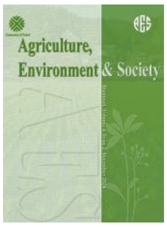
Agriculture, Environment & Society (2025) Volume 5, Issue 2, P. 63-74

Agriculture, Environment & Society

Journal homepage: www.aes.uoz.ac.ir



Assessment of groundwater status and factors affecting groundwater resources (Study area: Bam Plain)

Hadi Dehghan [a], Maryam Safavi [b], Somayeh Galdavi [*a], Mohammad Naderianfar [c]

[a] Water Science and Engineering Department, Kashmar Higher Education Institute, Kashmar, Iran
[b] Ph.D. Student of Water Resources, Birjand University, Birjand, Iran
[c] Water Science and Engineering Department, University of Jiroft, Jiroft, Iran

ARTICLE INFO

Article history:
Received: 18 May 2025
Accepted: 13 August 2025
Available online: 15 August 2025

Keywords:
Bam Plain
Excessive extraction
Groundwater depletion
Unit hydrograph

(CC BY 4.0)
Copyright © 2025 by the author(s)

ABSTRACT

Effective water resource management, particularly groundwater management, is essential in arid and semi-arid regions like Kerman Province, where recent natural and human-induced factors have led to critical groundwater depletion. Over the years, excessive groundwater extraction through well pumping has caused significant declines in water tables across many areas, including the Bam Plain of Kerman Province. To investigate this alarming trend, a study analyzed data from 56 observation wells over 15 years, from 2002 to 2017. The hydrograph of the Bam Plain was utilized to assess changes in groundwater levels, revealing a gradual decline until 2012, followed by a steeper drop from 2012 to 2017. Ultimately, the groundwater level in the Bam Plain decreased by approximately 10 meters over the 15 years. ArcGIS software was employed for further analysis using the Kriging method and inverse distance weighting (IDW), leading to maps that depicted groundwater flow directions, iso-depth, and iso-level for specific five-year intervals. The results indicated a decrease in both iso-depth (68-110 meters) and iso-level (940-1100 meters) over three successive five-year periods from 2008 to 2013. By the end of the third period (2013-2014), only a small central area of the plain maintained these depths and groundwater levels, highlighting a significant decline overall. The findings underscored that recent drought conditions, coupled with the unsustainable extraction of groundwater, have critically impacted groundwater levels. This decline poses serious implications for the rural economy, which predominantly relies on agriculture and is directly tied to water availability. Consequently, the welfare of farmers has been adversely affected. The study aims to inform better regional water management strategies to mitigate the ongoing crisis and ensure sustainable groundwater use moving forward.

Highlights

- 10-meter decline in groundwater level in Bam Plain over 15 years (2002-2017).
- Hydrograph analysis showing a steep drop from 2012 onwards.
- Use of Kriging and IDW for iso-depth and iso-level maps.
- Recommendation for sustainable management to preserve agricultural water resources.

1. Introduction

Groundwater, which is the second-largest source of irrigation after surface water, is declining due to overuse and excessive pumping (Abbas et al., 2025). It is less affected by immediate climate variation and serves as an important resource to manage droughts and reduce the impacts of climate change on limited freshwater supplies. However, excessive groundwater extraction and insufficient recharge pose significant risks to the viability of these essential freshwater systems (Kazemi et al., 2021). Semiarid regions encounter considerable water challenges due to climatic variability, changes in land use, and a growing dependence on groundwater for supply and irrigation (Williams et al., 2025). The combination of low rainfall and high rates of evapotranspiration leads to a negative water balance, underscoring the necessity for

---

[*] Corresponding author.
E-mail address: s.galdavi@kashmar.ac.ir

https://doi.org/10.22034/aes.2025.520344.1103

effective groundwater management strategies (Bouchaou et al., 2024). Iranian agriculture relies heavily on groundwater extraction. The extraction of groundwater from aquifers across Iran has escalated markedly over the past few years (Rahimi-Feyzabad et al., 2022). As a result of this increased withdrawal, many areas within the country are now experiencing a persistent and concerning decline in groundwater levels. This trend has been documented by the Iran Water Resources Management Company (IWRMC, 2023), which underscores the urgent need to address this pressing environmental challenge.

Groundwater stands as one of the crucial natural resources globally, playing an essential role in sustaining life and communities (Ingrao et al., 2023). To understand its current condition and how it changes over time, it is essential to implement a groundwater monitoring program (Kazemi et al., 2021). In Iran, a remarkable proportion of water consumption across various sectors relies on these hidden reservoirs beneath the earth's surface (Kermani and Mir-Abassi Najafabadi, 2017). The advantages of groundwater are noteworthy, particularly when compared to surface water. It often boasts superior quality and is typically subjected to lower levels of pollution, making it a more reliable source for drinking and agricultural needs. Groundwater quantity and quality are regularly evaluated using data from groundwater monitoring networks (Mahmoudpour et al., 2023). National statistics reveal that a staggering 63 percent of the drinking water consumed by the population is sourced from groundwater, while only 30 percent is derived from surface water (Zamani et al., 2018). In Iran’s arid and desert regions, where surface water sources are alarmingly scarce, groundwater emerges as a lifeline for countless communities. It serves as the primary and most dependable source of water supply, essential for both daily living and agricultural activities, thereby highlighting its critical importance in the nation’s water management strategy (Taghizadeh et al., 2008). The quality of groundwater exhibits considerable variation from one geographical location to another, shaped significantly by the water's journey through the underground layers and the concentration of dissolved minerals and substances it encounters along the way. This inherent variability poses serious challenges, particularly in arid and semi-arid regions, where water scarcity is already a pressing issue (Thakur et al., 2023). In recent decades, its contamination has emerged as a global concern, threatening human health and environmental sustainability (Abbas et al., 2025). In many parts of the world, the excessive extraction of groundwater has led to startling reductions in water table levels, raising alarms about the sustainability of these vital resources. Global statistics illustrate this alarming trend: each year, groundwater levels continue to decline. So, Groundwater monitoring is essential for effective water resource management. It supports the sustainable use of water and helps inform policy development (Thakur et al., 2025). The interplay of these factors highlights the urgent need for sustainable water management practices to preserve both the quantity and quality of groundwater across affected regions.

In a study conducted by Abbas Nejad and Shahidasht in 2013, the significant vulnerability of the Sirjan plain was analyzed, primarily attributed to the excessive extraction of groundwater resources. Nejad's findings highlighted a concerning trend: over the period from 2001 to 2007, the region experienced a steady decline in groundwater levels, averaging approximately 12 centimeters annually. This persistent drop raises alarms about the sustainability of water resources in this area, indicating an urgent need for better water management practices to prevent further depletion. In another research, Behzadi Karimi and Omidvar (2017) employed advanced geostatistical analysis techniques within ArcGIS software to investigate the spatial distribution of groundwater quality parameters in the Bayza-Zarqan plain of Fars province. Their approach involved the development of effective factors for each quality parameter, utilizing both deterministic and geostatistical methods guided by the Root Mean Square Error (RMSE) evaluation criterion. The outcomes of their study revealed that the kriging interpolation method emerged as the most effective technique for parameter estimation, with the notable exception of acidity, which suggested the need for alternative methods to accurately assess this specific quality indicator. This research not only provided insights into groundwater quality patterns but also underscored the importance of utilizing sophisticated analytical methods in environmental research.

In their study of the plains of northern Hamedan, Shamsipour and Habibi (2008) identified the decrease in groundwater levels as being influenced by climatic factors and drought over the 17 statistical years from 1379 to 1363, reporting a correlation coefficient of 42%. They suggested that the adoption of modern technologies could enhance decision-making and provide effective solutions. Geographic Information Systems (GIS) are among the most widely used technologies, offering significant benefits by accelerating work processes, improving planning, and identifying critical issues. The capacity of GIS for management, planning, and robust statistical analysis has made it a powerful tool for decision-making across various fields. In a separate study, Soltani et al. (2018) analyzed the groundwater quality in Shush County by comparing spatial changes using two methods: Kriging and Inverse Distance Weighted (IDW). They concluded that the Kriging method provided higher accuracy in estimating values across all parameters. Excessive groundwater extraction is causing a significant decline in groundwater levels across many regions worldwide. According to global statistics, the annual decline in groundwater is alarmingly evident. In particular, excessive use of groundwater resources in Iran has resulted in a negative balance of approximately six billion cubic meters each year (Alizadeh, 2020). Groundwater level decline and negative aquifer balance have been reported in many plains of Iran. Given the current situation, it is crucial to conduct further studies and investigations on the status of the country's aquifers. Understanding groundwater level fluctuations is vital for planning a reliable water supply and managing water resources effectively. For better decision-making and more accurate planning regarding the management and exploitation of these aquifers, a long-term study of the groundwater status in these plains is necessary, along with the development of comprehensive management solutions**.**

The groundwater level in the Bam Plain has been showing a consistent downward trend, raising concerns about the sustainability of this vital resource. This study aims to delve into the various factors contributing to this alarming decline. Several compelling reasons have influenced the decision to focus on the Bam Plain for this research. Firstly, the region faces significant limitations in available water resources within the groundwater sector, which exacerbates the issue. Additionally, the practice of excessive extraction beyond the sustainable capacity of the aquifers has led to a downward spiral in the groundwater levels. This over-extraction is not merely a number; it reflects a broader environmental challenge that the region faces. Moreover, the continued decline in groundwater levels has not only implications for water availability but also affects the geological stability of the area. One of the most concerning consequences of this decline is the phenomenon of land subsidence, where the ground begins to sink as groundwater is depleted. This combination of factors highlights the urgent need for a comprehensive understanding of the situation in the Bam Plain to develop effective management strategies for preserving this critical resource and protecting the landscape from further degradation.

2. Materials and Methods

2.1. Study Area

Bam City is located in Kerman province and has a population of over 300,000 people. The city experiences a dry, desert climate. The primary occupations of the residents in this region are agriculture and horticulture. The water supply for both drinking and agricultural purposes is mainly sourced from groundwater through canals and wells. Bam Plain, which runs in a southwest-northeast direction, lies approximately 207 km southeast of Kerman's provincial center and is situated on the edge of the Lut Desert, one of the driest areas in the country. Due to the presence of fertile agricultural land, digging deep and semi-deep wells is quite common in this plain. Given these factors, along with the flat terrain and the high population density, studying the groundwater, which serves as the main water source for the entire plain, becomes essential**.**

Iran faces a critical water shortage situation, significantly more severe than the global average. It is one of the arid and semi-arid regions of the world, with only 0.36% of the world's total renewable water resources. To address this water scarcity, it is essential to optimize the use of the available water resources. The location of the Bam Plain and the wells examined in this study are depicted in Figure 1.

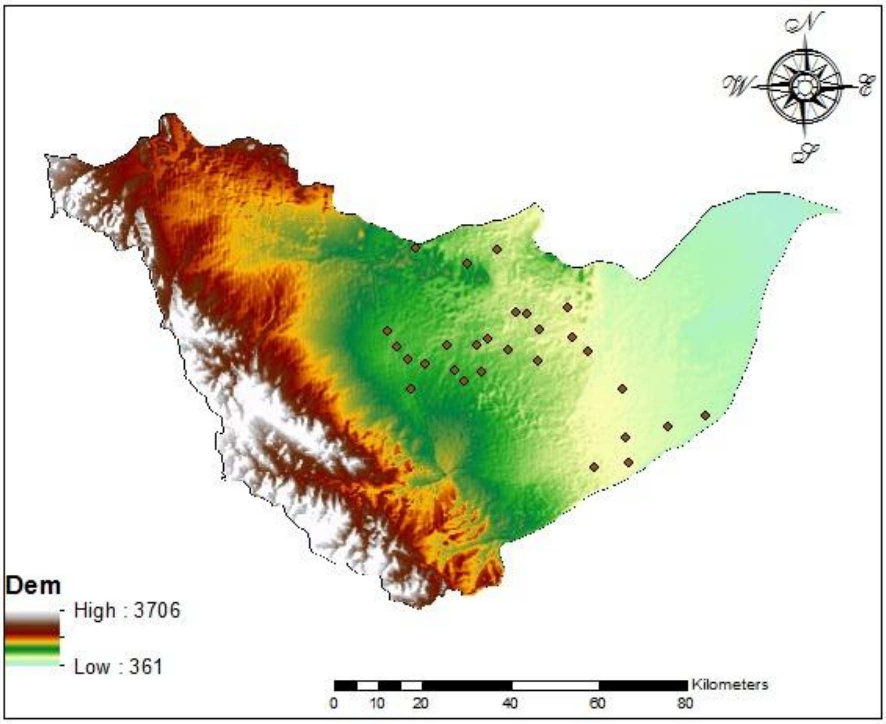


Figure 1. Location of the Bam Plain and the wells under investigation

2.2. Data

In this study, we used data from 56 observation wells, focusing on groundwater levels during the statistical period from 2002 to 2017. The data was obtained from the Kerman Province Water Resources Studies Department. ArcGIS software was used to perform interpolation methods.

2.3. Create of representative hydrograph for the Bam Plain

In this study, groundwater data were analyzed, which were collected from 56 observation wells in the region. The decline of the main aquifer by creating a representative hydrograph was calculated, which provides an overview of trends in groundwater level changes. To visualize these changes, the inverse distance weighting (IDW) interpolation method was employed, and Kriging was used to prepare iso-depth and level maps, as well as iso-depth and level zoning maps, every five years. Changes over 15 statistical years (2002-2017) using data from the 56 observation wells to assess groundwater level fluctuations in the Bam Plain area. Additionally, we created groundwater level and decline hydrographs using Excel. After organizing the data, we applied the Thyssen function to generalize the measured values to a regional level. Consequently, we generated the aquifer water level hydrograph and isopotential maps over a 15-year timeframe, divided into three five-year periods, using Excel and ArcGIS.

The purpose of drawing the aquifer hydrograph is to provide a comprehensive view of changes in groundwater levels. Since the existing piezometric wells do not cover the entire surface of the aquifer, the Thyssen model was used to define a surface area for each well based on the location and density of surrounding wells. These areas should be arranged so that the total of all individual areas equals the entire surface area of the aquifer. This concept is expressed in Equation 1.

$$A = \sum a_i \tag{1}$$

In this formula, a_i represents the area of the i^{th} polygon, while A denotes the total area of the aquifer.

Creating a hydrograph using the Thiessen model involves a weighted averaging operation. In this process, the weight assigned to each piezometer is calculated by dividing the area determined through the Thiessen method by the total area of the aquifer.

$$W_i = \frac{a_i}{A} \tag{2}$$

To calculate the numerical value of the aquifer hydrograph, multiply the weight obtained from Equation 2 (W_i) by the groundwater level of each well for the different months (h_{ij}). Then, sum all of these products for each month J. This process yields the groundwater level of the aquifer for the month J^{th}, as described in Equation 3.

$$\sum (h_{ij} \times w_i) \tag{3}$$

To create the aquifer hydrograph, a graph is drawn with the X-axis representing the months of the year and the Y-axis representing the groundwater level. This study utilizes ArcGIS software. After ensuring the quality and accuracy of the data using GS+ software, an appropriate semivariogram is fitted to the spatial structure of the data. Following this, geostatistical techniques are applied to generate interpolation maps.

2.4. Evaluation of interpolation methods

Due to the nature of data collection in geographical studies, data can be generalized to the surface using interpolation (Feki et al., 2017). The purpose of interpolation is to estimate unknown values based on known values. This process involves three main stages. First is data search and preparation, which includes identifying errors through simple statistical analyses, analyzing trends in the existing data, and examining the distribution of the data (Salah, 2009).

The second stage involves implementing deterministic or geostatistical models to create surfaces. Finally, the surfaces are analyzed, and the results are interpreted**.** Various interpolation methods have been employed for estimation. A review of the literature indicates that the optimal methods vary with location; therefore, a method suited for one area may not be applicable in another (Tsintikidis et al., 2002). Among the most widely used methods are Inverse Distance Weighting (IDW) and Kriging, which were utilized in this study for interpolation with ArcGIS**.** Geostatistical interpolation techniques use a statistical model to describe the spatial distribution of data. These techniques include different forms of Kriging, such as ordinary Kriging, co-Kriging, and indicator Kriging. The primary goal of Kriging is to estimate the values of a spatial random variable at locations where measurements have not been taken, while also providing an assessment of the associated error. This method relies on the assumption that there is spatial autocorrelation among the measured values of the variable being studied (Amini et al., 2024).

2.5. Variogram

A variogram is utilized to assess the spatial correlation of a variable over sampled intervals and to extract the necessary parameters for interpolation processes (Bastin et al., 1984). It serves as the initial step in modeling the spatial structure for kriging. The variogram is calculated using the following relationship (Webster and Oliver, 2001).

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n} [z(x+h) - z(x)]^2 \tag{4}$$

The semivariogram value of a pair of points that are a distance h apart is represented by gamma(h). The term n(h) refers to the number of sample pairs used for a specific distance h. The variable z(x) denotes the observed value at point x, while z(x+h) represents the observed value of the variable that is located a distance h away from x.

2.6. Kriging method

Geostatistical estimation is a process by which the value of a quantity at a point with known coordinates can be obtained using the value of the same quantity at other points with known coordinates (Hassani Pak, 2010). This geostatistical estimator is named Kriging in honor of one of the pioneers of geostatistics, D.J. Kriging, who was a South African mining engineer (Hassani Pak, 2010). This estimator is the best linear unbiased estimator (B.L.U.E.) (when an unbiased estimator is an estimator whose distribution mean coincides with the true mean) with the lowest variance of the estimate (Safavi Gardini, 2017)**.**

2.7. Simple Kriging Method

This method assumes that the mean is independent of the coordinates and that there is no trend in the data. Additionally, it is essential that the mean value of the variable, denoted as m(u), is known. In this type of kriging, the data value at the estimated point is calculated as follows (Goovaerts, 1997):

$$\hat{Z}_{SK}(u)=m(u)+\sum_{i=1}^{n(u)}\lambda_i(u)[Z(u_i)\text{-}m(u_i)] \qquad (5)$$

Where: ZSK(u) represents the estimated value of the variable Z at the unknown point u; $Z(u_i)$ denotes the value of the variable Z at the known point u_i; λ_i; is the weight assigned to the variable Z at the known point u_i; and n(u) indicates the total number of observations.

2.8. Inverse Distance Weighting (IDW)

In this method, the primary estimation relationship is identical to that of the ordinary Kriging estimator; however, the weights are assigned solely based on the distance between each known point and the unknown point, without considering the distribution of the points around the estimated location (Delbari et al., 2010). Thus, closer points receive greater weight, while points further away are given less weight.

The inverse distance weighting method, a specific variation of this approach, follows the same estimation relationship as the ordinary Kriging equation (Equation 2). The key difference is that, in this method, the weights are determined purely by the distance from each known point to the unknown point, disregarding how the points are arranged around the estimate (Mousavi et al., 2017). The weight value λ_i in this method can be calculated using Equation 6.

$$\lambda_i=\frac{Di^{-\alpha}}{\sum_{i=1}^{n}Di^{-\alpha}} \qquad (6)$$

In this equation, λ_i represents the weight of the ith station, and D_i denotes the distance from the ith observed point to the estimated point. The variable α refers to the power of the distance weighting, while n indicates the number of observed points. The power method typically considers the inverse of the distance, with values usually ranging between 1 and 5; however, a power of 2 is often used (Safavi Gerdini et al., 2016).

3. Results and Discussion

To assess changes in groundwater levels and the rate of groundwater loss, a hydrograph illustrating groundwater loss was created on a monthly basis for the statistical period from 2002 to 2017. Before conducting any calculations related to the hydrograph, the study area was interpolated using Thiessen through ArcGIS, and specific areas were defined for each well. Figure 2 presents the map of the Bam Plain.

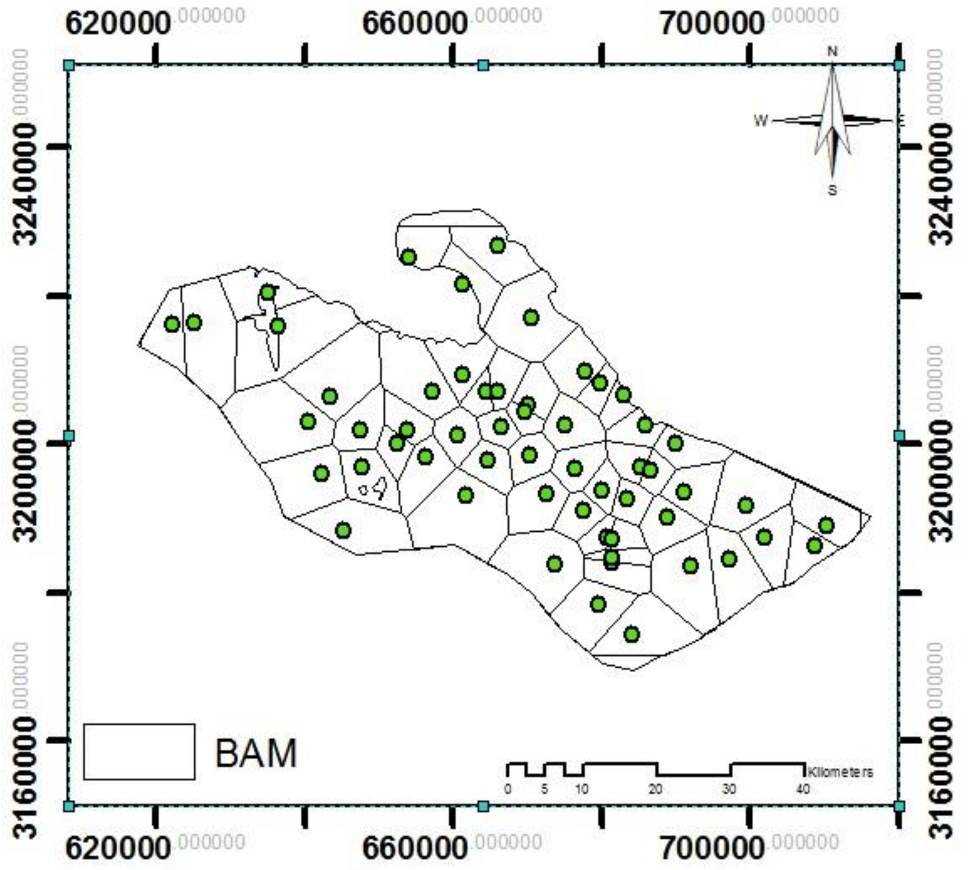


Figure 2. Thiessen map of the Bam aquifer

Changes in groundwater levels were studied in the Bam Plain during the years 2002-2007. Figure 1 is related to the hydrograph of the Bam Plain. In general, the groundwater level of the wells in the area in question has had a downward trend.

The hydrograph diagram of the Bam Plain unit (Figure 3) indicates a decreasing trend in groundwater levels. This decline was gradual until 2012, but from 2012 to 2017, the slope of the groundwater level decreased more sharply. Initially, water levels began to drop before 2012. As rainfall diminished and drought persisted, particularly during the water years of 2016 to 2017, the hydrograph displayed a sharp downward trend. Therefore, from the beginning of the balance period in October 2012 to the end of October 2017, the absolute groundwater level in the plain dropped from 746 meters to 736 meters**.** Several factors, including climate change, drought, and excessive groundwater extraction, have led to a decline in groundwater levels. In a study on the vulnerability of the Sirjan Plain, Abbas Nejad and Shahidasht (2013) concluded that the over-extraction of groundwater in the region has caused the water table to drop in recent years.

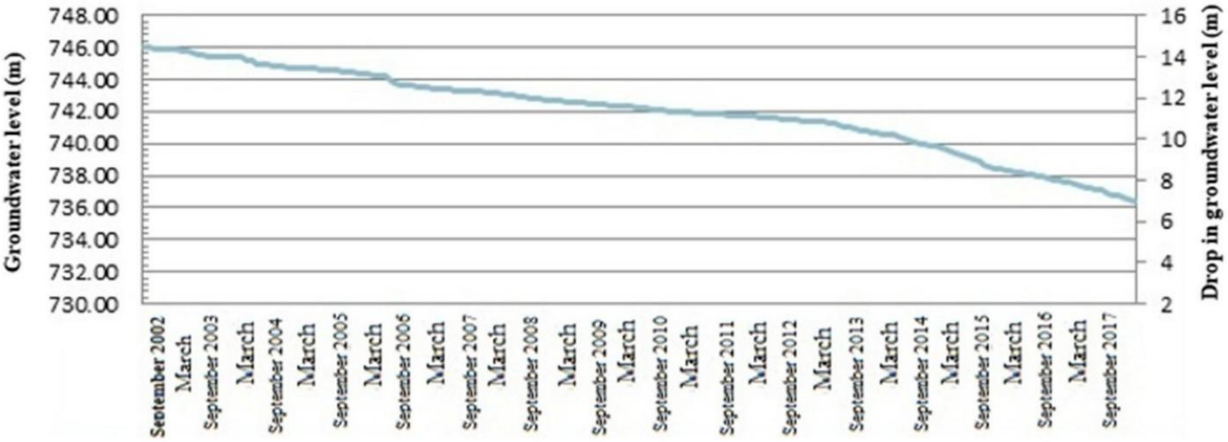


Figure 3. Hydrograph of the groundwater level of the Bam aquifer

Panda et al. (2007) investigated changes in water levels across 1,002 wells in the Indian state of Orissa from 1994 to 2003 to better understand how drought, combined with human usage pressures, impacts groundwater levels. Their findings indicated that water levels have dropped due to reduced rainfall during dry years, elevated temperatures, human extraction, and inadequate replenishment during wet years. While an increase in rainfall typically suggests a potential rise in groundwater levels, heavy and poorly distributed rainfall in the plains can hinder aquifer recharge. As a result, even in years with increased rainfall, aquifer depletion has been observed. It can therefore be concluded that a combination of excessive groundwater extraction and recurring droughts—whether individually or in concert—has contributed to the decline in groundwater levels in the region. Hamidianpour (2005), Arbabi and Bayat (2005), and Shahid and Hezarika (2009) highlighted drought and increased groundwater withdrawal as factors contributing to the decline in groundwater levels.

Following an initial data analysis using GS$^+$ software, we obtained the statistical characteristics of the data, which are presented in Table 1. An appropriate semivariogram was then fitted to the spatial structure of the data, with the results displayed in Table 1.

Table 1. Statistical characteristics of the data used in the research

Parameter	Mean (mm)	Standard deviation (mm)	Variance (mm2)	Minimum (mm)	Maximum (mm)	Skewness	kurtosis	Coefficient of variation
Iso-Depth 2002-2006	34.33	24.74	612.05	4.49	108.44	1.54	1.82	0.72
Iso-Depth 2007-2011	36.55	24.88	619.37	5.95	109.46	1.49	1.67	0.68
Iso-Depth 2012-2017	39.95	24.77	613.36	8.47	112.66	1.43	1.53	0.62
Alignment 2002-2006	722.36	115.57	13356.67	530.93	1144.12	1.49	3.36	0.159
Alignment 2007-2011	720.14	115.48	13335.88	529.58	1142.66	1.50	3.41	0.160
Alignment 2012-2017	716.74	115.82	13414.22	525.96	1141.8	1.51	3.45	0.161

Using the fitted semi-variogram model, zoning maps were created with the kriging method and inverse distance weighting in ArcGIS software. These maps were developed for both depth and elevation values for the years 2008-2009, 2010-2011, and 2012-2013. Figures 4 and 5 display the resulting interpolation maps.

The primary factors contributing to groundwater depletion in the Bam Plain include drought, excessive water extraction, population growth, an increase in cultivated land, and the presence of numerous wells. In this context, Lashkarpour et al. (2008) noted in their study on water table depletion and land subsidence in the Kashmar Plain that the over-extraction of groundwater, particularly for agricultural purposes, has led to significant groundwater depletion. Similarly, Rahmani et al. (2009) identified excessive extraction as one of the contributing factors to groundwater depletion in the Neyriz Plain of Fars Province. Shamsipour and Habibi (2008) identifie the impact of climatic parameters and drought as the primary causes of groundwater depletion in theHamedan Plains.

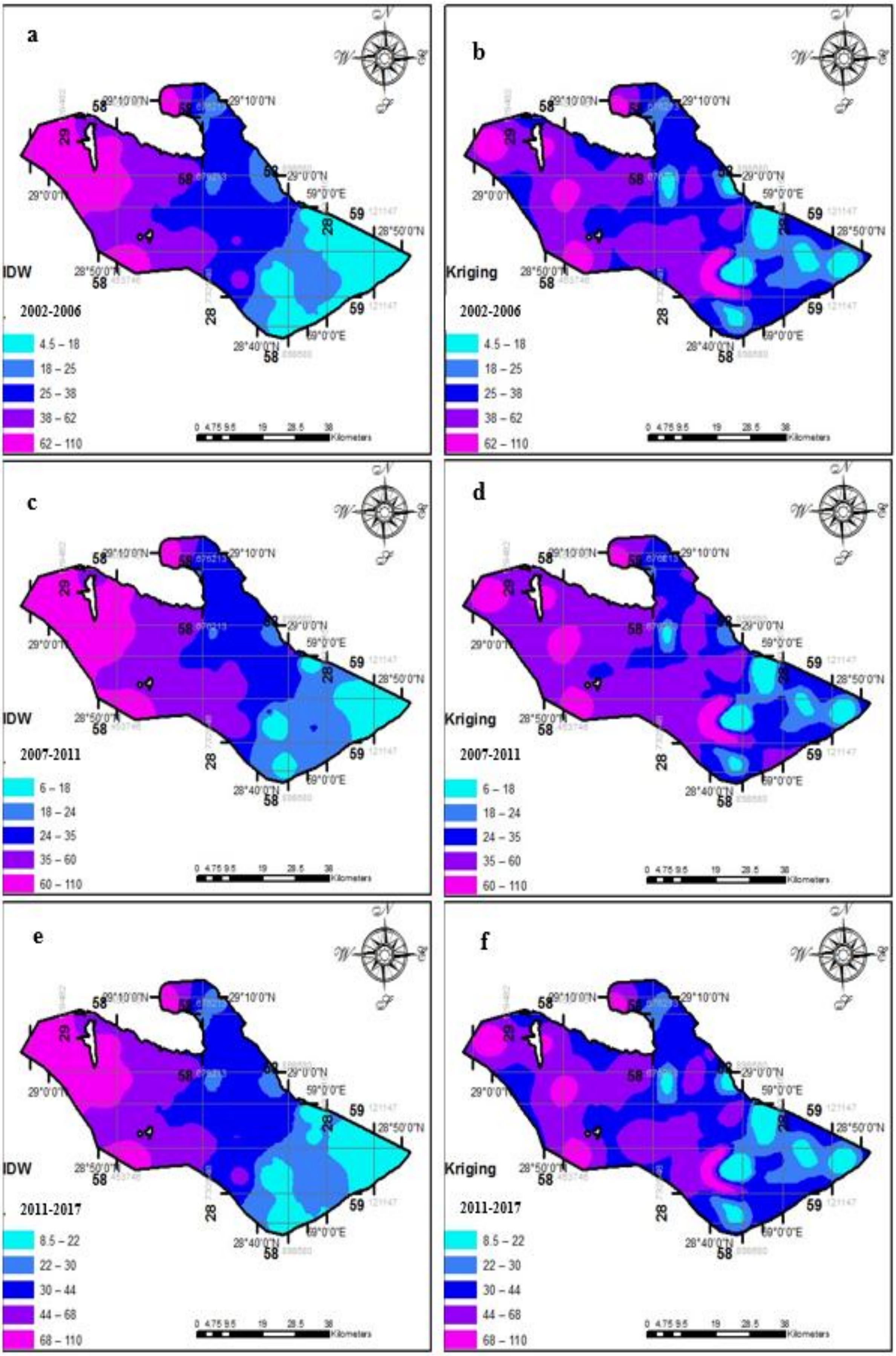


Figure 4. Iso-Depth maps over three 5-year periods

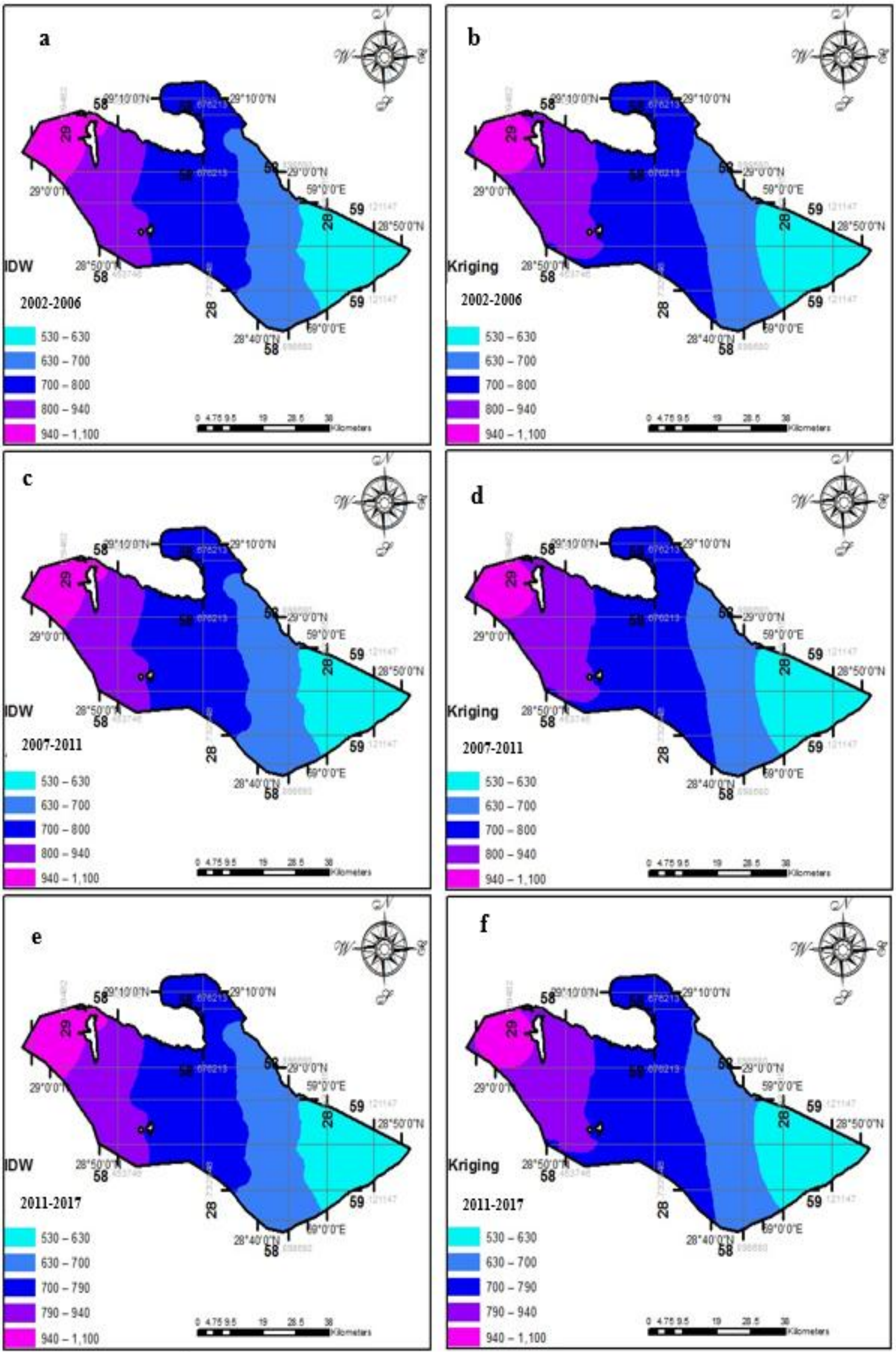


Figure 5. Alignment maps over three 5-year statistical periods

Similarly, Azizi (2003) attributed groundwater depletion in the Qazvin Plain mainly to drought. According to the results presented in Table 1, the highest coefficient of variation for the same-depth data from 2008-2009 is 0.72, while the lowest coefficient of variation for the same-level data during the same period is 0.159.

The analysis of the semivariogram related to the iso-depth and iso-level data over 5 years, from 2002 to 2007, indicates that the most suitable semivariogram model for the spatial structure of the iso-depth data is the spherical model. In contrast, the semivariogram for the iso-level data is best represented by the linear model. Additionally, the findings reveal that the radius of influence for the iso-depth data has increased, rising from 55,530 meters during the statistical period of 2008-2009 to 61,440 meters from 2010 to 2011. This suggests an upward trend in the range of influence in the area surrounding the piezometric wells of the plain. Furthermore, the threshold value has also risen, increasing from 564.9 during the 2010-2011 period to 720.9 in the 2011-2012 period. The interpolated maps shown in Figure 4 and the iso-depth maps in Figure 6 reveal that the greatest depths are located in the western and northwestern regions of the study area. Conversely, there are smaller areas in the southern and eastern parts that have relatively low depths. The minimum depth recorded is 4.5 meters, while the maximum depth reaches 110 meters.

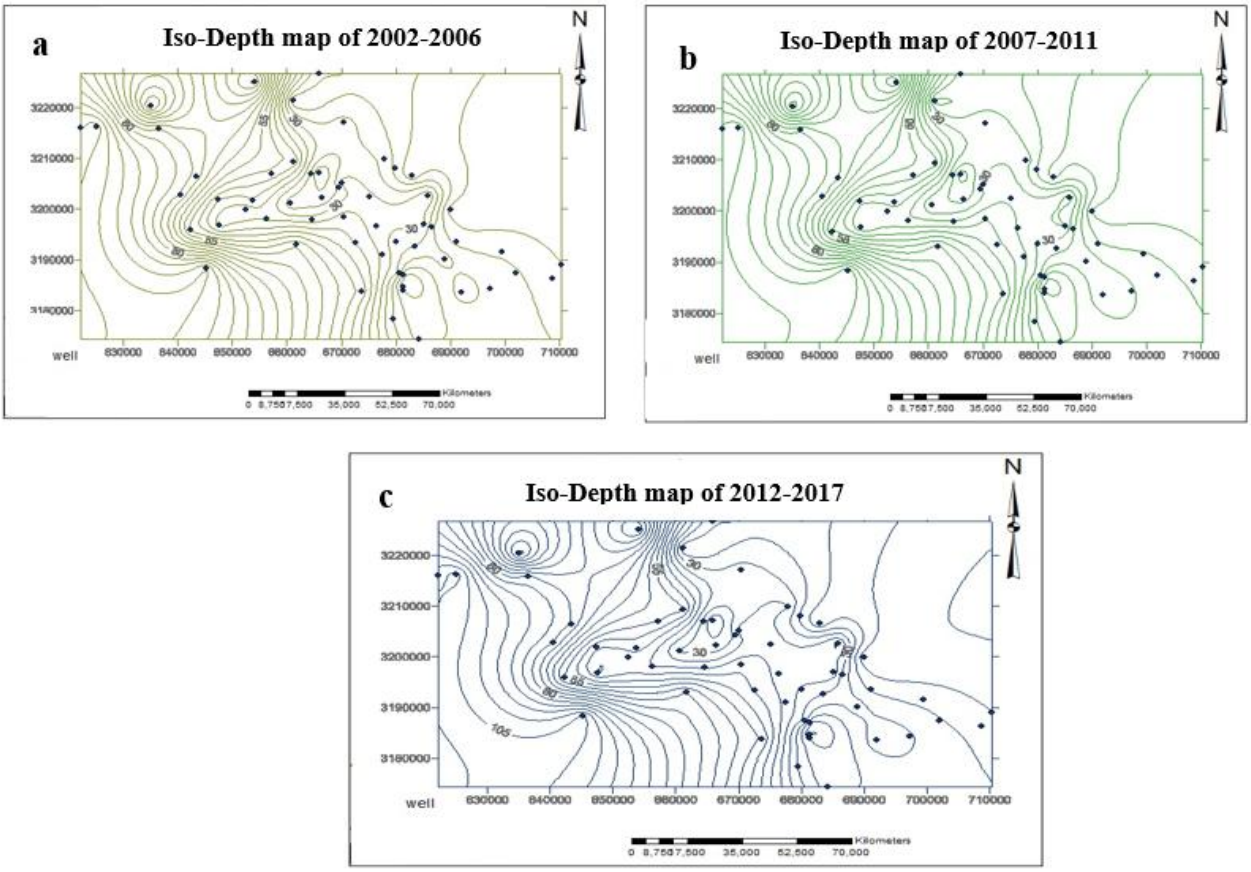


Figure 6. Iso-depth Maps for Three 5-Year Periods

Based on the interpolated maps of groundwater levels shown in Figure 4 and the groundwater level map in Figure 5, the eastern regions exhibit low groundwater levels, while the western and central areas of the study zone have higher levels. The plain aquifer receives groundwater recharge primarily from the west. However, the groundwater levels are declining in the east, center, and south of the area. This decline is primarily due to excessive well pumping and agricultural water use. The groundwater table of the Bam Plain is primarily formed by Quaternary alluvium. Numerous wells have been drilled in the central part of the plain, and groundwater flows from the edges toward the center. The bedrock in this area consists of a red series, which includes marl, conglomerate, and red sandstone, along with gypsum and salt cement (Kerman Regional Water Organization, 2012).

Consequently, the rise in groundwater levels in some areas of the region may be attributed to several factors, including the presence of numerous canals, soil consolidation due to groundwater outflow, reduced soil storage capacity, and the presence of shallow clay layers. According to the results of the semivariogram fitted to the data in Table 2, it can be seen that there is a strong spatial correlation between the data. The best model of the iso-depth data related to the iso-depth data of the period 2008-2010 was obtained with the spherical model (correlation of 0.88 and error value of 17246), and the best model between the iso-level data related to the statistical period 2008-2010 was obtained with a correlation of 0.98 and an error value of 1.625E-06.

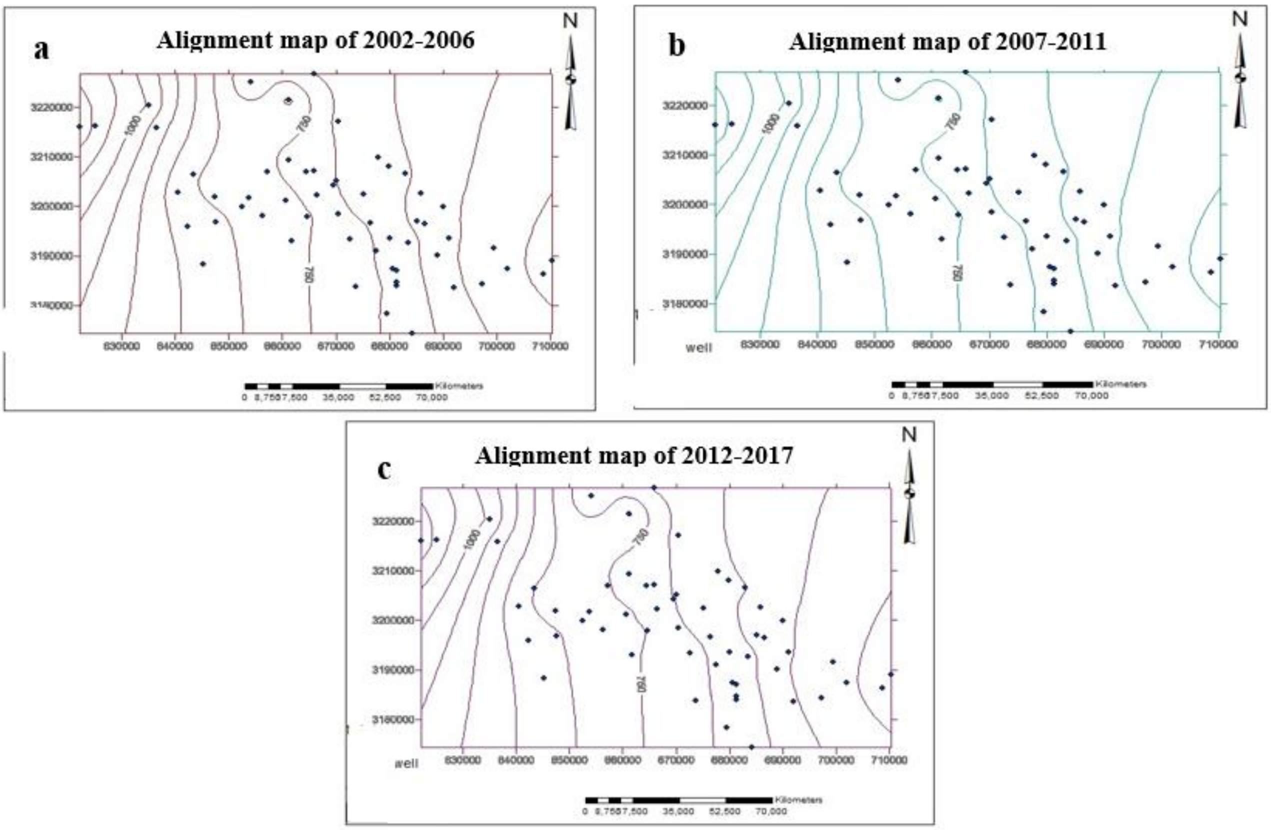


Figure 7. Alignment Maps for Three 5-Year Periods

Table 2. Properties of the Fitted Semi-Variogram

Parameter	Spatial structure model	Piece effect (C0)	Threshold (C+C0)	Radius of effect	$\frac{C0}{C+C_0}$	Correlation coefficient (R^2)	RSS
Iso-Depth 2002-2006	Spherical	27	564.9	55530	0.05	0.88	17246
Iso-Depth 2007-2011	Spherical	30	570.9	55210	0.052	0.87	18546
Iso-Depth 2012-2017	Spherical	5	720.9	61440	0.01	0.89	31718
Alignment 2002-2006	Linear	0.0001	0.038	81830	0.003	0.92	7.099E-05
Alignment 2007-2011	Linear	0.00001	0.021	61090	0.0005	0.93	1.653E-05
Alignment 2012-2017	Linear	0.00001	0.0097	41560	0.0005	0.98	1.625E-06

4. Conclusion

This study examined iso-depth maps over three 5-year periods, revealing a minimum depth of 4.5 meters and a maximum depth of 110 meters. The analysis of both iso-depth and iso-level maps during these periods indicated that from 2014 to 2016, the iso-depth range was between 68 and 110 meters, while the iso-level range varied from 940 to 1100 meters. This suggests a decrease in the maximum depth of groundwater. Additionally, the hydrograph for the Bam Plain unit showed that the groundwater level exhibited a decreasing trend with a gentle slope until 2012. From 2012 to 2017, the slope became steeper, indicating a more rapid decline in the groundwater level, which dropped by 10 meters during this time. On the other hand, the iso-depth and iso-level map of the studied area indicates that the deepest groundwater levels were found in the western regions. Over the three analyzed periods, these depths decreased in size. The statistical characteristics of the iso-depth maps reveal that from 2002 to 2012, the coefficient of variation of depth exceeded 50%. This high coefficient indicates significant fluctuations in groundwater levels within the area. Such variability may be attributed to external factors influencing the hydrological conditions, geological structures, and differing land use practices.

The Bam Plain is currently experiencing a negative water balance. The decline in groundwater levels, coupled with a deficit in reservoir capacity, has led to a deterioration in groundwater quality and gradual salinization. This situation has resulted in the encroachment of saline water into freshwater areas, creating severe hydraulic gradients and negative pressure gradients. Consequently, the direction of groundwater flow has reversed, allowing wastewater and pollutants from the riverbed to infiltrate the groundwater. Additionally, there has been an increase in the thickness of the unsaturated zone and a decrease in the upward resistant components that typically protect the alluvial layer. This has led to a reduction in the discharge of clean water and the drying up of aqueducts. The depth of the groundwater level has also increased, and there has been a significant decrease in recharge components, such as rainwater infiltration and agricultural return flow. The decline of the water table and the resulting land subsidence can lead to several issues. These include the formation of pipes in agricultural wells, the collapse or bending of well casings, and the failure of installed structures. Additionally, subsidence can reduce the aquifer's storage capacity, damage wells and garden walls, affect technical buildings and roads, disrupt the alignment of gas and water pipelines, and create inconveniences for farmers. It may also result in irrigation challenges and water wastage. As noted, the increasing extraction of groundwater, particularly in areas with shallow marine alluvial deposits or unconsolidated lake beds, can cause the ground surface to subside. This occurs because excessive withdrawal of groundwater lowers the water table significantly.

The maps, figures, and graphs obtained from this research and field operations confirm the previously mentioned cases in the Bam Plain. The economic prosperity of this region is primarily based on agricultural activities, which have led to a significant withdrawal of water from the groundwater table for farming purposes. While this agricultural success is crucial for the local economy, it has resulted in the depletion of water resources. A further decline in both the quantity and quality of water will pose a serious threat to the region's economy. Given the importance of water resources for the livelihoods of residents, it is essential to implement effective solutions to address this issue. Recommended actions include:

1- Preventing unauthorized water extraction and refraining from issuing new permits.
2- Protecting aquifers and promoting artificial recharge.
3- Valuing water as a vital resource and preventing unauthorized use.
4- Preventing the development of gardens along riverbanks.
5- Preserving riverbeds and their surroundings, which are crucial for aquifer replenishment.
6- Changing irrigation methods and cultivation practices to conserve water in agriculture.
7- Utilizing treated wastewater as an alternative to agricultural water.
8- Promoting a culture of responsible water use.
9- Conducting annual studies to monitor declines in water levels and to improve water distribution management.

Implementing these strategies can help manage water extraction more effectively and minimize the depletion of groundwater and its associated consequences.

Acknowledgments

This research is the result of the research project of the Kashmar Higher Education Institute (Code: GH779/1402/1312, date: 2024/03/11), and the authors acknowledge comprehensive support for this scientific work.

References

Abbas Nejad, A., & Shahidasht, A. (2013). Studying the vulnerability of Sirjan Plain concerning excessive extraction of groundwater from the region. *Journal of Geography and Urban-Regional Planning*, *3*(7), 85–96. (In Persian). https://doi.org/10.22111/gaij.2013.1090

Abbas, M., Arshad, M., & Shahid, M. A. (2025). Spatiotemporal zoning of groundwater quality in Rechna Doab: Analysis of Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC) variability. *EQA - International Journal of Environmental Quality*, *68*, 37–49. https://doi.org/10.6092/issn.2281-4485/21146

Alizadeh, A. (2020). *Principles of applied hydrology*. Imam Reza International University.

Amini, H., Ashrafzadeh, A., & Khaledian, M. (2024). Enhancing groundwater salinity estimation through integrated GMDH and geostatistical techniques to minimize Kriging interpolation error. *Earth Science Informatics*, *17*, 283–297. https://doi.org/10.1007/s12145-023-01157-7

Arbabi, A., & Bayat, M. (2005). Investigating the impact of drought on groundwater in Damavand region. *Geographical Space Journal*, *14*, 159–174. http://dorl.net/dor/20.1001.1.1735322.1401.22.78.3.2

Azizi, G. (2003). The relation between recent drought and groundwater resources in Ghazvin Plain. *Geographical Research*, *46*, 131–143. (In Persian). https://doi.org/10.52547/jwmr.12.23.65

Bastin, G., Lorent, B., Duque, C., & Gevers, M. (1984). Optimal estimation of the average areal rainfall and optimal selection of rain gauge locations. *Water Resources Research*, *20*(4), 463–470. https://doi.org/10.1029/WR020i004p00463

Behzadi Karimi, H., & Omidvar, K. (2018). Spatial analysis of chemical parameters affecting groundwater quality using factor analysis and geostatistical methods (Case study: Bayza-Zarghan plain). *Journal of RS and GIS for Natural Resources*, *4*(8), 17–35. http://dorl.net/dor/20.1001.1.26767082.1396.8.4.2.1

Bouchaou, L., Alfy, M., El Shanafield, M., Siffeddine, A., & Sharp, J. (2024). Groundwater in arid and semi-arid areas. *Geosciences*, *14*(12). https://doi.org/10.3390/geosciences14120332

Delbari, M., Afrasiab, P., & Mir-Emadi, S. R. A. (2010). Analysis of spatial-temporal changes in salinity and groundwater depth in Mazandaran Province. *Iranian Journal of Irrigation and Drainage*, *4*(3), 359–374. https://sid.ir/paper/131500/en

Feki, H., Slimani, M., & Cudennec, C. (2017). Geostatistically based optimization of a rainfall monitoring network extension: case of the climatically heterogeneous Tunisia. *Hydrology Research*, *48*(2), 514-541.

Goovaerts, P. (2000). Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. *Journal of Hydrology, 228*(1–2), 113–129. https://doi.org/10.1016/s0022-1694(00)00144-x

Hamidianpour, M. (2005). *Analysis of drought periods in Mashhad plain and its impact on water resources* (Master's thesis). Shahid Beheshti University.

Hassani Pak, V. (2010). *Geostatistics* (3rd ed.). Tehran University Press.

Ingrao, C., Strippoli, R., Lagioia, G., & Huisingh, D. (2023). Water scarcity in agriculture: An overview of causes, impacts, and approaches for reducing the risks. *Heliyon,* *9*(8). https://doi.org/10.1016/j.heliyon.2023.e18507

Iran Water Resources Management Company (IWRMC). (2023). http://www.wrm.ir. Date of view 2023/01/05.

Kazemi, H., Sarukkalige, R., & Shao, Q. (2021). Evaluation of non-uniform groundwater level data using spatiotemporal modeling. *Groundwater for Sustainable Development, 15.* https://doi.org/10.1016/j.gsd.2021.100659

Kerman Regional Water Organization. (2012). *Report on the continuation of studies of the Rafsanjan Plain.*

Kermani, M. N., & Mir-Abassi Najafabadi, R. (2017). Evaluation of interpolation methods in estimating groundwater levels (Case study: Sarkhon Plain). *Journal of Hydrogeology, 2*(2), 84–95. https://doi.org/10.22034/hydro.2018.5662

Lashkarpour, G. R., Ghafouri, M., & Demshenas, M. (2008). The effect of groundwater level drop on groundwater quality in the Fariman-Torbat-Jam plain. *Proceedings of the 12th Conference of the Geological Society of Iran*, 909–902.

Mahmoudpour, H., Janatrostami, S., & Ashrafzadeh, A. (2023). Optimal design of groundwater quality monitoring network using aquifer vulnerability map. *Water Resources Management, 37*, 797–818. https://doi.org/10.1007/s11269-022-03404-w

Mousavi, S. R., Sarmadian, F., Dehghani, S., Sadikhani, M. R., & Taati, A. (2017). Evaluating inverse distance weighting and kriging methods in estimation of some physical and chemical properties of soil in Qazvin Plain. *Eurasian Journal of Soil Science*, *6*(4), 327-336. https://doi.org/10.18393/ejss.311210

Panda, D. K., Mishra, A., Jena, S. K., James, B. K., & Kumar, A. (2007). The influence of drought and anthropogenic effects on groundwater levels in Orissa, India. *Journal of Hydrology, 343*(3–4), 140–153. https://doi.org/10.1016/j.jhydrol.2007.06.007

Rahimi-Feyzabad, F., Yazdanpanah, M., Gholamrezai, S., & Ahmadvand, M. (2022). Social network analysis of institutions involved in groundwater resources management: Lessons learned from Iran. *Hydrology, 613*. https://doi.org/10.1016/j.jhydrol.2022.128442

Rahmani, M., Movvarej, S. H., Hussein Darandi, H., & Najafi Nejad, A. (2009). Assessment of falling in ground water effect on creation of gully in Neiriz Plain of Fars Province. *The 5th Conference on Watershed Management (Natural Hazards Sustainable Management),* Gorgan, Golestan, Iran. (In Persian).

Safavi Gerdini, M. (2017). Investigation of spatial-temporal distribution of rainfall using geostatistical methods in the south and southeast of Iran (M.Sc. thesis). School of Water and Soil, University of Zabol. (In Persian).

Safavi Gerdini, M., Mohammadrezapour, O., Bahrami, E., Mohamadi Sedigh, M., & Salarijazi, M. (2016). Geostatistical assessment of spatial and temporal variations of groundwater quality parameters in Qorveh and Dehgolan South Plain. *Journal of Irrigation and Water Engineering, 33*(9), 167–183. (In Persian). https://doi.org/10.22125/iwe.2018.93441

Salah, H. (2009). Geostatistical analysis of groundwater levels in the south Al Jabal Al Akhdar area using GIS. *GIS Ostrava, 25*, 1–10.

Shahid, S., & Hazarika, M. K. (2010). Groundwater drought in the northwestern districts of Bangladesh. *Water Resources Management, 24*(10), 1989–2006. https://doi.org/10.1007/s11269-009-9534-y

Shamsipour, A. A., & Habibi, K. (2008). Assessment of drought effects on groundwater (Case study: North plains of Hammedan). *Proceedings Conference on Drought in Chaharmahal VA Bakhtiari Province and Mitigation Approaches.* Shahrekord University, Iran. (In Persian).

Soltani, A., Soltani, M., & Soleimani, K. (2018). Evaluation of groundwater quality in Shush city for drinking. *Ecohydrology,* *5*(4), 1135–1146. https://doi.org/10.22059/ije.2018.257339.873

Taghizadeh, R., Zareian, M., Mahmudi, S. H., Heidari, A., & Sarmadian, F. (2008). Evaluation methods for temporal interpolation to determine the spatial variability of water quality characteristics of groundwater in Rafsanjan. *Watershed Management Science and Engineering Iran, 2*(5), 63–70. (In Persian). https://dor.isc.ac/dor/20.1001.1.20089554.1387.2.5.7.4

Thakur, B., Kaur, S., Verma, V. K., & Biswas, A. (2025). Geostatistical evaluation and network optimization for precision groundwater resource mapping and management in Punjab State, India. *Hydrogeology, 33*, 591–609. https://doi.org/10.1007/s10040-025-02878-3

Tsintikidis, D., Georgakakos, K. P., Sperfslag, J. A., Smith, D. E., & Carpenter, T. M. (2002). Precipitation uncertainty and raingage network design within Folsum Lake watershed. *Journal of Hydrologic Engineering, 7*(2), 175–184. https://doi.org/10.1061/(asce)1084-0699(2002)7:2(175)

Webster, R., & Oliver, M. A. (2001). *Geostatistics for environmental scientists.* John Wiley & Sons, Ltd.

Williams, S. A., Megdal, S. B., Zuniga-Teran, A. A., Quanrud, D. M., & Christopherson, G. (2025). Mapping groundwater vulnerability in arid regions: A comparative risk assessment using modified DRASTIC models, land use, and climate change factors. *Land, 14*(1). https://doi.org/10.3390/land14010058

Zamani, R., Mahmoudi, A., Alimirzaei, Z., Gharahi, N., & Najafi, M. (2018). Relationship between land use and groundwater resources quality in Chaharmahal and Bakhtiari Province. *Natural Environment, Natural Resources of Iran, 72*(3), 353–364. https://doi.org/10.22059/jne.2019.271924.1599