qazvin provinces, the characteristics of total dissolved solids (TDS), sodium ion concentration (Na^+), sodium percentage (Na%), salinity (EC), acidity (pH), sodium absorption ratio (SAR), chloride ion concentration (Cl^-), sulfate ion concentration (SO_4^{2-}), total hardness (TH), calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium

(K^+) of groundwater in Fars and Qazvin provinces were obtained from all water wells covered by the Regional Water Organization. The water quality status was calculated using descriptive statistics including mean, median, standard deviation, minimum, maximum, and coefficient of variation using SPSS statistical software.

Two primary geostatistical interpolation techniques were employed to model the spatial distribution: Ordinary Kriging (OK) and Inverse Distance Weighting (IDW). Ordinary Kriging: This method was applied as the geostatistical benchmark. The procedure involved fitting a theoretical variogram model (e.g., Spherical or Exponential, …) to the experimental variogram derived from the raw data, followed by the application of the Kriging system to produce the final interpolated surface. Inverse Distance Weighting: As a deterministic interpolation method, IDW was used for comparative purposes. The weights assigned to known data points were inversely proportional to the distance from the estimation location, using a power parameter (p=2).

In order to explain the spatial continuity of the variables, the empirical semivariogram of the data was calculated using the GS+ geostatistical software. By fitting different linear, linear with ceiling, exponential, Gaussian and spherical models to the empirical semivariogram, the best variogram model was selected. The coefficient of determination (R^2) and residual sum of squares (RSS) were used to determine the efficiency of the models. Kriging interpolation and inverse distance weighting (IDW) methods were used to investigate the spatial changes of the aforementioned features in the ArcGIS environment and GS^+ software. Cross Validation and MAE, MBE, RMSE and MSDR statistics were used to evaluate the interpolation methods. After performing calculations and determining the best geostatistical and interpolation model, the spatial distribution and zoning of the features were drawn. The map was prepared as a multispectral composite, which shows the ranges of accessible groundwater properties, and the trends in their changes in the study areas and their accuracy were assessed. Analysis was performed based on geostatistical models, interpolation methods, and resulting maps that show changes in features over time and space. The status of groundwater resources and wetlands was also examined. The overall trend of temperature and precipitation changes in the long term was also examined.

Although the standard climate change scenario clearly shows climate change and warming in Fars and Qazvin Provinces, in this study, long-term graphs of precipitation, temperature, evapotranspiration, and other climate indicators were drawn and showed a decrease in precipitation, an increase in temperature and evapotranspiration, and a warming and drying of the contry over time. The above climatic factors reduce groundwater inflow and increase losses, concentration, and deterioration in the quality of groundwater resources.

3. Results and Discussion

The quality of water resources is declining due to both natural factors, such as parent materials, low rainfall, topography, groundwater level, saltwater intrusion, and salt marshes, and human intervention including the use of low-quality water, unprincipled irrigation, improper drainage, and mismanagement of the field. It is important to note that plants have a certain tolerance for salinity, known as the plant's tolerance threshold, and and excessive salinity can significantly reduce plant growth and yield. Furthermore, different field managements can lead to salt accumulation in various soil layers. This issue has become particularly evident in the wetlands of Fars province, which have dried up in a short period of time.

Several spatial interpolation techniques have been applied in groundwater quality studies, including deterministic methods such as inverse distance weighting (IDW), spline interpolation, and radial basis functions, which are often computationally simple, but do not consider spatial autocorrelation and do not provide uncertainty estimates. In contrast, geostatistical methods such as ordinary kriging considers statistical relationships between sampled locations and provide more reliable predictions, especially in heterogeneous environments. Given the irregular distribution of sampling points and the complex spatial variability of groundwater parameters in the study area, geostatistical was considered the most appropriate approach.

In recent years, all of lakes in Fars province have dried up. The largest of these lakes, Lake Bakhtegan, has completely dried up. With an area of 3,500 square kilometers, Lake Bakhtegan was once a vital source of water for the province, fed by the Kor River. With an approximate area of 800 square kilometers, Lake Tashk is also dependent on the Kor River for its water supply. In addition, Lake Harm, located in Larestan county, is the largest seasonal lake in Fars Provincewith an area of 130 square kilometers. Zarrin Koreh Lake, with an area of 4 square kilometers, and Bidshahr Lake, with an area of 38 square kilometers, are also seasonal. Lake Maharloo, Lake Barm Shur, Lake Parishan, and Lake and Wetland Arjan have also recently dried up.

A 13-year statistical period was used in the study of groundwater quality (water years 2006-2007 to 2018-2019), and due to limited space, only some results from one water year are presented. The models fitted to the empirical semivariogram and a summary of their geostatistical information on the characteristic data in 2018-2019 are presented in Table 1.

The ratio of the piecewise variance to the threshold ($C_0/(C_0+C)$) is an indicator of the strength of the spatial structure of the variables. If this ratio is less than 0.25, the variable has a strong spatial structure, and if the ratio is between 0.25 and 0.75, its spatial structure is moderate, and if this ratio is more than 0.75, its spatial structure will be weak (Camberdella et al., 1994). If the coefficient of

Table 1. Models fitted to the empirical semivariogram and a summary of their geostatistical information on the attribute data in the water year 2018-2019

properties	unit	model	Nugget effect	Sill	$\frac{C_0}{C_0+C}$	Range (m)	R^2	RSS
pH	-	exponential	0.0012	0.0025	0.498	181300	0.938	$2.58*10^{-8}$
EC	dS/m	spherical	0.187	1.056	0.177	57300	0.997	$2.18*10^{-3}$
Total hardness	mg/l	spherical	0.201	0.764	0.263	59400	0.997	$7.45*10^{-4}$
TDS	mg/l	spherical	0.205	1.038	0.198	57600	0.997	$2.20*10^{-3}$
SAR	-	spherical	0.338	1.491	0.227	54500	0.997	$3.07*10^{-3}$
chloride	mg/l	spherical	0.521	2.943	0.177	58900	0.999	$4.49*10^{-3}$
sulphate	mg/l	spherical	31.8	98.86	0.322	58200	0.999	4.84
potassium	mg/l	spherical	0.241	1.191	0.202	59900	0.998	$1.77*10^{-3}$
Sodium	mg/l	spherical	0.487	2.478	0.197	55800	0.998	$6.89*10^{-3}$
calcium	mg/l	spherical	0.189	0.662	0.286	60300	0.997	$7.29*10^{-4}$
Magnesium	mg/l	spherical	0.263	1.018	0.258	56800	0.999	$6.22*10^{-4}$

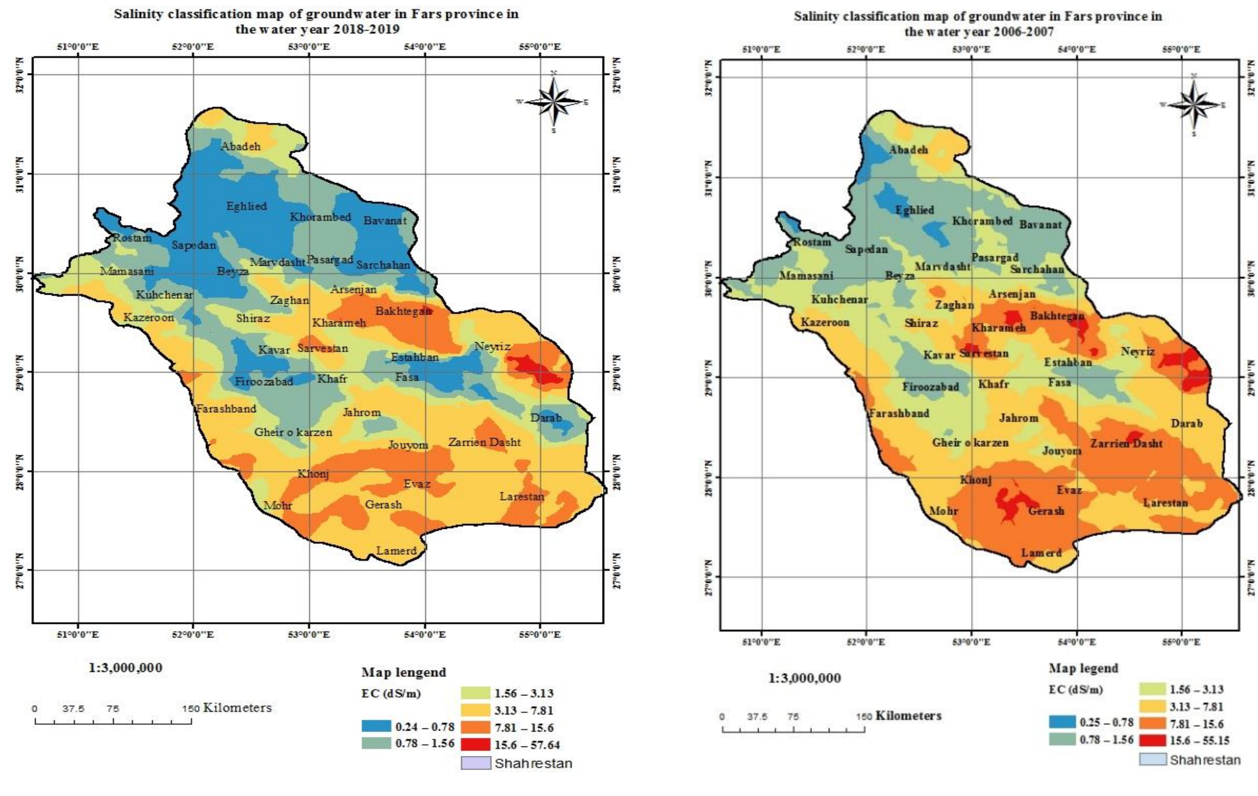
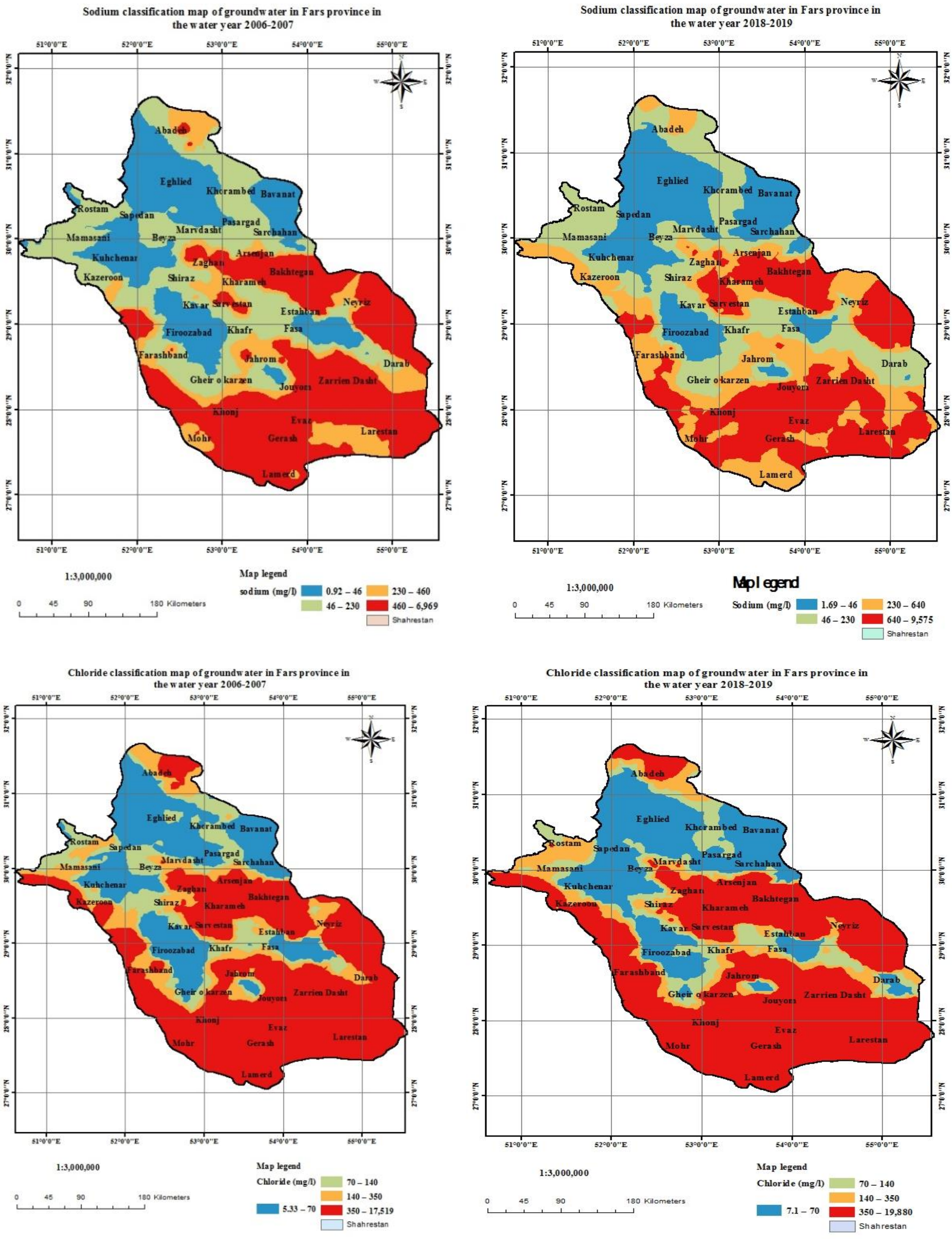


Figure 1. Spatial distribution map of groundwater characteristics in Fars province in two different water years

explanation of the best fitted model on the semivariogram is less than 0.5, weak spatial correlation is defined (Duffera et al., 2007). Changes in the values of groundwater resource characteristics are presented in Figure 1. The map data shows that the quality of water resources in the south of the province has declined more sharply, and over time, the quality of water resources in the center and north of the province is also declining.

Analysis of groundwater in Fars Province reveals that although the average and median of studied parameters fluctuated interannually, they demonstrated a clear upward trend over time. This trend represents a significant danger, threatening to degrade soils, destabilize the local ecosystem, impair agricultural production, and ultimately



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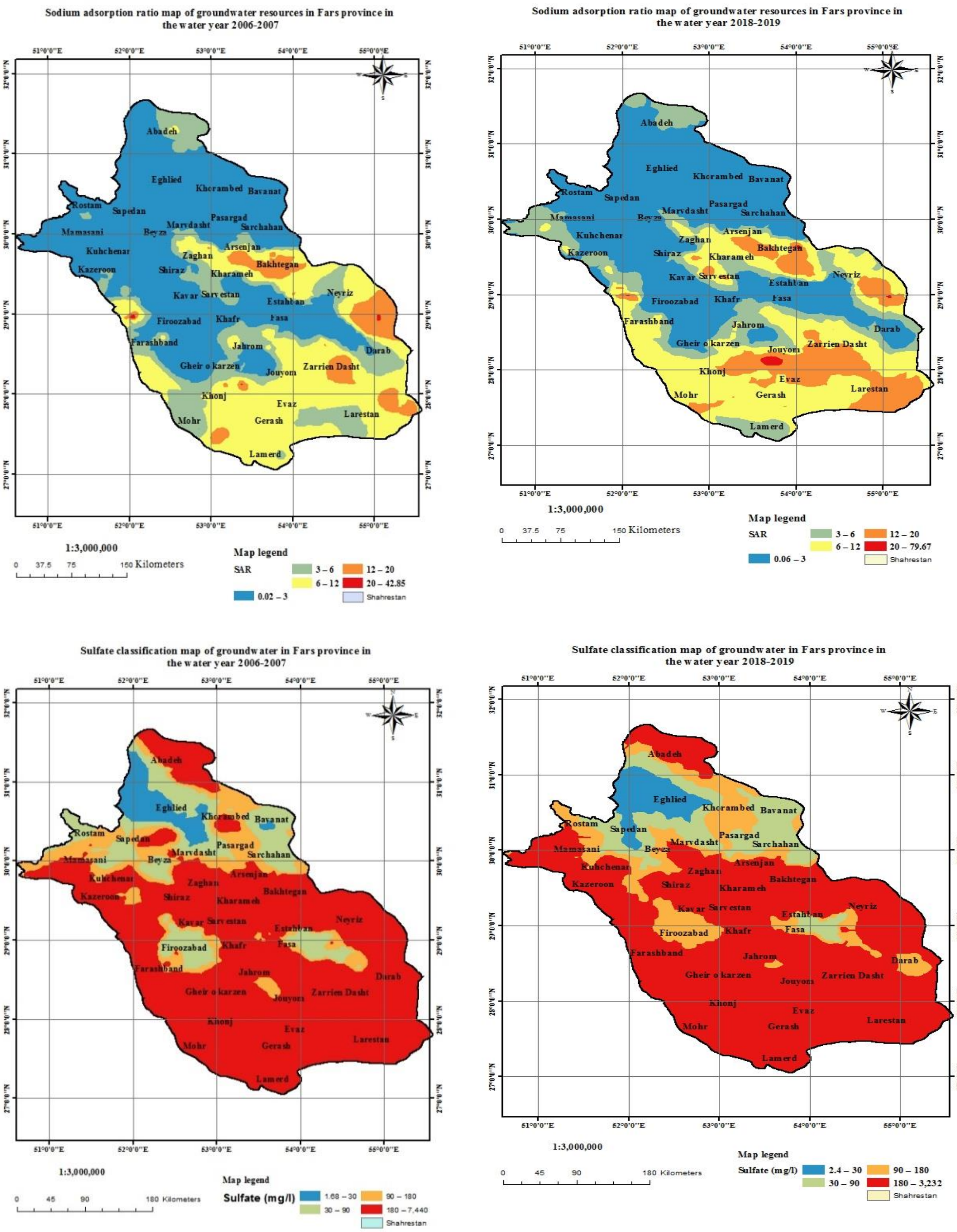

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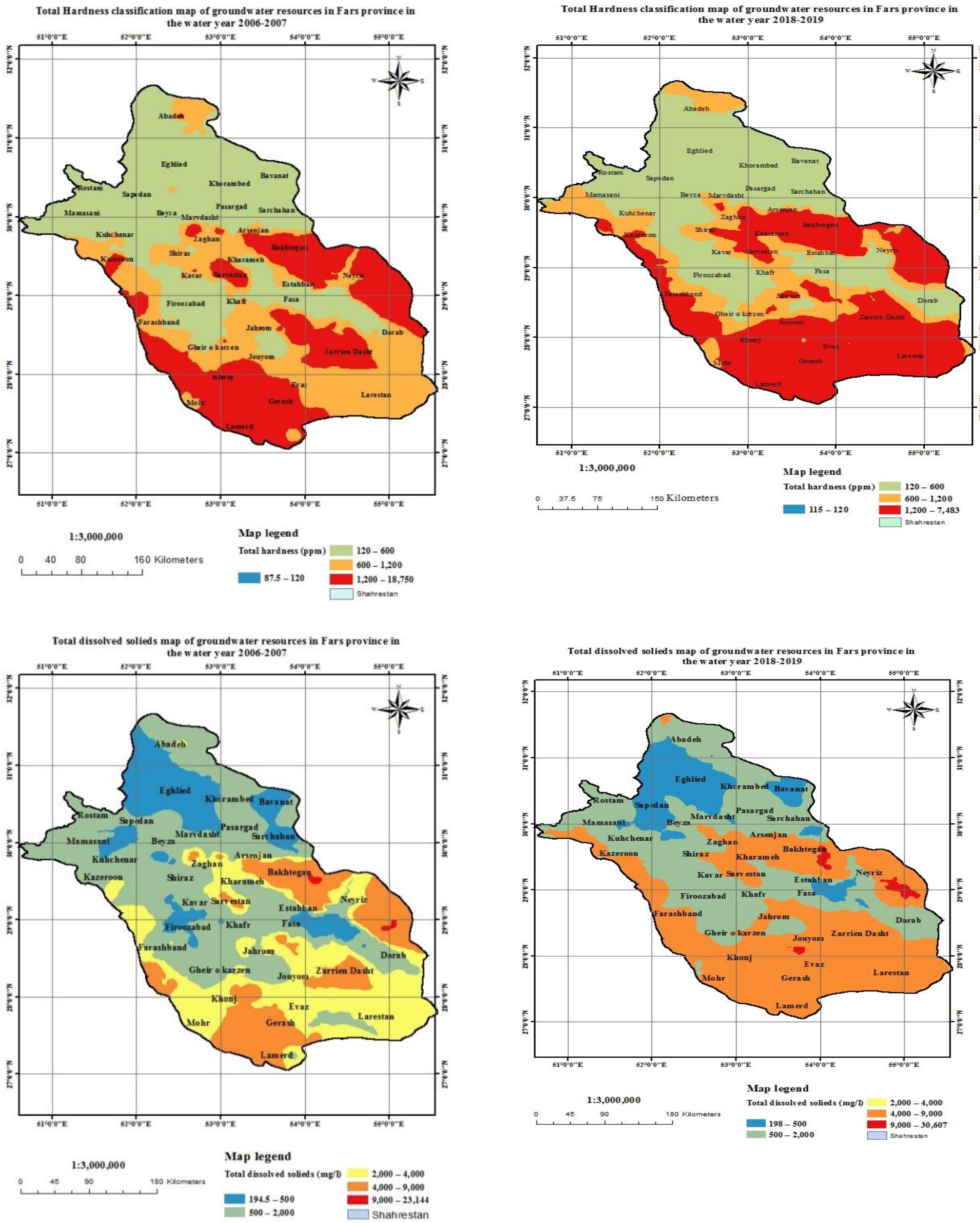


Figure 1. (Continued)

endanger life in the province. The above graphs were the average of the entire province, while in the north of the province the water resources are of better quality and the changes are very minor, and if examined separately in the southern plains, the trend will be very severe.

The spatial patterns of the studied characteristics showed that the quality of water resources in the southern parts of the province has declined more, which is due to the drier climate and inappropriate management. On the other hand, in the southern regions, the cultivation season is longer, evapotranspiration is higher, and water resources are withdrawn more, leading to a further decline in the quality of groundwater resources.

Groundwater quality degradation is a global threat at various scales (Lapworth et al., 2022), ranging from localized point sources of pollution such as septic tanks or pit latrines (Graham and Polizzotto, 2013) to diffuse pollution affecting large aquifer systems, such as nitrate pollution (Ascot et al., 2017) or salinity from irrigation (Bouarfa and Kuper, 2012).

The average and median of the water quality characteristics of groundwater in Fars province fluctuated in different years and all characteristics showed a decline in quality. Clearly, groundwater resources are being severely degraded. This graph is the average for the entire province, while a large part of the province, especially in the north of the province, has better water resources and the changes are very minor. If the southern plains are examined separately, the decline in quality will be much more severe (Figure 2).

The 50-year rainfall trends in the country and the ten-year moving average show a decrease in the average rainfall from 264 mm in the 1970-1980 to about 222 mm in the last two decades. The average rainfall in the country has been facing a decreasing rate of 0.6 mm per year. The highest precipitation was in 1992 with a volume of 380.5 millimeters, and the lowest precipitation was in 2008 and 2017 with about 146.8 millimeters (Figure 3).

Although this study was conducted in Fars and Qazvin Provinces, the modeling of this research can be validated for other arid and semi-arid regions facing similar groundwater quality problems. Combining geostatistical analysis with climate indicators and land management data provides a flexible approach that can be recalibrated for new conditions.

The temperature trend has been increasing, with the highest temperature recorded in 2017 at 18.1 degrees Celsius and the lowest in 1979 at approximately 15.1 degrees Celsius. The average temperature in the country has increased at a rate of 0.4 degrees every decade, the average minimum temperature in the country at a rate of 0.59, and the average maximum temperature in the country at a rate of 0.2 degrees Celsius per decade. The country's potential evapotranspiration has increased at a rate of 59.5 mm per year. The expansion of hot and dry areas in the country is also expanding (Figure 4).

Since the 1950s, many temperature observations have been unprecedented compared to the previous decades and even millions of years. The temperature increase of up to 1 degree Celsius compared to the pre-industrial period and 0.73 compared to the 1961-1990 baseline climate period, and the warming of the atmosphere and oceans, the occurrence of the strongest El Niño on record in 2015, the decrease in the amount of snow and ice on Earth, the rise in sea level, and the concentration of greenhouse gases prove that global warming is occurring.

The drought began in 2001, and the Very severe drought was in 2017, and this trend of drought continues (Figure 5).

Drought has extensive negative effects on agriculture, natural resources, and the environment.

In this study, using reliable statistics, the superior geostatistical method was identified for each feature, and the interpretation of the data went beyond a typical interpolation, and the maps show a general spatial pattern so that managers and operators can be informed about the situation of each point in the province. These maps allow the Water Organization, the Agricultural Jihad Organization, and Natural Resources to better plan for artificial nutrition, compliance with the crop pattern, nutrition management in saline conditions, and related matters. The decline in the quality of water resources has been clearly shown over time, which is an alarm that shows that with this trend, continuing irrigation with low-quality water in the near future will cause serious problems for soil resources. Decreased precipitation, increased temperature, and evapotranspiration are also other results of this study that exacerbate the decline in the quality of water resources. Therefore, the results of this study provide sufficient information for better management and more sustainable exploitation.

4. Conclusion

The results of this study reveal significant spatial variability in groundwater quality across Fars and Qazvin Provinces, which is influenced by both climatic stresses and unsustainable management practices. The use of geostatistical modeling allowed for a detailed representation of hotspots of quality degradation, which can identify optimal management strategies to mitigate the detrimental effects. These findings are consistent with recent studies that emphasize the role of climatic variability and overexploitation of water resources in groundwater degradation (e.g., El-Ramady et al., 2024; Stavi et al., 2021).

Based on the generated maps, the status of each feature in any point of the province can be observed, managed, and planned. Most of the features in the south of Fars province had high values, and as excessive groundwater extraction continues, the concentration of salts is increasing and expanding. Over time, the values of the features are increasing, and the quality of groundwater resources and soil in Fars province is deteriorating. The

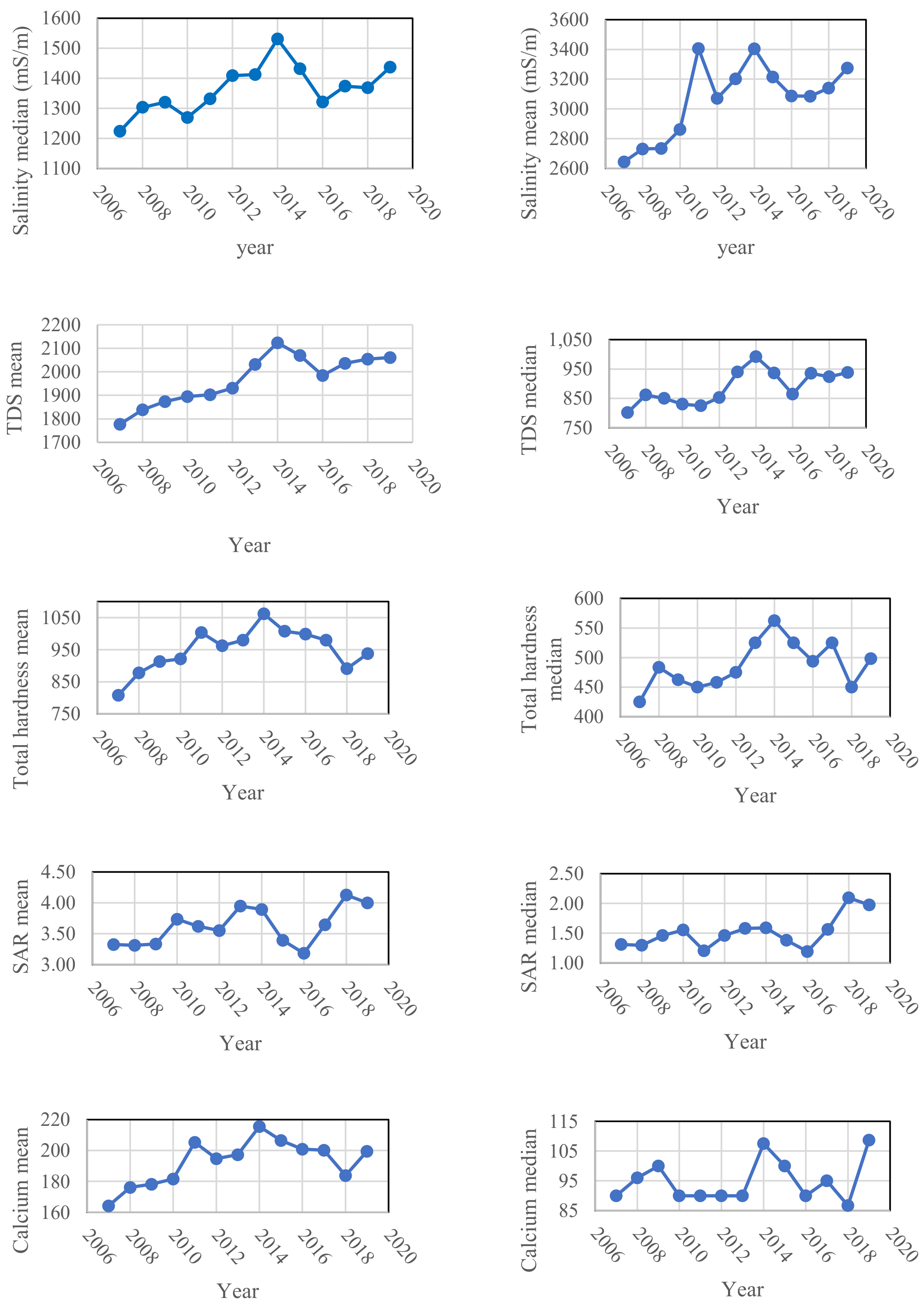
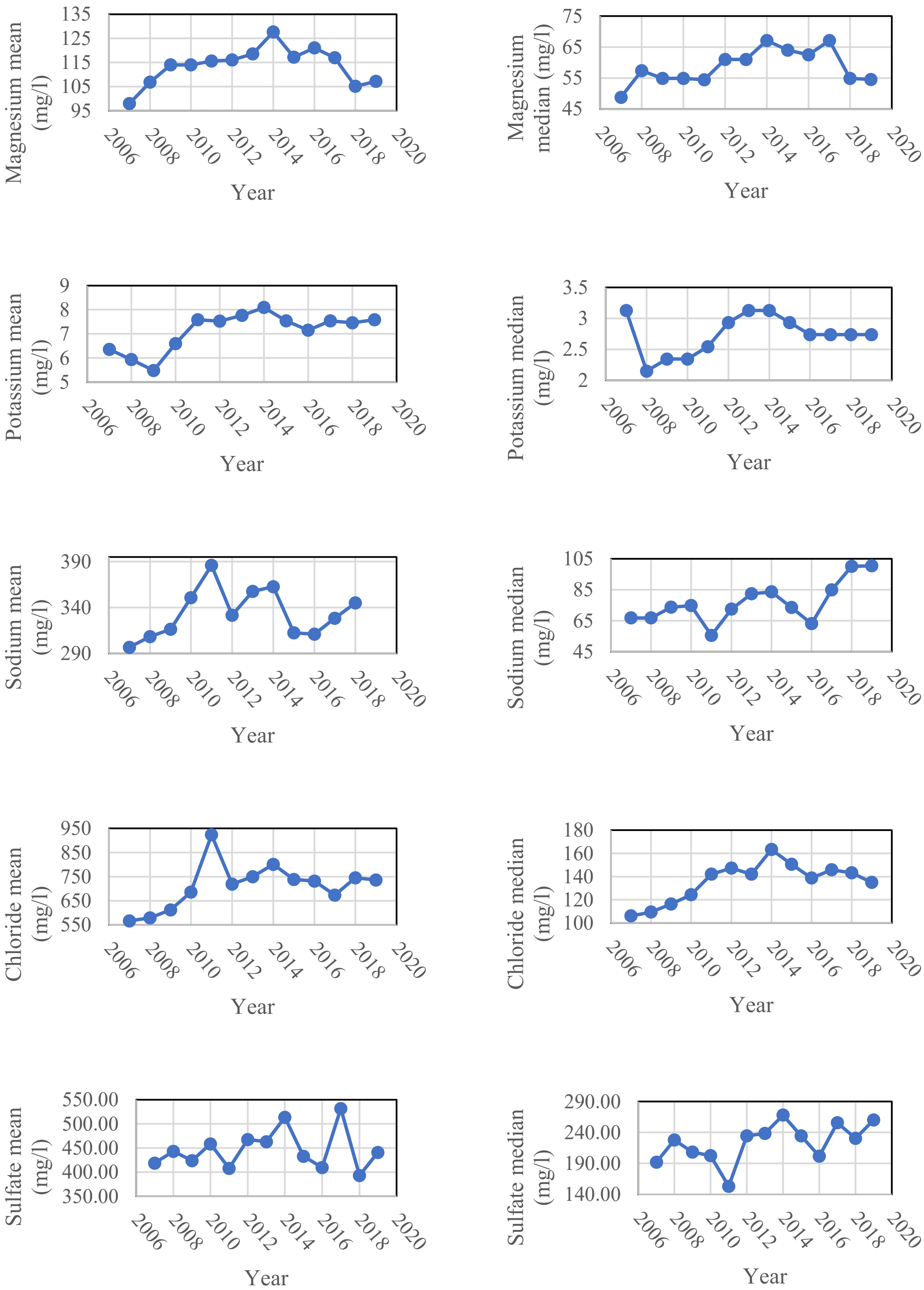


Figure 2. Average and median changes in various characteristics in groundwater of Fars province in different years



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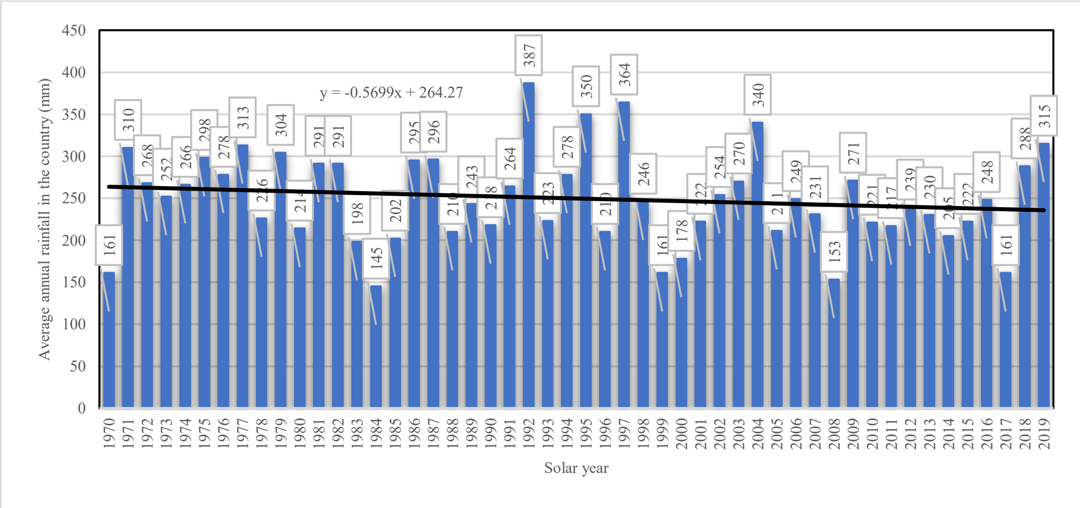

Figure 3. Trend of changes in total rainfall received across the country over a 50-year period until the end of March

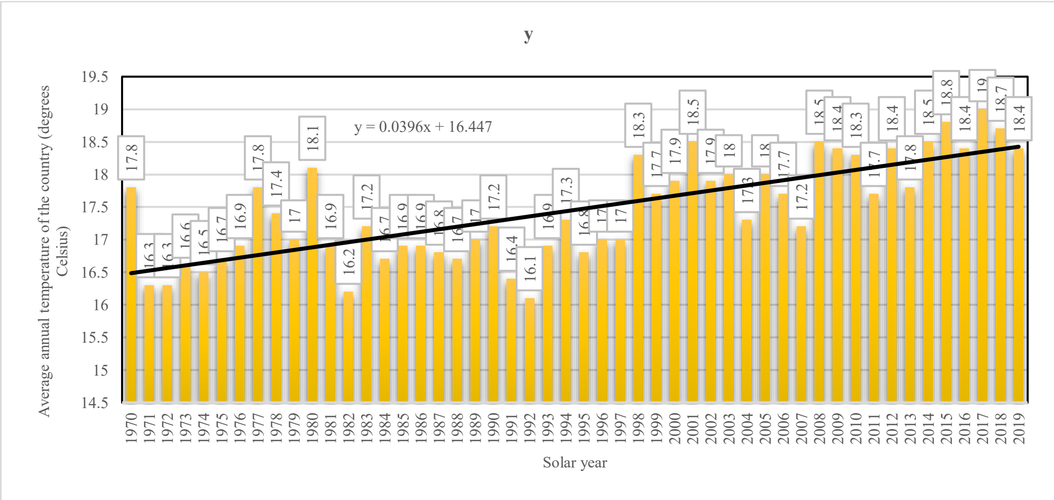

Figure 4. Trend of changes in average temperature across the country over a 50-year period

lack of a specific strategic plan, lack of funds, lack of group activities, and insufficient knowledge of salinity concepts are among the most important challenges in salinity research in Iran.

The results of the study showed that Ordinary Kriging (OK) is statistically superior method for spatial interpolation using water organization data. Spatial variability maps of water resource quality characteristics are an accurate tool for optimizing water resource management. Climate change and its warming, decreased precipitation, increased temperature, increased evaporation and transpiration, and increased drought occurrence trends presented in this study are a warning that if not taken seriously, the drought, heat, salinity, and frost stress trends resulting from climate change will increase in the province.

Analysis of groundwater quality for the 13-year period revealed a distinct upward trend in all measured parameters, posing a significant threat to soil and ecosystem health. For instance, the mean EC increased by 48%, and SAR also showed a 35% rise across the province during this period. the southern plains of province experienced a decline rate approximately 3.5 times more severe than the provincial average. Analysis of the 50-year rainfall trend demonstrates a clear climatic shift. Average annual precipitation has decreased from 264mm to approximately 222mm in the last two decades representing a 16% overall decline. This decrease corresponds to a long-term rate of 0.6mm per year. Concurrently, the temperature trend shows a significant warming. The average national temperature has increased at a rate of 0.4∘C per decade. This warming trend is further supported by a 59.5mm per year increase in potential evapotranspiration. The comprehensive decline in water

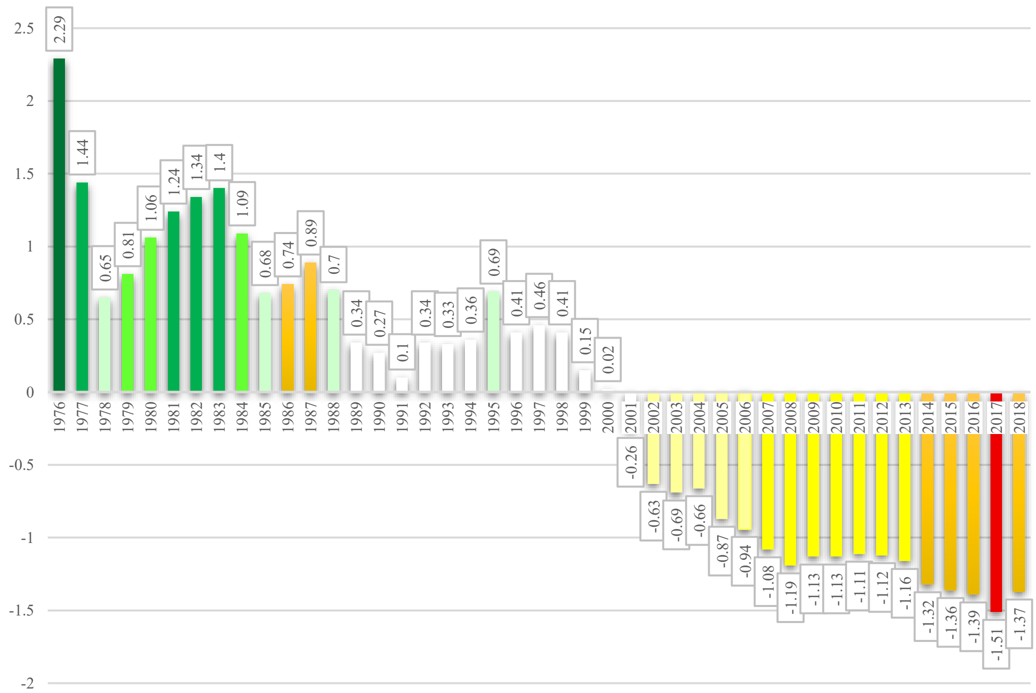

Figure 5. The trend of changes in the drought index based on the standardized precipitation and evapotranspiration index (SPEI) across the entire country.

resource quality and mismanagement have resulted in the complete desiccation of all major lakes and wetlands in Fars province within the last two decades (e.g., since 2000). Specifically, Lake Bakhtegan, the largest with an area of 3,500 km^2, has been totally dry since 2017, indicating a catastrophic environmental shift. Similarly, Lake Tashk (approx. 800 km^2) and Lake Maharloo have also lost 100% of their surface area.

5. Recommendations

Use rainwater effectively and control of green water usage, change the cultivation pattern and prioritize the cultivation of dryland and low-water-consuming plants. Strictly avoid irrigation of heavy-textured soils with saline water. Continuously monitor water quality and effectively manage irrigation with saline water. Monitor the level of aquifers and implement comprehensive water harvesting management. Reduce evaporation through conservation tillage, preserving residues, and using fertilizers with less salinity and organic matter sources. Introduce high-potential and salinity-tolerant varieties. Use a suitable irrigation system and observe irrigation intervals. Implement climate management and techniques and create artificial rain. Utilize cross-border water resources. Purify and using unconventional water source in green spaces and industries, as well as in non-food cycle areas. Implement smart agriculture techniques, to reduce damage and increase productivity. Improve weather forecasting accuracy and issue necessary warnings. Implement integrated water management strategies. Reduce land use change, increase soil organic carbon content to reduce erosion, salinity, compaction, and soil degradation. Provide comprehensive education and monitoring in the exploitation of water and soil resources at all levels.

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