NASA ENERGY AND WATER CYCLE SPONSORED RESEARCH (NEWS)

Final Report on

MULTISENSOR SPACEBORNE MONITORING OF LARGE LAKES WORLDWIDE: ASSESSMENT OF TRENDS IN WATER QUANTITY AND QUALITY

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1. Introduction

The world's large lakes represent an important reservoir of water for domestic consumption, agriculture, industry, fisheries, and a wide array of other uses. With increases in global population and development, demand on the world's lake resources is expected to increase during the 21st century. At the same time, lakes serve as robust indicators of regional-scale dynamics in both climate and human activity (Vörösmarty et al., 2004). Lake levels respond to changes in runoff within their watersheds, and to the diversion of water for human consumption. In-lake conditions such as water clarity, chlorophyll concentration, and suspended solids respond to climatic and human-induced changes; these parameters in turn affect the usability of lake water and the costs associated with water treatment.

In recent years much progress has been made towards understanding various components of the earth system, particularly through the use of earth observation satellites, biophysical models, and in-situ observations. However, much of the information acquired through these means has not been sufficiently exploited for its value in a global-scale assessment of surface water conditions and cycling (Vörösmarty, 2002). While the oceanographic community has made dramatic progress on operationalizing the use of satellite remote sensing, similar applications in the terrestrial hydrology community have been slower to materialize. This trend is beginning to change, with a wide array of types of sensors being applied to monitoring lakes, rivers, and wetlands (Alsdorf and Lettenmeier, 2003). NASA's Terrestrial Hydrology Program and the forthcoming SWOT satellite mission represent examples of the new focus on the terrestrial component of the global water system.

Lakes represent one major component of the terrestrial hydrologic cycle. A monitoring system that assesses the dynamics of water storage and water quality in large lakes can help answer several of the core questions driving NASA's Energy and Water Cycle research:

(1) How is the cycling of water changing on the global scale?
(2) How are variations in water resources related to global climate variation?
(3) What are the consequences of land cover/land use change for societies and ecosystems?
(4) How will water cycle dynamics change in the future?

The research program described in this report was designed to develop such a monitoring system for routine assessment of parameters related to water storage (quantity) and water quality in lakes.

2. Project Objectives and Hypotheses

As stated in the original proposal, the objectives and hypotheses for this research were as follows:

> The objective for this project is to demonstrate that a multisensor approach involving both spaceborne lidar and electro-optical sensors can contribute to a robust assessment of the dynamics of large lakes, including parameters related to water storage (lake level and surface area changes) and in-lake conditions related to water quality. The primary hypothesis to be tested is:
>
> *Changes in water storage in large lakes can be monitored on a global scale via satellite remote sensing; the accuracy of this monitoring system can be assessed; and when combined with field observations, estimates of parameters related to water quality can also be obtained.*

3. Methods

The research undertaken for this project was focused on three broad topics:

Measuring and monitoring changes in the surface area of large lakes using MODIS. A collection of large lakes worldwide (including lakes with large variability in water storage) were monitored using MODIS, yielding data on lake surface area and changes in area over time. Lake maps were derived from these images, with a numerical mixture analysis procedure used to derive fractional-cover percentages for pixels along lake edges. An early version of this approach was described in Chipman & Lillesand (2007), and illustrated for a cluster of six lakes in North Africa. Validation tests for these methods were conducted using high-resolution satellite imagery, as well as lake maps derived from aerial photo interpretation.

Estimating water levels in lakes using ICESat/GLAS. ICESat/GLAS lidar data were acquired and analyzed for each of the discrete operational periods following the system's launch in 2003, for test lakes in North America and Africa. These data were compared to in-situ measurements of water levels, and to estimates of water level derived from a geospatial modeling approach. One extensive pilot project was conducted in which GLAS data were combined with the MODIS-derived lake area measurements to calculate changes in lake volume between each pair of GLAS operational periods.

Characterizing water clarity and other parameters in selected lakes with satellite imagery. Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) have been used successfully in the US Midwest to remotely assess the clarity of inland lake water over large regional areas using an established relationship between measured lake water transparency and spectral radiance (Lathrop and Lillesand, 1986; Lathrop et al., 1991; Kloiber et al., 2002; Chipman et al., 2004). The empirical model used in the US Midwest applications relates the natural logarithm of Secchi depth to a function of observed spectral radiance in Landsat visible bands TM1 (blue) and TM3 (red). A somewhat similar approach has also been used in Washington State (Butkus, 2004). For our project, we used these previously developed methods to analyze optical properties of clusters of lakes in South America and in the northeastern US.

4. Results

Measuring and monitoring changes in the surface area of large lakes using MODIS. We analyzed MODIS data for approximately 60 large lakes grouped in 35 lake clusters in the Americas, Africa, and Eurasia (Table 1). For each lake cluster, 452 dates of Terra and Aqua MODIS imagery were processed, from the start of the Terra MODIS record in 2000 through 2011. With over 15,000 image data sets to analyze, a highly automated procedure was required. To facilitate this automation, and to reduce the impact of cloud cover, we used the multi-date composite data sets derived from the surface reflectance product, obtained from the NASA Land Processes archive center (LP-DAAC). The complete record analyzed for each lake cluster included one image every 16 days during the period prior to the launch of Aqua in mid-2002, and one image every 8 days thereafter.

The products developed for each lake include maps showing the extent of fully or partially inundated pixels on each date; maps showing the mean water coverage and decadal trend in water coverage over the duration of the project; and time-series tabular data on lake area for each date. Examples of the results are shown in Figures 1 and 2.

The methods used in this project were initially validated using a set of 28 test lakes in North America, whose surface area estimates were compared to those from maps derived from photointerpretation (Chipman and Lillesand 2007, Figure 3a). Lake areas in this validation set ranged from 8.4 km^2 to 670 km^2. The correlation coefficient between the predicted and true areas was > 0.999, and all the points fell near the 1:1 line. The root mean square error of prediction (RMSE) was equivalent to 2.65% of total lake area, or 4.44% of the lakeshore buffer zone area.

A more extensive validation process was undertaken using data for the Toshka Lakes in southern Egypt. These lakes were chosen because of their wide swings in lake surface area, water level, and volume during the study period; and because they represent a relatively simple system, having only a single source of water (the Lake Nasser spillway, whose flow rate is monitored in-situ). For these lakes, the lake surface area record was extended two years back in time, to 1998, using AVHRR imagery, so as to include the initial formation of the lakes following the summer 1998 flooding.

Figure 3 shows the MODIS and AVHRR-derived surface area time series data for the six Toshka lakes, along with much higher-resolution measurements of surface area from Landsat imagery. The two sets of area measurements are compared in Figure 4.

<u>Estimating water levels in lakes using ICESat/GLAS.</u> ICESat/GLAS lidar data were acquired for a set of lakes in the US Midwest, and the resulting elevations were compared to in-situ water level measurements. The GLAS data were characterized by nonrandom errors on the decimeter scale, probably associated with pointing error in the instrument. In addition, the 2003-2009 lifetime of GLAS was divided into a series of discrete operational periods, during which data were actively collected, separated by “rest” periods for the laser instruments, during which no data were collected. Taken together, these factors severely limit the use of GLAS for precise measurement of water levels in lakes except where long-term trends in water levels greatly exceed the sensor’s error level. In cases where there are long-term trends greater than the noise, GLAS data can be used to derive reasonably accurate estimates of those trends. This is illustrated using validation data from the Toshka lakes site.

For these lakes, we derived two different time series of lake surface area changes, one from GLAS, and one from combined analysis of a digital elevation model and the lake surface area maps. The latter approach, based on geospatial modeling, is described in Chipman and Lillesand (2007), and a sample of the results is shown in Figure 5. Next, Figure 6 compares the results of this geospatial modeling approach to the estimates of water level derived from 56 GLAS transects.

The estimated trends in lake water level, from geospatial modeling and from GLAS lidar measurements, are as follows:

Source	Loss Rate
Geospatial modeling (Lake 5):	2.65 m/yr
ICESat GLAS (Lake 5):	2.61
ICESat GLAS (Lake 4):	2.41
ICESat GLAS (Lake 1):	2.64

For reference, annual evaporation at the nearby Aswan Dam is 2.3 m/yr. Thus, 85-90% of the observed trends in these lakes are due to evaporation, with only 10-15% going to groundwater recharge. These results are in accordance with previous work in this region.

By combining estimates of lake surface area and water levels, it is possible to calculate trends in lake volume (Figure 7). This result could be considered to be anticipatory of the data that should soon be available from the SWOT satellite mission, which will include both imaging and altimetry sensors on a single platform. SWOT will thus be able to provide, on its own, the same data that we obtained here by combining data from multiple sensors in a rather complex analytical approach.

Characterizing water clarity and other parameters in selected lakes with satellite imagery. Two sub-projects were undertaken for this component of the study, one for lakes in South America, and one for lakes in the northeastern US. The Andean-Patagonia region of Argentina was selected because the mountainous terrain and volcanic landscape is radically different from that of the upper Midwest US and because a robust set of lake data (physical parameters and trophic indices) was collected for numerous lakes in the region in the 1980s (ALARE Database: Quiros, 1988; Quiros and Drago, 1999) once Landsat TM imagery became available.

This study was also designed to evaluate the accuracy and feasibility of applying the methodology to lakes in remote areas that are not easily accessible and only rarely field-sampled. Finally, an additional goal was to use strictly public-domain imagery in order to keep costs to a minimum and within the budget of governments and jurisdictions charged with monitoring water quality in remote locales. A challenge with the latter restriction is obtaining imagery acquired within a sufficiently small time window - preferably weeks - of the field sampling date.

The ALARE lake database contains water chemistry, nutrient levels and morphometric characteristics for 96 lakes and reservoirs throughout this region. Sixty-five of these lakes were used in our study (Figure 8); the remaining lakes were omitted because ambiguous nomenclature and imprecise longitudinal data precluded exact identification of the lakes on satellite imagery or other map sources.

Lakes in the database were identified on a set of 14 Landsat images. Clusters of pixels from each lake were sampled for their spectral signatures, and the values of bands TM1 and TM3 were regressed against measures of Secchi depth from the database using the empirical relationship developed for the upper Midwest USA. Despite the temporal uncertainty of the lake database measurements relative to the acquisition dates of the satellite images, and the large geographic and topographic differences between the Patagonian Andes and the relatively flat Midwest, the satellite data were reasonably well correlated with the lake clarity measurements, yielding an r^2 value of 0.732 using a sub-sample of 29 lakes (Figure 9). Many of the Patagonian lakes are finger lakes with multiple basins, with upstream reaches experiencing large sediment pulses in early summer. In these lakes, optical properties can vary dramatically both over space and time.

A second sub-project was conducted to test the Landsat/lake clarity methodology using lakes in the northeastern United States. Work on this project was done by Dartmouth undergraduate student Julia Kelson, and the results are currently being analyzed and compared to the previous studies in the US Midwest and in South America. Preliminary analysis of the results suggests that lakes in the northern parts of the northeastern US (northern New England) are characterized by a somewhat different relationship between the satellite spectral measurements and the in-lake optical properties; thus, the methods used in other regions may need to be modified for measurement of water clarity in this region. We are currently exploring the causes of this regional variation.

5. Education and Training

One post-doctoral researcher (Samantha Kaplan) was trained on this project. Dr Kaplan worked on the analysis of water clarity in South American lakes using multispectral satellite imagery. She is now Assistant Professor of Geography at the University of Wisconsin-Stevens Point.

At Dartmouth College, undergraduate Earth Sciences major Julia Kelson (class of 2012) has been working on analysis of water clarity in lakes in the northeastern United States.

Materials from the project have been used in course development for classes in remote sensing and geographic information systems at Dartmouth College, and have been included in the latest edition of the textbook Remote Sensing and Image Interpretation (see below).

Materials that resulted from satellite imagery collection and processing were integrated into a web mapping system for public display. The purpose is to make routine acquisitions of imagery available in a user-friendly mapping interface and also available as a stand-alone WMS map service for GIS software. Examples available here: http://wms.ssec.wisc.edu/ Additional material will be available as the technology matures and will be hosted at the http://www.lakesat.org website.

6. Publications and Presentations

The following papers provide reports on the work conducted in this project:

Chipman, J.W. and T.M. Lillesand. 2007. Satellite-based assessment of the dynamics of new lakes in southern Egypt. *International Journal of Remote Sensing*, 28(19): 4365-4379.

Chipman, J.W. 2007. Satellite monitoring of hydrologic transformations in southern Egypt. *Proceedings*, Annual Meeting of the American Society for Photogrammetry and Remote Sensing (ASPRS), 7-11 May 2007, Tampa, Florida.

Greb, S. R., Martin, A. A., and Chipman, J. W. 2009. Water clarity monitoring of Wisconsin lakes (USA) using Landsat satellites. Proceedings, 33rd International Symposium on Remote Sensing of Environment: Sustaining Millennium Development Goals, 4-8 May 2009, Stresa-Lago Maggiore, Italy.

Chipman, J. W. et al. In preparation. A multisensor approach to satellite monitoring of trends in lake surface area and volume. For submission to International Journal of Remote Sensing, Sept. 2011.

In addition, selected data, figures, or other results from this project are included in the following books:

Lillesand, T.M., R.W. Kiefer, and J.W. Chipman. 2008. *Remote Sensing and Image Interpretation*, 6th edition. John Wiley & Sons, NY.

Chipman, J., L.Olmanson, and A.Gitelson. 2009. *Remote sensing methods for lake management*. North American Lake Management Society, Madison, WI.

The following presentations included materials related to this project:

Chipman, J.W. 2007. Satellite monitoring of hydrologic transformations in southern Egypt. Annual Meeting of the American Society for Photogrammetry and Remote Sensing (ASPRS), 7-11 May 2007, Tampa, Florida.

Chipman, J. W. 2008. Satellite monitoring of lake ecosystems. Annual Meeting, New England Region – American Society for Photogrammetry and Remote Sensing, 6 October 2008, Hanover, New Hampshire.

Chipman, J. W. 2009. Remote sensing for lake management: fundamental concepts. Annual symposium, North American Lake Management Society (NALMS), workshop on Remote Sensing Methods for Lake Assessment, 27 October 2009, Hartford CT.

Chipman, J. W. 2009. Satellite remote sensing III: regional- to global-scale systems. Annual symposium, North American Lake Management Society (NALMS), workshop on Remote Sensing Methods for Lake Assessment, 27 October 2009, Hartford CT.

Chipman, J. W. and M. Durand. 2010. Remote sensing of the Great Lakes. Workshop on NASA's Role in Great Lakes Research, sponsored by NASA Physical Oceanography Program, 12 April 2010, NASA Glenn Research Center, Cleveland, OH.

7. References

Alsdorf, D., and D. Lettenmaier. 2003. Tracking fresh water from space. Science, 301:1491-1494.

Butkus, S. 2004. Trophic state census of Washington State Lakes by Satellite Imagery. Washington State Department of Ecology, Publication 04-03-011, 111p.

Chipman, J.W., Lillesand, T.M., Schmaltz, J.E., Leale, J.E., and M.J. Nordheim. 2004. Mapping lake clarity with Landsat images in Wisconsin, U.S.A. Can. J. Remote Sensing, 30:1-7.

Chipman, J.W. 2007. Satellite monitoring of hydrologic transformations in southern Egypt. Proceedings, Annual Meeting of the American Society for Photogrammetry and Remote Sensing (ASPRS), 7-11 May 2007, Tampa, Florida.

Chipman, J. and T. Lillesand. 2007. Satellite-based assessment of the dynamics of new lakes in southern Egypt. International Journal of Remote Sensing, 28(19): 4365-4379.

Kloiber, S.M., Brezonik, P.L., Olmanson, L.G., and Bauer, M.E. 2002. A procedure for regional lake water clarity assessment using Landsat and multispectral data. Remote Sens. Environ. 82:38-47.

Lathrop, R.G., and T.M. Lillesand. 1986. Use of Thematic mapper data to assess water quality in Green Bay and central Lake Michigan. Photogrammetric Engineering & Remote Sensing, 52:671-680.

Lathrop, R.G., Lillesand, T.M., and B.S. Yandell. 1991. Testing the utility of simple multi-date Thematic Mapper calibration algorithms for monitoring turbid inland waters. International Journal of Remote Sensing, 12:2045-2063.

Lehner, B. and Döll, P. 2004. Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology 296(1-4): 1-22.

Quiros, R. 1988. Relationships between air temperature, depth, nutrients and chlorophyll in 103 Argentinian lakes. Verh. Internat. Verein. Limnol., 23:647-658.

Quiros R. and E. Drago. 1999. The environmental state of Argentinean lakes: An overview. Lakes & Reservoirs: Research and Management, 4:55-64.

Vörösmarty, C. 2002. Global water assessment and potential contributions from Earth Systems Science. Aquatic Sciences, 64:328-351.

Vörösmarty, C., D. Lettenmeier, C. Levecque, M. Meybeck, C. Pahl-Wostl, J. Alcamo, W. Cosgrove, H. Grassl, H. Hoff, P. Kabat, F. Lansigan, R. Lawford, and R. Naiman. 2004. Humans transforming the global water system. EOS Transactions, 85:509-514.

8. Figures and Tables

Lake or Lake Cluster	Tile
Kariba	h20v10
Bangweulu	h20v10
Rukwa	h21v09
Eyasi	h21v09
Sulunga	h21v09
Balkhash	h23v04
Alakol	h23v04
Issykkul	h23v04
Qapshaghay	h23v04
Aral	h22v04
Sarykamysh	h22v04
Turkana	h21v08
Kyoga	h21v08
Albert	h21v08
Rift	h21v08
Urmia	h21v05
Van	h21v05
Chad	h19v07
Poyang	h28v06
Zhelin	h28v06
Toshka	h20v06
Hyargas	h24v04
Har	h24v04
Bositeng	h24v04
Edward	h20v09
Kivu	h20v09
Mwena	h20v09
Upemba	h20v09
Titicaca	h11v10
Poopo	h11v10
Cahora Bossa	h20v10 and h21v10
Malawi	h21v09 and h21v10
Tanganyika	h20v09 and h21v09
Aswan	h20v06 and h21v06
Aydarkul	h22v04 and h23v04

Table 1. Lakes and lake clusters included in the MODIS data analysis.

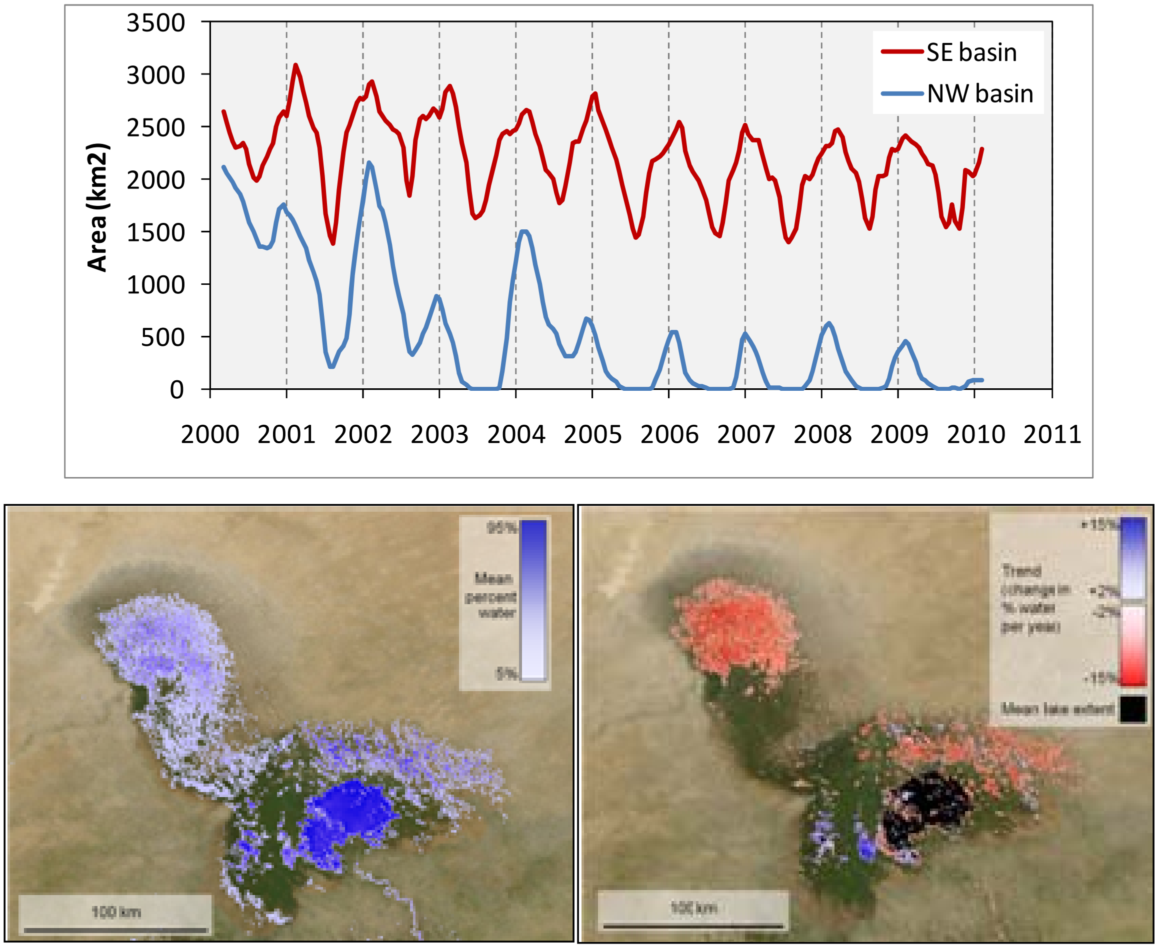

Figure 1. MODIS-derived lake surface area estimates for Lake Chad. *Top:* LOESS-smoothed time series graphs of surface area for the lake's two major basins. *Bottom left:* Map showing mean percent water for each grid cell over the entire time period. *Bottom right:* Map showing trend (change in water cover per year), with red colors indicating areas of decreasing water and blue colors indicating increasing water.

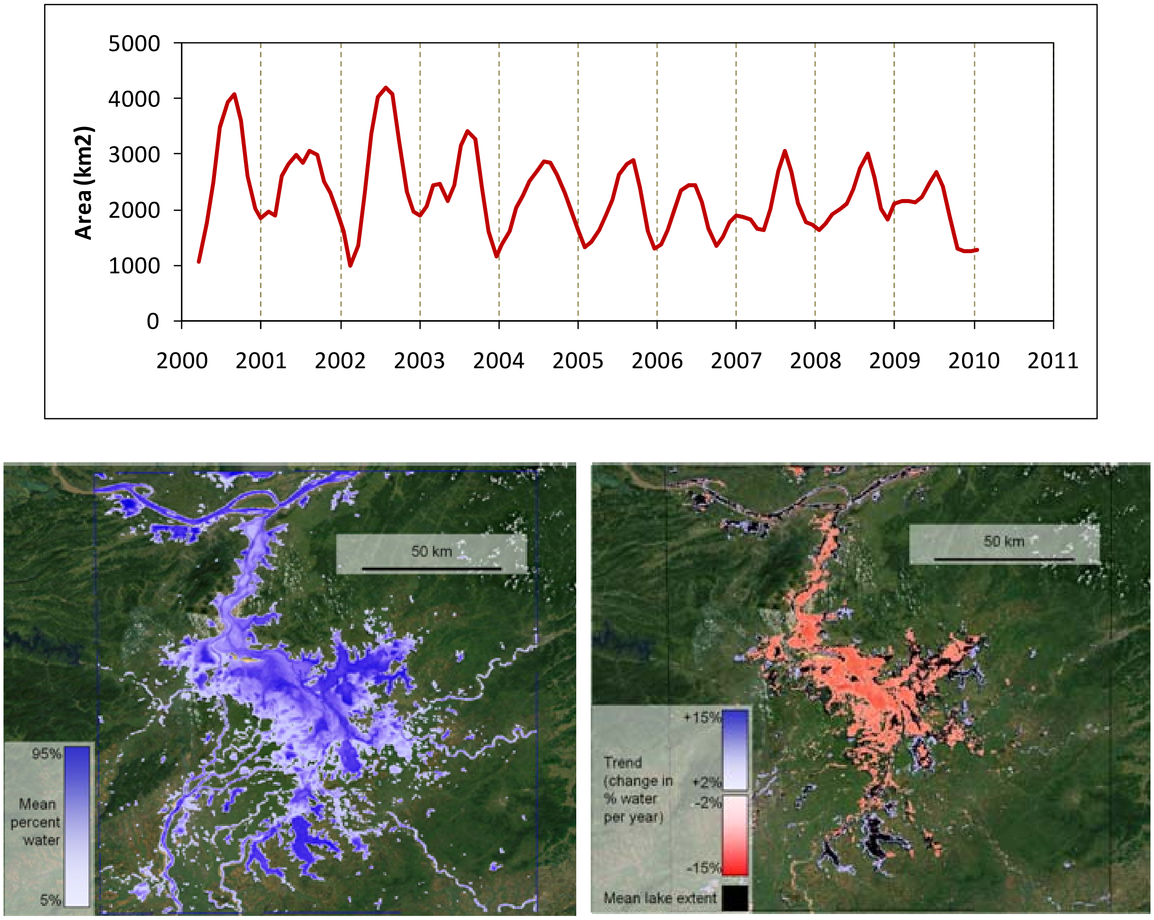

Figure 2. MODIS-derived lake surface area estimates for Poyang Lake, China. *Top:* LOESS-smoothed time series graphs of surface area, showing the lake's characteristic seasonal cycle associated with annual floods on the Yangtze and other rivers. *Bottom left:* Map showing mean percent water for each grid cell over the entire time period. *Bottom right:* Map showing trend (change in water cover per year), with red colors indicating areas of decreasing water and blue colors indicating increasing water.

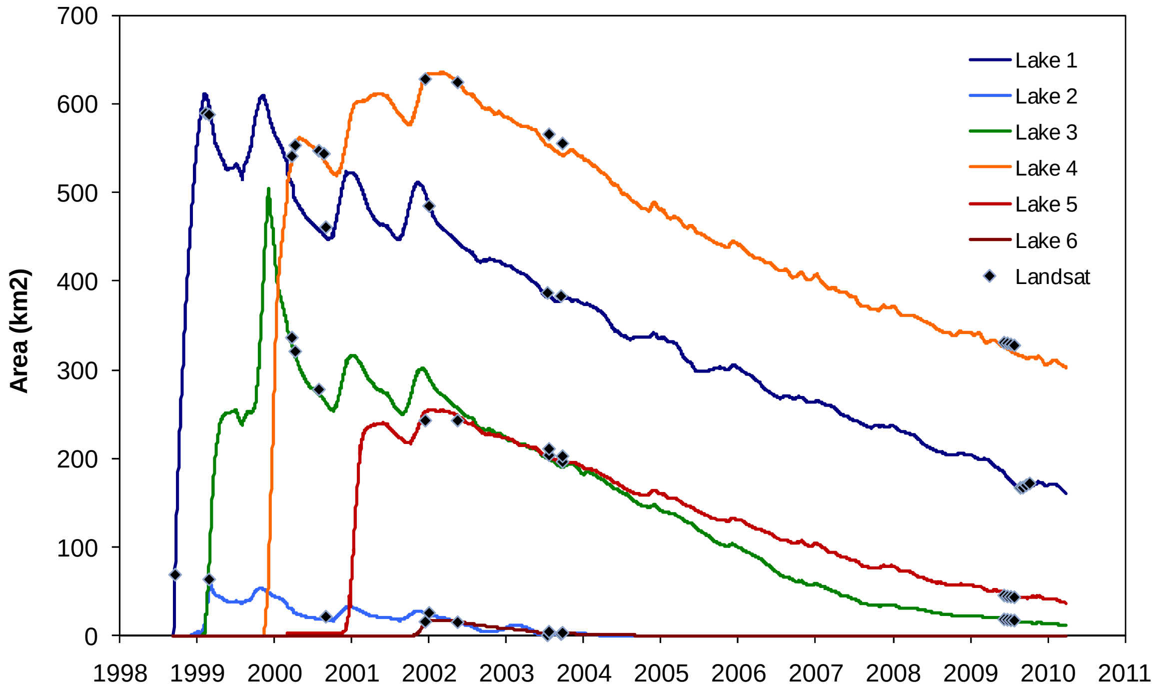

Figure 3. Validation of MODIS-derived lake area estimates, using higher resolution measurements from Landsat.

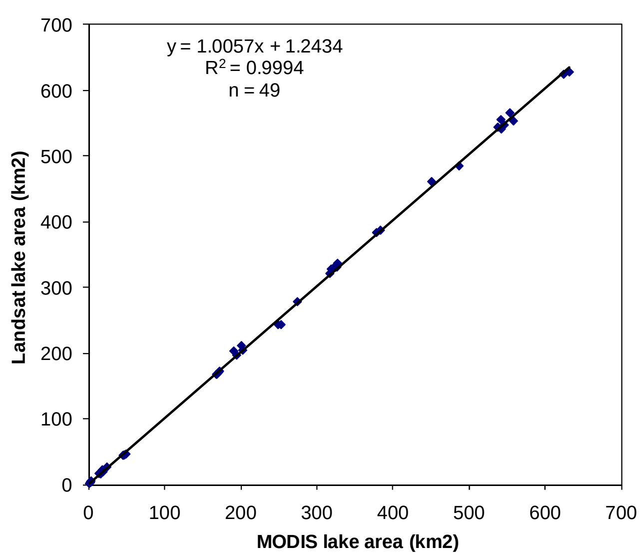

Figure 4. Comparison of Landsat and MODIS derived lake area measurements, for the lakes shown in Figure 3.

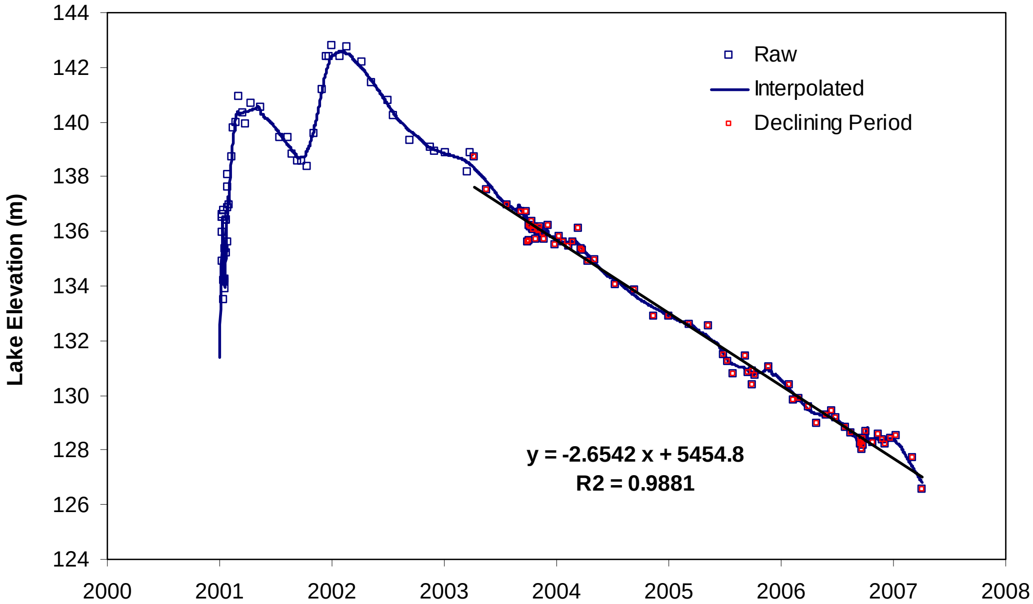

Figure 5. Water levels in Toshka Lake 5, derived from geospatial modeling using a DEM and lake surface area. See Chipman and Lillesand (2007) for details. Red boxes (post-2002) show the period with no additional water inflow, during which the trend in water level (-2.65 m per year) is attributable to evaporation and groundwater recharge.

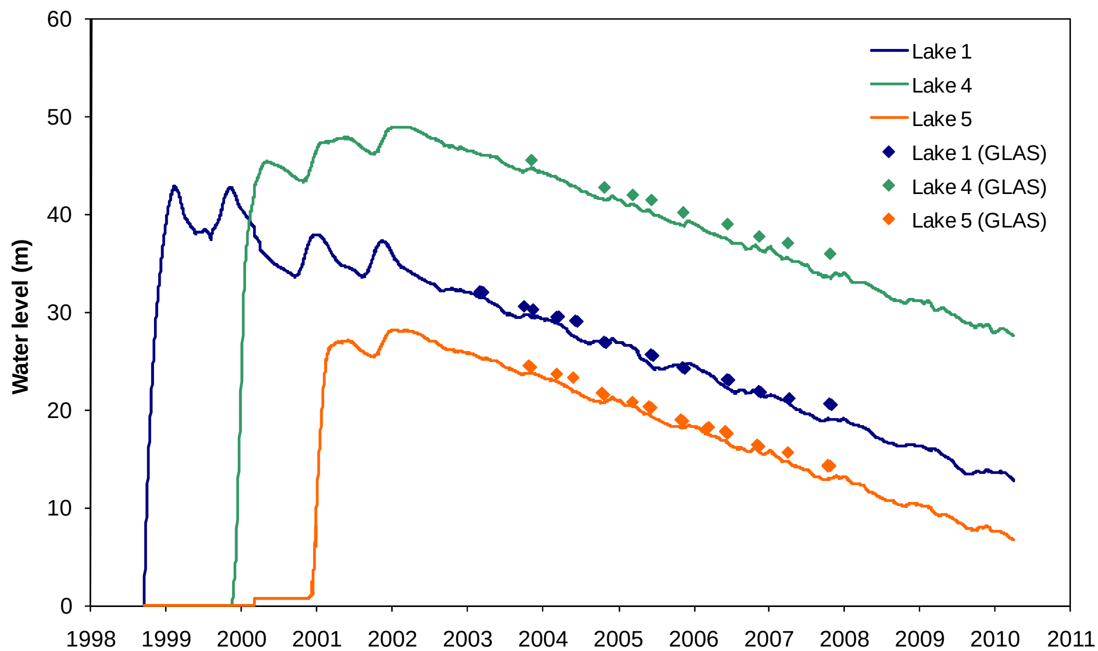

Figure 6. Comparison of estimates of water levels in Toshka Lakes, derived from geospatial modeling (solid lines) and from ICESat/GLAS lidar data (points).

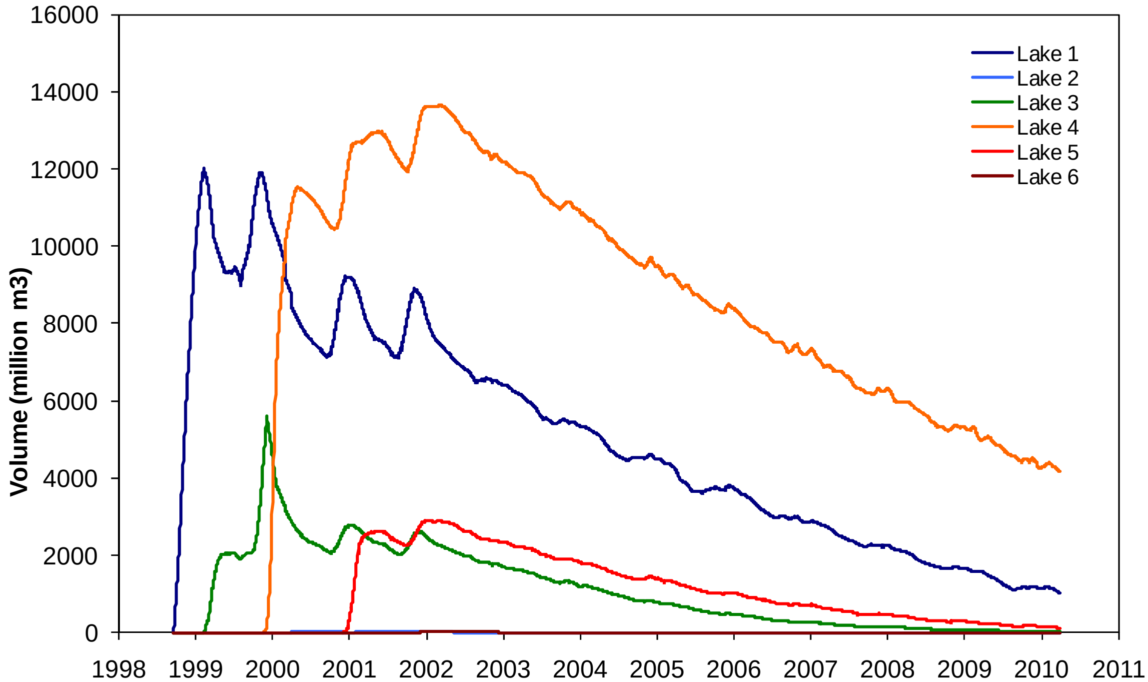

Figure 7. Volume of the Toshka Lakes, derived from MODIS lake area maps and water level trends from GLAS and geospatial modeling.

Figure 8. Map showing location of South American lake sites. Red oval encompasses lakes in the Patagonian Andes.

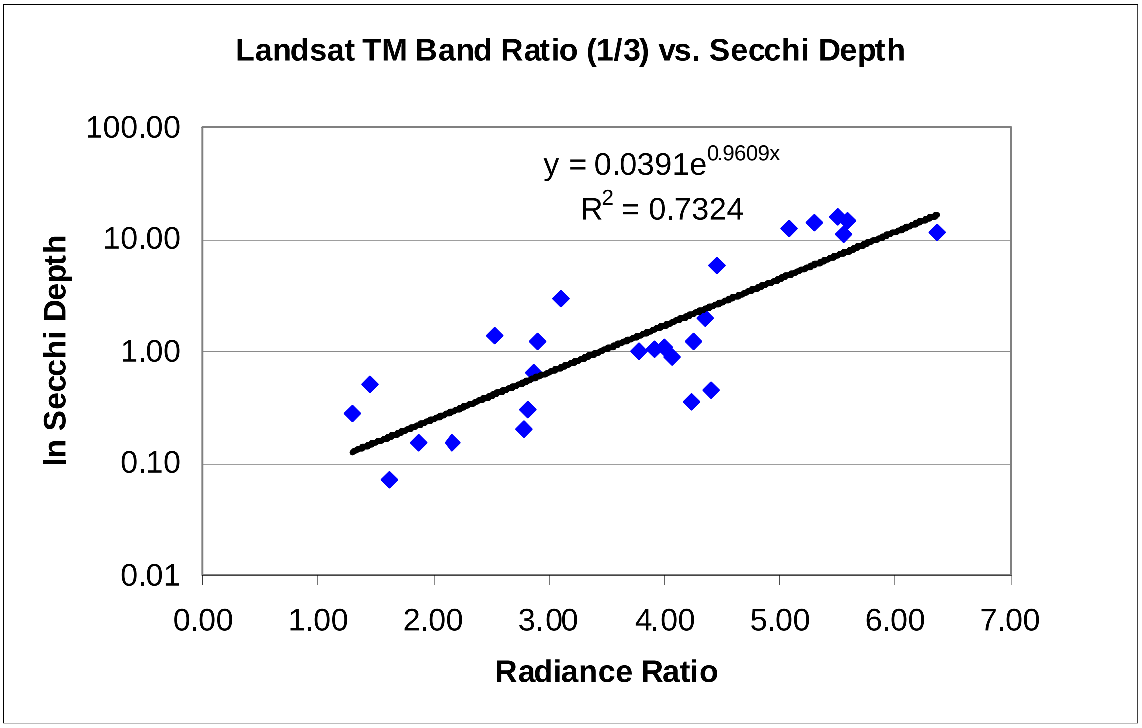

Figure 9. Relationship between Secchi depth and the ratio of Landsat TM band 1 to band 3 in the Patagonian Andes.