Acta Geodyn. Geomater., Vol. 22, No. 1 (217), 1–15, 2025
DOI: 10.13168/AGG.2025.0001

journal homepage: https://www.irsm.cas.cz/acta

ORIGINAL PAPER

TEMPORAL HYDROLOGICAL DROUGHT ANALYSIS IN LAKE IZNIK USING IN-SITU MEASUREMENTS AND SPACE-BASED DATA

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ARTICLE INFO

Article history:
Received 29 October 2024
Accepted 13 December 2024
Available online 18 December 2024

Keywords:
Hydrological Drought
İznik
Lake water level
SPEI/SPI
Hydro-Geodesy

ABSTRACT

The presented study aims to monitor a potential hydrological drought in Lake İznik, one of the largest freshwater lakes in Türkiye, located in the NW region of the country. In this context, in-situ and satellite altimetry-based water level data, meteorological data such as temperature and precipitation, and high-resolution multispectral satellite images from 2015 to 2024 have been utilized. A linear model was fitted to the water level data acquired from Turkish Directorate General for State Hydraulic Works and the altimetry-based data from HydroWeb data archive, which estimated a decreasing trend of -22.9±0.6 cm and -22.6±0.6 cm in lake water levels, respectively. The Mann-Kendall/Sen's slope trend analysis was performed on the series of temperature and precipitation data obtained from Turkish General Directorate of Meteorology, showing that there is a 0.049 °C increase in temperature and an annual -0.80 mm decrease in precipitation. According to the calculated temperature and precipitation values, which are increasingly high and low respectively, the hydrological drought indicators SPI and SPEI were determined to be showing an increasingly severe hydrological drought in this region. It then analyzed Sentinel-2 satellite imagery between 2015 and 2024 to determine the water surface area of the lakes with NDWI. According to Sentinel-2 images, the lake water surface area in 2023 went down by 2.7 km² compared with that in 2015. These findings bring forth crucial implications for regional water resource management and ecosystem sustainability, placing significant emphasis on proactive measures that should be considered in order to mitigate the long-term impacts of hydrological drought in Lake İznik and its surroundings.

INTRODUCTION

A critical part of managing water resources is observing hydrological drought and fully comprehending the shift from meteorological drought to hydrological drought, including the process and conditions involved. Meteorological drought acts because the precursor to hydrological drought, underscoring the importance of investigating the mechanisms that drive this transition (Zhou et al., 2021). Through the utilization of streamflow observations and drought indices including the Standardized Streamflow Index, it's far viable to quantify the spatio-temporal traits of hydrological drought events, thereby facilitating actual-time monitoring and evaluation (Rivera et al., 2021). Furthermore, the combination of remotely sensing data, like reservoir surface area, presents a global or regional framework for tracking hydrological droughts over long terms (Lai et al., 2019; Zhao and Gao, 2019).

The selection of suitable drought indices, including the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) and the Standardized Streamflow Index, is key factor in tracking hydrological drought events. These indices, coupled with models that integrate water and energy balances, establish a foundation for characterizing and predicting drought at finer scales, thereby enhancing tracking abilities (Ma et al., 2015). Additionally, the correlation between meteorological drought indices like SPI and hydrological drought indices just like the Standardized Streamflow Index aids in figuring out the reaction time of streamflow droughts to meteorological situations, contributing to the development of effective tracking techniques (Lorenzo-Lacruz et al., 2013).

In regions in which hydrological information availability is restrained, multivariate drought indicators that embody meteorological, agricultural, and hydrological data can offer a comprehensive knowledge of drought situations (Wei et al., 2010; Forootan et al, 2019; Zheng et al., 2021; Fisher et al., 2021). Moreover, the application of probabilistic procedures for hydrological drought forecasting offers precious insights for early caution systems and mitigation strategies (Araghinejad, 2010; Ogutu-Ohwayo et. al., 2016). Understanding the progression of drought from meteorological to hydrological levels is paramount, and the components of comprehensive drought indices based on diverse variables can decorate the tracking and evaluation of hydrological drought occasions (Zheng et al., 2021).

Cite this article as: Erkoç MH, Doğan U, Keser B, Bayram B: Temporal hydrological drought analysis in Lake İznik using in-situ measurements and space based data. Acta Geodyn. Geomater., 22, No. 1 (217), 1–15, 2025. DOI: 10.13168/AGG.2025.0001

A decrease in lake water levels may be caused by drought and greatly impact the ecological health of the lake according to Fergus et al. (2022). This study quantified the response of lake level to meteorological drought, providing insights for water resource management, as highlighted by Wang et al. (2018) and Zou et al. (2024). For instance, Frondini et al. (2019) observed a significant decrease in lake level during a drought period. The water level in Lake Urmia decreased due to drought, climate change, and water resource overuse (Dehghanipour et al., 2020). Meteorological drought exacerbated the water level decrease in Lake Urmia (AghaKouchak et al., 2015; Alizadeh et al., 2016). The water flow of the Jordan River and the level of Lake Kinneret were impacted by drought (Inbar and Bruins, 2004). Reduced freshwater inflows caused water level recession in lakes (Wedderburn et al., 2012). Major droughts and water abstraction contributed to decreased water levels in Lake Chad (Hussaini et al., 2019). Drought impacts on water levels in Lake Ontario and the St. Lawrence River were analyzed (Biron et al., 2014). Attitudes toward water conservation were evaluated at a drought-impacted lake (Brownlee et al., 2014).

While previous studies have focused on meteorological drought indices, limited research has integrated high-resolution satellite imagery to assess hydrological drought. In this study, in-situ (water gauge and meteorological stations) and space-based data (satellite altimetry and multispectral high-resolution satellite imagery) are analyzed with a wide range of methods (linear model and Mann-Kendal/Sen's slope, SPEI12/SPI12, NDWI) to comprehensively address the hydrological drought conditions in Lake Iznik. Thus, it will be concluded how the lake is affected by hydrological drought temporaly. The four main stages of the study are as follows:

(I) Estimation of lake water level trends using Water Gauge and Satellite Altimetry data

(II) Trend analysis of meteorological data such as temperature and precipitation using Mann-Kendall/Sen's Slope and calculation of SPI12/SPEI12 hydrological drought indices

(III) Determination of changes in lake surface area using Sentinel-2.

(IV) Examination of all findings together and interpretation of the effects of hydrological drought in the lake.

Through these stages, the study aims to provide a hydrological examination of all drought parameters related to Lake İznik, which is expected to form a basis for the management and planning of water resources in the region. The novelty of the study is expressed by the fact that there has been no previous study in the region using this approach and that the lake is highly sensitive to drought.

DATA AND PROCESSING

STUDY AREA

Lake İznik is a vital freshwater resource for agriculture, industry, and tourism in the region, making its hydrological health crucial for local sustainability. The lake also is one of the largest freshwater lakes in Türkiye, located in the Northwestern region, with an area of approximately 300 square kilometers. The elevation of lakes is approximately 85 meters above sea level and maximum depth of 80 meters. The environment of the lake is predominantly protected through agricultural lands, small settlements, and forests, with several commercial facilities located nearby (Fig. 1). The lake is of local importance because it serves as a source for tourism, agricultural and industrial irrigation, and fisheries. The lake basin is characterized by using a Mediterranean climate, with dry and hot summers and moderate, wet winters. The common annual precipitation is around seven-hundred mm (Türkeş, 1996). The primary water sources for the lake are rainfall and a few small streams, and the only outflow from the lake is through the Karsak River. Therefore, the lake is hydrologically very sensitive to changes in precipitation and temperature.

Within the scope of the study, the focus will be on:

- Determining the changes in the water level of Lake İznik,
- Concentrating on meteorological parameters and drought indicators,
- Focusing on the changes in the lake's water surface area.

WATER LEVEL DATA AND ANALYSIS

For centuries, changes in the water levels of lakes and rivers have been monitored by water gauges, which are positioned along the shore and equipped with measurement mechanisms at specific intervals. However, with the launch of the Topex/Poseidon satellite in 1993, the era of altimetry began, and satellite altimetry came to be seen as a supplementary technique (Erkoç, 2023a and 2023b).

Along the lake shore, various numbers of water level measuring devices (water gauges) are installed depending on the size of the lake, the water structure, and chemical properties (Munyaneza et al., 2009). Throughout history, these devices have been used for centuries, initially requiring an operator to manually take daily, weekly, or monthly measurements and record the data in a logbook. However, modern water level measuring devices today are equipped with radar systems, allowing authorities to conduct observations at desired intervals. In addition to measuring lake water levels, these modern devices can also monitor parameters such as pressure, wind, temperature, and precipitation thanks to meteorological modules (Erkoç, 2023b). These values can be analyzed using

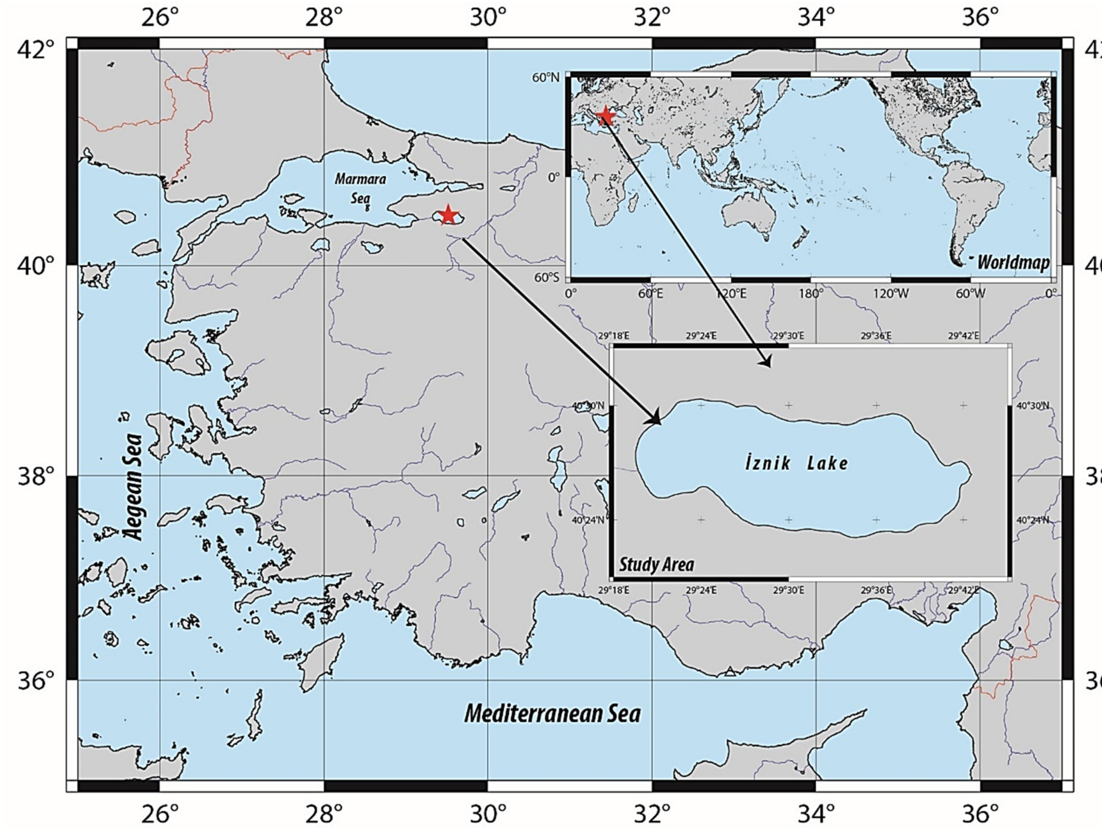

Fig. 1 Study area.

the classical linear model with the least square method (Eq. 1).

$$WL(t) = \\ = a + b\,t_i + \sum_{j=1}^{n} A_j \cos \omega_j t_i + B_j \sin \omega_j t_i \quad (1)$$

In this context, t_i represents the i'th observation in the time series, where i indexes the observations. a represents the average water level at the reference time, b denotes the linear trend in the lake's water level, ω_j stands for the angular frequency, and A_j and B_j are the coefficients of the linearized seasonal signals, derived from the cosine and sine terms of the periodic function.

In satellite altimetry, the principle involves calculating the time it takes for a wave sent from the satellite to reflect off the water surface and return to the satellite, and then multiplying this time by the speed of light to obtain the distance. To calculate the sea surface height (SSH) using altimetry, this distance (S) is subtracted from the satellite's altitude (Alt) (Eq. 2). Since the distance may include some measurement and physical errors, it is necessary to correct these effects to calculate the corrected distance (S_{cor}) and thus determine the accurate water level.

$$SSH = Alt - S_{cor} \quad (2)$$

$$S_{cor} = S + \\ +\left(h_i + h_{iono} + h_{dry} + h_{wet} + h_{stide} + h_{ptide}\right) \quad (3)$$

To calculate S_{cor}, the effects of ionospheric (h_{iono}) and dry/wet tropospheric effects (h_{dry} and h_{wet}), Solid Earth Tide Height (h_{stide}), and Pole Tide Height (h_{ptide}) need to be removed (Equation 6) (Cretaux and Birkett, 2006; Zhao et al., 2017; Erkoç, 2023a).

In this study, data from the water gauge station located on the shore of Lake Iznik and operated by the State Hydraulic Works were utilized. Since Lake Iznik is not a closed basin and the lake's water is used for agricultural irrigation and industrial purposes, the amounts of water usage related to the lake were also obtained from Turkish Directorate General for State Hydraulic Works. On the other hand, satellite altimetry data were acquired from the HydroWeb data archive (https://hydroweb.next.theia-land.fr/, accessed July 2024). The details of the data are shown in Table 1.

Table 1 Data Information of water level

Station	Position		TG Data (Monthly)		Hydroweb Data (Monthly)	
	Latitude	Longitude	Time Span	Data Gaps (%)	Time Span	Data Gaps (%
İznik	40° 26' 37''	29° 30' 30''	2007-2024	<1	2013-2024	<1

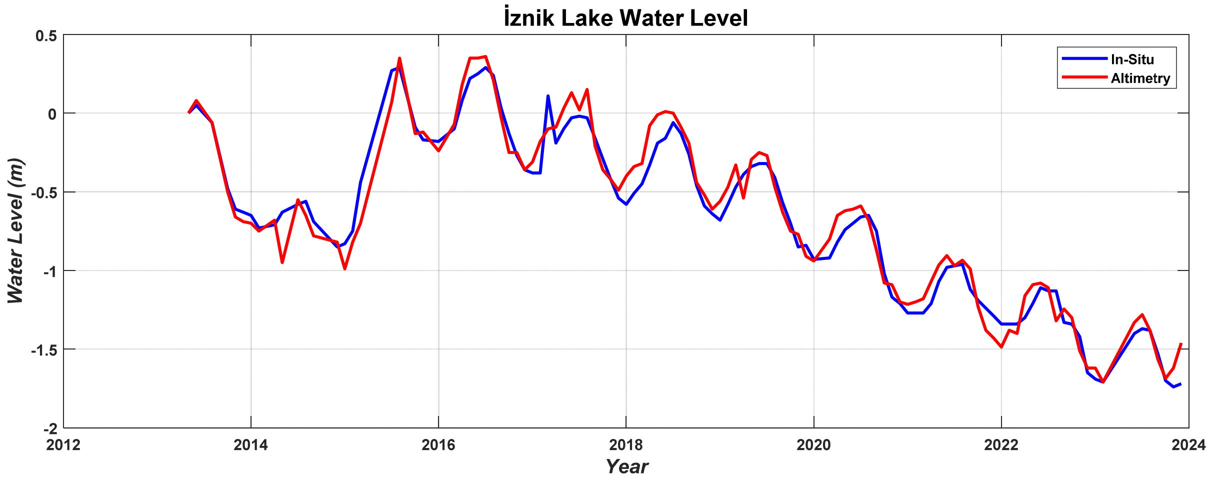

Fig. 2 Water level of İznik Lake from 2013 to 2024.

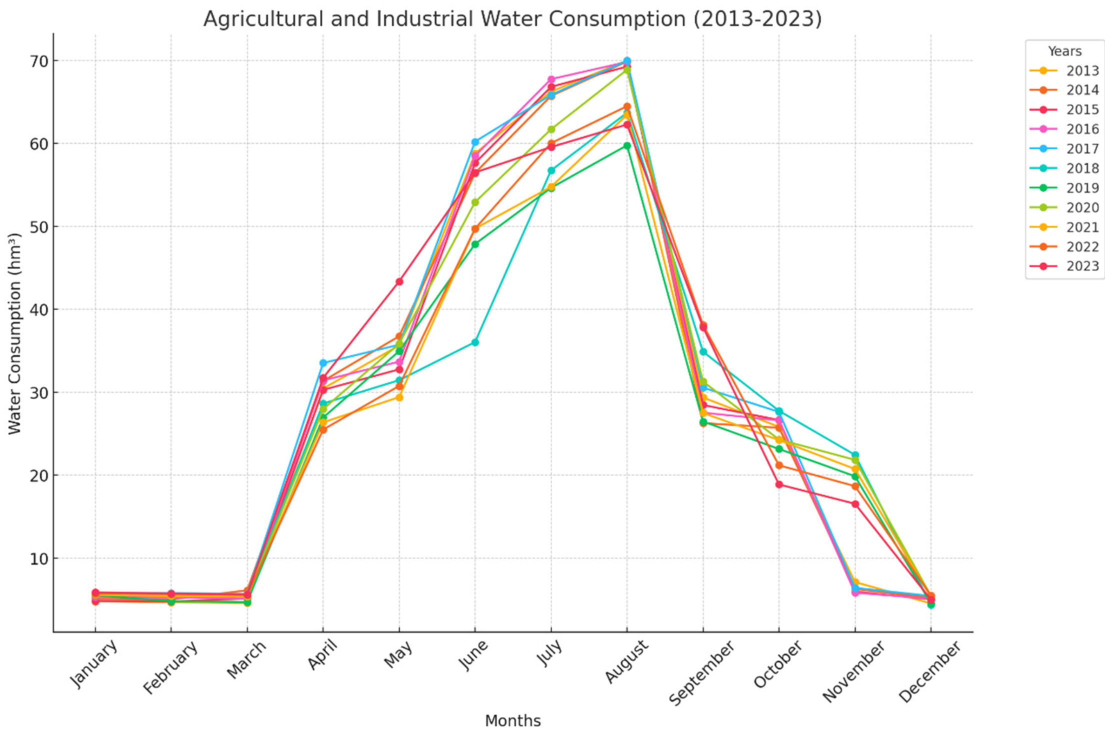

Fig. 3 Agricultural and industrial water consumption from 2013 to 2024.

The time series of lake water levels for both methods is shown in Figure 2. When focusing on the figure, it can be seen that both methods are in agreement, with the RMSD between the datasets being 9 cm and the Pearson correlation coefficient calculated as 0.95. The anomalies observed in 2014 and 2015 may be related to unusually low precipitation and potential discrepancies in data collection or calibration processes of the observation systems.

A concept that needs to be considered with Lake Iznik is the inflow of water from small streams and the release of water into the Karsak stream in case of excessive water level rise in the lake. Turkish Directorate General for State Hydraulic Works has stated that the amount of water entering the lake and the amount released into the Karsak stream have been equal for the past 10 years. Additionally, the amount of water used from the lake for agricultural irrigation and industrial purposes is shown in Figure 3. When examining Figure 3, it can be observed that the water consumption amounts follow the same pattern each year. In other words, there is no excessive water usage from the lake, no variable annual consumption, and no imbalance in the inflow/outflow water quantities. The decision not to attribute the observed changes to excessive water use was based on consistent annual water consumption patterns reported by the Turkish Directorate General for State Hydraulic Works. These patterns showed no significant variation over the analyzed period, indicating that the observed water changes are more likely attributed to climatic factors rather than increased water usage.

METEOROLOGICAL DATA AND ANALYSIS

To investigate the meteorological data influencing lake areas, studies have identified key meteorological factors that play a significant role in driving changes in lake surface area. Tang and Sun (2024) highlighted the importance of factors such as temperature and precipitation in influencing lake surface area changes. These findings underscore the intricate relationship between meteorological variables and lake dynamics. Two methods stand out in the estimation of meteorological parameters. The first of these methods is the parametric solution provided by the linear model. The linear model, used in the analysis of water level data and expressed by Equation 1, is also employed for the estimation of meteorological parameters. On the other hand, the Mann-Kendall/Sen Slope approach provides a non-parametric solution and yields significant results in the estimation of meteorological parameters.

The Mann-Kendall test is employed for identifying monotonic trends in the data. The test statistic S for the Mann-Kendall test is computed in the following manner (Mann, 1945; Kendall, 1975):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \qquad (4)$$

where $\boldsymbol{sgn}$ is the sign function:

$$sgn(x_j - x_i) = \begin{cases} 1 & if\ x_j - x_i > 0 \\ 0 & if\ x_j - x_i = 0 \\ -1 & if\ x_j - x_i < 0 \end{cases} \qquad (5)$$

The Mann-Kendall test assesses if there is a trend present. Sen's Slope Estimator can be utilized to estimate the magnitude of a detected trend. Sen (1968) calculates Sen's slope β:

$$\beta = median\left(\frac{x_j - x_i}{j - i}\right) \quad \text{for all } i < j \qquad (6)$$

This slope estimator gives the median of the slopes calculated between all pairs of data points and provides an estimate of the rate of change over time.

The trends in meteorological parameters estimated using parametric and non-parametric methods could be a precursor to a potential drought. Therefore, a drought analysis can be conducted using these data. The calculation of commonly used drought indices is a situation frequently encountered in studies (Liu et al., 2020). The Standardized Precipitation Index (SPI) is an extensively used tool for drought evaluation that focuses totally on precipitation, with SPI-12 supplying insights into lengthy-time period precipitation deficits or surpluses over a 12-month duration, that may imply the onset of hydrological drought. The Standardized Precipitation-Evapotranspiration Index (SPEI) extends the SPI by way of incorporating capability evapotranspiration (PET) into the evaluation, providing a more comprehensive degree of drought that money owed for both the supply of precipitation and the call for via evaporation. SPI and SPEI were selected due to their proven efficacy in quantifying long-term drought trends in similar climatic and hydrological settings, and their formulas are presented in Table 2 (McKee et al., 1993; Vicente-Serrano et al., 2010; Benzougagh et al., 2022).

In this study, data from the meteorological station located on the shore of Lake İznik were used. The data have been continuously collected by the Turkish General Directorate of Meteorology since 2005, and there are no data gaps. Information about the meteorological data is presented in Table 3.

The time series of temperature and precipitation are shown in Figure 4. Focusing on the Figure 4, it is noticeable that there is an increase in temperature and a decrease in precipitation.

Table 2 SPI-12 and SPEI-12 formulas.

SPI12	**SPEI12**
$SPI12_t = \frac{X_t - \mu_X}{\sigma_X}$ (7)	$SPEI12_t = \frac{D_{12,t} - \mu_D}{\sigma_D}$, $D_t = P_t - PET_t$ (8)
▪ X_t is the total precipitation over the 12 months ending at month t ▪ μ_X is the mean of the 12-month precipitation totals for the reference period ▪ σ_X is the standard deviation of the 12-month precipitation totals for the reference period	▪ P_t is the precipitation for month t ▪ PET_t is the potential evapotranspiration for month t ▪ $D_{12,t}$ is the cumulative water balance over the 12 months ending at month t ▪ μ_D is the mean of the 12-month cumulative water balances ▪ σ_D is the standard deviation of the 12-month cumulative water balances

Table 3 Meteorological data.

Station	**Position**		**Temperature Data**		**Precipitation Data**	
	Latitude	Longitude	Time Span	Data Gaps (%)	Time Span	Data Gaps (%
Iznik	40° 26' 37''	29° 30' 30''	2005-2024	0	2005-2024	0

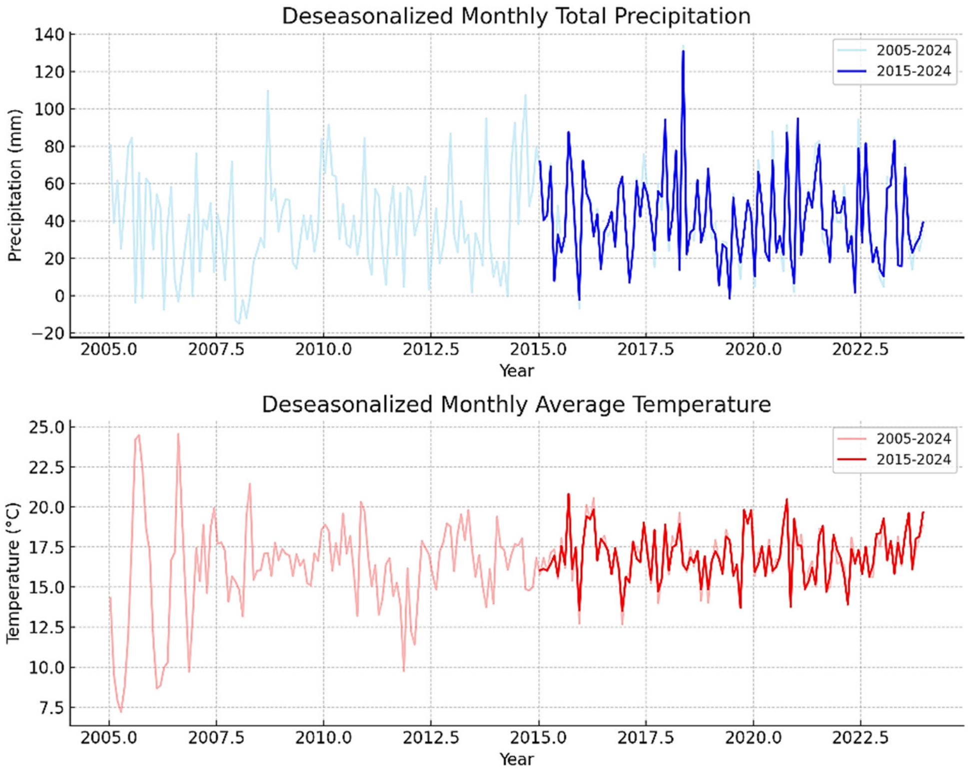

Fig. 4 Temperature and precipitation of İznik Meteorological Station from 2015 to 2024.

SATELLITE IMAGERY SOLUTION

The Normalized Difference Water Index (NDWI) is a broadly used far off sensing index for extracting water bodies, which includes lakes, from satellite imagery (Ho et al., 2016; Ismail et al., 2022). NDWI compares the reflectance of near-infrared (NIR) and inexperienced bands to successfully delineate water capabilities because of their specific spectral properties. By using NDWI, researchers can as it should be estimated the water surface area of lakes, providing valuable insights into changes in water extents over time.

The surface area of Lakes can be estimated using the Normalized Difference Water Index (NDWI), calculated from high resolution multispectral satellite images such as Sentinel-2 or Landat-8. NDWI is defined as follows (McFeeters, 1996; Akbari, 2022):

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \tag{9}$$

In this study, Sentinel-2 data were utilized to determine the lake surface area. Sentinel-2 images were selected for their high spatial resolution, ensuring detailed mapping of lake surface changes. The data were analyzed manually using ESA's SNAP software and through the Google Earth Engine platform. The algorithm proposed by Erkoç (2023b) was employed in the processing of Sentinel-2 data using SNAP software. Since Sentinel-2 imagery has been available since 2015, the time period for the lake surface area analysis was set as 2015-2023.

The Intersection over Union (IoU) accuracy metric is widely used to determine how well the water surface areas derived from satellite images overlap with the actual area (Sikander et al., 2024). It is particularly useful for evaluating the accuracy and consistency of the identified areas when comparing segmented images obtained from analysis with data sets from different sensors. The mathematical formula for IoU is as follows (Zhang et al., 2020; Wang et al., 2022; Ozdemir, 2024):

$$IoU = \frac{A \cap B}{A \cup B}$$

Here, $A \cap B$ represents the intersection of areas A and B, while $A \cup B$ represents the union of areas A and B. The IoU value ranges from 0 to 1; a value of 1 indicates that the two areas completely overlap, while a value of 0 indicates no overlap at all. When used to evaluate the overlap of water surface areas derived from satellite images, this metric provides valuable insights into the accuracy of the data sets. IoU values above 0.8 were deemed satisfactory based on prior studies, indicating a strong overlap between derived and actual water surface areas (Zhang et al., 2020; Wang et al., 2022).

RESULT

The analyses conducted to determine whether Lake İznik has been affected by hydrological drought can be summarized as the identification of lake water trends, drought indicators based on meteorological

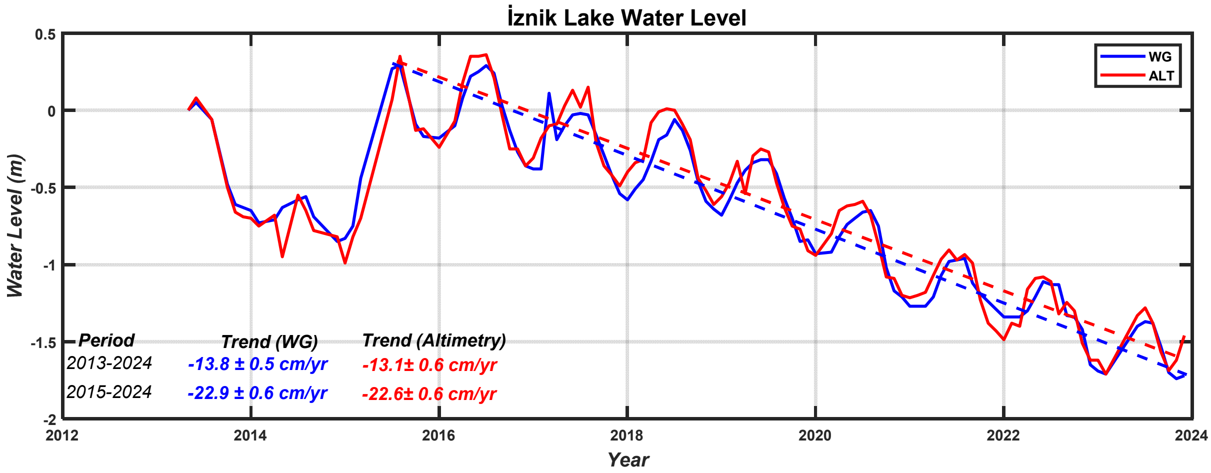

Fig. 5 Water level trends of İznik Lake.

Table 4 Trends of temperature and precipitation.

Station	Temperature Data			Precipitation Data		
	Kendal Tau	P-Value	Sen's Slope (Degree/yr)	Kendal Tau	P-Value	Sen's Slope (mm/yr)
İznik	0.029	0.065	0.049	-0.690	0.291	-0.80

Table 5 Values of SPI12 and SPEI12.

Year	SPI12		SPEI12	
	Value	Condition	Value	Condition
2015	1.0244	Moderately wet	1.6722	Moderately wet
2016	-0.0140	Mildly drought	-0.6044	Mildly drought
2017	-0.1866	Mildly drought	-0.3270	Mildly drought
2018	-0.3928	Mildly drought	-0.2994	Mildly drought
2019	-0.1200	Mildly drought	-0.4375	Mildly drought
2020	-0.2881	Mildly drought	-0.4365	Mildly drought
2021	-0.0975	Mildly drought	-0.6081	Mildly drought
2022	-0.1888	Mildly drought	-0.4621	Mildly drought
2023	-0.4933	Mildly drought	-0.4258	Mildly drought

data, and the detection of the lake's water surface area using satellite imagery. First, to determine the lake water level, in-situ observations from Turkish Directorate General for State Hydraulic Works and satellite altimetry-based data from HydroWeb were obtained (Figure 2), analyzed using Equation 1, and subjected to time series analysis. As a result of these analyses, trends between the years 2013-2024 and 2015-2024 were identified. The main reason for determining two separate trends is the different time periods of the data for lake water level, meteorological parameters, and satellite imagery. The importance of this selection is highlighted by the decrease in lake water level and the changes in meteorological parameters between 2015-2024, as seen in Figures 2 and 4. The water level between 2015-2024 was estimated to be -22.9±0.6 cm/yr based on water gauge data and -22.6±0.6 cm/yr based on HydroWeb altimetry data (Fig. 5).

If the meteorological data shown in Figure 3 are subjected to non-parametric trend analysis using the Mann-Kendall/Sen's Slope method, the values presented in Table 4 are obtained. According to the analyses, the temperature data show an increasing trend, while the precipitation data show a decreasing trend.

The SPI12 and SPEI12 values expressed in Table 2 and calculated using Equations (7) and (8) represent hydrological drought. In Erkoç's (2023b) study, July was selected for SPI12, SPEI12, and lake surface area calculations derived from satellite imagery to minimize the impact of cloud cover and seasonal variability. Beyond these considerations, July represents the peak of the dry season in the Mediterranean climate of the region, making it critical for capturing the most pronounced hydrological impacts of drought. Moreover, agricultural water use, which significantly influences lake dynamics, reaches its annual peak during this period. Therefore, July is an optimal month for assessing drought conditions and their effects on Lake İznik. Following a similar rationale in this study, calculations for SPI12, SPEI12, and lake surface areas were also performed based on the month of July (Table 5).

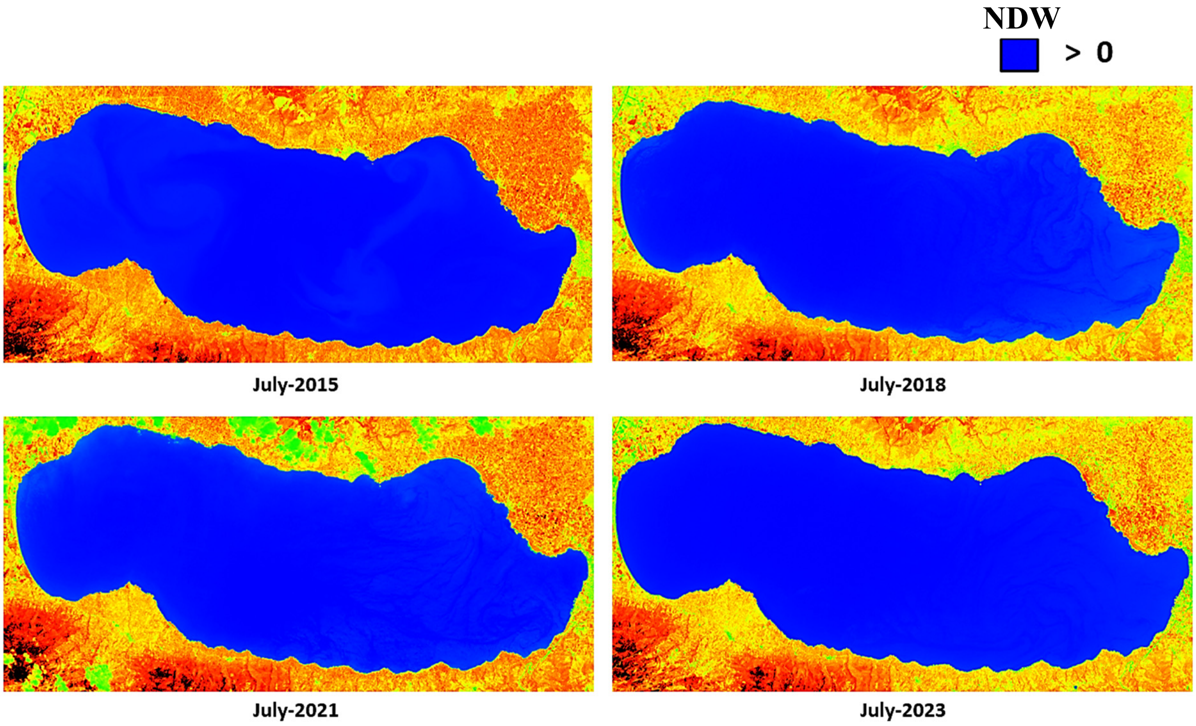

Fig. 6 Water surface area of Lake İznik from NDWI.

Table 6 Water surface area of Lake İznik from 2015 to 2024.

Year	Lake Surface Area from Sentinel-2 (km2)		
	Output of SNAP Software	Solution of Google Earth Engine	IoU Results (SNAP-Truth Data)
2015	300.876750	299.843907	0.89
2016	300.812100	299.656849	0.91
2017	300.695778	299.285787	0.81
2018	300.521603	299.226653	0.93
2019	300.377096	299.17795	0.90
2020	300.145218	298.357211	0.88
2021	299.645601	297.653435	0.92
2022	298.345408	297.513315	0.86
2023	298.173022	297.222127	0.91

The temperature-based drought index SPI and the temperature and precipitation-based drought index SPEI values shown in Table 5 have yielded negative results for all years except 2015. Negative results indicate the presence of hydrological drought in the region. The consistent decrease in SPI/SPEI values corresponds directly with the observed reduction in lake surface area, confirming a strong linkage between meteorological and hydrological drought. The following points are considered for interpreting the SPI and SPEI values (Zhu et al., 2016; Gumus and Algin, 2016; Kumanlioğlu, 2019; Erkoç, 2023b; Patidar et al., 2024). According to these interpretations, Table 5 indicates that mild drought conditions are observed from a hydrological perspective SPI and SPEI values;

- Greater than 2.0 indicate extreme wet conditions,
- Between 2.0 and 1.5 indicate severe wet conditions,
- Between 1.5 and 1.0 indicate moderate wet conditions,
- Between 1.0 and 0.0 indicate mildly wet conditions,
- Between 0.0 and -1.0 indicate mild drought conditions,
- Between -1.0 and -1.5 indicate moderate drought conditions,
- Between -1.5 and -2.0 indicate severe drought conditions,
- Less than -2.0 indicate extreme drought conditions.

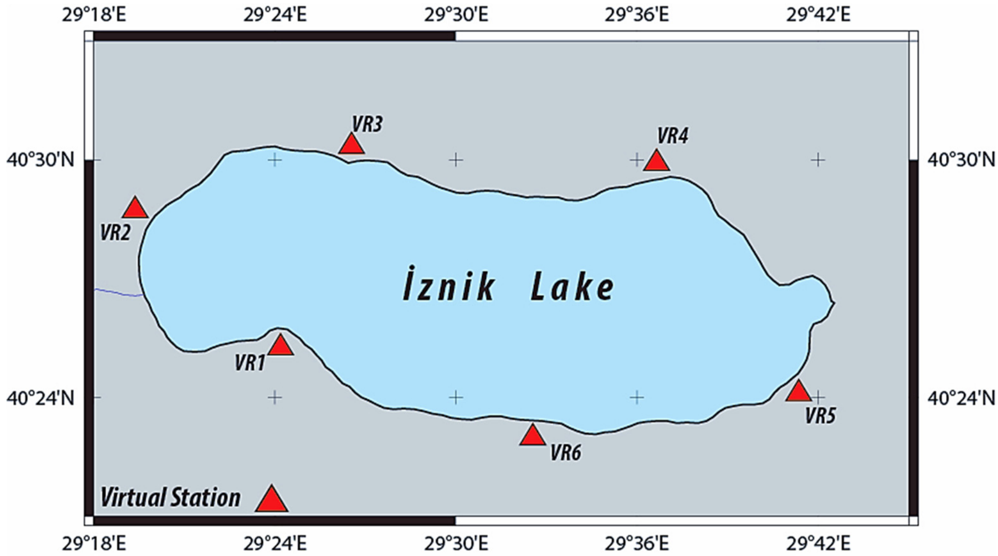

Fig. 7 Locations of virtual stations.

Some Sentinel-2 images, assessed using the SNAP software for determining the lake water surface area, are shown in Figure 6. The areas shown in blue represent regions where the NDWI value is greater than 0, indicating water surfaces. The lake surface area values based on Sentinel-2 images analyzed using the SNAP software and Google Earth Engine platform are presented in Table 8. The IoU analysis shown in Equation 10 was conducted to validate the lake surface areas derived from Sentinel-2 images. In this context, Google Earth images (0.5 m resolution) for each July were manually digitized (truth data) and subjected to IoU analysis with the lake surface areas obtained through NDWI. Additionally, the IoU results are provided in Table 8.

Focusing on Table 6, the lake water surface areas calculated based on images from both satellite systems show a decreasing trend. It is observed that the lake surface area decreased by 2.7 km² based on Sentinel-2 images (SNAP solution) and by 2.6 km² based on Google Earth Engine solution. Additionally, if one wishes to determine the trend of changes in the lake's water surface area using a linear model, as described by the equation in Equation 1, the trend can be estimated as -0.3446±0.05 km² per year for Sentinel-2 SNAP output and -0.3509±0.09 km² per year for Sentinel-2 Google Earth Engine Solution.

DISCUSSION

Figure 3 shows that the lake water is used for both industrial and agricultural purposes and that this usage has remained constant over the years. Therefore, it can be said that the decrease in lake water is due to a decrease in precipitation rather than excessive water usage. Various studies have determined that Lake İznik is affected by factors such as tectonic activity and climate change, and that climate-related changes in the lake level have been identified through geochemical and mineralogical analyses (Miebach et al., 2016; Gastineau, 2022; Mercan and Arslan, 2023). Similar patterns of drought-induced water level decline have been observed in Lake Urmia and Lake Chad, highlighting the broader implications of climate variability (AghaKouchak et al., 2015; Hussaini et al., 2019). On the other hand, similar studies by Dutucu and Koç (2022), Uzun and Garipağaoğlu (2016) have also argued that the water level of Lake İznik is highly sensitive and needs to be monitored. Since other studies have not directly focused on changes in the lake water level, this study is the first in the region to be based on water gauge and satellite altimetry data. Considering that the decrease in water level may indicate a possible drought in the region, temperature and precipitation data were examined, and an increase in temperature and a decrease in precipitation were observed. Other studies have also indicated that the area around Lake İznik is sensitive to climate change (Akçaalan et al., 2014; Roeser et al., 2016; Mercan and Arslan, 2023). Ceribasi (2018) found an increase in temperature and a decrease in precipitation around Lake İznik in his study. On the other hand, Bahadır and Özdemir (2011) predicted that the temperature around Lake İznik would increase by 0.5 to 5 degrees, and as a result, the water level would decrease by 1.4 meters. In this study, it was observed that the temperature had a trend of increasing by 0.049 °C per year, and the average temperature in 2023 had increased by 1.2 °C compared to 2015. Moreover, the meteorological analyses in this study were conducted using data from a single meteorological station, as no other stations are located in the region. To compensate of this limitation, six virtual reference stations, believed to represent the dynamics surrounding the lake, were created using the ERA5 (European Centre for Medium-Range Weather Forecas Reanalysis v5) datasets (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5/, accessed September 2024) (Fig. 7).

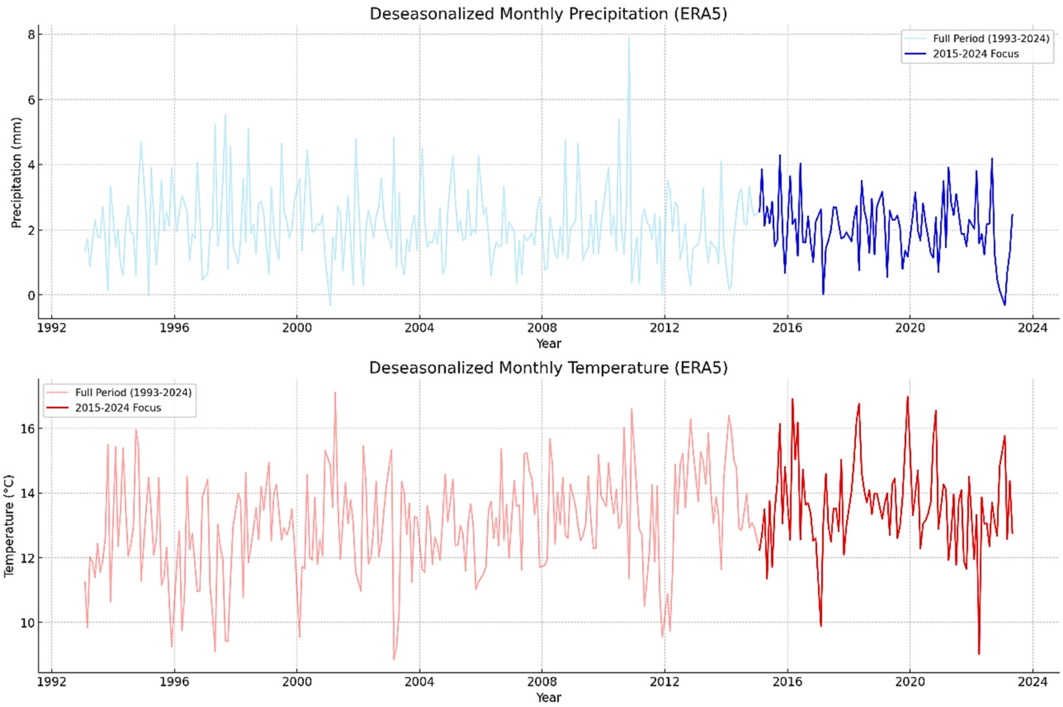

Fig. 8 Temperature and precipitation of VR1 Station from 2015 to 2024.

Table 7 Temperature and precipitation trends for virtually stations.

Station	Temperature Data			Precipitation Data		
	Kendal Tau	P-Value	Sen's Slope (Degree/yr)	Kendal Tau	P-Value	Sen's Slope (mm/yr)
VR1	0.191	0.032	0.048	-0.082	0.268	-0.70
VR2	0.182	0.080	0.047	-0.072	0.319	-0.60
VR3	0.201	0.087	0.051	-0.106	0.138	-0.66
VR4	0.209	0.044	0.053	-0.163	0.023	-0.90
VR5	0.228	0.071	0.054	-0.161	0.019	-0.83
VR6	0.200	0.062	0.054	-0.135	0.055	-0.72

A key limitation of this study is the reliance on a single meteorological station. Although virtual stations were created, additional ground-based observations would enhance data robustness.

The monthly average temperature and total precipitation data for these virtual stations were obtained from the ERA5 reanalysis model. As an example, Figure 7 shows the locations of the virtual stations, while Figure 8 presents the time series for the VR1 station. The trend values for all virtual stations are summarized in Table 7. The temperature and precipitation trends obtained from the virtual meteorological stations created using the ERA5 dataset align closely with the trends derived from the meteorological station operated by the Turkish State Meteorological Service in the region. The differences between the two data sources are found to be statistically insignificant, indicating that the single Turkish State Meteorological Service's station accurately represents the meteorological dynamics of the area. Statistical metrics, including the Pearson correlation coefficient (r), were calculated to evaluate the consistency between the datasets. The results showed a strong agreement ($r > 0.9$ for temperature and $r > 0.8$ for precipitation), confirming the suitability of ERA5 data for complementing the single in-situ station.

Both this study and previous studies have shown that climatic changes in temperature and precipitation indicate the need to investigate whether there is a drought in the region, and the SPI12 and SPEI12 drought indices, representing hydrological drought, were calculated as part of the study. These calculations indicate that there is hydrological drought in the region. Ozturk et al., (2016), Bacanlı and Kargı (2019), and Dutucu and Koç (2022) calculated short- and long-term droughts in the region and mentioned the existence of hydrological drought. The drought indicators in this study are consistent with other studies in the region. After identifying the decrease in lake water levels and hydrological drought, NDWI values based on Sentinel-2 satellite images were calculated to determine the changes in lake surface area, and lake surface areas were determined. An IoU analysis was conducted between the NDWI-based lake surface area generated here and the actual lake surface area, and the values were found to be greater than 0.8, indicating a high level of agreement. Sikander et al., (2024) stated in their study that as this ratio approaches 1, the overlap increases, and a value greater than 0.8 indicates a very good overlap. This indicates that the NDWI derived from the images of Lake İznik has a high sensitivity to changes in Lake İznik. In alignment with this finding, Günen and Atasever (2024) also emphasized the importance of selecting appropriate water indices and thresholding methods for water body detection using remote sensing and demonstrated the robustness of NDWI indices under various environmental conditions in lakes, including Lake İznik. The decrease in lake surface area, consistent with the hydrological drought in the lake, shows that the analyses are consistent.

If we consider the findings of the study in isolation, all the findings indicate the presence of hydrological drought in the lake. Figure 9 shows the SPI12, SPEI12, water level, and lake water surface area data for the month of July between 2015 and 2024. The decrease in water level indicates that drought has begun, the drop from positive to negative in SPI and SPEI indicates that drought has occurred, and the shrinkage in lake water surface area indicates that the lake is at risk of continuing to shrink.

All the findings prove the hydrological drought in the lake. The effects of hydrological drought in Lake İznik can be explained as follows (Sala et al., 2000; Schindler, 2001; Gleick, 2003; Eakin and Lemos, 2006):

- ***Negative Impact on Water Quality***: Decreasing of water level can lead to a rise on some elements, ions, chemicals or dissolved things in the lake water (Salinity, nutrient levels).
- ***Impact on Biodiversity***: A possible decrease in water level and the resulting adverse change in water quality may result in a change in the living conditions of plant and animal species in the lake. In this case, a decrease in the species and numbers of living organisms in the lake and even the extinction of some species can be observed.
- ***Impact on Water Use:*** With hydrological drought, the water needs of industrial facilities operating with lake water and irrigation areas for agricultural purposes may not be met. In this case, there may be restrictions in water use.
- ***Economic and Social Impacts:*** Decrease in lake water level may adversely affect tourism, fishing and other water-dependent economic activities. In addition, those living around the lake and local people who make their living from the lake resources may face social and economic difficulties.

CONCLUSION

Hydrological drought is a natural disaster that affects different sectors such as agriculture, industry, tourism, and ecosystems. This study applies comprehensive analyses to identify hydrological drought in Lake İznik and to secure the sustainability of the lake. This study calls explicitly for proactive water management at Lake İznik that ensures ecological and economic sustainability in light of changing climatic conditions. A wide range of data sources, including in-situ observations (water gauge and meteorological data) and satellite-based observations (satellite altimetry and high-resolution satellite images), were evaluated using various analytical methods (linear model, Mann-Kendall/Sen's slope, SPI12/SPEI12) to identify the effects of hydrological drought. The lake's water level was determined through the analysis of water gauge and Hydroweb altimetry-based water level data using a linear model, showing a decreasing trend of - 22.9±0.9 cm/year with water gauge data and - 22.6±0.6 cm/year with HydroWeb data between 2015 and 2024. To determine whether this decrease was related to hydrological drought, temperature and precipitation data were subjected to Mann-Kendall/Sen's Slope analysis, which estimated a trend of 0.049 °C/year increase in temperature and - 0.80 mm/year decrease in precipitation. Additionally, the hydrological drought indicators SPI12 and SPEI12 showed negative values from 2015 to 2024, indicating drought in the region. To assess whether hydrological drought has led to a reduction in lake surface area, Sentinel-2 data were analyzed using ESA's SNAP software and the Google Earth Engine platform, with NDWI-based area changes determined. According to the data, the water surface area showed a decreasing trend of -0.3446±0.05 km²/year (a reduction of 2.7 km² from 2015 to 2024) from SNAP solution, while Google Earth Engine solution indicated a decreasing trend of -0.3509±0.09 km²/year (a reduction of 2.6 km² from 2015 to 2024). All these findings suggest that Lake İznik is highly sensitive to hydrological drought and is affected by it, which may lead to adverse effects on the lake ecosystem and surrounding areas.

ACKNOWLEDGEMENTS

We dedicate this work to all the scientists who contribute to the development of the Turkish Republic and celebrate the 100th anniversary of the Republic of Türkiye. The authors extend sincere thanks to all data providers. Water gauge data were obtained from the Turkish State Hydraulic Works, and satellite altimetry data were sourced from the Hydroweb data archive. ESA's Sentinel-2 were utilized, with meteorological data provided by the Turkish General Directorate of Meteorology. Additionally, ESA's SNAP software and Google Earth Engine were employed for processing multispectral satellite images. The figures were prepared using GMT (Wessel et al., 2013).

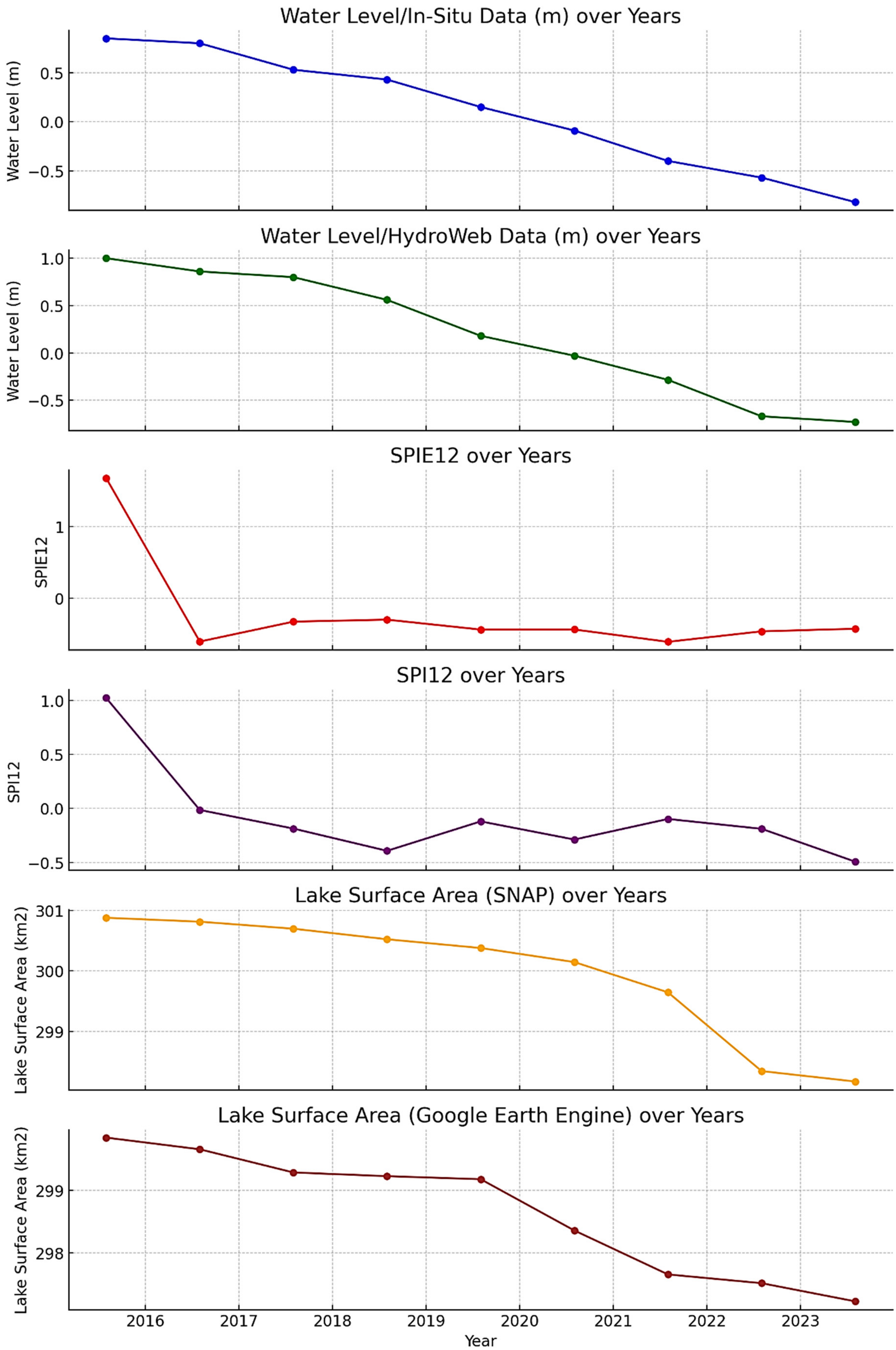

Fig. 9 Comparison of all data sets.

Additionally, ChatGPT was utilized for English language checks in certain sections. Furthermore, this study was supported by Yildiz Technical University Scientific Research Projects Coordination Unit under project number FKD-2024-6190, and by the TÜBİTAK Scientist Support Programs Presidency under the 2209-A University Students Research Projects Support Program, with project number 1919B012309107.

DATA AVAILABILITY

The meteorological data can be obtained from the Turkish General Directorate of Meteorology, and the lake water level data can be acquired from the Turkish Directorate General for State Hydraulic sales offices. Satellite altimetry data can be freely downloaded from the HydroWeb website (https://hydroweb.next.theia-land.fr/, accessed June 2024). Sentinel 2 data can be downloaded on Sentinel-Hub (https://dataspace.copernicus.eu/analyse/apis/sentinel-hub, accessed June 2024) and accessible through the Google Earth Engine Platform. If someone wishes to request the data from this study, they can contact the corresponding author via email (mherkoc@yildiz.edu.tr).

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