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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 km^2 but increased for three lakes at a mean annual rate of 0.17 km^2. 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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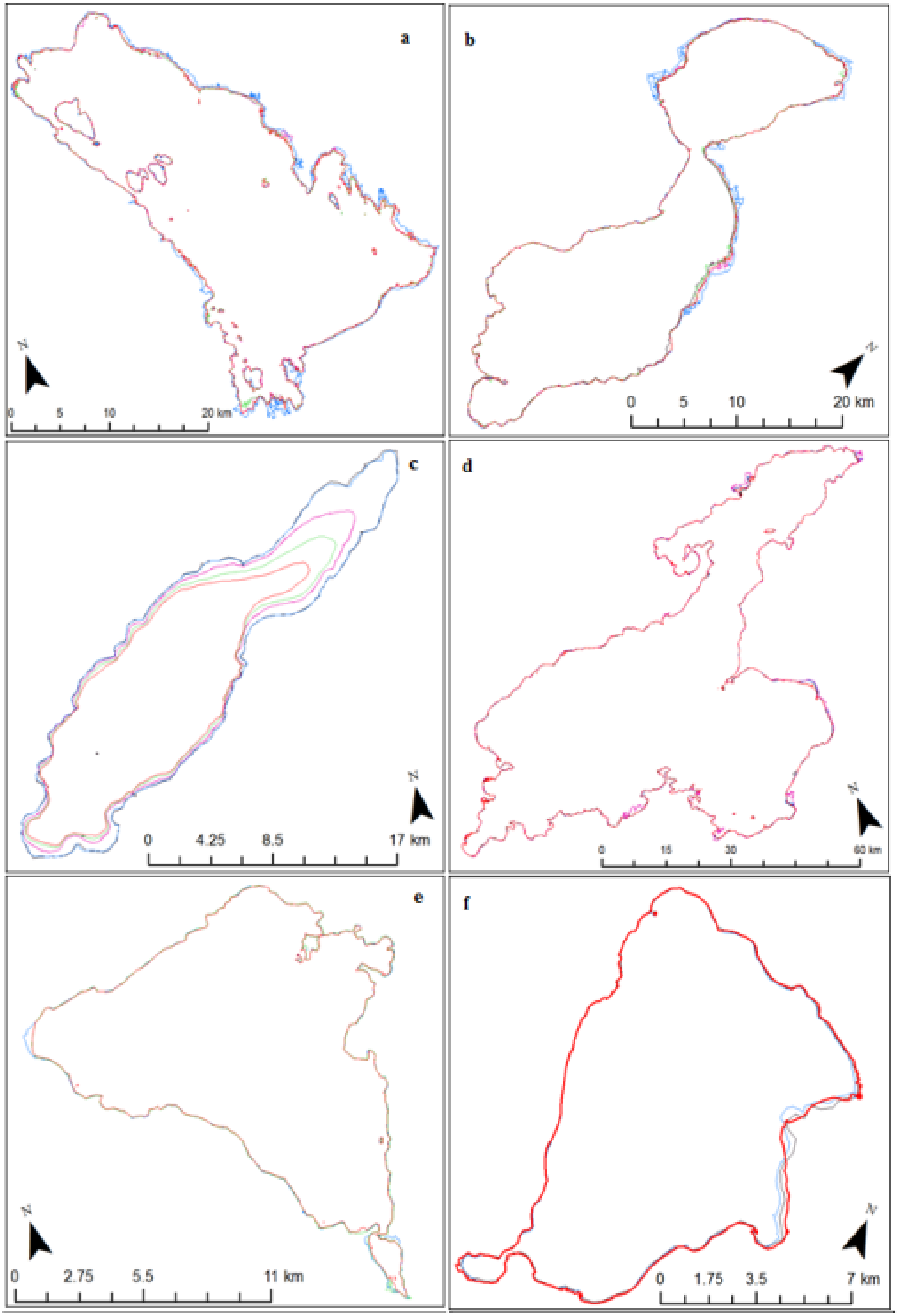
Table 1: Types and dates of 82 Landsat imageries used in the present study to quantify spatiotemporal changes in water surface areas of the 18 largest lakes in the five major regions and 14 provinces of Turkey.

Region	Lake name*	Lake type	Province & coordinates	Landsat date and type				
				1972-1979	**1980-1989**	**1990-1999**	**2000-2009**	**2010-2014**
Mediterranean	Beyşehir (a)	freshwater	Konya 37°46′25″N 31°31′13″E		16.07.1984 Landsat-5	08.08.1998 Landsat-5	27.08.2002 Landsat-7	03.07.2014 Landsat-8
	Eğirdir (b)	freshwater	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)	brackishwater	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-7	03.07.2014 Landsat-8
Eastern Anatolia	Van (d)	soda	Van 38°36′56″N 42°55′10″E	07-08.06.1975 Landsat-2	31.07.1984 09.08.1984 Landsat-5	10.08.1999 19.08.1999 Landsat-5		03.08.2014 12.08.2014 Landsat-8
	Çıldır (e)	freshwater	Ardahan 41°03′32″N 43°12′40″E		22.06.1987 Landsat-5		13.06.2001 Landsat-7	03.08.2014 Landsat-8
	Erçek (f)	freshwater	Van 38°40′12″N 48°35′18″E	14.07.1973 Landsat-2	28.06.1986 Landsat-5			28.08.2014 Landsat-8
	Hazar (g)	freshwater	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)	freshwater	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)	freshwater	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-5	18.08.2014 Landsat-8
	Köyceğiz (j)	freshwater	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
	Işıklı (k)	freshwater	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)	brackishwater	Afyonkarahisar 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)	saltwater	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)	saltwater	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
Marmara	İznik (o)	freshwater	Bursa 40°26′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)	freshwater	Balıkesir 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)	freshwater	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)	freshwater	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.

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).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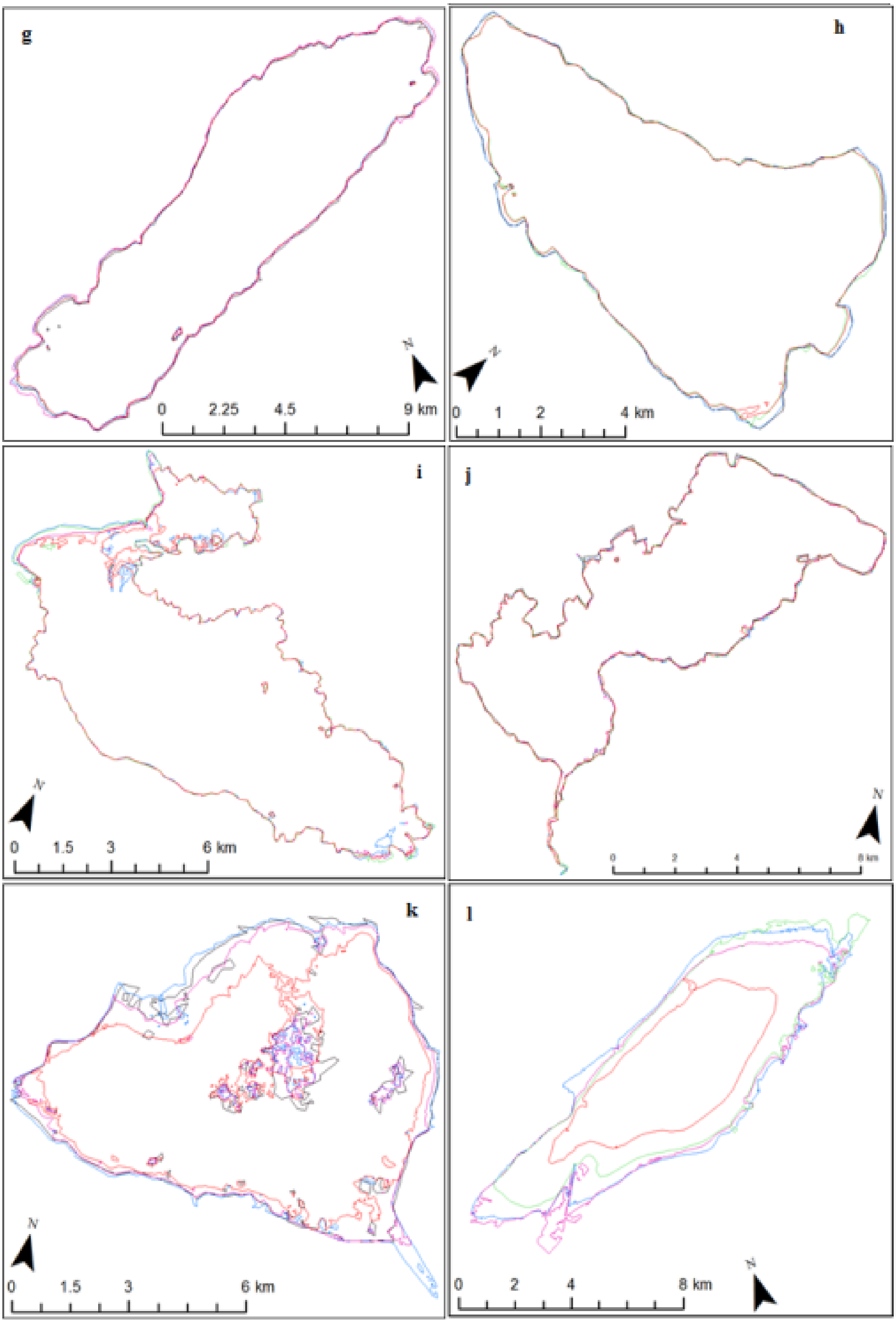
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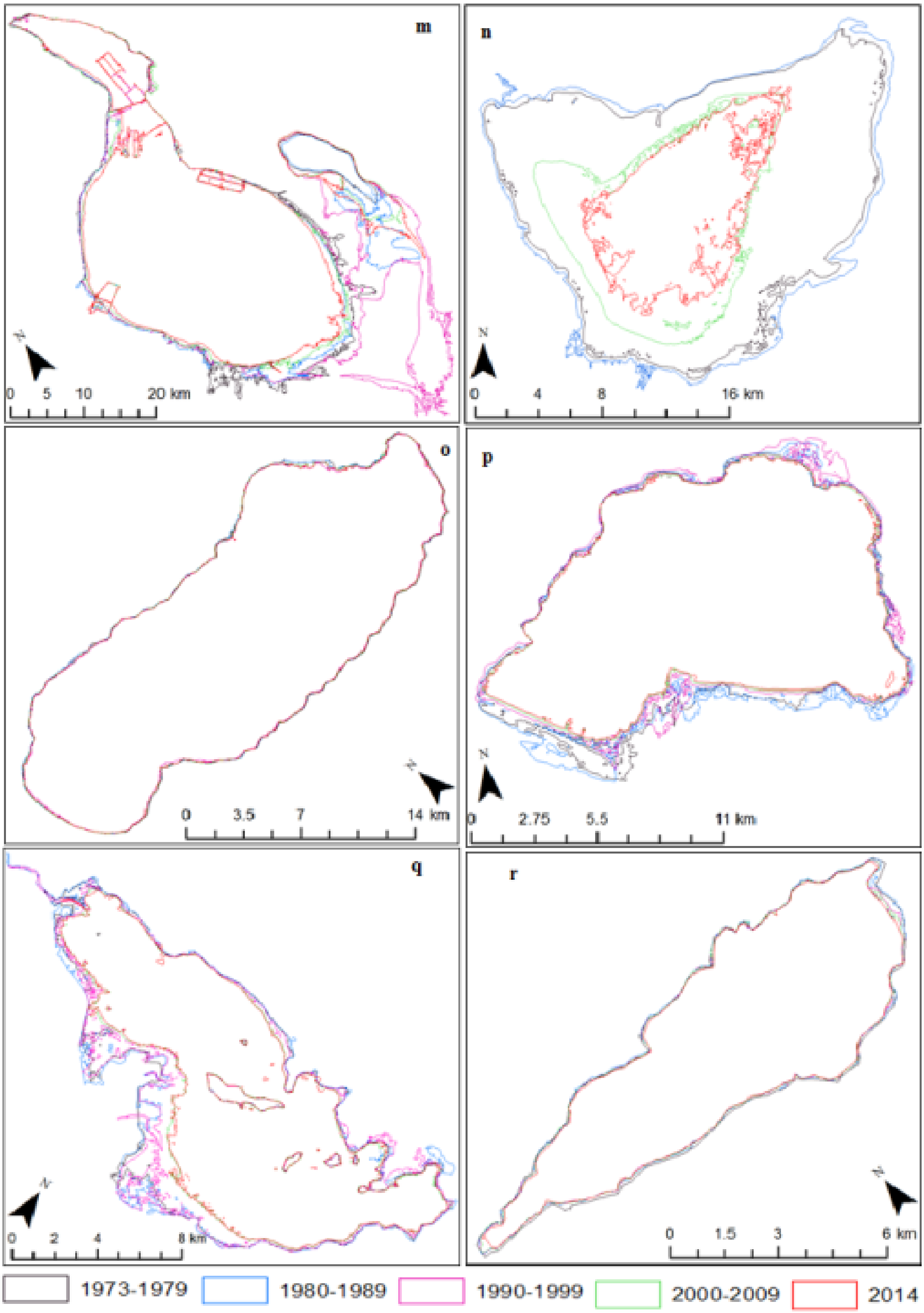

Figure 1: Spatiotemporal changes in the surface areas of the 18 largest Turkish lakes based on Landsat time series data between 1973 and 2014 (The letters in parenthesis show the lake names presented in Table 1).

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 km^2) of Turkey. The maximum and minimum surface areas belong to Lakes Van (3549 km^2) and Acıgöl (23.7 km^2), 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 km^2 for the 15 lakes but increased by 19.7 km^2 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. The overall mean amount and rate of decrease in the Turkish lake water surface areas were estimated at 13.5% (29 + 61 km^2) and 0.4% year-1 (0.8 + 2 km^2 $year^{-1}$), 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 km^2) and 0.1% year-1 (0.1 km^2 $year^{-1}$), respectively. Relative to the year 2014, the 39-year maximum amount of decrease and increase in the water surface areas took place with 249 km^2 (73.4%) for Lake Akşehir and 10.8 km^2 (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 km^2 $yıl^{-1}$ (1.8% year-1) and for Lake Van at 0.28 km^2 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.

Lake name	Baseline Landsat image date	Landsat image date	Area (km^2)	Amount of change		Rate of change	
				(%)	(km^2)	(% $yıl^{-1}$)	(km^2 $yıl^{-1}$)
Beyşehir	16.07.1984		665.2				
		08.08.1998	610.6	-8.2	-54.6	-0.59	-3.9
		27.08.2002	628.3	-5.5	-36.9	-0.31	-2.05
		03.07.2014	636.4	-4.3	-28.8	-0.14	-0.96
Eğirdir	16.06.1975		448.2				
		16.07.1984	471.6	5.2	23.4	0.58	2.6
		08.08.1998	455.8	1.7	7.6	0.07	0.33
		27.08.2002	452.9	1	4.7	0.04	0.17
		03.07.2014	456.1	1.8	7.9	0.05	0.2
Burdur	16.06.1975		207.8				
		16.07.1984	206.5	-0.6	-1.3	-0.07	-0.14
		06.07.1995	171.0	-17.7	-36.8	-0.89	-1.84
		27.08.2002	151.4	-27.1	-56.4	-1.01	-2.09
		03.07.2014	135.4	-34.8	-72.4	-0.89	-1.86
Van	07-08.06.1975		3538.0				
		31.07.1984-09.08.1984	3563.0	0.7	24.8	0.08	2.76
		10-19.08.1999	3566.0	0.8	27.2	0.03	1.13
		03-12.08.2014	3549.0	0.3	10.8	0.01	0.28
Çıldır	22.06.1987		125.1				
		13.06.2001	124.7	-0.3	-0.4	-0.02	-0.03
		03.08.2014	122.9	-1.8	-2.2	-0.07	-0.08
Erçek	14.07.1973		105.0				
		28.06.1986	103.5	-1.4	-1.5	-0.11	-0.12
		28.08.2014	106.1	1	1.1	0.03	0.03
Hazar	16.07.1975		78.0				
		14.08.1984	77.8	-0.3	-0.2	-0.03	-0.02
		04.07.1998	79.9	2.4	1.9	0.11	0.08
		17.08.2014	77.8	-0.3	-0.2	-0.01	-0.01
Nazik	06.09.1975		46.3				
		13.07.1984	46.7	0.9	0.4	0.1	0.04
		12.08.2000	45.5	-1.7	-0.8	-0.07	-0.03
		03.08.2014	45.1	-2.6	-1.2	-0.07	-0.03
Bafa	16.09.1975		61.7				
		28.06.1984	65.4	6	3.7	0.67	0.41
		11.06.1995	65.5	6.2	3.8	0.31	0.19
		04.08.2003	66.7	8.1	5	0.29	0.18
		18.08.2014	57.4	-7	-4.3	-0.18	-0.11

Köyceğiz	05.07.1975		53.1				
		30.06.1987	53.5	0.8	0.4	0.06	0.03
		06.07.1995	52.9	-0.4	-0.2	-0.02	-0.01
		02.08.2002	53.5	0.8	0.4	0.03	0.01
		27.08.2014	53.0	-0.2	-0.1	-0.005	-0.003
Işıklı	05.07.1975		50.4				
		01.08.1987	55.4	9.9	5	0.83	0.42
		06.07.1995	51.1	1.4	0.7	0.07	0.04
		27.08.2014	40.4	-19.8	-10	-0.51	-0.26
Acıgöl	30.06.1987		54.9				
		06.07.1995	51.7	-5.8	-3.2	-0.73	-0.4
		02.08.2002	48.2	-12.2	-6.7	-0.81	-0.45
		27.08.2014	23.7	-56.8	-31.2	-2.1	-1.16
Tuz	07.08.1975		1103.0				
		12.08.1987	1091.0	-1.1	-12.1	-0.09	-1.01
		01.08.1998	1353.0	22.6	249.6	0.98	10.85
		17.06.2002	1054.0	-4.5	-49.3	-0.17	-1.83
		13.08.2014	1009.0	-8.6	-94.4	-0.22	-2.42
Akşehir	16.06.1975		338.6				
		16.06.1984	369.3	9.1	30.7	1.01	3.41
		31.07.2001	142.4	-57.9	-196.2	-2.23	-7.55
		20.08.2014	90.0	-73.4	-248.6	-1.88	-6.37
İznik	17.06.1975		303.5				
		05.06.1987	303.3	-0.1	-0.2	-0.01	-0.02
		11.06.1995	297.9	-1.8	-5.6	-0.09	-0.28
		05.07.2001	301.7	-0.6	-1.8	-0.02	-0.07
		14.08.2014	300.8	-0.9	-2.7	-0.02	-0.07
Manyas	18.07.1975		162.5				
		05.06.1987	168.6	3.8	6.1	0.31	0.51
		11.07.1995	160.5	-1.2	-2	-0.06	-0.1
		05.07.2001	148.5	-8.6	-14	-0.33	-0.54
		01.07.2014	146.8	-9.7	-15.7	-0.25	-0.4
Uluabat	18.07.1975		142.8				
		05.06.1987	148.6	4.1	5.8	0.34	0.48
		11.06.1995	140.4	-1.7	-2.4	-0.08	-0.12
		05.07.2001	115.7	-19	-27.1	-0.73	-1.04
		01.07.2014	114.9	-19.5	-27.9	-0.5	-0.72
Sapanca	17.06.1975		46.6				
		08.08.1984	45.7	-1.9	-0.9	-0.21	-0.1
		06.07.1995	44.9	-3.6	-1.7	-0.18	-0.09
		07.08.2004	44.9	-3.6	-1.7	-0.13	-0.06
		11.08.2014	43.8	-6	-2.8	-0.15	-0.07
Grand total value in 2014			7009	-243	-523	-7	-14
Grand mean value in 2014				-13.5	-29.0	-0.4	-0.8
Standard deviation				21	61	1	2
Median value in 2014				-5.2	-3.6	-0.1	-0.1

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_{adj} 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 ($p = 0.2$ and 0.25, 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 (km^2), while the three-way interaction term alone elucidated 67.3% of variation in the rate (km^2 year^{-1}) of changes in the lake surface area ($p = 0.001$).

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,ᵒC) data according to the 14 provinces where the 18 largest lakes selected in the study are located.

Location of meteorological station	Latitude	Longitude	Elevation	5-year MAT (ᵒC)			Change between the first and last periods (%)
	(decimal degree)	(decimal degree)	(m)	1968-1972	2000-2004	2009- 2013	
Afyonkarahisar	38.77	30.55	1034	10.9	11.6	12.5	14.5
Ardahan	41.07	42.43	1829	3.5	4.0	5.2	46.2
Aydın	37.83	27.83	57	17.5	18.1	18.3	4.4
Balıkesir	39.65	27.87	3	14.6	14.6		0.2
Bitlis	38.37	42.1	1550	9.6	9.5	10.1	6.2
Burdur	37.72	30.27	967	13.0	13.3	14.2	9.7
Bursa	40.18	29.03	100	14.1	14.8	15.4	8.6
Denizli	37.77	29.07	426	15.5	16.7	17.5	12.9
Elazığ	38.68	39.23	991	12.9	13.0	13.8	7.7
Isparta	37.75	30.55	997	12.2	12.6	12.9	5.8
Konya	37.88	32.5	1026	11.4	11.6		1.7
Muğla	37.13	28.22	646	14.9	15.5	15.7	5.0
Sakarya	40.47	30.25	30	14.2	14.8	16.1	13.2
Van	38.53	43.35	1725	8.2	10.0	10.2	23.4

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 km^2) 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.

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