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Assessing climate change effects on declining groundwater levels using wavelet entropy (case study of Khorramabad city)

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ABSTRACT

Changing global climate suggests a warmer future which may alter the hydrological cycle, affecting surface water as well as groundwater resources. The wavelet entropy (WE) criterion is a new indicator for analyzing time series fluctuations. In this study, effective factors decreasing the groundwater level in Khorramabad city during the years 2005–2018 were evaluated by the use of WE criterion. In general, it can be said that the decreasing WE criterion or time series complexity of a phenomenon shows the time series decrease of natural fluctuation, which leads to an unfavorable trend. In this regard, in order to identify the factors affecting groundwater level decrease in Khorramabad, the groundwater level was divided into 4 time periods, and after being investigated, the monthly time series of runoff, temperature, and precipitation of this city were also divided into 4 periods. Each of these subsets were decomposed into several other subsets at different time scales under the wavelet transform, and finally, after calculation of the normalized wavelet energy for this subset, the WE criterion was calculated for each period. Investigation of WE complexity shows a 21.3% decrease in groundwater level in the second period, but in the third and fourth periods, it increased by 145 and 272%, respectively. Also, according to the results of analysis of WE changes for the precipitation time series, 35.2, 32.8, and 10.06% decrease in the second, third, and fourth periods were shown, respectively. The air temperature time series complexity decreased by 26.8% only in the third time period and in the second and fourth period, it shows an increase of 29.65 and 34.7%, respectively. However, the runoff time series did not show any reduction complexity according to the WE criterion. These results indicate that the impact of climatic factors has been more effective than human factors in reducing the groundwater level of Khorramabad.

Key words: air temperature, complexity, groundwater level, Khorramabad, wavelet entropy

HIGHLIGHTS

- Temperature and precipitation parameters are considered as climatic factors.
- Runoff parameters are considered as human factors.
- Used the wavelet entropy criterion to investigate the cause of decrease in groundwater level.

1. INTRODUCTION

Sustainable management and the use of water resources is very important for all human development and without water, sustainable development is not possible. Groundwater resources as one of the most sensitive water resources are directly related to human life and the sustainable development of a community. In recent decades, many changes in groundwater level have occurred due to climate change and human activity. In many parts of Iran, declining groundwater levels have not only limited the exploitation of water resources but also led to land subsidence, environmental disaster, financial losses, and decrease water quality. Anomalies and changes in groundwater resources that are influenced by climatic and human factors can be deduced in various ways, including by the concept of complexity. In this regard, the wavelet entropy (WE) criterion is one of the methods which can be used in this field. The theory of entropy, which was proposed quantitatively and mathematically by Shannon (1948), is defined as a comparison of irregularity and uncertainty in a system. The WE criterion can provide a suitable indicator in predicting future conditions to make better use of water resources using correct water resources management.

Combining the concepts of wavelet and entropy, the new tool called wavelet entropy was developed to calculate complexity. Using this method, it is possible to discern at what time scale the main signal is examined. In this research, the WE method has been used to measure the complexity of hydrological processes. In investigating the complexity of hydrological series, due to the seasonal nature of hydrological processes, using the wavelet method is considered favorable for entropy results. Much research has been done to identify factors that decrease groundwater levels. For example, Salem *et al.* (2018) studied the impacts of climate change on groundwater level and irrigation cost in a groundwater dependent irrigated region. The results showed that the impact of climate change-induced fluctuations in groundwater level on crop production cost is much less compared to other costs, but it may be significant in locations where groundwater level is declining fast. Also, Faramarzi *et al.* (2014) studied the effect of land-use changes on the drop in groundwater level in the Dehloran plain (Iran). the results showed that there is a high correlation between increasing dry and irrigated lands with a decreasing water table. Zhang *et al.* (2019) studied the prediction of groundwater level in seashore reclaimed land using a wavelet and artificial neural network (WA-NARX)-based hybrid model. The results showed that the hybrid model provides better prediction performance, especially for short-term periods. Ghimire *et al.* (2021) in the Bangkok area, Thailand investigated climate and land-use change impacts on spatiotemporal variations in groundwater recharge. The findings showed that groundwater decrease in high and medium urbanization areas, ranging from 5.84 to 20.91 mm/yr for Representative Concentration Pathway (RCP) 4.5 scenario and 4.07 to 18.72 mm/yr for RCP 8.5. Komasi *et al.* (2016) investigated the routing and classification of factors affecting the reduction of groundwater level by using cross and coherence wavelet transformation in the Silakhor plain. The results showed that runoff time series caused by human harvesting had an average wavelet coherence coefficient of 0.83, whilst for precipitation and air temperature time series that are caused by climate change, the average wavelet coherence coefficients were 0.52 and 0.58, respectively, which have more of an impact on reducing the aquifer level of Silakhor plain. In general, results of researches on drought and water scarcity in Iran have been contradictory and have not yet achieved any comprehensive and clear goals. Rising population and rising living standards in many countries have led to increasing demand for groundwater due to various uses such as drinking, agriculture, and industry (Nakhaei *et al.* 2009). Rezvankhah *et al.* (2018) examined the drop in groundwater level in the Birjand plain. The groundwater level of this plain has decreased by 2.6 m during the last 30 years, since around 10% of surface water resources and around 90% of groundwater resources are harvested, therefore the highest amount of water harvested from the groundwater in the study area used in irrigation of agricultural lands. Razzaq *et al.* (2018) used the WE criterion, to identify the effective factors in the fluctuation of groundwater resources in Tasuj plain. The results showed that pumping had more effect on groundwater level drop than changes in air temperature and precipitation. Some researchers believe that the water shortage crisis is due to climate changes (Rabani & Alikhani 2010; Vahidi 2011), and others believe that the uncontrolled regard of humans for water resources and the lack of proper management of these waters has reduced water resources (Faskhodi & Mirzaei 2013; Nourani *et al.* 2015). In recent years, identifying the factors affecting groundwater decrease is one of the most important points that politicians should pay attention to, to preserve this vital resource for the future. Wavelet entropy can be used to rank the factors and the percentage of the impact of different factors on groundwater changes. Shannon (1948) first used the entropy method to measure the content of signal information. After Shannon, other researchers in different fields used the entropy method to analyze signal and time series. (Pincus 1991; Varanis & Pederiva 2015). In this regard, Mishra *et al.* (2009) used the concept of entropy to study the local and temporal changes of rainfall time series in the US state of Texas. Using this criterion, they extracted several characteristics from the rainfall time series, including the number of rainy days. In another study, Komasi *et al.* (2016) used entropy to identify the factors that reduce the groundwater level of Silakhor plain. Their results showed that the 71% reduction in the complexity of river runoff flowing out of this region rather than the changes in precipitation and temperature (with a decrease in complexity respectively of 13 and 10.5%) has affected the reduction of groundwater level complexity, and this indicates the precedence of the impact of human factors on climate change factors in reducing the groundwater level in this plain. Anine & Madan (2017) compared the analytic hierarchy process (AHP), catastrophe and entropy techniques for evaluating groundwater prospects of hard-rock aquifer systems. The validation results revealed that the groundwater potential predicted by the AHP technique had a pronounced accuracy of 87% compared to the catastrophe (46% accuracy) and entropy techniques (51% accuracy). It was concluded that the AHP technique is the most reliable for the assessment of groundwater resources followed by the entropy method. The developed groundwater potential maps can serve as a scientific guideline for the cost-effective siting of wells and the effective planning of groundwater development at a catchment or basin scale. Mohammadrezapour & Kabiri (2016) evaluated the quality of groundwater resources in the Shahrekord plain using entropy theory. The results of this study showed the appropriate efficiency of this method in qualitative evaluation of groundwater resources. Mohd & Abhishek (2020) investigated groundwater quality assessment in the Lower Ganga Basin using entropy information theory and GIS. The results obtained are useful for identifying suitable sites for tube-wells and bore-wells for drinking and agricultural purposes, and also for developing an effective strategy to avoid further contamination of groundwater aquifers in the region. Mirabbasi *et al.* (2020) studied application of entropy theory in assessing the groundwater quality monitoring network of Sefiddasht. The results showed that the optimum station for groundwater quality in this plain is Safarpour well and the Tahmasebi well and Shadikhar Qanat, gaining low rank in the network, have a critical situation and their continuation requires a general revision. Singh & Cui (2015) examined the theoretical potential of relative entropy, configured entropy, and Borg entropy in hydrology and groundwater modeling. They used the groundwater depth characteristic observed from the earth's surface to evaluate the mentioned theories. The hourly time series of groundwater level obtained show considerable daily alternation, which shows the relative entropy of this alternation with the highest resolution. The results also showed that for modeling the groundwater level, the relative and configured entropies covered the observed well and had fewer errors than the Borg entropy. Nygren *et al.* (2020) studied the changes in seasonality of groundwater level fluctuations in a temperate-cold climate transition zone. The results demonstrate that increasing temperatures in cold climate regions may change the seasonality of groundwater recharge by altering the main recharge period from being snowmelt-dominated (spring) to rain-dominated (winter). As the time series of hydrological processes are very complex, using wavelet transform and time series decomposition into several sub-series gives a correct and better understanding of short-term and long-term behaviors of time series (Nourani *et al.* 2012). Zhang *et al.* (2020) modeled a groundwater-dependent vegetation index using entropy theory. The results showed that higher vegetation coverage exist at places of shallow groundwater depth (GWD), also the values of the Normalized Difference Vegetation Index (NDVI) gradually increase with increasing GWD until reaching a maximum at the optimum depth, after which they decrease with increasing GWD when GWD is less than approximately 10 m. Lam *et al.* (2021) investigated the coupled modelling approach to assess effects of climate change on a coastal groundwater system. The results of this study showed that future rainfall was projected to decrease both in wet and dry seasons, and groundwater recharge was projected to decrease significantly in the dry season (10.9%) compared to the wet season (2.6%). Based on this background research, it can be concluded that the entropy theory and wavelet method are efficient indicators in analyzing and evaluating the complexity of time series, especially time series of hydrological data. So far, not much comparison has been made between the effects of climate change on the decrease of groundwater level in Khorramabad city, so in this study, by combining wavelet and entropy theory an attempt has been made to investigated the effects of climate change on the decrease of Khorramabad city groundwater levels in the years 2005–2018.

1.1. Case study

Khorramabad city is located in the west of Iran and is one of the cities of Lorestan province (Figure 1). This study area is located between latitudes 47° 55′ to 48° 50′ east and latitudes 32° 40′ to 34° 20′ north. The study area is 2501 square kilometers and is an average 1903 meters a.s.l. The Khorramabad study area is one of the study areas of the Karkheh watershed. The city has a Mediterranean climate with favorable precipitation, especially in spring. The most important studies conducted in this area are water resources census operations in the study areas of the Lorestan province in 2003 and 2009 and semi-detailed studies of water resources. According to the 2009 census, Khorramabad study area has 611 wells, 7 aqueducts, 230 springs spring, 23 creeks, 115 mobile motor pump and a fixed pumping station which are used to supply water in different sectors (drinking, agriculture, and industry). Also, this plain has rivers such as the Khorram river, Karganeh, Bahramjoo, Navehkesh, and Changaei. Table 1 shows the average statistical characteristics of the study area during 2005–2018. According to the available information from Lorestan province regional water company, the volume of discharge from the groundwater resources is 25.24 million cubic meters per year. Figure 2 shows the average groundwater level and precipitation in the study area. It should be noted that in Table 1 and Figure 2, the groundwater level is the average of the total groundwater in Khorramabad. Figures 3 and 4 show changes in air temperature and runoff.

2. MATERIALS AND METHODS

Complex systems are phenomena that are highly complex due to the relationship between their components as well as communication with other phenomena and show different collective behavior. This means that by studying each component of a complex system, its collective behavior cannot be achieved. Therefore, understanding complexity in such systems requires

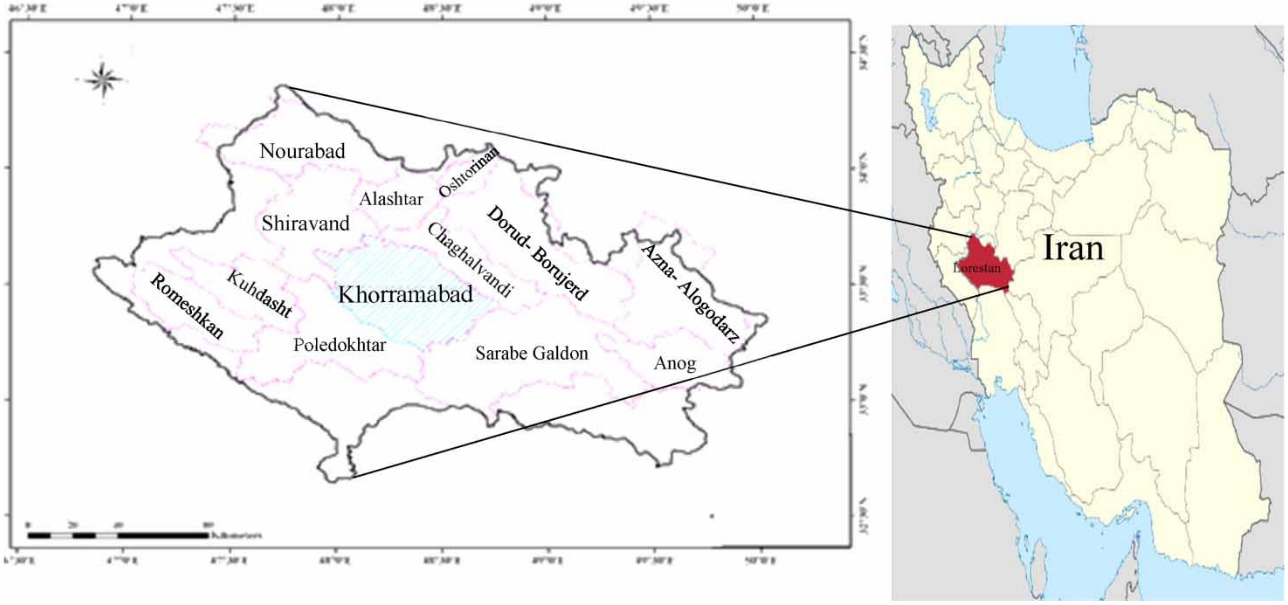

Figure 1 | Study area.

Table 1 | Statistical features of case study (average from 2005 to 2018)

Parameter	Minimum	Maximum	Average	Standard deviation	Skewness
Average groundwater level (meters)	1,223.3	1,226.5	1,224.9	2.5	0.7
Precipitation (mm)	0	117.5	38.1	47.1	1.5
Temperature (degrees Celsius)	1	31.1	17.2	8.1	0.7
Evaporation (mm per month)	0	365	160	142.7	0.3
Runoff (cubic meters per second)	146.5	452.1	238.2	144.7	2.2

understanding the nature of these systems and their structure and components. The tendency when studying complexity is to develop mathematical, computational or simulation tools based on understanding the physical behaviors that govern them to describe and predict such phenomena.

2.1. Entropy criterion

To calculate the entropy criterion, the wavelet energy must first be calculated, or in other words, the signal energy calculated with the symbol E_m from Equation (1):

$$E_m = |W_m(t)|^2 \tag{1}$$

where $W_m(t)$ is a subset of time $M = 1,2, 3,\ldots, m$. if X is a discrete random variable with the values $x_1,x_2,x_3,\ldots,x_n$, and the corresponding probabilities P_1, P_2, $P_3,\ldots,P_n$, the Shannon Entropy is calculated from Equation (2) (Singh 2011).

$$H(x) = H(P) = -\sum_{i=1}^{n} P(xi)\log[P(xi)] \tag{2}$$

In Equation (2), H(x) is the X Entropy, which is also called the Shannon Entropy function. P is the probability distribution and is defined as $P = \{P_i,\ i = 1,2,3,\ldots, N\}$. If the probability of a phenomenon occurring is high, its Entropy rate is low, and vice versa.

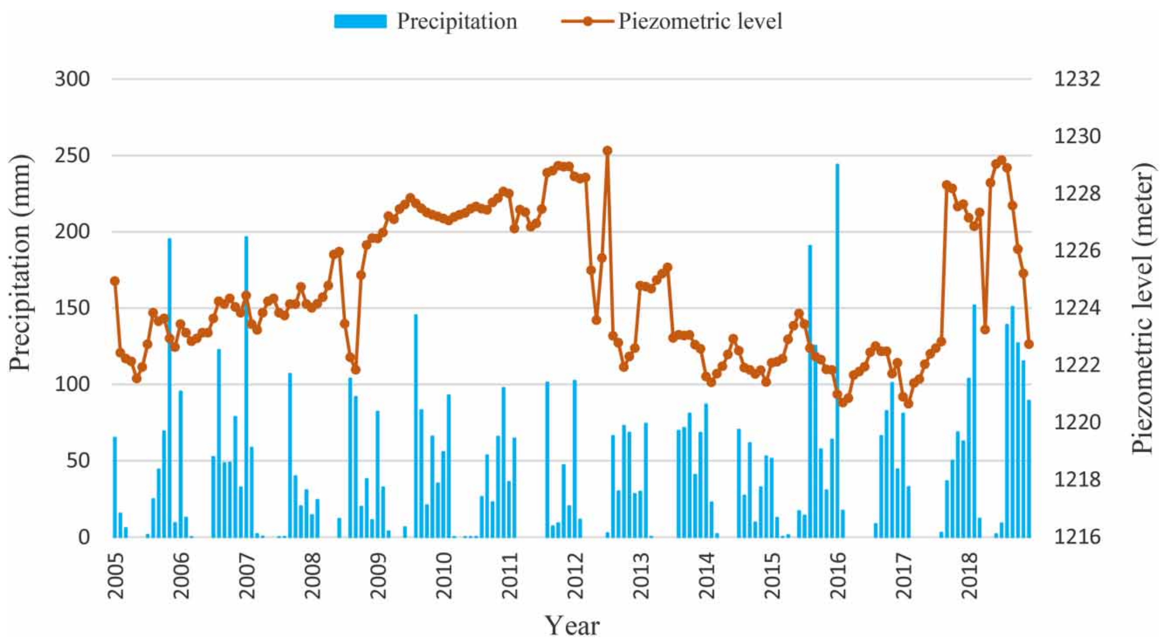

Figure 2 | Comparison of time series of changes in precipitation and groundwater level average in Khorramabad.

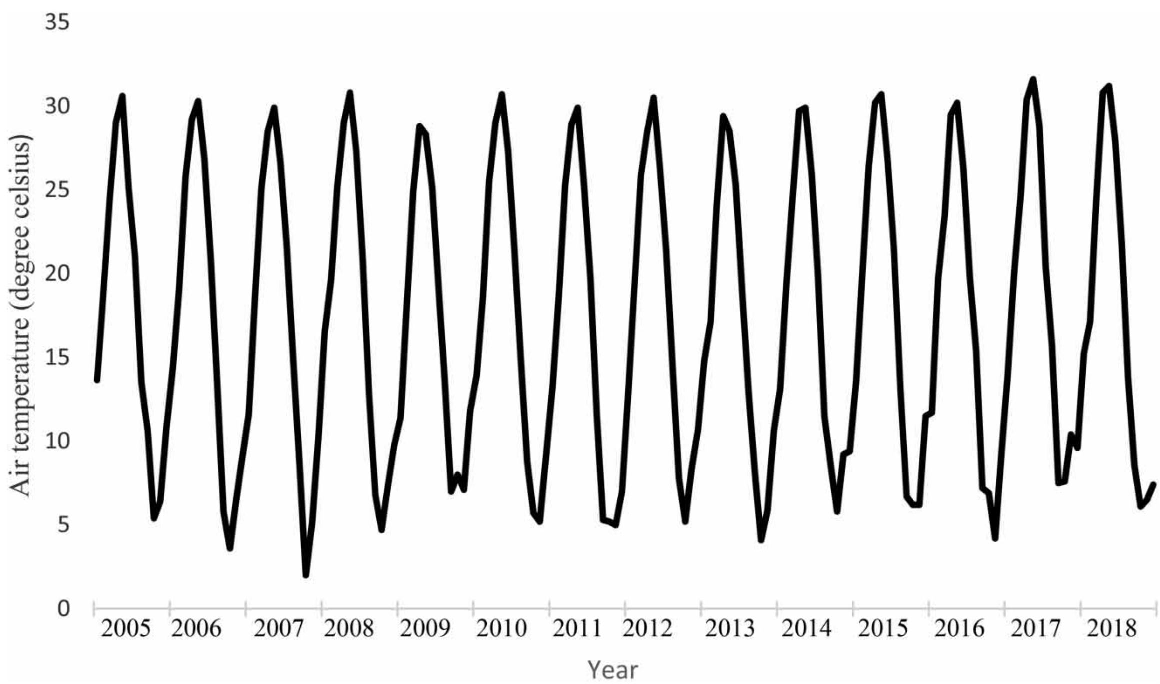

Figure 3 | Air temperature average time series graph for Khorramabad.

2.2. Wavelet theory

Wavelet theory is a mathematical method, the main idea of which was taken from Fourier in the 19th century. The main purpose of cross wavelet analysis is to obtain a complete time-frequency representation of a local and temporary event that varies on time scales. Continuous wavelet transform diagrams are examined to identify periods that offer regions with high wavelet spectra. Cross wavelet diagrams to identify periods that provide areas with high wavelet spectra are examined. Using

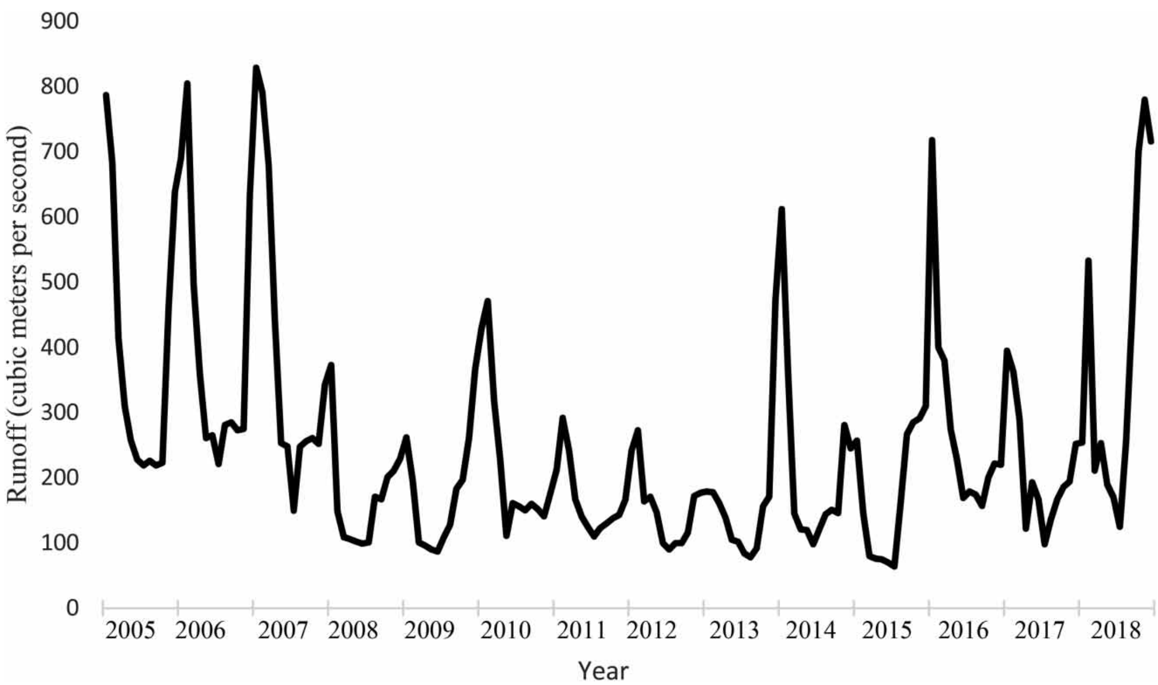

Figure 4 | Runoff averaging time series graph in Khorramabad.

Equation (3) with any desired mother wavelet, such as Morlet's mother wavelet, Equation (4) can estimate the wavelet transform for the time series of each of the hydrological data x(t) (Labat 2010).

$$C^{*x}_{\psi}(a, b) = \int x(t)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{3}$$

$$\psi_0(\eta) = \Pi^{-\frac{1}{4}} e^{i\omega_0\eta} e^{-\eta^2/2} \tag{4}$$

where ψ_0 is a function of the mother wavelet, e is the exponential function and ω is frequency without dimension, and η times are dimensionless, the '*' sign also refers to the complex conjugate of the mother wavelet. The parameter a is expressed as a scale factor if $\alpha > 1$, the time series expands along the time axis, and if $\alpha < 1$ the time series contracts along the time axis. Parameter 'b' is used as a position factor and allows you to study the time series x(t) around time b. The concept of wavelet transform can be used to investigate the relationship between two different time series related to two separate hydrological processes. For this purpose, the wavelet spectrum W_x(a,b) of the time series x(t) is similar to Fourier analysis and is defined by the absolute value of the wavelet coefficient.

$$W_x(a, b) = C^{x}_{\psi}(a, b)C^{*x}_{\psi}(a, b) = |cx(a, b)|^2 \tag{5}$$

This wavelet spectrum can in time also average out, which is then generally defined as the average wavelet power spectrum and allows a scale specification to be given (Torrence 2001). The vacillation alternation period specification is determined using the overall wavelet spectrum. Similar to the Fourier coherence spectrum and wavelet coherence spectrum, W_{xy}(a,b) between two different hydrological time series x(t) and y(t) is defined as follows.

$$W_{xy}(a, b) = C^{x}_{\psi}(a, b)C^{*x}_{\psi}(a, b) \tag{6}$$

in which $C^{x}_{\psi}(a, b)$ and C^{*x}_{ψ}(a, b), representing the continuous-time series wavelet coefficients x(t) and y(t), are multiplied together. The wavelet spectrum averaging technique is used to express the mutual covariance of time series x(t) and y(t) and its distribution at different scales. There are many types of mother wavelet functions, the most important and most widely used of which are shown in Figure 5 (Mallat 1998).

2.3. Wavelet entropy criterion

The wavelet transform function can decompose time series into several time subsets with different scales and by studying the time subsets obtained from the general time series, analyzes the small-scale and large-scale behavior of a hydrological process. By combining the concepts of wavelet and entropy, a new tool called wavelet entropy (WE) is obtained to calculate complexity. Using this method, the time series can be decomposed into several subsets and the wavelet energy of each subset can be calculated, and consequently, the WE criterion can be calculated for each of them. The entropy criterion actually indicates the amount of time series fluctuations and the value of this criterion is directly in relationship to the intensity of the series oscillation. The wavelet energy is calculated in each subset of Equation (7) (Singh 2011).

$$E_m = r_m^2 = \sum_n |c_m|^2 \tag{7}$$

In this relation, m is the main signal separation scale and c_m are the partial coefficients, and n is the number of coefficients on the scale m. The signal total energy (E_{total}) is obtained from Equation (8) (Singh 2011).

$$E_{total} = \sum_m \sum_n |Cm(n)|2 \sum_m .E_m \tag{8}$$

Using Equation (9), the normalized wavelet energy of each subset is calculated:

$$\rho_m = \frac{E_m}{E_{total}} \tag{9}$$

After calculating the normalized energy of each subset, finally, the WE criterion is calculated using Equation (2) as follows:

$$WE = -\sum_m \rho_m \; L_n \, [\rho_m] \tag{10}$$

Figure 6 shows the process of calculating the WE criterion schematically. In this figure, the time series is first decomposed by converting the wavelet into several time subsets and then the normal energy of each subset is calculated. Finally, using Equation (10), the WE criterion is obtained from the normalized energies.

3. RESULTS AND DISCUSSION

3.1. Wavelet entropy criterion

Figure 2 shows the fluctuations of Khorramabad groundwater level in the period 2005–2018. As can be seen from the figure, from the beginning of 2005 to the end of 2018, the groundwater level average has decreased by about three meters, and from 2009 to 2016, the groundwater level has dropped sharply. In this regard, to evaluated changes and

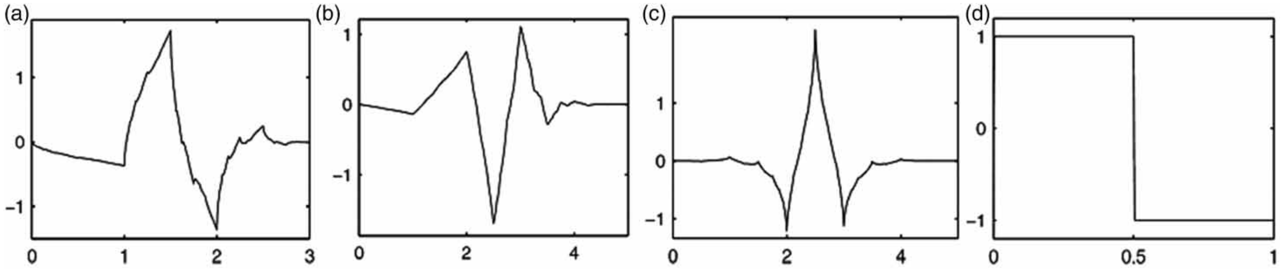

Figure 5 | Diagrams of (a) Wavelet function Sym3, (b) Wavelet function Coif1, (c) Wavelet function Coif1, and (d) Wavelet function Haar.

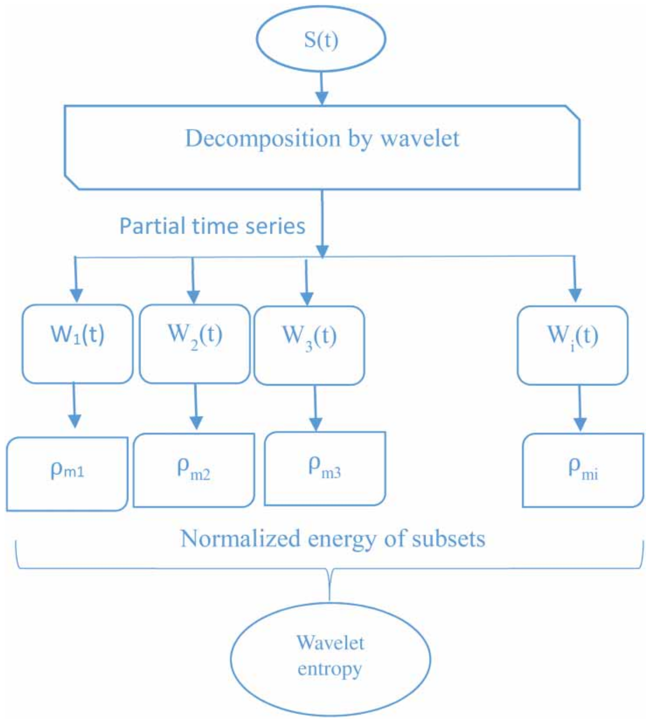

Figure 6 | Schematic structure of wavelet entropy algorithm.

find the effective factors in this reduction, the WE criterion is used. In the first step of this research, wavelet transformation is used for the transformation and decomposition of the time series. In this regard, the 224-month time series of the average groundwater level is divided into four 56-month periods, and then each of these time series is transformed into a db2 wavelet with a decomposition degree of 1–5. It should be noted that after a decomposition degree of 5, the values of normal energy suddenly approach zero and the expression Ln $[P_m]$ becomes zero, and as result, the values of normal energy from decomposition degree 5 onwards will not affect the WE transform from a degree of decomposition of 1–5. The WE criterion is used to analyze the time series of groundwater level and observe irregular changes in the time series trend. In this regard, the normalized energy (ρ_n) is calculated for each of the subsets obtained from the wavelet transform, and finally, the WE criterion is calculated in all four time intervals (Table 2). Figure 7 shows the groundwater level WE changes in four time periods of 56-months.

According to Table 2, the WE criterion for groundwater time series decreased by 21.3% in the second period, but it increased in the third and fourth periods by 145.8 and 272%, respectively. Reducing the WE criterion indicates a reduction in the rate of complexity or, in fact, a reduction in the fluctuation of the second time series. Reduction of fluctuations in hydrological time series, indicate the deterioration of a hydrological feature (Nourani *et al.* 2015). Therefore, the groundwater level of the study area is involved in the deteriorating condition in the second period and the main purpose of this study is to identify the cause of the deterioration among climatic and human factors. Hence, by recognizing the effective factors in the occurrence of this anomaly, it is expected that with the correct, efficient, and timely management measures and methods by the relevant institutions, the progress of the anomaly in the groundwater cycle can be prevented.

3.2. Investigating the effect of climatic and human factors on reducing the average level of groundwater

In recent decades, increasing population, industry, agriculture, and uncontrolled and unprofessional harvesting of groundwater, as well as changes in cultivation patterns that are not compatible with the state of water resources in the region have all caused a great need for water in the study area. As a result, exploitation of groundwater resources by digging multiple wells, and exploitation of surface water has directly and indirectly affected the reduction of the groundwater level. Also, rising air temperatures and consequent climate changes are some of the biggest challenges facing the world and changing climate patterns. Figure 8 shows the location of aquifers and water sources in the study area. According to Figure 8, 611 wells have

Table 2 | Calculation of WE criterion for time series of average groundwater level

56-month subsets				
Normalized energy of subsets	**First period**	**Second period**	**Third period**	**Fourth period**
ρ_1	0.00003166	0.00003308	0.0001881	0.0001012
ρ_2	0.00005792	0.00003808	0.0001163	0.0003665
ρ_3	0.0003600	0.0001160	0.0001867	0.0029
ρ_4	0.00020182	0.00030972	0.0008781	0.0029
ρ_5	0.9993	0.9995	0.9986	0.9937
WE criterion	0.0061	0.0048	0.0118	0.0439
Percentage of changes	***	−21.3%	145.8%	272%

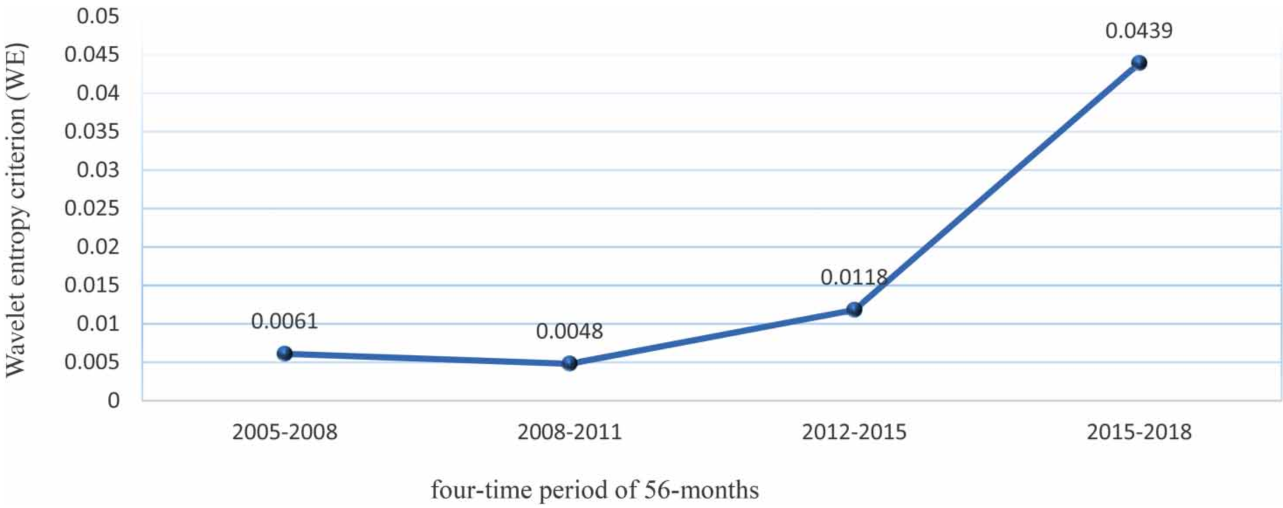

Figure 7 | The WE value for groundwater level in four different periods.

been drilled in the study area. In this study, to investigate the impact of climatic and human factors on reducing the groundwater level, three parameters have been used: precipitation, runoff (runoff refers to the water flow in the study area), and air temperature. Precipitation and air temperature are representative of climatic factors, and the runoff parameter due to increased human harvesting from surface water resources to meet the needs of drinking, agriculture, and industry reducing water flow is considered as a human factor. It should be noted that changes in the runoff parameter cannot be clear and precise criterion for the effect rate of human actions on groundwater resources because the runoff of surface currents is somehow affected by atmospheric and climatic factors, but because there is no accurate criterion to assess the impact of humans, runoff water is considered as a human factor. It can be clearly said that the withdrawal from this groundwater for various uses has played an important role in reducing the level of these waters. On the other hand, land-use changes also affect groundwater level, but due to the lack of accurate information from land-use change in the study area, only the parameters of precipitation, temperature, and runoff have been investigated. These time series are divided into four 56-months periods and then placed under a wavelet function db2 with degree of decomposition 1–5. Then the normalized energy is calculated for each decomposed subset. And at the end, the WE criterion is obtained for each precipitation interval time, air temperature, and runoff (Table 3–5). Figure 9 shows a graph of changes in precipitation, air temperature, and runoff in the four time periods.

The reviews in Table 3 show that the WE criterion rate for the runoff time series in the second, third, and fourth periods increased for 36.1%, 13.4%, and 24.1%, respectively. As a result, there has not been any fluctuation reduction in the runoff time series. Also according to Table 4, the WE criterion rate for the air temperature time series in the second and fourth periods increased for 29.65% and 34.7%, respectively, and decreased by 26.8% in the third period. Table 5 shows the WE changes in four periods for the precipitation time series. As it is known, the fluctuations of this time series have decreased

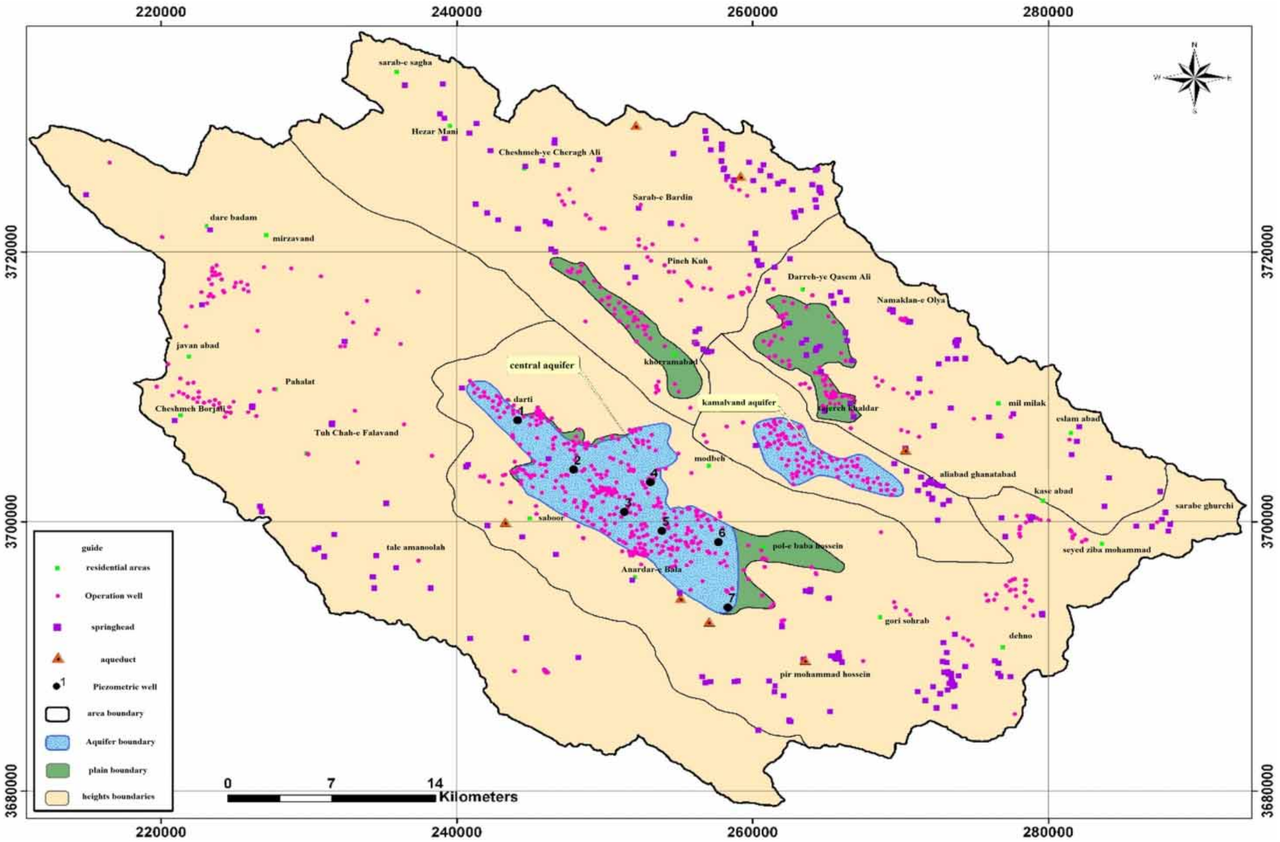

Figure 8 | Location of aquifers and water resources in the study area of Khorramabad.

Table 3 | WE criterion for time series of the runoff

56-month subsets

Normalized energy of subsets	First period	Second period	Third period	Fourth period
ρ_1	0.00051057	0.00086550	0.0028	0.0021
ρ_2	0.00054702	0.0092	0.0035	0.0051
P_3	0.0148	0.0254	0.0208	0.0314
ρ_4	0.0136	0.0063	0.0206	0.0252
ρ_5	0.9705	0.9583	0.9522	0.9363
WE criterion	0.1578	0.2149	0.2438	0.3027
Percentage of changes	***	36.1%	13.4%	24.1%

by 35.2% in the second period, 32.8% in the third period and 10.06% in the fourth period. So it can be concluded that the precipitation time series in the second period has been the greatest decrease in WE criterion compared to runoff time and air temperature series. To better understand the changes in this criterion, a graph of its changes for all three time series is drawn in Figure 9. According to Figure 9 and according to the results obtained from the investigation of the complexity of runoff time series, air temperature, and precipitation and their correspondence with the time period when the groundwater level decreased, it is concluded that in the second time period, the 35.2% reduction in the precipitation parameter has had the greatest impact on a 21% decrease in groundwater level. Also, in the second period, when the groundwater level decreased, only the precipitation parameter decreased according to the WE criterion, and the temperature and runoff parameters show an increase. The time series of air temperature also in the third period has decreased by 26.8% according to the WE criterion,

Table 4 | WE criterion for time series of air temperature

56-month subsets				
Normalized energy of subsets	**First period**	**Second period**	**Third period**	**Fourth period**
ρ_1	0.00032250	0.0005988	0.00027663	0.0006321
ρ_2	0.0023	0.0064	0.0024	0.0062
P_3	0.0302	0.0369	0.0286	0.0354
ρ_4	0.0075	0.0102	0.0066	0.0106
ρ_5	0.9596	0.9460	0.9622	0.9472
WE criterion	0.1986	0.2575	0.1884	0.2539
Percentage of changes	***	29.65%	−26.8%	34.7%

Table 5 | WE criterion for time series of precipitation

56-month subsets				
Normalized energy of subsets	**First period**	**Second period**	**Third period**	**Fourth period**
ρ_1	0.0433	0.0189	0.0094	0.0118
ρ_2	0.0243	0.0341	0.0078	0.0168
ρ_3	0.0738	0.0297	0.0416	0.0153
ρ_4	0.0558	0.0251	0.0105	0.0127
ρ_5	0.8028	0.8921	0.9307	0.9434
WE criterion	0.7559	0.4892	0.3287	0.2956
Percentage of changes	***	−35.2%	−32.8%	−10.06%

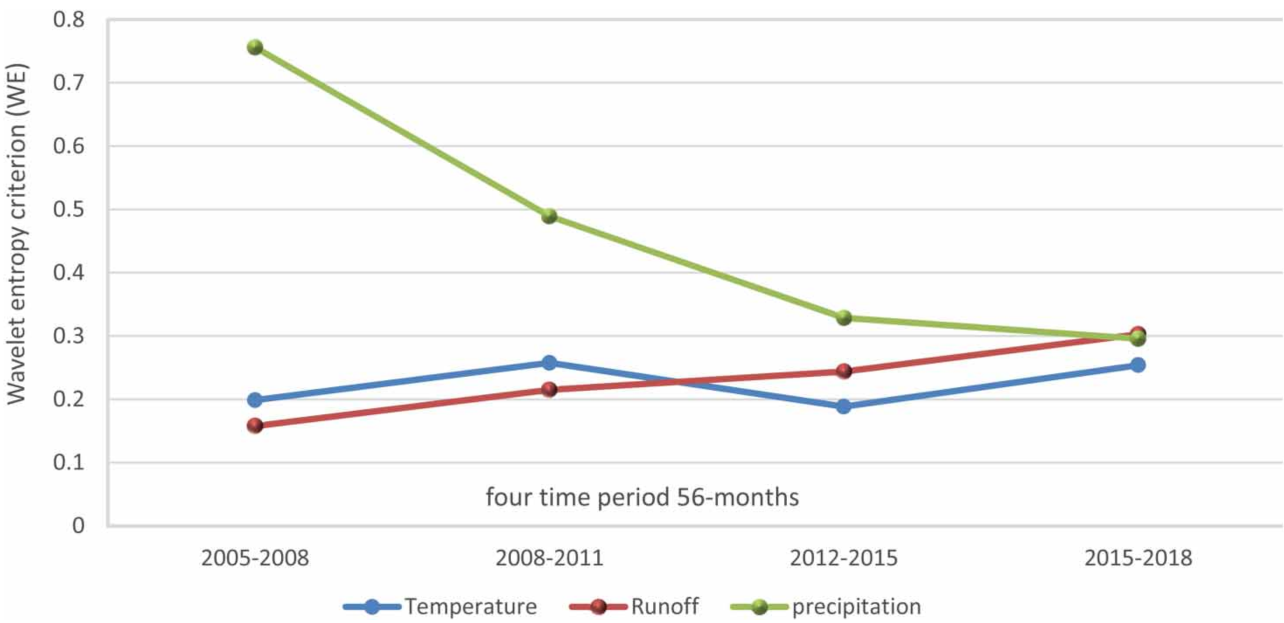

Figure 9 | WE criterion changes for precipitation, runoff, and air temperature in 4 different periods.

but as it can be seen, the time series of groundwater level increased in this period, so we can say that air temperature has no significant effect on groundwater level fluctuations. Also, the runoff time series has not decreased according to the WE criterion, so the role of human factors in reducing the groundwater level of Khorramabad is low. Therefore, because precipitation changes are the most important example of climate change effects in this region, as a result, it can be said that the impact of climate change factors has been greater than the human factor in the occurrence of adverse trends groundwater level in Khorramabad. On the other hand, human intervention in the environment of the region, lack of management in the use of running water resources, misuse and traditional use of groundwater, population increase, land-use change and changes in cultivation pattern also leading to a decrease in groundwater level has been seen in Khorramabad. The impact of climatic factors on the decrease of groundwater level has been investigated by Kaur *et al.* (2021) using MODFLOW, and it has been concluded that precipitation has had the greatest impact on groundwater level fluctuations in Punjab.

4. CONCLUSION

Identifying the most important factor or factors in lowering the groundwater level is very important for future planning. In this research, to analyze the time series of groundwater level in the Khorramabad aquifer, first this series was divided into four time periods, and then the WE criterion was obtained for each period of the groundwater level time series. The results showed that in the second period (between 2008 and 2011) the WE criterion had a decrease of 21.3%. This decrease indicates a decrease rate in groundwater level fluctuations and finally indicates the occurrence of an unfavorable trend in groundwater level changes in the study area. After examining the changes in the WE criterion in the same four time series periods for precipitation, air temperature, and runoff, it was shown that in the second period, the WE complexity criterion for precipitation time series decreased at the rate of 35.2%, and this issue proved the significant effect of changes in precipitation relative to runoff and temperature on the deterioration or in fact the occurrence of an undesirable trend in groundwater level fluctuation in Khorramabad. Therefore, climatic factors have the greatest impact on decrease in the groundwater level of Khorramabad. According to the results that show the effects of climatic factors in decreasing the groundwater level of Khorramabad, it is recommended to prevent the uncontrolled abstraction of groundwater by performing proper management practices and increasing the efficiency of irrigation systems: if the groundwater level decreases in the future with the same trend, it will not be long before other precipitation cannot be effective and the region will face a major crisis. In completing the present study, the proposed method is suggested to be applied to daily and annual data to compare the results with the obtained results from monthly data. Other wavelets such as coherence and cross wavelet and Man-Kendal can be used to analyze data to examine different time series at different time scales.

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COMPLIANCE WITH ETHICAL STANDARDS

On behalf of all authors, the corresponding author states that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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