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Evaluation of GIS-based spatial interpolation methods for groundwater level: a case study of Türkiye

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Abstract: Groundwater is a valuable and universally distributed resource on Earth. Understanding the spatial and temporal dynamics of groundwater is of utmost importance for effective management. Normally, groundwater levels are recorded at arbitrary points, but groundwater modeling requires interpolating the measured values at specific grid nodes. The aim of this study was to identify and evaluate the geographical variations of groundwater levels in Türkiye using three geostatistical interpolation techniques. Data from 355 groundwater wells from 1970 to 2019 were used for this purpose. In addition, an investigation of changes in annual average temperature and precipitation was conducted for two different time periods: 1985–2000 and 2001–2016. The results show an increase in annual average temperature in Türkiye by 0.82 °C during the reference period (1985–2000). Despite regional differences in the precipitation regime, the average annual precipitation in Türkiye has not changed significantly overall. Especially in the Meriç-Ergene, Konya Closed (Konya Kapalı), and Euphrates-Tigris basins, a significant decrease in groundwater levels was observed, even though this decrease is less than 100 m in some wells. After a comprehensive analysis of all these data, possible explanations for the changes in groundwater levels were considered.

Key words: Agriculture, GIS, groundwater resources, water resources, interpolation, Türkiye

1. Introduction

Groundwater resources play a crucial role in environmental sustainability, as these resources provide water to humans and ensure the continuity of economic and domestic purposes such as agriculture and industry (Holman et al., 2012; Patil et al., 2020). According to Giordano (2009), more than 650 km^3 of groundwater is exploited worldwide each year, with 1.5 to 3 billion people relying on groundwater for their drinking water supply. The use of groundwater for irrigation purposes accounts for around 60%–70%, although these figures vary depending on climate and location (Jakemann et al., 2016; Amanambu et al., 2020). Due to the increasing use of groundwater resources, it has been estimated that groundwater levels have decreased by 4500 km^3 worldwide between 1900 and 2008 (Frappart and Ramillien, 2018).

Groundwater includes all subsurface water in the soil, in the deeper vadose zone and in unconfined and confined aquifers (Green et al., 2011). Climatic conditions around the world affect hydrological systems both directly and indirectly. Recharge and discharge rates of groundwater resources depend on climatic variables as they change the feedback processes in the hydrological cycle (Cuthbert et al., 2019). Aquifers are primarily recharged by precipitation or interaction with surface waters. Consequently, the direct influence of climate on precipitation and surface water ultimately changes the amount of groundwater storage (Bates et al., 2008; Franssen, 2009).

The Mediterranean region is facing significant impacts of climate change on water quantity and quality (Iglesias et al., 2007; Bangash et al., 2013; Lionello and Scarascia, 2018). Climate change affects groundwater, which is often tapped during periods of drought when surface water is scarce. This dependency could become unsustainable in areas where more frequent and longer droughts are expected. In addition, sea level rise due to climate change will threaten coastal aquifers, particularly those that are already salinized as a result of overuse (Jakemann et al., 2016). As stated in the IPCC report Climate Change 2021 The Physical Science Basis[1], there is strong evidence

1 IPCC (2021). Climate Change 2021: The Physical Science Basis [online]. Website. https://www.ipcc.ch/report/ar6/wg1/ [accessed 12 Apr 2023]

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that groundwater reserves have been depleted since at least the beginning of the 21st century, primarily due to groundwater abstraction for irrigation in agricultural regions in arid areas. Furthermore, the report emphasizes that the ongoing trend of global warming is expected to intensify the global hydrological cycle, affecting its variability, global monsoon precipitation and the severity of both wet and dry events (Masson-Delmotte et al., 2021).

Like other Mediterranean countries, Türkiye also will become hotter and drier due to climate change and face unpredictable rainfall.[2] While there has been extensive research on water resources and climate change, the focus has been primarily on surface water systems, mainly due to their visibility and accessibility (Kumar, 2012; Amanambu et al., 2020). Assessing the impact of climate change on groundwater is a complex task that usually requires the use of numerical models that take into account the characteristics of the subsurface, aquifer systems, boundaries, and recharge and abstraction rates (Secci et al., 2021). Geostatistics, commonly used in groundwater management, helps to assess groundwater storage, reservoir capacity, level fluctuations and water quality (Uyan and Cay, 2013; Xiao et al., 2016).

Per capita water availability is primarily influenced by the size of a country's population. At present, the annual per capita water availability in Türkiye is around 1400 m^3. The United Nations World Water Development Report defines a state of 'water stress' for a country when its annual water resources fall below 1700 m^3 per capita. In other words, Türkiye is already a country suffering from water stress. Moreover, it is estimated that Türkiye's population will reach about 100 million people by 2040[3], resulting in a decrease in annual available water per capita to 1120 m^3, which is a sign of water scarcity[4] (Pilevneli et al., 2023).

The distribution of water use in Türkiye shows that 71.5% is used for irrigation, 17.8% for industrial purposes, and 10.7% for drinking and service water supply, which corresponds to a total withdrawal of 61.5 km^3 in 2018. According to the latest joint data from the State Hydraulic Works (SHW), groundwater use in Türkiye is around 16 km^3 per year.[5] Most of the extracted water is used for agricultural irrigation (Çetin, 2020). The growing population and increasing human activities, especially in the field of agriculture, have contributed to an accelerated use of groundwater resources.

This study aims to comprehensively assess the dynamics of the groundwater table in Türkiye over the last 50 years. Three different interpolation techniques are used—simple kriging (SK), empirical Bayesian kriging (EBK), and inverse distance weighting (IDW). The study stands out from similar studies as it uses extensive data sets from different locations across the country and takes a holistic approach. As a result, maps of the groundwater table are produced that provide an overall view of the country's hydrological landscape. The study also attempts to clarify the interplay between climate, agriculture, population dynamics, and regional groundwater levels.

2. The study area

Türkiye is located in the northern subtropical climate zone of the earth, between 36–42 °N and 26–45 °E (Altinbilek and Hatipoglu, 2020). Although the country is located in the expansive geographical Mediterranean region, its climate depends on its location due to the different mountain ranges along the coasts. Türkiye's coasts have a Mediterranean climate, while the interior of the country has a continental climate (Türkeş, 2020).

2.1. Population

Türkiye has around 85 million inhabitants, who are mainly concentrated in the coastal regions of the country. About 54% of this population lives in the Marmara, Aegean, and Mediterranean regions[6]. Figure 1[7] illustrates the distribution of Türkiye's total population by city. The five most populous cities are İstanbul, Ankara, İzmir, Bursa, and Antalya, respectively. Among these cities, Antalya, İzmir, Kayseri, Bursa and Manisa are the cities with the highest use of groundwater resources for municipal purposes.[8]

2.2. Groundwater use and agriculture

Türkiye is the seventh largest agricultural producer in the world (Giray, 2012). The agriculture and food sector is an important economic sector that enables Türkiye to play

2 World Bank Group (2016). Valuing Water Resources in Türkiye: A Methodological Overview and Case Study [online]. Website. https://hdl.handle.net/10986/25291 [accessed 22 June 2023]

3 TSI (2018). Population Projections, 2018-2080. [online]. Website https://data.tuik.gov.tr/Bulten/Index?p=Nufus-Projeksiyonlari-2018-2080-30567 [accessed 15 Dec 2023]

4 FAO (2014). AQUASTAT database [online]. Website http://www.fao.org/nr/aquastat

5 SHW (2020). YAS Tahsisi ve Sulamada Kullanılan Yüzey Suyu Miktarı Karşılaştırması, 2000-2019 (in Turkish) [online]. Website https://www.dsi.gov.tr/Sayfa/Detay/1344 [accessed 10 May 2023]

6 TSI (2023). Population of Türkiye [online]. Website https://data.tuik.gov.tr/ [accessed 09 Dec 2023]

7 TSI (2023). Population of Türkiye [online]. Website https://data.tuik.gov.tr/ [accessed 09 Dec 2023]

8 Koçbay A (2022). Groundwater Management in Türkiye, World Water Day Event (in Turkish) [online]. Website https://www.youtube.com/watch?v=YhVNx-Cm_hw [accessed 01 May 2023]

Figure 1. Türkiye's total population map by city (in persons).

an active role in international trade markets. According to the Turkish Statistical Institute (TSI), it accounts for about 28.5% of the country's imports, which is more than a quarter of total imports (Taşkın et al., 2022). The country has a considerable water footprint of around 139.6 billion m^3 per year, 89% of which is accounted for by the agricultural sector. The remaining 7% is for domestic use and 4% for industrial use.[9] Cereals account for the largest share of this water footprint (38%), followed by forage crops (31%), industrial crops (13%), oil crops (5%), and vegetables/legumes (2%).[10] Figure 2[11] depicts Türkiye's agricultural landscape, highlighting Konya, Şanlıurfa, and Ankara as the primary agricultural hubs. Following these are Afyon, Adana, Çorum, Diyarbakır, Eskişehir, Kayseri, Manisa, Sivas, and Yozgat provinces. It can be seen that agricultural activity is concentrated in several regions of Türkiye, including the central interior, the northwest, the southeast, and the west. These areas also have high population density and industrialization, which contributes to increased water consumption for agricultural, industrial, and domestic purposes.

In addition, Figure 3 provides a visual representation of land use and land cover in Türkiye: agricultural areas nationwide are highlighted in yellow, urban areas in red, and industrial areas in purple. Blue shades indicate surface water resources. The distribution of agricultural land in the country can be examined in more detail using this map. Recognizing and monitoring evolving patterns of land use in terms of physical, social, and temporal aspects is becoming increasingly crucial. Various methods are employed to detect shifts in urban landscapes, and ongoing advancements in these methods continue to emerge. GIS stands out as a particularly effective technique for scrutinizing urban expansion, employing a multifaceted approach that considers both qualitative and quantitative factors. GIS is adept at handling spatial and digitized data, exemplified by its use in modeling and forecasting urban growth and development (Karabulut et al., 2022).

Despite the significant contribution that irrigation makes to the Turkish economy, the desired optimal land use pattern within the irrigation systems has yet to be realized or established. Moreover, the remarkably low irrigation efficiencies (37% on average) and irrigation ratios (42% in irrigation systems operated by SHW and 66% in irrigation systems operated by water user associations) highlight the challenges associated with inadequate irrigation management and inherent problems of irrigated agriculture in Türkiye. In addition, the water consumption of small private irrigation systems and municipal irrigation is not officially documented (Çetin, 2020). For this reason, it can be assumed that the extent of irrigation is actually higher than the official figures.

Figure 4 displays the quantity of water extracted from various sources based on their usage, while Figure 5 illustrates groundwater allocations in Türkiye. As can be seen from the figures, water resources (surface water

9 World Bank Group (2016). Valuing Water Resources in Türkiye: A Methodological Overview and Case Study [online]. Website. https://hdl.handle.net/10986/25291 [accessed 22 June 2023]

10 WWF (2014). Türkiye'nin Su Ayak İzi Raporu: Su, Üretim ve Uluslararası Ticaret İlişkisi (in Turkish) [online]. Website https://www.wwf.org.tr/?2720/trkiyeninsuayakiziraporu [accessed 09 Dec 2023]

11 TSI (2023). Population of Türkiye [online]. Website https://data.tuik.gov.tr/ [accessed 09 Dec 2023]

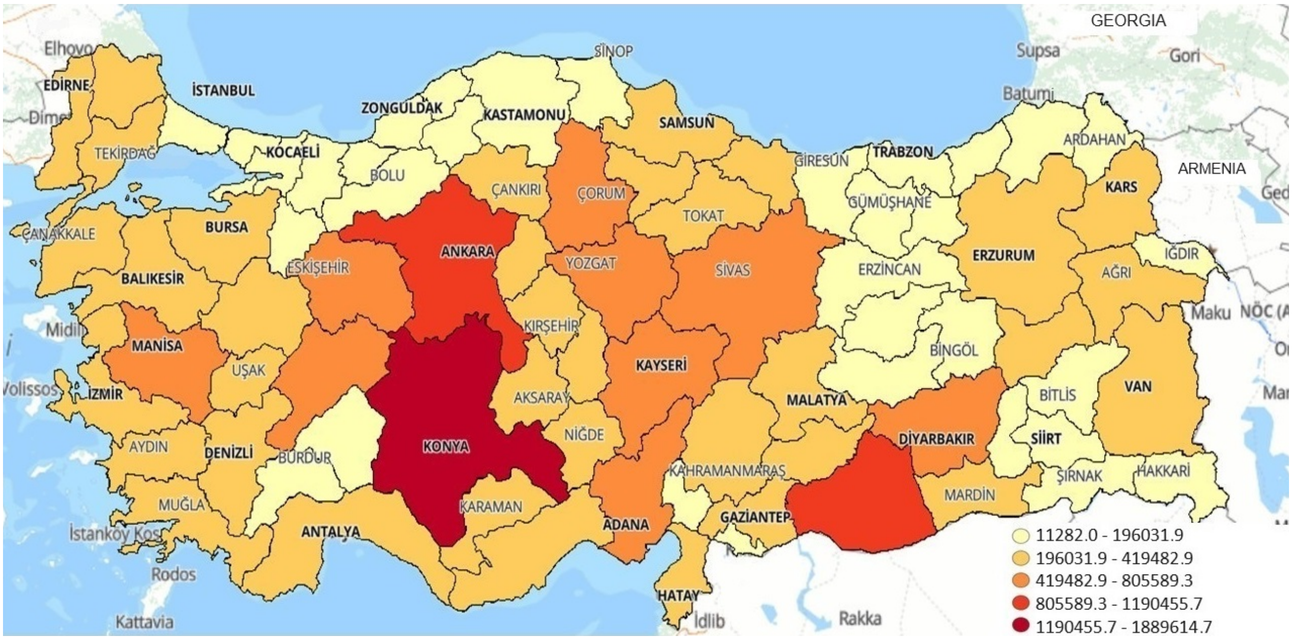

Figure 2. Türkiye's city-based agricultural area map for 2022 (hectares).

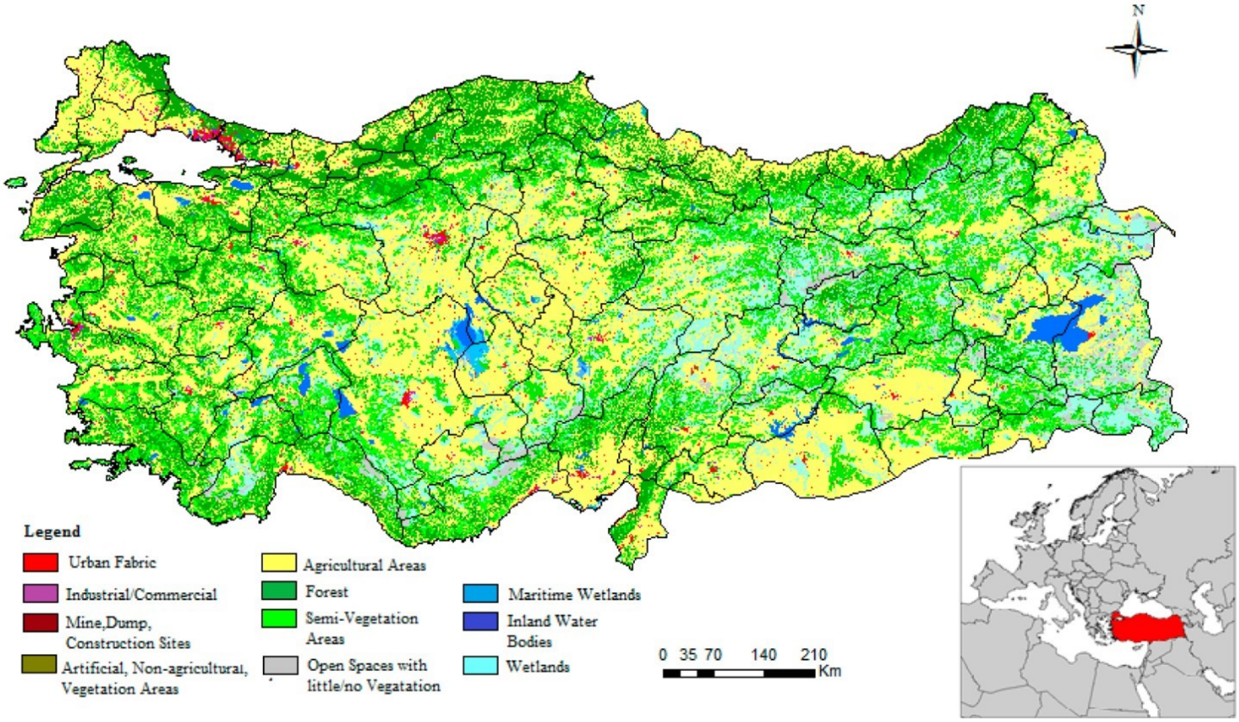

Figure 3. Land use/cover classes visualized with 100-m resolution (Ustaoglu and Aydinoglu, 2019).

and groundwater) in Türkiye are mainly consumed for irrigation purposes. In 2018, 61.5 km^3 of water was consumed. Approximately 16.2 km^3 of this was covered by groundwater resources. The use of groundwater for irrigation has seen a remarkable increase over the years. In 1995, the share of groundwater for irrigation in the total groundwater allocation was about 55%, and by 2019, this figure had risen to 67%.[12] Another factor contributing to the increase in water consumption in agriculture is the transition from dryland agriculture to irrigated agriculture.

12 SHW (2020). YAS Tahsisi ve Sulamada Kullanılan Yüzey Suyu Miktarı Karşılaştırması, 2000-2019 (in Turkish) [online]. Website https://www.dsi.gov.tr/Sayfa/Detay/1344 [accessed 10 May 2023]

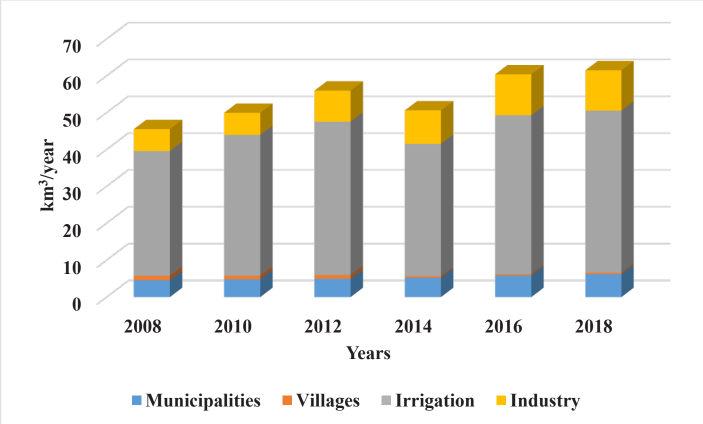

Figure 4. Amount of water (km3/year) extracted from water sources according to their usage (data obtained from SHW).

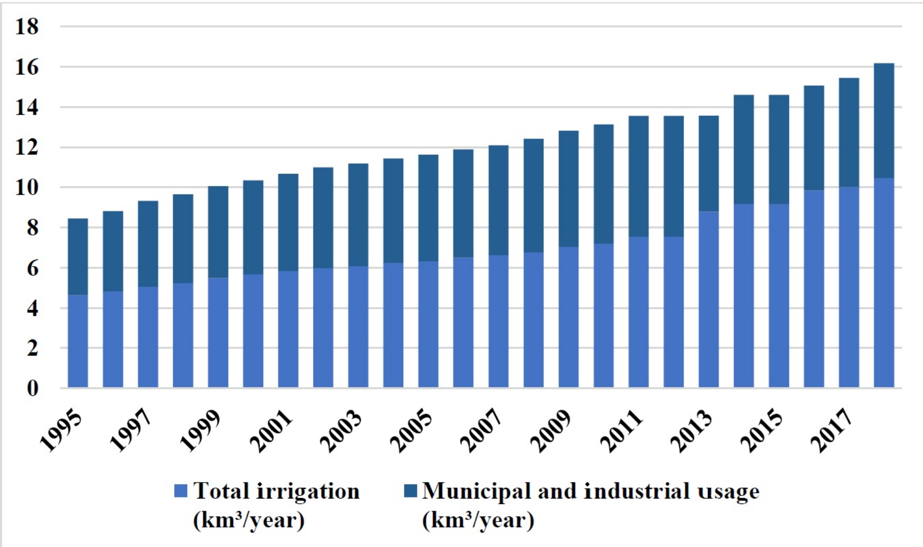

Figure 5. Groundwater allocations in Türkiye (1995–2019) (data obtained from SHW).

For example, in the Harran Plain, where dry agriculture was previously practiced, the GAP project introduced irrigated agriculture. In 1990, the share of irrigated agricultural land in the total land area was 21%, and by 2020, this share had increased to 54.45% (Karabulut et al., 2023). In addition, climate change is expected to further increase the demand for irrigation water in the Mediterranean region. Forecasts range from 4% to 18%, a trend that is already evident.[13]
There are 450 thousand registered and certified wells in the State Hydraulic Works inventory. Approximately 389 thousand of these wells are used for irrigation and 11,930 hm^3 of irrigation water is consumed annually.[141]
Water abstraction from unlicensed wells is one of the most critical problems affecting Türkiye's groundwater resources. It is estimated that there are more than 100 thousand unlicensed wells in the country, of which more than 60 thousand are located in the closed Konya basin.[15]
Especially in the Aegean and Central Anatolia regions, there has been a significant decline in groundwater. In some places, ground subsidence has even occurred due to groundwater depletion (Caló et al., 2017).

13 Galeotti M (2020). Mediterranean Yearbook (IEMed): The Economic Impacts of Climate Change in the Mediterranean [online]. Website https://www.iemed.org/publication/the-economic-impacts-of-climate-change-in-the-mediterranean/ [accessed 20 Jun 2023]

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15 Koçbay A (2022). Groundwater Management in Türkiye, World Water Day Event (in Turkish) [online]. Website https://www.youtube.com/watch?v=YhVNx-Cm_hw [accessed 01 May 2023]

3. Materials and methods

3.1. Data collection

The meteorological data were obtained from the Turkish State Meteorological Service. Figure 6 shows the distribution of the meteorological observation stations used in this study. The monthly data from 115 meteorological observation stations were converted into annual average values. The precipitation and temperature data were divided into two equal periods as a 15-year average (reference period: 1985–2000 and 2001–2016). These periods were compared in terms of average precipitation and temperature. These data were transferred to the ArcGIS Pro (ESRI, USA) environment. The results section includes maps of average annual precipitation and temperature in Türkiye and data scatter plots.

Data on groundwater levels were obtained from The General Directorate of State Hydraulic Works (SHW), which operates the wells on a monthly basis and monitors the levels regularly. In this study, 355 groundwater monitoring wells throughout Türkiye were analyzed. Figure 7 displays the locations of the groundwater wells analyzed in this study. The time intervals and the corresponding number of wells within each interval are outlined in Table. Although there are 355 wells in total, the number of wells analyzed for each period is different. The reason for this is that the years in which data collection began and ended are different for each well. The analyzed wells were examined for a total of 5 equal time intervals. According to the SHW data, the level measurements in the wells began in 1970. The time periods and the number of wells included in the time periods are summarized in Table.

3.2. Interpolation techniques

Groundwater levels were analyzed between 1970 and 2019 using (1) simple kriging (SK), (2) empirical Bayesian kriging (EBK), and (3) inverse distance weighting (IDW) interpolation methods in Geostatistical Wizard of ESRI ArcGIS Pro. The interpolation method enables the prediction of variables in regions where measured values are unavailable. It is based on the assumption that attribute values are continuous throughout space.

3.2.1. Simple kriging

Kriging is one of the most well-known and researched statistical interpolation techniques. It employs statistical models that allow for various outcomes, including estimations, standard errors of prediction, probability, and quantity. Equation 1 defines the simple kriging interpolation. The simple kriging predictor, Z^*_W for estimating the value of Z(x) at a specific point x_0 is calculated by adding the mean value μ to a weighted average of the differences between the random function Z(x) evaluated at each sample point x_i and the mean value μ.

$$Z^*_W(x_0) = \mu + \sum_{i=1}^{n} w_i\,(Z(x_i) - \mu) =$$

$$\sum_{i=1}^{n} w_i\,(Z(x_i) + \mu(1 - \sum_{i=1}^{n} w_i) = \mu + w^T(z - \mu\,1)$$

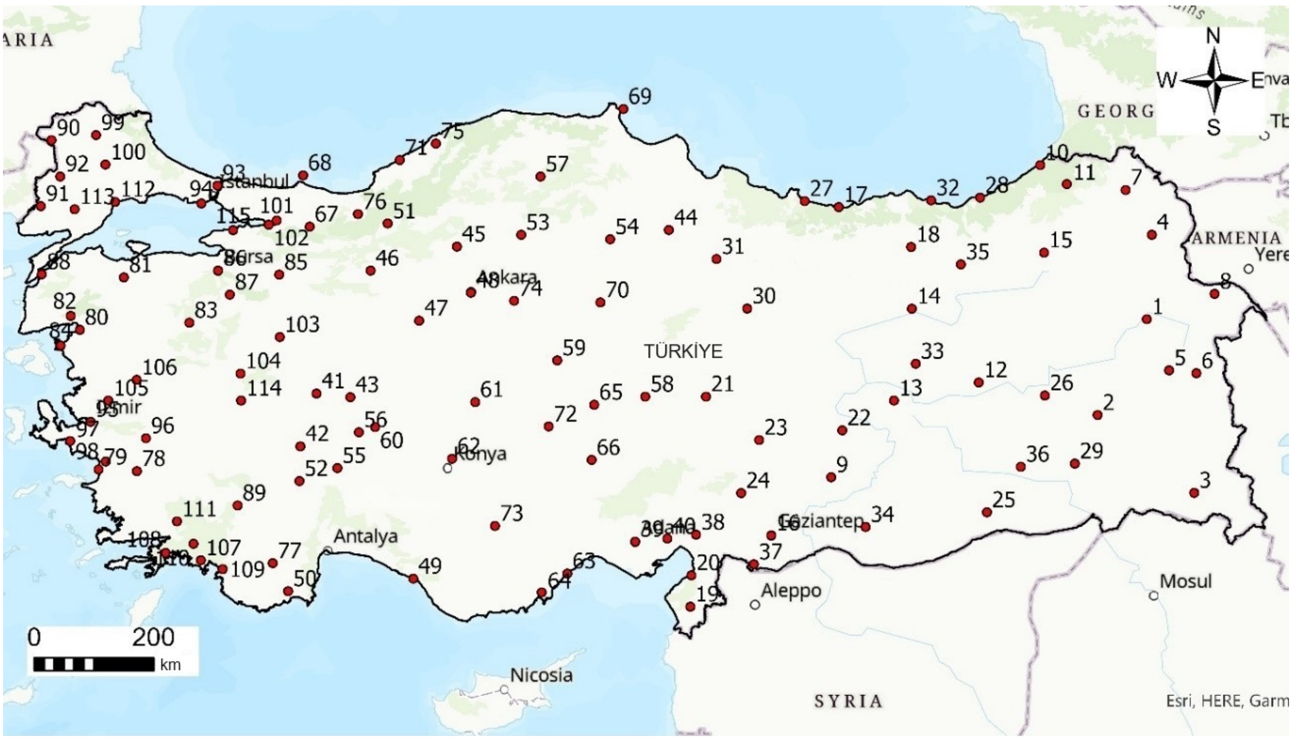

Figure 6. Meteorological observation stations

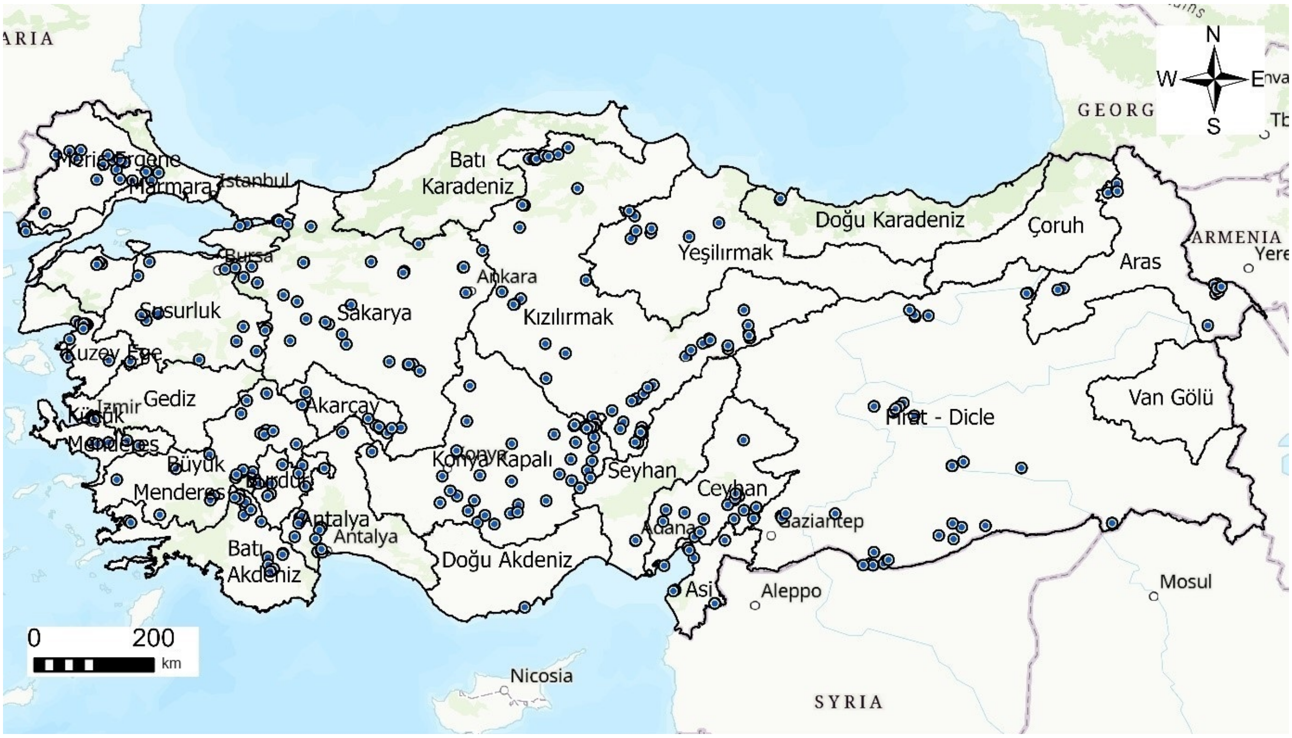

Figure 7. Locations of groundwater wells.

Table. Periods and the number of wells.

Period	**1970-1979**	**1980-1989**	**1990-1999**	**2000-2009**	**2010-2019**
Count	110	144	270	310	310

Simple kriging allows for estimating and developing methods for regions with limited data (Kamińska and Grzywna, 2014). It permits the attribute to be estimated inside the data border. Another assumption is that the character is spatially dependent, implying that similar values are more likely to be comparable than those far apart.

3.2.2. Empirical Bayesian kriging (EBK)

Empirical Bayesian kriging is a development over the conventional geostatistical kriging techniques employed in the ESRI® software package (which only use one variogram), as introduced by Krivoruchko and Gribov (2019). EBK approach (Equation 2) decreases error by automating the semivariogram modelling process. Empirical Bayesian kriging combines Bayes' theorem and kriging interpolation, and repeated simulations are used to account for the inaccuracy in predicting the true semivariogram. It selects the best model from randomly created models. This method enables moderately nonstationary data and surpasses other kriging methods for small datasets (Zirakbash et al., 2020). EBK models, as described by Gribov and Krivoruchko (2020), offer several advantages over traditional kriging models, including: 1) the ability to handle moderate local and significant nonstationarity in the data; 2) the ability to accommodate varying levels of measurement error; 3) the option to apply a local normal score process to transform the data into a spatial Gaussian distribution; 4) the ability to divide large datasets into subsets of specified size, with or without overlap; and 5) the capacity to generate the distribution of different possible variograms and provide predictions for each subset.

$$z_i = t^{-1}\left(y_i \mid \Theta\right) = t^{-1}\left(y(S_i) + \epsilon_i \mid \Theta\right), i = \overline{1 \dots K}$$

In this equation, z_i is the measured value at the site that was observed (s_i). The transformed measured value is denoted by y_i, the transformed Gaussian process is denoted by y(s), the normally distributed measurement error of the transformed z_i value with mean zero denoted by ϵ_i, the transformed Gaussian process is denoted by $t(\bullet \mid \Theta)$, the parameters describing the process are denoted by Θ, and the number of measurements is denoted by K.

3.2.3. Inverse distance weighted (IDW)

The inverse distance weighting (IDW) technique is rooted in Tobler's first law (also known as the first law of geography) from 1970. It posits that all things are interrelated, but nearby things are more strongly connected than those that are far apart. In other words, the proximity of a point to the center of the processing cell determines its influence in the averaging process. The IDW method is widely recognized as a standard spatial interpolation technique in the field of geographic information science. It has been recommended by experts such as Burrough and McDonnell in 1998, and Longley et al. in 2001, and has been integrated into various GIS software programs. Consequently, many GIS users who do not possess extensive knowledge in spatial statistics or geostatistics employ IDW as their default method for creating a surface when attribute values are only available at sampled locations. The IDW method (Equations 3 and 4) calculates an estimate of an unknown value at a location Z by taking into account the observed values (Z) at surrounding sampled locations (x_i). To calculate the approximate value at location S_0, a linear combination is utilized, which involves the weights (λ_i) and the observed values (y) at the surrounding locations (x_i).

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \quad (3)$$

$$\lambda_i = d_{0i}^{-a} / \sum_{i}^{n} d_{0i}^{-a}$$

4. Results and discussion

4.1. Cross-validation

The results of the cross-validation for the SK, EBK, and IDW interpolation methods can be found in the supplementary material (Table S1 and Figure S1). The mean value is the value that indicates whether the model tends to have very high or low values. If the mean value is close to 0, the predicted values are close to the measured values. When the results are evaluated in terms of mean value, the EBK method seems to be the best. Root-mean-square (RMS) is the parameter that indicates the average difference between the predicted value and the measured value. The closer the RMS value is to 0, the more accurate the predicted values are. When comparing the RMS values of the methods in this study, it can be said that SK provides more accurate results when the number of samples is small, and IDW and EBK provide more accurate results when the number of samples increases. The scatterplot compares the predicted values with the measured values. It is best if the reference line matches the regression line. EBK and IDW interpolation methods have similar results if the SK method has a regression line parallel to the reference line. However, it should be noted that the regression of the EBK and IDW methods is a good fit to the data as the number of data increases. In the area where the number of data is high, it can be seen that the reference line and the regression line match. Therefore, EBK and IDW provide a more accurate and realistic result map for spatial and geological features in this study.

4.2. Climate trend

The monthly average values for precipitation and the annual average temperature in Türkiye were divided into two equal periods (1985–2000 and 2001–2016). Figures 8 and 9 illustrate maps with the 15-year average monthly

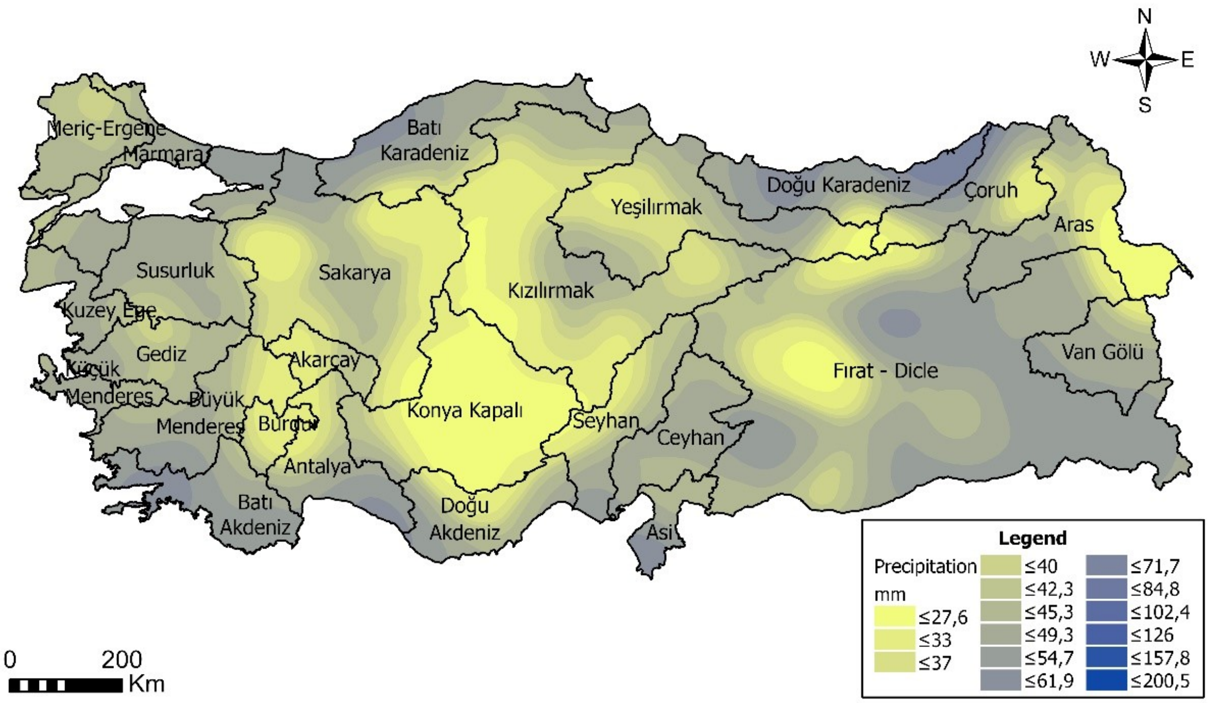

Figure 8. Türkiye's 15-year average precipitation map for the period of 1985–2000.

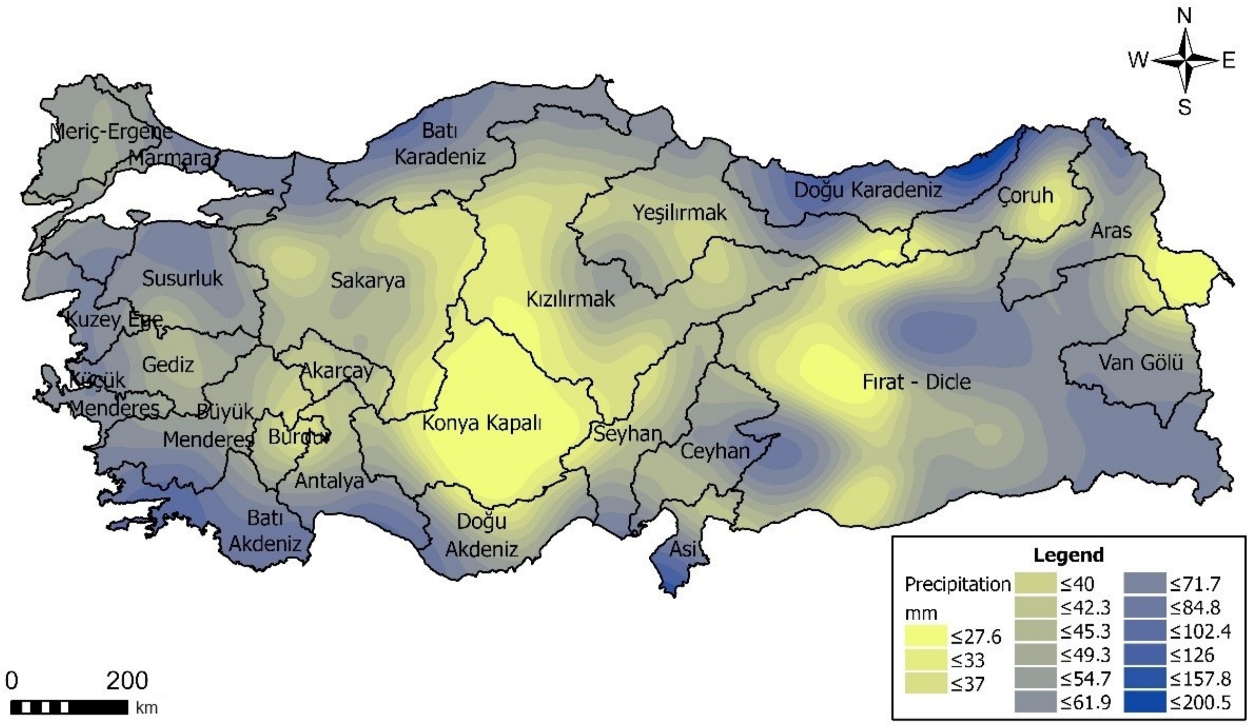

Figure 9. Türkiye's 15-year average precipitation map for the period of 2001–2016.

precipitation, while Figures 10 and 11 show maps with the 15-year average temperature.

Precipitation maps show areas with below-average monthly precipitation (less than 55 mm) in yellow and areas with above-average values in blue. Temperature maps display regions with average temperatures in light green, while yellow and orange hues indicate above-average temperatures, and blue denotes below-average temperatures. In the coastal areas of Türkiye, from the northwest to the southeast, temperatures are higher than the national average.

Data from 115 meteorological stations show that the average annual temperature in Türkiye was 13.28 °C between 1985 and 2000 and rose to 14.10 °C between 2001 and 2016. This represents a temperature increase of 0.82 °C during these periods. Several studies, including Türkeş (2012), Sensoy et al. (2013), and Hadi and Tombul (2018), also emphasize a warming trend in Türkiye, especially after the 1990s.

In terms of precipitation, Türkiye had a monthly average of 55.2 mm between 1985 and 2000, which increased slightly to around 58 mm between 2001 and 2016. While there are regional variations in the precipitation regime, the total annual precipitation in Türkiye has remained relatively constant overall. A detailed analysis reveals a slight increase in autumn precipitation and a proportional decrease in winter precipitation, with no significant changes in other seasons (Şen, 2013). In addition, it can be seen from the maps that precipitation increases more significantly in regions with higher precipitation, especially in the Marmara, Aegean, Mediterranean, Black Sea, and Eastern Anatolia regions. Conversely, in the dry regions characterized by low precipitation (shown in yellow and its various shades), there is a significant decrease in precipitation over time. In other words, while precipitation increased over time in the coastal regions of Türkiye, it continued to decrease in the inland regions. These findings are supported by the results obtained in the study conducted by Şensoy and Demircan (2016). Türkiye's agricultural sector is most expansive in the provinces of Konya, Ankara, and Şanlıurfa, where rainfall is the lowest and the intensity of yellow tones is the highest. Therefore, it can be said that in these cities, where irrigation demand is high, low rainfall will further increase the pressure on water resources. Studies that have used long-term precipitation data and statistical testing with the Mann-Kendall method also show a decreasing trend for precipitation in Anatolia (Altın et al., 2012; Çiçek et al., 2015), in the southern region (Çiçek and Duman, 2015) and in the western part of Türkiye (Aşıkoğlu and Çiftlik, 2015; Bacanlı and Tanrıkulu, 2016; Bacanlı, 2017). It has been shown that precipitation only shows an increasing trend in the eastern Black Sea and north-eastern Anatolia (Tayanç et al., 2009; Unal et al., 2012; Şen, 2013; Çiçek and Duman, 2015).

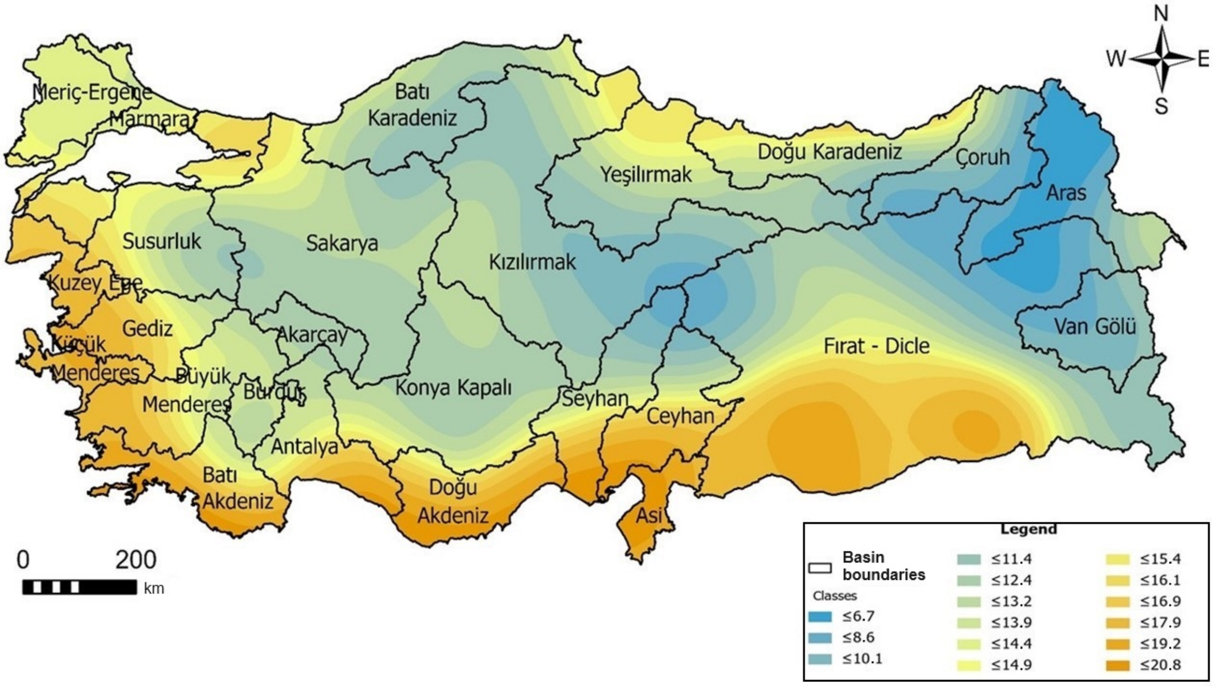

Figure 10. Türkiye's 15-year average temperature map for the period of 1985–2000.

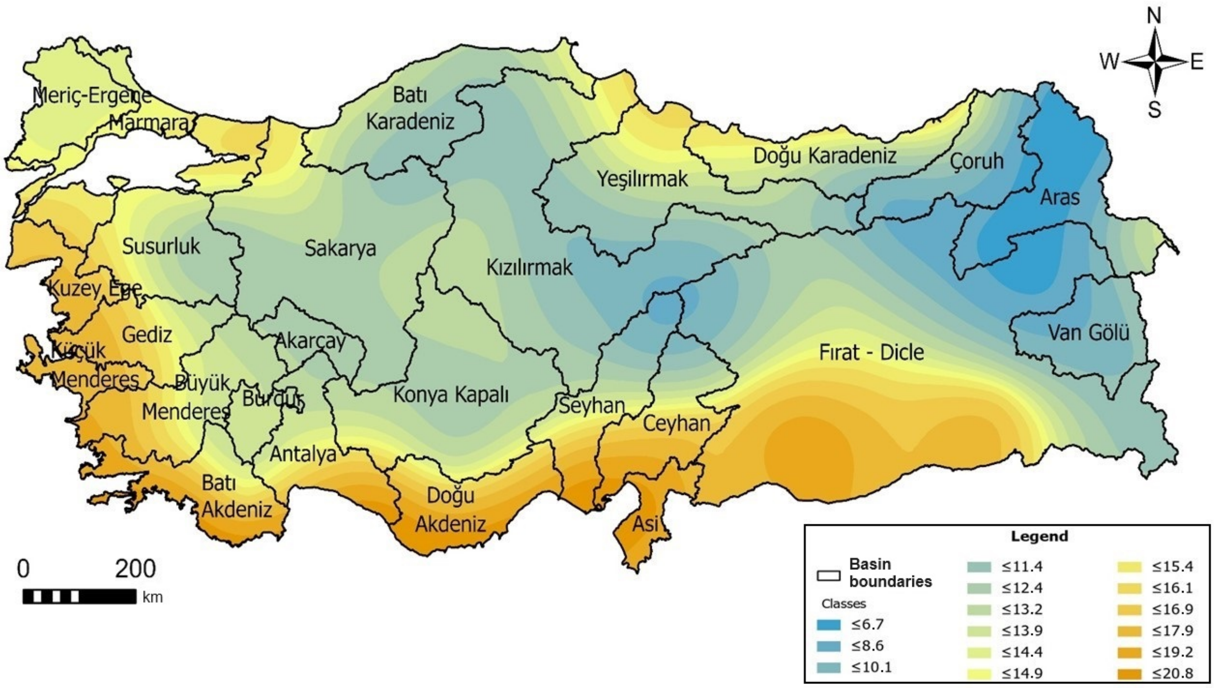

Figure 11. Türkiye's 15-year average temperature map for the period 2001-2016.

4.3. Groundwater level

Figure 12 shows the groundwater levels in Türkiye for 10-year periods according to the SK, EBK, and IDW interpolation methods. Especially after the 1990s, all three methods show that the decline in groundwater levels in the Meriç-Ergene, Marmara, Gediz, Büyük Menderes, Küçük Menderes, Konya Closed, and Euphrates-Tigris catchment areas has taken on serious proportions. In some regions, the groundwater table is lower than 108 m. The population density influences the water demand in Meriç-Ergene, Marmara, Küçük Menderes, and Gediz. On the other hand, Meriç-Ergene, Büyük Menderes, Gediz,

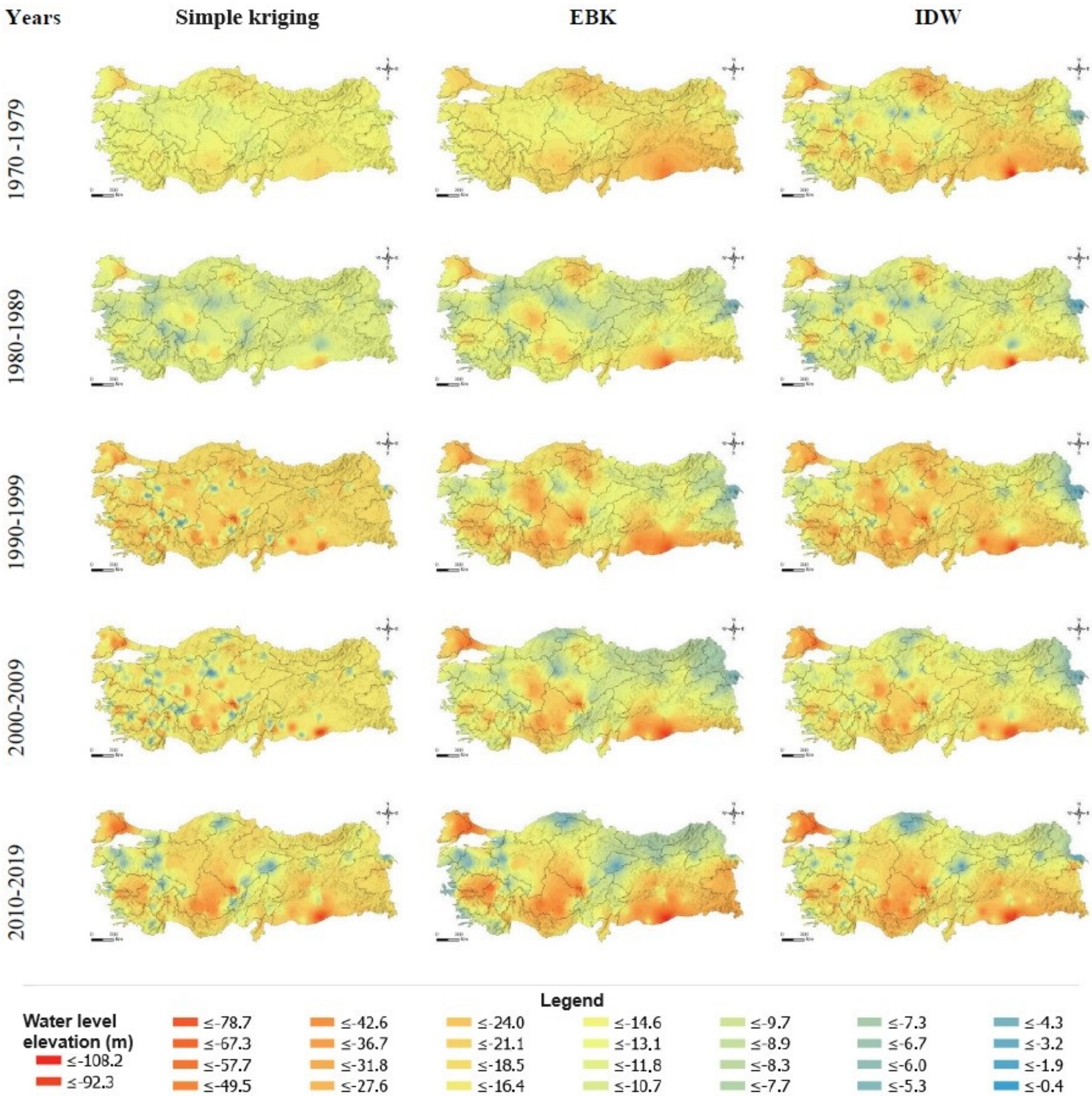

Figure 12. Groundwater level elevation changes between 1970 and 2019.

Konya Closed, and Euphrates-Tigris are also the regions where agriculture is intensively practiced in Türkiye. For example, in a study for the Euphrates-Tigris Basin, Çelik (2015) emphasized that using groundwater for irrigation in the basin, which has semiarid climate characteristics, causes a decrease in the groundwater table.

For the period of 2010–2019, groundwater levels in the catchments in the Black Sea region (Western Black Sea, Yeşilırmak, Eastern Black Sea, Çoruh) are close to the surface, especially for the EBK and IDW methods. Looking at the climate trend, these catchment areas are above the average for Türkiye in terms of precipitation and below in terms of temperature. The number of wells used for groundwater analysis is lower than in other catchments; it was even found that there is no well data for some catchments. This situation shows that the demand for groundwater in these catchments is low.

Figures 13–15 show the changes observed in certain wells within regions where the groundwater level has experienced the most significant decline, namely the Meriç-Ergene, Konya Closed, and Euphrates-Tigris basins. Groundwater levels in the Meriç-Ergene Basin have declined to 100 m, while in the Konya Closed Basin, they have dropped to 90 m, and in the Euphrates-Tigris Basin,

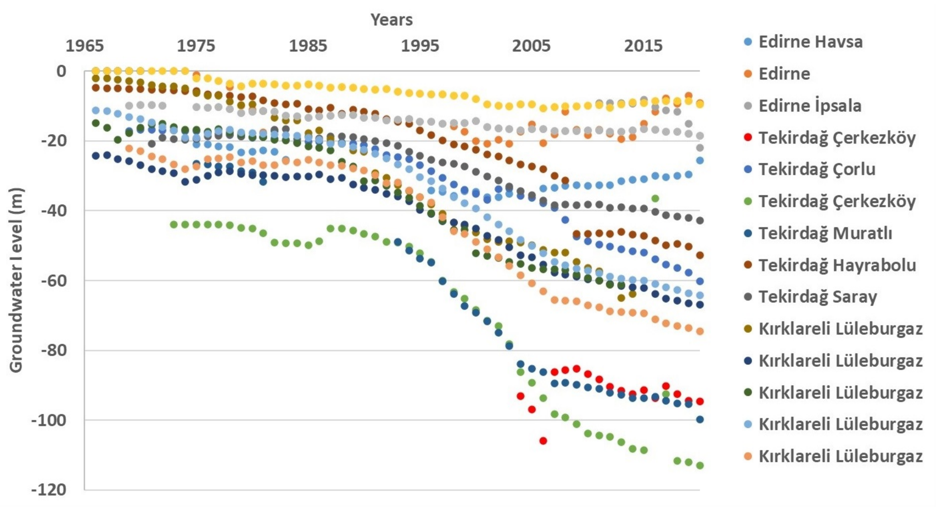

Figure 13. Meriç-Ergene Basin groundwater level change over the years.

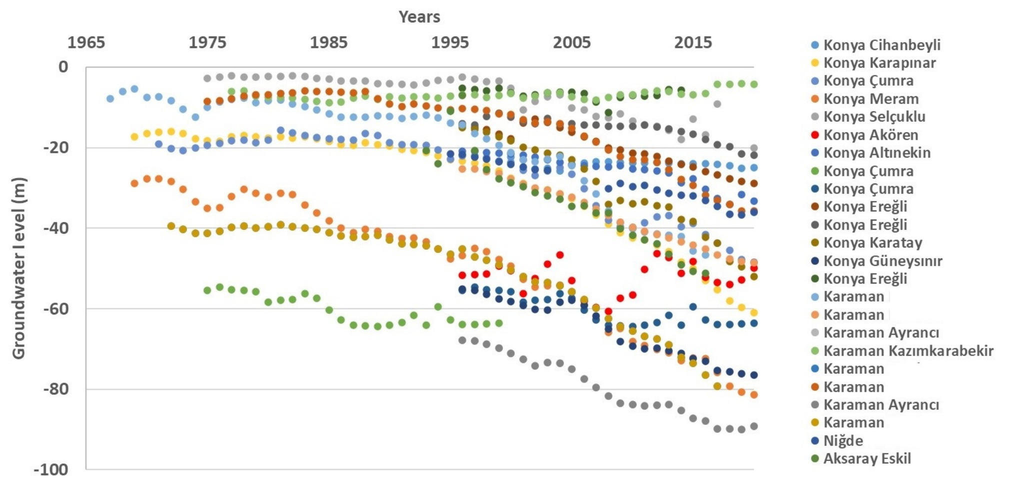

Figure 14. Konya Closed Basin groundwater level change over the years.

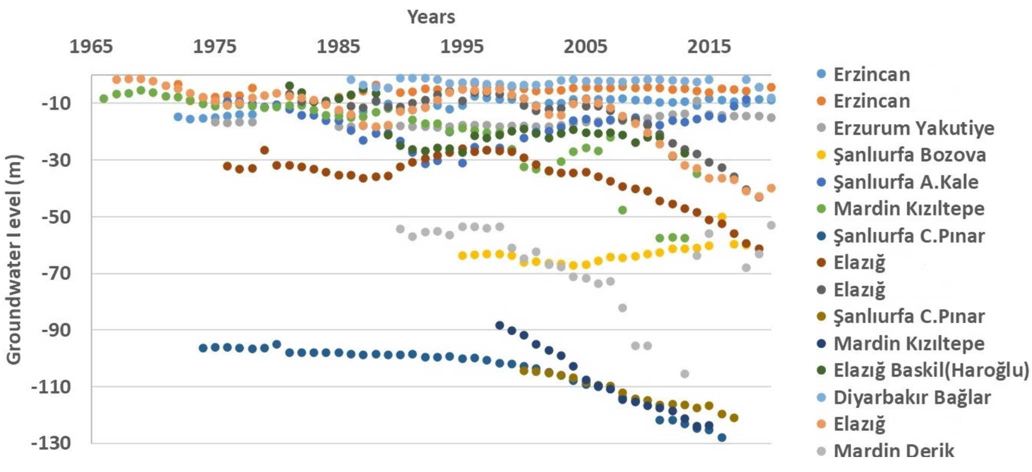

Figure 15. Euphrates-Tigris Basin groundwater level change over the years.

they have dropped to 130 meters. Most wells across these three basins are showing a consistent downward trend in their groundwater levels in years.

When examining the climate trends, an increase in average temperature values can be observed, especially in the basins on the Aegean and Mediterranean coasts, in the closed Konya Closed and in the Euphrates-Tigris basins. As can be observed in the precipitation maps mentioned in the previous sections, precipitation in the Konya Closed and Euphrates-Tigris basins has decreased significantly compared to other regions. Over the years, precipitation in these basins has gradually decreased, which is particularly remarkable given the high agricultural activity in these areas. This decrease in precipitation has led to increasing pressure on groundwater levels. Consequently, the presence of red colors in the maps displayed by all three interpolation methods reflects the consequences of this precipitation shift, which is a crucial element in the hydrological cycle. In addition, this observation is supported by the provision of detailed information on the decline in levels of selected observation wells from these catchments, as shown in Figures 13–15.

Studies carried out for different regions of Türkiye also confirm the decrease in groundwater levels over time. Apaydin (2010) showed that the Halacli aquifer, which is characterized as a shallow aquifer, is susceptible to climate fluctuations. Although it was not exploited before, the groundwater level dropped between 1989 and 1997, but when exploitation began in the summer of 1998, the water levels rose again. In order to get a grip on the natural fluctuations in water levels and well discharges, it is important to analyze the reaction of the groundwater system to climate fluctuations and human activities. Another research paper underlines the importance of the Gravity Recovery and Climate Experiment (GRACE) as a valuable tool for studying fluctuations in terrestrial water storage (TWS) at medium and large spatial scales. Using GRACE observations from March 2003 to March 2009, the study estimated linear trends in TWS variations in Türkiye. Especially in the southern part of the Central Anatolian region, a significant decrease in TWS was observed, which amounted to up to 4 cm/year (Lenk, 2013). Çelik's study of the upper Tigris Basin revealed that the changes in groundwater levels in this region are influenced by three main factors. (1) Climate change and associated precipitation variability; (2) population increase has led to increased demand for groundwater resources for drinking and domestic purposes; and (3) increasing demand for wells to meet agricultural irrigation needs is another factor affecting groundwater levels in the area (2015). In another study, Yagbasan (2016) calculated a reduction in groundwater recharge of approximately 15% using the hydrological budget method for the observation period (1964–2011) in the Küçük Menderes River Basin. Arkoc (2022) conducted research using different interpolation methods in the Ergene Basin. This research has revealed that the groundwater prediction maps show a decrease in groundwater levels in areas where the Organized Industrial Zones (OIZ) are located, mainly due to the excessive pumping capacity of the factories. There has also been a decline in groundwater levels due to pumping for agricultural irrigation during the summer. The accuracy of estimating the groundwater level in this region using interpolation methods depends on the amount of data included in the analysis.

In addition, findings from modeling studies underscore the worrying prospect that groundwater resources in certain regions could deteriorate due to the dual impact of changing climatic conditions and escalating overconsumption. For example, Şimşek et al. (2020) used a GIS-integrated method to analyze groundwater level fluctuations and determine groundwater recharge in the Alaşehir alluvial aquifer for a specific hydrological period. This approach facilitated the calculation of total groundwater discharge from the aquifer and showed a decrease in groundwater volume amounting to 235.82 hm^3, with the largest decrease observed during a dry season. The study indicates that the decrease in groundwater volume exceeds the increase during the hydrological period, which is primarily due to overexploitation of groundwater resources. Long-term analyses of groundwater level data show an annual decrease of about 1 m. Ertürk et al. (2014) investigated the effects of climate change on groundwater resources in a specific area of the Köyceğiz–Dalyan watershed. Using the Soil and Water Assessment Tool (SWAT) model, they assessed the impacts on different components of the water balance considering climate change and land use scenarios. The results of the study's simulations showed an overall decrease in various elements of the water balance, leading to a decrease in the allocation of irrigation water by SWAT due to the effects of climate-induced water decline. As a result, there was an increase in days of water and temperature stress, leading to a reduction in crop yields. This study highlights the urgent concern of impending water scarcity and emphasizes the need to explore and implement more efficient irrigation techniques and promote crops with lower water requirements. Avcı et al. (2021) show that the current groundwater use pattern in the Demre coastal aquifer may no longer be sustainable by 2050 if agricultural practices do not change and lateral recharge from the mountainous karst aquifer continues. However, the discrepancies between the expected climate change scenarios (RCP 4.5 and 8.5) and the observed precipitation and temperature values cast doubt on the reliability of the groundwater flow model that predicts the future conditions of the aquifer. They emphasize the importance of improving the accuracy of climate projections before formulating reliable groundwater management strategies based on predictive models. This underlines the call for future research to focus on refining the input data and assessing the uncertainties within these models.

6. Conclusion

This study examines the changes in groundwater levels in Türkiye from 1970 to 2019, analyzing data from 355 wells using three geostatistical interpolation methods. GIS provides effective solutions for managing complex data. GIS tools are able to improve the routine calculation of performance indices and provide valuable insights into the state of water systems for both water managers and decision makers. By utilizing satellite imagery with high spatial and temporal resolution, remote sensing facilitates the extraction of information and deepens the understanding of the relationships between different parameters. It also saves time by analyzing a large number of parameters quickly, making it easier to take action against problems.

The results of this study show that the water level is continuously decreasing in all catchment areas, including Meriç-Ergene, Gediz, Konya Closed, Büyük Menderes, Küçük Menderes, and Euphrates-Tigris. These areas are characterized by high agricultural production and dense population, so the decline in groundwater levels is a cause for concern. The main causes of this decline are excessive agricultural irrigation practices and changing climate conditions. The study highlights the potentially irreversible consequences of these changes to groundwater, particularly in arid and semiarid regions where pressure on groundwater has increased.

To address groundwater depletion comprehensively and ensure sustainable water management in Türkiye, an integrated approach is essential. This includes the implementation of strict regulations on groundwater abstraction in all catchment areas, with a particular focus on densely populated areas, in order to conserve water resources. At the same time, it is necessary to support the introduction of water-saving irrigation technologies in agriculture, incentivize farmers to adopt sustainable practices and promote awareness of responsible water use. Key components include monitoring and regulating population growth, introducing water-saving initiatives, and investing in water recycling and reuse systems in urban areas. In agricultural regions, strict regulations on agricultural and urban groundwater use must be enforced, complemented by the introduction of efficient water management practices and the development of alternative water sources. In addition, promoting sustainable agriculture through water-saving practices, implementing groundwater monitoring programs and educating farmers on water conservation are crucial measures. Promoting precision irrigation techniques, exploring alternative water sources, such as treated wastewater, and enforcing regulations on the withdrawal of water from unlicensed wells also contribute to a holistic strategy. Finally, the development and enforcement of regulations on groundwater use for irrigation, combined with investment in climate-resilient agricultural practices and exploration of sustainable water supply options, will promote a resilient and balanced framework for water management in Türkiye.

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Author contributions

Nilüfer Tirol Kırçiçek: conceptualization; data curation; investigation; methodology; visualization; writing the original draft. Alper Baba: conceptualization; investigation; methodology; writing the original draft. Ayhan Koçbay: data provision, review. Murat Mert Toklu: data provision, review.

References

Altın TB, Barak B, Altın BN (2012). Change in precipitation and temperature amounts over three decades in central Anatolia, Turkey. Atmospheric and Climate Sciences 02 (01): 107-125. https://doi.org/10.4236/acs.2012.21013

Altinbilek D, Hatipoglu MA (editors) (2020). Water resources development: Water Resources of Turkey. In: Harmancioglu N, Altinbilek D (editors). World Water Resources. vol 2. Cham, Switzerland: Springer, pp. 61-84. https://doi.org/10.1007/978-3-030-11729-0_3

Amanambu AC, Obarein OA, Mossa J, Li L, Ayeni SS et al. (2020). Groundwater system and climate change: present status and future considerations. Journal of Hydrology 589. https://doi.org/10.1016/j.jhydrol.2020.125163

Apaydin A (2010). Response of groundwater to climate variation: fluctuations of groundwater level and well yields in the Halacli aquifer (Cankiri, Turkey). Environmental Monitoring and Assessment, 165 (1–4): 653–663. https://doi.org/10.1007/s10661-009-0976-8

Arkoc O (2022). Modeling of spatiotemporal variations of groundwater levels using different interpolation methods with the aid of GIS, case study from Ergene Basin, Turkey, Modeling Earth Systems and Environment, 8 (1): 967–976. https://doi.org/10.1007/s40808-021-01083-x

Aşıkoğlu OL, Çiftlik D (2015). Recent rainfall trends in the Aegean Region of Turkey. Journal of Hydrometeorology 16 (4): 1873-1885. https://doi.org/10.1175/JHM-D-15-0001.1

Avcı P, Bayarı CS, Özyurt NN (2021). Assessing the effect of climate change on groundwater use in Demre coastal aquifer (Antalya, Turkey), coupled use of climate scenarios and numerical flow modeling. Environmental Earth Sciences, 80 (6). https://doi.org/10.1007/s12665-021-09517-6

Bacanlı UG, Tanrıkulu A (2016). Trends in yearly precipitation and temperature on the Aegean Region, Turkey. Ovidius University Annals Series: Civil Engineering 18.

Bacanlı UG (2017). Trend analysis of precipitation and drought in the Aegean Region, Turkey. Meteorological Applications 24 (2): 239-249. https://doi.org/10.1002/met.1622

Bangash RF, Passuello A, Sanchez-Canales M, Terrado M, López A et al. (2013). Ecosystem services in Mediterranean river basin: climate change impact on water provisioning and erosion control. Science of the Total Environment 458–460: 246–255. https://doi.org/10.1016/j.scitotenv.2013.04.025

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (editors) (2008). Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Burrough PA, McDonnell RA (1998). Principles of Geographical Information Systems. 3rd ed. Oxford, UK: Oxford University Press.

Caló F, Notti D, Galve J, Abdikan S, Görüm T et al. (2017). DInSAR-Based detection of land subsidence and correlation with groundwater depletion in Konya Plain, Turkey. Remote Sensing 9 (1): 83. https://doi.org/10.3390/rs9010083

Cressie NAC (1993). Statistics for Spatial Data. 1st ed. Wiley Series in Probability and Mathematical Statistics: Applied Probability and Statistics. New York, NY, USA: John Wiley & Sons, Inc.

Cuthbert MO, Gleeson T, Moosdorf N, Befus KM, Schneider A et al. (2019). Global patterns and dynamics of climate–groundwater interactions. Nature Climate Change 9 (2): 137–141. https://doi.org/10.1038/s41558-018-0386-4

Çelik R (2015). Temporal changes in the groundwater level in the Upper Tigris Basin, Turkey, determined by a GIS technique. Journal of African Earth Sciences, 107: 134–143. https://doi.org/10.1016/j.jafrearsci.2015.03.004

Çetin M (2020). Agricultural water use. In: Harmancioglu N, Altinbilek D (editors). Water Resources of Turkey. World Water Resources 2. https://doi.org/10.1007/978-3-030-11729-0_9

Çiçek İ, Duman N (2015). Seasonal and annual precipitation trends in Turkey. Carpathian Journal of Earth and Environmental Sciences 10 (2): 77-84.

Ertürk A, Ekdal A, Gürel M, Karakaya N, Guzel C et al. (2014). Evaluating the impact of climate change on groundwater resources in a small Mediterranean watershed. Science of the Total Environment, 499: 437-447. https://doi.org/10.1016/j.scitotenv.2014.07.001

Franssen HJH (2009). The impact of climate change on groundwater resources. International Journal of Climate Change Strategies and Management (3): 241-254. https://doi.org/10.1108/17568690910977465

Frappart F, Ramillien G (2018). Monitoring groundwater storage changes using the Gravity Recovery and Climate Experiment (GRACE) satellite mission: a review. Remote Sensing 10 (6). https://doi.org/10.3390/rs10060829

Giordano M (2009). Global groundwater? Issues and solutions. Annual Review of Environment and Resources 34: 153–178. https://doi.org/10.1146/annurev.environ.030308.100251

Giray H (2012). Turkish agriculture at a glance. Journal of Food, Agriculture & Environment 10 (3-4), 292 -295.

Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM et al. (2011). Beneath the surface of global change: impacts of climate change on groundwater. Journal of Hydrology 405 (3–4): 532–560. https://doi.org/10.1016/j.jhydrol.2011.05.002

Gribov A, Krivoruchko K (2020). Empirical Bayesian kriging implementation and usage. Science of the Total Environment 722: 137290. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.137290

Hadi SJ, Tombul M (2018). Long-term spatiotemporal trend analysis of precipitation and temperature over Turkey. Meteorological Applications 25 (3): 445–455.

Holman IP, Allen DM, Cuthbert MO, Goderniaux P (2012). Towards best practice for assessing the impacts of climate change on groundwater. Hydrogeology Journal 20 (1): 1–4. https://doi.org/10.1007/s10040-011-0805-3

Iglesias A, Garrote L, Flores F, Moneo M (2007). Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resources Management, 21 (5): 775–788. https://doi.org/10.1007/s11269-006-9111-6

Jakemann A, Randall O, Huntt J, Andrewwross JD (2016). Integrated Groundwater Management Concepts, Approaches and Challenges. Springer Open. https://doi.org/10.1007/978-3-319-23576-9

Kamińska A, Grzywna A (2014). Comparison of deteministic interpolation methods for the estimation of groundwater level. Journal of Ecological Engineering 15 (4): 55–60. https://doi.org/10.12911/22998993.1125458

Karabulut Aİ, Yazici-Karabulut B, Derin P, Yesilcinar Mİ, Cullu MA (2022). Landfill siting for municipal solid waste using remote sensing and geographic information system integrated analytic hierarchy process and simple additive weighting methods from the point of view of a fast-growing metropolitan area in GAP area of Turkey. Environmental Science and Pollution Research (29): 4044–4061 https://doi.org/10.1007/s11356-021-15951-7

Karabulut Aİ, Yazıcı Karabulut B, Demir-Yetiş A (2023). Socioeconomic driving forces of land use/cover changes in the semi-arid Harran plain and their probable implications on arising groundwater level, the GAP area of southeastern Türkiye. Acta Geophysica (71): 2795–2810. https://doi.org/10.1007/s11600-023-01162-w

Krivoruchko K, Gribov A (2019). Evaluation of empirical Bayesian kriging. Spatial Statistics, 32: 100368. https://doi.org/10.1016/J.SPASTA.2019.100368

Kumar CP (2012). Climate Change and its Impact on Groundwater Resources. Research Inventy: International Journal of Engineering and Science 1 (5): 43-60.

Lenk O (2013). Satellite based estimates of terrestrial water storage variations in Turkey. Journal of Geodynamics 67: 106–110. https://doi.org/https://doi.org/10.1016/j.jog.2012.04.010

Lionello P, Scarascia L (2018). The relation between climate change in the Mediterranean region and global warming. Regional Environmental Change 18 (5): 1481–1493. https://doi.org/10.1007/s10113-018-1290-1

Longley PA, Goodchild MF, Maguire DJ, Rhind DW (2001). Geographic Information Systems and Science. 4th ed. New York, NY, USA: John Wiley & Sons.

Masson-Delmotte V, Zhai P, Chen Y, Goldfarb L, Gomis MI et al. (2021). Climate Change 2021: The Physical Science Basis – Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Patil NS, Chetan NL, Nataraja M, Suthar S (2020). Climate change scenarios and its effect on groundwater level in the Hiranyakeshi watershed. Groundwater for Sustainable Development 10: 100323. https://doi.org/10.1016/J.GSD.2019.100323

Pilevneli, T, Capar, G, Sanchez-Cerda C (2023). Investigation of climate change impacts on agricultural production in Turkey using volumetric water footprint approach. Sustainable Production and Consumption 35: 605-623. https://doi.org/10.1016/j.spc.2022.12.013

Secci D, Tanda MG, D'Oria M, Todaro V, Fagandini C (2021). Impacts of climate change on groundwater droughts by means of standardized indices and regional climate models. Journal of Hydrology 603. https://doi.org/10.1016/j.jhydrol.2021.127154

Şen ÖL (2013). Türkiye'de iklim değişikliğinin bütünsel resmi. Türkiye'de İklim Değişikliği Kongresi (TİKDEK 2013), 3-5 Haziran, İstanbul, Türkiye (in Turkish).

Sensoy S, Turkoglu N, Akcakaya A, Ekici M, Ulupinar Y et al. (2013) Trends in Turkey climate indices from 1960 to 2010. In: The 6th Atmospheric Science Symposium, ITU, İstanbul, Türkiye.

Şensoy S, Demircan M (2016). State of the climate in Turkey in 2015. Republic of Türkiye Ministry of Forestry and Water Affairs Turkish State Meteorological Service.

Şimşek C, Demirkesen AC, Baba A, Kumanlıoğlu A, Durukan S et al. (2020). Estimation groundwater total recharge and discharge using GIS-integrated water level fluctuation method: a case study from the Alaşehir alluvial aquifer Western Anatolia, Turkey. Arabian Journal of Geosciences, 13 (3): 143. https://doi.org/10.1007/s12517-020-5062-0

Taşkın Ö, Somuncu M, Çapar G (2022). An evaluation on the effects of climate change on water resources and agriculture sector in Türkiye (in Turkish with an abstract in English). TÜCAUM 2022 International Geography Symposium, 12-14 October 2022, Ankara, Türkiye. pp. 468-485.

Tayanç M, Im U, Doğruel M, Karaca M (2009). Climate change in Turkey for the last half century. Climate Change 94 (3-4): 483-502. https://doi.org/10.1007/s10584-008-9511-0

Türkeş M (2012). Observed and projected climate change, drought and desertification in Turkey. Ankara Üniversitesi Çevrebilimleri Dergisi 4 (2): 1-32 (in Turkish with an abstract in English). https://doi.org/10.1501/Csaum_0000000063

Türkeş M. (2020). Climate and drought in Turkey. In: Harmancioglu N, Altinbilek D (editors). Water Resources of Turkey. World Water Resources 2. Springer. https://doi.org/10.1007/978-3-030-11729-0_4

Ustaoglu E, Aydınoglu AC (2019). Regional variations of land-use development and land-use/cover change dynamics: a case study of Turkey. Remote Sensing 11: 885. https://doi.org/10.3390/rs11070885

Uyan M, Cay T (2013). Spatial analyses of groundwater level differences using geostatistical modeling. Environmental and Ecological Statistics 20 (4): 633–646. https://doi.org/10.1007/s10651-013-0238-3

Unal YS, Deniz A, Toros H, Incecik S (2012). Temporal and spatial patterns of precipitation variability for annual, wet, and dry seasons in Turkey. International Journal of Climatology 32 (3): 392-405. https://doi.org/10.1002/joc.2274

Xiao Y, Gu X, Yin S, Shao J, Cui Y et al. (2016). Geostatistical interpolation model selection based on ArcGIS and spatio-temporal variability analysis of groundwater level in piedmont plains, northwest China. SpringerPlus 5 (1): 425. https://doi.org/10.1186/s40064-016-2073-0

Yagbasan O (2016). Impacts of climate change on groundwater recharge in Küçük Menderes River Basin in Western Turkey. Geodinamica Acta 28 (3): 209–222. https://doi.org/10.1080/09853111.2015.1121802

Zirakbash T, Admiraal R, Boronina A, Anda M, Bahri PA (2020). Assessing interpolation methods for accuracy of design groundwater levels for civil projects. Journal of Hydrologic Engineering 25 (9). https://doi.org/10.1061/(asce)he.1943-5584.0001982

Supplementary material

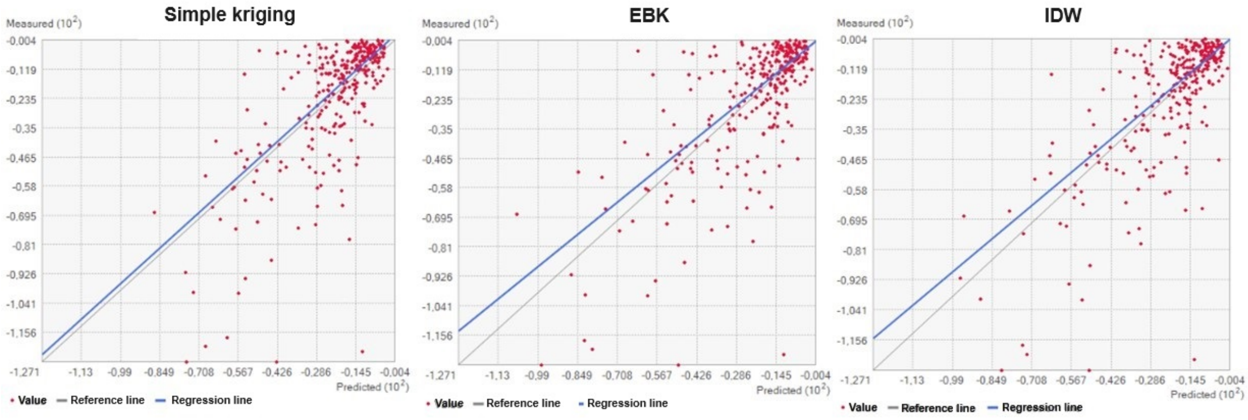

Figure S1. Cross-validation results of each interpolation method.

Table S1. Cross-validation results of the interpolation methods.

	Period	**1970-1979**	**1980-1989**	**1990-1999**	**2000-2009**	**2010-2019**
	Count	**110**	**144**	**270**	**310**	**310**
Mean	**SK**	0.15	0.21	–0.26	0.07	0.20
	EBK	0.12	0.19	–0.14	–0.09	0.29
	IDW	0.51	0.77	–0.54	–0.34	0.71
Root-mean-square	**SK**	12.17	11.42	14.52	14.73	16.88
	EBK	12.91	12.16	14.43	14.10	16.62
	IDW	13.18	11.87	14.68	14.18	16.32