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**RESEARCH ARTICLE** **ARAŞTIRMA MAKALESİ**

# Kars province (Türkiye) GIS-based evaluation of wetland sustainability under land-use dynamics and climate variability

# Kars ili Türkiye'de arazi kullanım dinamikleri ve iklim değişkenliği altında sulak alan sürdürülebilirliğinin CBS tabanlı değerlendirilmesi

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**Abstract:** This study investigates the spatiotemporal dynamics of wetland ecosystems in Kars province, northeastern Türkiye, focusing on Aygır, Çalı, and Kuyucuk Lakes between 1990 and 2018. Land use/land cover changes were analyzed using CORINE Land Cover data in relation to climatic variables, demographic shifts, and sustainability indicators. The results revealed marked transformations in wetland extent and adjacent land uses. Around Aygır Lake, agricultural areas expanded from 67.3% to 69%, while wetlands declined from 19.3% to 17.8%. In the Çalı Lake region, agriculture increased from 21.1% to 28%, whereas wetlands nearly disappeared (0.05%) by 2018. Kuyucuk Lake exhibited the most severe degradation, with wetlands decreasing from 11.8% in 1990 to 6.1% in 2018. Although precipitation exhibited a clear increasing trend over the study period, wetland recovery was not observed. Population decreased substantially (662,155 to 288,878), suggesting that human-induced land-use intensity rather than demographic growth is the main driver of degradation. Principal Component Analysis associated 1990 with high precipitation and population, while 2018 correlated with urbanization and agriculture. Markov Chain Analysis estimated trend-based transition probabilities indicating a high likelihood of wetland conversion to agricultural and/or urban land under the assumption that the observed land-use dynamics persist. A strong positive correlation was observed between wetland extent and precipitation ($r = 0.975$, $p < 0.01$). The findings emphasize the combined impacts of climate change, land-use intensification, and anthropogenic pressures, underscoring an urgent need for adaptive wetland management strategies in Kars province.

**Keywords:** Anthropogenic, climate change index, conservation, ecosystems, mitigation, wetland sustainability index

**Öz:** Bu çalışma, Türkiye'nin kuzeydoğusunda yer alan Kars ilindeki sulak alan ekosistemlerinin mekânsal ve zamansal dinamiklerini 1990–2018 dönemi için incelemekte ve Aygır, Çalı ile Kuyucuk gölleri üzerine odaklanmaktadır. Arazi kullanımı/arazi örtüsü değişimleri, CORINE Arazi Örtüsü verileri kullanılarak iklim değişkenleri, demografik değişimler ve sürdürülebilirlik göstergeleriyle ilişkili biçimde analiz edilmiştir. Bulgular, sulak alan alanı ve çevresindeki arazi kullanımlarında belirgin dönüşümler olduğunu göstermiştir. Aygır Gölü çevresinde tarım alanları yüzde 67,3'ten yüzde 69'a genişlerken sulak alanlar yüzde 19,3'ten yüzde 17,8'e gerilemiştir. Çalı Gölü bölgesinde tarım alanları yüzde 21,1'den yüzde 28'e yükselmiş, buna karşılık sulak alanlar 2018 itibarıyla neredeyse tamamen ortadan kalkmış ve yüzde 0,05 düzeyine inmiştir. Kuyucuk Gölü en ağır bozulmayı sergilemiş, sulak alanların payı 1990'da yüzde 11,8 iken 2018'de yüzde 6,1'e düşmüştür. İncelenen dönemde yağışta belirgin bir artış eğilimi gözlenmesine karşın sulak alanlarda bir toparlanma saptanmamıştır. Nüfusun 662.155'ten 288.878'e önemli ölçüde azalması, bozulmanın temel belirleyicisinin demografik büyümeden ziyade insan kaynaklı arazi kullanım yoğunlaşması olduğunu düşündürmektedir. Temel Bileşenler Analizi, 1990 yılını yüksek yağış ve nüfusla, 2018 yılını ise kentleşme ve tarımla ilişkilendirmiştir. Markov Zinciri Analizi, gözlenen arazi kullanım dinamiklerinin sürmesi varsayımı altında sulak alanların tarımsal ve/veya kentsel alanlara dönüşme olasılığının yüksek olduğunu gösteren eğilim temelli geçiş olasılıkları üretmiştir. Sulak alan alanı ile yağış arasında güçlü ve pozitif bir ilişki saptanmış, korelasyon katsayısı $r = 0,975$ olup istatistiksel olarak anlamlı bulunmuştur $p < 0,01$. Elde edilen bulgular, iklim değişikliği, arazi kullanımının yoğunlaşması ve antropojen baskıların birleşik etkilerine işaret etmekte ve Kars ilinde uyarlanabilir sulak alan yönetim stratejilerine acil gereksinimi vurgulamaktadır.

**Anahtar kelimeler:** Antropojenik etkiler, iklim değişikliği indeksi, koruma, ekosistemler, azaltım, sulak alan sürdürülebilirlik indeksi

## INTRODUCTION

Climate change represents one of the most pressing global environmental challenges, exerting profound impacts on ecosystem structure and functioning worldwide (Malhi et al., 2020). Wetlands are among the most productive ecosystems and provide essential ecosystem services (Ramsar Convention on Wetlands, 2018; Davidson, 2014; Mitsch et al., 2013), including water purification, flood regulation, carbon sequestration, and the maintenance of habitats for numerous species (Lal et al., 2005; Balwan and Kour, 2021; Kolka et al., 2021). However, wetlands are highly sensitive to both climatic variability and anthropogenic pressures (Junk et al., 2013; Ramsar Convention on Wetlands, 2018). Rising temperatures, altered precipitation regimes, and the increasing frequency of extreme events can modify hydrological dynamics, accelerate evapotranspiration, and disrupt ecological processes, ultimately leading to wetland degradation and loss of ecosystem services (Hayala et al., 2012; Salimi et al., 2021; Ballut-Dajud et al., 2022). As a result, robust monitoring and assessment approaches are required to support effective conservation and sustainable management strategies (Ahmed et al., 2022).

In recent decades, remote sensing products and standardized land-cover datasets, together with Geographic Information Systems (GIS), have become indispensable for quantifying land-use/land-cover (LULC) dynamics and evaluating wetland vulnerability over long time periods (Çelekli and Zariç, 2023; Çelekli and Zariç, 2024; Çelekli and Zariç, 2025; Ozesmi and Bauer, 2002). CORINE Land Cover (CLC) data, produced within the Copernicus Land Monitoring Programme through standardized image interpretation procedures, provide a consistent, multi-temporal framework for assessing regional LULC change and its implications for wetland systems (Copernicus Land Monitoring Service, 2024; European Environment Agency, 2019). Integrating LULC information with climatic indicators (e.g., temperature and precipitation) and socio-demographic dynamics can help identify dominant drivers of wetland change and support evidence-based management.

Kars Province (northeastern Türkiye) is characterized by distinctive climatic and geographic conditions and holds particular importance for wetland research due to its location along major migratory routes of birds. Wetlands in Kars—especially Lakes Aygır, Çalı, and Kuyucuk—play critical ecological, economic, and social roles by sustaining biodiversity and supporting local livelihoods through agriculture, livestock activities, and nature-based tourism. Among these, Kuyucuk Lake is internationally recognized as a Ramsar Site and is reported to host a high diversity of bird species, highlighting its conservation value. Despite their significance, these wetlands have faced increasing threats associated with climate variability and LULC transformations. Irregular precipitation patterns, reduced snow cover, and enhanced evaporation may contribute to hydrological stress, while agricultural expansion, overgrazing, and unsustainable water use intensify anthropogenic pressures that disrupt natural hydrological and ecological cycles.

Although several studies have investigated wetlands in different regions of Türkiye, an integrated, GIS-based evaluation focusing on the combined influence of climate variability, land-use dynamics, and sustainability indicators in Kars Province remains limited (Bakırman et al., 2022). Therefore, this study aims to quantify spatiotemporal changes in wetland extent and surrounding LULC patterns in Kars Province between 1990 and 2018 by integrating CLC-derived GIS analyses with climatic variables (temperature and precipitation) and population dynamics. To ensure consistency between objectives and analyses, we applied Spearman correlation and Principal Component Analysis (PCA) to identify dominant relationships and drivers, and we used Markov Chain Analysis (MCA) to estimate trend-based land-use transition probabilities under the assumption that observed dynamics persist. Finally, the Climate Change Index (CCI) and Wetland Sustainability Index (WSI) were calculated to provide an integrated assessment of wetland sustainability under combined climatic variability and anthropogenic pressure. By combining these approaches within a unified analytical framework, this study provides region-specific insights and a scientific basis for developing adaptive and sustainable wetland management strategies in Kars Province.

## MATERIALS AND METHODS

### Study area

Kars Province is located in northeastern Türkiye and is characterized by high-altitude plateaus, cold continental climate conditions, and complex tectonic and volcanic geology. The region lies within the Eastern Anatolian Plateau, where elevation commonly exceeds 1,500 m a.s.l., resulting in long snow-covered periods and strong seasonal hydrological variability. These distinctive climatic and geographic conditions make Kars a key region for wetland research in Türkiye (Figure 1). Geologically, the study area is dominated by volcanic and tectonic formations associated with the Eastern Anatolian fault system. Basaltic and andesitic units, together with alluvial deposits in low-lying areas, strongly influence basin morphology, soil permeability, and surface–groundwater interactions around the lakes. This study encompasses areas classified as wetlands in Kars, according to the Ministry of Agriculture and Forestry (Ministry of Agriculture and Forestry, 2024) The studied lakes (Aygır, Çalı, and Kuyucuk) are shallow, high-altitude wetland systems characterized by closed or semi-closed basins. Their hydrological regime is primarily controlled by precipitation, snowmelt, and limited groundwater inflow, with minimal surface outflow. Seasonal snow accumulation and spring melt play a key role in maintaining water levels, while increased evaporation during summer months enhances hydrological stress. Table 1 presents the locations of wetlands in Kars. However, due to the limitation of CLC data to the year 2018, it is not possible to make current observations (European Environment Agency, 2021) The WGS coordinate system recorded the station coordinates using a Garmin eTrex Vista® HCx GPS device. Due to the lack of consistent watershed datasets compatible with CORINE Land Cover (1990–2018) (European Environment Agency, 2021) standardized rectangular buffers were established around lake centroids. These windows ensure methodological consistency while capturing the immediate terrestrial environment where land-use pressures most directly impact wetland dynamics. Rectangular study areas were delineated by generating fixed-distance buffers around the centroid of each lake using ArcMap 10.7. The buffer extent was selected to encompass the immediate surroundings of the lakes where land-use changes exert the strongest influence on wetland dynamics. For each lake, the same spatial extent was applied consistently across all analyzed years (1990, 2000, 2006, 2012, and 2018) to ensure temporal comparability.

**Table 1.** Wetlands name and geographical data of the study

| Wetlands Name | Latitude | Longitude | Altitude (m) | Surface Area (ha) | Registration Status |
|---|---|---|---|---|---|
| Lake Kuyucuk | 40.7395 | 43.4542 | 1630 | 0.207 | Ramsar Site |
| Lake Aygır | 40.7641 | 43.0067 | 2130 | 0.405 | Wetland of National Importance |
| Lake Çalı | 40.5166 | 43.2712 | 2270 | 0.017 | Wetland of National Importance |

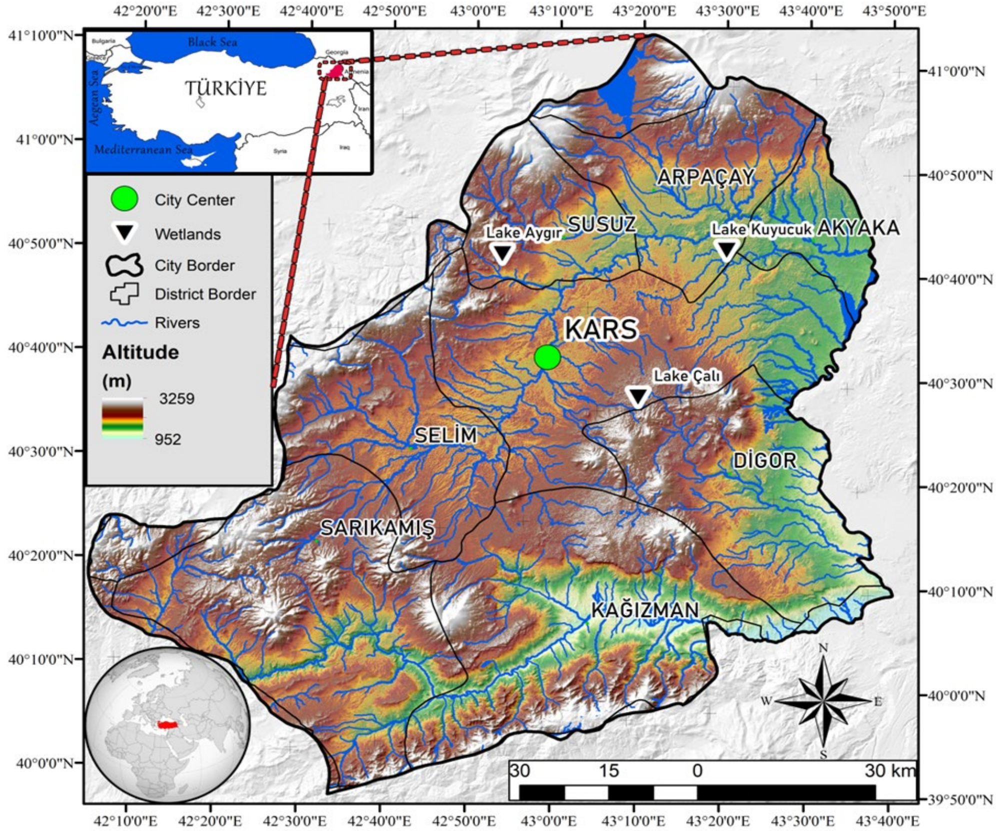


**Figure 1.** Location of the study area in northeastern Türkiye, showing Kars Province and the positions of Lake Aygır, Lake Çalı, and Lake Kuyucuk

### Data collection

Historical climate data, including temperature and precipitation records, were gathered from 1990 to 2022 to assess long-term climate trends and their potential effects on wetlands. The primary source for this data was the NASA Power data archive, which provided visualizable records specifically for 2001-2002 (NASA, 2024) Missing and inconsistent data were supplemented and cross-verified using datasets from Climate Data and Tutiempo (Climate Data, 2024; Tutiempo, 2024). Meteorological variables (temperature and precipitation) were obtained from the NASA POWER database, which provides spatially continuous, long-term climate data derived from satellite observations and reanalysis products. The suitability of NASA POWER variables has been evaluated by comparing them with station observations, with generally strong performance reported for temperature and acceptable performance for several trend and variability applications (Aboelkhair et al., 2019; Halimi et al., 2023). In addition, NASA provides tools (e.g., PRUVE) that support systematic validation workflows for POWER data (NASA, 2024). Population data was obtained from the Turkish Statistical Institute (TURKSTAT, 2024). For this purpose, existing data derived from the CLC database were employed (European Environment Agency, 2021) The CLC dataset used in this study is produced through the interpretation of satellite imagery, primarily derived from multispectral remote sensing data within the Copernicus Land Monitoring Programme. Although no primary image classification or digitization was performed by the authors, remote sensing forms the basis of the original land cover information. Geographic Information Systems (GIS) were subsequently used to extract, quantify, and compare land-use and wetland areas across different time periods. Land use data encompassing categories such as agriculture, forest, swamp, wetlands, and urban areas were compiled for the years 1990, 2000, 2006, 2012, and 2018. To ensure consistency and comparability, classifications were conducted at the primary category level rather than through detailed subcategories. Recently established artificial ponds and reservoirs were excluded from the analysis due to their limited temporal coverage. Satellite imagery and GIS datasets were utilized to map and evaluate the spatial distribution of wetlands and other land use types in the Kars region, offering a visual depiction of temporal changes in wetland coverage. All mapping and spatial analyses were performed using ESRI ArcMap 10.7 software.

### Data analysis

The Spearman rank correlation test was employed to identify significant relationships among the examined environmental variables. This analysis provided insights into the direct and indirect influences of climate change on wetland dynamics. All statistical analyses and visualizations were carried out using R and Python software environments (Bedogni, 2010; Ishak, 2017). Principal Component Analysis (PCA) was applied to identify the key factors driving changes in wetland areas, thereby reducing data dimensionality and emphasizing the most influential environmental variables (ter Braak and Šmilauer, 2002) Data were log-transformed using the formula ln(x + 1) to minimize skewness and stabilize variance. Markov Chain Analysis (MCA) was subsequently applied to examine temporal transitions among land use categories, enabling the estimation of probabilities associated with the conversion of one land use type into another over time (Izquierdo et al., 2009). Z-score standardization was applied to all indices to normalize the dataset and facilitate comparability among variables, representing a widely adopted statistical technique in scientific research for harmonizing data measured on different scales (Izquierdo et al., 2009)

The Climate Change Index (CCI) was computed to quantify the magnitude of climate change within the study region. The calculation was performed using the following formula (Eq. 1)

$$CCI = \frac{(T-T_{avg})}{\sigma_T} + \frac{(P-P_{avg})}{\sigma_P} \quad \text{(Eq. 1)}$$

Where $T$ is the annual temperature, $T_{avg}$ is the average temperature, $\sigma_T$ is the standard deviation of temperature, $P$ is the annual precipitation, $P_{avg}$ is the average precipitation, and $\sigma_P$ is the standard deviation of precipitation (Baettig et al., 2007)

The Wetland Sustainability Index (WSI) was calculated to evaluate the ecological condition and long-term sustainability of the wetland ecosystems. The index was derived using the following formula (Eq. 2):

$$\text{WSI} = (W_{wetland} \times Wetland) + \left(W_{temperature} \times (1 - Temperature)\right) + (W_{precipitation} \times Precipitation) \quad \text{(Eq. 2)}$$

$W_{wetland}$, $W_{temperature}$, and $W_{precipitation}$ denote the respective weights assigned to wetland area, temperature, and precipitation. Wetland represents the total wetland area in a given year, while Temperature and Precipitation correspond to the mean annual temperature and total annual precipitation for the same period. The term (1 – Temperature) accounts for the inverse relationship between temperature and wetland sustainability, indicating that rising temperatures adversely affect wetland stability.

The Eq. 2 integrates the combined influence of wetland area, temperature, and precipitation to provide a comprehensive assessment of wetland sustainability. This index is particularly valuable as it encapsulates the complex interactions between climatic variability and anthropogenic pressures on wetland ecosystems. By incorporating both temperature and precipitation, the WSI effectively reflects the climatic sensitivity of wetland health. The weighting parameters are essential for adjusting the relative contribution of each variable according to its ecological significance. Overall, the WSI serves as a robust analytical tool for evaluating the current condition of wetlands and supporting informed decision-making for their conservation and sustainable management (Yadav and Kansal, 2022).

## RESULTS

The spatial and temporal assessments revealed substantial transformations in the wetland ecosystems of Kars Province between 1990 and 2018. As summarized in Table 2 and illustrated in Figure 2, the CLC-based analysis demonstrated a continuous expansion of agricultural lands and a simultaneous decline in wetland coverage across all three study sites—Aygır, Çalı, and Kuyucuk Lakes. In the Aygır Lake basin, agricultural areas increased gradually from 67.3% in 1990 to 69.0% in 2018, while wetland areas decreased from 19.3% to 17.8% during the same period. Although this reduction may appear moderate, it reflects a persistent downward trend in wetland extent and potential degradation in hydrological stability. The conversion of peripheral wetland zones into arable land suggests intensifying human intervention, likely driven by the need to expand crop production and pasture areas. The Çalı Lake basin exhibited more dramatic transformations. Agricultural expansion rose sharply from 21.1% in 1990 to 28.0% in 2018, while wetlands, once occupying a small but ecologically valuable portion of the basin, almost disappeared by 2018, representing only 0.05% of the total area. This near-total loss indicates severe ecological stress and underscores the vulnerability of small, shallow wetland systems to both climatic fluctuations and direct human pressure. The most severe degradation was observed in Kuyucuk Lake, a site internationally recognized under the Ramsar Convention for its outstanding ornithological importance. Wetland coverage declined from 11.8% in 1990 to 6.1% in 2018, accompanied by a continuous increase in agricultural land from 88.2% to 93.6%. The near doubling of agricultural dominance around Kuyucuk Lake points to extensive habitat encroachment, fragmentation of reed and marsh zones, and possible alteration of hydrological inflows.

**Table 2.** Land use rates around wetlands according to 1990–2018 CLC data (1: Urban Areas 2: Agricultural Areas, 3: Forest 4: Swamp 5: Wetland)

| Wetlands | Code | Year (%) | | | | |
|---|---|---|---|---|---|---|
| | | 1990 | 2000 | 2006 | 2012 | 2018 |
| Lake Aygır | 1 | 1.20 | 1.45 | 1.60 | 1.75 | 1.90 |
| | 2 | 67.30 | 67.85 | 68.20 | 68.50 | 69.00 |
| | 3 | 12.20 | 11.90 | 11.80 | 11.50 | 11.30 |
| | 4 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 19.30 | 18.80 | 18.40 | 18.25 | 17.80 |
| Lake Çalı | 1 | 0.30 | 0.40 | 0.45 | 0.50 | 0.55 |
| | 2 | 21.12 | 22.80 | 24.20 | 26.10 | 28.00 |
| | 3 | 78.58 | 76.60 | 75.25 | 73.30 | 71.35 |
| | 4 | 0 | 0 | 0.05 | 0.05 | 0.05 |
| | 5 | 0 | 0.20 | 0.05 | 0.05 | 0.05 |
| Lake Kuyucuk | 1 | 0 | 0.10 | 0.15 | 0.20 | 0.25 |
| | 2 | 88.16 | 90.30 | 91.40 | 92.50 | 93.60 |
| | 3 | 0 | 0 | 0 | 0 | 0 |
| | 4 | 0 | 0 | 0 | 0 | 0 |
| | 5 | 11.84 | 9.60 | 8.45 | 7.30 | 6.15 |

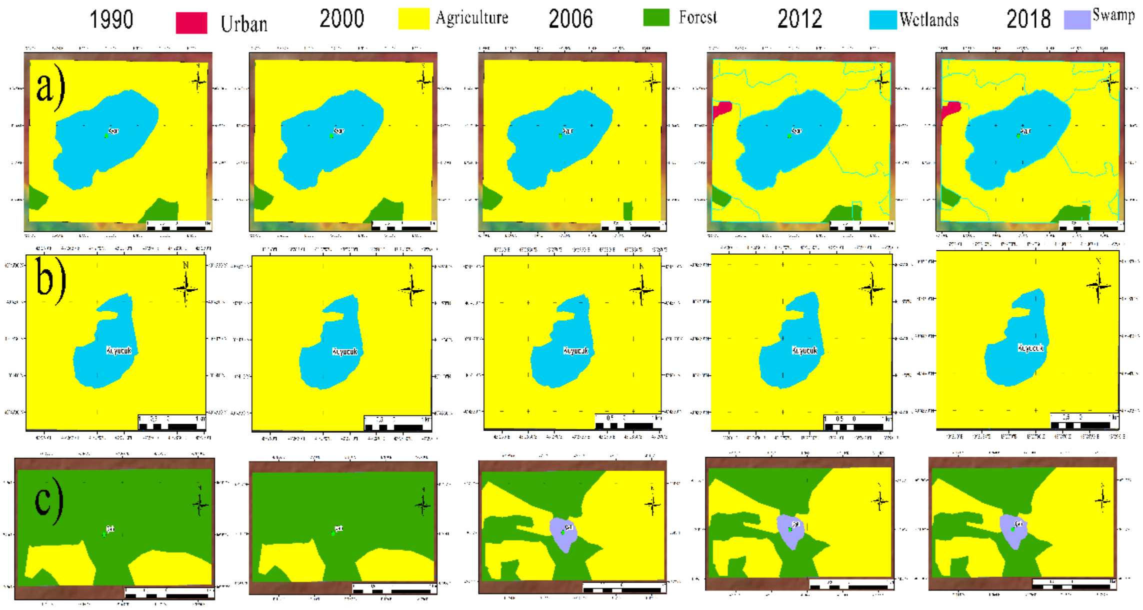


**Figure 2.** Spatiotemporal land-use and land-cover LULC maps around a)Lake Aygır, b) Lake Kuyucuk, and c) Lake Çalı for the years 1990, 2000, 2006, 2012, and 2018 based on CLC data. The study years are shown in the upper row, and land-use classes are indicated in the legend beneath the maps

Spatial visualizations derived from CLC-based thematic maps (Figure 2) further highlight the progressive replacement of wetland and forested areas by agricultural and urban classes over nearly three decades. The reduction in swamp and wetland classes, particularly evident after 2006, coincides with intensified land reclamation and water abstraction activities. The climatic characteristics of Kars Province between 1991 and 2021 exhibit clear evidence of ongoing climatic variability and warming trends (Table 3; Figure 3). The data reveal a steady rise in average temperatures across all months, with particularly pronounced increases during the spring and summer periods. The long-term mean temperature ranged from –8.2 °C in January to 17.7 °C in August. Over the three-decade period, the annual mean temperature demonstrated a persistent upward trajectory, consistent with regional warming patterns across northeastern Türkiye. Precipitation patterns were irregular but generally showed an increasing trend, rising from 158.2 mm in 1990 to 474.6 mm in 2018. Table 3 presents long-term monthly climatological averages, whereas Figure 3 illustrates interannual variability in total annual precipitation.

Despite this increase, wetland expansion did not occur; rather, progressive wetland shrinkage persisted. Relative humidity remained around 70%, while sunshine duration increased during the summer months (up to 10.4 h in July–August), promoting evaporation and intensifying hydrological stress. The Spearman rank correlation analyses revealed statistically significant relationships among land use categories, climatic variables, and population dynamics. In Aygır Lake, agricultural expansion was inversely related to wetland area ($r = –1.00$, $p < 0.01$), while precipitation correlated positively with wetland extent ($r = 0.975$, $p < 0.01$). Similar but site-specific patterns emerged in Çalı and Kuyucuk Lakes, where precipitation exhibited negative correlations with land-use intensity ($r = –0.56$ to $–0.975$, $p < 0.01$).

**Table 3.** Average climatic variables for Kars province between 1991 and 2021

| Month | Average Temperature (°C) | Lowest Temperature (°C) | Highest Temperature (°C) | Precipitation (mm) | Relative humidity (%) | Number of Rainy Days | Average Sun Time (hours) |
|---|---|---|---|---|---|---|---|
| January | -8.2 | -14.5 | -1.8 | 41 | 74% | 6 | 5.1 |
| February | -5.7 | -11.9 | 0.4 | 46 | 71% | 6 | 6.1 |
| March | -0.7 | -6.5 | 5.1 | 69 | 69% | 9 | 7.1 |
| April | 5.0 | -1.3 | 11.1 | 106 | 70% | 13 | 8.1 |
| May | 9.8 | 3.3 | 16.0 | 133 | 71% | 16 | 8.7 |
| June | 14.1 | 7.4 | 20.5 | 96 | 68% | 12 | 10.2 |
| July | 17.3 | 11.1 | 23.7 | 65 | 68% | 10 | 10.4 |
| August | 17.7 | 11.6 | 24.4 | 52 | 64% | 8 | 10.4 |
| September | 13.6 | 7.2 | 20.5 | 37 | 61% | 5 | 9.2 |
| October | 7.8 | 2.0 | 14.0 | 54 | 68% | 7 | 7.3 |
| November | 0.6 | -3.8 | 6.1 | 41 | 70% | 6 | 6.2 |
| December | -5.2 | -10.1 | 0.4 | 42 | 70% | 6 | 5.3 |

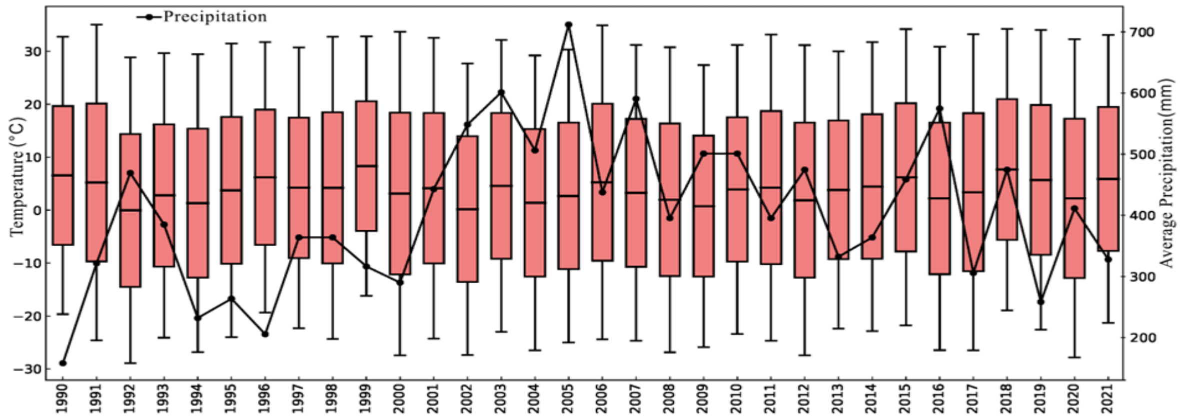


**Figure 3.** Graph showing the annual mean temperature (boxplot) and total annual precipitation (line chart) values for Kars province between 1990 and 2021

PCA (Figure 4) identified precipitation and population density as dominant variables in 1990, whereas urbanization and agriculture became the most influential by 2018. Unlike correlation and PCA analyses, which describe past and present relationships, The Markov Chain Analysis MCA provides scenario-based insights by estimating the probability of land-use transitions under the assumption that current trends persist. MCA revealed distinct land-use transition tendencies in the surroundings of the studied wetlands. The highest transition probabilities were observed from wetland classes to agricultural land, indicating a strong likelihood of continued wetland conversion under existing land-use pressures. In contrast, reverse transitions from agricultural land to wetlands exhibited very low probabilities, suggesting limited natural recovery potential. Urban land classes showed moderate persistence probabilities, particularly around Lake Aygır, reflecting gradual but stable expansion of built-up areas. MCA results indicate high transition probabilities from wetland classes to agricultural and urban categories under the assumption that observed land-use dynamics persist; therefore, these outputs represent trend-based transition probabilities rather than deterministic future projections.

The CCI and WSI results corroborate these findings. CCI values fluctuated between positive and negative phases (Figure 5), reflecting alternating climatic stress periods, while WSI values showed a steady decline from 0.78 in 1990 to 0.62 in 2018 (Figure 6), indicating deteriorating wetland sustainability.

Demographic data (Figure 7) revealed a population decline from ~700,000 in 1980 to ~290,000 in 2021, yet land-use intensity increased, largely due to mechanized agriculture and intensified resource use.

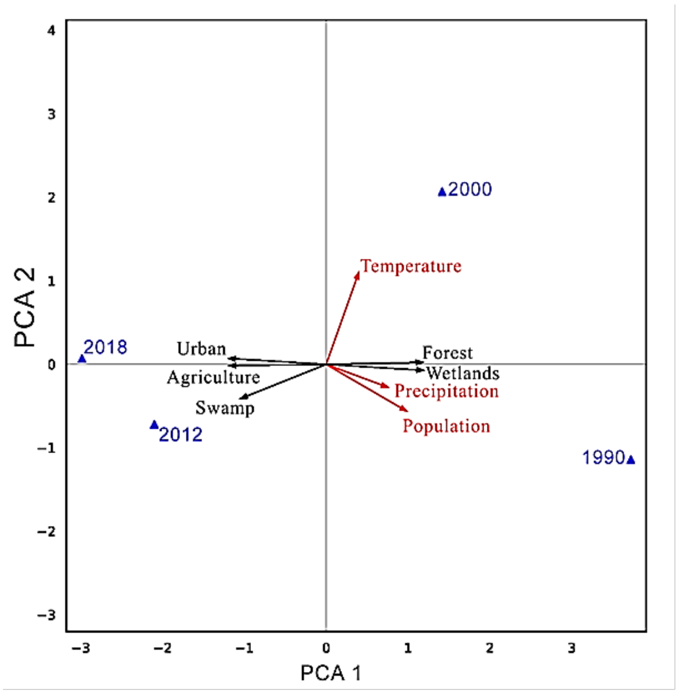


**Figure 4.** PCA diagram of wetland ecosystems of Kars province

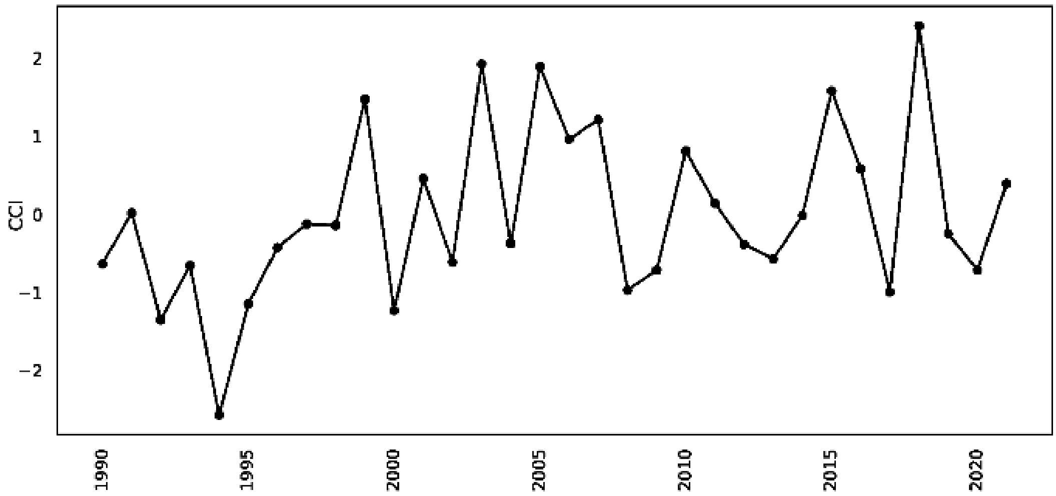


**Figure 5.** Distribution of Climate Change Impact Index (CCI) values calculated between 1990 and 2018 by year

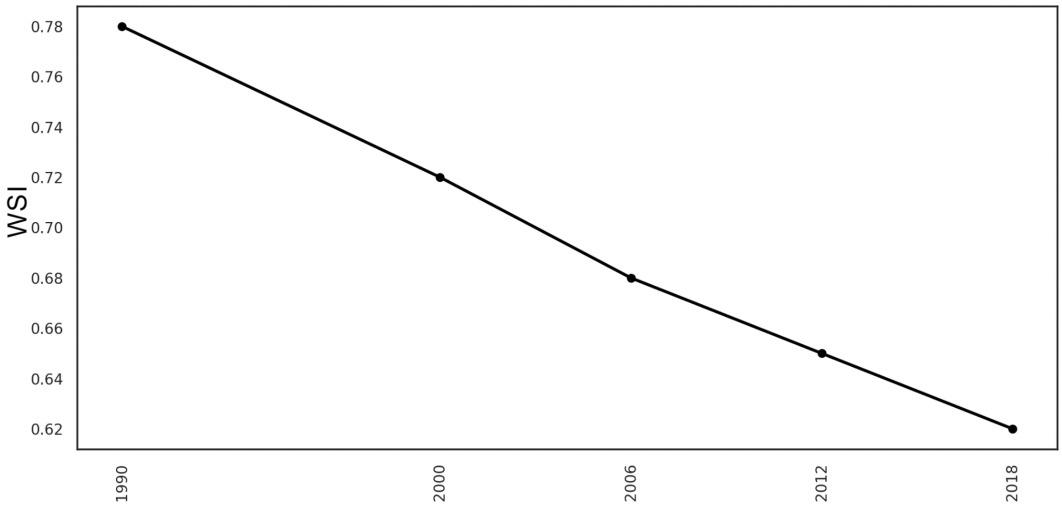


**Figure 6.** Change in WSI values between 1990 and 2018

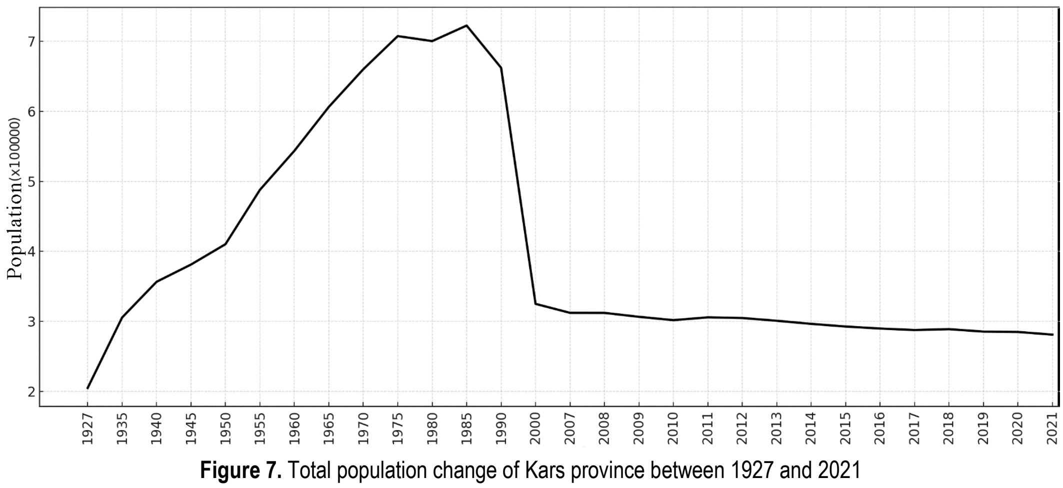


**Figure 7.** Total population change of Kars province between 1927 and 2021

## DISCUSSION

The spatial and temporal dynamics observed in the wetlands of Kars Province reveal a pronounced transition from climate-dominated to anthropogenic-dominated drivers of ecological change. The consistent contraction of wetland areas across Aygır, Çalı, and Kuyucuk Lakes aligns with broader evidence showing that agricultural development is the most common proximate cause of wetland conversion globally (van Asselen and Verburg, 2013; Zariç et al., 2024) and that land-use change remains a key driver of ecosystem degradation at multiple scales (Foley et al., 2005). Despite increases in annual precipitation, the combined effects of temperature rise, prolonged evaporation periods, and unregulated water abstraction appear to have outweighed potential hydrological gains. Similar "precipitation–water loss paradoxes" have been reported in climate-sensitive basins where warming-enhanced evapotranspiration and reduced effective recharge offset rainfall increases (Junk et al., 2013; Salimi et al., 2021). The observed LULC conversions indicate direct ecological consequences for these wetlands, including loss of marsh/reed habitats, reduced hydrological buffering capacity, and increased fragmentation of wetland-dependent biodiversity.

The MCA transition probabilities indicate that, under the assumption that current land-use dynamics persist, wetland classes have a high likelihood of transition towards agricultural and/or urban categories. Importantly, this MCA output should be interpreted as trend-based transition probabilities rather than deterministic future projections, consistent with standard use of Markov transition modeling in land-cover dynamics. This pattern is coherent with global syntheses demonstrating that wetland-to-agriculture transitions frequently dominate conversion pathways, particularly where irrigation expansion and water abstraction intensify (van Asselen and Verburg, 2013).

Meteorological variables (temperature and precipitation) were obtained from the NASA POWER database, which provides spatially continuous, long-term climate data derived from satellite observations and reanalysis products. The suitability of NASA POWER variables has been evaluated in multiple regions by comparing them with ground observations, with generally strong performance reported for temperature and acceptable performance for several applications involving climatic trends and variability assessments (Aboelkhair et al., 2019; Halimi et al., 2023). In addition, NASA has released tools (e.g., PRUVE) that facilitate systematic comparative validation workflows, supporting transparent use of POWER data in research settings (NASA, 2024).

The shift revealed by PCA from climatic to anthropogenic dominance is particularly noteworthy. In the early 1990s, precipitation and population density were the main determinants of wetland extent, but by 2018, agriculture and urbanization had emerged as the most influential variables. Mechanized irrigation systems and the expansion of cropland into peripheral marsh zones are known to disrupt local hydrology, causing losses in wetland vegetation and biodiversity, especially in shallow systems where small hydrological changes can trigger disproportionate ecological impacts (Ballut-Dajud et al., 2022). The correlation results in this study—particularly the inverse relationship between agricultural area and wetland extent ($r = -1.00$, $p < 0.01$)—further support the strong linkage between land-use intensification and wetland degradation, consistent with global conversion evidence (van Asselen and Verburg, 2013).

The MCA results suggest that wetlands in Kars Province are exposed to persistent conversion pressure primarily driven by agricultural expansion. The low probability of transitions from agricultural land back to wetland classes indicates that wetland loss is likely to be largely irreversible without active restoration measures, which is consistent with international experiences where wetland recovery is constrained once drainage, land leveling, and irrigation infrastructure become established (Ramsar Convention on Wetlands, 2018). These findings highlight a critical risk for long-term wetland sustainability, particularly for small and shallow systems such as Lake Çalı.

The temporal trajectories of the Climate Change Impact Index (CCI) and the Wetland Sustainability Index (WSI) provide additional insight into ecosystem resilience. The inverse trends observed between CCI and WSI are indicative of increasing climatic stress and declining ecological stability. The decline in WSI from 0.78 in 1990 to 0.62 in 2018 suggests a reduction in self-regulatory capacity, implying that these wetlands may be approaching ecological thresholds beyond which recovery becomes increasingly difficult without intervention.

Although population density in Kars Province has decreased sharply since the 1980s, wetland pressure has paradoxically increased, driven by mechanized agriculture and rural economic intensification. Comparable patterns have been documented in depopulating landscapes where fewer—but more capitalized and input-intensive—actors can sustain or increase pressure on land and water resources (Bruno et al., 2021). This emphasizes that sustainable wetland management should focus less on demographic trends alone and more on regulating land-use practices, irrigation technologies, and water governance.

Site-specific assessments highlight differential sensitivity among the three basins. The almost complete disappearance of wetland zones in the small and shallow Çalı Lake system underscores the high vulnerability of confined basins with limited hydrological buffering capacity. Conversely, Kuyucuk Lake—an internationally designated Ramsar site—exhibited more gradual but extensive degradation, reflecting the combined influence of climatic variability and agricultural encroachment. International reviews of Ramsar-listed wetlands indicate that designation alone may be insufficient when catchment-scale drivers such as agriculture, water abstraction, invasive species, and unregulated local pressures remain unmanaged (Farheen et al., 2022).

Overall, the integrated use of CLC, PCA, MCA, CCI, and WSI analyses provides a robust framework for diagnosing multi-dimensional drivers of wetland change. The results suggest that climatic fluctuations alone cannot explain the observed transformations; instead, human-induced alterations in land cover, hydrology, and water allocation practices play a decisive role. Therefore, adaptive management strategies should prioritize basin-scale land-use regulation, irrigation efficiency, and continuous GIS-based monitoring to enhance resilience and restore ecosystem functionality. Implementing Ramsar principles through coordinated catchment management remains crucial for preventing further degradation and sustaining the ecological and socioeconomic services provided by these high-altitude wetlands.

## CONCLUSION

This study provides a comprehensive assessment of the spatial, climatic, and anthropogenic factors driving wetland degradation in Kars Province, Türkiye. By integrating GIS-based land use analysis, climatic trend evaluation, and sustainability indices, the research demonstrates that agricultural expansion, irregular precipitation, and rising temperatures collectively contribute to the progressive loss of wetland ecosystems. The results highlight that despite increasing rainfall in recent decades, elevated evapotranspiration and intensified land-use practices have disrupted hydrological balance and reduced ecosystem resilience. The observed decline in the WSI and the fluctuating CCI confirm that climate-induced stress, combined with unsustainable land management, is the principal cause of ecological instability. To mitigate these impacts, adaptive and science-based management strategies are essential. Establishing continuous GIS monitoring, regulating agricultural water use, and implementing climate-resilient conservation plans are crucial for protecting these vulnerable ecosystems. Ultimately, ensuring the sustainability of the Kars wetlands requires coordinated efforts among policymakers, researchers, and local communities to balance ecological preservation with socio-economic development.


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## AUTHOR CONTRIBUTION

Abuzer Çelekli and Özgür Eren Zariç designed the overall review work.

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## ETHICAL APPROVAL

There is no need for ethical approval for this study.

## DECLARATION OF AI USE

A generative AI tool was used to enhance language clarity, improve readability, and ensure grammatical accuracy in certain sections of this manuscript. The authors, however, maintain full responsibility for the accuracy of all information, ideas, interpretations, and conclusions presented.

## DATA AVAILABILITY

Data used in this study are available from the corresponding author upon reasonable request.

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