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ORIGINAL ARTICLE

Satellite Derived Bathymetry and Water Level Change in Beysehir Lake

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ABSTRACT

Several factors, including water level, depth, water quality, biodiversity, and tourist activities, play a crucial role in the sustainability of lakes, and therefore require constant monitoring. This study aimed to examine the water level changes of Lake Beysehir between 2015 and 2020 and determine whether there was a difference in bathymetry as the lake water level changed. To achieve this, lake water level data was first obtained from Copernicus Global Land Service, which uses satellite altimetry data to determine water level changes in Beysehir Lake. Sentinel-2 multispectral high-resolution satellite images obtained from Sentinel-Hub were then used to determine the depth of the lake. Finally, these high-resolution satellite images were processed using the open-source SNAP software developed by the European Space Agency. A decreasing trend of -9.8 ± 0.8 cm/yr in the lake water level between 2015 and 2020 was revealed by the analysis. The Empirical Satellite-Derived Bathymetry map was produced, and the maximum and average depth of the lake was determined after the required corrections were applied to the Sentinel-2 satellite images. The average depth, which was 8.44 meters in 2015, was found to have decreased to 4.06 meters in 2020. Additionally, a 0.92 correlation was found between the decrease in the lake water level and the average depth change.

INTRODUCTION

Lakes and rivers undergo physical changes that are closely related to their structure. These changes include alterations in water levels, tide datums, shorelines, and bathymetry. In order to maintain tourism, fishing, and agricultural activities in these bodies of water and prevent them from disappearing, it is crucial to monitor their water levels and bathymetry. The water level of a lake can fluctuate due to various factors, such as meteorological conditions, surface soil type, changes in groundwater, droughts, and the use of water for agriculture and drinking. Conversely, bathymetry refers to the measurement of depth and topography of underwater features, such as the seafloor, lakes, and rivers (Monahan, 2019). The changes in bathymetry over time can be influenced by multiple factors, including sea level change, coastal morphology (shape), coastal erosion, human activities, tides, and underwater landslides (Dierssen and Theberge, 2014).

The lake water level was determined using staff gauge like batten bars based on manpower. With technological advancements, water levels are now measured using advanced instruments like acoustic or radar tools in water gauge stations. These instruments can provide continuous measurements of water levels at different intervals, ranging from every second to every hour, which allows for more accurate and frequent monitoring of changes in water levels over time. This is essential for detecting potential floods or droughts, as well as managing water resources (Erkoç, 2023). With the data provided by the Topex/Poseidon satellite in 1993, satellite altimetry emerged as a secondary method for determining water levels in the oceans using space technology (Cazenave et al., 2014; Cazenave, 2020). With technological developments, more precise estimation of concepts such as orbital information, sea state bias, and atmospheric corrections have been ensured, resulting in the use of satellite altimetry in coastal areas, lakes, and rivers (Birkett, 1995; Aladin et al., 2005; Cretaux and Birkett, 2006; Arabsahebi et al., 2018). The water level of a lake can be measured or estimated using various methods, such as a water gauge or satellite altimetry missions. The accuracy of these measurements is expressed in terms of their RMS (root mean square) values, which indicate the level of measurement accuracy. According to the Shum et al. (2003), the estimated RMS values for lake water level measurements obtained through water gauge is less than 1 cm and satellite altimetry missions are approximately 3-5 cm. This means that the measured or estimated values may deviate from the actual water level by up to 3-5 cm due to measurement errors, noise, or other factors. However, this level of accuracy is generally considered to be quite good for most applications, including scientific research, engineering, and environmental monitoring (Cazeneve, 2020).

In recent years, there has been a growing focus on studying lake water level changes. Liu et al. (2022) conducted a study on the water level and volume changes of 11 lakes and 8 reservoirs in the Yellow River Basin, using data from the ICESat-2 altimetry mission on the Google Earth Engine platform to estimate these changes. A study investigating the potential to monitor inland water dynamics on the Great Lakes and the lower Mississippi River, geodetic data from 22 water gauges and ICESat-2 satellite data were used (Xiang et al., 2021). GEOSAT and Topex/Poseidon satellite altimetry missions were used in another study which aimed to examine gravity anomalies, seasonal variation of lake level and lake surface profile in Lake Michigan (Kim and Lee, 2002).

In the past, ropes attached to a heavy object were used to estimate the sea floor topography in bathymetric measurements. However, with the development of technology, echo sounders have become the standard tool for measuring bathymetry. Echo sounders can accurately predict peaks and valleys in the seabed, but ocean ditches or sand bars can still affect the accuracy of the results. To achieve greater precision, Multi-Beam Echo Sounder Bathymetry is employed. This technique

uses multiple audio signals to detect the seabed, resulting in more precise bathymetric measurements.

Advancements in satellite technology and the widespread use of remote sensing have made it easier to determine the physical properties of surface water, bottom topography, and atmosphere using multi-spectral high-resolution images, as opposed to traditional techniques (Dickens and Armstrong, 2019). Satellite derived bathymetry is useful techniques for estimating the bathymetry of shallow water areas, but their accuracy and precision depend on various factors such as the water clarity, bottom reflectance, and the quality of the input data (Wan and Ma, 2021). Conventional hydrographic methods such as single beam and multibeam echo sounding provide accurate and precise measurements of the bathymetry, but their spatial resolution may be limited. The choice of the method depends on the specific application and the characteristics of the study area. Remote sensing data can be obtained with wide spatial resolution, broad temporal coverage, and at lower costs than traditional bathymetric surveying methods. Satellite-derived bathymetry estimates depth values in near-shore areas, lakes, and rivers using ocean optics principles and satellite imagery from platforms like Sentinel-2, Landsat 8, or ICESat-2.

In a study of the Saemangeum region located in the southwest of the Korean Peninsula, Kim and Yun (2018) found that the satellite-derived bathymetry model was highly compatible with ship observations-based bathymetry in the shallow water area near the shore, estimated by the Korea Rural Community Corporation. Ma et al. (2020) created an empirical bathymetry map using satellite data from ICESat-2 and Sentinel-2 multispectral images in their study of the South China Sea. Caballero and Stumpf (2019) generated bathymetric maps of South Florida, USA using high-resolution multispectral images from Sentinel-2 and a ratio transformation model.

Beysehir Lake is the largest freshwater lake in Türkiye, covering approximately 650 km^2 with an average depth of 8-10 meters. The lake, situated at an altitude of approximately 1120 meters above sea level, supports various activities such as fishing and tourism. Satellite altimetry has been widely used to estimate water levels in lakes, and satellite-derived bathymetry is recommended for lakes with an average depth of up to 15 meters (Pacheco et al., 2015; Chenier et al., 2018; Traganos et al., 2018). This study has two main objectives:

(a) to estimate water level changes in the lake between 2015 and 2020 using satellite altimetry data,

(b) to estimate the average depth between 2015 and 2020 by generating satellite-derived bathymetry maps using Sentinel-2 multispectral high-resolution satellite images.

The study's novelty lies in monitoring the lake's water level and depth changes with satellite-based data without in-situ observations in the study area. This approach enables the determination of how the bathymetry changes with the decrease in lake water, providing valuable insights into the lake's dynamics.

METHODOLOGY AND MATERIAL

Study Area

Lake Beysehir is located on the border of Konya and Isparta provinces in the Central Anatolia Region of Türkiye (Fig. 1). Agriculture and animal husbandry are the most important livelihoods in the surrounding area. The geographical coordinates of the center of the lake are 37°47'0" N, 31°33'0" E. It is the largest freshwater lake in Türkiye and the third largest lake in terms of surface area among all lakes. The approximate surface area is 650 km^2 and the average depth is 8-9 meters. Its height above sea level is approximately 1120 meters (geoidal heights expressed with respect to EGM 2008). There is an estimate for the maximum and average depth of the lake being referred to. Specifically, it suggests that the maximum depth is thought to be 12 meters, which means that there are some areas within the lake that may reach or exceed that depth. Additionally, the average depth is

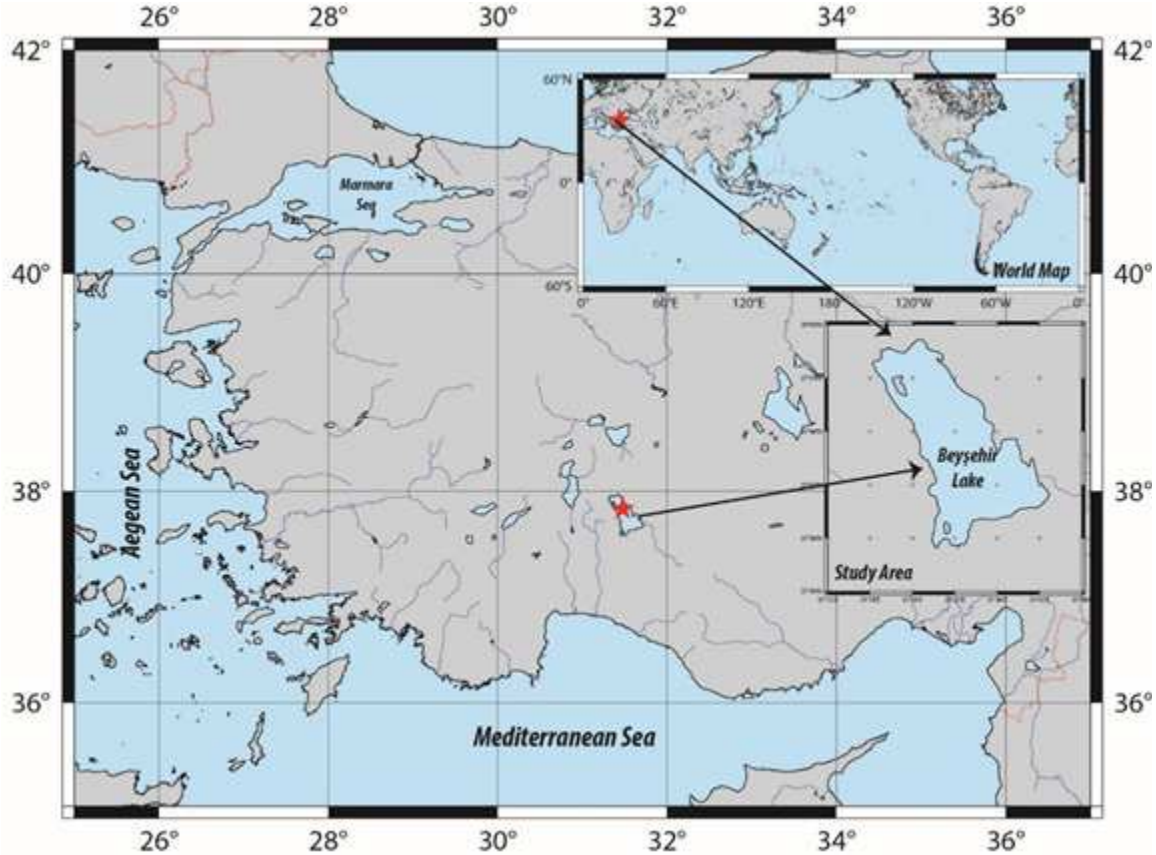

Fig. 1. Lake of Beysehir

believed to be between 8 and 10 meters, which indicates that the major portion of the lake has a depth within that range. It's important to note that these values may not be exact and could vary based on factors such as the measurement method or the time of year in which the measurement was taken. The length of northwest and southeast is 50 km and the width of northeast and southwest is 26 km. Fishing is carried out in the lake in which there are lots of carp, pike, perch and tench. The lake is also one of the hunting, breeding and wintering destination of migratory birds.

Water level Determination for Lake

Two methods are used to determine the lake water level. The first method is water gauges, which have been used for centuries. They consist of two types, classical and modern (Fig. 2, (a) is traditional water gauge (https://www.locss.orgarticlewhen-should-we-measure-lake-levels, accessed October 2022) and (b) is modern water gauge (https://www.vega.comen-trcompanyblog2019measuring-water-level-of-earths-largest-lakes_application-of-the-month, accessed October 2022). Conventional water gauges are stored by processing values recorded manually by an operator into a report card. These values are then computerized and evaluated as numerical observations. In traditional water gauges, the measurement is carried out daily, weekly or monthly. In contrast, modern water gauges not only record the lake water level using a radar system at intervals of secondly but also equipped to store meteorological and atmospheric data such as pressure, wind and temperature information. The data obtained from water gauges can be analyzed by evaluating using the least squares method after having the necessary quality control and corrections (Erkoç and Dogan, 2022).

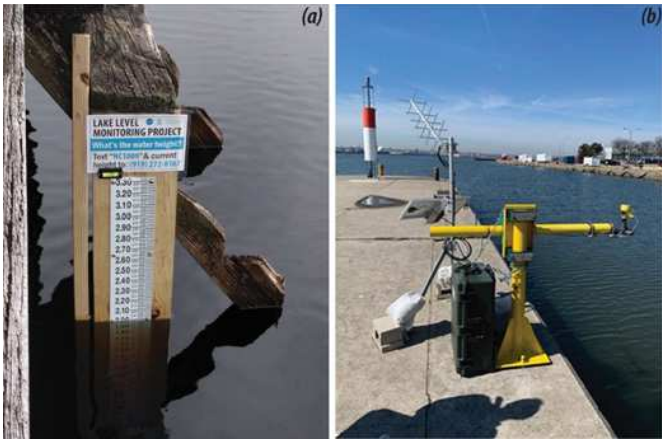

Fig. 2. Water Gauges **(a)** shows a traditional water staff gauge and **(b)** indicates modern radar water gauge

Satellite altimetry, which appeared as a secondary method in sea level observations with the availability of the Topex/Poseidon satellite data in 1993, has expanded to be used in coasts, lakes and rivers over time. Satellite altimetry functions based on the principle of processing the signal coming from the satellite by reflecting it from the water surface (AVISO, 1996). The precise position of the satellite altimetry is determined based on a Geodetic Reference System using the GNSS receiver placed on it. The water level is determined by subtracting the satellite height from GNSS by determining the distance traveled by the wave reflected from the water (Eq.(1)). The distance (*S*) traveled by the pulse reflected from the water contains some errors. These errors consist of instrumental errors (h_i), range correction and geophysical correction components. Range correction is implemented by removing the ionospheric (h_{iono}) and dry/wet tropospheric effects (h_{dry} and h_{wet}) and geophysical correction is implemented by removing the effects of Solid Earth Tide Height (h_{stide}) and Pole Tide Height (h_{ptide}) (Eq.(2)) (Cretaux and Birkett, 2006; Erkoç and Dogan, 2022).

$$SSH = Alt - S_{cor} \tag{1}$$

Here, *SSH* is the current water level, *Alt* is the satellite height at the time of measurement, and S_{cor} is the distance between the satellite and the sea surface.

$$S_{cor} = S + (h_i + h_{iono} + h_{dry} + h_{wet} + h_{stide} + h_{ptide}) \tag{2}$$

In this study, the water level data of lake Beysehir is derived monthly using multi-mission altimetry data because of non-public in the water gauge station data from the lake. The data were downloaded ready-made from the "Water Level-Water Level V2 lakes NRT" data catalog provided by Copernicus Global Land Service (Fig.3).

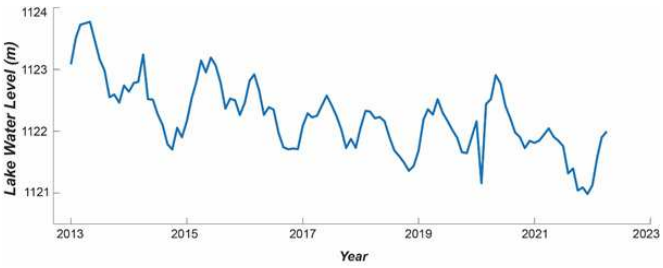

Fig. 3. Water level variation on Beysehir lake obtained from Copernicus Land Service (2013-2022)

Figure 4 illustrates that the lake water level data followed a normal distribution, as indicated by the EGM2008 geoid model. The maximum water level reached 1123.77 meters, while the minimum water level was recorded at 1120.98 meters. Furthermore, the average lake water level during the specified time period was calculated to be 1222.20 meters. This average water value serves as the vertical reference for hydrological application such as bathymetry, and all depth calculations are relative to this reference (Jigena-Antelo et al., 2016; Nwanko et al., 2020; Jigena-Antelo et al., 2023).

Satellite Derived Bathymetry

With the development of concepts such as higher resolution, multiple spectral bands, open data access, and the rapid technological developments, satellite-based solutions have emerged in the coastal area monitoring and management. The satellite-derived bathymetry approach is a low-cost method for detailed mapping of shallow areas in coastal areas, lakes and rivers. In contrast to traditional methods, results can be obtained quickly, and it can be produced based on the

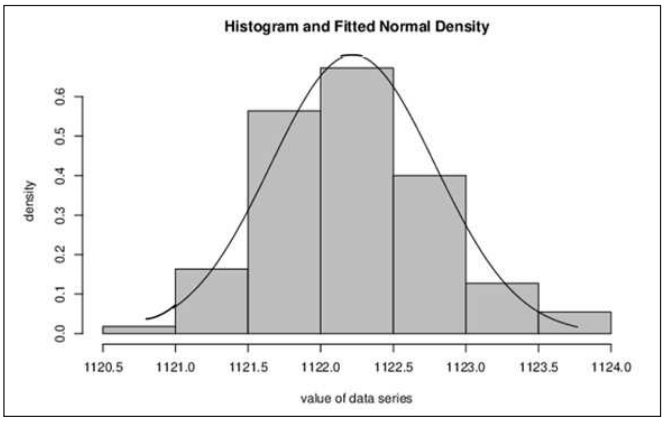

Fig. 4. Histogram of water level data (2013-2022)

anticipated purpose anywhere in the world without the need for permission from official authorities.

In satellite derived bathymetry, there are two approaches through which finer resolution can be obtained. They are based on the principle of using the attenuation of light with depth as a function of wavelength and examining the effect of topography on shallow waters. Lyzenga et al. (2006) proposed a log-linear correlation between multi-band and water depth values and mainly focused on removing all other reflected parameters that weaken the water floor signals. In this method, empirical data is used for model calibration using a minimum of two spectral bands (Eq. 3).

$$\hat{h} = h_0 - \Sigma_{j=1}^{N} h_j X_j \quad (3)$$

Here, $\hat{h}$ refers to the derived bathymetry, h_0 refers to regression coefficient, h_j is regression coefficient of the respective spectral band, X_j is a linear transformation that takes into account the logarithmic attenuation of light at depth.

$$X_j = \ln (L'_j - L'_{Sj}) \quad (4)$$

Here, L'_j, represents the corrected signal of the corresponding band and L'_{Sj} is the optically corrected signal band for deep waters.

However, in the log-linear approach proposed by Lyzenga et al. (2006), at least five variables derived empirically using two spectral bands must be known, which may limit its use in large areas (Stumpf et al., 2003). In order to correct this, an algorithm using the log ratio between two spectral bands was proposed by Stumpf et al. (2003) (Eq.5).

$$\hat{h} = h_1 \times pSDB - h_0 \quad (5)$$

$$pSDB = \frac{\ln (nR_W(\lambda_i))}{\ln (nR_W(\lambda_j))} \quad (6)$$

$\hat{h}$ is the satellite-derived bathymetry, h_1 is the changeable constant (based on lake, river or region), h_0 is the depth shift, *pSDB* is the pseudo depth, *n* is the constant used to obtain a positive logarithm from the environmental factor and R_W is the spectral signal for the corresponding band (λ_i and λ_j indicates the surface and the spectral intensity components of the incident sunlight).

This study aimed to determine empirical satellite derived bathymetry using ratio transform algorithm proposed by Stumpf et al. (2003). In the study, Sentinel-2 high resolution multi-spectral satellite images for every July between the years 2015-2020 were used. Table 1 shows the information of the images. The data were obtained from the Copernicus Open Access Hub (https://scihub.copernicus.eu/ , accessed October 2022). The attention was paid not to exceed 10% of the cloud ratio while obtaining the data.

Sentinel-2 data in Table 1 were processed using the open-source SNAP software provided by the European Space Agency. The data were evaluated based on the steps in the webinar held by RUS-Copernicus (https://rus-copernicus.eu/portal/rus-webinar-bathymetry-derivation-using-sentinel-2-data/, accessed October 2022).

Table 1. Information of Sentinel-2 Satellite and MSI1C Images

Parameter	Sentinel-2	Pass Date	Orbits	Tile ID
Start Date	23 June 2015	July 2015	R064	T36SUG and T36SUH
Wide Swath	290 km	July 2016		
Revisit time	5 days	July 2017		
Spatial Resolution	10 m (4 bands : RGB and NIR)	July 2018		
Spatial Resolution	20 m (6 bands: Red Edge and SWIR)	July 2019		
Spatial Resolution	60 m (3 bands: Atmospheric correction)	July 2020		

In order to obtain satellite derived bathymetry from Sentinel-2 high resolution multi-spectral satellite images with SNAP software, the steps suggested by Drakopoulou et al. (2018) in Fig. 5 were followed. After the data were obtained, the images with T36SUG and T36SUH tile ID in the orbit numbered R064 passing over the lake were merged, and a subset was created from the region covering the lake area. Then, Land mask was performed to remove the land areas from the images (Fig. 6).

RESULTS AND DISCUSSION

Satellite altimetry data was used to determine the water level of Beysehir lake. "Water Level-Water Level V2 lakes NRT" data cataloged by Copernicus Global Land Service was retrieved from the website (https://land.copernicus.eu/, accessed October, 2022). The data for the years 2013-2022 are shown in Fig. 3. In the study, the lake level trend was determined using the monthly average lake level values between 2015-2020. In order to ensure quality control on the data, first, gross errors (outliers) were identified through the Gaussian

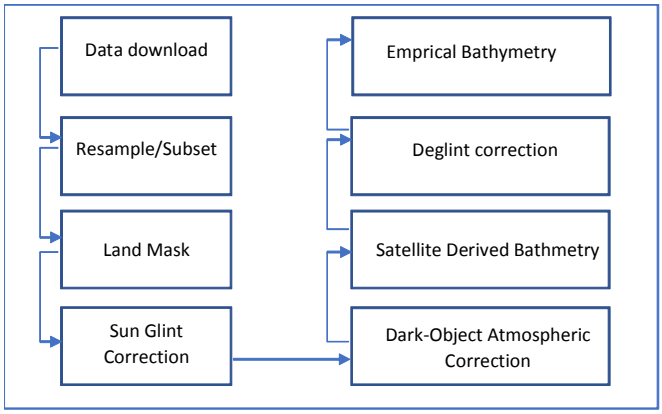

Fig. 5. The algorithm of Creating of Satellite Derived Bathymetry in SNAP Software

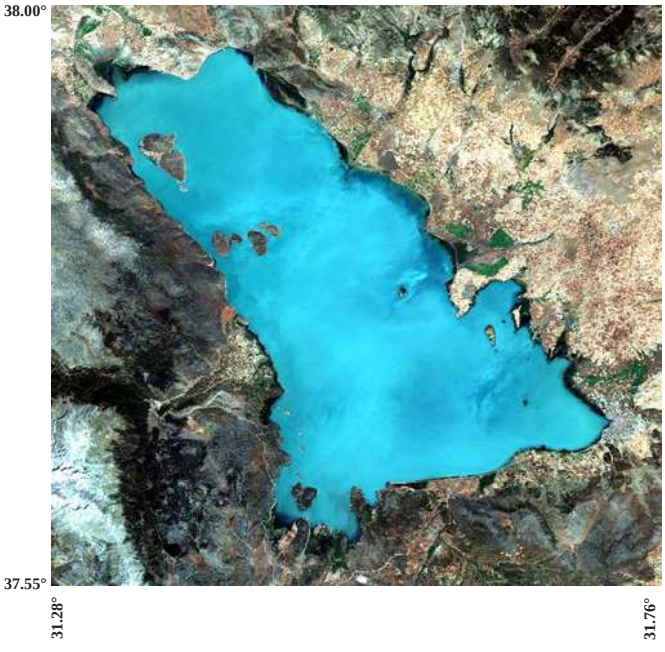

Fig. 6. Red-Green-Blue Images of Lake Beysehir from Sentinel-2

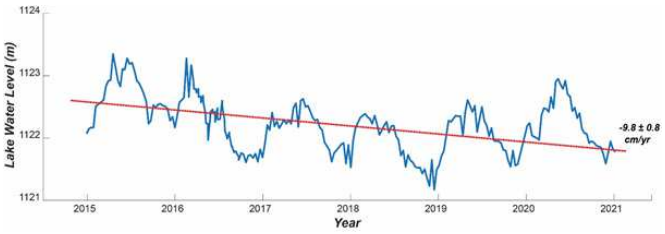

Fig. 7. Water Level Trends

Distribution Function (3-sigma) and removed from the data (Erkoç and Dogan, 2022). After removing the outliers, a significant decrease trend of -9.8 ± 0.8 cm/yr was found in the lake level using the Least Squares Parameter Estimation method (Erkoç et al., 2022) (Fig. 7).

Some studies on the water level of lake Beysehir (Isildar, 2010; Demir and Keskin, 2020; Erkoç, 2023). Isildar (2010) investigated the causes of anthropogenic effects on lake Beysehir and found that the lake level decreased. Similarly, Demir and Keskin (2020) indicated a decrease in the lake level. On the drought signs in Lake Beysehir, Erkoç (2023) determined a decreasing trend in the lake water level using satellite altimetry data and, it was proved that this decrease was due to drought through meteorological indexes (Standardized Precipitation Index/ Standardized Precipitation Evapotranspiration Index) and water indexes (Normalized Difference Water Index/ Modified Normalized Difference Water Index) obtained from Sentinel-2 satellite images.

High resolution multispectral satellite images are exposed to the sunglint effect due to the reflection of the sun on water surfaces as if it were a mirror. Sentinel-2 is affected by sunlight because of the geometry of satellite images. If any bathymetric measurements are made in seas, lakes or rivers, this effect must be removed since sunglint correction will affect the visibility of the seabed. In this study, the deglint model proposed by Hedley et al. (2005) was applied. In this model, the relationship between NIR and visible bands is determined using linear regression based on a sample of pixels in the image. After sun glint correction, dark object subtraction phase, in which atmospheric scattering from dark objects is considered to be an important component of atmospheric correction method, was started. This correction was removed by subtracting an atmospheric offset from the image itself from each pixel in the band used. After these corrections, Satellite Derived Bathymetry data were obtained on a pixel basis. Figure 8 shows (a) land mask applied image, (b) the image obtained after sun glint correction, dark object subtraction and deglint correction (the analysis of the image in 2017 is shown as an example).

The process steps in Fig. 5 were followed and Satellite Derived Bathymetry was obtained. Then, the bathymeter map was produced using the Empirical Bathymetry Processor in the Sen2cor module in the SNAP software (Fig. 9).

Since Beysehir lake has an area of approximately 650 km^2, bathymetric map with in-situ data is both tedious and costly. For this reason, in-situ data and bathymetry of the lake cannot be determined frequently. Mercan and Kabdasli (2011) provided a bathymetry model based on the observations of the Turkish General Directorate of State Hydraulic Works and reported that the depth of lake Beysehir was 6-8 meters in 2001. It was also stated in the same study that the lake level between 1993-2001 was approximately 1123 m (Mercan and Kabdasli, 2011). Simav and Yildiz (2021) aimed to determine bathymetry in the seas and large lakes of Türkiye using in-situ data and space born gravity. In their study, lake Beysehir was among the big lakes, and the maximum depth was calculated as 6.1 m and the average depth as 3.8 m (Simav and Yildiz, 2021). In the present study, satellite derived bathymetry didn't compare with in-situ bathymetrical observation or model because the data was non-public. Because of this reason the study's results were confirmed with Simav and Yildiz (2021)'s study. The in-situ observations made in that study and the time span in this study are quite compatible with each other. The values in Table 2 also seem to be in consistent with those in previous studies in the literature. Here, the difference of the present study with Mercan and Kabdasli (2011) is thought to be due to the limitations of the observation in 2001 when the study was conducted. In addition, the Pearson Correlation was performed between the decrease in water level and the average depth, and the correlation coefficient (r) was found to be 0.92 (Fig. 10) (Erkoc and Dogan, 2022). In addition, Erkoç (2023) reported that the reason for the decrease in the lake level was drought. The decrease in the lake water level caused by the drought may lead to a change in the bathymetry due to the sedimentation of the reeds and plants on the lake surface. Thus, it can be concluded that there is a positive relationship between bathymetry and drought.

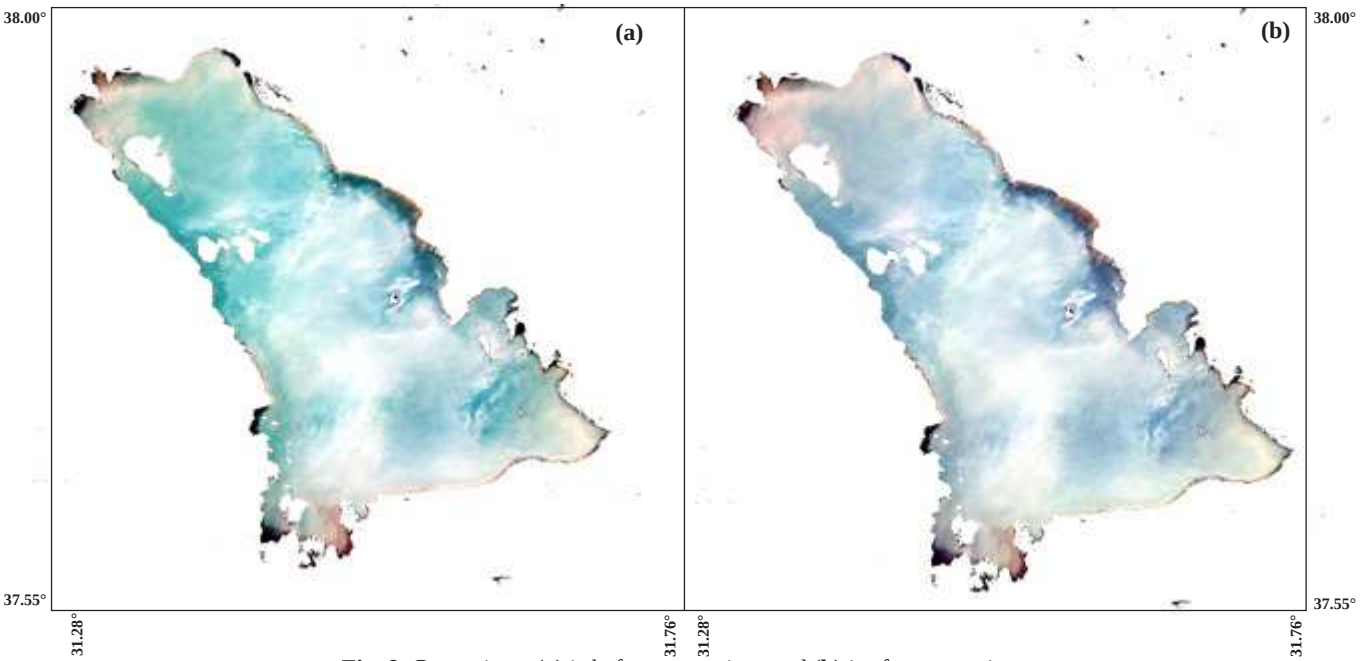

Fig. 8. Corrections, **(a)** is before corrections and **(b)** is after corrections

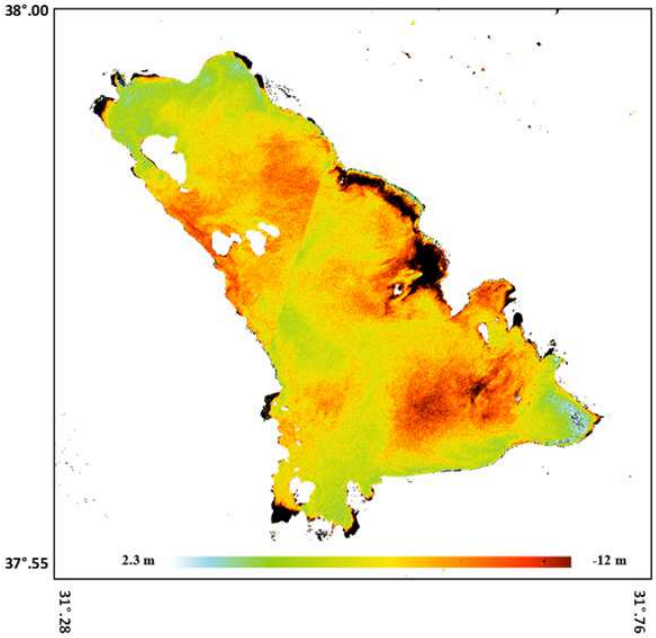

Fig. 9. Shows Empirical Satellite Derived Bathymetry values.

Table 2. Water Level, Maximum and Mean Depth of Beysehir Lake

Year	Lake Water Level (m)	Maximum Depth (m)	Mean Depth (m)
2015	1123.07	13.44	8.44
2016	1122.35	12.88	8.02
2017	1122.42	12.75	6.94
2018	1121.90	11.32	5.92
2019	1122.17	10.20	5.51
2020	1121.75	9.15	4.06

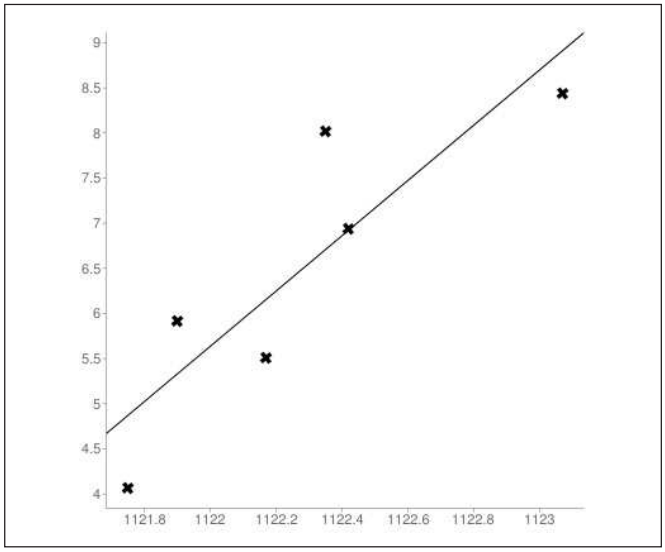

Fig. 10. Pearson correlation coefficients between water level and bathymetry.

CONCLUSIONS

Lake Beysehir is the third largest lake in Türkiye in terms of surface area and the largest freshwater lake in Türkiye. In this study, the "Water Level-Water Level V2 lakes NRT catalog data" provided by Copernicus Global Land Service was used to estimate the change in Lake Beysehir water level between 2015-2020. These data are provided to the user with all corrections. According to the data, it has been determined that the water level in the lake gradually decreased between the years 2015 and 2020, based on the months of July, and it was found that there was a decrease of more than 1 meter in July 2020 compared to July 2015. The downward trend was estimated as -9.8 ± 0.8 cm/yr. Considering that there would be a change in bathymetry with this decrease in water level, Sentinel-2 high resolution multi-spectral satellite images were downloaded from the website of the Sentinel-hub data provider and evaluated using SNAP software. After the necessary corrections were made on the satellite images, the Satellite Derived Bathymetry Values were obtained. Accordingly, it was found that the average depth in the lake changed by approximately 5 meters between the years 2015-2020. In addition, there was a decrease of 4 meters at the maximum depth. The most important reason for such a finding is thought to be the decrease in the water level and the reeds and plants on the surface forming sediment at the bottom and solidifying. In addition, a 92% of correlation was calculated between the decrease in lake level and the depth change. Furthermore, this study proposes that satellite data can be used to determine water levels and bathymetry in situations where in-situ or traditional observations are not accessible.

Acknowledgements: The author thanks all data providers. Satellite altimetry data were obtained from Copernicus Global Land Service. The Sentinel-2 images were downloaded via Copernicus Open Access Hub and processed with open source SNAP software.

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