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Drought analysis in the Lakes of Iran (Case study: Lake Urmia and Gavkhuni Swamp)

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A B S T R A C T

The lakes are vulnerable to the effects of drought. In this study, Lake Urmia and Gavkhuni Swamp were selected to detect the changes in moisture levels and analysis of drought severity using the SPEI index. This article aims to introduce the appropriate spectral indices for detecting the changes in the humidity of lakes and find the role of teleconnection patterns in the drought of the lakes. Based on the results the MNDWI index has better performance to identify humidity anomalies than the NDWI index in the Gavkhuni Swamp. While in Lake Urmia, the NDWI humidity index revealed the humidity anomalies better than MNDWI. The statistical trend analysis of the meteorological drought indicates a significant increasing trend of drought severity in both lakes at the significant level of 1% during the last decades, and the severity of drought in Lake Urmia was more intense than the Gavkhuni Swamp. In contrast, the water equivalent thickness analysis indicated a more intense negative trend in the underground water level of Gavkhuni compare to the Urmia basin which can be because of the significant anthropogenic effects in the basin. To investigate the cause of the dryness in Iranian lakes, the correlation between the selected teleconnection indices and the meteorological drought index was examined. The results indicated that the drought of Lake Urmia located in the northwest of Iran has a significant correlation with teleconnection indices of the AMO and SOI, and this correlation is more robust in the Lake Urmia basin than the central basin.

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1. Introduction

The lakes are valuable resources to control the stability of the natural ecosystems. Climate change and Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2018). The most important consequence of global warming will be an increase in extreme climatic events such as droughts that are usually rare, unpredictable, and short-lived, but have devastating effects on agriculture and natural ecosystems (Marengo et al., 2009). Any change in precipitation and temperature components will affect the rate of evapotranspiration. Global warming will intensify drought conditions in arid regions of the world by increasing the potential for evapotranspiration and increasing desertification (Alizadeh et al., 2010). The teleconnection patterns and oceanic atmospheric interactions play the main role in climate change and affect the balance of water bodies in the basins (Akbari Azirani and Pazhoh, 2022). Gavkhuni Swamp is an international wetland as representative of the dry climate of Iran where is Located in the central basin as a sub-basin and was registered globally in the Ramsar Convention in 1969 (Hajian, 2013).

Researchers have studied significant moisture changes in Gavkhuni Wetland in recent years (Ramesht, 1998; Ataei and Oroojian, 2017). Ataei and Oroojian (2017) studied the effects of climate change on Gavkhuni Wetland using the Kendall method over 10 years from 1995 to 2010, and revealed a notable trend of drought in the basin. The spectral analysis of the humidity index during three time periods (1985-2000, 2000-2013 and 2013-2020) in the Jazmurian basin revealed that both Modification of Normalized Difference Water Index (MNDWI) and Normalized Difference Water Index (NDWI) indices were effective in detecting drought and revealed negative moisture anomalies in the basin. However, the interpretation and analysis of spectral composite indices could not provide detailed information about drought characteristics in this basin (Akbari Azirani, 2022). Lake Urmia is the largest permanent reservoir in West Asia, located in the semi–arid region of northwestern Iran. This lake with an area of between 4500 and 6000 square kilometers is of special importance as the largest inland lake in Iran and the twentieth lake in the world. The lake is currently facing many issues and threats; including intensification of agricultural and irrigation activities, construction of highways on the lake, increase in pollution from agricultural, industrial and urban activities, unsustainable use of lake resources and most importantly, the occurrence of severe droughts during the year. Recent developments are one of the main concerns and threats to this lake (Alinya, 2016). The lakes have been severely affected by heating and droughts, and the water level of lakes has decreased with the increase of the drought process, and if this process continues, the desertification of the areas around Lake Urmia will increase (Roshan and Mohammadnejad Arouq, 2012; Sadeghfam et al., 2022). Due to Lake Urmia’s location in the path of western winds and better conditions for receiving precipitation, the study of moisture anomalies in the Lake Urmia basin area was also investigated and compared in this study. A review of the research history in the study area showed that there is not enough research for analysis of drought in two selected climatic regions, Gavkhuni Wetland and Lake Urmia, using a combined approach of meteorological data and oceanic and satellite indices. This study aims to investigate and analyze drought and moisture anomalies and compare the effects of oceanic atmospheric indices on drought in two selected climatic regions in Iran. The study also examines the efficiency of spectral indices and the use of programming in the GEE[1] platform to detect moisture anomalies in the study area, among other objectives. Additionally, the outlook for the role of teleconnection patterns in the occurrence of moisture anomalies in these two basins and to introduce of the possible strategies for water management related to droughts caused by climate change and man-made are other objectives of this study.

2. Material and Methods

2.1. Study area

In Iran, six major basins provide water to the region. For this study, two lakes were chosen: Urmia Lake from the Urmia basin in northwest Iran and Gavkhuni Swamp as a sub-basin from the Central basin with codes h3 and h4.2, respectively. According to the climatic classification, the Urmia basin is representative of the semi-dry climate while the Central basin, which is the largest basin in Iran, has a dry climate (Figure 1).

2.2. Data

This research is based on a descriptive analysis method by using spectral composite indices to detect the humidity changes in the Gavkhuni Swamp and Lake Urmia. Then the useful approaches for water management are discussed by reviewing the references. The data used in this study include the time series obtained from visible bands, infrared and short wavelengths of Landsat 5 and 8 images with a resolution of 30 meters during the last 35 years (1985-2020) to investigate moisture anomalies in two water basins of Lake Urmia and Gavkhuni Swamp. Moisture anomaly of the two study areas was investigated by calculating spectral indices. The data used included Landsat 5 visible and infrared satellite images from 1985 to the end of 2012, as well as Landsat 8 visible, infrared, and shortwave bands from 2013 to 2020. The spectral band characteristics used in the preparation of multi-temporal maps of the lake

[1] Google Earth Engine

and the analysis of spectral indices are described in Table[2] 1. GRACE satellite is the only satellite that does not use electromagnetic waves for remote sensing and collects data based on changes in the Earth's gravity field. Studies have shown that changes in groundwater levels, such as rising or falling, have an impact on the Earth's gravity field (Ahrarri, 2020). In this study, GRACE satellite data was used to investigate and compare changes in groundwater levels in two selected basins from 2002 to 2017. The GRACE Dataset consists of monthly measurements of equivalent water thickness in centimeters with a spatial resolution of 50 kilometers. These data were recorded by the United States National Aeronautics and Space Administration (NASA) (Tapley et al., 2004). Since one of the objectives of this research is to analyze the time series of changes in groundwater levels, the data used in this study is the single-band lwe_thickness of the GRACE[3] satellite which includes monthly corrected data on groundwater equivalent depth (ee.ImageCollection"NASA/GRACE/MASS_ GRIDS/MASCON_CRI). Meteorological drought indices standard precipitation evapotranspiration index (SPEI) data were extracted on an annual scale from 1980 to 2015 using data from https://global-drought-crops.csic.es for Lake Urmia and Gavkhuni Swamp. Monthly anomalies of atmospheric-oceanic indices from NCAR's website during the period (1980-2015) were used to investigate the effect of teleconnection patterns on the moisture conditions of the basins. These indices included Arctic Oscillation (AO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and El Niño-Southern Oscillation (ENSO), as shown in Table 2.

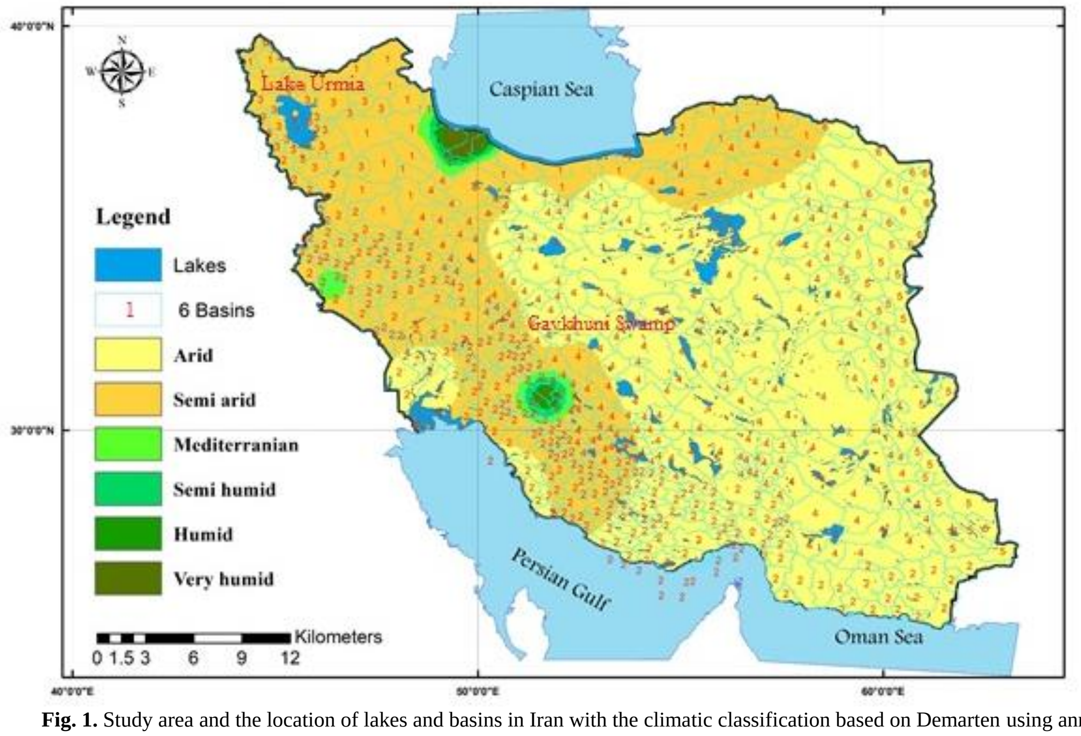

Fig. 1. Study area and the location of lakes and basins in Iran with the climatic classification based on Demarten using annual mean precipitation and temperature data (1980-2018)

2.3. Moisture anomalies analysis

Figure 2 showed the steps of the research. GEE is a web-based system that provides access to the necessary algorithms for processing global satellite raster and vector time-series data (Kumar and Mutanga, 2018). This system is a powerful tool for working with time-series data, compensating for the lack of strong hardware for processing large numbers of images. Additionally, many of the satellite images and data provided by GEE do not require preprocessing or initial corrections but are ready for processing (Ahrarri, 2020).

[2] Gravity Recovery and Climate Experiment

[3] GRACE Monthly Mass Grids - Global Mascon (mass concentration elements) (CRI Filtered)

Table 1. The characteristics of the satellite data used in this study

Satellite/ Sensor	Bands	Longwave (Micrometer)	Database	Spatial Resolution	Time period
Landsat 5 (TM)	2: Green 3: Red 4: Near-infrared 7: Short infrared	0.52-0.60 0.63-0.69 0.77-0.90 2.09-2.35	LT05/C01/T1_SR	30m	1985-2000 2000-2013
Landsat 8 (OLI/TIRS)	3: Green 4: Red 5: Near-infrared 7: Short infrared	0.53-0.59 0.64-0.67 0.85-0.88 2.11-2.39	LC08/C01/T1_SR	30m	2013-2020
Grace	lwe_thickness	-	NASA/GRACE/MASS_GRIDS/MASCON_CRI	50km	2002-2017

Table 2. Teleconnection indices[4]

Teleconnection patterns	Indices abbrevation	Location
Arctic Oscillation	AO	High lattitude of 45°North
Atlantic Multi-decadal Oscillation	AMO	North Atlantic Oscillation
North Atlantic Oscillation	NAO	in Island
Southern Oscillation	SOI	In the Pacific Ocean between the islands of Darwini and Tahiti

Moisture indices NDWI: Since water has the highest reflectance in the green band, the normalized difference of bands 2 and 4 in Landsat 5 images and bands 3 and 5 in Landsat 8 images are used to calculate the normalized difference water index for water areas (Soltanian and Halabian, 2018). Band with letter b is shown based on equation number (1). Studying moisture anomalies in water areas requires calculating spectral indices. For this purpose, the NDWI and MNDWI were calculated in the GEE platform (Fig. 2). (https://code.earthengine.google.com).

$$NDWI = \frac{Green - NIR}{Green + NIR} \rightarrow NDWI_{L5} = \frac{Band2 - Band4}{Band2 + Band4}, \quad NDWI_{L8} = \frac{Band3 - Band5}{Band3 + Band5} \qquad (1)$$

$$MNDVI = \frac{Green - SWIR}{Green + SWIR} \rightarrow MNDVI_{L5} = \frac{Band2 - Band7}{Band2 + Band7}, \quad MNDVI_{L8} = \frac{Band3 - Band7}{Band3 + Band7} \qquad (2)$$

Moisture Indices MNDWI: This index has slightly more sensitivity than the previous index in displaying water areas because it takes into account the values of the shortwave band based on equation 2. In other words, this index can be considered an improved version of the NDWI moisture index. The threshold values for water areas include positive numbers greater than zero in both indices (Soltanian and Halabian, 2018).

2.3. Trend Analysis of SPEI drought index

The drought status in the two water bodies of Gavkhuni and Lake Urmia was identified by examining the standard evaporative-transpiration drought index on a 12-month scale from 1980 to 2015 AD (35 years) in the basin area, and the intensity of drought was measured (Table 3). The trend analysis of drought intensity was performed using the non-parametric Kendall method and Sen's slope estimator. In addition, selected teleconnection indices including NAO, AO, Southern Oscillation Index (SOI) and AMO were evaluated concerning drought intensity in the studied years (1980-2015) using the Pearson correlation statistical method.

Table 3. Drought Severity Scale (Vicente Serrano et al., 2010)

Drought conditions	**SPEI index value**
Extremely wet	(2)-(3)
very wet	(1.5)-(2)
Relatively humid	(1)-(1.5)
Close to normal	(1)-(-1)
Relatively dry	(-1)-(-1.5)
Severe drought	(-1.5)-(-2)
Extremely dry	(-2)-(-3)

[4] Oceanic-atmosphere indices (Teleconnection Patterns)

Statistical Deduction was analyzed through the use of Minitab version 20. Linear regression (model: Linear Fit) was calculated to examine the slope of underground water changes in the 7 last years. Then, a non-parametric statistical Mann-Kendall test was carried out to study the SPEI series trend. The test was first developed by Mann and then by Kendall (Chang and Jung, 2010) which predicts the trend of the series without providing an estimate of the value (Monteiro et al., 2021). To test the null hypothesis without a trend, the Kendall (t) statistic is calculated based on (Equation 3):

$$t = \frac{4\sum H}{N(N-1)} - 1 \quad (3)$$

Where ∑H is the cumulative frequency of the number of ranks placed above each row, and N is the number of years of the statistical period, which in this study is 17 years. The standard statistic (T) is calculated from the following equation. In this formula, tg is the significant level of test reliability (Equation 4).

$$t0 = \pm\, tg\sqrt{\frac{4N+10}{9N(N-1)}} \quad (4)$$

According to the value obtained, the following three modes were established:

If +0/21> t> -0/21, there is no significant trend in time series;

If t <-0/21, there is a significant negative trend in time series;

If t <+0/21, there is a significant positive trend in time series (Huang et al., 2015).

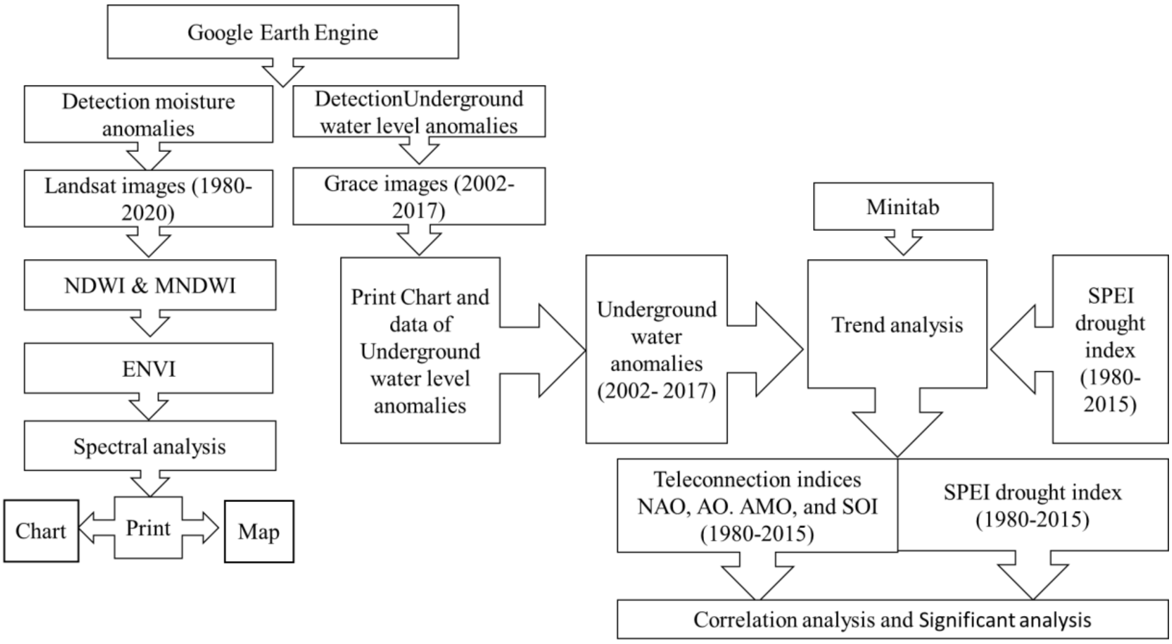

Fig. 2. Research steps in the GEE platform and Minitab

3. Results and discussion

Based on the results of calculating the moisture indices, it was found that each of the two studied indices shows independent information about the changes in the moisture level of Gavkhuni and Lake Urmia. The combination of the two indices was able to reveal the dry periods in the studied region (Figure 3). The multi-temporal map obtained from the combination of NDWI and MNDWI moisture indices is shown in Figure 3. This figure is the result of studying Landsat satellite data and extracted moisture indices, and the following details the findings of each moisture index in the studied periods:

3.1. Detection of moisture anomalies in the study areas in the period of 1985-2000

The NDWI and MNDWI indices usually show water areas with values greater than zero. However, since the threshold value usually leads to exaggeration in the results, a threshold value greater than 0.1 was considered as the final threshold for identifying water areas in the lakes (Ahrarri, 2020). Therefore, the threshold values for this study were set to be greater than 0.1 for detecting water areas. Spectral analysis of this moisture index in the period of 1985-2000 in Gavkhuni Swamp and Lake Urmia (Figures 4 and 5) respectively showed that the water area of Gavkhuni was revealed by the NDWI index in the range of 0.75, while Lake

Urmia was revealed at 0.48. However, the MNDWI index showed moisture anomalies with three peaks at maximum values of 0.74, 0.87, and 0.89 in Gavkhuni Swamp (Figure 4). Therefore, during this period, the NDWI index indicated water coverage on the surface of the wetland, and the combination of two moisture indices indicated the presence of water in the Gavkhuni Swamp. In Lake Urmia, similar to Gavkhuni, moisture anomalies were revealed by the MNDWI index compared to the NDWI index, with one peak at a maximum value of 0.8 (Figure 5).

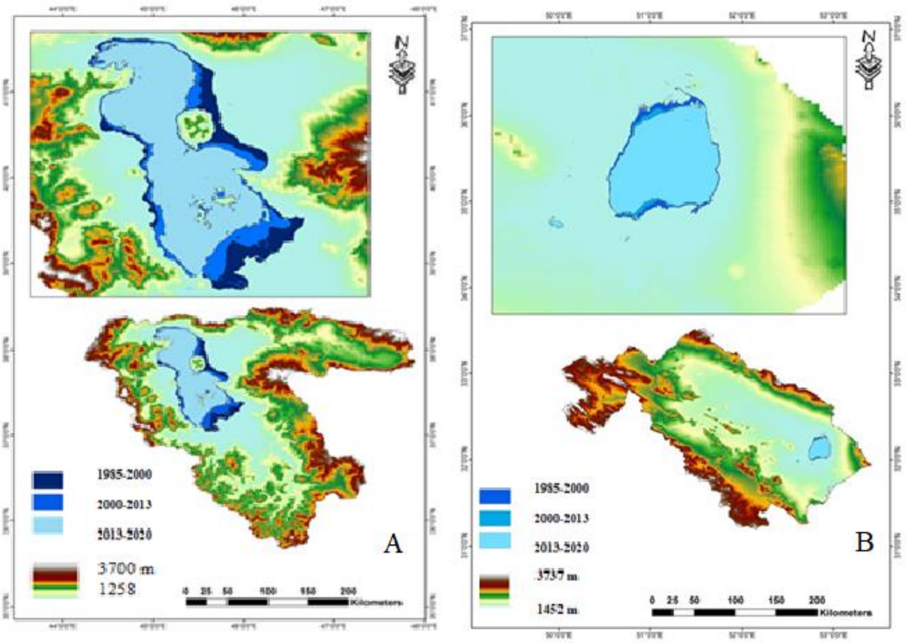

Fig. 3. Topography and combined map of NDWI and MNDWI moisture index in the period of 1985-2020 in A) Lake Urmia, and B) Gavkhuni Swamp.

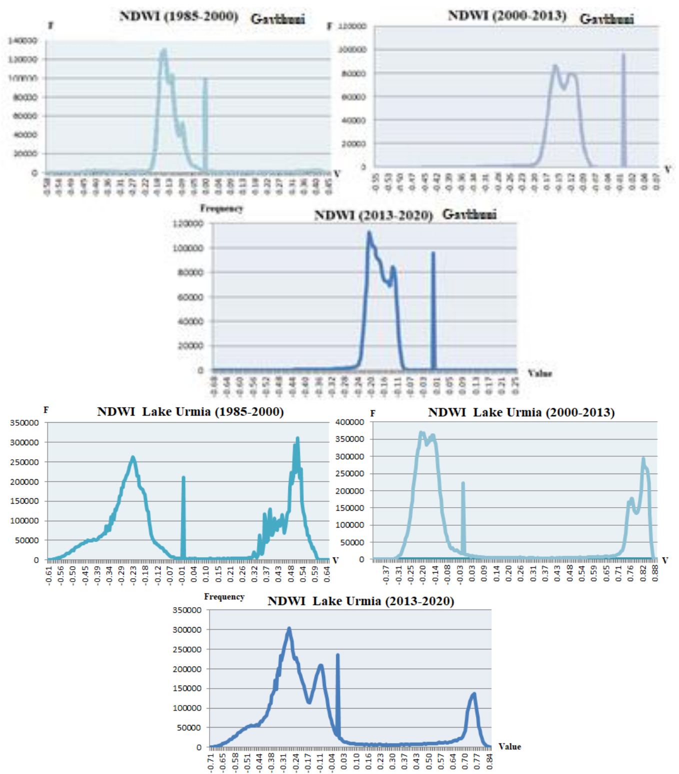

Fig. 4. Descriptive information for NDWI moisture index in Lake Urmia and Gavkhuni Swamp during three time periods

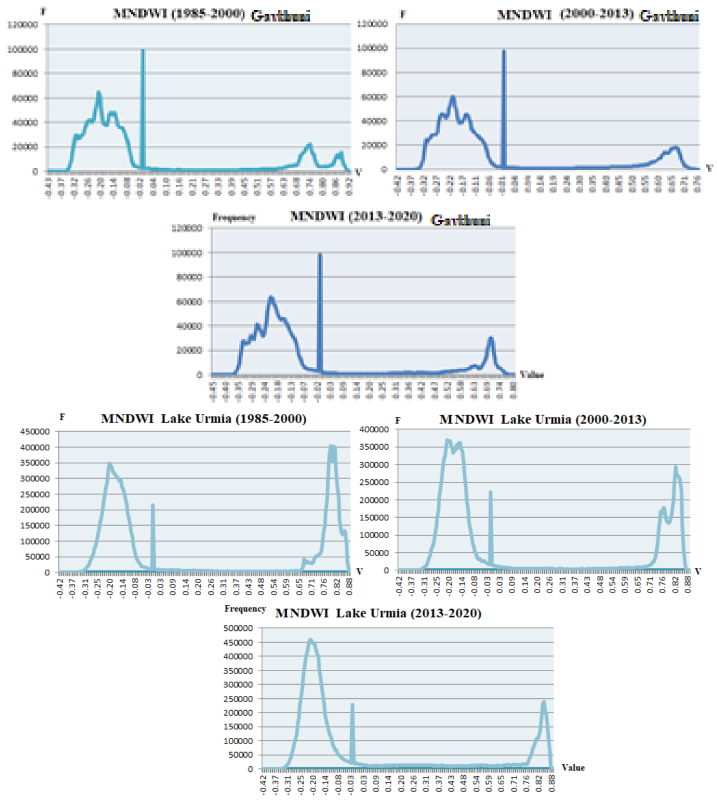

Fig. 5. Descriptive information for MNDWI moisture index in Lake Urmia and Gavkhuni Swamp during three time periods

3.2. Detection of moisture anomalies in the lakes during the period of 2000-2013

The combination of moisture spectral indices to investigate the presence of water in the wetland during this period showed that the NDWI index indicates the absence of water coverage on the surface of the wetland, which is also evident in the spectrum with a uniform line without any specific anomalies. However, during the same period, the MNDWI index with a maximum value of 0.67 in the spectrum indicates the presence of moisture on the surface of the wetland, which is likely to be due to the vegetation present on the surface of the wetland. The presence of two peaks with maximum values of 0.64 and 0.67 during this period in the Gavkhouni wetland may be due to the greater sensitivity of the MNDWI index compared to moisture anomalies compared to the NDWI index. The combined moisture index obtained from both indices as a moisture area during the period of 2000-2013 is shown in a brighter blue color than the period of 1985-2000 (Figure 3).

3.3. Detection of moisture anomalies in the lakes during the period of 2013-2020

The combination of moisture spectral indices to investigate the presence of water in the lake from 2013 to 2020 showed that the NDWI index indicates the absence of water coverage on the surface of the lake, which is also evident in the spectrum with a uniform line without any specific anomalies (Figure 4). However, during the same period, the MNDWI index with a maximum value of 0.70 in the spectrum indicates the presence of moisture on the surface of the wetland, which is likely to be due to the vegetation present on the surface of the lake (Figure 5). The presence of two peaks with maximum values of 0.64 and 0.70 in this graph may be due to the greater sensitivity of the MNDWI index compared to moisture anomalies in the lake surface (Figure 5). The combined moisture index obtained from both indices as a moisture area from 2013 to 2020 is shown in a brighter blue color than from 2000 through 2013 (Figure 3). Therefore, comparing moisture anomalies in the two aquatic areas of Lake Urmia and Gavkhuni wetland using the NDWI index indicates complete dryness of Gavkhuni wetland from 2013 to 2020, while the MNDWI index can better represent moisture anomalies in the two aquatic areas due to its greater sensitivity.

3.4. Comparison of changes in the underground water level of the study area

In the study the two points were selected for analyzing the trend of the monthly corrected data of the equivalent water thickness. The data of underground liquid water have a spatial resolution of 50 km and is accessible from NASA image collection in a period of 15 years (2002- 2017). This study determined the mean trend of the underground water level by programming in GEE and using the data of the Grace satellite in two points of the study area. The graph showed a negative trend at the underground level of both basins at the significant level of 1%. The estimation off R-square equal 53% in the Gavkhuni basin compared to R- square equal 21% in Urmia basin suggested that the intensity of the significant negative trend in Gavkhuni basin is more than in Urmia basin during the last 15 years (Fig. 6). This fact may indicate the effect of significant anthropogenic effects in these environments to make drop in underground water level. Sadeghfam et al. (2022) also suggested that groundwater depletion in Lake Urmia is due to poor management rather than from droughts, and the ecological damage and potential mass migration from the region could be devastating. However, the effects can still be prevented with prompt and effective planning (Jani et al., 2023).

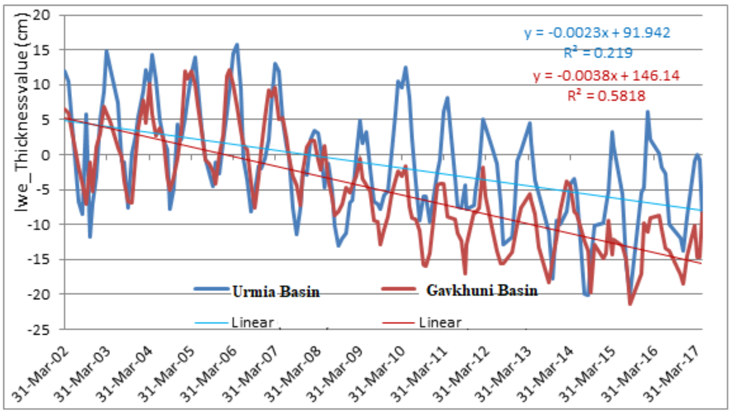

Fig. 6. Comparison of changes in the underground water level in two points of the Gavkhuni and Urmia basins in the period of 2002-2017 using the data of the Grace satellite.

3.5. Analysis of meteorological drought intensity associated with teleconnection indices

The standard evapotranspiration drought index (SPEI) was calculated and analyzed from 1980 to 2021 on a 12-month scale in the two water areas of Gavkhuni Swamp and Lake Urmia (Figures 7 and 8). The extremely drought and severe drought took place in the Lake Urmia and Gavkhuni Swamp in 2008 respectively. Based on the non-parametric method of the Mann-Kendall test and Sen's estimator of slope, the trend of drought index changes was determined in Table 3. The SPEI index in Lake Urmia and Gavkhuni Swamp has a significant downward trend at the significant level of 1% during the last 35 years, so the severity of drought has increased significantly, and the drought intensity in Lake Urmia, located in the northwest of Iran, is greater than that of Gavkhuni Wetland in the central watershed (Table 4).

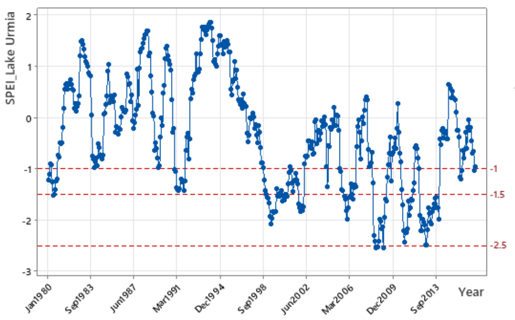

Fig. 7. SPEI drought index of Lake Urmia

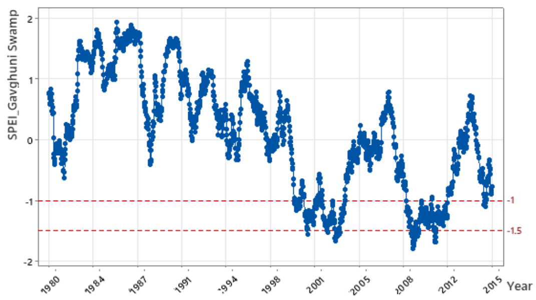

Fig. 8. SPEI drought index of Gavkhuni Swamp

Table 4. The results of trend analysis of SPEI index using Mann-Kendall test and Sen's estimator of slope (1980-2015)

Lake	Trend	Significant level	p-value	z	Sen's Slope
Gavkhuni Swamp	Downward	5%	0.000001	-11.34	-0.00293253
Lake Urmia	Downward	5%	0.00001	-9.52	-0.00383485

Table 5. The results of Correlation analysis between the SPEI index and teleconnection indices (1980-2015) using the Spearman correlation test

Indices abbreviation	Significant level	*The correlation coefficient between SPEI in the Lake Urmia*	*p-value*	The correlation coefficient between SPEI in the Gavkhuni Swamp	*p-value*
AO	5%	0.17	*0.062*	0.08	0.12
AMO	5%	0.23	*0.039*	0.10	0.11
NAO	5%	0.08	*0.075*	0.07	0.18
SOI	5%	0.20	*0.046*	0.18	0.10

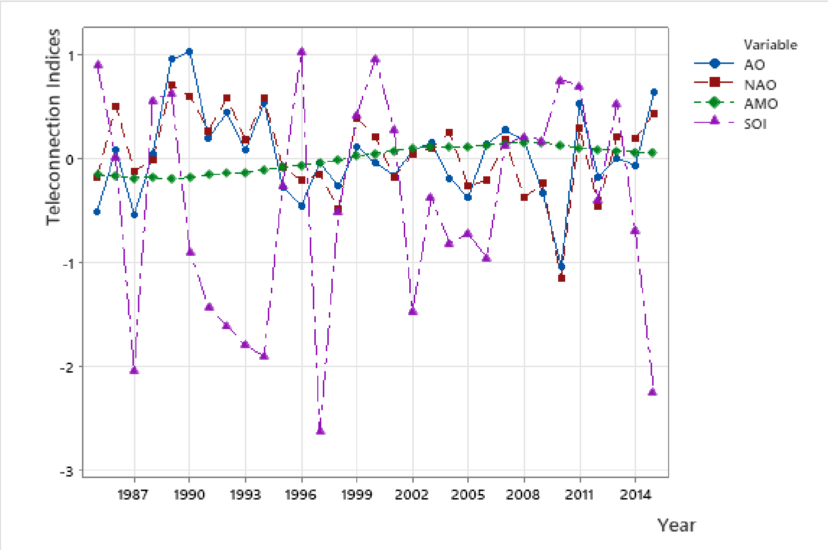

Fig. 9. NAO & AO indices (1985-2015) data source: (https://www.cpc.ncep.noaa.gov/products) AMO, SOI indices data source: (https://climatedataguide.ucar.edu/sites/default/files)

The cause of dry periods in Iranian lakes can be related to oceanic atmospheric indicators. The annual mean of teleconnection indices NAO, AO, SOI, and AMO was illustrated from 1985 to 2015 (Fig. 9). The result of correlation analysis shows a significant correlation between SPEI drought index and AMO equal 0.23 and SOI equal 0.20 in Lake Urmia respectively. Although the correlation results were significant for Lake Urmia drought index, the SPEI does not have a significant correlation in Gavkhuni Swamp (Table 5). AMO index had a strong relationship with SPI drought intensity in the north and west of Iran (Mohammadrezaei et al., 2020). It seems that the location of Lake Urmia in the northwest of Iran and in the path of western atmospheric systems is an important factor in the significant relationship between the ocean-atmospheric indices and the SPEI drought index. Therefore, not only has the SPEI trend in Lake Urmia risen, but also the intensity of SPEI has more increased than the Gavkhuni Swamp located in the central basin of Iran.

3.6. Discussion

In this study, we tried to analyze drought in two representative lakes of arid and semi-arid climates, respectively, Gavkhuni Swamp and Lake Urmia using the Landsat satellite images. Calculation of NDWI index in study area during 1985-2020 and spectral analysis of this moisture index indicates three drought phases in both lakes (Fig. 3). Considering threshold values greater than 0.1 intended for detection of water zones in the lakes using NDWI and MNDWI indices. Therefore, the NDWI index represents water cover at the lakes and the combination of two moisture indices indicates the possibility to detect water in the lakes during 1985-2000. The study show that the NDWI index indicates the absence of water in the lakes, While MNDWI index with a high value of 0.67 indicates the presence of moisture during 2013-2020, which is the evidence of plants in the wetlands (Fig. 4, 5). Also in both lakes, the decrease in the level of underground water was also investigated by programming in

GEE and using GRACE satellite data from 2002 to 2017 (Figure 5). This may be an evidence of anthropogenic effects and seems as a result of destroying the regional water management based on indigenous knowledge (Ghorbani et al., 2021; Akbari Azirani, 2021). The SPEI drought index illustrated the extremely drought and severe drought in 2008 in Lake Urmia and Gavkhuni Swamp respectively. The occurrence of severe drought in Gavkhuni Swamp in 2008 is in agreement with SPI index are calculated by Mirahsani et al. (2016). This study analyzed the SPEI drought time series for trend analysis to find more about the drought intensity by using Mann-Kendall test. The results verified the significant downward trend in SPEI in the both lakes during 1980-2015 which the drought intensity in Lake Urmia is more intensive than Gavkhuni Swamp. Masoodian (2019), pointing out that changes in land use had an effect on the rising the land surface temperature in the two basins of Zayanderood and Urmia during past half-century, so considers the role of human intervention in the environment as the main cause of disrupting the hydrological balance of these two basins. Javan et al. (2021) indicated that the causes of the Lake Urmia crisis include the implementation of large dam construction projects, changing the pattern of irrigation, digging unauthorized wells, improper extraction of water from surface and underground sources, ignoring the environmental principles by policymakers, the construction of a bridge over the lake, and as well as climate change are the causes of the crisis in Lake Urmia. This study show that the ocean-atmospheric indices affect the dry and wet periods of Iranian lakes, although due to the distance between the location of the teleconnection patterns and the lakes of Iran, the simultaneous effect of the ocean-atmospheric indices may not be observed. Based on the results of the multiple regression model, the AMO explained more than 70% of the drought anomaly in the Jazmurian basin, and the drought in the Jazmurian basin was significantly related to the AMO and SOI indices at a 95% significance level (Akbari Azirani, 2022). The water level of Lake Urmia is affected from NAO and SOI indices and the fluctuation has a significant relationship with the climatic indices SOI and NAO (Jalili et al., 2013). Moreover, the weak significant relationship between rainfalls in Urmia and NAO and SOI indices were identified (khorshiddust et al., 2009; Fatehi Maraj and Mahdian, 2008). Although the shrinkage of Lake Urmia is unlikely to be driven by climate change in the time projection of 2011-2030, a decrease in precipitation during near future is serious, and governments need to respond quickly with policy solutions to save Lake Urmia (Jani et al., 2023). In addition, this study suggests that the use of lag time can be considered in the analysis of the relationship between ocean-atmospheric indices and drought to get a better result in the study area’s next studies. This paper presents a study on the vulnerability of Lake Urmia and Gavkhuni Swamp to drought, with a focus on identifying appropriate spectral indices for detecting changes in moisture levels and analyzing drought severity using the SPEI index. While the study provides valuable insights into the impact of drought on these lakes, there are several limitations that need to be considered. Firstly, the study only focuses on two lakes in Iran, which limits the generalizability of the findings. The results may not be applicable to other lakes in the region or around the world, as different lakes may have unique characteristics that affect their vulnerability to drought. Secondly, the study relies on remote sensing data to analyze changes in moisture levels and drought severity. While remote sensing is a useful tool for monitoring large bodies of water, it has limitations in detecting changes at a finer spatial scale. The study does not consider the impact of local factors such as land use change, water management practices, and human activities on the lakes' vulnerability to drought. Thirdly, the study does not provide a comprehensive analysis of the causes of drought in the region. While the study examines the role of teleconnection patterns in occurring the drought in the lakes, it does not consider other factors such as climate change, precipitation patterns, and water management policies that may contribute to drought. Lastly, the study does not provide recommendations for mitigating the impact of drought on these lakes. While understanding the vulnerability of these lakes to drought is essential, it is equally important to develop strategies to reduce their vulnerability and increase their resilience to drought. In conclusion, while this study provides valuable insights into the vulnerability of Lake Urmia and Gavkhuni Swamp to drought, there are several limitations that need to be considered. Further research is needed to address these limitations and provide a more comprehensive understanding of the impact of drought on lakes and other bodies of water in Iran.

4. Conclusion

This research determined the performance of GEE in estimating the drought conditions of the representative lakes of Iran. The use of composite indices NDWI, MNDWI, SPEI, and estimation of the underground water level changes using updated time series of satellite data is another advantage of this research. The result revealed that the MNDWI index is a more appropriate tool than the NDWI index for detecting the humidity anomalies in the time series of Landsat image data. This result can be used as a model for other lakes in Iran. Also, the successful detection of humidity anomaly by using a composite index implies the idea of combining a larger number of indices to detect the humidity and drought conditions in the lakes of Iran. Although this study suggested a more intensify negative trend in the underground water level of Gavkhuni compare to the Urmia basin, the SPEI drought intensity in Lake Urmia is much more severe than in Gavkhuni Swamp effects can play a much more important role than climatic factors in disrupting the hydrological balance of the Lake Urmia and Gavkhuni Swamp. Finally, to mitigate the drought crisis and anthropogenic effect on the lakes of Iran, people should refer to historically-dependent community roles that establish the local contract for distributing water with social responsibility. In addition, Lake Urmia is currently facing numerous threats that are endangering its existence. The occurrence of severe droughts, intensification of agricultural and irrigation activities, construction of highways on the lake, increase in pollution from agricultural, industrial, and urban activities and unsustainable use of lake resources are some of the challenges that need to be addressed (Javan et al., 2021; Jani et al., 2023; Azizadeh and Javan, 2018). It is essential to conduct more research and analysis of drought in the region using a combined approach of meteorological data and oceanic and satellite indices. Effective water management strategies need to be implemented to prevent further damage to Lake Urmia and other bodies of water facing similar threats. The study of moisture anomalies in the Lake Urmia basin area and the comparison of the effects of oceanic atmospheric indices on drought in two selected climatic regions in Iran are vital steps toward addressing these challenges. It is crucial to take action to protect our natural resources and ensure their sustainability for future generations. It was also observed that the level of underground water in both lakes has decreased, which suggests hydrologic drought may be due to anthropogenic effects and a lack of regional water management based on indigenous knowledge (Ghorbani et al., 2021). The SPEI drought index illustrated extremely and severely dry periods in 2008 in Lake Urmia and Gavkhuni Swamp and is in agreement with Mirahsani et al. 2016. The study also analyzed the SPEI drought time series for trend analysis and found a significant downward trend in both lakes during 1985-2015, with Lake Urmia experiencing more intensive droughts than Gavkhuni Swamp. The study suggests that the ocean-atmospheric indices affect dry and wet periods of Iranian lakes and a multiple regression model showed that the AMO explained the significance of the drought anomaly in the Iranian basins. The AMO is a climate mode occurring on multidecadal time scales in the North Atlantic. It is a measure of sea surface temperature variation in the North Atlantic, adjusted to remove trends in anthropogenically forced warming (Enfield et al., 2001; McCabe et al., 2004). The water level of Lake Urmia is affected by NAO and SOI indices, and there is a weak significant relationship between rainfalls in Urmia and NAO and SOI indices. Finally, the study suggests using lag time in analyzing the relationship between ocean-atmospheric indices and drought for better results in future studies. This study has demonstrated that ocean-atmospheric indices have a significant impact on the dry and wet periods of Iranian lakes. Although the distance between the location of the teleconnection patterns and the lakes of Iran may not allow for the simultaneous effect of the ocean-atmospheric indices to be observed, the AMO was found to explain more than 70% of the drought anomaly in the Jazmurian basin. Furthermore, the water level of Lake Urmia was found to be affected by NAO and SOI indices, and the fluctuation had a significant relationship with the climatic indices SOI and NAO. While it may be unlikely that climate change is driving the shrinkage of Lake Urmia in the time projection of 2011-2030, the decrease in precipitation during the near future is a serious concern. Governments need to respond quickly with policy solutions to save Lake Urmia. This research highlights the importance of lakes in maintaining natural ecosystems and the potential impact of global warming on the lakes. It states that climate change and human activities have caused a significant increase in global warming, which is likely to cause more extreme climatic events such as droughts. The changes in precipitation and temperature components will affect the rate of evapotranspiration and intensify drought conditions in arid regions. This study also mentions that teleconnection patterns and oceanic atmospheric interactions play a significant role in climate change and affect the balance of water bodies in the basins of Iran. This study also suggests that the use of lag time can be considered in analyzing the relationship between ocean-atmospheric indices and drought to obtain better results in the study area for future studies.

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