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Mapping chlorophyll-*a* through in-situ measurements and Terra ASTER satellite data

Bilgehan Nas · Hakan Karabork · Semih Ekercin · Ali Berktay

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Abstract This paper presents an application of water quality mapping through real-time satellite and ground data. The Lake Beysehir which is the largest freshwater lake and drinking water reservoir in Turkey was selected as the study area. Terra ASTER satellite image is used as remote sensing data source for water quality mapping in addition to simultaneously performed in-situ measurements. Ground data is collected simultaneously with the ASTER overpass on June 09, 2005 over the Lake Beysehir. The spatial distribution map is developed by using multiple regression (MR) technique for water quality parameter, which is chlorophyll-*a* (chl-*a*). The results indicate that simultaneous ground and satellite remote sensing data are highly correlated ($R^2 > 0.86$). In the image processing step, geometric correction, image filtering and development of water quality map procedures are performed with the ERDAS Imagine and ArcGIS 9.0 software. The trophic status of Lake Beysehir is considered to be oligotrophic with an average 1.55 μg/l chl-*a* concentration.

Keywords Chl-*a* · Lake Beysehir · Terra ASTER · Trophic state · Remotely sensed data · Water quality monitoring

B. Nas (✉) · A. Berktay
Department of Environmental Engineering, Selcuk University, 42075 Konya, Turkey
e-mail: bnas@selcuk.edu.tr

A. Berktay
e-mail: aberktay@selcuk.edu.tr

H. Karabork
Department of Geodesy and Photogrammetry Engineering, Selcuk University, 42075 Konya, Turkey
e-mail: hkarabork@hotmail.com

S. Ekercin
Department of Geodesy and Photogrammetry Engineering, Aksaray University, 68100 Aksaray, Turkey
e-mail: ekercin@itu.edu.tr

Introduction

Traditional water quality monitoring methods can be precise, but are usually expensive and time consuming, especially for a large water body like Lake Beysehir. A solution could be to optimise our efforts and more frequently base our surveillance on remote sensing techniques to improve the information content and limit the costs (Östlund et al. 2001). Water quality assessment of ocean and inland waters using satellite data has been carried out since the first remote sensing satellite Landsat-MSS became operational (Thiemann and Kaufmann 2000). Today, there are many satellites which have high enough resolution for use in water quality monitoring studies (Bilge et al. 2003). Many research projects have estimated water quality parameters in inland, estuarine and near-shore ocean waters using various types of satellite imagery (Baban 1993; Nellis et al. 1998; Thiemann and Kaufmann 2000; Wang and Ma 2001; Koponen et al. 2002; Östlund et al. 2001; Hellweger et al. 2004; Hedger et al. 2001; Lillesand et al. 1983; Kloiber et al. 2002b, a). The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) has three bands in the visible and near-infrared (VNIR) with 15-m spatial resolution. The high spatial resolution has advantages for studying small aquatic areas, such as bay and lakes (Kishino et al. 2005).

Chlorophyll-*a* is photosynthetic pigment found in all green plants, and the main pigment in algae. The concentration of chlorophyll a is used to estimate the amount of algae (all phytoplankton in a given area) in surface water. While it is normal to find algae in streams and lakes, high levels of algae can lead to low levels of dissolved oxygen in a water body.

Chl-*a* content is a good descriptor for bioproduction and can be related linearly to biomass as a function of species composition, light adaptation, age of an algae community, and nutrient supply of the cells (Thiemann and Kaufmann 2000). As physical, chemical, and biological conditions in the lake change over time, some species will be effectively eliminated from a lake because they cannot tolerate the new conditions. These changes represent an important ecological pattern in lakes known as algal succession. In most natural systems the seasonal succession of algae (and macrophytes) is a recurrent yearly cycle.

Chlorophyll concentration within individual lakes varies spatially at a wide range of spatial scales. There are causes of this scale-dependent variation. Variation at macro-scales may result from differential growth arising from systematic gradients in nutrient throughput (Steinman et al. 1997). Variation at smaller scales may be related to the wind environment, according to the interaction between phytoplankton buoyancy characteristics and wind-induced hydrometry (Hedger et al. 2001).

The use of remote sensing in lake management is based on the fact that the causes of eutrophication and an increase in productivity will be associated with a change in the optical properties of water. Increases in chlorophyll-*a* are associated with a decrease in the relative amount of energy in the blue wavelength (0.45–0.52 μm) and increases in the green wavelength (0.52–0.60 μm). These changes are detectable using by remote sensing techniques (Baban 1999).

The trophic state index is a vital factor to evaluate the conditions of water quality. Carlson (1977) suggested the most suitable and acceptable method for evaluating inland lake's eutrophication. Carlson's Trophic State Index (TSI) is based on the interrelationships of TP, chlorophyll-*a*, and Secchi transparency.

This paper presents an application of water quality mapping through real-time satellite and ground data. The Lake Beysehir (Turkey) was selected as the study area. A Terra ASTER satellite image is used as remote sensing data source for water quality mapping. Simultaneous in-situ measurements of chlorophyll-*a* were also collected. A spatial distribution map of chlorophyll-*a* is developed by using multiple regression (MR) techniques. Carlson's TSI is used as the basis for estimating the trophic status of Lake Beysehir.

Materials and methods

Study area and materials

In the study, the Lake Beysehir was selected as the study area. It is located between 31° 17′ and 31° 44′ E and 37° 34′ and 37° 59′ N in Central Anatolia, Turkey (Fig. 1). The Lake Beysehir, which is the largest freshwater lake and drinking water reservoir in Turkey, is located between the Beysehir (Konya) and Sarkikaraagaç (Isparta) provinces. The current surface area of Beysehir Lake is approximately 654 km^2, and the average depth is about 5 m.

The lake is the most important drinking and irrigation water source for Central Anatolia. Although it has some protected statues, the lake has a number of problems such as variations in water level due to inappropriate water policy over growth up aquatic macrophytes in the lake ecosystem, uncontrolled fishing, urbanization and water pollution.

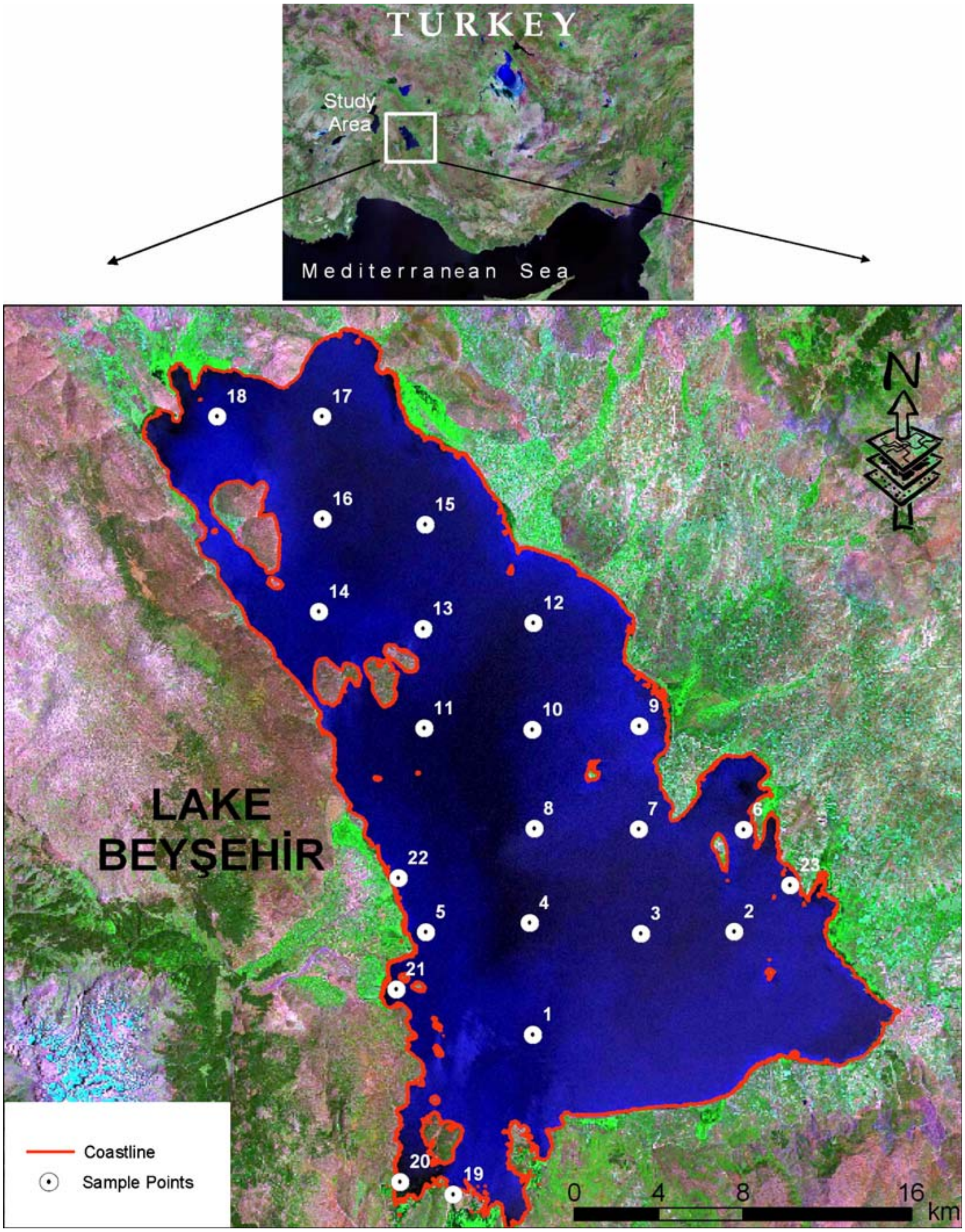

Fig. 1 Study area and sampling sites

For this study, cloud-free Terra ASTER imagery data acquired on June 09, 2005 was used as the satellite image data for mapping water quality in the lake. The ASTER instrument has three spectral bands in the visible near-infrared (VNIR), six bands in the shortwave infrared (SWIR), and five bands in the thermal infrared (TIR) regions, with 15, 30, and 90 m ground resolution respectively. The VNIR subsystem is specifically endowed with a backward-viewing telescope for high-resolution

Table 1 Technical characteristics of ASTER sensor data used in the study

Technical specifications	Terra ASTER
Bands in visible/near-infrared	3
Bands in short wavelength infrared	6
Bands in thermal infrared	5
Panchromatic band	–
Stereo capability	Yes
Stereo imaging geometry	Along-track
Pixel size	15 m VNIR 30 m SWIR 90 m TIR
Scene coverage	60 × 60 km
Orbital altitude	705 km
Repeat cycle	16 days
Data acquired for this study	09.06.2005

stereoscopic observation in the along-track direction (3B). Technical characteristics of the ASTER sensor are given in Table 1. However, only VNIR and SWIR bands (first four bands 0.52–1.70 μm) were used to correlate remotely sensed data and water quality parameters. Image processing procedure and the evaluation of results were carried out using Erdas Imagine© and ArcGIS© 9.0 software packages.

Image processing

Raw images usually contain such significant systematic and non-systematic (geometric) distortions that they cannot be used as a map (Jensen 2000; Sabins 1996; Toutin 2004). Therefore in this study, ASTER image data were geometrically corrected as a first stage of the image processing procedure.

The ASTER scene acquired on June 09, 2005 was rectified using a set of 40 ground control points (GCPs) extracted from 1:25,000 scale maps. A first-order polynomial transformation was used to create the output images with 15 m ground resolution, because the study area presents an almost flat topography and the study includes analysis of the surface water in a lake (Metternicht and Zinck 1998). The root mean square error (RMSE) of the transformation was not permitted to exceed ±0.5 pixel. ASTER image data was registered to Universal Transverse Mercator coordinates zone 36, WGS 84 Datum, and resampled to 15 m by the nearest neighbor interpolation method (Almeida-Filho and Shimabukuro 2002).

In situ data and laboratory analysis

The field work involving water sampling and ground truthing was carried out on June 09, 2005. It coincided with the overpass of the Terra ASTER instrument (09/06/2005). Taking into account the distribution of sample points, it was decided to collect water samples at twenty three points for this case study covering the Lake Beysehir. At each sample site, a 2,500 ml water sample was collected with a vertical point water sampler at 50 cm below the surface. The locations of points were checked and recorded by using a hand held GPS.

Chlorophyll-*a* (Chl-*a*) was the water quality parameter selected for this case study. This was chosen over other water quality parameters for several reasons. First, when present in sufficient concentrations chlorophyll-*a* has a distinct effect on the reflectance spectrum from inland water, notably absorption peaks at approximately 400 nm and 670 nm, making it detectable by remote sensing techniques. Second, spatial patterns of chlorophyll-*a* tend to be complex, being a result of biological as well as physical and chemical factors, so are ideal for evaluating sampling strategies. Third, the spatial distribution of chlorophyll-*a* is important in lakes and merits further study. Fourth, chlorophyll-*a* is the most commonly used parameter in estimating phytoplankton biomass in lakes.

Chlorophyll-*a* was analyzed in the laboratory according to the methods given in Standard Methods. The extraction and measurement of the chlorophyll-*a* concentrations were made with acetone following the SM 10200 H-spectrophotometric method (APHA et al. 2005).

Correlating image data and water quality parameters

In this study, the average digital number of pixels (a 3 × 3 window) surrounding the sample pixel is used to perform multiple regression. Reddy (1997) found that the results of *t*-tests proved that the 5 × 5 and 3 × 3 array sizes were the best,

Table 2 Chl-*a* concentration, digital numbers and averages (3 by 3 windows) at the sample points obtained from the ASTER 2005 image data

Sample point no.	Chl-*a* concentration	Band 1 0.52–0.60 μm		Band 2 0.63–0.69 μm		Band 3 0.76–0.86 μm		Band 4 1.60–1.70 μm	
	μg/l	DN	Average	DN	Average	DN	Average	DN	Average
1	1.31	81	80.22	30	30.00	19	19.56	9	9.56
2	1.68	71	71.11	30	31.00	23	23.67	12	12.17
3	0.37	71	71.22	30	29.67	21	20.89	10	9.44
4	1.31	63	62.78	26	26.89	19	18.89	11	9.67
5	1.87	64	63.44	29	28.44	21	20.89	13	12.89
6	0.75	71	71.89	30	31.22	24	22.89	12	12.00
7	0.56	77	78.44	29	28.56	21	20.89	10	9.78
8	0.94	64	63.49	28	27.44	20	20.67	9	9.33
9	1.31	100	99.11	39	38.56	24	23.22	12	11.78
10	0.75	60	60.78	26	27.22	21	21.33	9	9.44
11	1.12	79	79.22	30	30.22	21	21.67	11	10.78
12	1.50	73	73.11	30	30.44	23	23.00	10	10.78
13	0.79	85	84.89	34	33.56	23	23.44	11	11.33
14	1.68	108	108.67	44	43.89	25	25.44	13	12.78
15	1.31	73	72.78	33	32.33	26	24.67	12	12.00
16	1.68	87	89.44	38	37.89	25	25.33	13	12.78
17	1.12	87	86.22	38	38.56	26	26.56	12	12.56
18	2.43	108	106.56	49	48.89	18	29.56	16	15.67
19	4.11	56	56.56	30	30.33	25	25.56	19	19.33
20	3.18	58	57.44	31	31.44	25	25.78	18	17.89
21	2.43	60	60.11	32	32.22	24	25.33	16	16.00
22	2.06	62	61.00	30	30.33	23	22.78	14	14.33
23	1.50	58	57.33	30	30.00	23	22.67	14	14.00

and there was no significant difference between these two arrays (Wang et al. 2006). The following multiple regression equation is widely used in water quality research relating to remote sensing (Hellweger et al. 2004).

$$\mathrm{WQP} = a + b^{*}\mathrm{Band}\ 1 + c^{*}\mathrm{Band}\ 2 + d^{*}\ \mathrm{Band}\ 3 + e^{*}\mathrm{Band}\ 4 \qquad (1)$$

where WQP is the dependent water quality parameter and four independent variables Band 1, Band 2, Band 3 and Band 4, which are digital numbers in the ASTER image data from band 1 (Green) to band 4 (SWIR) as presented in Table 2.

Estimation of trophic state index for lakes

There are many mathematical methods for the lake eutrophication assessment. The Trophic State Index (TSI) proposed by Carlson (1977) is the most acceptable method for lake eutrophication evaluation. Carlson's TSI is one means available to examine the relationship between total phosphorus, chlorophyll-*a*, and Secchi disk readings in a lake and its overall productivity. The TSI scale ranges from 0 (ultra-oligotrophic) to 100 (hypereutrophic). TSI value for chl-*a* can be calculated from the following equation:

$$\text{Chlorophyll-}a\ \mathrm{TSL} = 9.81^{*}\left[\ln\left(\text{Chlorophyll-}a\ \text{average}\right)\right] + 30.6 \qquad (2)$$

Table 3 Multiple regression analysis of chlorophyll-*a* concentration and spectral reflectance

Water quality parameter (WQP)	Regression equation	Coefficient (R^2) of determination
Chlorophyll-*a* (Chl-*a*)	Chl-*a* = −1.024 + 0.0086 * Band 1 − 0.013 * Band 2 − 0.096 * Band 3 + 0.367 * Band 4	0.863

Carlson and Simpson (1996) recommended that if data for chlorophyll and phosphorus are available, chlorophyll should be used as the primary index for trophic state classification. Total phosphorus, chlorophyll-*a*, and Secchi disk depths were determined in Lake Beysehir. Chlorophyll-*a* concentrations were used to evaluate the trophic state of Lake Beysehir in the study.

Results and discussion

Table 2 lists raw DNs and chl-*a* concentrations of 23 sample sites. It can be seen in Table 2 that the minimum and maximum chl-*a* concentrations were observed to be 0.37 μg/l and 4.11 μg/l with the average value of 1.55 μg/l in the sample sites. The Trophic State Index (TSI) as calculated from chl-*a* measurements was 34.9. This means that Lake Beysehir was oligotrophic on June 9, 2005. But, during the summer chl-*a* increase, and thus TSI (chl-*a*) get up to the maximum in August. TSI is based on the interrelationships of TP, chlorophyll-*a*, and Secchi transparency. Therefore, the trophic state of the Lake must be estimate using summer average values of these water quality parameters.

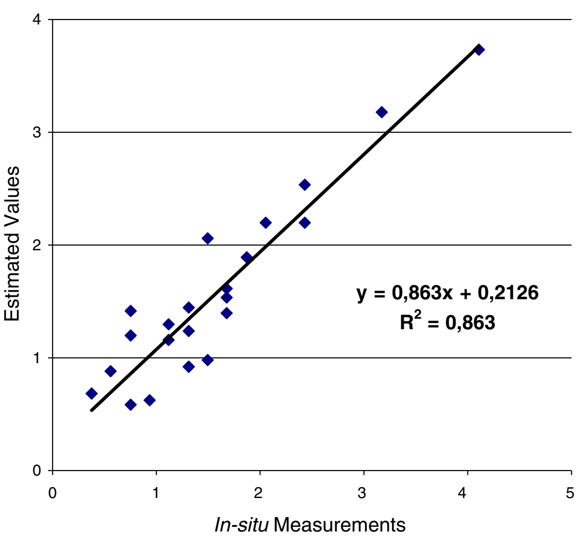

Fig. 2 Regression model for chl-*a* with ASTER 2005 image data

The results of multiple regression show that in-situ data and remotely sensed data are in good agreement with an R^2 value of over 0.86. Table 3 shows the value of each coefficient (a, b, c, d, e) the coefficient of determination from multiple regression for chlorophyll-*a*. It is obvious that multiple regression model predictions of chlorophyll-*a* (calculated values) are satisfactory. (Fig. 2).

Application of our regression equation for calculation of chl-*a* from remote sensing reflectance resulted in a distribution map of chl-*a* (Fig. 3). As can be seen Fig. 3, areas showing the highest concentration of chl-*a* are areas which receive untreated sewage from villages in adjoining areas of the lake. Prolific growths of macrophytes are observed near the north, south and west banks of the lake due to agricultural runoff. It is also observed that around islands high chl-*a* concen-

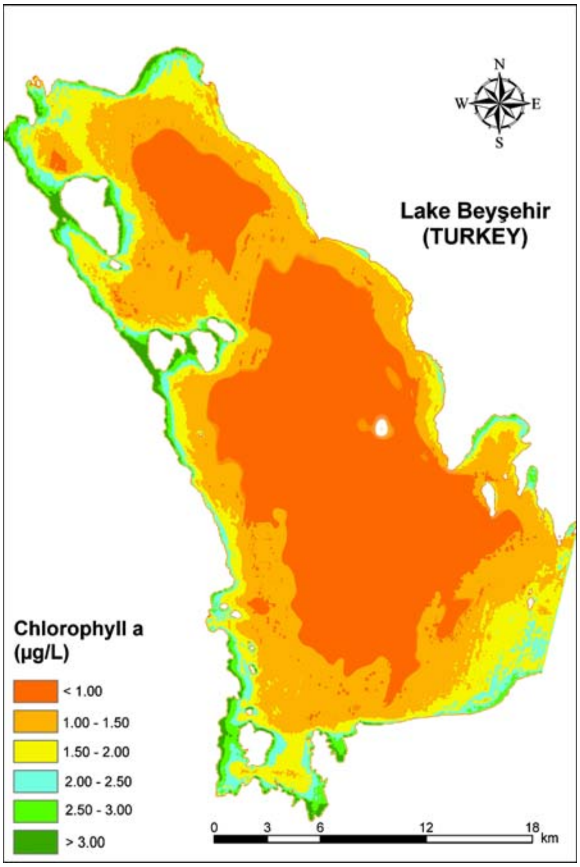

Fig. 3 Water quality map showing distribution of the chlorophyll-*a* concentration over the Lake Beysehir

trations occur. A large area in the middle portion of the lake shows very low chl-*a* concentrations as it is away from point and non-point sources of incoming nutrients.

Conclusions

Remote sensing is an effective tool in lakes where spatial variation of water quality is high. For the best result, conventional monitoring of lakes (water sampling) should be synchronized with satellite overpasses.

Remote sensing was chosen as the ideal technique for determining spatial distributions because it allows comprehensive coverage of the whole lake, which would not have been possible through surface sampling. Spatial distributions of surface chlorophyll-*a* in Lake Beysehir were determined from remotely sensed images. Terra/ASTER based observations have been presented to evaluate chl-*a* concentration and lake's eutrophication in this study.

The results gives a good correlation between chl-*a* determination from satellite remote sensing data and *in situ* chl-*a* measurements ($R^2 > 0.86$). The obtained results show that Terra/ASTER can be used effectively to determine chl-*a* levels in Lake Beysehir of Turkey.

The areas close to shorelines where there is human activity have relatively poor water quality, as compared to the areas far away from the shorelines. Our results show that Lake Beysehir is oligotrophic on June 9, 2005.

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