Spatiotemporal Change Detection Analysis of Turkish Lake Water Surface Area in Response to Anthropogenic Ecosystem Disturbances Using Long-Term Landsat TM/ETM+ Data

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Abstract

The provision of diverse ecosystem goods and services by lakes is vital to ecosystem health and economic well-being of nations or regions. Securing ecologically safe lake water quality and quantity through sustainable uses and management practices concerns both present and future generations. The present study quantifies long-term impacts of human-induced disturbances including climate change on water surface areas of the 18 largest Turkish lakes. Spatiotemporal change detection analysis was carried out using long-term Landsat time series data between 1973 and 2014 with the aid of geographical information systems (GIS). Supervised and unsupervised classification techniques were combined to temporally differentiate and spatially delineate lake water surface areas using ancillary data. Over the period of about 40 years, lake surface area decreased for 15 lakes at a mean annual rate of 0.96 km² but increased for three lakes at a mean annual rate of 0.17 km². These spatiotemporal changes may be attributed to such human-induced pressures as drought, sectoral water uses/withdrawals, draining, and landfilling. These changes in turn lead to losses of or damages to both marketable and non-marketable ecosystem benefits that the lakes provide with humans at the local-to-regional spatial scales in the long-to-short-term temporal scales. The integration of remote sensing and GIS techniques adopted in this study allows for dynamic monitoring of not only lake water quality and quantity but also other natural resources, thus facilitating a timely and effective development of preventive and mitigative measures.

Keywords: Spatiotemporal monitoring; Ecosystem dynamics; Ecosystem health; Ecosystem disturbance regimes

Introduction

Related literature showed that lakes are of vital importance owing to their provision of a wide and diverse range of ecosystem goods and services unsubstitutable through technological progress or fix [1]. Some examples of such life-supporting ecosystem goods and services include regulation of hydrological and climatic regimes; provision of water for drinking, irrigation, fisheries, electricity generation, and recreation; protection of terrestrial and aquatic biodiversity; and scientific and cultural information. Though mostly limited to anthropocentric values, environmental valuation studies have recently intensified so as to reflect the monetary values of non-marketable ecosystem services and natural capital. For example, Mueller et al. [2] estimated the total value of ecosystem services in 2012 provided by Lake Rotorua (New Zealand) to vary between 64.3 million and 95.1 million USD and the total value loss associated with its eutrophication to vary between 9.7 million and 33.1 million USD (based on 1 USD = 1.45 New Zealand dollar in 2016).

Every lake ecosystem with declining water quality and quantity adversely affects all the ecosystem components including people both directly and indirectly. The most pronounced signals of degradation and destruction of lake ecosystems occur in the form of drying, algal blooms, water color changes, and death of aquatic organisms. Main driving forces behind the degradation and destruction include rapid rates of population growth and consumption, poverty, and the inadequate level of integration of the awareness to secure non-marketable but life-supporting ecosystem services with decision-making mechanisms [3]. Global climate change, and land-use and land-cover (LULC) changes due to migrations, urban sprawl, lack of land suitability/compatibility analyses, and mismanagement practices are the two main factors that threaten lake water quality and quantity [4-6]. In the face of human-induced pressures on the environment unprecedented in terms of their rate and magnitude such as climate change, there is an urgent need for dynamic monitoring, decision-support and early warning systems so that institutional and societal will regarding the sustainable use and management of natural resources can be put into practice [7]. The objective of this study was to quantify spatiotemporal changes in surface water areas of the 18 largest Turkish lakes analyzing long-term Landsat time series imageries over about 40 years with GIS.

Materials and Methods

18 Turkish lakes with the largest surface areas were selected as the study areas (Table 1). Mean annual air temperature data between 1968 and 2013 were acquired from the Turkish State Meteorological Service (http://www.mgm.gov.tr/en-US/forecast-5days.aspx) in order to relate temperature changes to lake water surface areal changes as a proxy for climate change impacts. Population data in 2015 for the regions where the lakes occur were obtained from the Turkish Statistical Institute (http://www.turkstat.gov.tr/Start.do) and were used as an indicator of urbanization- and population growth-related environmental impacts.

Landsat TM/ETM+ data between 1973 and 2014 were acquired from the US Geological Survey database (http://earthexplorer.usgs.gov/). The selection of the imagery was based on the summer period of

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June to October, and the ones with less than 10% cloudiness. ArcGIS 10.2 was used in the generation of LULC classifications based on the combined use of supervised and unsupervised techniques with composites of related bands of the Landsat imagery. The five LULC classes of built-up land, water body, forest land, agricultural land including grassland and rangeland, and barren land were classified initially and aggregated into the two classes of water body and the other lands. Raster data of the 82 Landsat images were converted into polygons to estimate changes in lake surface areas.

The statistical analyses of correlation matrix and multiple non-linear regression (MNLR) models were performed at the significance level (p) of less than 0.05 using Minitab 17. The Correlation coefficients (r) from the Pearson’s correlation matrix were used to detect the direction and strength of significant linear relationships. The direction, shape, rate and strength of significant non-linear relationships were quantified using the best-fit MNLR models based on adjusted coefficient of determination (r²adj).

Table 1: Types and dates of 82 Landsat imageries used in the present study to quantify spatiotemporal changes in water surface areas of the 18 largest lakes in the five major regions and 14 provinces of Turkey.

| Region                      | Lake name*                          | Province & coordinates          | Landsat date and type                  |
|-----------------------------|-------------------------------------|----------------------------------|----------------------------------------|
| Mediterranean               | Beyşehir (a)                        | Konya 37°46′25″N 31°31′13″E      | 16.07.1984 Landsat-5 08.08.1998 Landsat-5 27.08.2002 Landsat-8 03.07.2014 Landsat-8 |
|                            | Eğirdir (b)                         | Isparta 38°03′21″N 30°52′14″E     | 16.06.1975 Landsat-2 16.07.1984 Landsat-5 08.08.1998 Landsat-5 27.08.2002 Landsat-7 03.07.2014 Landsat-8 |
|                            | Burdur (c)                          | Burdur 37°43′53″N 30°10′11″E      | 16.06.1975 Landsat-2 16.07.1984 Landsat-5 06.07.1995 Landsat-5 27.08.2002 Landsat-8 03.07.2014 Landsat-8 |
| Eastern Anatolia            | Van (d)                             | Van 38°36′56″N 42°55′10″E         | 07-08.06.1975 Landsat-2 31.07.1984 Landsat-2 09.08.1984 Landsat-5 10.08.1999 Landsat-5 19.08.1999 Landsat-5 03.08.2014 Landsat-8 12.08.2014 Landsat-8 |
|                            | Çıldır (e)                          | Ardahan 41°03′32″N 43°12′40″E     | 22.06.1987 Landsat-6 13.06.2001 Landsat-7 03.08.2014 Landsat-8 |
|                            | Erçek (f)                           | Van 38°40′12″N 48°30′18″E         | 14.07.1973 Landsat-2 28.06.1986 Landsat-5 28.08.2014 Landsat-8 |
|                            | Hazar (g)                           | Elazığ 38°29′41″N 39°24′16″E      | 16.07.1975 Landsat-2 14.08.1984 Landsat-5 04.07.1998 Landsat-5 17.08.2014 Landsat-8 |
|                            | Nazik (h)                           | Bitlis 38°51′21″N 42°17′13″E      | 06.09.1975 Landsat-2 13.07.1984 Landsat-5 12.08.2000 Landsat-5 03.08.2014 Landsat-8 |
| Aegean                     | Bafa (i)                            | Aydın 37°30′01″N 27°26’36″E       | 16.09.1975 Landsat-2 28.06.1984 Landsat-5 11.06.1995 Landsat-5 04.08.2003 Landsat-8 18.08.2014 Landsat-8 |
|                            | Köyceğiz (j)                        | Muğla 36°53′05″N 28°36′55″E       | 05.07.1975 Landsat-2 30.06.1987 Landsat-5 06.07.1995 Landsat-5 02.08.2002 Landsat-7 27.08.2014 Landsat-8 |
|                            | İçliki (k)                          | Denizli 38°14′50″N 29°53′34″E     | 05.07.1975 Landsat-2 01.08.1987 Landsat-5 06.07.1995 Landsat-5 27.08.2014 Landsat-8 |
|                            | Acıgöl (l)                          | Akyonkarahisar 37°49′50″N 29°53′35″E | 30.06.1987 Landsat-5 06.07.1995 Landsat-5 02.08.2002 Landsat-7 27.08.2014 Landsat-8 |
| Central Anatolia           | Tuz (m)                             | Konya 38°45′51″N 33°21′00″E       | 07.08.1975 Landsat-2 12.08.1987 Landsat-5 01.08.1998 Landsat-5 17.06.2002 Landsat-7 13.08.2014 Landsat-8 |
|                            | Akşehir (n)                         | Konya 38°30′43″N 31°25′20″E       | 16.06.1975 Landsat-2 16 06.1984 Landsat-5 31.07.2001 Landsat-5 20.08.2014 Landsat-8 |
|                            | İzmir (o)                           | Bursa 40°29′52″N 29°32′02″E       | 17.06.1975 Landsat-2 05.06.1987 Landsat-5 11.06.1995 Landsat-5 05.07.2001 Landsat-7 14.08.2014 Landsat-8 |
|                            | Manyas (p)                          | Balikesir 40°12′06″N 25°56′55″E   | 18.07.1975 Landsat-2 05.06.1987 Landsat-5 11.07.1995 Landsat-5 05.07.2001 Landsat-7 01.07.2014 Landsat-8 |
|                            | Uluabat (q)                         | Bursa 40°08′58″N 28°36′53″E       | 18.07.1975 Landsat-2 05.06.1987 Landsat-5 11.06.1995 Landsat-5 05.07.2001 Landsat-7 01.07.2014 Landsat-8 |
|                            | Sapanca (r)                         | Sakarya 40°43′01″N 30°15′42″E     | 17.06.1975 Landsat-2 08.08.1984 Landsat-5 06.07.1995 Landsat-5 07.08.2004 Landsat-7 11.08.2014 Landsat-8 |

*The letters in parenthesis are presented to show the lake names in Figure 1.
Figure 1: Spatiotemporal changes in the surface areas of the 18 largest Turkish lakes based on Landsat time series data between 1973 and 2014 (The letters in parenthesis show the lake names presented in Table 1).
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Results and Discussion

Spatiotemporal changes in the surface areas of the 18 largest Turkish lakes chosen in this study were quantified using the Landsat time series and presented in Figure 1. The total water surface area of the 18 largest lakes selected in this study comprised 0.9% (7009 km²) of Turkey. The maximum and minimum surface areas belong to Lakes Van (3549 km²) and Açıgöl (23.7 km²), respectively. When the first and last (2014) dates of the Landsat images were compared, our findings showed that the total water surface area decreased by 548.8 km² for the 15 lakes but increased by 19.7 km² for the three lakes (Table 2). Water surface areas of Lakes Van, Erçek and Eğirdir increased at rates of 0.3%, 1%, and 1.8% over the entire periods, respectively. Since mean values are sensitive to outliers, median values were also computed which indicated that the overall median amount and rate of decrease in the Turkish lake water surface areas were 5.2% (3.6 km²) and 0.1% year⁻¹ (0.1 km² year⁻¹), respectively. Relative to the year 2014, the 39-year maximum amount of decrease and increase in the water surface areas took place with 249 km² (73.4%) for Lake Akşehir and 10.8 km² (1.8%) for Lake Van, respectively. Similarly, maximum rate of decrease and increase in the water surface areas was estimated for Lake Akşehir at 6.37 km² yıl⁻¹ (1.8% year⁻¹) and for Lake Van at 0.28 km² year⁻¹ (0.01% year⁻¹), respectively (Table 2).

Increased growth rates of population and urbanization are one of the main root causes of anthropogenic disturbances of lake ecosystems. According to the 2015 population data (Table 3) for the regions where the lakes are located, the Marmara region where the surface area of all the four lakes decreased ranked in the first place. The same case applied to the two lakes in the Central Anatolia region and to the four lakes in the Aegean region that ranked second and third in population in 2015, respectively (Table 3). However, the water surface area increased

Table 2: Long-term spatiotemporal change regimes of water surface areas of the 18 largest Turkish lakes relative to the baseline Landsat images.
in two of the five lakes in the Eastern Anatolia region that ranked last in population. According to the 45-year mean annual air temperature (MAT) data for the 14 provinces, the maximum and minimum MAT increases were observed for Ardahan (Lake Çıldır) by 46.2% and for Balıkesir (Lake Manyas) by 0.2%, respectively (Table 4). Though not found to the amount and rate of changes in the lake surface areas based on the correlation matrix analysis, a significant linear relationship of the long-term MAT increase (%) was detected to latitude \((r = 0.51; p = 0.03)\), longitude \((r = 0.61; p = 0.007)\), and elevation above sea level \((r = 0.54; p = 0.01)\) \((n = 18)\). However, significant non-linear relationships between the long-term MAT increase and the amount and rate of changes in the lake surface areas were captured using the best-fit MNLR models. Given \(R^2\) values of the best-fit MNLR models, the three-way interaction term of long-term MAT increase × lake surface area × region accounted for 69.5% and 70.0% of variations in the amount (%) and rate (% year\(^{-1}\)) of changes in the lake surface area, respectively \((p = 0.2 \text{ and } 0.25, \text{ respectively)}\). Likewise, together with this three-way interaction term, the two-way interaction of long-term MAT increase × region explained 94.7% of variation in the amount of changes \((\text{km}^2)\), while the three-way interaction term alone elucidated 67.3% of variation in the rate \((\text{km}^2 \text{ year}^{-1})\) of changes in the lake surface area \((p = 0.001)\).
As far as the disappearing, shrinking or warming lakes with the significant losses of ecosystem services are concerned, the most recent one among many examples of from around the world such as Aral Sea in central Asia is Lake Poopo, the second largest inland lake (3192 km²) in Bolivia [8]. Evidence suggests that the surface water temperatures of the world’s lakes have on average risen by 0.34°C per decade since 1985 [9]. The surface area of ponds in northern Alaska was estimated to have diminished by nearly a third and to have vanished by nearly a fifth over the last 60 years [10]. On the other hand, a total of 1099 new lakes in the Third Pole region including the Pamir-Hindu Kush-Karakoram-Himalayas and the Tibetan Plateau were found to have emerged due to rapid glacier melting using Landsat TM/ETM+ data between 1990 and 2010 which amounted to a 23% increase in surface area [11].

Conclusions

Interaction and main effects of such main degradation drivers of lake water quality and quantity as increased growth rates of population and urbanization, climate change impacts (e.g. increased temperature, evapotranspiration, snow-melting and extreme weather events), LULC changes, and mismanagement practices (e.g. landfilling, drainage, and excessive amounts of agricultural, industrial, municipal, recreational and energetic water uses) remain to be explored in the future studies. Also, uncertainty and sensitivity analyses of quantified impacts need to be carried out for results of dynamic monitoring systems to be incorporated within the decision-making process. The establishment of spatiotemporally dynamic monitoring and database systems at the national and watershed scales based on remote sensing and GIS analyses provides the basis for the receipt of warning signals prior to occurrence of irreversible or socially unacceptable environmental damages, restoration/rehabilitation of damaged ecosystems, and the adoption of sustainable management practices.

Table 3: Population data in 2015 according to the regions where the 18 largest lakes selected in the study are located.

| Region name       | Number of lakes | Population in 2015 |
|-------------------|-----------------|--------------------|
| Marmara           | 4               | 23,608,079         |
| Central Anatolia  | 2               | 12,381,363         |
| Aegean            | 4               | 10,023,549         |
| Mediterranean     | 3               | 9,906,771          |
| Eastern Anatolia  | 5               | 5,927,630          |

Table 4: Long-term (1968-2013) five-year mean annual air temperature (MAT,°C) data according to the 14 provinces where the 18 largest lakes selected in the study are located.

| Location of meteorological station | Latitude (decimal degree) | Longitude (decimal degree) | Elevation (m) | 5-year MAT (°C) | Change between the first and last periods (%) |
|------------------------------------|---------------------------|---------------------------|---------------|-----------------|-----------------------------------------------|
| Afyonkarahisar                     | 38.77                     | 30.55                     | 1034          | 10.9            | 11.6                                          |
| Ardahan                            | 41.07                     | 42.43                     | 1829          | 3.5             | 4.0                                           |
| Aydın                              | 37.83                     | 27.83                     | 57            | 17.5            | 18.1                                          |
| Balıkesir                          | 39.65                     | 27.87                     | 3             | 14.6            | 14.6                                          |
| Bitlis                             | 38.37                     | 42.1                      | 1550          | 9.6             | 9.5                                           |
| Burdur                             | 37.72                     | 30.27                     | 967           | 13.0            | 13.3                                          |
| Bursa                              | 40.16                     | 29.03                     | 100           | 14.1            | 14.8                                          |
| Denizli                            | 37.77                     | 29.07                     | 426           | 15.5            | 16.7                                          |
| Elazığ                             | 36.68                     | 39.23                     | 991           | 12.9            | 13.0                                          |
| Isparta                            | 37.75                     | 30.55                     | 997           | 12.2            | 12.6                                          |
| Konya                              | 37.88                     | 32.5                      | 1026          | 11.4            | 11.6                                          |
| Muğla                              | 37.13                     | 28.22                     | 646           | 14.9            | 15.5                                          |
| Sakarya                            | 40.47                     | 30.25                     | 30            | 14.2            | 14.8                                          |
| Van                                | 38.53                     | 43.35                     | 1725          | 8.2             | 10.0                                          |

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