Analysis of trends and drivers: Identifying water conservation opportunities in the Eskandari Watershed, Iran

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Abstract

Water scarcity is a significant issue in Iran, especially on its central plateau. Although climate change contributes to this problem, mismanagement and over-exploitation of available water resources worsened the situation. This study investigated water conservation opportunities in the Eskandari watershed, a crucial agricultural region in the Zayandeh-Rud River basin. We examined the trend of changes in all the factors affecting water resources in this watershed, including precipitation, discharge, leaf area index (LAI), inter-basin water transfer, and groundwaters from 2004 to 2019 at an annual scale. The classic Mann-Kendall (MK) and the non-parametric Trend-Free pre-whitening Mann-Kendall (TFPW-MK) statistical tests were employed to analyze the changing trends of these parameters over time. The results indicated that precipitation, discharge, and cultivated area have not shown any significant trend over 16 years. While in this period, the inter-basin water transfer tunnel entered into the basin with an upward trend, the water volume of all three aquifers experienced a drastic negative trend, suggesting an imbalance between the inflow and outflow of the watershed. Based on the groundwater depletion and the inter-basin water transfer inflow, an estimated 336.14 million cubic meters of water were consumed over the study period. This loss aligned with estimated water wastage in the form of wind drift and evaporation losses (WDEL) caused by the development of sprinkler irrigation systems in the study area. To address water scarcity and conserve water resources in the Eskandari watershed, it is essential to adopt sustainable irrigation practices that consider reducing the pressure on aquifers.

Introduction

The increase in the world's population led to an increase in water demand and put a severe strain on water resources. This problem has become particularly critical, especially in the countries located in the Middle East and North Africa, where unsustainable utilization of water resources exacerbated the situation. This region is home to 15 out of the 20 countries that face the most challenges of water shortage, including Iran, and is likely to worsen (*Beyond Scarcity: Water Security in the Middle East and North Africa*, 2017). This region is home to 15 out of the 20 of the world's most water-scarce countries, including Iran, and is likely to worsen. Geographically, Iran is one of the arid and semi-arid regions of the world and is facing a significant water shortage, especially in its central plateau. Water stress in the Zayandeh-Rud River, the largest river in this plateau, threatens both the historical city of Isfahan downstream and the Gavkhuni Wetland Reserve, the final recipient of the river water (Abou Zaki et al., 2020). In recent decades, the basin has witnessed a significant increase in water stress due to severe droughts. Our research focused on the Eskandari watershed, an important agricultural area in the Zayandeh-Rud River basin. Unfortunately, this watershed has also experienced a notable decline in water resources, primarily caused by human interventions, such as land use changes, crop pattern changes, and increased water consumption consumption (Kakaei et al., 2019).

Several studies investigated the water scarcity in the Zayandeh Rud basin and the Eskandari sub-basin. These studies focused on the different aspects of water scarcity, including the influence of climate change on water availability (Zareian, 2021),

the effect of different climate change scenarios on the Zayandeh-Rud River basin (Gohari et al., 2017) and in the Eskandari Watershed ("Climate change impact on rainfall, temperature and surface water quality in Eskandari Watershed of Isfahan", 2022), future droughts (Motevali Bashi Naeini et al., 2020), the impact of land use change and human activities on the hydrological balance of the system in Eskandari Watershed (Barati et al., 2021). Additionally, (Sharifi et al., 2021) identified groundwater extraction and inter-basin water transfers as significant contributors to the declining water resources. All these studies highlight the need for effective water management strategies to address the water scarcity issue in this region. Therefore, a comprehensive understanding of water availability and usage at the farm, system, and basin levels is necessary to adopt an integrated and basin-wide approach to water management ("An overview of the hydrology of the Zayandeh Rud Basin", 2000).

Water resource management strategies are supply-oriented and demand-based. Demand management strategies in the region can involve enhancing irrigation efficiency, reducing water consumption, and promoting water conservation among communities (Gohari et al., 2017). On the other hand, supply-oriented strategies, include expanding water storage capacity, inter-basin water transfers, and adopting water-efficient technologies. Studies have shown that to tackle the water scarcity problem, a combination of demand management and supply-oriented strategies are necessary (Gohari et al., 2014; Madani & Mariño, 2009; Sharifi et al., 2021). However, it is essential to consider the social, economic, and political aspects of water management to ensure the effectiveness and sustainability of any adopted approach (Madani & Mariño, 2009). Traditionally, water resource management in this watershed was adapted to local conditions, effectively balancing water consumption with natural inflows. With the population growth and agricultural expansion over time, this balance has been disturbed and intensified water scarcity challenges. In recent decades, the excessive development of modern irrigation systems promoted by the government as a solution to water scarcity. However, the effectiveness of these systems in reducing water consumption remains a subject of debate (Perry et al., 2017). In contrast to some studies that have shown that modern irrigation systems can increase water use efficiency (Kahlown et al., 2007; Koech & Langat, 2018), others have criticized their poor utilization of resources despite their popularity and increasing use (Molle et al., 2011), This criticism stems from their water losses due to Wind Drift and Evaporation Losses (WDEL) (Playán et al., 2005).

Globally, agriculture is responsible for approximately 70 percent of freshwater withdrawals (FAO, 2011). However, this share varies significantly by country across different countries. Based on the available statistics, agriculture consumes more than 90 percent of water in the Zayandeh-Rud River basin (Abou Zaki et al., 2020). As a result, while climate change intensifies the water scarcity in the Eskandari watershed, withdrawals and water waste in this sector also contribute significantly to the problem. It's essential to note that the studies mentioned above failed to consider the substantial water loss amount in the agriculture sector.

Therefore, The main objective of this research is to investigate the wastage of the available water resources in the Eskandari watershed due to wind drift and evaporation losses in sprinkler irrigation systems and how they contribute to water consumption in the region. A comprehensive approach was adopted to achieve this objective, all the factors that influence water management in the watershed were analyzed using the classic Mann-Kendall (MK) and Trend-Free pre-whitening Mann-Kendall (TFPW-MK) non-parametric statistical tests. These factors encompass precipitation, discharge, leaf area index (LAI), inter-basin water transfer, and groundwater extraction over the 16 years from 2004 to 2019. The findings emphasized the need for sustainable irrigation practices to mitigate water scarcity in the region and provide actionable solutions for optimizing water management strategies and irrigation techniques in the Eskandari watershed, aiming to achieve a sustainable balance between agricultural productivity and water conservation.

2 Materials and Methods

2.1 Study site

The studied area is the Eskandari watershed (Figure 1), situated at an elevation of 2620 meters above sea level and covers an area of approximately 1649 square kilometers. The case study covers a geographical location that extends from 50 degrees 2 minutes to 50 degrees 40 minutes east longitude and 32 degrees 41 minutes to 33 degrees and 11 minutes north latitude. This watershed is located within the Zayandeh-Rud basin, home to the largest river in the Iranian plateau in the center of Iran. The Plasjan River, the second most significant river in the Zayandeh-Rud basin, originates from the heights of Fereydon Shahr and flows into the Eskandari watershed. Eventually, it joins the Zayandeh-Rud River at the western end of the Zayandeh-Rud Dam, the primary water source for agriculture, drinking, and industry in Isfahan province. As the water demand increased in the region, the Cheshmeh-Langan tunnel, an inter-basin water transfer project, was implemented in 2005. This tunnel, depicted by the green line in Figure 1, transfers water from the Sardab River, Sibak River, and Cheshmelangan Spring into the Palasjan River within the Zayandeh-Rud River basin. It is located 176 kilometers west of Isfahan, specifically in Fereydon Shahr City. The tunnel's geographic coordinates range from 50° 5 min to 50° 15 min east longitude and 32 degrees and 45 min to 33 degrees north latitude.

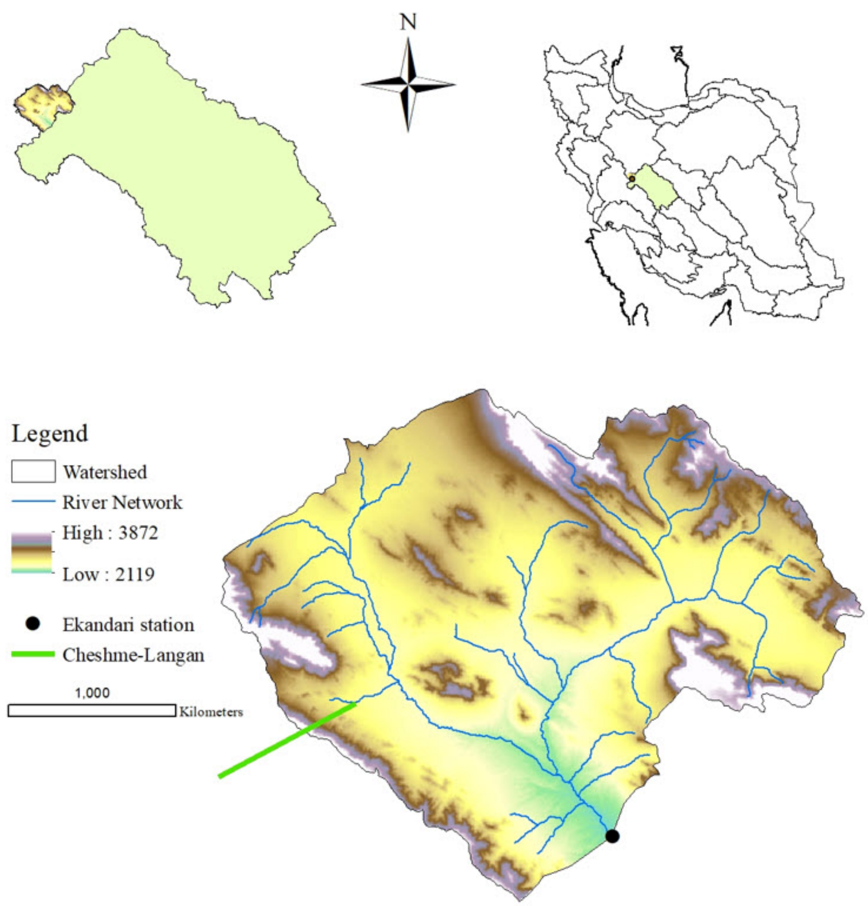


Figure 1: Location of the study area (DEM)

2.2 Assessing trends

The present study employed a non-parametric test to assess changes in the time series of data. The MK test, developed by (Mann, 1945) and (Kendall, 1948), has been extensively employed in studies detecting trends in hydrological variables due to its suitability for non-normally distributed and missing data (Hirsch & Slack, 1984). The MK test null hypothesis (H0) states, there is no monotonic trend in a sample series of data (X_i, i=1, 2…, n). Conversely, the alternate hypothesis (H_1) suggests the presence of a trend. The initial step in the Mann-Kendall test for a time series involves calculating the statistic S using the following formula:

$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)(1)$

Where n is the length of the dataset and sgn(x) is the sign function that takes the values 1 if x > 0, 0 if x = 0, and -1 if x < 0. The sequential data values at times i and j are represented by Xi and Xj, respectively. The MK test statistic z standardizes to determine whether there is a statistically significant trend in the time series data. This statistic follows the standard normal distribution, which has a mean of zero and a variance of one, and it is calculated using:

$$z = \begin{cases} \frac{s-1}{\sqrt{\mathrm{Var}(s)}} & amp; s \succ 0 \\ 0 & amp; s = 0 \\ \frac{s+1}{\sqrt{\mathrm{Var}(s)}} & amp; s \prec 0 \end{cases} \quad (2)$$

The sign of the z-statistic indicates the direction of the trend. Thus, positive, negative and zero z-statistics indicate an upward, a downward and no trend, respectively. The MK test assumes that the time series data is uncorrelated. However, most hydrological data exhibits positive autocorrelation. Therefore, (von Storch, 1999) suggested pre whitening method, which transforms the time series data to remove autocorrelation. This method, which employs the lag-1 serial correlation coefficient (r_1) of the sample data X_i, has been widely used by researchers since its introduction (Douglas et al., 2000; Kulkarni & von Storch, 1992; "Evaluation of Snow Cover Changes Trend Using GEE and TFPW-MK Test (Case Study: Marber Basin-Isfahan)", 2021; Zhang et al., 2000):

$Y_t = X_t - r_1 X_{t-1}(3)$

Yt is the residual time series, X_t is the original sequence, and t represents the sequence rank ranging from 1 to n. If r_1 is less than 0.1, the MK test was applied to the original time-series. Otherwise, the Mann-Kendall test was applied to the prewhitened series (x_2-r_1x_1, x_3-r_1x_2,…x_n-r_{1n-1}). The Trend-Free Pre-Whitening Mann-Kendall Test (TFPWMK) is a variant of the MK test that specifically addresses autocorrelation issues in time series data. The TFPWMK test first applies a pre-whitening step to remove autocorrelation and then applies the MK test to the pre-whitened data. This approach provides a more accurate assessment of the trend in time series data with autocorrelation compared to the classical MK test. The trend's slope can be estimated using the TSA (Sen, 1968; Theil, 1950) as follows:

$\beta = \text{ Median } \left(\frac{X_j - X_l}{j-1}\right) \forall l \prec j(4)$

β represents the linear trend of the original sequence X_t, and X_i and X_j represent the original sequences of the i^{th} item and the j^{th} item, respectively. If the slope is nearly zero, there is no need for trend analysis. However, the trend is considered linear if it deviates from zero, and the linear trend is computed by eliminating the trend term (T_t). This results in the formation of the sequence Yt, which does not include the trend term.

$X_t' = X_t - T_t = X_t - \beta t(5)$

After calculating r_1 for the detrended series X'_t, the lag-one autoregressive was removed from the X'_t:

$Y_t' = X_t' - r_1 X_{t-1}(6)$

T_t the identified trend and Y'_t the residual mixed (Y_t):

$Y_t = Y_t' - T_t (7)$

The significance of the trend in the mixed series $\mathrm{Y_t}$ was evaluated using the MK test. In this study, we examined the hydrological sequence of the Eskandai watershed from 2004 to 2019 using the classic Mann-Kendall (MK) and the Trend-Free pre-whitening Mann-Kendall method (TFPW-MK) tests. Unlike the classical MK method, the TFPW-MK method effectively eliminates the impact of sequence autocorrelation on the test outcomes ("Evaluation of Snow Cover Changes Trend Using GEE and TFPW-MK Test (Case Study: Marber Basin-Isfahan)", 2021).

2.3 Data collection

Precipitation and discharge data from meteorological stations, and groundwater information, from 60 piezometer wells in the three aquifers within the Eskandari watershed (Chehel Khaneh, Damaneh-Daran, and Buin Miandasht) were collected over a 16-year timeframe (from 2004 to 2019) for this study. Furthermore, data regarding the Cheshmeh-Langan tunnel was obtained from the Vahdat Abad meteorological station from 2005 (the start of its operation) to 2019. All of the required data were obtained from Iran's Water Resources Management Company(IWRMC, 2019).

3 Results

3.1 Precipitation

We employed the Thiessen polygon method to determine the average precipitation across the study area. The Thiessen polygon method is considered more reliable and accurate than other methods for its ability to account for the uneven distribution of rainfall effectively. While the arithmetic mean method averages rainfall measurements from all stations, potentially overlooking extreme values, the Thiessen polygon method mitigates this issue by assigning weights to each station based on the area it represents. This approach ensures a more accurate reflection of average rainfall across the study area (Faisal & Gaffar, 2012). The Thiessen polygon method creates a network of polygons around each rainfall station. The boundaries of these polygons are determined by drawing perpendicular bisectors between adjacent stations. The area of each polygon is then calculated and used to weigh the corresponding rainfall measurement. The weighted rainfall measurements were then summed together to obtain the average rainfall for the entire study area.

To utilize this approach in the Eskandari watershed, the initial step involved gathering data from 44 meteorological stations located within and around the watershed boundary. Subsequently, ArcGIS software was employed to create a Thiessen polygon. Overlaying this network onto the study area divided the Eskandari Watershed into nine distinct regions, namely Eskandari, Ashann, Agche, Buin, Shafi al-Qassab, Fereydun Shahr, Qaleh-ye Baba Mohammad, Mirabad, and Meydanak stations. Figure 2 shows a DEM map of the Eskandari Watershed with the selected meteorological stations.

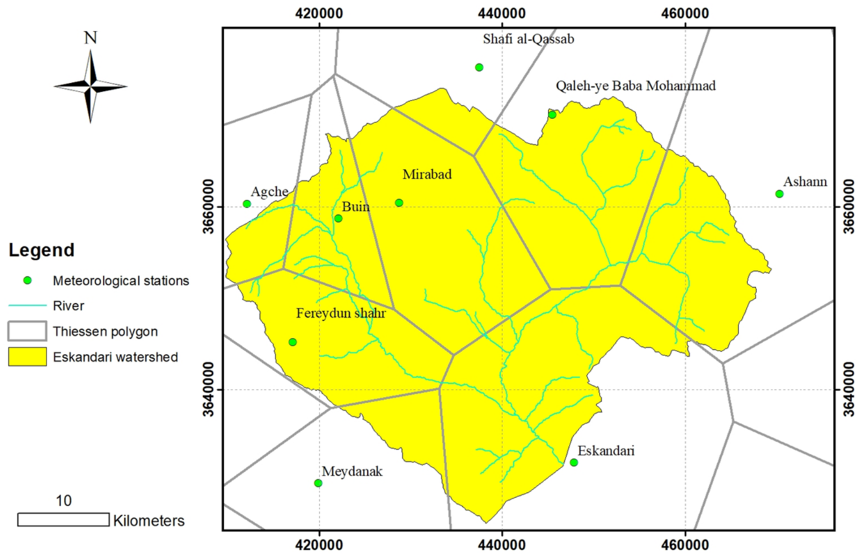


Figure 2: Location of selected meteorological stations by the Thiessen polygons in the study area

To calculate the average precipitation across the watershed, Equation (**??**) was used, which weights the precipitation at each station based on the area it represents.

$\bar{P} = \frac{1}{A}\sum_{i=1}^{n} p_i a_i (8)$

Where $\overline{p}$ represents the average precipitation across the basin, i=1,2,., n, and A is the overall area of the watershed. The area of the i^{th} Thiessen polygon and its corresponding precipitation are represented by a_i and p_i, respectively (Faisal & Gaffar, 2012). Table 1 provides information on the area, location, and average precipitation for each Thiessen polygon from 2004 to 2019. The average precipitation of the studied area using the Thiessen method was equal to 391 mm over the 16 years.

Meteorological stations	Area (km2)	Longitude	Latitude	Average Precipitation (mm)
Eskandari	355.94	50-26-34	32-49-31	369.4
Ashann	202.76	50-40-54	33-05-26	209.2
Agche	45.78	50-03-28	33-04-42	392.3
Buin	126.28	50-09-54	33-03-52	357.5
Shafi al-Qassab	37.64	50-19-46	32-12-49	395.6
Fereydun Shahr	206.08	50-06-48	32-56-30	577.1
Qaleh-ye Baba Mohammad	284.25	50-24-55	33-10-06	461.5
Mirabad	333.04	50-14-10	33-04-48	330.8
Meydanak	57.1	50-08-38	32-48-09	573.6

Table 1: The area, location, and average precipitation from 2004 to 2019 of nine selected meteorological stations

The average annual precipitation in the Eskandari watershed from 2004 to 2019 is presented in Figure 3. Based on the results summarized in Table 3, the MK test suggested an upward trend in precipitation with a slope of 0.334, but the zero value of Z and P statistics indicated that this trend is not statistically significant. This is further supported by the TFPWMK test, with a z-statistic of 0.494 and a p-value of

37.94. Accordingly, the amount of precipitation received in the region has remained relatively stable over the study period.

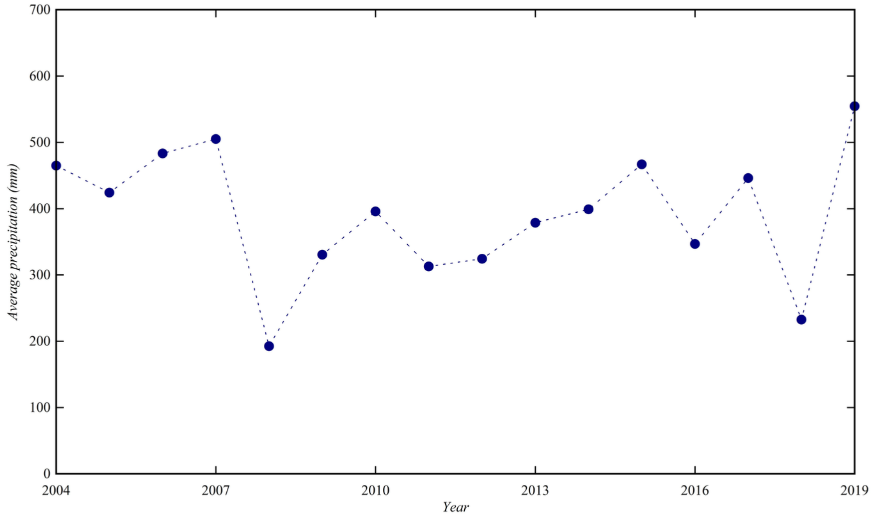


Figure 3: The average annual precipitation in the Eskandari watershed from 2004 to 2019

3.2 Discharge

The annual discharge of the Palasjan River between 2004 and 2019, has been determined and presented in Figure 4 by utilizing the daily data from the Eskandari meteorological station, which serves as the watershed outlet (refer to Figure 1). The results of assessing the presence of a trend in the discharge time series, are plotted in Table 3. The MK test indicated an upward trend in discharge with a slope of 0.078. However, the z-statistic (z=0.49) and p-value (p=37.94) suggested that the trend was not statistically significant. Even after addressing autocorrelation in the prewhitened series the upward trend was still insignificant. The discharge data analysis suggested that the amount of water flowing out of the Eskandari watershed experienced no marked fluctuations over 16 years.

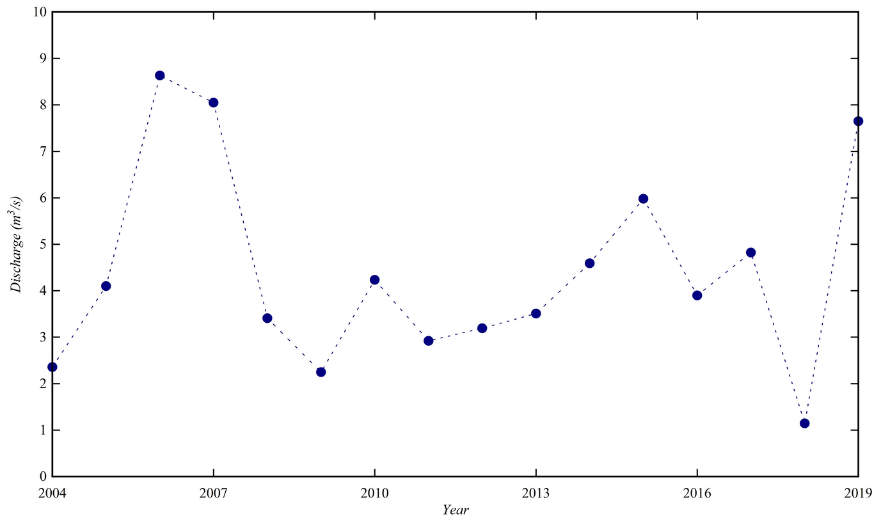
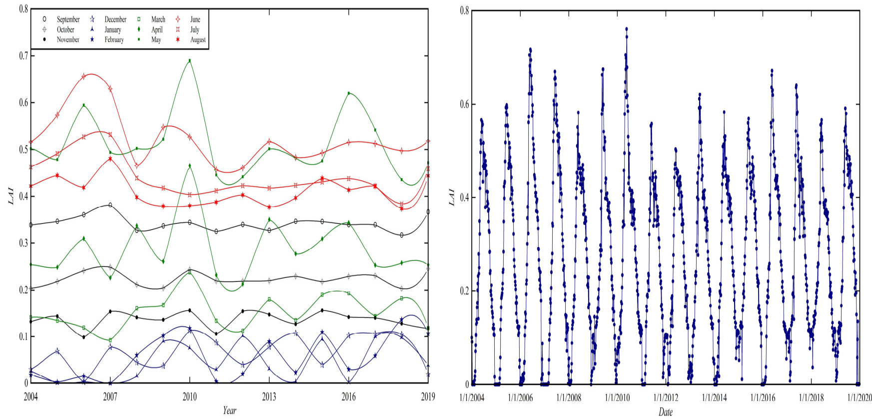


Figure 4: Discharge in the Eskandari Station from 2004 to 2019

3.3 Leaf Area Index (LAI)

In this section, the trend of changes in the cultivated area from 2004 to 2019 was tracked in the region using the remote sensing penology method. This method utilizes satellite imagery to assess land use patterns, and the Leaf area index (LAI), a measure of vegetative cover directly related to the expansion of cultivated area, was considered. LAI is defined by (Watson, 1947) as the total one-sided area of leaf tissue per unit of ground surface area. According to this definition, LAI is a dimensionless quantity characterizing the canopy of an ecosystem. The data used in this section were all derived from the Google Earth Engine (GEE) cloud platform. The platform includes a large number of remote sensing datasets. In this study, the datasets were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) to define LAI. The LAI data was compiled from the best pixels collected by both the MODIS sensors on NASA's Terra and Aqua satellites in the four day period with a 500-meter pixel size ("MODIS/Terra+Aqua Leaf Area Index/FPAR 4-Day L4 Global 500m SIN Grid V061 [Data set]", 2021). Figure 5 shows the monthly and annual LAI index in the study area from 2004 to 2019, respectively.



a. Monthly b. Annually

Figure 5: LAI changes in the Eskandari watershed from 2004 to 2019

The Leaf area index trend analysis results presented in Table 3, showed that the overall vegetation cover and the cultivated area neither expanded nor reduced in the Eskandari watershed over the period. Although there is a slight negative trend, it was not significant statistically; because the statistics of Z with the value of -0.78 and -0.85 and p with the value of 56.75 and 60.74, in the MK and TFPW-MK tests respectively confirmed that the negative trend was not significant. We also used GEE to extract vegetation cover images. The study period was divided into 4-year intervals, and the LAI index on the first day of January in the years 2004, 2009, 2014, and 2019 is shown in Figure 6. The results indicated that, despite some fluctuation, the overall vegetation cover remained stable, and this was consistent with the findings of the trend analysis.

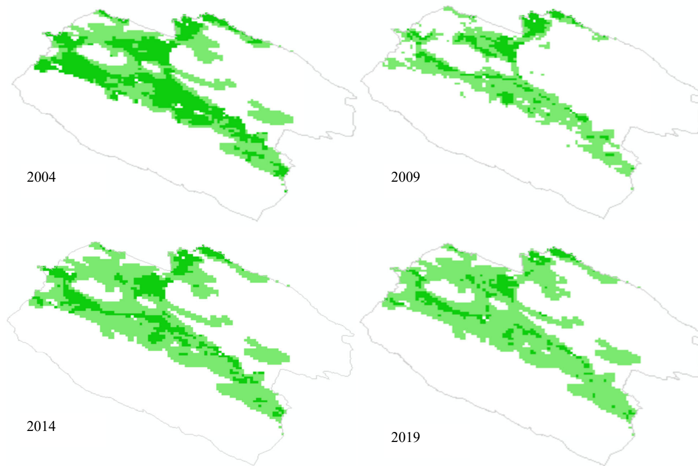


Figure 6: Maps of vegetation indices produced from GEE in 4 years (2004,2009,2014,2019)

3.4 Interbasin water transfer

The annual discharge of the Cheshmeh-Langan inter-basin water transfer tunnel with data collected from the Vahdat Abad meteorological station (Longitude 50-10-21 and latitude 32-55-42), which was constructed, for monitoring tunnel-related data from 2005 (start of operation) to 2019. The collected data are shown in Figure 7.

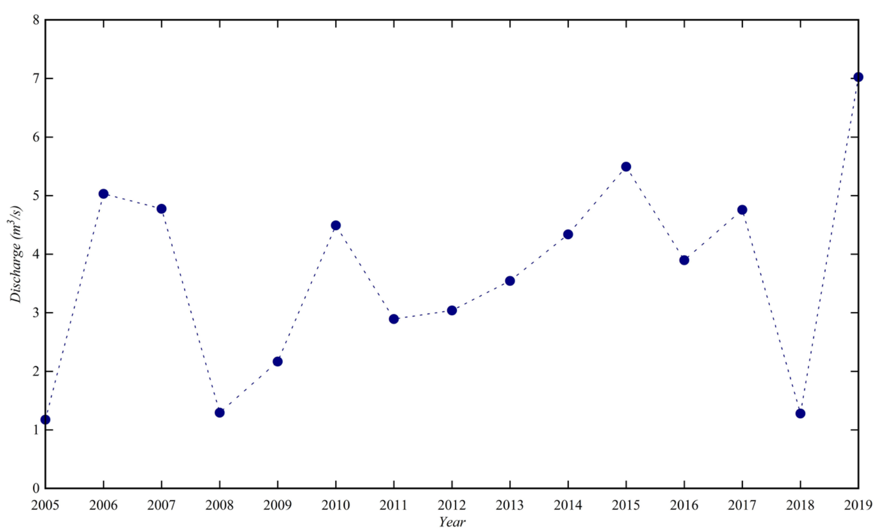


Figure 7: The annual discharge of the Cheshmeh-Langan tunnel from 2005 to 2019

The changes in the time series of annual discharge of the tunnel, using MK and TFPW-MK tests, were presented in Table 3. The result indicated an upward trend in tunnel discharge with a slope of 0.2477. This trend was statistically significant at the 10% level in the (z=1.755, p=92.07) MK test, and the outcomes of the TFPW-MK Test with a z-statistic of 1.38 and a p-value of 83.39 confirmed there is a statistically significant upward trend in the discharge of the inter-basin water transfer tunnel to the Eskandari watershed over the study period.

3.5 Groundwater

In this study, in addition to surface water, we also analyzed the groundwater component because understanding the trends in groundwater is crucial for the effective planning and management of water resource projects. As displayed in Figure 8 there were three aquifers located in the Eskandari watershed: Buin Miandasht, Damaneh-Daran, and Chehel Khaneh.

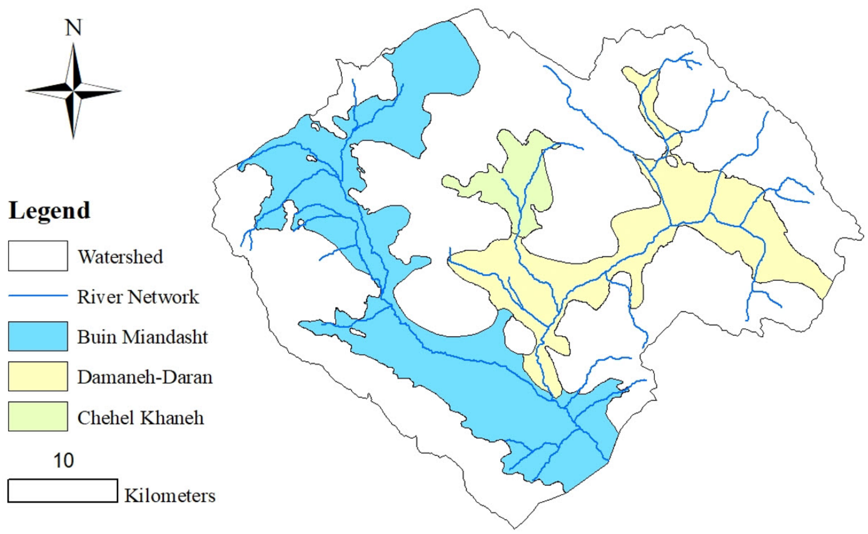


Figure 8: The position of aquifers towards the Eskandari watershed

Table 2 presents data on the areal extent, perimeter, number of piezometers, and average storage coefficient for each confined aquifer.

	Areal extent (km^2)	Perimeter (km)	Number of piezometers	Storage coefficient
Buin Miandasht	478.83	285.67	35	0.01
Damaneh-Daran	220.31	158.27	18	0.05
Chehel Khaneh	45.38	46.54	7	0.01

Table 2: Aquifers specifications

We conducted an evaluation focused on the cumulative average storage volume in aquifers over time (2004-2019), and the results presented in Figure 9. As it was evident that all three aquifers experienced a negative trend in aquifer storage during the reviewed period, the trend analysis results of both the MK and TFPW-MK tests also confirmed this (Table 3). All three aquifers exhibit a statistically significant downward trend in aquifer water volume at the 95% confidence level, suggesting that the overall water storage in these aquifers was decreasing over time. The magnitude of the downward trend in aquifer storage, with a total of around 450 million cubic meters, was most significant in the Damaneh-Daran aquifer, which covers an area of roughly half of Buin Miandasht, suggests that this aquifer experienced the most severe depletion of groundwater resources. Meanwhile, the Buin Miandasht and Chehel Khaneh aquifers had fluctuations in aquifer storage ranging from 8.7 to -30.2 and -0.6 to -2.85 million cubic meters, respectively.

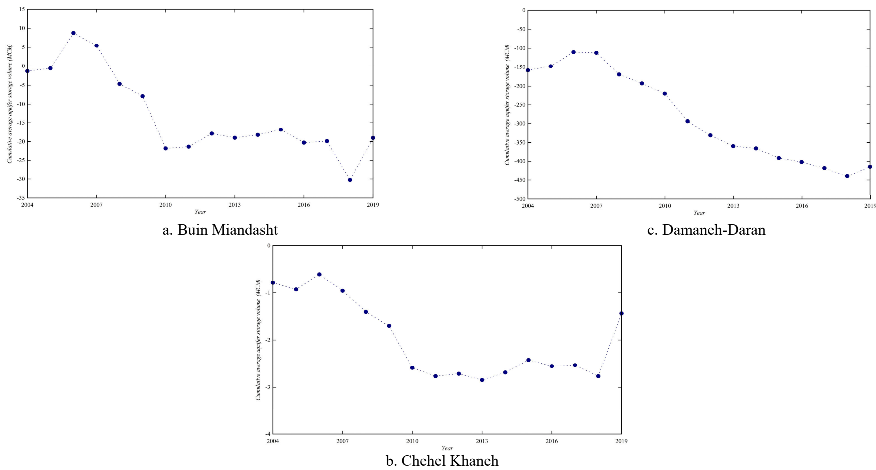


Figure 9: The cumulative average annual aquifer storage volume (MCM) from 2004 to 2019

4 Discussion

Trend analysis results of all the relevant factors in the water resource management of the watershed over time (Figure 10 and Table 3) indicated that precipitation, discharge, and cultivated area have not displayed any significant trends. These factors were trend-free, while the inter-basin water transfer tunnel showed a positive trend and the aquifer storage volume experienced a drastic negative trend. Therefore, there is an imbalance between the inflow and outflow. Otherwise, there was either an upward or downward trend in the discharge of the Eskandari station (watershed outlet). The imbalance suggested a water loss during the period. So, we first determined the extent of water loss in the watershed, and then investigated the plausible factors contributing to this water loss.

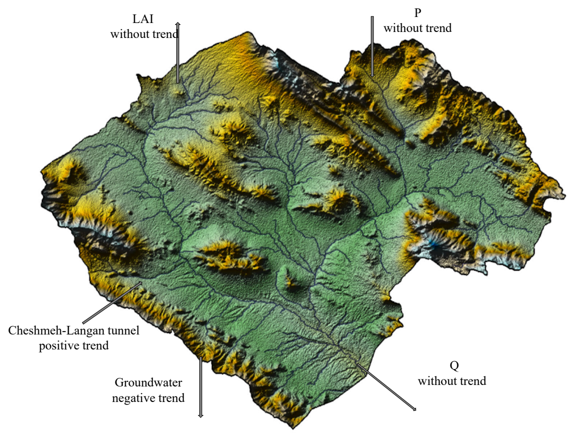


Figure 10: The trend of changes over time

		Slope	Z	P	Z_TFPW	P_TFPW
	precipitation	0.33	0	0	0.49	37.94
	Discharge	0.08	0.49	37.94	0.29	23.2
	LAI	-0.0	-0.78	56.75	-0.85	60.74
	Cheshmeh-Langan tunnel	0.24	1.75	92.07	1.38	83.39
Aquifer	Buin Miandasht	-1.75	-2.83	99.54	-3.06	99.78
	Chehel Khaneh	-0.13	-2.29	97.83	-2.57	99
	Damaneh-Daran	-23.5	-4.72	99.89	-4.94	99.89

Table 3: Slope, Z and P statistics, trend-free pre-whitened Z and P statistics

4.1 Lost water

To determine the extent of water loss in the watershed, we first calculated the exact amount of this loss by analyzing the factors that displayed trend, inter-basin water transfer tunnel, and aquifer storage volume. The annual excess water volume of the Cheshmeh-Langan tunnel was determined by removing the trend from the tunnel's discharge data. The tunnel's discharge and trend-free data and Annual excess water volume (MCM) are shown in Figure 11 and Table 4, respectively.

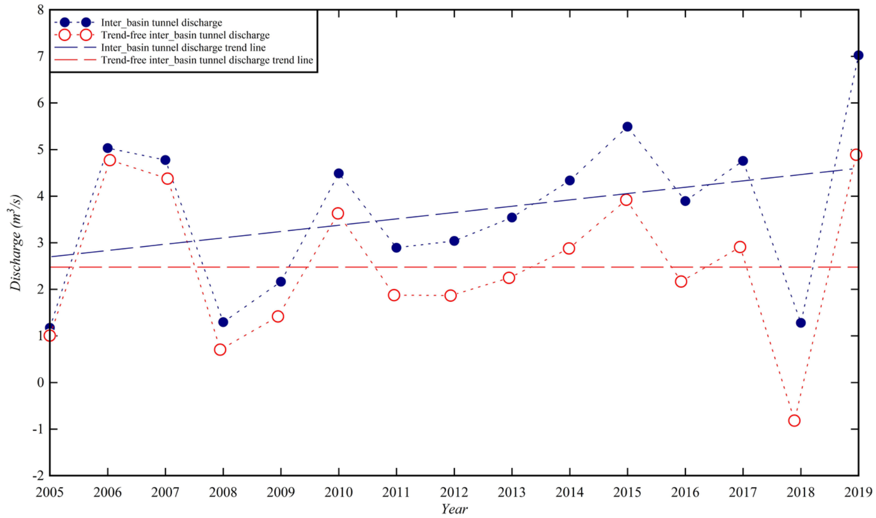


Figure 11: The discharge of the Cheshme Langan tunnel and trend-free data

On the other hand, the extent of the negative trend in aquifer storage volume within the three aquifers upstream of the Eskandari station from 2005 to 2019 was evaluated and demonstrated in Table 4. A total of 430.69 million cubic meters water depleted in the three aquifers in 2019. We then calculated the reduction in aquifer storage for each subsequent year relative to the initial value in 2004 (-160.58), resulting in a cumulative depletion of 270 million cubic meters of water from the underground water table between 2004 and 2019. Surprisingly, this over-extraction from the aquifers, which has placed significant pressure on the groundwater resources occurred despite implementing the Cheshmeh-Langan inter-basin water tunnel in 2005, which was expected to replenish the underground water table in the region. To assess the total water volume drifted out from the watershed, the combined effects of the cumulative depletion of aquifer storage and the excess water volume of the Cheshmeh-Langan tunnel were considered on an annual basis (Table 4). The findings revealed a total decrease of 336.14 million cubic meters over 16 years.

Year	Reduction in aquifer storage volume Damaneh -Daran	Buin Mian-dasht	Chehel Khaneh	Overall reduction	Cumulative depletion	Cheshme Langan tunnel Annual excess water volume	Total de-crease
2004	-158.7	-1.07	-0.79	-160.58	0	0	0
2005	-148	-0.5	-0.93	-149.37	11.21	0	11.21
2006	-110.3	6.97	-0.61	-103.97	56.61	8.8	47.81
2007	-112.1	4.34	-0.96	-108.71	51.88	13.21	38.67
2008	-169.7	-3.69	-1.41	-174.83	-14.25	17.61	-31.86
2009	-192.7	-6.32	-1.71	-200.75	-40.16	22.01	-62.18
2010	-220.6	-17.29	-2.59	-240.43	-79.85	26.41	-106.26
2011	-293.9	-16.93	-2.77	-313.62	-153.03	30.82	-183.85
2012	-331.2	-14.24	-2.72	-348.17	-187.58	35.22	-222.8
2013	-359	-15.11	-2.85	-377	-216.42	39.62	-256.04
2014	-364.9	-14.5	-2.69	-382.06	-221.48	44.02	-265.51
2015	-391.4	-13.4	-2.43	-407.21	-246.62	48.43	-295.05
2016	-401.8	-16.1	-2.56	-420.49	-259.91	52.83	-312.74
2017	-417.7	-15.78	-2.54	-436.03	-275.45	57.23	-332.68
2018	-439.8	-24.03	-2.77	-466.55	-305.97	61.63	-367.6
2019	-414.1	-15.13	-1.44	-430.69	-270.1	66.04	-336.14

Table 4: Overall water volume drifted out from the watershed (MCM)

Three main areas could account for the consumption of this amount of water, namely domestic, industry, and agriculture. Concerning domestic water consumption, according to the Statistical Centre of (SCI, 2019) the total population in 2019 was 144,505 individuals, with 67,042 residing in urban areas and 77,463 residing in rural areas. The per capita consumption of potable water for domestic use in Iran is reported to be around 157 L per day ("Residential end uses of water, version 2 (Executive report). Denver, CO: Water Research Foundation", 2016). Consequently, the consumption of drinking water in 2019 was approximately 8 million cubic meters. Assuming that the population has doubled during this period of 16 years, domestic consumption has only increased by 4 million cubic meters. In addition, the use of absorption wastewater wells in rural areas and treated surface wastewater in urban areas, return a very high percentage of this volume of water to the basin. Therefore, water loss in this sector was a small portion of the overall water volume that has drifted out. Given that the Eskandari watershed is primarily an agricultural area rather than an industrial one, the growth of the industrial sector does not significantly impact water consumption in the region. Consequently, drifted-out water volume water cannot be attributed to population growth and industrial development, leaving the agriculture sector as the sole plausible explanation.

4.2 Agriculture

The agriculture sector was responsible for significant water loss over 16 years. Factors such as poor irrigation systems, evaporation, and overall inadequate water management could be the reasons for this waste of water resources. Table 5 summarizes the lands under different irrigation systems in hectares, including sprinkler, drip, and pressurized, in 2019, in two agricultural areas in the Eskandari watershed (of Iran, 2019). More than 86% of cultivated lands were under sprinkler irrigation, 23100 hectares. For this reason, we investigated the potential decrease in irrigation efficiency in the region, primarily caused by the adoption of sprinkler irrigation. This type of irrigation method increases water loss through evaporation and wind drift (WDEL) (Playán et al., 2005), resulting in the depletion of valuable water resources from the watershed. In many situations, Wind Drift and Evaporation Losses (WDEL, %) can be larger than the other types of water losses, such as runoff and deep percolation (Dylla & Shull, 1983). As a result, we evaluated and estimated wind drift and evaporation losses in sprinkler irrigation and compared them with the calculated volume of lost water (336.14 MCM).

City	Sprinkler	Drip	Pressurized	Total
Fereydan- Damaneh	16000	1000	150	17150
Fereydun Shahr	7100	400	2000	9500
Total	23100	1400	2150	26650

Table 5: Lands under different irrigation methods (ha) in 2019

Due to the lack of precise data regarding the annual expansion of cultivated lands under the sprinkler irrigation, water requirements for cultivated crops, and WDEL in the region, certain assumptions were made:

- Firstly, it assumed that the development of the sprinkle irrigation system began in 1989 with a linear distribution, which was not unrealistic and was consistent with the annual development of this type of irrigation in the region. Based on this assumption, the estimated expansion of the sprinkler irrigation system from 2004 to 2019 was approximately 11,550 hectares, as shown in Figure 12.

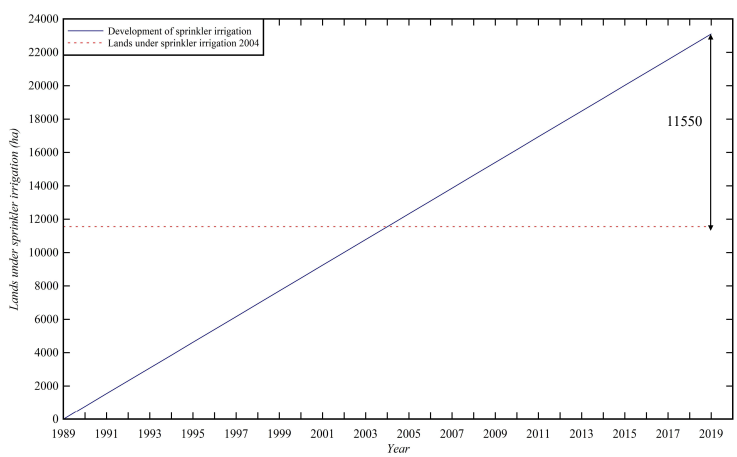


Figure 12: sprinkler irrigation system expansion in the region

- Secondly, cultivated crops in the region include alfalfa, potatoes, onions, and beans, with water requirements ranging from 7,000 to 15,000, 3,500 to 7,000, 3,000 to 5,500, and 2,500 to 5,000 cubic meters per hectare per year, respectively. Therefore, water requirements in this region were assumed to be the equivalent of 6062 cubic meters per hectare on average.
- Lastly, WDEL depends on various factors, such as relative humidity, air temperature, wind speed, pressure head at the nozzle, drop diameter, and riser height (Tarjuelo et al., 2000). On the other hand,

night watering is not common in the region, and most irrigation takes place during daylight hours. Therefore, based on the findings of previous studies (Sarwar et al., 2019; Sheikhesmaeili, 2008), the amount of wind drift and evaporation lost in the study area was considered to be equal to 20%.

Based on the assumptions mentioned above, the sprinkler irrigation systems development in the study area has led to estimated annual wind drift and evaporation losses. According to Table 6, 336.1 million cubic meters of water, in 16 years upstream of the Eskandari station evaporated and left the watershed due to wind drift and evaporation losses. This estimation was consistent with the overall decrease in flow volume within the study area, as indicated by the decrease in aquifer storage and the positive trend observed in the Cheshmeh-Langan tunnel, as shown in Table 4**.**

Year	Cultivated Area (ha)	Annual WDEL **(MCM)**
2004	11550	14
2005	12320	14.94
2006	13090	15.87
2007	13860	16.81
2008	14630	17.74
2009	15400	18.67
2010	16170	19.61
2011	16940	20.54
2012	17710	21.47
2013	18480	22.41
2014	19250	23.34
2015	20020	24.27
2016	20790	25.21
2017	21560	26.14
2018	22330	27.08
2019	23100	28.01
		Total = 336.1

Table 6: Estimated annual wind drift and evaporation losses

5 Conclusions

A comprehensive assessment of all input and output parameters affecting water resources in the watershed revealed an inconsistency between them. The analysis indicated that a total of 336.14 million cubic meters of water was consumed over 16 years, and it was evident that population growth and development in industry did not contribute to this significant consumption. Thereby the only plausible explanation for this high level of water usage was the agriculture sector. After making certain assumptions, we estimated that the development of sprinkler irrigation systems in the study area has caused a significant water withdrawal and wastage of resources in the form of wind drift and evaporation losses upstream of Eskandari station. This estimation was consistent with the total decrease in flow volume based on aquifer storage decrease, up to Eskandari station and the positive trend of the Cheshmeh-Langan tunnel.

The sprinkler irrigation system's excessive development in recent decades has caused a severe strain on the region's water resources. While measures to tackle these issues, such as reducing water consumption, purifying and reusing wastewater, and using any available water, seem straightforward, the most effective solution in this region upstream of the Zayandeh-Rud River lies in gradually replacing the sprinkler irrigation system with greenhouses. The construction of greenhouses effectively eliminates wind drifts and evaporation losses caused by sprinkler irrigation systems, returning lost water to the system. Although this plan may face resistance from farmers in the region, the government should implement a comprehensive strategy to persuade them. This strategy should focus on raising awareness of the importance of water conservation and creating a culture of water-saving practices. Additionally, the government should provide financial incentives such as zero-interest loans, and tax breaks to farmers who install greenhouse irrigation; the government should also create market access for greenhouse-grown produce to help farmers recoup their investment.

Furthermore, the taken measures should also consider reducing the pressure on aquifers. Therefore, we recommend encouraging farmers to utilize surface irrigation. This traditional irrigation method is more sustainable than sprinkler irrigation, as it can help to conserve water and, more importantly, play a crucial role in replenishing aquifers. By collectively adopting these measures, the water scarcity issue in the Eskandari watershed which requires immediate attention can be effectively addressed and ensure sustainable water management for future generations.

Open Research

The primary data related to precipitation, Discharge, and groundwater used in this research, are available in the data archive on the Iran Water Resources Management Company (IWRMC) website (http://www.wrm.ir/). Statistics related to the population and data related to the cultivated area were obtained from Iran Statistical Yearbook 1397 (2018–2019) (https://www.amar.org.ir/english/Iran-Statistical-Yearbook/Statistical-Yearbook-2018-2019). All of these data are freely accessible on a registered personal page.

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