



Landscape-based assessment of trophic shift: integrating remote sensing for sustainable management of Lake Beyşehir

Ö. K. Örücü^{1,2} · S. Örücü^{1,2}

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Abstract

Freshwater lakes are increasingly affected by anthropogenic pressures, leading to rapid changes in trophic status and water quality. This study investigates the spatial and temporal dynamics of trophic status and water quality in Lake Beyşehir, one of Türkiye's largest freshwater lakes, between 2020 and 2025 using a multi-temporal remote sensing and landscape-based assessment approach. Chlorophyll-a (ensemble), Carlson Trophic Status Index, Secchi depth, and Total Suspended Solids were derived from Sentinel-2 imagery within the Google Earth Engine platform, and spatial-temporal changes were evaluated using class transitions and change matrix analyses. The results indicate that approximately 53–64% of the lake surface experienced changes in at least one water quality indicator, corresponding to nearly 46,000 ha. Secchi depth showed the greatest change (63.9%), indicating a substantial decline in water clarity. A clear shift from oligotrophic and mesotrophic conditions toward eutrophic and high-eutrophic states was observed, particularly along the northern and eastern shores, reflecting increasing nutrient enrichment and ecosystem pressure. These findings demonstrate that lake management strategies cannot be limited to the water body alone but must incorporate landscape-based and watershed-scale planning approaches to ensure sustainable water quality management.

Keywords Remote sensing · Trophic status · Water quality · Change detection · Landscape planning · Lake Beyşehir

Introduction

Wetlands are among the most productive and biologically rich ecosystems on our planet, but they are also the natural systems most intensely affected by human activities (Mitsch and Gosselink 2015). These regions constitute the fundamental basis of human well-being, serving not only as sanctuaries for biological diversity but also by delivering essential ecosystem services, including water purification, flood mitigation, climate regulation, and cultural benefits (MEA 2005). However, freshwater lakes in particular are becoming increasingly vulnerable to point and nonpoint

pollution loads caused by agricultural intensification, urban sprawl, and industrialization (Smith and Schindler 2009). These pressures often trigger eutrophication, leading to a series of ecological disturbances, including excessive nutrient inputs (nitrogen and phosphorus), algal blooms, reduced water clarity, and oxygen depletion (Carpenter et al. 1998). In this study, eutrophication emerges not only as a water-quality issue but also as an indicator of failure in holistic landscape management.

The discipline of landscape planning offers an approach to these complex environmental problems that treats the area not as a sum of independent parts, but as a dynamic "system" or "mosaic" in which ecological, social, and economic processes are in constant interaction (Forman 1995; Nas-sauer 2012). The fundamental goal of landscape architecture and planning is to sustain these services provided by this mosaic by preserving its structural and functional integrity and establishing a harmonious balance between human uses and natural processes (Opdam et al. 2006). From this perspective, wetland management should be approached not within the boundaries of the water body itself, but at the scale of the entire watershed that feeds it and is affected by

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✉ S. Örücü
sedaorucu@sdu.edu.tr

¹ Department of Landscape Architecture, Faculty of Architecture, Süleyman Demirel University, Isparta, Türkiye

² Lakes Region Water Resources Application and Research Center, Süleyman Demirel University, Isparta, Türkiye



it. Land use decisions, soil management practices, and urban development models within the watershed are ultimately the main factors determining the lake's trophic status and ecological health (Weller and Baker 2014). Therefore, effective wetland management requires an integrated planning and design approach at the landscape scale, going beyond direct interventions targeting the water body itself.

Traditional water quality monitoring methods, which rely on point measurements, may be insufficient to capture the spatial heterogeneity and temporal variability of lakes, which are large-scale, dynamic systems. At this point, remote sensing technologies offer a unique opportunity to landscape planners and water resource managers (Matthews 2011). Satellite sensors, by collecting synchronized data from large geographic areas at regular intervals, enable the production of maps of the temporal and spatial distribution of water quality parameters (chlorophylla concentration, suspended solids, water temperature, and water clarity). The emergence of high-resolution (10–20 m), multispectral, and open-access satellite data, such as the Sentinel-2 mission, has further democratized this process and paved the way for operational monitoring applications (Drusch et al. 2012).

The integration of remote sensing data into the landscape planning process provides several critical contributions. First, these data quantitatively reveal the extent and intensity of degradation, providing concrete and indisputable scientific evidence of the problem's existence (Kallio et al. 2001). Second, by visualizing the spatial patterns and spread corridors of degradation processes (e.g., eutrophication), it helps decision-makers determine intervention priorities. Third, and perhaps most importantly, landscape planning enables an understanding of the root causes of the problem and the identification of critical intervention areas, such as the "land–water interface," by integrating remote sensing maps with traditional land use/cover maps and socio-economic data (Steiner 2008). This integration plays a vital role in the design of nature-based solutions and green infrastructure networks (Nesshöver et al. 2017). However, traditional water quality monitoring approaches are often constrained by limited temporal frequency, high operational costs, and insufficient spatial coverage, highlighting the need for more efficient and scalable monitoring methods (Zheng et al. 2026).

In recent years, the development of cloud computing platforms has initiated a revolutionary transformation in remote sensing data processing and analysis. Google Earth Engine (GEE) is a leading platform in this field, providing free, online access to a petabyte-scale satellite data archive and high processing power (Ahmad 2025; Gorelick et al. 2017; Jin et al. 2023; Salas et al. 2025). GEE enables users to analyze large datasets (entire satellite collections), create time series, and run complex algorithms without the need for local download and processing

(Kwong et al. 2022; Viani et al. 2024). This capability enables highly efficient, consistent, and multi-temporal water quality assessments at the landscape scale. Approaches that average different methods, such as ensemble algorithms, reduce the uncertainty of a single algorithm and produce more reliable results. The ability to perform such analyses on GEE could create a powerful common language and analytical foundation for scientists, planners, and decision-makers.

Lake Beyşehir, Türkiye's largest freshwater lake and a protected area within the boundaries of Kızıldağ and Lake Beyşehir National Park (Örücü and Arslan 2020), is a critical case study in which all the theoretical and practical discussions mentioned above are concretized. Historically, the lake has been integrated into the lives of surrounding communities through multiple functions such as agriculture, fishing, drinking water supply, and recreation (Altay 2012). However, in recent years, increased agricultural activity, inadequate wastewater treatment infrastructure, the effects of climate change, and fragmented management have placed severe pressures on the lake's ecological balance (Bucak 2017). The most obvious result of these pressures is a change in trophic status and a trend towards eutrophication (Bucak et al. 2018). Similar patterns of nutrient enrichment and water quality degradation have been reported in freshwater systems in Türkiye under increasing anthropogenic pressures such as agriculture and aquaculture (Özşeker et al. 2026). Understanding the current state of the lake and charting a course for a sustainable future requires a systematic reading of the surrounding landscape and mapping the flows of matter and energy between land and water systems. The selected temporal framework (2020–2025) allows comparison between two representative summer periods under similar environmental conditions, enabling a consistent assessment of spatial and temporal changes in water quality.

This study demonstrates how remote sensing can monitor lake ecosystem health and support sustainable management, particularly in landscape planning and wetland management. Despite the increasing use of remote sensing in water quality studies, there remains a need for integrated approaches that combine multi-parameter analysis with spatial change detection to better understand complex lake dynamics. In addition, there is a lack of tool-based analytical approaches that enable consistent and reproducible spatio-temporal assessment of water quality.

Guided by this main goal, the study aims to address the following specific research questions:

1. What are the spatial patterns and magnitude of change in key trophic state indicators Chlorophyll-a (Chl-a), the Carlson Trophic Status Index (TSI), Secchi Depth and Total Suspended Solids (TSS) in Lake Beyşehir between the summer periods of 2020 and 2025, as derived from



Sentinel-2 satellite data on the Google Earth Engine platform?

2. How can the observed spatial–temporal changes in these water quality parameters be interpreted in relation to the surrounding landscape characteristics and land use/land cover patterns?
3. Based on this integrated landscape-based assessment, what specific insights and geospatial tools can be provided to inform sustainable management strategies and landscape planning interventions for Lake Beyşehir and similar lacustrine ecosystems?

Materials and methods

Study area: Lake Beyşehir

Lake Beyşehir is Türkiye's largest freshwater lake, located on the borders of the provinces of Isparta and Konya, between 31°14' and 31°42' E and 37°34' and 37°59' N in Central Anatolia (Şener et al. 2010). (Fig. 1). It has an area of approximately 650 km², a length of 45 km, and a width of 20 km, and is located at an elevation of roughly 1,116–1,122 m above sea level (Kazanç 2013; Tümer and Akkuş 2016). Core data reveal that during the early Holocene (8,500 years BP), the lake level was 6–8 m lower than

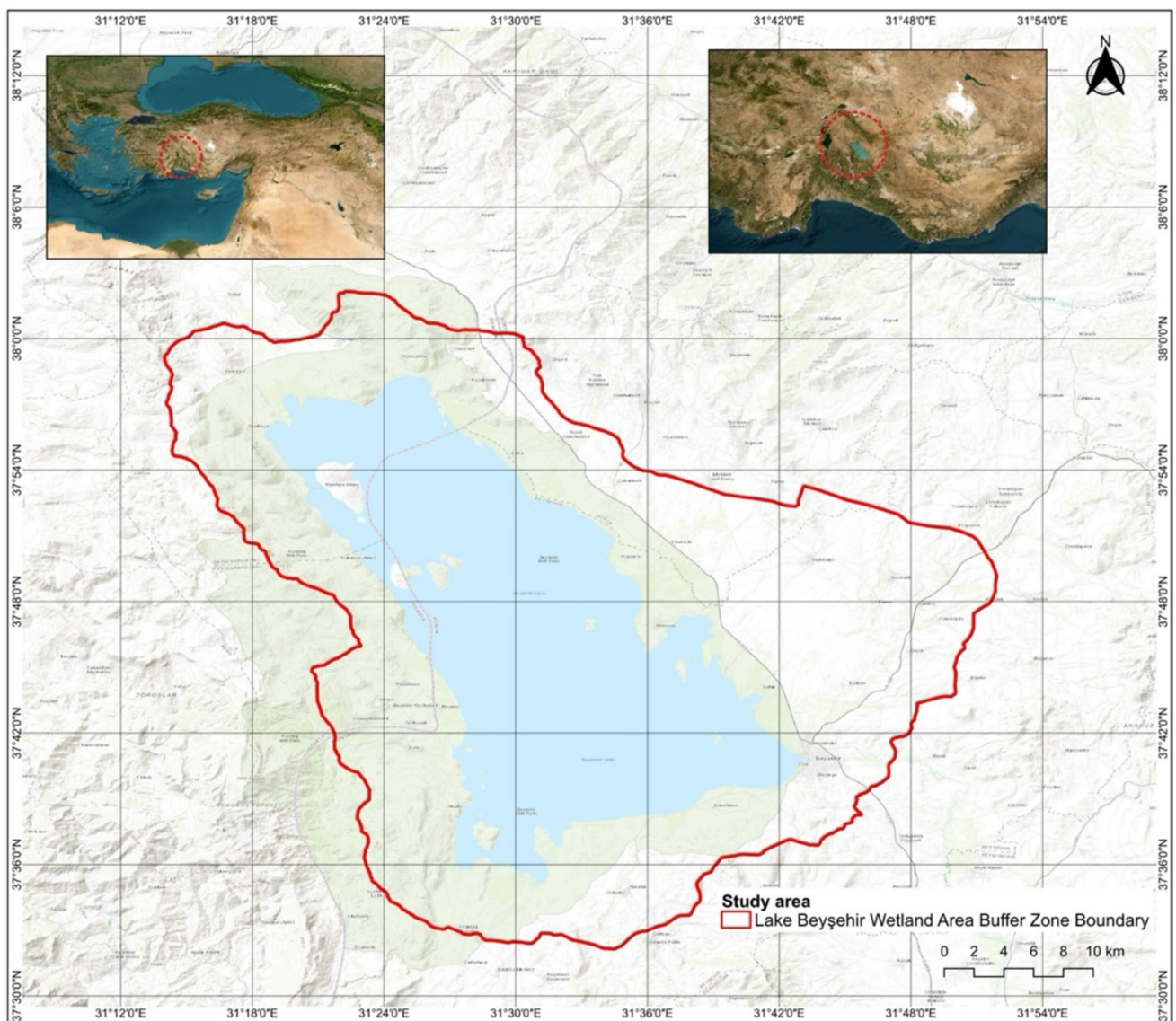


Fig. 1 Study area map of Lake Beyşehir. The boundary represents the analysis buffer zone, and the points indicate reference locations used in the study. Basemap source: Esri World Imagery accessed via QGIS



today; this regression caused the settlements of Erbaba (6th millennium BC) and Kuşluca (3rd millennium BC) to be 2–4 km behind the shoreline. These data show that climatic aridity–humidity cycles in the Beyşehir basin directly influenced coastal archaeology (Kuzucuoğlu et al. 2019).

The Eflatun Pınar sacred water monument, located on the lake shore and dating to the Hittite Empire period (thirteenth century BCE), is a concrete manifestation of the water cult's limnological phenomenon attributed to the lake's sacredness in the Taurus highlands (Dinçol and Dinçol 2018). Similarly, depictions of water birds and fish in the tile decorations of the Kubadâbâd Palace (13th-century Seljuk) on the western shore of the lake reflect the lake ecosystem in medieval political iconography (Aslanapa 1972). Lake Beyşehir was declared a "Beyşehir Lake National Park" by the Council of Ministers' decision No. 1993/495; with this status, an area of 89,151 ha was designated as IUCN Category II (National Park).

Google earth engine: cloud-based geo-spatial analysis platform

In this study, the Google Earth Engine (GEE) platform was used to analyze water-quality parameters at temporal and spatial scales. Multispectral Instrument (MSI) data from the Sentinel-2A and Sentinel-2B satellites were used for water-quality monitoring. Sentinel-2 has 13 spectral bands with a spatial resolution of 10–60 m, offering optimal spectral characteristics for water quality monitoring (Drusch et al. 2012; Goroe and Bazrafshan 2025; Johansen et al. 2024; Salas et al. 2025; Sherjah et al. 2023; Zhao et al. 2024). The leading bands used in the study, along with their characteristics, are summarized in Table 1. During data preprocessing, atmospheric correction and cloud masking were applied using the "COPERNICUS/S2_SR_HARMONIZED" collection. The summer periods (June–August) of 2020 and 2025 were selected for analysis, and seasonal average composites were created for both years.

Water quality indices and scientific formulations

Water Quality Indices (WQIs) are fundamental tools that enable rapid, clear assessment of water quality by reducing

complex water quality parameters to a single numerical value (Bordalo et al. 2006; Tyagi et al. 2013). These indices are generally created through the mathematical aggregation of physicochemical (temperature, pH, dissolved oxygen), chemical (nutrients, heavy metals), and biological (chlorophyll-a, coliform) parameters weighted using multivariate statistical techniques (PCA, AHP) or expert opinions. In particular, TSI is widely used to classify the eutrophication level of lakes based on parameters such as chlorophyll-a, total phosphorus, and Secchi depth (Carlson 1977). With advances in remote sensing technologies, traditional WQIs have been integrated with satellite-derived spectral indices (NDCI, CDOM, TSS), significantly improving water quality monitoring capacity at spatial and temporal scales (Gholizadeh et al. 2016; Mishra and Mishra 2012).

The algorithms used in this study are widely applied across diverse aquatic environments and are primarily intended for comparative and spatial analyses rather than site-specific calibration.

Given the variability in optical water properties across lake systems, the results from these models should be interpreted relative to spatial patterns and temporal changes rather than absolute concentration values.

Chlorophyll-a estimation using an ensemble approach

Chlorophylla concentration is the most important indicator of primary production and eutrophication levels in aquatic systems (Albanai 2022; Matthews 2011). This study employed an Ensemble Approach by averaging the results of three validated methods to minimize the uncertainty associated with any single algorithm, as shown in Table 2.

Although the ensemble approach reduces the uncertainty associated with individual algorithms, it does not fully eliminate potential systematic bias, particularly under varying optical water conditions.

Factors such as water depth, suspended matter composition, and optical variability may influence model performance. Therefore, the results should be interpreted in relative terms, focusing on spatial patterns and temporal dynamics of change rather than absolute concentration values.

Table 1 Sentinel-2 MSI bands and their use in water quality analysis

Band	Wavelength (nm)	Resolution (m)	Use in water quality analysis
B2 (Blue)	490	10	Optically deep waters, chlorophyll-a
B3 (Green)	560	10	Chlorophyll-a, turbidity
B4 (Red)	665	10	Critical for chlorophyll-a determination
B5 (Red-Edge)	705	20	Chlorophyll-a, water vapor
B8 (NIR)	842	10	Water mask, plant stress
B11 (SWIR)	1610	20	Water mask, soil moisture



Table 2 Satellite-based algorithms and formulations used to derive chlorophyll-a

Parameter/Index	Algorithm/Formula
NDCI-Based Method	$\text{Chl_NDCI} = 194.325 \times (\text{NDCI})^2 + 86.115 \times \text{NDCI} + 14.039$ Where NDCI (Normalized Difference Chlorophyll Index): $\text{NDCI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$ NIR and Red represent near-infrared and red band reflectances, respectively (Mishra and Mishra 2012)
Two-Band Ratio Method	$\text{Chl_2Band} = 23.1 \times (\text{NIR} / \text{Red}) - 16.4$ This method is based on the spectral relationship between the red and near-infrared bands (Gitelson et al. 2008)
Moses Method	$\text{Chl_Moses} = \exp [1.024 \times \ln(\text{Red} / \text{Green}) - 0.677]$ This algorithm models the logarithmic relationship between the red and green bands (Moses et al. 2009)
Final Ensemble Value:	$\text{ChlA_Final} = (\text{Chl_NDCI} + \text{Chl_2Band} + \text{Chl_Moses}) / 3$ The ensemble approach balances the limitations of individual methods and provides more reliable estimates

Trophic status, water clarity, and suspended solids estimation

TSI was calculated using chlorophyll-a concentration to express lake trophic status as a single numerical value (Carlson 1977). In this study, the chlorophyll-a-based formulation of TSI was used because chlorophyll-a can be estimated from satellite imagery and serves as a practical proxy for trophic condition in remote sensing applications. Total phosphorus was not included because it cannot be directly retrieved from Sentinel-2 data, while Secchi depth was evaluated separately as an independent indicator.

Secchi depth, a traditional indicator of water transparency, was estimated using an optical model based on red-band reflectance, reflecting the relationship between light penetration and phytoplankton density (Kutser et al. 2005).

Total Suspended Solids (TSS) concentrations were derived using a semi-analytical algorithm that models the nonlinear relationship between red-band reflectance and suspended sediment concentration (Nechad et al. 2010). TSS values provide insight into sediment transport, erosion processes, and algal biomass. Satellite-based algorithms and formulations used to determine trophic status, secchi depth, and total suspended solids are shown in Table 3.

Spatial-temporal analysis and change detection

Four water quality index maps (Chlorophyll-a, TSI, Secchi Depth, TSS) calculated in Google Earth Engine and exported as rasters were imported into QGIS 3.40.13 for spatial analysis and quantitative change detection. Maps for each index for the summer periods of 2020 and 2025 were

systematically analyzed using the "Water Quality Temporal Change Analysis" plugin. Developed by the authors, this custom-developed QGIS plugin enables an objective, reproducible assessment of temporal dynamics in water-quality parameters. The analysis process consisted of two main stages:

To facilitate spatial analysis and interpretation, the continuous raster data for each water quality index were classified into meaningful status categories. This classification was performed separately for the 2020 and 2025 data using established threshold values from the literature such as the oligotrophic, mesotrophic, and eutrophic classes for the TSI or through the objective Jenks Natural Breaks method. This process yielded a set of categorical maps for each time, enabling a clear comparison of trophic and water-quality classes. The Jenks Natural Breaks method was preferred as it objectively identifies natural groupings within the data by minimizing within-class variance and maximizing differences between classes, thereby improving the interpretability of spatial patterns.

To quantify and visualize the spatial-temporal dynamics, the 2020 and 2025 maps were compared using the "Change Analysis" module, which performs pixel-by-pixel comparison. The output included a "Change Matrix" of class transitions and a "Change Type Map" showing the spatial pattern of changes across the lake.

The Change Matrix provides a statistical summary of transitions between index classes; for example, it shows how many pixels transitioned from "oligotrophic" to "mesotrophic" status or remained stable. This matrix provides quantitative data on the direction, magnitude, and classes of change.

Table 3 Satellite-based algorithms and formulations used to determine trophic status, secchi depth, and total suspended solids

Parameter/Index	Algorithm/Formula
Carlson Trophic Status Index (TSI)	$\text{TSI} = 9.81 \times \ln(\text{Chl-a}) + 30.6$
Secchi Depth	$\text{Secchi} = \exp(-1.4856 - 0.8604 \times \ln(\text{Red}))$
Total Suspended Solids (TSS)	$\text{TSS} = 289.29 \times \text{Red} / [1 - (\text{Red} / 0.1686)]$



The Change Type Map, on the other hand, visualizes the distribution of areas of improvement, deterioration, or no change on the lake surface while preserving the spatial context. This map is critical for identifying the spatial patterns, hotspots, and spread corridors of trophic status change.

In the final stage, all analysis results (original index maps, classified maps, change matrices, and change type maps) were compiled into a layout suitable for scientific communication and decision-support processes, and outputs were generated in high-resolution JPEG format. These visual products serve as a basis for understanding the spatial-structural characteristics of the trophic shift in Lake Beyşehir and for developing sustainable management strategies in the context of landscape planning.

This study does not aim to perform site-specific calibration or full empirical validation of the applied algorithms. Instead, the analytical framework is designed to enable consistent spatial and temporal comparisons using established, widely applied models. In addition, long-term, spatially coincident in situ water quality datasets are typically generated within multi-stakeholder projects and are not publicly available in Türkiye. Consequently, independent validation by individual researchers is constrained. Given this context, our study adopts a relative change detection framework rather than aiming for absolute concentration accuracy. The consistency of spatial patterns across four independent indices supports the robustness of the observed changes. Furthermore, our 2020 satellite-derived chlorophyll-a estimates fall within the range of previously published in situ measurements for Lake Beyşehir (e.g., Bucak et al. 2018), providing indirect confidence in the retrievals. We explicitly frame this work as a transferable monitoring tool that can be validated by future studies with local in situ data. This study does not include formal in situ validation. The results should be interpreted as relative spatial-temporal change patterns rather than absolute concentrations. Future studies with access to local in situ data are needed to calibrate and validate the algorithms for Lake Beyşehir specifically.

Result and discussion

Multi-temporal remote sensing analyses conducted over five years (2020–2025) revealed significant and essential changes in the trophic status and water quality parameters of Lake Beyşehir. Approximately 53% to 64% of the lake's total surface area showed changes in at least one water quality index, indicating the system's dynamic nature and vulnerability to anthropogenic pressures (Le Moal et al. 2019; Zhang et al. 2023). The analysis of change matrices and class transitions documents not only shifts in the overall level of water quality

but also a spatially heterogeneous and complex mosaic of degradation/improvement (Li et al. 2024a, b; Olmanson et al. 2022; Shi et al. 2021; Topp et al. 2021; Xue et al. 2023). This mosaic reflects watershed-scale land-use decisions, land-management practices, and landscape structure. Below, quantitative changes for each index, the main transition patterns, their ecological implications, and their implications for landscape planning and wetland management are detailed (Damanik-Ambarita et al. 2018; Li et al. 2019; Sun et al. 2023; Wu et al. 2021; Zhao et al. 2024).

In addition, the consistency of spatial patterns observed across multiple independent indices (chlorophyll-a, TSI, Secchi depth, and TSS) provides further support that the detected changes represent coherent system-level dynamics rather than methodological artifacts.

It should be noted that the analysis is based on two temporal snapshots rather than a continuous time series. Therefore, the results do not represent long-term trends but rather indicate changes between the selected periods.

Inter-annual variability, including differences in precipitation, water level fluctuations, and seasonal environmental conditions, may influence the observed patterns. These factors should be considered when interpreting the results. The observed spatial distribution of trophic changes is not random but closely corresponds to specific landscape features surrounding the lake. Areas showing strong transitions toward eutrophic conditions spatially coincide with zones influenced by agricultural activities, drainage inputs, and settlement-related pressures.

These patterns indicate that the detected changes are directly linked to landscape configuration and land-use dynamics at the watershed scale. The concentration of change hotspots along specific shoreline segments further supports the role of land–water interactions in shaping water quality conditions. In shallow nearshore areas, bottom reflectance may influence the observed signals and should be considered when interpreting the results.

This interpretation is consistent with the class transition results and the spatial distribution of change areas identified in the analysis, demonstrating that the observed trophic shifts are supported by empirical evidence rather than purely conceptual reasoning.

Chlorophyll-a ensemble change and landscape management implications

Chlorophyll-a is a key indicator of phytoplankton biomass and, consequently, aquatic productivity (Bricker et al. 2008; Carlson 1977; Cloern and Jassby 2010; Paerl and Otten 2013; Reynolds 2006; Wetzel 2001). The Chlorophyll-a



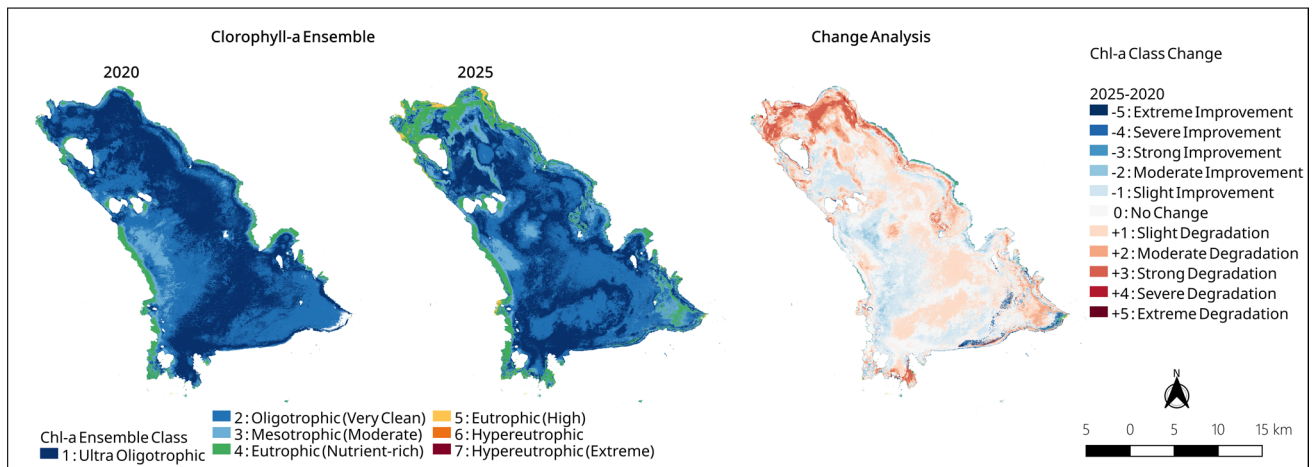


Fig. 2 Spatio-temporal changes in chlorophyll-a ensemble concentration and trophic state (2020 → 2025)

concentration maps for Lake Beyşehir (Fig. 2), spanning the 2020–2025 period, indicate a significant deterioration in the lake's trophic state, reflecting elevated nutrient levels and heightened eutrophication pressures.

While most of the lake was classified as “Mesotrophic (Moderate)” in 2020, by 2025, there was a noticeable increase in cyan, green, and yellow areas representing the “Eutrophic” and “Eutrophic (High)” classes. This study further divides eutrophic conditions into levels that more accurately reflect variations in nutrient intensity and the severity of trophic states. The “Eutrophic” class refers to moderate nutrient enrichment, while “Eutrophic (High)” represents more advanced eutrophic conditions approaching hypereutrophic levels. This increase is particularly noticeable along the lake's northern and eastern shores. The change map confirms that areas classified as “Oligotrophic (Very Clean)” and “Mesotrophic” have largely shrunk, giving way

to classes indicating higher nutrient and algae levels. This rapid change indicates an increasing nutrient load (particularly nitrogen and phosphorus) on the lake ecosystem, which may be associated with factors such as agricultural inputs, wastewater effects, or internal nutrient accumulation (Birk et al. 2020; Hansen et al. 2021; Le Moal et al. 2019; Pilla et al. 2022; Şener et al. 2018; Withers et al. 2020; Zhang et al. 2023) (Fig. 3).

Changes were detected in 60% of the total area (46,297 ha). The most striking finding is a marked decrease in Class 1, the lowest chlorophyll-a class (-9,206 ha; -25.6%), and a sharp increase in classes with high chlorophyll concentrations (Classes 3, 4, and 5). In particular, the extreme increases in Class 4 (159) and Class 5 (5,441) indicate the emergence of local hyper-eutrophication hotspots in the lake (Table 4).

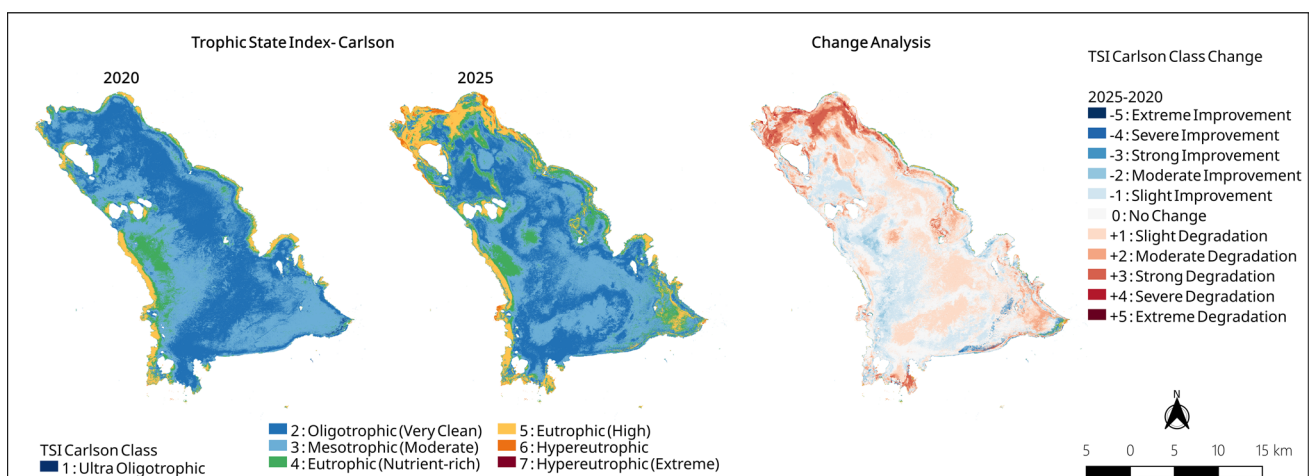


Fig. 3 Spatial and temporal changes in the TSI of Lake Beyşehir between 2020 and 2025



Table 4 Chlorophyll-a ensemble class area changes

Class	2020 (ha)	2025 (ha)	Change (ha)	Change (%)
Oligotrophic (Clean)	35,921.57	26,715.38	−9206.19	−25.6
Mesotrophic (Moderate)	31,872.99	30,893.59	−979.40	−3.1
Eutrophic (Nutrient-Rich)	6007.11	10,233.10	4225.99	70.3
Eutrophic (High)	3356.48	8695.80	5339.32	159.1
Hypereutrophic	11.40	631.73	620.33	5441.5
Hypereutrophic (Extreme)	0.13	0.08	−0.05	−38.5

The most common transition observed was between the two lowest classes, indicating an unstable mesotrophic status. These reciprocal and widespread transitions suggest that the trophic condition of extensive sections of the lake is in a state of dynamic equilibrium (Birk et al. 2020; Ma et al. 2024; Wang et al. 2025). This instability is likely driven by the variability of diffuse pollution loads within the basin, particularly nitrogen and phosphorus inputs from agricultural areas, which fluctuate with seasonal and annual rainfall patterns (European Environment Agency 2018; Li et al. 2024a, b; Ma et al. 2024). Consequently, effective water quality management must move beyond a sole focus on point sources. It highlights the critical importance of implementing "green infrastructure" measures such as buffer strips, rain gardens, and infiltration ditches across the entire watershed to control surface runoff (Fletcher et al. 2015; Golden et al. 2021; McPhillips et al. 2022).

A clear shift towards net eutrophication was observed, with transitions from the lower classes (1 and 2) to the higher classes (3, 4, and 5) accounting for approximately 30% of the total change. Of particular concern are the direct transitions to Class 4, which covered substantial areas (Class 1 → 4: 2,883 ha; Class 2 → 4: 2,587 ha) (Table 5).

Mapping the spatial distribution of these sharp degradations reveals that they are highly likely to coincide with critical points on the land–water interface. These include wastewater discharge points from the Beyşehir settlement and the mouths of drainage channels from intensively farmed plains that flow into Lake (Birk et al. 2020; Jarvie et al. 2015; Sharpley et al. 2018). Addressing such diffuse and point-source pressures necessitates a landscape-planning approach that transcends the traditional "polluter pays" principle, adopting a proactive strategy focused on the "management of

areas with pollution potential." (Withers et al. 2014). Consequently, reorganizing land use in these critical areas for example, by converting agricultural land near the shore into natural wetland restoration zones or ecotone buffers and strengthening urban green infrastructure are vital management interventions (Netti et al. 2024; Wang 2024; Wu 2013).

Carlson trophic status index (TSI carlson) change

TSI maps reveal a significant increase in overall nutrient levels and productivity in Lake Beyşehir during 2020–2025. TSI is an important indicator that comprehensively assesses the lake's trophic status (nutrient richness level). The "Mesotrophic" (moderately nutrient-rich) cyan tones, which were dominant in the 2020 map, have largely been replaced by green and yellow tones representing the "Eutrophic" (nutrient-rich) classes in all coastal areas that showed an increase in 2025, particularly in the villages of Armutlu, Karayaka, Belceğiz, and Gedikli, as well as the coastal areas of Beyşehir city. The change map shows a clear transition from the "Mesotrophic" class to the 'Eutrophic' and "Hyper-eutrophic" classes across the lake. This rapid rise in trophic level indicates that the lake's eutrophication is accelerating, the potential for algal blooms is increasing, and water quality is deteriorating (Dokulil and Teubner 2011; Jenny et al. 2016; Paerl and Otten 2013; Schindler et al. 2016; Smith and Schindler 2009).

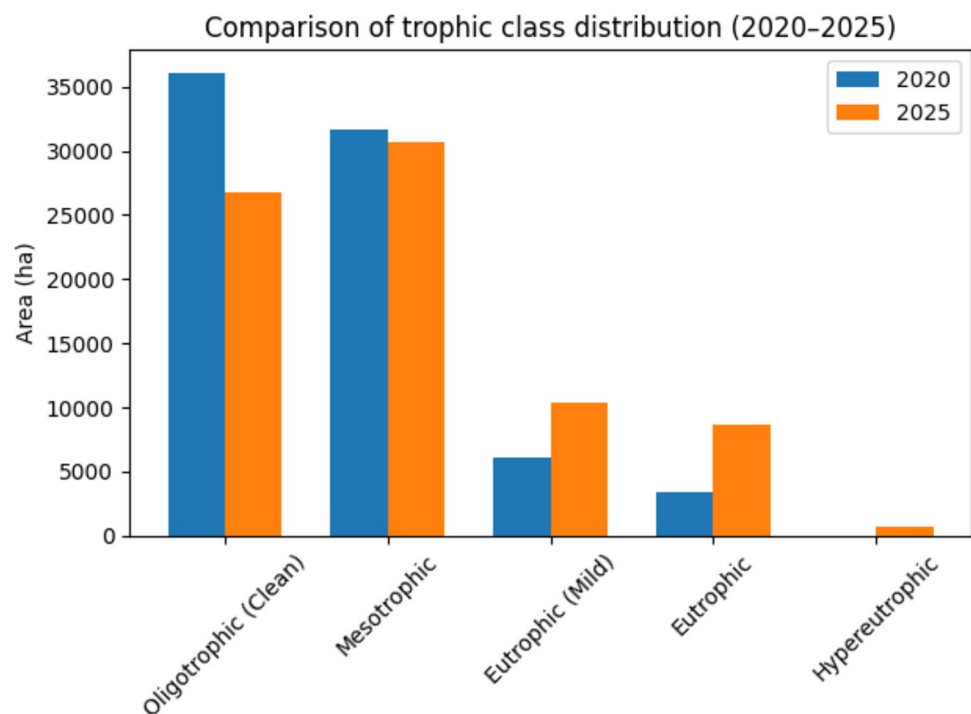
Consistent with chlorophyll-a data, a 60.1% change in area (46,374 ha) was also detected in TSI. When reviewing the class definitions, a clear change between periods of deterioration in the lake's trophic structure is evident.

Figure 4 reveals a significant loss of oligotrophic areas, with the oligotrophic class decreasing by 9,240 ha,

Table 5 Chlorophyll-a ensemble major change patterns (> 5% of changed area)

From → To	Change area
Oligotrophic (Clean) → Mesotrophic (Moderate)	15,416.71 ha (33.3%)
Mesotrophic (Moderate) → Oligotrophic (Clean)	11,462.33 ha (24.8%)
Mesotrophic (Moderate) → Eutrophic (Nutrient-Rich)	4520.09 ha (9.8%)
Oligotrophic (Clean) → Eutrophic (Nutrient-Rich)	3452.58 ha (7.5%)
Oligotrophic (Clean) → Eutrophic (High)	2882.62 ha (6.2%)
Mesotrophic (Moderate) → Eutrophic (High)	2586.58 ha (5.6%)



Fig. 4 TSI class distribution**Table 6** TSI major change patterns (> 5% of changed area)

From → To	Change area
Oligotrophic (Clean) → Mesotrophic	15,380.84 ha (33.2%)
Mesotrophic → Oligotrophic (Clean)	11,407.56 ha (24.6%)
Mesotrophic → Eutrophic (Mild)	4547.06 ha (9.8%)
Oligotrophic (Clean) → Eutrophic (Mild)	3509.59 ha (7.6%)
Oligotrophic (Clean) → Eutrophic	2868.45 ha (6.2%)
Mesotrophic → Eutrophic	2539.32 ha (5.5%)

corresponding to a 25.6% reduction. This substantial decline signals a critical erosion in the lake's ecosystem services, most notably its drinking water quality and recreational value. Such an overall shift is a direct consequence of the lack of an integrated pollution prevention strategy operating at the watershed level. Consequently, effective management cannot be confined to the lake itself but must adopt the principle of "watershed-based management." Any forward-looking planning must systematically account for the cumulative impact on the lake from all settlements, agricultural lands, and industrial areas within the watershed's boundaries.

The emergence of hyper-eutrophication hotspots represents the most severe and unambiguous signal of localized ecosystem degradation. This is evidenced by direct transitions to the hyper-eutrophic class, such as the "Oligotrophic → Hyper-Eutrophic" shift affecting 2,868 ha (Nietch 2024; Rizzo et al. 2023) (Table 6).

These areas constitute critical source areas that demand the highest priority for intervention (Wang 2024). Effective management must aim to sever the landscape connectivity that channels pollutants into the lake at these points. This requires the urgent implementation of targeted nature-based solutions, including the restoration of contributing streambeds and the pre-treatment of agricultural drainage through constructed wetlands, such as artificial or floating islands (Joint Research Centre (JRC) 2022; Netti et al. 2024).

The tables show that certain percentage changes are quite high, primarily because of small baseline areas; thus, these should be considered along with the absolute area changes.

Secchi depth (Water clarity) change

Looking at the Secchi depth maps for the 2020–2025 period for Lake Beyşehir, they reveal a clear, widespread change of deterioration in the lake's water clarity. In 2020, the red and brown areas representing the "Very Low (Very Turbid)" and "Low (Turbid)" classes were mainly limited to the western shores of the lake, but by 2025, both the density and spread of these low-clarity areas had increased. In particular, the northern parts of the lake and the area around Mada Island have become the regions where these turbid (cloudy) water masses have increased most significantly in 2025. The change map illustrates the potential stress this negative change could pose to the lake ecosystem. The decrease in Secchi depth is strongly linked to increases in phytoplankton



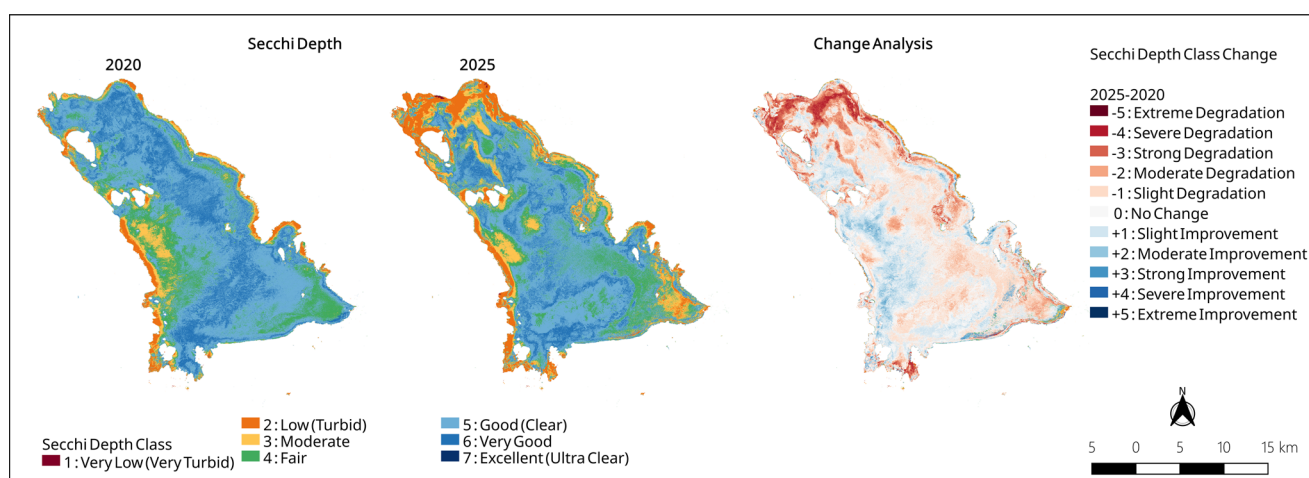


Fig. 5 Spatial and temporal changes in the secchi depth of Lake Beyşehir between 2020 and 2025

Table 7 Secchi Depth class area changes

Class	2020 (ha)	2025 (ha)	Change (ha)	Change (%)
Very Low (Very Turbid)	2.00	53.76	51.76	2588.0
Low (Turbid)	2949.53	8084.99	5135.46	174.1
Moderate	5247.93	10,049.46	4801.53	91.5
Good	13,680.84	13,992.42	311.58	2.3
Very Good	40,367.08	34,433.36	−5933.72	−14.7
Excellent (Clear)	14,922.30	10,555.69	−4366.61	−29.3

Table 8 Secchi depth major change patterns (> 5% of changed area)

From → To	Changed area
Excellent (Clear → Very Good	7907.84 ha (16.0%)
Very Good → Class 4	7745.02 ha (15.7%)
Very Good → Excellent (Clear	6201.07 ha (12.6%)
Good → Very Good	5691.14 ha (11.5%)
Very Good → Moderate	4303.41 ha (8.7%)
Very Good → Low (Turbid)	2668.48 ha (5.4%)

biomass and chlorophyll-a concentrations, indicating that the lake's trophic level has risen and shifted toward eutrophication (Dokulil and Teubner 2011; Paerl and Otten 2013). The intensification of turbidity in hydrodynamically sensitive areas, such as around the islands and in the northern parts of the lake, indicates that these areas are critical stress zones for sediment accumulation and coastal erosion (Jenny et al. 2016). Therefore, the observed temporal and spatial deterioration in Secchi depth indicates that the Beyşehir Lake ecosystem is experiencing environmental stress due

to increasing sedimentation and nutrient enrichment, emphasizing the need for integrated watershed-lake management approaches (Smith and Schindler 2009; Wu 2013) (Fig. 5).

The highest rate of change among the four indices was observed in Secchi Depth, at 63.9% (49,314 ha). This demonstrates widespread deterioration in the lake's optical properties and light penetration (Tables 7 and 8).

The analysis reveals a general increase in turbidity, marked by a decrease in the most clear water class and a dramatic expansion of turbid water classes. This widespread decline in water clarity is likely driven not only by phytoplankton growth but also by increased soil erosion and sediment transport across the watershed (Bihonegn 2023; Mirghaed et al. 2023). Key landscape factors that directly influence the lake's total suspended solids (TSS) and clarity include the condition of forest cover, overgrazing in pastures, improper soil cultivation practices in agriculture, and construction activities (Bihonegn 2023; Donovan and Monaghan 2021). Therefore, a cornerstone of sustainable lake management must be the integration of comprehensive "soil and water conservation" measures such as terracing, contour farming, and windbreak plantations into the broader basin management plan (Adusumilli and Wang 2018).

Total suspended solids (TSS) change

Total Suspended Solids (TSS) maps (Fig. 6) indicate a significant increase in suspended sediment, organic matter, and planktonic particle concentrations in Lake Beyşehir from 2020 to 2025. TSS is a fundamental physicochemical parameter that directly affects water turbidity and light transmittance (Bilotta and Brazier 2008; Davies-Colley and Smith 2001; Kirk 1994; Stramski et al. 2004; Wetzel 2001).



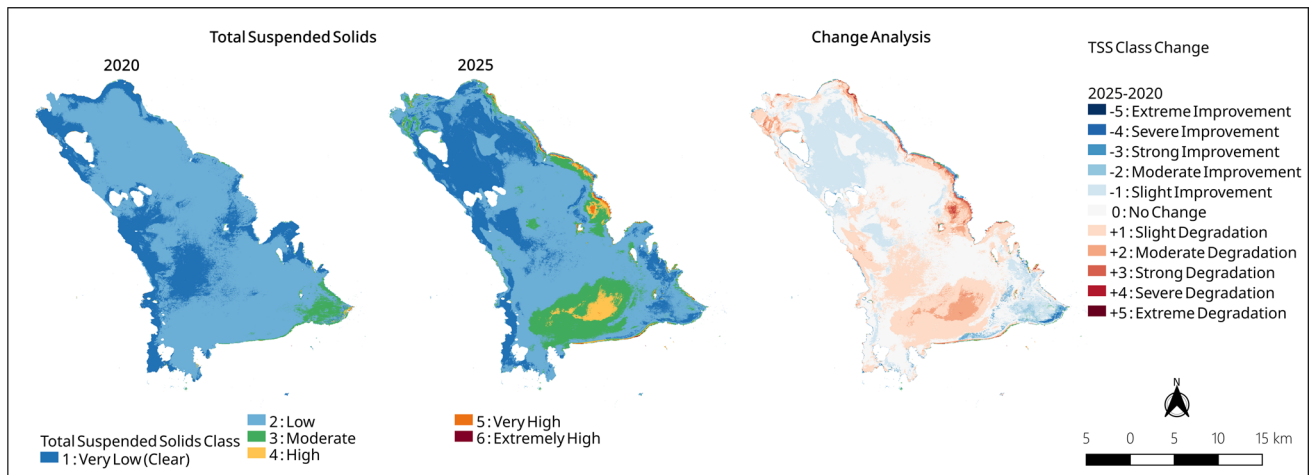


Fig. 6 Spatial and temporal changes in the total suspended solids (TSS) of Lake Beyşehir between 2020 and 2025

Table 9 Total suspended solids (TSS) class area changes

Class	2020 (ha)	2025 (ha)	Change (ha)	Change (%)
Very Low	18,638.10	20,464.22	1826.12	9.8
Low	56,854.11	42,268.80	-14,585.31	-25.7
Moderate	1675.03	11,486.38	9811.35	585.7
High	1.62	2474.47	2472.85	152,645.1
Very High	0.61	396.90	396.29	64,965.6
Extremely High	0.46	79.16	78.70	17,108.7

Table 10 Total suspended solids (TSS) major change patterns (> 5% of changed area)

From → To	Changed area
Low → Very Low	14,160.63 ha (34.6%)
Very Low → Low	11,063.62 ha (27.0%)
Low → Moderate	9998.13 ha (24.4%)
Low → High	2202.86 ha (5.4%)

The blue-cyan tones representing the “Very Low (Clean)” and “Low” classes that were dominant in 2020 have largely shifted to green, yellow, and orange tones representing the “Moderate,” “High,” and “Very High” classes in 2025. This increase is particularly evident along the lake's northwestern, southern, southeastern, and eastern shorelines. The change map confirms that a large portion of the lake has transitioned to higher TSS classes. This indicates an increase in sediment transport in the lake, coastal erosion, increased algal biomass (consistent with increased chlorophyll-a), or

increased sediment load from external sources (Bilotta and Brazier 2008; Syvitski et al. 2005). High TSS values indicate deteriorating water quality, reduced light for aquatic plants, and the potential for increased transport of sediment-bound pollutants (Smith et al. 1999; Stramski et al. 2004).

TSS showed a change rate of 53% (40,906 ha). The most striking change was the exponential increase observed in the high and very high TSS classes (Classes 3, 4, 5). (Table 9).

Excessive sediment input is clearly observable, especially in coastal regions, as evidenced by significant transitions such as “Class 2 → Class 3” (9,998 hectares) and “Class 2 → Class 4” (2,203 hectares) (Table 10).

The spatial analysis of these regions indicates a strong correlation with “high erosion risk sub-basins,” which are characterized by steep slopes, sparse vegetation coverage, or dense stream networks. (Alemu et al. 2025). Within a comprehensive management plan, these critical sub-basins must be designated as “priority protection and restoration areas,” with land use strictly regulated or coupled with intensive erosion-control interventions (Santos et al. 2025). Furthermore, the natural filtering capacity of littoral zones must be leveraged. Existing reed beds and marshlands along lake shores are highly effective natural filters for sediment retention (Hu et al. 2025). Therefore, safeguarding and proactively restoring riparian zones and wetlands represent a pragmatic approach within landscape engineering. These initiatives mitigate surface runoff, improve sediment retention, and substantially decrease total suspended solids (TSS) loads prior to their entry into the lake ecosystem (Allan 2004; Dosskey et al. 2010; Mitsch and Gosselink 2015; Peterjohn and Correll 1984).



Conclusion

Key findings and system-level interpretation

Within the scope of this study, spatial and temporal changes in chlorophylla (ensemble), TSI, Secchi depth, and Total Suspended Solids (TSS) parameters were analyzed using Sentinel-2 satellite images of Lake Beyşehir from the summer periods of 2020 and 2025. Multi-temporal remote sensing-based assessments clearly revealed significant deterioration in water quality and an increase in trophic level within a relatively short period in the lake ecosystem. However, the results should be interpreted as relative indicators of spatial and temporal change, and future studies integrating in situ measurements will be necessary for site-specific calibration and validation.

According to the analysis results, at least one water quality indicator changed class in approximately 53–64% of the lake surface. This finding shows that Lake Beyşehir is not a static system but instead has a dynamic structure that is extremely sensitive to anthropogenic pressures at the basin scale. Change matrices and class transition analyses revealed not only a general decline in water quality but also the formation of a spatially heterogeneous, patchy, and complex mosaic of deterioration/improvement across the lake. This spatial pattern indicates that different parts of the lake are not equally exposed to the same pressures; instead, they respond differently depending on local land use, hydro-morphological conditions, and nutrient input pathways. The presented matrices are not normalized transition matrices but are intended to highlight absolute and percentage changes between classes.

The increase in chlorophyll-a concentrations was particularly pronounced along the northern and eastern shores of the lake; the oligotrophic and mesotrophic classes lost area, while the eutrophic and high-eutrophic classes expanded. This indicates an increase in phytoplankton biomass and, consequently, an increase in primary production. TSI results are consistent with these findings, indicating that the lake's overall trophic status has shifted toward higher trophic classes. The observation of direct transitions from the oligotrophic class to the hyper-eutrophic class in some areas reveals the development of serious “eutrophication hotspots” at the local scale.

Secchi depth analyses showed a widespread decrease in water clarity across the lake. Low-clarity classes, observed in limited areas in 2020, had expanded in both intensity and area by 2025. This situation can be linked to increased suspended solid loads, phytoplankton density, and potentially sediment resuspension. TSS maps also support this interpretation; high TSS values were concentrated particularly

in areas where agricultural drainage channels reach the lake and in coastal zones.

When the findings are evaluated as a whole, the observed increase in trophic level and deterioration in water quality in Lake Beyşehir cannot be explained solely by internal lake processes. On the contrary, these changes are directly related to watershed-scale land use decisions, agricultural production practices, wastewater inputs from settlement areas, structural changes in coastal areas, and landscape connectivity. The spatial mosaic that emerges in this context is a concrete reflection of the strong ecological and functional connection between the lake and the surrounding land system.

Implications for landscape planning and sustainable wetland management

The findings clearly demonstrate that management and planning approaches for Lake Beyşehir should not be limited to narrow interventions targeting only the lake surface. Instead, it is imperative to adopt a landscape-based, holistic management approach that encompasses the entire watershed feeding the lake.

First, the areas identified in the study where rapid, sharp trophic class transitions are concentrated should be defined as “critical source areas” and treated as the highest-priority areas for intervention. In these areas, planning decisions should aim to reduce landscape connectivity at the land–water interface. Agricultural drainage channels that flow directly into the lake should be redesigned, and natural or artificial wetland buffers should be created along these channels.

Second, “soil and water conservation” measures should become a fundamental component of landscape planning throughout the basin. Practices such as contour plowing, terracing, windbreak afforestation, and field edge buffer strips should be encouraged in agricultural areas. These measures can significantly reduce TSS and nutrient inputs reaching the lake by reducing sediment and nutrient loads carried by surface runoff.

Thirdly, land-use conversions should be evaluated for agricultural and residential areas near the shore. Gradually reducing agricultural activities in sensitive areas along the lake shore and converting these areas into natural wetland restoration or ecotone buffer zones will increase the lake ecosystem's long-term resilience. Similarly, surface runoff should be controlled by promoting green infrastructure solutions (rain gardens, permeable surfaces, biofilters) in residential areas.

Fourth, considering the potential for internal nutrient loading, monitoring and research on the lake's sediment dynamics should be increased. Remote sensing



data, supported by on-site measurements, should be used to develop early warning systems; critical thresholds for trophic level increases should be detected before they are exceeded.

Finally, it is recommended that the Google Earth Engine-based approach used in this study be developed into a continuous monitoring and decision support system for Lake Beyşehir. This system, integrated into landscape planning, wetland management, and environmental impact assessment processes, will enable the creation of a scientifically data-driven, spatially targeted, and adaptable management model.

In conclusion, the observed increase in trophic level and deterioration of water quality in Lake Beyşehir are not only environmental problems; they are also multidimensional governance issues that require re-examination of land-use policies, planning decisions, and landscape management approaches. This study clearly demonstrates that remote sensing-based landscape analyses are an indispensable tool for sustainable lake and wetland management. The proposed methodological framework, supported by a custom-developed tool, is transferable and can be applied to other lake systems with similar data availability.

Future studies should focus on integrating long-term time-series data and in situ measurements to further enhance the robustness and validation of the analytical framework.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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