SATELLITE MONITORING OF HYDROLOGIC TRANSFORMATIONS IN SOUTHERN EGYPT

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ABSTRACT

Human actions are altering the hydrologic regimes of many regions. Where these transformations are occurring over broad spatial scales, satellite remote sensing may provide the only effective means to monitor their extent and impacts. Over the past decade, two processes (irrigation, and the overflow from high water levels on the Lake Nasser reservoir) have introduced large quantities of water into the previously hyper-arid Toshka region of southern Egypt. We have developed an automated, satellite-based system for monitoring the expansion and contraction of a series of vast new lakes that formed as a result of floodwater diversion beginning in September 1998. Analysis of 166 satellite images shows that the surface area of the six lakes rose to 1740 km^2 in December 2001, and then declined to 845 km^2 by January 2007. Changes in water level and volume were measured for Toshka Lake 5, which reached its maximum volume of 3130 million m^3 in February 2002 before declining to 685 million m^3 by January 2007. The ICESat GLAS laser altimeter may also provide remote measurements of lake levels, with a precision of ± 2 cm or better if all systematic errors are removed. Finally, a new monitoring program is being developed to track the expansion of irrigated agriculture in the nearby Southern Valley Development Project. As agricultural practices and climate change apply pressure on water resources in arid and semi-arid regions in the 21st century, satellite remote sensing will play an increasingly critical role in monitoring these region's hydrologic systems.

INTRODUCTION

The world's rivers, lakes, and aquifers represent an important part of the global water cycle, and provide many critical ecological and economic services. While human actions are now transforming the global water cycle at broad spatial scales, the impacts of these transformations are not fully understood (Vörösmarty et al. 2004). Aquatic systems located in arid landscapes are particularly vulnerable to the effects of human interventions and climate variability (Coe and Foley, 2001). In remote areas and in developing nations, in-situ monitoring of water resources are often limited in scope and may not provide sufficient information for scientists and water resource managers. In these regions, satellite remote sensing may provide the only means to detect and understand long-term changes in water storage and water use (Alsdorf and Lettenmeier, 2003; Vörösmarty, 2002).

The Toshka Depression is a hyper-arid region located in southern Egypt, west of the Nile River valley (Figure 1a). Annual precipitation averages 1.5 mm or less, and the potential evaporation rate is 14-15 mm/day (Vogg and Wehmeier, 1985). Since the late 1990s, two factors have introduced large quantities of water into the Toshka region (Kim and Sultan, 2003; Yan et al., 2003). First, in January 1997 the Southern Valley Development Project (SVDP) began construction of a network of canals to transport Nile River water into the Depression from Lake Nasser, the reservoir created by construction of the Aswan High Dam. The SVDP is intended to provide irrigation water for up to 336,000 hectares of new agricultural lands. Second, in September 1998 rising water levels in Lake Nasser forced the diversion of water out of the reservoir to prevent the dam from being overtopped. The floodwaters flowed westward through a spillway/channel system, before pooling in a basin to form a new lake. In subsequent years, as water continued to flow through the spillway, five additional lakes were created to the west (Figure 1b).

In this study, we used 160 MODIS and AVHRR images to monitor the changes in water storage in the Toshka Lakes, from their initial formation in 1998 through early 2007. During this time, the lakes first underwent a rapid expansion, then a gradual decline (Figure 2). These lakes are of interest because of the dramatic fluctuations in their extent that have occurred over the past nine years, because of their role in the introduction of large quantities of water into a previously waterless region, and because of their proximity to the new SVDP agricultural development zone. Finally, we also discuss plans for future efforts to monitor the expansion of the SVDP irrigation program.

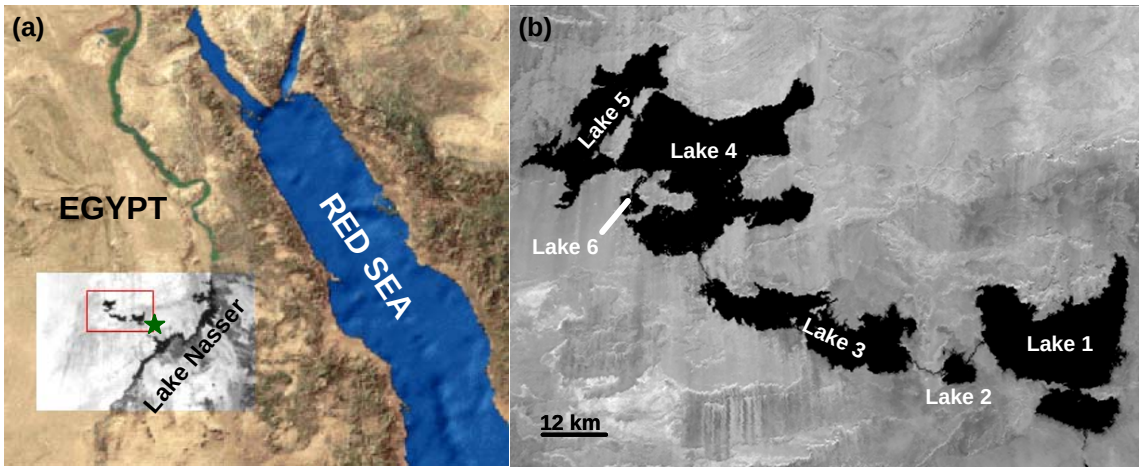

Figure 1. (a) Map showing location of the Toshka Lakes region (red box) and Southern Valley Development Project (green star) west of Lake Nasser in southern Egypt. (b) Image map of the Toshka Lakes.

MEASURING LAKE SURFACE AREA

To measure the changing surface area of the Toshka Lakes, a total of 154 MODIS and six AVHRR images of the study region were acquired and preprocessed. An automated method was then developed to calculate the surface area of each individual lake in the system. Briefly, the method consists of the following steps (Chipman and Lillesand, 2007):

1. The normalized difference vegetation index (NDVI) was computed, and a simple numerical threshold was used to create a first approximation of the land/water boundary.
2. A buffer zone was delineated around this boundary. Pixels falling outside the buffer zone were considered to represent either 100% water or 100% land (depending on which side of the boundary they were located on). Pixels within the buffer zone were considered to include a mixture of land and water.
3. Spectral statistics from the imagery were calculated for the land and water zones, and were then used in a linear mixture model to compute the fractional coverage of water for each pixel in the buffer zone.
4. Two different methods were used to aggregate the water pixels associated with each individual lake; one based on pre-defined basin boundaries, and one involving a spatial clumping procedure.

Steps 1-3 from this list are illustrated in Figure 3. The resulting lake area measurements for all six Toshka Lakes are shown in Figure 4.

Two different approaches were used to validate these methods. First, higher-resolution Landsat imagery was used to test the consistency of the results across widely varying spatial scales. Discrepancies between the same-date ETM+ and MODIS area measurements ranged from 0.1 to 8.1 km^2 for individual lakes, with an RMS error of 4.7 km^2 (for lakes ranging from under 100 km^2 to over 600 km^2) Second, the methods were applied to MODIS images of a set of North American lakes whose surface areas were known precisely. The correlation coefficient between the calculated and true areas was > 0.999, and all the points fell near the 1:1 line. The root mean square (RMS) error was equivalent to 2.65% of total lake area, or 4.44% of the lakeshore buffer zone area. Both of these validation methods suggested that the methodology employed here is highly accurate (Chipman and Lillesand, 2007).

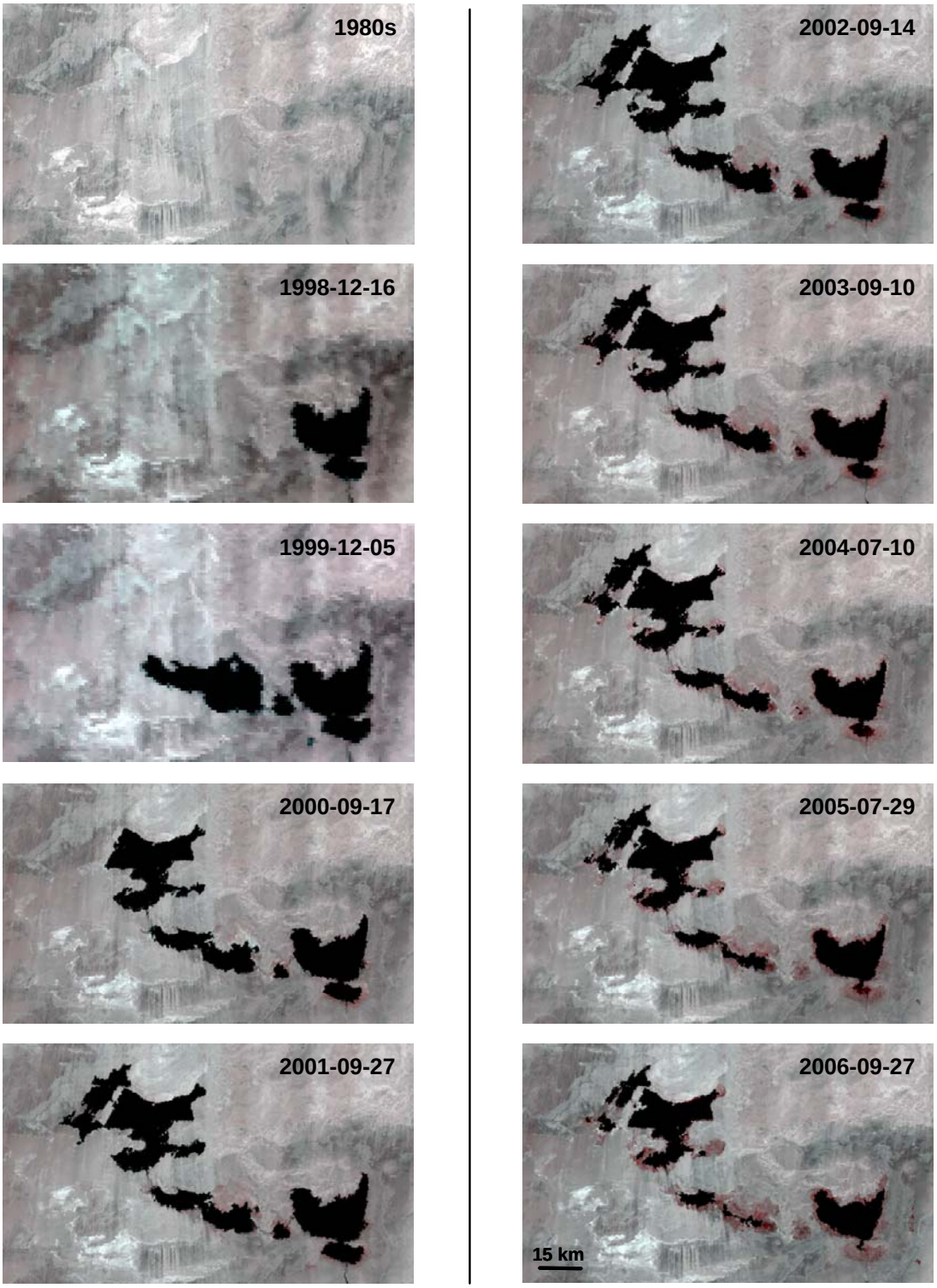

Figure 2. Time-series of satellite images of the Toshka Lakes. 1980s: Landsat TM image mosaic. 1998, 1999: AVHRR bands 1 and 2, 1000 m resolution. 2000-2007: Terra MODIS bands 1 and 2, 250 m resolution.

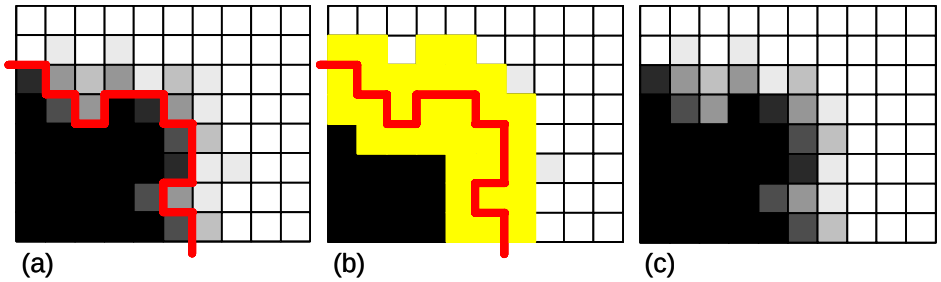

Figure 3. Linear mixture modeling of lake area. (a) Raw image, with line indicating first approximation of land-water boundary. (b) Division into water, buffer zone, and land areas. (c) Fractional water image, with pixel values ranging from 0 (entirely land, white) to 1 (entirely water, black).

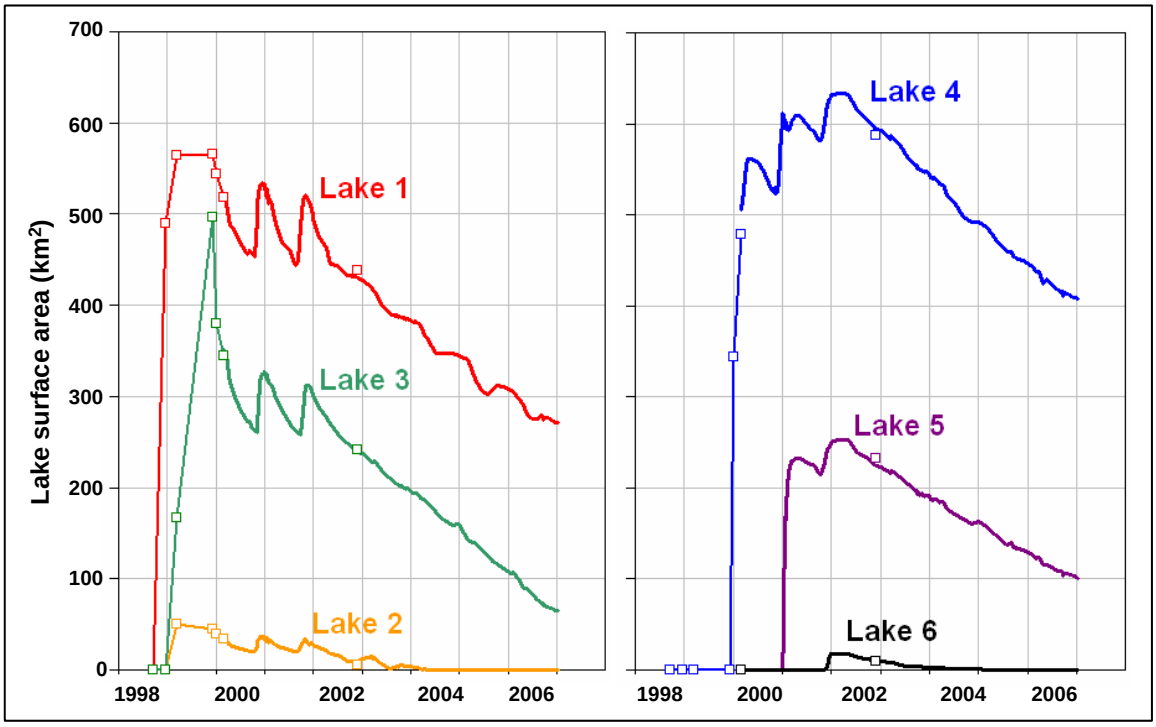

Figure 4. Surface area measurements for Lakes 1-3 (left) and 4-6 (right), 1998-2007. Thick lines represent 154 dates of MODIS imagery; thin lines and squares represent six AVHRR images.

MEASURING LAKE VOLUME

An object-oriented approach was used to automatically determine the mean water level and total volume for individual water bodies (Chipman and Lillesand, 2007). This approach used the lake surface area maps derived from MODIS (see previous section) in combination with a digital elevation model (DEM) produced by the Shuttle Radar Topography Mission (SRTM; Farr and Kobrick, 2000). Groups of adjacent water pixels in the MODIS data were clumped together to create lake polygons. The water level of each lake was then computed as the mean elevation of DEM pixels along the polygon boundary. Next, for each pixel in the lake polygon, the DEM height (representing the elevation of the bottom of the basin) was subtracted from the lake level to compute the depth of the lake at that pixel, and was then multiplied by the surface area of the pixel to derive its volume. The volumes of water at all pixels in the lake were then summed to obtain the total volume.

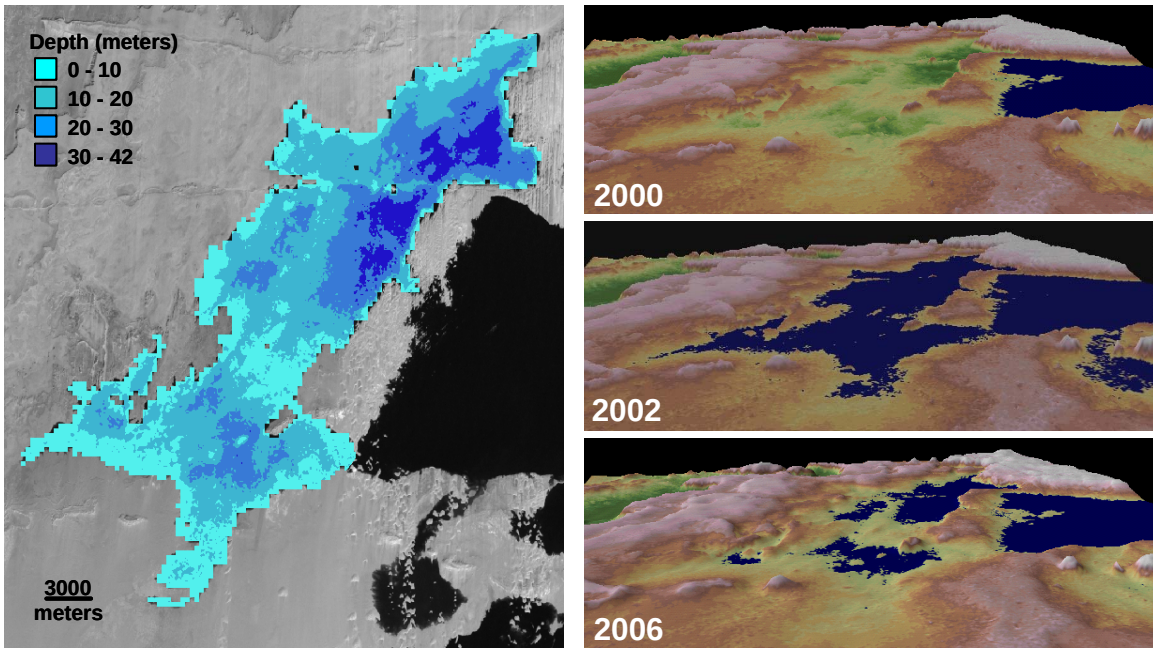

Figure 5. Left: bathymetry of Lake 5 on 18 December 2001, based on MODIS-derived lake-area map and SRTM DEM. Right: simulated perspective views of the vicinity of Lake 5 from 2000 (before the lake formed), 2002 (maximum lake extent), and 2006.

The basins for Lakes 1-4 were already filled prior to the SRTM mission in February 2000, so it was not possible to use this DEM to calculate volumes for these basins. For Lake 5, which formed after the SRTM mission, the DEM provides the original topography of the basin prior to flooding. Thus, we were able to calculate water levels and volumes for this lake from its formation in January 2001.

Figure 5 shows the results of overlaying the MODIS-derived lake surface area maps on the SRTM DEM for the area around Lake 5. The left half of the figure shows the bathymetry of the lake as of 18 December 2001, based on subtracting the SRTM elevation in every pixel from the mean water level along the lake shoreline. The right half of the figure shows a series of perspective views of the SRTM DEM, with simulated lakes added in based on the MODIS lake area and water-level measurements for three dates in 2000, 2002, and 2006.

The trend in water storage in Lake 5 is shown in Figure 6. During the month of January, 2001, when the lake was initially being formed (from floodwaters spilling out of Lake 4), the volume of the lake increased at a rate of 78 million m^3 per day (R^2 = 0.98). Over subsequent years, water levels (and volumes) in the lake rose and fell, eventually dropping below 700 million m^3 in late 2006 and early 2007.

To validate these estimates of changes in water storage, we used spaceborne laser altimeter data from the GLAS instrument on ICESat (Schutz et al., 2005) to measure the elevation of Lakes 1, 3, 4, and 5 along 17 orbit tracks in 2003-2005. For Lake 5, there were five GLAS passes during this two-year period, during which time the lake level dropped by 7.13 mm/day (95% CI of 6.77-7.13 mm/day). For comparison, the MODIS/SRTM-based method yielded a rate of 7.41 mm/day during the same time interval (95% CI of 7.00 -7.82 mm/day). Thus, there appears to be reasonably good agreement between the two methodologies used for measuring changes in water levels.

FUTURE DIRECTIONS

We will continue to monitor the changing water storage in the Toshka Lakes, while simultaneously working to improve the methods used (in particular, we are further examining the accuracy of ICESat GLAS data for measuring lake levels). As of this writing, water levels in Lake Nasser had again begun rising, but water does not yet appear to be flowing through the spillway into the Toshka Lakes. If water levels continue to rise in the fall of 2007 or beyond, we anticipate that water would once again begin flowing into the lakes, reversing their recent declining trend.

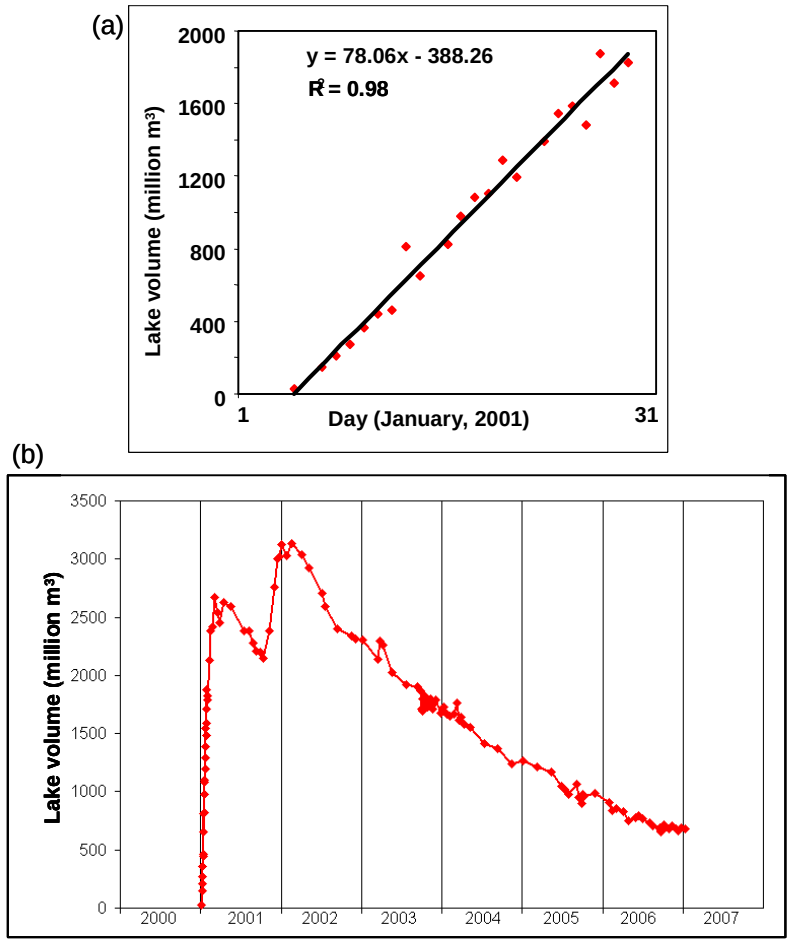

Figure 6. Volume of Lake 5, from analysis of MODIS imagery and SRTM DEM. (a) Increasing volume during January 2001. Rate of increase is 78 million m^3/day. (b) Fluctuations in volume, December 2000 through January 2007. After Chipman and Lillesand (2007).

In addition, we have begun monitoring the expansion of irrigated agricultural land associated with the SVDP. Phase 1 of the project is well under way, with water flowing through the canal network located to the east of the Toshka Lakes. Figure 7 shows MODIS images from January of 2002, 2004, 2006, and 2007, illustrating the expansion of center-pivot and other irrigated agricultural fields in this area. This monitoring project will use a combination of weekly to monthly MODIS image acquisitions, plus periodic acquisitions of higher-resolution images (e.g., Landsat and SPOT scenes) to track the extent of agricultural development and to measure various indices related to vegetation cover within the fields. The results of this remote sensing analysis could then be used for biophysical modeling of environmental conditions at the local to regional scale.

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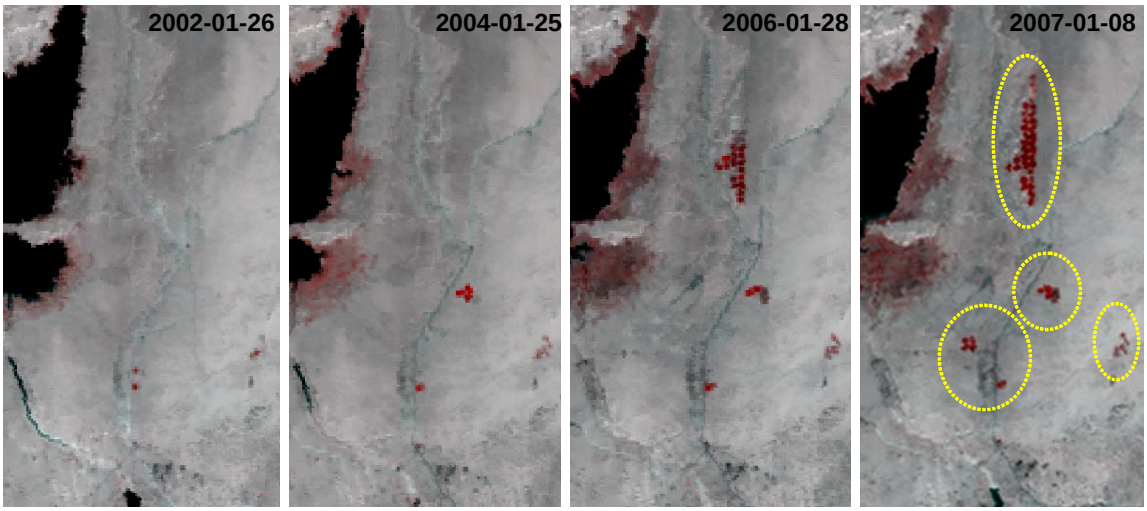

Figure 7. Terra MODIS images showing expansion of irrigated agriculture east of Lake 1, associated with the Southern Valley Development Project.

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