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ORIGINAL ARTICLE

Spatial distribution, hydrological status of Karst Lakes in Türkiye

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Abstract
Türkiye hosts a wide range of karst lakes developed within extensive soluble rock terrains; however, their spatial distribution and current hydrological conditions have not yet been comprehensively quantified at the national scale. This study provides a nationwide assessment of the spatial distribution, morphometric characteristics, and current hydrological status of karst lakes in Türkiye utilising Geographic Information Systems (GIS) and remote sensing (RS) techniques. Based on multi-temporal satellite imagery and topographic maps, 688 karst lakes were identified and classified into doline (69%), glaciokarstic (24%), and polje (7%) lake types. Mean surface areas were 0.021 km^2 for doline lakes, 0.017 km^2 for glaciokarstic lakes, and 29 km^2 for polje lakes, and the lake elevations span a broad altitudinal range from 23 to 3400 m a.s.l., with mean elevations of 1345 m for polje lakes, 1657 m for doline lakes, and 2870 m for glaciokarstic lakes. The 2020–2023 assessment indicates that 41% of the karst lakes have completely dried, with desiccation reaching 54% for polje lakes. Wet lakes generally occur under cooler, wetter climatic conditions than dry lakes, suggesting a strong hydroclimatic control on lake persistence, particularly in doline and glaciokarstic systems. In contrast, polje-lake desiccation is more strongly associated with long-term anthropogenic impacts, including drainage and water abstraction, than with climatic gradients alone. These findings document an accelerated loss of karst lake ecosystems in Türkiye and underline the need for integrated, climate-responsive strategies for groundwater and wetland management.

Keywords Karst geomorphology · Karst lake classification · GIS · Satellite imagery · Türkiye

Introduction

Lakes provide essential ecosystem services, including freshwater supply, biodiversity support, climate regulation, and recreation (Baker & Newman 2013; Bonacci et al. 2009; Ravbar et al. 2021; Sterner et al. 2020; Tockner 2021; Worthington & Lowe-Mcconnell 1994). However, many lakes are increasingly threatened by pollution, eutrophication, climate change, excessive water abstraction, and other human pressures (Dudgeon et al. 2006; O'Reilly et al. 2015; Schindler 2006; Smith & Schindler 2009) and nearly one-third of the world's lakes are affected by significant human-induced stress (Mammides 2020; Modaresi Rad et al. 2022; Vavassori et al. 2022). These pressures undermine the ecological integrity and functioning, with consequences for biodiversity and human wellbeing (Carpenter et al. 1998).

Karst lakes are especially sensitive to these pressures because they are strongly connected to groundwater systems and can respond rapidly to both hydroclimatic variability and anthropogenic disturbance (Goldscheider 2019; Radulović, 2018; Vrsalović et al. 2022). They also provide unique habitats that support high biodiversity, including rare and endemic species (Lopez et al. 2009; Morant et al. 2024; Siegel et al. 2023), making them priority targets for integrated management and protection (Goldscheider 2019).

Türkiye is rich in karst landscapes due to the widespread distribution of soluble rocks, which cover approximately 40% of the country's surface area (Nazik et al. 2019) (Fig. 1). Although numerous studies have examined karst lakes in Türkiye (Akpınar & Akbulut 2007; Aşıkkutlu et al. 2014; Biricik & Bozyiğit 1996; Çayır & Küçükönder 2018; Çelik & Gülersoy 2013; Duman & Çiçek 2012; Ekmekçi, 1998; Güldalı, 1976; Kahraman & Öztürk 2025; Kurt 2001; Özdemir & Bahadır, 2009; Öztürk, Poyraz, et al. 2025b, a;

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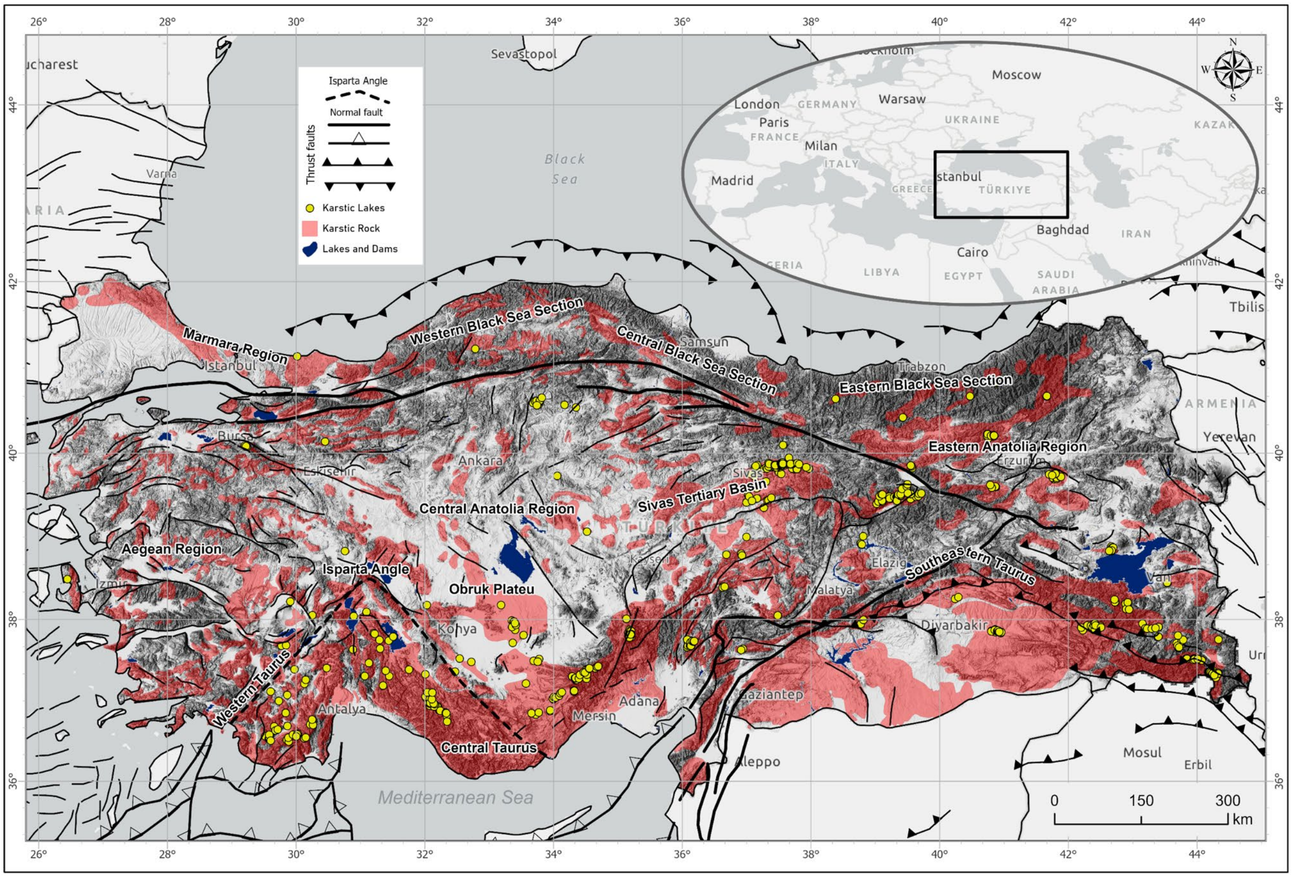


Fig. 1 Location map and distribution of karst lakes on soluble rocks (karstic rock data modified from Nazik et al. 2019, and active fold data modified from Emre et al., 2018)

Pınar et al. 2018; Polat 2011; Zeybek 2004) Existing work has primarily focused on individual lakes or limited regions and therefore does not provide a systematic nationwide evaluation of their spatial distribution, morphometric properties, and current hydrological status. This knowledge gap constrains evidence-based conservation planning and sustainable water management at the national scale.

The primary aim of this study is to provide a comprehensive, nationwide assessment of the current status of karst lakes in Türkiye. To achieve this objective, we identify the spatial distribution of karst lakes across the country, quantify key morphometric characteristics, particularly surface area, and evaluate present hydrological conditions. The findings are expected to provide critical insights into the current condition of these sensitive ecosystems across diverse settings, from coastal zones to high mountain ranges in karst-rich Türkiye, and to establish an essential baseline for future monitoring and management. The pronounced reductions in lake surface area documented by our analyses further underline the urgency of such a national-level assessment.

Study area

Türkiye lies within the Alpine–Himalayan Orogenic Belt and is characterised by a high plateau bordered by seas on three sides. The present-day topography of Türkiye largely reflects neotectonic processes, including regional uplift (Göncüoğlu 2019; Okay et al. 2020; Şengör & Yazıcı, 2020). Geodynamic reconstructions indicate uplift progressively exposed neritic and shallow-marine deposits to subaerial conditions, which in turn promoted the establishment of fluvial networks and widespread karstification (Kuzucuoğlu et al. 2019; Monod et al. 2006; Şener et al. 2023; Umhoefer et al. 2020). Within this tectonic framework, structural deformation plays a key role: faulting and fracturing enhance rock permeability, facilitate groundwater circulation, and accelerate karst development in soluble lithologies (Bayarı et al. 2017; Frisia & Borsato 2010; Günay 2009). Consequently, extensive carbonate and evaporite terrains across Türkiye host a wide range of karst landforms and karstic hydrological systems (Nazik et al. 2019; Şener et al. 2023).

In addition to geology and structure, karstification in Türkiye is strongly influenced by present and past climatic conditions. According to the Köppen–Geiger climate classification, 14 distinct climate types occur across country (Taşoğlu et al. 2024). This climatic heterogeneity controls effective recharge, evapotranspiration demand, and seasonal water availability, thereby influencing both karst processes and the hydrological functioning of karst lakes. In mountainous regions, cryospheric conditions further modulate the water balance through snow accumulation and melt, which can be particularly important for high-altitude karst basins (Çallı et al. 2022).

During Quaternary glacial periods, alpine glaciers formed in the high mountainous areas of Türkiye, leading to glacial erosion and the development of cirques and overdeepened depressions in carbonate terrains (Öztürk, Şimşek, et al., 2025; Şimşek et al. 2019, 2023). Following the Last Glacial Maximum, as glaciers retreated, former cirque areas within limestone formations were further modified by karst processes and locally filled with water, resulting in the formation of glaciokarstic lakes (Öztürk et al. 2021). In this context, the coexistence of lowland and plateau karst basins, high mountain karst with glacial imprint, and diverse climate settings has produced a rich spectrum of karst geomorphology and lake environments across Türkiye (Atalay 2016; Ekmekçi, 2005; Günay et al. 2015; Nazik & Poyraz 2017; Öztürk 2020; Şener & Öztürk 2018).

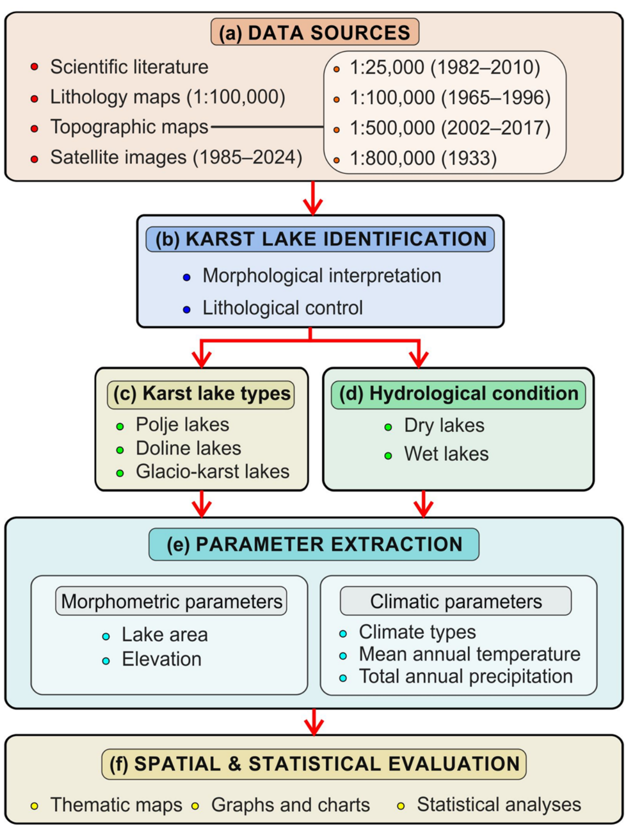


Fig. 2 Workflow diagram of the study

Karst lakes constitute an essential component of Türkiye's freshwater resources because they commonly interact with groundwater systems and may respond rapidly to changes in recharge conditions and human water use (Fig. 2). Although Türkiye is often considered to have relatively abundant water resources, spatial and seasonal imbalances in water availability, recurrent drought conditions, and increasing demand create growing pressure on both surface and groundwater resources (Altinbilek & Hatipoglu 2020; Cetin 2020; Kilic & Gunal 2021; Yavaşlı & Erlat 2023). These pressures are especially relevant in arid and semi-arid regions where irrigation and groundwater abstraction can intensify hydrological stress and accelerate the vulnerability of karst lakes.

Methodology

This study employed GIS and RS techniques to compile a nationwide inventory of karst-origin lakes in Türkiye and to evaluate their recent hydrological condition and key morphometric and climatic attributes. Compared with purely field-based or site-specific surveys, these techniques provide efficient, repeatable, and spatially comprehensive analyses for detecting lake-area changes and assessing lake status across large and topographically diverse regions (Ahmood et al. 2024; Al-Lami et al. 2023; Bao et al. 2024; Demir & Keskin 2020; Dervişoğlu et al. 2022; Dörnhöfer & Oppelt 2016; Günbey & Böcük, 2024a, 2024b; Luo et al. 2024; Mulu et al. 2024; Sağır et al. 2024; Wang et al. 2024). In addition, the GIS environment facilitates standardised morphometric measurements and supports comparative evaluations of lake behaviour across different karst settings and climate zones.

The main workflow of the study (Fig. 2) consisted of the following steps: (a) To identify karst lakes, satellite images from various periods, topographic and geological maps at different scales, and relevant literature were reviewed. (b) All identified lakes were digitised in a GIS environment as polygon vector data, based on their surface areas at the time of their most recent water retention. (c) The digitised lakes were classified into three main groups based on geomorphological setting and morphological characteristics: polje lakes, doline lakes, and glaciokarstic lakes. The classification of lakes is explained in detail in the next section. (d) The hydrological status of the lakes was evaluated using satellite imagery from 2020 to 2023. Lakes with a visible water surface during this time were classified as "wet," while those without a visible water surface were categorised as "dry." (e) Additional datasets were used to determine the morphometric and climatic characteristics of the identified lakes. Elevation data were extracted from a 5-m resolution

Digital Elevation Model (DEM). For temperature and precipitation characteristics, monthly average temperature and monthly total precipitation data from the CHELSA-V2.1 dataset were used (Karger et al. 2021). This dataset was selected due to its proven accuracy in high-resolution precipitation estimation (Osejo et al. 2019) and reliability in ecological modelling (Bobrowski et al. 2021). The climate zones in which the lakes are located were derived from the 700 m resolution Köppen-Geiger climate classification map of Türkiye (Taşoğlu et al. 2024). (f) In the final stage, the resulting morphometric, climatic, and classification data were subjected to statistical analysis, and the findings were visualised and presented through maps and graphs.

Classification of Karst lakes

Lakes can be classified into different types based on their origin and the geomorphological settings (Lapierre et al. 2023; Lewis Jr., 1983). Karst lakes represent a distinct group that develops within terrains dominated by soluble rocks (mainly limestone and gypsum), where dissolution and related karst processes create closed depressions that may retain water seasonally or permanently (Chervyatsova et al. 2025; Nicod 2006; Zerga 2024). Karst lakes can be classified in different ways. In this study, they were grouped into three genetic types based on their geomorphological context and developmental characteristics: polje lakes, doline lakes, and glaciokarstic lakes.

Polje lakes: Poljes are broad, flat-floored, closed depressions that are characteristic features of karstic regions and are generally formed through the combined effects of tectonic movements and karst dissolution (Bonacci 2013; Ford & Williams 2007). In Türkiye, poljes are particularly widespread within the Taurus Mountains (Şimşek et al. 2021) and Sivas gypsum karst area (Doğan et al. 2022; Gökkaya & Gutiérrez 2022; Poyraz et al. 2021). Permanent or seasonal lakes may develop on polje floors when ponors are blocked and/or during periods of high precipitation, and such water bodies are referred to here as polje lakes (Figs. 3a,b).

Doline lakes: Dolines are small, typically circular or oval-shaped closed depressions and represent one of the most common landforms in karst regions (Ford & Williams 2007; T. Waltham et al. 2005). Depending on local drainage properties and hydrological conditions, some dolines host seasonal or permanent lakes (Figs. 3c,d).

Glaciokarstic lakes: Glaciokarst refers to terrains shaped by the combined effects of glacial processes and karstic dissolution (Veress 2023; Žebre & Stepišnik 2016). During Quaternary glaciations, alpine glaciers in Türkiye's high mountain belts excavated cirques and overdeepened depressions in carbonate terrains and, in some cases, further deepened pre-existing dolines (Öztürk, Şimşek, et al., 2025; Şimşek et al. 2023). Following deglaciation, these depressions were modified by karst processes and locally filled with meltwater and precipitation, forming glaciokarstic lakes (Figs. 3e,f). In this study, lakes situated within glacially eroded limestone terrains were classified as glaciokarstic lakes. Because their water balance is strongly influenced by snow accumulation and melt, combined with karstic drainage, these lakes can be sensitive indicators of environmental change, particularly under ongoing warming and glacier retreat (Veress & Lóczy 2019).

At the national scale, the distribution of karst lakes reflects broader regional differences in Türkiye's karst development. Based on the morphogenetic and morphometric characteristics of surface and subsurface landforms, the karst of Türkiye is classified into six main karst regions (Nazik et al. 2019): the Taurus Mountains, Thrace and the Black Sea Mountains, Central Anatolia, Eastern Anatolia, Western Anatolia, and Southeastern Anatolia karst regions (Fig. 4a). Each region exhibits distinct developmental patterns arising from differences in lithology, tectonic framework, and Quaternary climatic history. This spatial differentiation has important implications for the distribution of karst-lake types across the country. For example, polje lakes are most characteristic of the Western Taurus. In contrast, doline lakes are more widespread in the Central Taurus, Central Anatolia, the Sivas gypsum karst, and high karst plateaus. In comparison, glaciokarstic lakes primarily develop in the formerly glaciated alpine belts of the Eastern Taurus, where Quaternary glaciation created cirques and overdeepened depressions that were later modified by karst processes.

Results

A total of 688 karst lakes were identified across Türkiye using literature, multi-temporal satellite imagery, and topographic–geological map interpretation. Although lakes occur countrywide, the distribution is strongly clustered in four belts: (i) the Taurus Mountain karst belt, (ii) the Obruk Plateau in the Central Anatolia Karst Region, (iii) the Sivas gypsum karst in the Upper Kızılırmak karst region, and (iv) the Plateau karst area in the Central Anatolia Karst Region (Fig. 4a). In terms of origin, doline lakes dominate (473; 69%), followed by glaciokarstic lakes (167; 24%) and polje lakes (48; 7%). While doline lakes are dispersed nationwide, polje lakes are concentrated mainly in the Western–Central Taurus and the Sivas gypsum karst. In contrast, glaciokarstic lakes are restricted to previously glaciated high-mountain sectors along the Taurus belt (Fig. 4a).

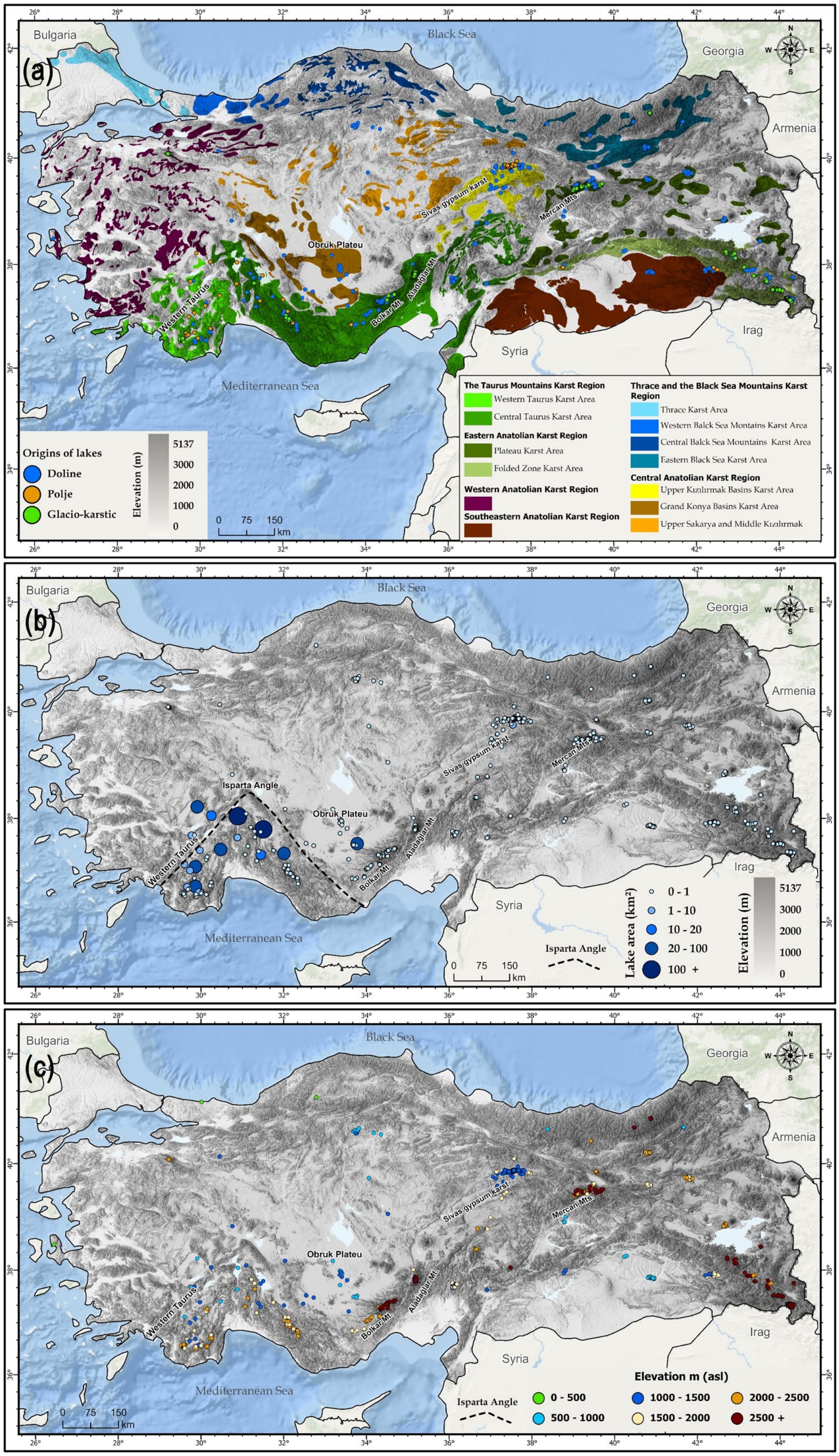
According to average surface area values, doline lakes cover approximately 0.021 km^2, glaciokarstic lakes 0.017

Fig. 3 Examples of karst lakes: **a** a polje lake (Lake Avlan), **b** a dried polje lake (Gembos Polje), **c** a dried doline lake (Çıralı Sinkhole), **d** a doline lake developed on gypsum, **e** examples of glaciokarstic lakes: Dipsiz Lake in the Aladağlar Mountains, and **f** Çinili Lake in the Bolkar Mountains

km^2, while polje lakes are significantly larger, with an average area of 29 km^2. The largest polje lakes are located in the region known tectonically as the Isparta Angle, which encompasses the western sections of the Western and Central Taurus Mountains (Fig. 4b). This region was shaped during its most recent developmental phase under the influence of extensional tectonic processes, resulting in the formation of extensive poljes and large polje lakes within them (Şener et al. 2023).

Excluding polje lakes, lake-area statistics show that the vast majority of lakes have surface areas < 1 km^2. Mean lake areas are 0.021 km^2 for doline lakes, 0.017 km^2 for glaciokarstic lakes, but a much larger 29 km^2 for polje lakes (Fig. 4b). The largest polje lakes occur in the Isparta Angle, encompassing the western parts of the Western and Central Taurus Mountains, where their spatial pattern suggests strong structural and tectonic control on the formation of large closed depressions (Fig. 4b). Because polje lakes are few but very large, they dominate national-scale surface-water storage within karst-lake systems. Therefore, even a small number of polje-lake drying events can produce

Fig. 4 **a** Distribution of karst lakes by origin and the number of wet and dry karst lakes. **b** Distribution of karst lakes by surface area. (Based on their most recent water-retaining state). **c** Elevation distribution map of the lakes



disproportionately large losses in total lake area and ecosystem services compared to numerous small doline lakes.

Karst lakes span a broad altitudinal range (23–3400 m a.s.l.) with a marked increase in lake frequency above 1300 m (Fig. 4c; Fig. 5). Mean elevations differ strongly by type: polje lakes 1345 m, doline lakes 1657 m, and glaciokarstic lakes 2870 m, reflecting distinct geomorphic settings. Regionally, lakes in the Western Taurus are mostly < 1000 m, whereas many other regions concentrate between 1000–2000 m; glaciokarstic lakes cluster > 2000 m. The increase in lake counts above ~ 1300 m (Fig. 5) is caused by the higher frequency of closed depressions on karst plateaus in Central Anatolia and the Sivas gypsum karst region (Fig. 4c). Although over one hundred thousand solution dolines have developed along the Taurus belt (Çetinkaya et al. 2023; Öztürk et al. 2018; Utlu & Öztürk 2023). Most do not retain water because they form on bare limestone and are located within deep karst systems. For this reason, doline lakes are rare across the high karst plateaus.

Based on their current conditions between 2020 and 2023, 409 of the identified karst lakes (59%) retained visible surface water, while 279 (41%) were classified as completely dry. By lake type, 286 doline lakes are wet, and 187 are dry; among glaciokarstic lakes, 101 are wet, and 66 are dry; and for polje lakes, 22 remain wet while 26 are dry. These figures indicate that, in percentage terms, polje lakes have experienced the highest rate of desiccation, at 54%. Considering the most recent dates at which these lakes held water, approximately 14% of the total karst lake surface area has been lost due to drying (Fig. 5).

The desiccation process of karst lakes dates back to the 1970s, but a significant increase has been observed after 2009 (Figs. 6, 7). The temporal distribution of dried lakes reveals specific patterns. For example, one or several polje lakes dry every few years. The prolonged timeline of polje lake desiccation suggests that the cause is not solely climate change but also substantial anthropogenic pressure. In particular, drainage efforts represent the primary factor contributing to the drying of polje lakes in Türkiye.

The drainage of wetlands in Türkiye began in the mid-nineteenth century during the Ottoman Empire. At that time, efforts were initiated to reclaim marshlands through drainage canals, primarily to combat malaria and to gain agricultural land (Çaylı, 2025; Esgibay 2019; Güngör, 2013). In the Republic's early years, drainage activities became formal state policy with the enactment of the "Malaria Control Law" in 1925. Between 1925 and 1932, tens of thousands of hectares of wetlands were systematically reclaimed and converted into farmland. After the 1950s, wetland drainage efforts in Türkiye accelerated significantly, and large-scale projects were implemented under state direction. With the establishment of the State Hydraulic Works (DSİ) in 1953, the drying of many lakes and marshes was systematically planned and executed. As a result of intensive drainage projects, particularly between 1950 and 1975, essential wetland systems and polje lakes such as Lake Işıklı, Lake Amik,

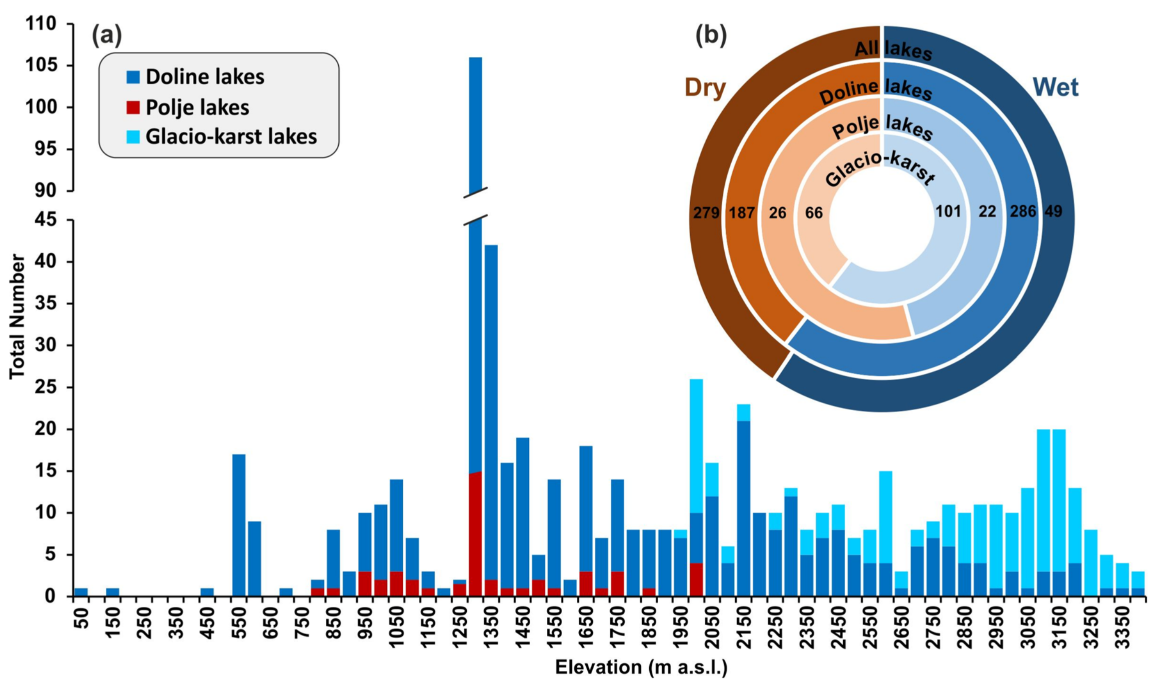


Fig. 5 Distribution of karst lakes according to elevation based on their origins (A broken y-axis (45–90) is used to prevent scale distortion caused by exceptionally high lake frequencies at specific elevation intervals)

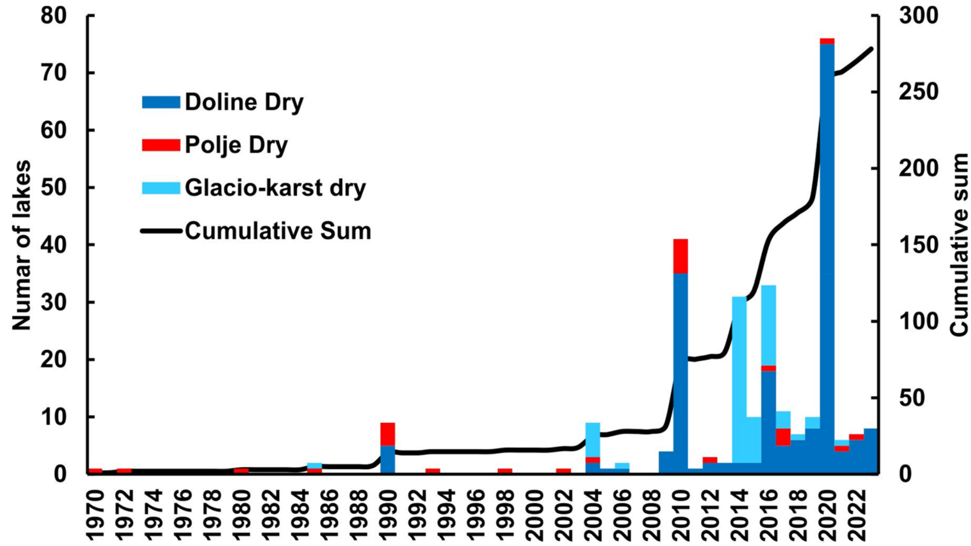


Fig. 6 Temporal change in the number of dried lakes by year

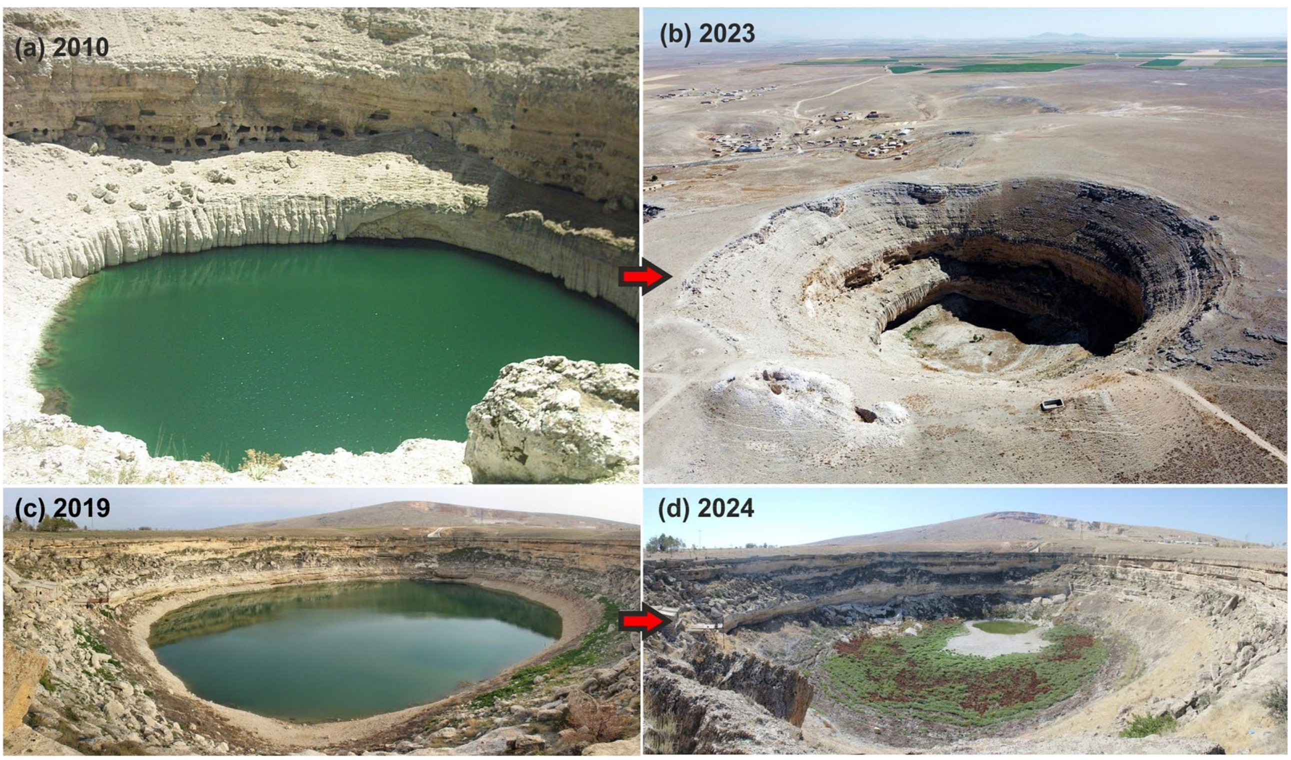


Fig. 7 Examples of dried lakes (a,b) Çıralı doline and (c,d) Timraş doline

Lake Gavur, Lake Hotamış, and Lake Avlan were drained (Çalişkan 2003; Esgibay 2019; Korkmaz 2008).

Doline lakes' desiccation is driven by climate change and excessive groundwater extraction (Öztürk, Poyraz, et al. 2025b, a). This is especially evident in Central Anatolia, where collapse dolines, locally known as “obruk,” have mostly dried up or experienced significant reductions in water volume. 2010, 2016, and 2020 stand out as particularly critical in doline lake desiccation. Glaciokarstic lakes are primarily influenced by snowfall and rainfall in mountainous regions. A significant drying trend was observed in these lakes from 2014 to 2017 (Fig. 6).

There are significant differences in climatic characteristics among lake types. According to the Köppen-Geiger climate classification, the lakes are predominantly distributed within continental (D subtypes) and temperate (C subtypes) climate zones. Approximately 57% of all lakes are located in regions characterised by warm, dry summers, specifically within the Dsb (dry-summer continental) and Csb (Mediterranean) climate types. Among the wet lakes, 67% are concentrated in the Dsb, Dsc (cold-summer continental), and Csb climate zones. In contrast, dry lakes are mainly in the Csb (37%) and Dsb (33%) types. Beyond these dominant categories, many dry lakes are also found in the semi-arid BSk and cold alpine ET climate types (Figs. 8 and 9a).

Lake types also differ significantly between annual total precipitation and average temperature. All lakes are distributed within a climatic range of 200 to 2,700 mm of annual precipitation and average temperatures between −3.4 °C and +17 °C. Regarding current hydrological status, wet lakes receive an average of 975 mm of annual precipitation, whereas dry lakes receive approximately 675 mm. Wet lakes have an average temperature of 5.5 °C, while dry lakes are exposed to warmer conditions, averaging 7.0 °C. These values indicate that dry lakes are generally located in warmer regions with lower annual precipitation (Fig. 9e).

By lake type, wet doline lakes receive an average of 833 mm of precipitation and have a mean temperature of 6.8 °C. In contrast, dry doline lakes receive only 482 mm and experience a higher mean temperature of 8.7 °C (Fig. 9f). Among glaciokarstic lakes, wet ones receive approximately 1,475 mm of precipitation and have an average temperature of 0.9 °C. In comparison, dry glaciokarstic lakes receive around 1,243 mm and have a slightly higher temperature of 1.1 °C (Fig. 9h). In contrast, polje lakes show the opposite pattern: wet polje lakes receive about 538 mm of precipitation with a mean temperature of 9.9 °C, whereas dry polje lakes receive slightly more precipitation (629 mm) and have a slightly lower temperature (9.4 °C) (Fig. 9c). These data indicate that, for doline and glaciokarstic lakes, above-average temperatures and below-average precipitation are key drivers of desiccation. In contrast, precipitation and temperature appear to have no apparent influence on the drying of polje lakes.

Discussion

Globally, karst lakes are increasingly threatened by the combined effects of climatic variability and intensifying human pressure, particularly in arid and semi-arid lowlands where irrigation demand is high (Akbas 2024). Their strong connectivity with groundwater systems makes karst lakes highly sensitive to both climate-driven recharge variability and anthropogenic disturbances such as groundwater abstraction and contamination (Cao et al. 2023; Kalhor et al. 2019). Given that karst aquifers provide freshwater resources for a substantial share of the global population, monitoring karst-lake dynamics and managing karst water resources sustainably are of critical importance (Brinkmann & Parise 2012; Goldscheider et al. 2020).

In Türkiye, climatic variability and anthropogenic pressures have substantially influenced the recent hydrological evolution of karst lakes. The years 2010, 2014, 2016, and 2020 stand out as critical turning points in the desiccation trends of these lakes. Although 2010 witnessed above-average precipitation nationwide, mean temperatures were 2.4 °C higher than the long-term national average (MGM

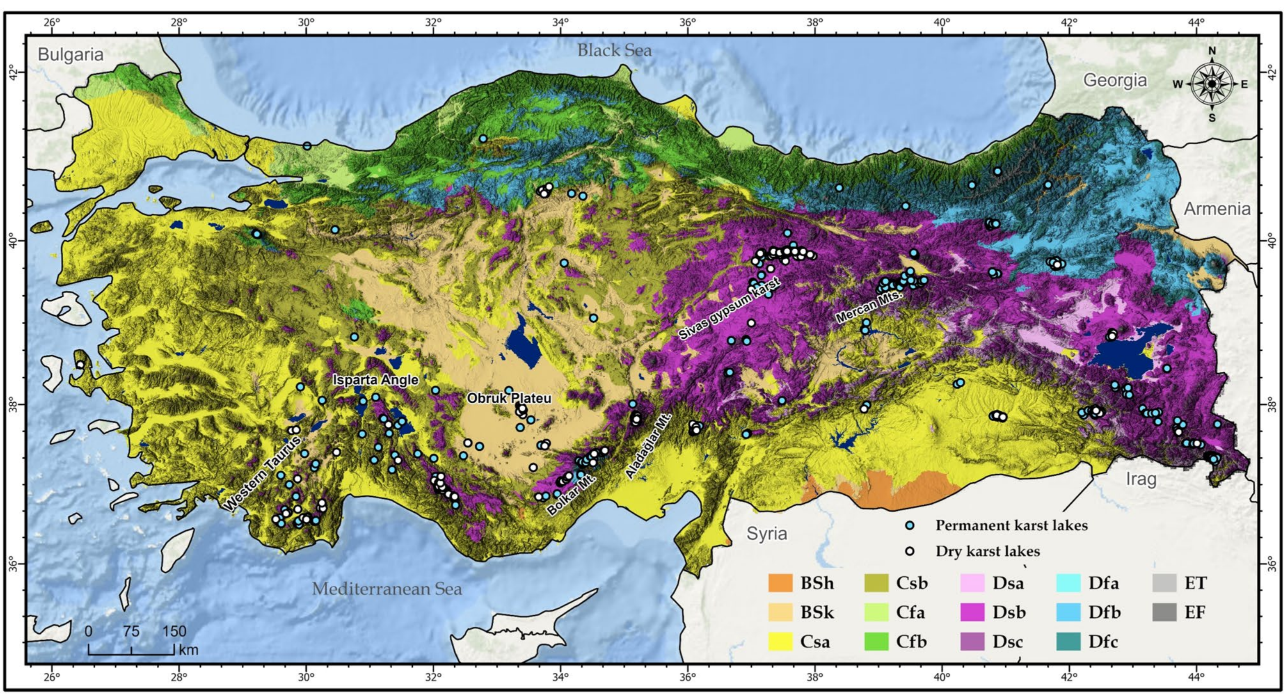


Fig. 8 Distribution of wet and dry lakes by climate zones (Climate zones modified from Taşoğlu et al. 2024)

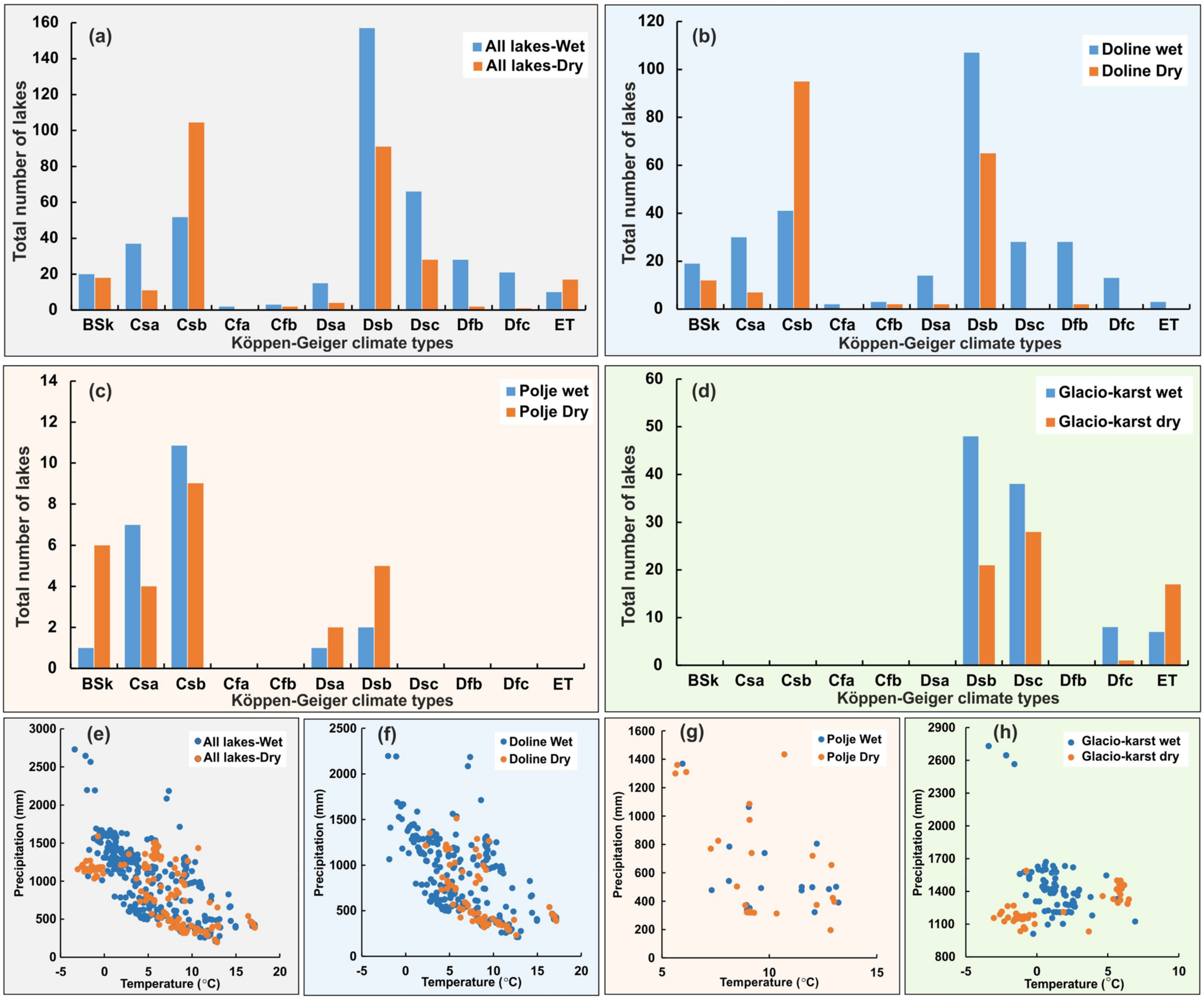


Fig. 9 Distribution of lakes by Köppen-Geiger climate types and associated temperature and precipitation values of their respective locations

2012). In 2014, despite high overall precipitation, significant spatial disparities in rainfall distribution were observed. In particular, Eastern Central Anatolia (including Sivas and surrounding areas), as well as all of Eastern and Southeastern Anatolia, recorded below-average precipitation (MGM 2015). While the overall precipitation in 2016 aligned with national averages, southern regions experienced notable deficits (MGM 2017). In 2020, total annual precipitation was 13% below average, and drought conditions prevailed across much of the country, with some provinces recording the driest year in the past four decades (MGM 2021). These data suggest that major drying events in Türkiye's karst lakes occurred during these years. Although the total annual precipitation may have appeared sufficient, elevated temperatures, seasonal and regional imbalances in rainfall distribution, and the pronounced deficit observed in 2020 emerged as primary natural drivers of lake desiccation.

Long-term climate trends further amplify these vulnerabilities. Türkiye, as part of the Mediterranean Basin, is recognised as one of the regions most vulnerable to climate change, exhibiting pronounced warming trends and regionally differentiated precipitation patterns over recent decades (Yavaşlı & Erlat 2023). Observational datasets and reanalysis-based studies consistently indicate statistically significant increases in annual and seasonal mean air temperatures across the country, with a marked acceleration of warming since the early 1990s (Yavaşlı, 2025; Yavaşlı & Erlat 2023). This sustained temperature increase has led to a substantial rise in potential evapotranspiration demand, thereby intensifying pressure on hydrological systems and surface water resources. In contrast, precipitation trends do not display a uniform signal at the national scale; while increasing tendencies have been observed in the Marmara and Black Sea regions, long-term declines and heightened

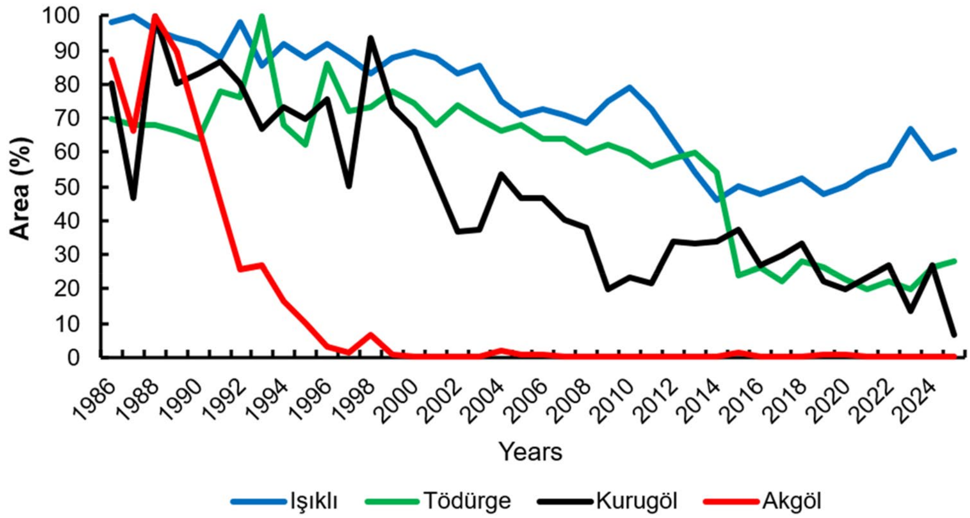


Fig. 10 Interannual changes in the surface area of selected polje lakes (Area values are shown as percentages (%) normalized to the maximum (largest observed) area of each lake (maximum = 100%))

seasonal irregularity dominate in the Mediterranean, Central Anatolia, and Southeastern Anatolia regions (Erlat & Yavaşlı, 2025; Nacar 2023). Beyond changes in total precipitation amounts, alterations in the temporal distribution and intensity of rainfall have further reduced effective groundwater recharge and surface water retention by enhancing rapid runoff processes (Mersin et al. 2022; Nacar 2023). Consequently, the combined effects of increasing temperatures and decreasing or increasingly irregular precipitation regimes have disrupted lake water balances by amplifying evaporation losses and constraining renewable water inputs. Recent declines in water levels and surface areas observed in numerous natural lakes across Türkiye can therefore be attributed mainly to these climate-driven processes, highlighting the growing impact of climate change on lacustrine hydrology and ecosystem stability.

In addition to these climatic factors, increasing groundwater extraction for agricultural irrigation, particularly in Central Anatolia, has significantly decreased groundwater levels. These declines have resulted in the drying of groundwater-fed doline lakes and accelerated the formation of subsidence and collapse dolines in the region (Eren et al. 2024; Orhan et al. 2024; Öztürk, Poyraz, et al. 2025b, a).

Drying trends in glaciokarstic lakes have also become more pronounced in recent years. These lakes are predominantly fed by snowmelt, and meteorological station data indicate a significant downward trend in snow depth and the number of snow-covered days (Akyurek et al. 2023; Topuz 2023; Topuz & Karabulut 2021). Under continued warming, such changes may increasingly affect high-altitude glaciokarstic systems, even where annual precipitation remains relatively high.

Factors such as the extent of agricultural land surrounding the lakes, the number of water wells, and the depths of those wells play a significant role in the desiccation of polje and doline lakes. These conditions should be considered in future studies. In addition to anthropogenic influences, the intermittent reopening of previously blocked ponors also plays a significant role in the desiccation of polje lakes (Doğan et al. 2025).

Although 46% of polje lakes still contain permanent water bodies, water extraction has significantly reduced lake volume, particularly for agricultural purposes (Fig. 10). For example, in Lake Akgöl, the surface water area was approximately 53 km^2 during the winter of 1985, but by the winter of 2023, it had decreased to just 0.41 km^2. This represents a nearly 99% reduction in surface area (Öztürk, Poyraz, et al. 2025b, a). Similarly, the surface area of Lake Suğla declined from 89 km^2 in 1984 to 38 km^2 in 2022 (Coşkun & Minaz 2024).

When compared to global studies, the spatial distribution and hydrological dynamics of karst lakes in Türkiye align closely with similar systems in the Mediterranean Basin, Central Europe, and parts of Asia (Filipović et al. 2023; Goldscheider 2019; Heino et al. 2021; Liang et al. 2024; A. C. Waltham & Fookes 2003). Geological and tectonic processes, along with regional hydrological cycles, largely shape the global distribution of karst lakes. Karst lakes in Türkiye exhibit characteristics comparable to those of the Dinaric Karst in the Balkans, the Alps, and the karst systems of Guizhou and Yunnan provinces in China (Rogora et al. 2003; Thompson et al. 2021; Tolmachev & Leonenko 2005; Wang et al. 2024). For instance, doline lakes are the most widespread type in Türkiye (69%), typically concentrated at elevations between 1,150 and 1,350 m. Similarly, the elevation-based differentiation observed in doline lakes in the Balkans and glaciokarstic lakes in Italy is consistent with the elevational patterns seen among doline and glaciokarstic lakes in Türkiye (Lopez et al. 2009; Thompson et al. 2021; Vrsalović et al. 2022). Most of Türkiye's glaciokarstic lakes are located in the high-altitude zones of the Taurus Mountains and Eastern Anatolia, and they exhibit high sensitivity to seasonal variations. In Germany and Poland, most karst lakes have been lost due to agricultural expansion and urbanisation (Kubiak et al. 2017; Staśko 2024). In China, karst lakes are predominantly found in areas with high precipitation and evaporation rates. For example, the hydrological balance of karst lakes in Yunnan and Guizhou provinces depends heavily on monsoonal rainfall and seasonal temperature fluctuations (Liang et al. 2024). The similar sensitivity of doline lakes in Türkiye's Taurus Karst Belt to precipitation and temperature variability indicates the influence of standard global processes. Climate change is one of the most critical factors affecting the long-term hydrological sustainability of karst lakes. In particular, lakes in semi-arid and continental climate zones are rapidly shrinking due to increasing evaporation and fluctuating precipitation (Heino et al. 2021; Puigserver et al. 2024; Shugar et al. 2020). Most of Türkiye's karst lakes are located within the Dsb (cold-summer continental) and Csb (warm-summer Mediterranean) climate types. This pattern parallels changes observed in the La Mancha lakes of Spain and karst lakes in the southwestern United States (Ford & Williams 2007; Mammides 2020). The extensive anthropogenic desiccation of polje lakes in Türkiye resembles processes seen in the Guadiana River Basin of Spain and the Po Valley of Italy, where many karst lakes have been entirely lost due to agricultural irrigation and groundwater withdrawal (Monteagudo & Moreno 2016). A similar trend has been observed in Türkiye's Konya-Karapınar region, where excessive water use has led to an increase in the formation of sinkholes and the rapid shrinkage of doline lakes (Erol 1990; Kuzucuoğlu 2019; Nazik & Poyraz, 2015; Orhan 2021; Üstün et al. 2007). The long-term sustainability of karst lakes is directly linked to changes in precipitation regimes associated with climate change. Annual fluctuations in water levels observed in the Taurus Karst Belt doline lakes are primarily driven by increased temperatures and reduced rainfall. Similar impacts of climate change have been reported in comparable systems in Italy and Spain (Puigserver et al. 2024; Ravbar et al. 2021; Šarović & Klaić, 2023). Agricultural expansion and groundwater withdrawal are among the main threats to the ecological balance of karst lakes. In Türkiye, many polje lakes have been significantly reduced or completely dried due to drainage projects (Günay et al. 2011; Günay & Çörekçioğlu 2022). Similar trends have been observed in agricultural regions such as Cerkniško Polje in Slovenia and northern Italy (Blatnik et al. 2024; Mayaud et al. 2019). Many karst lakes across Europe have lost their ecological functions due to industrial activities and urban development (Kubiak et al. 2017). Studies conducted in Slovenia indicate that karst lakes are closely linked to groundwater levels and that excessive extraction can lead to irreversible degradation of lake ecosystems (Blatnik et al. 2024; Mayaud et al. 2019). In Türkiye, particularly in the Western Mediterranean and Central Anatolia, seasonal water losses and ecosystem changes have been observed due to declining groundwater levels (Goldscheider 2019).

Conclusion

This study provides the first comprehensive nationwide evaluation of the spatial distribution and current hydrological condition of karst lakes in Türkiye based on GIS and remote sensing data. A total of 688 karst lakes were identified and classified into doline, glaciokarstic, and polje types, revealing precise controls of elevation, climate, and geomorphological setting. The analysis demonstrates that karst lakes in Türkiye are experiencing extensive desiccation, with more than two-fifths of the lakes having entirely dried up in recent years. Drying rates differ markedly among lake types, indicating contrasting sensitivities to climatic variability and human intervention. Polje lakes exhibit the highest vulnerability, primarily reflecting long-term anthropogenic modification, while doline and glaciokarstic lakes are mainly affected by rising temperatures, reduced precipitation, and declining snow availability. Climatic conditions play a key role in lake persistence, with lakes in warmer, drier regions at significantly greater risk of desiccation, particularly in continental and Mediterranean climate zones. These findings highlight the strong coupling between karst lake dynamics and hydroclimatic change. Overall, the rapid loss of karst lakes poses a serious threat to groundwater–surface water interactions and the integrity of karst ecosystems in Türkiye. The results underline the urgent need for integrated groundwater management, regulation of water abstraction, and long-term monitoring strategies to ensure the sustainable conservation of karst lake systems under changing climatic conditions.

Author contributions M.P. and M.Z.Ö. designed the research, performed data collection, and conducted GIS and remote sensing analyses. M.P. wrote the main manuscript text and prepared the majority of the figures. M.Z.Ö. contributed to the preparation of several figures and data interpretation. Both authors discussed the results, contributed to the final version of the manuscript, and approved its submission.

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Declarations

Conflict of interests The authors declare no competing interests.

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