# Understanding the decline of water storage across the Ramser-Lake Naivasha using satellite-based methods

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## Abstract

It has been postulated that Lake Naivasha, Kenya, has experienced a rapid decrease (and fluctuations) in its spatial extent and level between the years 2002 to 2010. Many factors have been advanced to explain this, with horticultural and floricultural activities, as well as climatic change, featuring prominently. This study offers a multi-disciplinary approach based on several different types of space-borne observations to look at the problem bedeviling Lake Naivasha, which is a Ramsar listed wetland of international importance. The data includes: (1) Gravity Recovery and Climate Experiment (GRACE) time-variable gravity field products to derive total water

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storage (TWS) variations within a region covering the Lakes Naivasha and Victoria basins; (2) precipitation records based on Tropical Rainfall Measurement Mission (TRMM) products to evaluate the impact of climate change; (3) satellite remote sensing (Landsat) images to map shoreline changes and to correlate these changes over time with possible causes; and (4) satellite altimetry observations to assess fluctuations in the lake's level. In addition, data from an in-situ tide gauge and rainfall stations as well as the output from the African Drought Monitor (ADM) model are used to evaluate the results. This study confirms that Lake Naivasha has been steadily declining with the situation being exacerbated from around the year 2000, with water levels falling at a rate of 10.2 cm/yr and a shrinkage in area of 1.04 $km^2$/year. GRACE indicates that the catchment area of $4^\circ \times 4^\circ$ that includes Lake Naivasha loses water at a rate of 1.6 cm/year for the period from August 2002 to May 2006, and 1.4 cm/year for the longer period of May 2002 to 2010. Examining the ADM outputs also supports our results of GRACE. Between the time periods 2000-2006 and 2006-2010, the lake surface area decreased by 14.43% and 10.85%, respectively, with a corresponding drop in the water level of 192 cm and 138 cm, respectively, over the same periods. Our results show a correlation coefficient value of 0.68 between the quantity of flower production and the lake's level for the period 2002-2010 at 95% confidence level, indicating the probable impact of anthropogenic activities on the lake's level drop.

*Keywords:* multi-disciplinary satellite data, lake hydrology, total water storage , Lake Naivasha, climate change, floriculture

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## 1. Introduction

Lake Naivasha (Kenya, Figure 1) is the only freshwater lake in the Great Rift Valley of East Africa in an otherwise soda/saline lake series (Everard et al., 2002). In fact, it is the freshness of the water of Lake Naivasha that is the basis for its diverse ecology (Harper et al., 1990), and in 1995, it was declared as a Ramsar wetlands giving it an international status (see, e.g., Mekonnen et al. 2012). During the years 2002 to 2010, the lake has seen a rapid decline in its extent to the point where questions are being raised in the local media as to whether the lake is dying.

The study of fluctuations in Lake Naivasha's water levels has been carried out, e.g., by Richardson and Richardson (1972) and Nicholson (1998). Richardson and Richardson (1972), for instance, stated that the lake was nearly twice as extensive in the 1920's as it was in 1960-61. Nicholson (1998) noted trends of lower levels during the first half of the 19th century, very high levels during the last decades of the 19th century, with a rapid decrease occurring during the 20th century. He further pointed out that the lake returned to a relatively large extent during the 1960's, but this ended in the 1970's. The decrease in water level of the lake between the 1920's to 1960's is attributed by Richardson and Richardson (1972) to a slight trend of decreasing rainfall during this period, averaging 5 mm/year over the basin between 1920 and 1949 (see also Sansome, 1952), as well as an increase in human consumption from river influent and boreholes. In the 1980s, the fall of the level continued, with the local Olkaria geothermal power station and subsurface drainage thought to be the main cause (Darling et al., 1990). At this time, there was little notice taken of the influence of the flower farms, since the first farms had just started in the early 1980's (see, e.g., Becht et al., 2005). However, during the 1990's, over 100 km$^2$ of land around Lake Naivasha was converted to floriculture for the flower trade (see, e.g., ILEC, 2005). With this growth came an influx of workers, leading to a greater extraction of water from the lake (see e.g., Mekonnen et al., 2012), local aquifers, and the inflowing rivers for agriculture, floriculture and domestic use by the rapidly increasing population (ILEC, 2005).

At this point, the impact of such development on the water resources of the lake begun to be felt, with its size shrinking due to the direct extraction from the lake and also indirectly from closely connected aquifers. In the work of Abiya (1996), it was pointed out that the exploitation of the resources of Lake Naivasha posed serious threats to the fragile lake ecosystem and its biodiversity. Abiya (1996) considered the dynamics of the changing lake ecosystem, the imminent threats to this system, and the community-based approach towards the sustainable utilization of the lake. The results showed that the sustainable use of the lake was not going to be fully realized without a sound management plan, and recommended the enaction of consolidated environmental legislation in Kenya in order to strengthen the necessary environmental conservation and protection measures. This recommendation in turn led to other proposals for the sustainable use of the lake and its basin (e.g., Everard and Harper, 2002).

In the last decade, the level of Lake Naivasha has continued to drop with floriculture being blamed for excessive water extraction from the lake and aquifers, and the small holder farms in the upper catchment being blamed for nutrient loadings, leading to outcry in both the local and international media that this Ramsar site could be dying as a result of the very resource that it supports (see, e.g., ILEC, 2005; FWWCC, 2008; Mekonnen and Hoekstra, 2010). For example, Mekonnen and Hoekstra (2010) and Mekonnen et al. (2012) observed that the total virtual water exported in relation to the cut flower industry from the Lake Naivasha basin was 16 $Mm^3$/yr during the period 1996-2005. This total virtual water ($m^3$/yr) in relation to export cut flower and vegetables is obtained by multiplying the trade volumes (tones/yr) by their respective water foot print in Kenya ($m^3$/ton), see e.g., Mekonnen et al., (2012). Other factors that have also been proposed as influencing Lake Naivasha's water changes include irregular rainfall patterns (Harper et al., 1990), and trade winds (Vincent et al., 1979). All of these discussions, therefore, point to the need for the reliable mapping of the lake and its basin in order to properly understand its dynamics. The importance of monitoring the lake was captured by Becht and Harper (2002), who pointed out the urgency of accurately measuring all abstractions in order to provide consistent, reliable, hydrological and meteorological data from the catchment, so that a 'safe' yield may be agreed upon by all stakeholders and sustainable use of the lake waters achieved.

However, lack of reliable basin mapping techniques has hampered the proper monitoring of its changes, while also not allowing accurate predictions of the likely future situation, despite modelling methods being used to calculate its water balance (see e.g., Becht and Harper, 2002). The situation is compounded by the fact that Lake Naivasha has no surface outlet that could assist in hydrological monitoring, and that changes in its water level occur rapidly, over the order of several meters over just a few months, shifting the shoreline by several meters (Becht et al., 2005).

The emergence of satellite-based methods offers the possibility of providing a broader and more integrated analysis of the lake and its basin. Using time-variable gravity field products of the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004), variations in the total water storage (TWS) of the region extending from the Lake Naivasha basin to Lake Victoria is assessed in this study, to determine whether the changes are climatic or human induced. GRACE-TWS products are then compared with soil moisture and separated into its compartments (i.e., precipitation and evaporation) using the African Drought Monitor (ADM) model. Changes in precipitation are further examined by analysing monthly products of the Tropical Rainfall Measurement Mission (TRMM), as well as four in-situ rainfall stations (Naivasha, Narok, Nakuru, and Kisumu), allowing us to determine the proportion of the fluctuations in Lake Naivasha that are related to changes in precipitation during a long-term period (1960 to 2010) and the study period (2002 to 2010). Note that analysing long-term precipitation variations also evaluates the impact of climate variability such as the dominant El Niño-Southern Oscillation (ENSO) phenomenon on the hydrological compartments of TWS variations within the region of study (Omondi et al., 2012; 2013a,b).

The fluctuations in the water level of Lake Naivasha are determined using both ground-based tide-gauge observations and satellite altimetry data (TOPEX/Poseidon and Jason-1). These results are then related to the use of satellite imagery (e.g., Landsat) and change detection techniques to map the shoreline changes of Lake Naivasha, analysing the trend of changes over the study period of interest, and correlating shoreline changes to the proposed causes. Therefore, this study pioneers the use of both space-borne and ground-based observations for monitoring Lake Naivasha.

This study is organized as follows; in section 2, we present a more detailed overview of the Lake Naivasha region. Section 3 outlines the sources of the data that are used, as well as the methods employed to process and analyse the data. In Section 4, we present and discuss the results of our analyses, before concluding this work in Section 5.

## 2. Study Area

Lake Naivasha (00° 40' S - 00° 53' S, 36° 15' E - 36° 30' E) is the second largest fresh water lake in Kenya with a maximum depth of 8 m. It is situated in the Eastern African Rift Valley at an altitude of 1890 m above sea level and is approximately 80 km northwest of the Kenyan capital, Nairobi. Its basin (Figure 1) lies within the semi-arid belt of Kenya with mean annual rainfall varying from about 60 cm at the Naivasha township to some 170 cm along the slopes of the Nyandarua mountains, with open water evaporation estimated to be approximately 172 cm/year (Becht et al., 2005). Mount Kenya and the Nyandarua Range capture moisture from the monsoon winds, thereby casting a significant rain shadow over the Lake Naivasha basin (Becht et al., 2005). Unlike Lake Victoria which has its highest rainfall during the March-April-May (MAM) wet season (e.g., Awange et al., 2008a, b), the Lake Naivasha basin experiences its highest rainfall period during April-May-June (AMJ). There is also a short rainy season from October to November. The lake's levels, therefore, follow this seasonal pattern of rainfall cycle, with changes of several meters possible over a few months. Superimposed upon this seasonal behaviour are longer-term trends, for example, there has been a change in the lake's water level of 12 m over the past 100 years (Becht et al., 2005).

FIGURE 1

The lake is fed by three main river systems: Gilgil, Malewa and Karati, the last of which only flows during the wet season (see Figure 2). Becht et al. (2005) observed that whereas a small portion of the groundwater evaporates and escapes in the form of fumaroles in the geothermal areas, the remaining water flows into Lakes Magadi and Elmentaita, taking thousands of years to reach them. The basin's water balance has been calculated from a model based upon long-term meteorological observations of rainfall, evaporation and river inflows (Becht and Harper, 2002). This model reproduced the observed level from 1932 to 1982 with an accuracy of 95% of the observed monthly level, differing by 0.52 m or less (ILEC, 2005). This pattern was, however, noticed to deviate after 1982 and by 1997, the differences had reached 3-4 m (Becht et al., 2005). In fact, the onset of this reduced ability to model the lake's level coincided with the increase in horticultural and floricultural activities.

In general, three contemporary global water issues can be identified as occurring in this region, namely *water scarcity/availability*, *water quality*, and *water security*. While the focus of this study is on water scarcity/availability, several previous works have focused on the problem of water quality and competition for water resources within the study area (see e.g., Kitaka et. al 2002; Becht, 2007). Although water security issues are a reality in the

Lake Naivasha basin, few studies have been done to better understand the underlying conditions. For example, Carolina (2002) asserts that the area of the Lake Naivasha basin is of high economic and political importance to Kenya, and presents a wide variety of economic activities based around the water resources, with many different stakeholders often competing for the water resources.

The flower industry in Kenya has experienced a phenomenal growth, maintaining an average growth rate of 20% per year over the last decade. It is an industry that is the second largest export earner for Kenya, employing 50,000 - 60,000 people directly and 500,000 others indirectly through affiliated services (KFC, 2011). Although flowers are now grown in many areas with temperate climate and an altitude above 1,500 m in Kenya, the region around Lake Naivasha still remains the nation's main floriculture farming center. The foremost categories of cut flowers exported from Kenya include roses, carnations, statice, alstromeria, lilies and hyperricum. Indeed, Kenya is arguably the largest exporter for flowers in the world, supplying over 35% of cut flowers to the world's largest market - the European Union (KFC, 2011).

FIGURE 2

## 3. Datasets and Methodology

### *3.1. Gravity Recovery and Climate Experiment (GRACE) Data*

The GRACE space mission employs two low-earth orbiting satellites in the same orbital plane at an altitude of $\sim$ 400 km and an inclination of

89.5°. The separation between the two satellites is measured by a K-Band range rate system (KBRR) and the locations of the satellites are determined by Global Positioning System (GPS) receivers on-board the spacecraft and satellite laser ranging (Tapley et al., 2004). Other information are provided by accelerometers that help to correct for non-gravitational effects such as atmospheric drag (Tapley et al., 2004).

One of the GRACE main products is its level-2 time-variable gravity fields (Flechtner, 2007). There are a number of institutions that provide various GRACE level-2 products, each employing different processing procedures, background models and assumptions. The products employed in this work are the Release 2 from the Centre National d'Etudes Spatiales/Groupe de Recherche de Geodesie Spatiale, France (CNES/GRGS, Bruinsma et al., 2010), Release 4 of the Centre for Space Research, University of Texas at Austin, USA (CSR, Bettadpur, 2007), and Release 4 of the German Research Centre for Geosciences (GFZ, Flechtner, 2007). The CSR and GFZ time series have a monthly temporal resolution, while the CNES/GRGS is for every 10 days.

GRACE results have been used for assessing the relationships between water storage changes and climate change in a number of cases (e.g., Becker et al., 2010, Forootan et al., 2012). Awange et al., (2008b) and Swenson and Wahr (2009) used multi-satellite data to study the water storage changes of Lake Victoria. However, we will only use the GRACE products to examine the area covering the Lakes Naivasha and Victoria basins to determine whether the climatic behaviour there correlates with that over Lake Victoria. This is because the area of Lake Naivasha is much too small for it to be adequately assessed by GRACE, where areas of the order of 200,000 to 400,000 $km^2$ are necessary (Swenson et al., 2003; Rowlands et al., 2005), as opposed to the 140 $km^2$ that Lake Naivasha covers (Becht et al., 2005). Lake Victoria basin covers an area of more than 250,000 $km^2$ (see, e.g., Awange and Ong'ang'a, 2006), which, when combined with Lake Naivasha basin, suffices for GRACE satellite analysis.

In order to derive TWS maps, first, monthly products were filtered using a Gaussian filter (Jekeli, 1981) of 500 km radius. Then, residual gravity field solutions were computed with respect to the temporal average (assumed static) over the considered study period (2002-2010). The residual coefficients were transformed into monthly TWS values using the approach of Wahr et al. (1998). Note that there are alternative filters for de-noising GRACE products, e.g., non-isotropic filters discussed in Kusche et al. (2009). However, this study used the Gaussian filter due to the simplicity of its implementation.

### *3.2. The Princeton African Drought Monitor (ADM) model*

As mentioned above, GRACE products provide information about TWS changes that need to be separated into its components. From a hydrological modeling point of view, large-scale GRACE-TWS over land relates to the instantaneous values of the individual water balance components by (Swenson and Wahr, 2006):

$$\frac{d(TWS(t))}{dt} \sim \frac{d(S(t))}{dt} = P(t) - E(t) - R(t), \tag{1}$$

where $S$ stands for soil moisture, $P$ for precipitation, $E$ for evaporation and $R$ for discharge measured in time ($t$). For assessing GRACE-TWS results, and also to extract more information about each of the water balance components, therefore, we used the outputs of the African Drought Monitor (ADM) model (http://drought.icpac.net/) for the period of 2002 to 2012, which contains data from both historic reconstruction (1950 to 2008) and real-time monitoring (2009 to Present) of the hydrological cycle and drought events over Africa (Sheffield et al., 2006). The outputs of the model has been used for monitoring drought in Africa (see, e.g., Sheffield et al., 2009), while the performance of the model for monitoring droughts in the USA and Africa is discussed in Luo et al. (2008).

In order to compute TWS for the Naivasha basin using ADM, three layers of basin's averaged soil moisture are extracted and integrated. The values are then compared with GRACE-TWS changes (see Section 4.2). We also compared the values of rainfall and discharge in Eq. 1 with GRACE-TWS. Note that, for computing basin averages using the ADM outputs, we took the yellow dotted border in Figure 1 as our averaging region. The same Gaussian filter as used for filtering GRACE-TWS products is also applied to the ADM output. Statistics of the ADM parameters corresponding to Lake Naivasha is reported in Section 4.3.

### *3.3. Tropical Rainfall Measuring Mission (TRMM) Data*

TRMM is a joint mission between the United States (NASA) and Japan (Japan Aerospace Exploration Agency) (Kummerow et al., 1998; Kummerow et al., 2000). TRMM is designed to monitor tropical rainfall in the latitude range $\pm 50°$. The primary instruments are the TRMM Microwave Imager (TMI), the Precipitation Radar (PR), and the Visible and Infrared Radiometer System (VIRS) (Kummerow et al., 1998). There are a number of products based on the TRMM observations, whose use is dependent upon the subject of interest. In this work, we used monthly averaged 3B43 rainfall rate products over the latitude range $\pm 50^{\circ}$, which is inferred from not only the TRMM observations, but also employs data from a number of other satellites and ground-based rain gauge data (Huffman et al., 2007). TRMM observations have been used in several studies of rainfall over Africa (e.g., Adeyewa and Nakamura, 2003; Nicholson et al., 2003). In particular, Awange et al. (2008b) investigated the falling levels of Lake Victoria using a combination of TRMM, GRACE and CHAMP satellite data. TRMM rainfall maps are filtered using a Gaussian 500 km filter to be consistent with GRACE-TWS and ADM products.

### *3.4. Landsat Images*

The Landsat series of Earth observations provide a unique historical data set for land surface and climate change studies covering almost 40 years. In this study, four Landsat images were used, gathered by the Landsat 5 spacecraft using its Thematic Mapper (TM) and Multispectral scanners. The acquired imagery were for the 30th March in the years 1989, 1995, 2000, and 2006. All images are made available from the Global Land Cover Facility (GLCF) of the Maryland University (USA) and constitute part of NASA's global orthorectified Landsat data set (Tucker et al., 2004). Landsat TM has seven spectral bands that cover the visible, near infrared, short-wave infrared and thermal infrared regions of the electromagnetic spectrum (Mather, 2004). Ancillary data for validating remote sensing measurements usually consists of topographical (digital elevation model) and soil data. These were mainly used to assist in the interpretation of the imagery, with supervised image classification employing the minimum distance classifier.

These images were used in conjunction with field studies. Field surveys and data collection were subdivided into two phases; 1) familiarization and reconnaissance surveys, and 2) observation and data collection surveys. A four days exploratory field survey was conducted to gain an initial impression of the general characteristics of the Lake Naivasha shoreline, water resource utilization and river systems, climate, vegetation, soils and accessibility. The reconnaissance field surveys then focused on those areas perceived to be most affected by shoreline changes. These field observations were mainly done to verify the image classification results through ground truthing/confirmation. To geo-reference the satellite imagery, positions of various fixed features were estimated during the field surveys using GPS.

### *3.5. Satellite Altimetry Data*

Observing water level fluctuations provided by existing altimetry missions is of major importance in monitoring water reservoirs, as they provide additional information besides the traditional in-situ data sets (Becker et al., 2010; Crétaux et al., 2011; Sharifi et al., 2012). From the available satellite altimetry missions, TOPEX/Poseidon (T/P) and its follow-on mission Jason-1 have provided observations for Lake Naivasha. During 1993 to 2002, we used data provided by the NASA Physical Oceanography DAAC (PO-DAAC) at the Jet Propulsion Laboratory, California Institute of Technology, which is in a format termed the Merged Geophysical Data Record (MGDR) (Benada, 1997). Over this time period, we found that 273 of the 369 T/P's cycles contained one valid observation over Lake Naivasha (See Figure 4). To cover the remaining period of the study, we examined the Jason-1 Interim

Geophysical Data Record (IGDR) data sets that are also available via the PODAAC website. However, we found that Jason-1 does not cover the region of interest because of its slightly different orbit compared to T/P, except for one observation in December 2009, which was not accurate enough to be considered in this work.

### *3.6. Other Data Sets Employed*

Several other data sets were used in this work and related to the above-described satellite products. First, in-situ water level measurements from a tide gauge were used to study the long-term variation (1985 to 2010) of Lake Naivasha. These records were provided by the Lake Naivasha Riparian Association organization (http://web.ncf.ca/es202/naivasha/) and were used to validate the satellite-derived water level variation discussed below.

The observed rainfall data used in this study consists of monthly rainfall totals for the period 1961-2010 for some in-situ synoptic stations located within the basin encompassing Naivasha ($0.72°\mathtt{S}, 36.4°\mathtt{E}$), Kisumu ($0.1°\mathtt{S}, 34.8°\mathtt{E}$), Nakuru ($0.28°\mathtt{S}, 36.1°\mathtt{E}$), and Narok ($1.1°\mathtt{S}, 35.9°\mathtt{E}$) (obtained from the Kenya Meteorological Department, KMD).

In addition, the amounts of flowers exported by the flower industry in Kenya were obtained from the Kenya Flower Council (KFC 2011). The production data are presented for the period from 1995 to 2010 in the form of annual averages. Figure 3 shows the significant rise in the quantities of cut flowers exported from Kenya, which has more than doubled in tonnage over the last decade.

In Table 1, a complete set of data set used in this study are presented.

Table 1: Summary of the data sets used in this study.

| Data | Period | Time steps |
|---|---|---|
| GRACE | 2002.8 - 2010 | monthly and 10-days |
| Altimetry | 1992 - 2003 | 10-days |
| ADM | 2002 - 2012 | monthly |
| TRMM | 2002 - 2012 | monthly |
| In-situ rainfall | 1960 - 2010 | monthly |
| Tide gauge | 1985 - 2010 | monthly |
| Landsat | 1989 - 2006 | 1989, 1995, 2000, and 2006 |
| Flower export | 1990 - 2010 | yearly |

FIGURE 3

## 4. Results and Discussions

### *4.1. Lake Level Analysis*

The computed time series of level changes for Lake Naivasha derived from the T/P observations and in-situ measurements are shown in Figure 4. The T/P observation cover only the period between 1992 and 2003. The calculated satellite altimetry results were noisy at the first step, which may be related to the shallow depth of the lake (i.e., 8 m). To reduce this noise, the altimetry derived levels were smoothed using a moving average filter and interpolated according to the tide gauge time steps. As Figure 4 illustrates, the smoothed monthly altimetry derived levels are comparable to the available tide gauge measurements. We found a significant correlation coefficient of

0.69 between smoothed altimetry data and tide gauge observations (Figure 4,(Bottom)). Figure 4,(Top) confirms that although the lake level has been fluctuating both annually and seasonally over time up to around the year 2000, thereafter, a general downward trend at a rate of -10.2 cm/year before the onset of the 2007 ENSO rains is visible.

FIGURE 4

### 4.2. GRACE Analysis

Next, we estimated the changes in water mass over the Lake Naivasha basin as derived from GRACE observations. Because the GRACE-TWS results have a low spatial resolution, we compare two segments, one centred over Lake Victoria (to the west of Lake Naivasha) and the other centred over Lake Naivasha, as shown in Figure 5. The black boxes mark the areas where the GRACE-TWS and TRMM-total rainfall values were inferred. We chose a $4^\circ \times 4^\circ$ degree window as this is the limit to what can be confidently resolved from GRACE. Whereas GRACE is appropriate for areas the size of Lake Victoria (see section 3.1), our intention was to determine if it could still provide some information when comparing the variation of water within the basins of Lakes Naivasha and Victoria, which in turn may be compared to TRMM datain order to infer the influence of climatic change to the region around Lake Naivasha.

FIGURE 5

Figure 6 (a) shows the TWS changes as described by the three GRACE products considered; CSR, CNES/GRGS and GFZ. Evidently, all GRACE solutions indicate water loss in both Lakes Naivasha and Victoria regions from 2002 to late 2006. The increase in late 2006 is attributable to the ENSO effect, with water loss continuing again after an increase in late 2006-early 2007. Previous studies have demonstrated that the fall in Lake Victoria during that period was due to anthropogenic factors such as the expanded Nalubale dam (see, e.g., Awange et al., 2008a,b; Swenson and Wahr, 2009). Similar findings are shown by the cumulated water as illustrated in Figure 6 (b). The cumulative annual TWS of the Naivasha catchment lost water at a rate of 72 cm/yr from 2003 to May 2006. From January 2007 to December 2009, this loss was 41 cm/yr.

GRACE-TWS (as computed in Section 3) consists of a summation of terrestrial water storage (WS), i.e., related to the catchment, and surface WS, i.e., related to the lake itself. To enhance the interpretation of the GRACE's results in Figure 6, Lake Naivasha's surface WS changes are computed using its surface area, as shown with the solid-blue line in Figure 7 (top). To compute the blue line, the surface level changes (Figure 4) are transformed to the spherical harmonic domain and used to generate the surface WS changes time series (e.g., as done in Swenson and Wahr (2009) for the derivation of hydrological trend of the East African lakes). The red line of Figure 7 (top) shows the time series computed for the GFZ GRACE products for the Naivasha region (i.e., Figure 5; the right-hand-side box). Note that the leakage caused by Lake Victoria fluctuations is already removed from the red line, following Swenson and Wahr (2009). The catchment signal (terrestrial WS), shown on the bottom part of the figure as a black line, is the difference between GRACE-TWS (red line) and surface WS (blue line).

From Figure 7, we computed the slope of the blue line from August 2002 to 2010 to determine the trend, obtaining a declining trend of 1.9 cm/year, while the period from May 2006 to 2010 saw a decline of 1.8 cm/year. After removing the signals of Lake Naivasha, the catchment area (black line in Figure 7 (bottom)) loses water at a rate of 1.6 cm/year for the period from August 2002 to May 2006 and 1.4 cm/year from May 2006 to 2010, thus signifying that not only is water lost from the Lake Naivasha but also from its catchment. The loss of water in the catchment could be attributed to floriculture and horticultural activities, and also boreholes providing water to the population that largely depends on the floricultural industry. In the next section, the use of ADM is employed to further enhance the GRACE results.

FIGURE 6

FIGURE 7

### *4.3. ADM Analysis*

The red line in Figure 8 (top) shows the output of the ADM model derived from the right hand side of Eq. 1 compared to GFZ GRACE-TWS, averaged over the Lake Naivasha basin (i.e., Figure 7 (top), the red line). The mean of $P$ for the years 2002 to 2012 was 103.7 mm and the standard deviation was 90.8 mm (maximum $P$ was 645.8 mm). For $E$, ADM estimated a mean of 62.4 mm with a standard deviation of 20.1 mm (maximum $E$ was 112.7 mm). The ADM-derived $P$ and $E$ are considerably smaller than what Becht et al. (2005) report, i.e., $P$ of between 600 and 1700 mm/year and $E$ of

1700 mm/year. Since the runoff parameter is not available after the year 2000 for Lake Naivasha (see also Ayenew and Becht, 2008) and the fact that Ojiambo et al. (2001) suggest that yearly $R$ is negligible for the lake, we did not include it in our computations.

From the derived patterns, one can see that the ADM model responds more quickly to climatic variations such as ENSO in 2006 (red line in Figure 8 (A)) than the observed GRACE outputs (black line in Figure 8 (A)). Computing a correlation coefficient at 95% level of confidence shows a value of 0.68 between the two outputs, thus giving a reasonable level of agreement (Figure 8 (B)).

Visually comparing GRACE-derived terrestrial WS changes (shown by the black line in Figure 7 (Bottom)) with ADM-integrated soil moisture layers (Figure 8 (C)) reveals a similar pattern. The amplitude of the soil moisture signal is one third of the GRACE terrestrial WS changes. The reason for this inconsistency requires further research. Fitting a linear trend to the soil moisture results shows a TWS loss of 1.4 cm/year for the period from August 2002 to May 2006, and 0.6 cm/year from May 2006 to 2010.

Comparing the modeled precipitation (the green line in Figure 8 (D)) with in-situ precipitation (the cyan line in Figure 8 (D)), shows some inconsistencies, mainly in terms of the differences in the amplitudes between the modeled and in-situ values. A phase difference of one month is also evident between the two data sets. The dark-blue line in Figure 8 (D) represents the amount of evaporation changes for the period of July 2002 to 2012 showing almost steady range when compared to precipitations and soil moisture changes. As a result, one can see that the water capacity corresponding to soil moisture layers and rainfall is declining within the basin.

FIGURE 8

### *4.4. Rainfall Analysis*

From the in-situ rainfall observations, the rainfall regime over the Naivasha basin has seen a downward trend since 1960 (see Figure 9). For instance, Figure 9 (bottom) shows a time series of the annual total (the black line), March-May (MAM, the blue line), June-August (JJA, the red line) and October-December (OND, the green line) rainfall seasons over Naivasha. In this study, we employed both graphical and statistical methods (described in WMO, 1966) to superficially test the significance of the observed trends (see also discussions in Wilks (1995) and Omondi et al. (2012; 2013a)). The data were analysed for trends using linear regression, and the significance of trends was tested using the non-parametric Mann-Kendall tau test (Sneyers, 1990). An overview of the total amount of annual rainfall variation derived from the four stations is summarized in Figure 9, while their corresponding linear rates are reported on each graph. However, although the derived long-term linear trend values were negative, they were not large enough to pass the tau test (see also Omondi et al., 2013b).

There is also a high degree of variability, within both the wet periods (during strong El Niño years) and dry periods (during strong La Niña years). Several studies have investigated the relationship between eastern Africa rainfall and evolutionary phases of ENSO, and have shown strong relationship. Therefore, ENSO plays a significant role in determining the monthly and seasonal rainfall patterns in the East African region (e.g., Ogallo, 1988;

Janowiak, 1988; Indeje, 2000; Mutemi, 2003, Nyakwada 2009 and Omondi et al., 2012). Considering the trends from the rain-gauge stations shown in Figure 9 suggests that the prolonged rainfall decrease over the catchment during the period 1960 to 2010 might contribute to the drop in the lake's level. Note that the linear trends for the period 2002-2010 (Figure 9, bottom) shows sharper decreasing values in all seasons and in the annual total rainfall than for 1960 to 2010. The result is in agreement with the variation in TWS as shown by GRACE analysis (Figure 7) and ADM (Figure 8). In Figure 11, the total amount of rainfall from the in-situ stations is compred to the GRACE TWS and the soil moisture WS from ADM.

FIGURE 9

Figure 10 illustrates the total rainfall of the catchment and its accumulated values as described by the TRMM 3B43 product over the $4 \times 4$ degree windows defined in Figure 5. The larger rainfall over Lake Victoria is seen both in terms of the time series, and also in the greater rate of increase in the accumulated values. Comparatively, while there seems to have been an increase in the precipitation rate over the Lake Victoria basin after late 2006, there seems to be little change in the rainfall over the Lake Naivasha basin. Comparing the TRMM results in Figure 10 with the GRACE results in Figure 6 for period 2002-2010, while no significant change is visible in the TRMM results, those from GRACE show a loss of water from the Lakes Naivasha and Victoria basins. This could therefore mean that the drop in Lake Naivasha's water level (as is the case for Lake Victoria) may be more influenced by anthropogenic factors compared to climatic factors.

FIGURE 10

### 4.5. Comparing TWS Changes Across Lake Naivasha with Rainfall

Figure 11 compares the accumulated annual TWS over the Naivasha catchment derived from GRACE as well as soil moisture from ADM (Figure 7) with the total annual rainfall variations derived from the four rainfall stations in Figure 9. To make the comparison easier, the values for 2003 are set to zero. As a result, one can see that soil moisture and rainfall are decreasing between 2002 to 2010. For 2006, GRACE still shows that TWS is decreasing, while precipitation increased as a result of ENSO, and soil moisture stays almost steady. The sharper rate of change that the GRACE results exhibit for 2002-2006 might also be related to the correlation of the derived TWS over Naivasha to that of Victoria. After 2006, again all component exhibit declining trends, showing that the impact of the 2006 ENSO has subsided.

FIGURE 11

### 4.6. Image Analysis

Next, we present the approach undertaken to map the shoreline variations of Lake Naivasha, using satellite images.

*Image classification*: To validate the results obtained from using GRACE and TRMM data sets, satellite remote sensing and GIS analysis were performed. Landsat imagery of the study area acquired from different epochs was employed and different land use / land cover types were discriminated. The interpretation of Landsat imagery was undertaken using the minimum distance supervised classifier. The overall accuracy of the land use / land cover map was estimated to be 85.0% with a kappa statistic of 0.79. This meets the minimum threshold established by the United States Geological Survey (USGS) classification scheme (Anderson et al., 1976). As an example, the classification results for the first epoch (1989) are shown in Figure 12 (a). The classified image depicts a clear demarcation between land/vegetation and water, hence revealing a clear picture of the shoreline position. The red colour depicts water, yellow represents general vegetation cover while green represent general bare land. There is a significant intrusion onto the northern shoreline by vegetation, indicating a positional change of the shoreline. Figure 12 (b), showing the second eopoch examined (1995) shows a significant departure from Figure 12 (a), especially in the north, where vegetation has significantly receded, leaving only scattered traces in contrast to the 1989 image that showed a thick vegetation cover around the same area. There is also a change around Crescent Bay (formerly Crescent Island, see Figure 2). While the 1989 image shows a near excision of the bay from the main lake, the situation is different in the 1995 image. This is because of the general increase in water volume caused by increased rainfall over the same period.

Figure 12 (c) shows that there is an increase in water volume in 2000, due to more rainfall, compared with the preceding maps in Figures 12 (a and b). Crescent Bay has swollen with the south eastern section joined to the main lake to form the original Crescent Island, indicating an increase in water volume. This increase is probably due to the 1997 ENSO rainfall (see also the satellite altimetry results in Figure 4). The traces of vegetation that had infringed the northern part of the lake have fully disappeared by

2000. However, there are some traces of vegetation at the centre of the lake. These might be due to the presence of water lillies in the lake or traces of leaves transported by run-off into the lake. Figure 12 (d) shows that the scattered traces of vegetation in the middle of the lake that were part of the preceding images have disappeared. However, the Crescent Bay has receded and a section of it is almost cut-off from the main lake to form an independent lake. There is also a significant change in the shape of the island when compared to the previous images. The amount of grassland cover has also increased along the shoreline compared to the 2000 image, indicating a relationship between vegetation and the lake's surface area.

FIGURE 12

*Extraction*: It is visually clear from the classified land cover maps above that there is a perpetual shifting of the Lake Naivasha shoreline between different epochs. Due to the difficulty in quantifying the amount and rate of the change, and in defining the actual trend through visual interpretation, the actual position of the shoreline in each epoch was extracted and then compared to that obtained for the reference year, 1989. This allowed the actual change and subsequently the rate of change to be estimated.

This was done by digitizing the shoreline from the respective classified images in a Geographic Information System (GIS) environment using ArcGIS version 9.3. The shorelines from each epoch were then overlaid to reveal the general change trend. To allow for a detailed analysis, the overlay result was further divided into five segments as shown in Figure 13. In general, the results show that there was an increase in water level in Lake Naivasha between 1989 and 1995. This increase continued until 2000, however, the 2006 shoreline shows a decline in water level between 2000 and 2006. Detailed scrutiny shows that there was a steady northern (outward) shift of the shoreline from 1989 to the year 2000, indicating an increase in water level. This was followed by an inward shift in 2006, indicative of a drop in water level. However, the magnitude of the shoreline change is not uniform over the different epochs. The lack of uniformity can be attributed to variations in the local terrain, resulting in, obviously, the shoreline changing more in flatter terrain as opposed to steeper areas.

FIGURE 13

*Shoreline change and variation*: The surface area of the lake in each epoch was computed in the GIS environment. A summary of the changes in the surface area between different epochs for the different land cover classes, with 1989 as the reference year, is shown in Table 2, which indicates a direct relationship between the lake's level and surface area. The increase in area in 1995 compared to 1989 (i.e., 14.8%) is represented by an increase in water level (1.19 m). The situation is even more apparent between 1989 and 2000 where there is an increase of 20% in surface area and a corresponding increase of 2.33 m in water level. There was a drop in surface area of the lake between 2000 and 2006 (i.e., a drop of about 4.7%) and again this is shown by a drop of 1.92 m in the water level during this period. This general trend is corroborated by results obtained from both satellite altimetry and GRACE illustrated in Figures 4 and 7, respectively. Figure 14 shows the variation of the surface area for the lake, vegetation, and bare land classes between 1989

Table 2: Summary of the changes in the area of Lake Naivasha and the surrounding bare land and vegetation, with 1989 serving as the reference year (see Figures 12 and 14).

| Year | Lake area ($km^2$) | Vegetation ($km^2$) | Bare land ($km^2$) | Mean Lake level (asl) | Lake area (%) | Vegetation (%) | Bare land (%) |
|---|---|---|---|---|---|---|---|
| 1989 | 113.67 | 95.35 | 174.18 | 1885.41 | 0.00 | 0.00 | 0.00 |
| 1995 | 130.47 | 90.37 | 162.35 | 1886.60 | 14.78 | -5.22 | -6.89 |
| 2000 | 136.42 | 26.70 | 219.77 | 1887.74 | 20.01 | -72.00 | 26.17 |
| 2006 | 130.07 | 48.44 | 204.12 | 1885.82 | 14.43 | -49.20 | 17.19 |
| 2010 | 126.01 | 48.93 | 207.69 | 1884.44 | 10.85 | -48.69 | 19.24 |

and 2010.

FIGURE 14

From the above results, it is clear that Lake Naivasha has experienced shoreline variations over the last 17 years as indicated by the changes in surface area. There was a positive gain in area by 16.80 $km^2$ between 1989 and 1995 (i.e., 14.8%), with a further gain by the year 2000 of 5.95 $km^2$, due largely to the 1997 ENSO rainfall. However, there was a drastic decline in the surface area between 2000 and 2006, with the lake loosing 6.35 $km^2$ of its surface area (i.e., 4.7%), indicating a recession in its shoreline. The surface area of the lake in 2006 is comparable to that of 1995 (both $\sim$ 130 $km^2$). After 2006, the lake continued shrinking with a surface area of 126.01 $km^2$ in 2010 (i.e., a reduction of about 7.6%). In general, from these images, it was calculated that the lake's area is shrinking at a rate of 1.04 $km^2$/year.

These findings agree with those of the satellite altimetry and tide gauge observations (see, e.g., Figure 4 in Sect. 4). The variation around the area shows that there is loss of vegetation around the lake as the lake surface area increases. There was a decline in the vegetation cover between 1989 and 1995, despite a gain in the surface area over this period. The same scenario was seen between 1995 and 2000. This can be attributed to the fact that the area around the lake is comprised of papyrus, which are normally swallowed by the increase in water level. There was, however, an increase in the vegetation cover between the years 2000 and 2006 as the lake receded and vegetation sprouted up along the shores of the lake .

### *4.7. Comparing Lake Levels with Rainfall and Flower Exports*

In light of the previous results, the relationship between the decline of WS within the catchment, the lake itself, and the local and catchment precipitation were explored. To finalize this study, a simple comparison is made between the level of lake (one of the main water sources of the catchment) and other data sets considered in this work, including rainfall recorded by the Naivasha station (a representation of climate variability) and flower production (a representation of human use) (see Figure 15). Considering first rainfall and the lake's levels (Figure 15 (A)), where we plot annual rainfall against annual average lake level, a correlation coefficient of -0.24 is obtained, suggesting no statistically significant correlation between these quantities. On the other hand, considering lake levels with flower production (Figure 15 (B)), where we have plotted tonnage of flower production against the annual averages of the lake levels for the years where the tonnage data were available, we find a strong statistically significant correlation, with a correlation coefficient of -0.68. This suggests strongly that flower exports could have influenced the reduction in Lake Naivasha's water level. Finally, Figure 15 (C) shows an insignificant correlation coefficient of -0.19 between rainfall and flower production.

Caution should be exercised, however, when one is interpreting the correlation results above. This is due to the fact that flower production, though it is a useful proxy for estimating water consumption in the Lake Naivasha region, and indeed constitutes the main cause of water consumption, depends on other factors unrelated to water withdrawal from the lake, e.g., in-put fertilizers. Therefore, an analysis of other factors that influence flower production, e.g., the amount of water withdrawn and used to irrigate the flowers, would be desirable. Along these lines, Mekonnen et al. (2012) quantified the water footprint within the Lake Naivasha Basin related to cut flowers and analysed the possibility of mitigating the footprint by involving cut-flower traders, retailers and overseas customers. Hagos (2008) assessed the possibility of using shallow and deep underground water, while Reta (2011) simulated a long term groundwater and lake water balance of Lake Naivasha in an attempt to establish the relationship between water consumption and water levels. Both Hagos (2008) and Reta (2011) highlighted the importance of underground water in the dynamics of Lake Naivasha's water levels. Such influence has been investigated, e.g., by Becht et al. (2002) and Becht and Nyaoro (2005), who considered the influence of groundwater fluctuations on Lake Naivasha and found it to have an important effect on the water balance of the Lake. In fact, Becht and Nyaoro (2005) deduced that the interaction of the groundwater and the Lake dynamics introduces a degree of inertia to the lake groundwater system, resulting in delayed reactions to external (meteorological) stresses where the groundwater acts as an extra reservoir absorbing water during wet periods and releasing water during droughts. Evaporation also plays a key role in Lake Naivasha's water balance as evident by the results of Farah et al., (2004), who obtained in-situ evaporation values at a grassland and woodland site in the Lake Naivasha basin for about a year. Another example of extraneous factors affecting Lake Naivasha's water levels is presented, e.g., in Olago et al. (2009), who showed that the hydrology of the Rift Valley is controlled mainly by climate and water table variation, among other factors.

FIGURE 15

## 5. Conclusions

As a Ramsar wetland, Lake Naivasha is a very important area not only to East Africa, but internationally. It supports a rich ecosystem with hundreds of species of diverse flora and fauna. Moreover, being the only freshwater lake in the Kenyan sector of the East African Rift, Lake Naivasha serves as the home of the flower industry in Kenya and is one of the most important flower producing regions world-wide. The results of this study have demonstrated that:

1. During the study period 1989 to 2010, Lake Naivasha experienced variation in its spatial extent and significant fluctuations in its level. However, from around the year 2000, a steady decline in its spatial extent

has been observed with the lake receding at a rate of 1.41 $km^2$/year, accompanied by a corressponding drop in water level of about 33 cm/year.

2. Although the lake's level has been fluctuating both annually and seasonally over time in the past, there is a visible general downward trend observed from around 2000. This coincides with the period during which the flower exports from Kenya increased significantly. This is supported by the results of the linear regression analysis that gave a correlation coefficient of -0.68 between Lake Naivasha's water levels and the flower exports from the region for the period 2000-2010. Since much of the irrigation water used in the flower farms comes from Lake Naivasha, the recent decline in the lake water level and spatial extend could feasibly be largely attributed to adverse anthropogenic influences, with climatic factors such as prolonged rainfall decrease of the catchment during 1960-2010 also having a noticeable influence. A climatic influence is supported by the fact that in-situ rain gauge stations for the annual rainfall totals clearly indicate decreasing trends in the catchment area. The results support the findings in Mekonnen et al. (2012), who established a relationship between cut-flower production and level changes of Lake Naivasha.

3. Not only is the lake losing water, but also the catchment area of $4^\circ \times 4^\circ$ that includes Lake Naivasha as a whole is noticed to have lost water at a rate of 6.8 cm/yr from August 2002 to May 2008, and 1.7 cm/yr from May 2002 to 2010. The results are supported by the ADM output showing a decrease in soil moisture content, although the magnitude of the changes was one third of that shown by the GRACE results. While

the long-term trend in the changes in precipitation was considerably less than those associated with soil moisture content and GRACE-TWS, the decline in the basin's water storage could possibly be related to the increased human use of groundwater within the catchment for horticulture, subsistence farming and domestic use.

These findings provide independent confirmation based on both ground and space-based observations on what has long been suspected, that is, floriculture has been exploiting the water resources of Lake Naivasha and the surrounding basin at an unsustainable rate. As pointed out in Sect. 4.7, however, floriculture may not be the sole cause of the decline of Lake Naivasha water levels. Other factors, such as evaporation, fluctuation of groundwater level and climate among others, could also be contributing to the decline. Future studies on Lake Naivasha water levels should also include the effects of fluctuations of the Maleva and Gilgil rivers, especially the Maleva, which accounts for over 80% of inflows into the lake.

Remedial measures for the conservation and management of Lake Naivasha should thus be seriously considered before this Ramser wetland becomes extinct. Already, the potential seriousness of the consequences arising from the decline of Lake Naivasha has finally been appreciated by the Government of Kenya, who has appointed an administrative body known as the Imarisha Lake Naivasha Management Board, for managing the Lake Naivasha Catchment Restoration Programme, whose aim is to restore Lake Naivasha and its catchment.

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- GFZ Information Systems and Data Center (http://isdc.gfz-potsdam.de).
- CNES/GRGS GRACE solutions (http://bgi.cnes.fr:8110/geoid-variations/README.html).
- TRMM, Goddard Earth Sciences Data and Information Services Center (http://disc.sci.gsfc.nasa.gov/precipitation).
- Landsat data, Global Land Cover Facility (GLCF), Maryland University, USA (http://www.landcover.org/data/landsat/ ).

- Tide-Gauge data. Lake Naivasha Riparian Association organization (http://web.ncf.ca/es202/naivasha/). Thanks to Mrs. Sara Higgins (the chair person of the Lake Naivasha Riparian Association) for providing these tide gauge data.
- Flower export data. Kenya Flower Council (http://www.kenyaflower council.org/).
- Rainfall anomaly data. IGAD Climate Prediction and Application Centre, Nairobi, Kenya.

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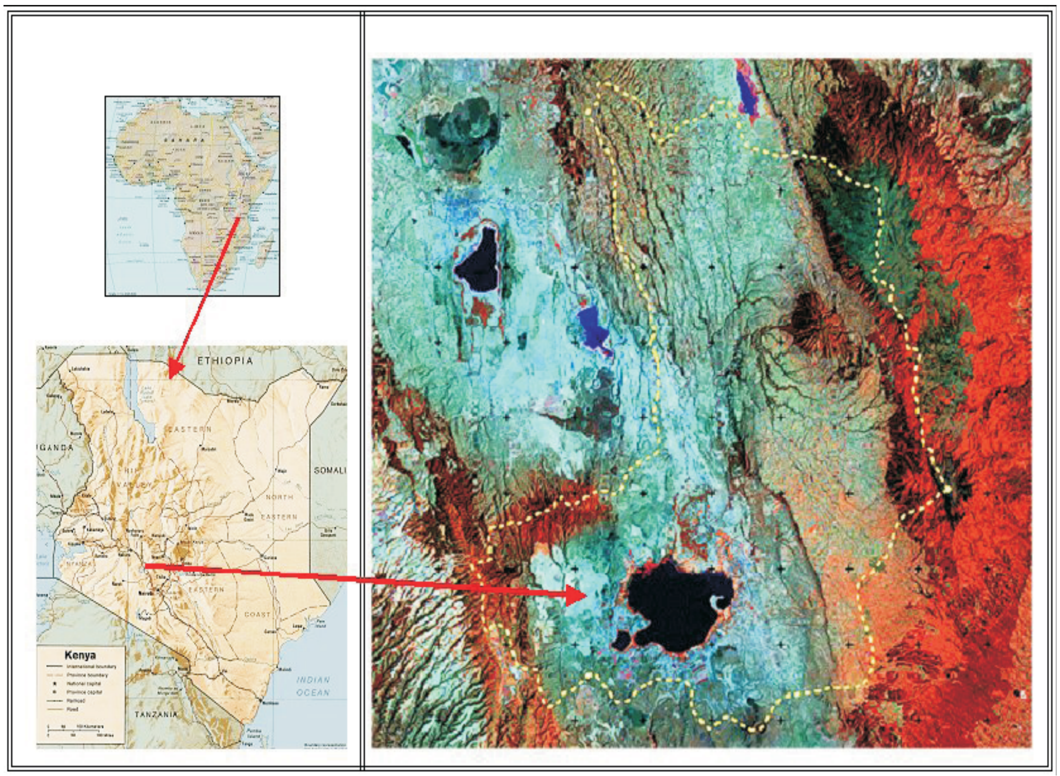


Figure 1: Location map of the Lake Naivasha Basin (Becht et al., 2005).

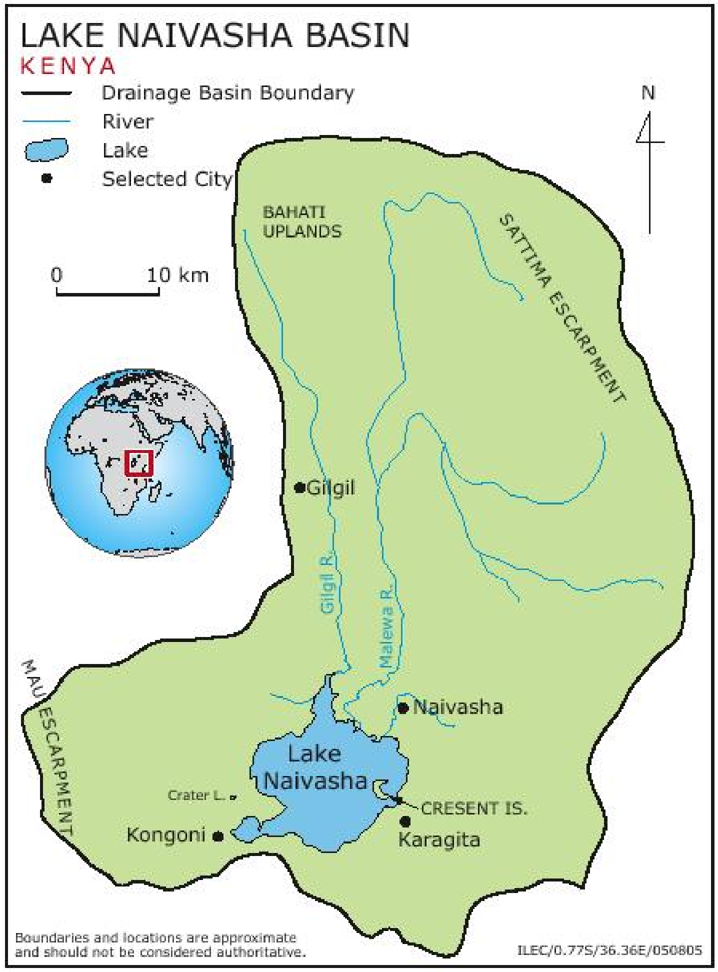


Figure 2: Lake Naivasha drainage system (Becht et al., 2005).

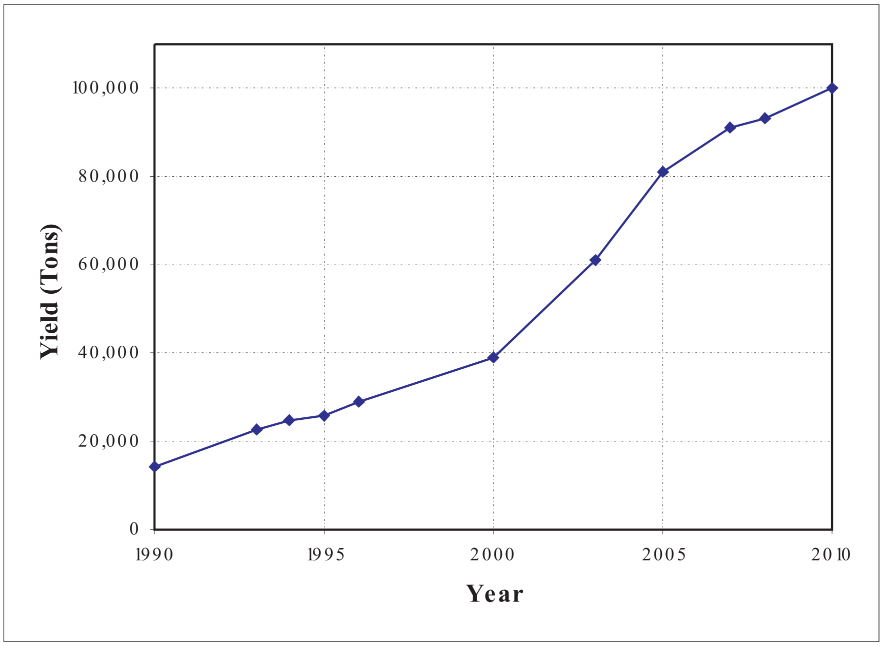


Figure 3: Annual flower exports from Kenya (KFC 2011).

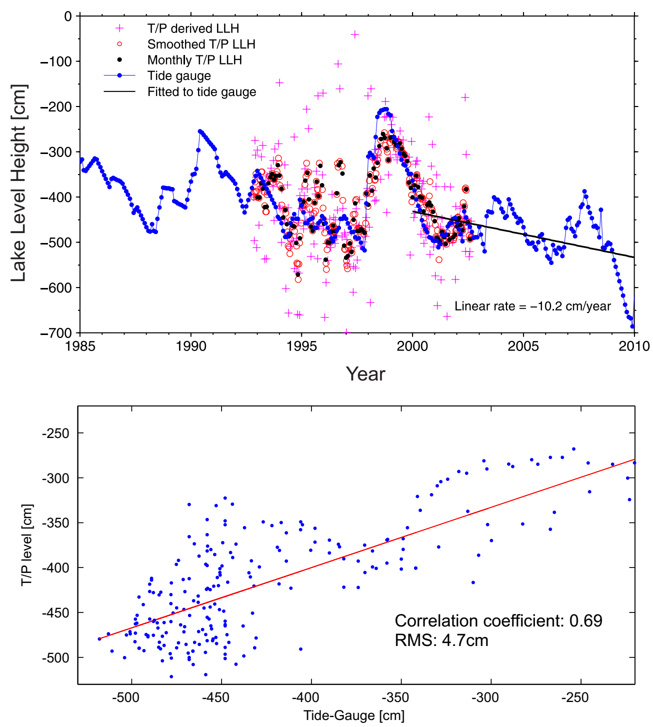


Figure 4: (Top) Time series of lake level height changes for Lake Naivasha as provided by satellite altimetry (T/P) and a tide gauge. (Bottom) Correlation between the lake level heights given by the tide gauge and the T/P altimery.

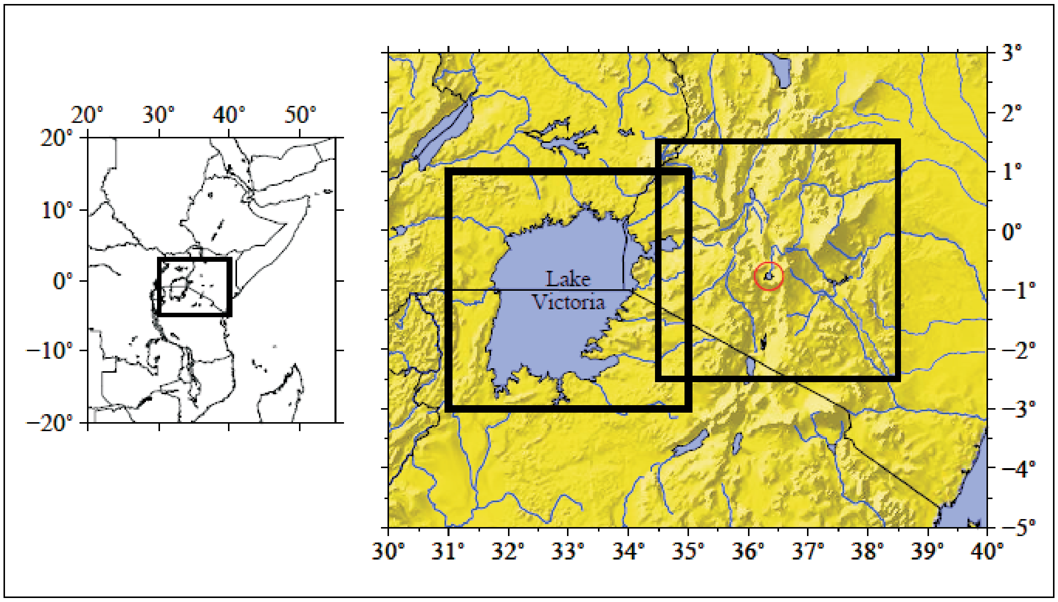


Figure 5: The areas defined over the Lakes Naivasha and Victoria basins considered in the GRACE and TRMM analysis (see Figures 6 and 10). The red circle marks the location of Lake Naivasha.

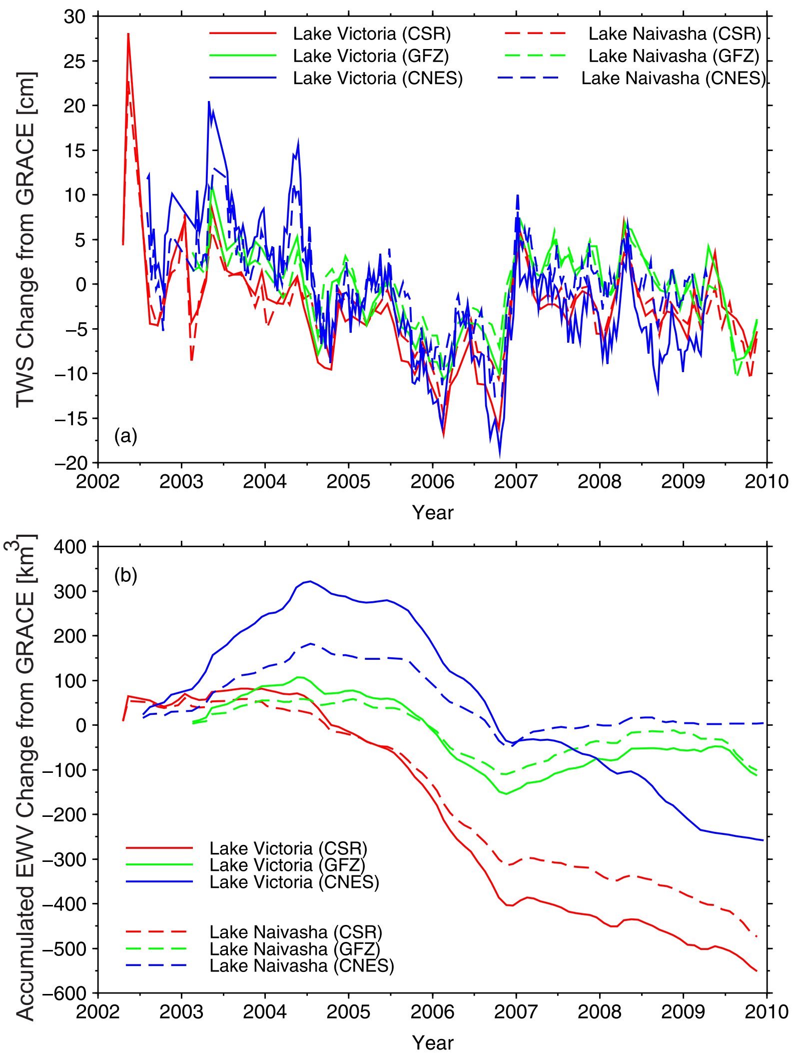


Figure 6: Variations in stored waters (an integration of surface and terrestrial water storage changes) over Lakes Naivasha and Victoria derived from GRACE products. (a) Change in TWS and (b) accumulated changes of TWS in equivalent water volume (EWV) (see Figure 5, for the Victoria and Naivasha catchments).

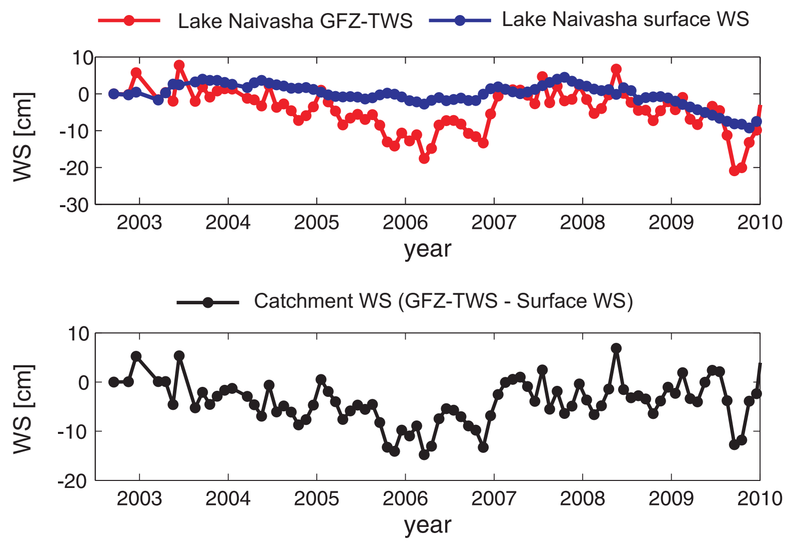


Figure 7: Top, the red line shows the average TWS computed from the GFZ GRACE data (related to Figure 5, the black box on the right-side). The blue line is surface WS belonging only to Lake Naivasha. The catchment terrestrial WS signal is then obtained from the difference between GRACE-TWS signal (red line) and the Lake's surface WS signal (blue), i.e., the bottom graph with the black line.

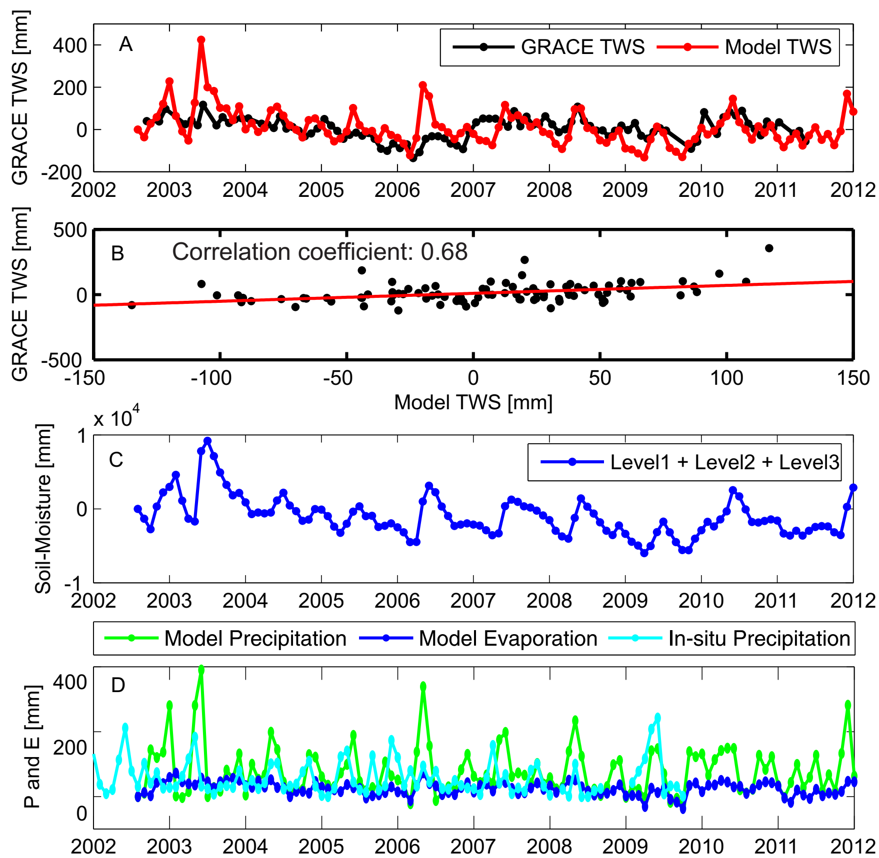


Figure 8: (A) A comparison between the calculated TWS from the ADM TWS and the GRACE TWS, (B) shows the GRACE TWS against ADM TWS changes, (C) a basin averaged soil moisture layers over Naivasha, and (D) a comparison between model-derived precipitation and in-situ measurements along with the temporal pattern of evaporation.

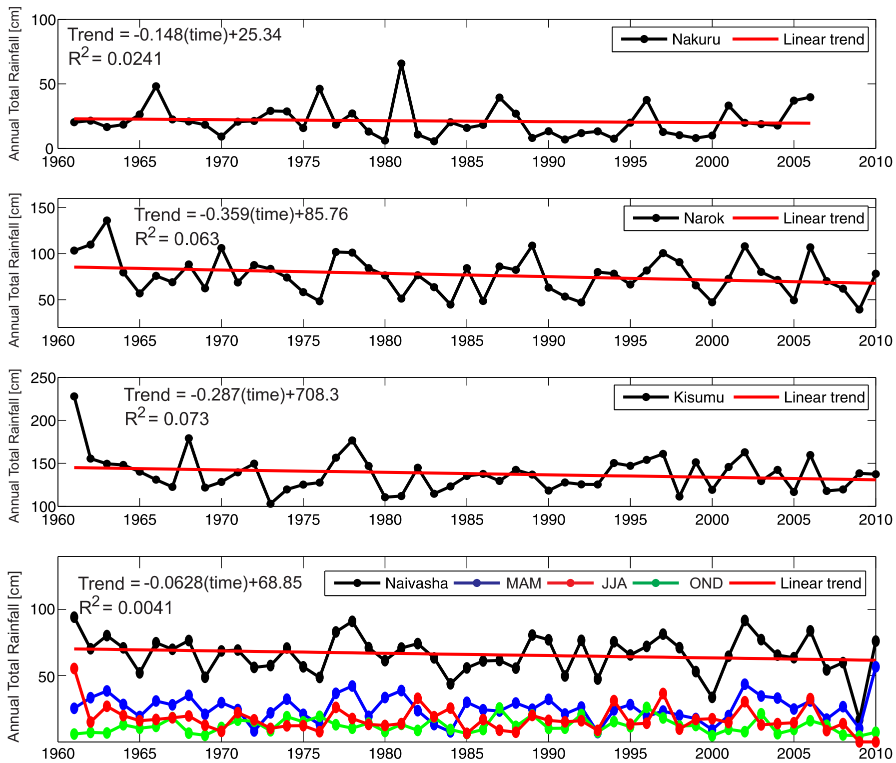


Figure 9: Annual rainfall time series over four stations in the region of Lake Naivasha. From top, Nakuru ($0.28°\mathtt{S}, 36.1°\mathtt{E}$), Narok ($1.1°\mathtt{S}, 35.9°\mathtt{E}$), Kismu ($0.1°\mathtt{S}, 34.8°\mathtt{E}$) and Naivasha ($0.72°\mathtt{S}, 36.4°\mathtt{E}$) stations. For Naivasha, MAM [blue], JJA [red] and OND [green] yearly values are also provided.

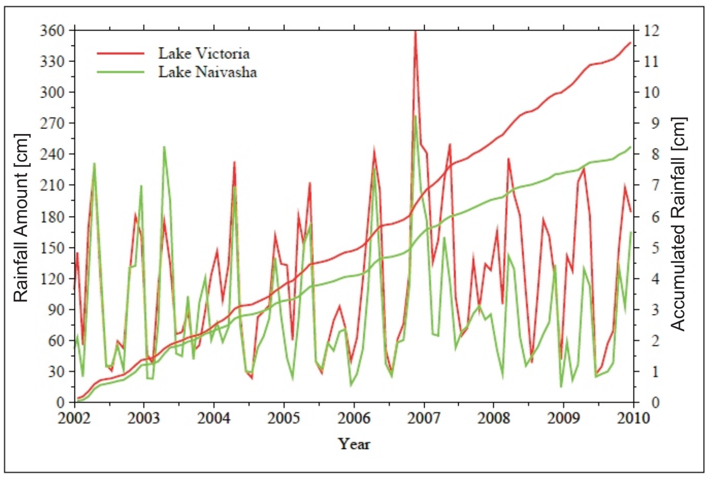


Figure 10: Rainfall over the Lakes Naivasha and Victoria basins (see Figure 5) as provided by the TRMM 3B43 product. Rainfall amounts are shown by the solid lines and the accumulated values are dashed.

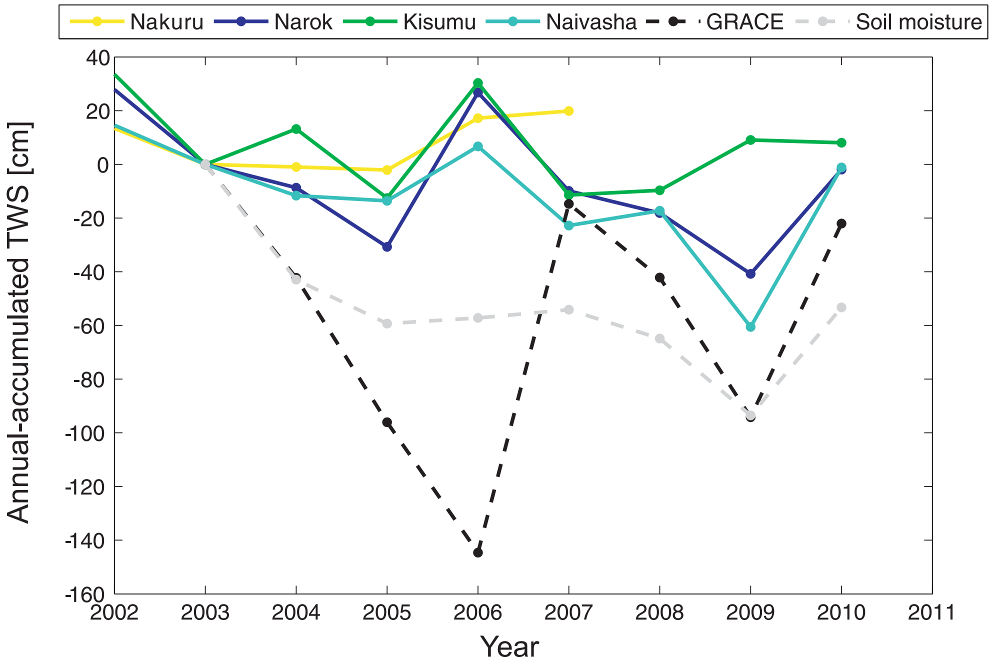


Figure 11: Comparing annual total water storage variations derived from GRACE with annual soil moisture contents (from ADM) and annual rainfall (from in-situ stations).

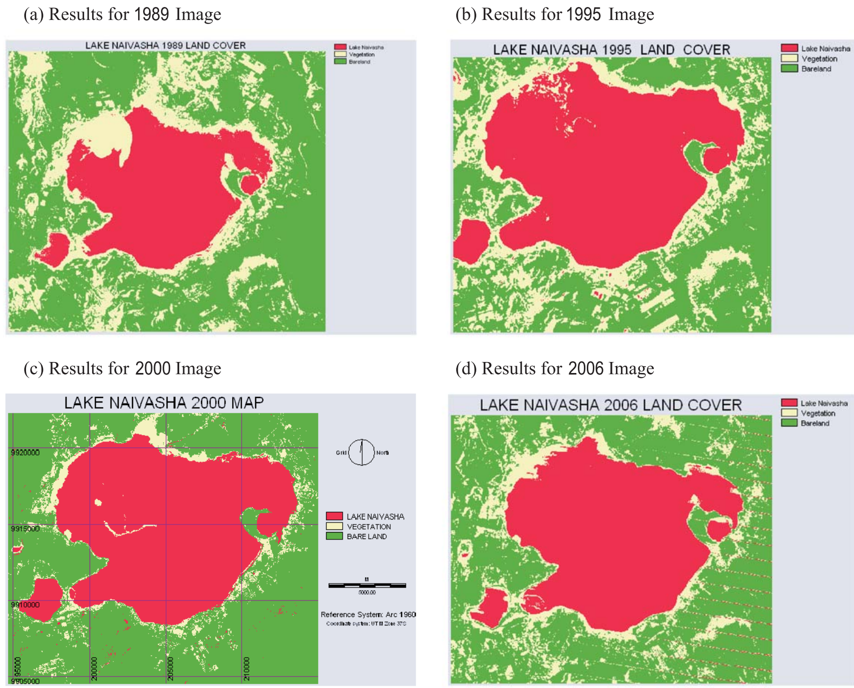


Figure 12: Surface-type classification results for the considered Landsat images. (a) 1989, (b) 1995, (c) 2000 and (d) 2006.

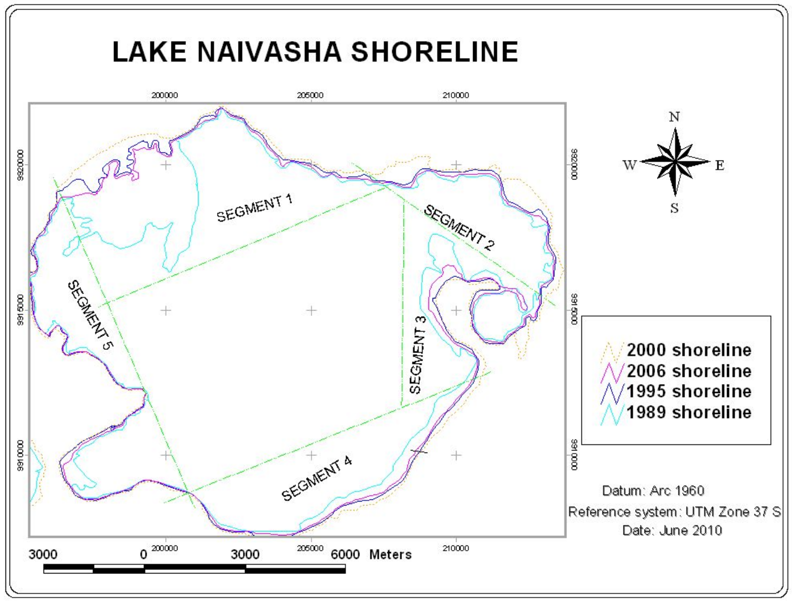


Figure 13: Segmentation of the changes in the Lake Naivasha shoreline for the years 1989, 1995, 2000 and 2006.

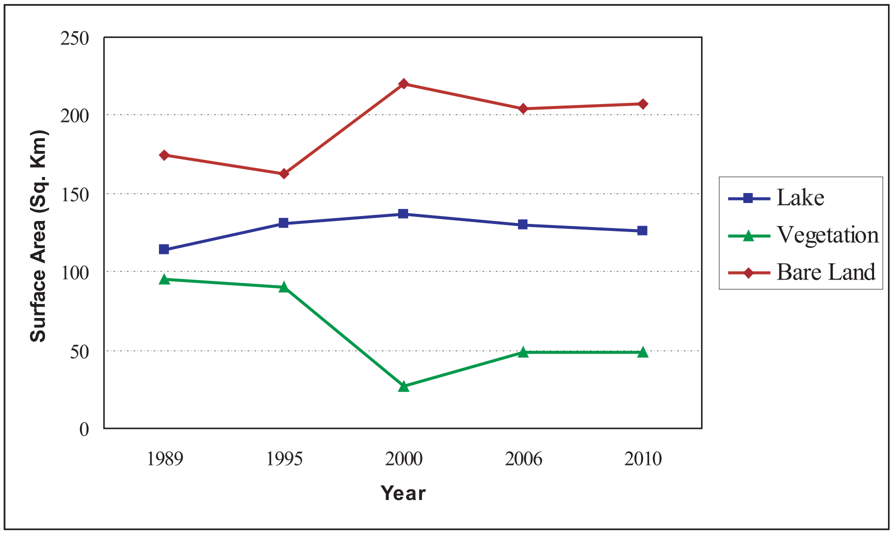


Figure 14: Variation in the area of the different land types around Lake Naivasha.

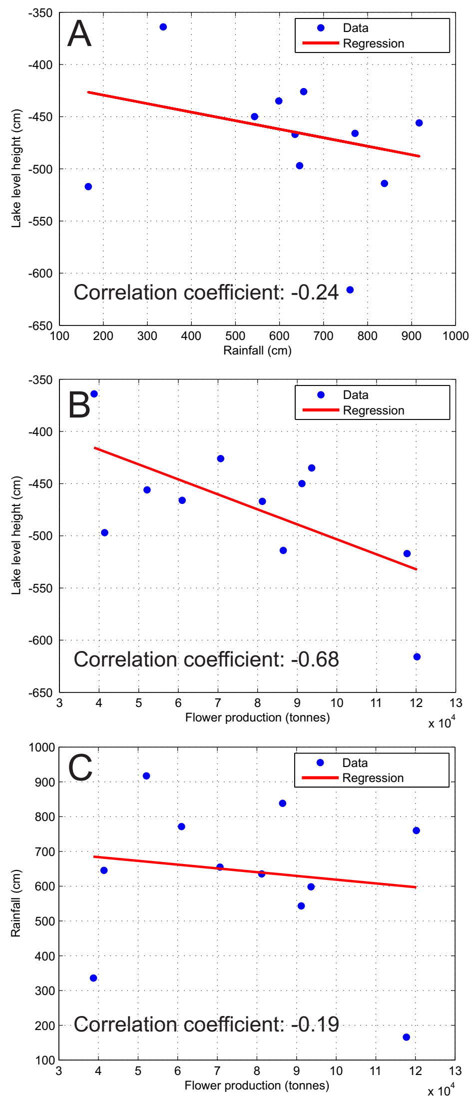


Figure 15: Comparing annual average lake levels with (A) rainfall observed at the Naivasha station and (B) flower exports. (C) Comparing annual average rainfall of the Naivasha station and flower exports. The solid lines are fitted linear trends, along with the correlation coefficients.