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

J.L. Awange^{a,e}, E. Forootan^b, J. Kusche^b, J.B.K. Kiema^c, P.A. Omondi^d, B. Heck^e, K. Fleming^{a,f}, S.O. Ohanya^c, R. M. Gonçalves^g

^a*Western Australian Centre for Geodesy and The Institute for Geoscience Research, Curtin University, Perth, Australia*

^b*Institute of Geodesy and Geoinformation, Bonn University, Bonn, Germany*

^c*Department of Geospatial and Space Technology, University of Nairobi, Nairobi, Kenya*

^d*IGAD Climate Prediction and Applications Centre (ICPAC), Nairobi, Kenya*

^e*Geodetic Institute, Karlsruhe Institute of Technology, Karlsruhe, Germany*

^f*Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany*

^g*Department of Cartography Engineering, Federal University of Pernambuco (UFPE), Geodetic Science and Technology of Geoinformation Post Graduation Program, Recife, PE, Brazil*

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 be-deviling 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

Email addresses: J.Awange@curtin.edu.au (J.L. Awange),
forootan@geod.uni-bonn.de (E. Forootan)

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 km²/year. GRACE indicates that the catchment area of 4° × 4° 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

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

26 first farms had just started in the early 1980's (see, e.g., Becht et al., 2005).
27 However, during the 1990's, over 100 km² of land around Lake Naivasha was
28 converted to floriculture for the flower trade (see, e.g., ILEC, 2005). With
29 this growth came an influx of workers, leading to a greater extraction of wa-
30 ter from the lake (see e.g., Mekonnen et al., 2012), local aquifers, and the
31 inflowing rivers for agriculture, floriculture and domestic use by the rapidly
32 increasing population (ILEC, 2005).

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

47 In the last decade, the level of Lake Naivasha has continued to drop with
48 floriculture being blamed for excessive water extraction from the lake and
49 aquifers, and the small holder farms in the upper catchment being blamed
50 for nutrient loadings, leading to outcry in both the local and international

51 media that this Ramsar site could be dying as a result of the very resource
52 that it supports (see, e.g., ILEC, 2005; FWWCC, 2008; Mekonnen and Hoek-
53 stra, 2010). For example, Mekonnen and Hoekstra (2010) and Mekonnen et
54 al. (2012) observed that the total virtual water exported in relation to the
55 cut flower industry from the Lake Naivasha basin was 16 Mm³/yr during the
56 period 1996-2005. This total virtual water (m³/yr) in relation to export cut
57 flower and vegetables is obtained by multiplying the trade volumes (tones/yr)
58 by their respective water foot print in Kenya (m³/ton), see e.g., Mekonnen
59 et al., (2012). Other factors that have also been proposed as influencing
60 Lake Naivasha's water changes include irregular rainfall patterns (Harper et
61 al., 1990), and trade winds (Vincent et al., 1979). All of these discussions,
62 therefore, point to the need for the reliable mapping of the lake and its basin
63 in order to properly understand its dynamics. The importance of monitoring
64 the lake was captured by Becht and Harper (2002), who pointed out the ur-
65 gency of accurately measuring all abstractions in order to provide consistent,
66 reliable, hydrological and meteorological data from the catchment, so that a
67 'safe' yield may be agreed upon by all stakeholders and sustainable use of
68 the lake waters achieved.

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

76 the shoreline by several meters (Becht et al., 2005).

77 The emergence of satellite-based methods offers the possibility of provid-
78 ing a broader and more integrated analysis of the lake and its basin. Using
79 time-variable gravity field products of the Gravity Recovery and Climate
80 Experiment (GRACE) mission (Tapley et al., 2004), variations in the total
81 water storage (TWS) of the region extending from the Lake Naivasha basin to
82 Lake Victoria is assessed in this study, to determine whether the changes are
83 climatic or human induced. GRACE-TWS products are then compared with
84 soil moisture and separated into its compartments (i.e., precipitation and
85 evaporation) using the African Drought Monitor (ADM) model. Changes
86 in precipitation are further examined by analysing monthly products of the
87 Tropical Rainfall Measurement Mission (TRMM), as well as four in-situ rain-
88 fall stations (Naivasha, Narok, Nakuru, and Kisumu), allowing us to deter-
89 mine the proportion of the fluctuations in Lake Naivasha that are related to
90 changes in precipitation during a long-term period (1960 to 2010) and the
91 study period (2002 to 2010). Note that analysing long-term precipitation
92 variations also evaluates the impact of climate variability such as the domi-
93 nant El Niño-Southern Oscillation (ENSO) phenomenon on the hydrological
94 compartments of TWS variations within the region of study (Omondi et al.,
95 2012; 2013a,b).

96 The fluctuations in the water level of Lake Naivasha are determined us-
97 ing both ground-based tide-gauge observations and satellite altimetry data
98 (TOPEX/Poseidon and Jason-1). These results are then related to the use
99 of satellite imagery (e.g., Landsat) and change detection techniques to map
100 the shoreline changes of Lake Naivasha, analysing the trend of changes over

101 the study period of interest, and correlating shoreline changes to the pro-
102 posed causes. Therefore, this study pioneers the use of both space-borne and
103 ground-based observations for monitoring Lake Naivasha.

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

109 **2. Study Area**

110 Lake Naivasha ($00^{\circ} 40' S - 00^{\circ} 53' S, 36^{\circ} 15' E - 36^{\circ} 30' E$) is the second
111 largest fresh water lake in Kenya with a maximum depth of 8 m. It is situated
112 in the Eastern African Rift Valley at an altitude of 1890 m above sea level and
113 is approximately 80 km northwest of the Kenyan capital, Nairobi. Its basin
114 (Figure 1) lies within the semi-arid belt of Kenya with mean annual rainfall
115 varying from about 60 cm at the Naivasha township to some 170 cm along the
116 slopes of the Nyandarua mountains, with open water evaporation estimated
117 to be approximately 172 cm/year (Becht et al., 2005). Mount Kenya and the
118 Nyandarua Range capture moisture from the monsoon winds, thereby casting
119 a significant rain shadow over the Lake Naivasha basin (Becht et al., 2005).
120 Unlike Lake Victoria which has its highest rainfall during the March-April-
121 May (MAM) wet season (e.g., Awange et al., 2008a, b), the Lake Naivasha
122 basin experiences its highest rainfall period during April-May-June (AMJ).
123 There is also a short rainy season from October to November. The lake's
124 levels, therefore, follow this seasonal pattern of rainfall cycle, with changes of

125 several meters possible over a few months. Superimposed upon this seasonal
126 behaviour are longer-term trends, for example, there has been a change in
127 the lake's water level of 12 m over the past 100 years (Becht et al., 2005).

FIGURE 1

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

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

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

154 The flower industry in Kenya has experienced a phenomenal growth,
155 maintaining an average growth rate of 20% per year over the last decade. It
156 is an industry that is the second largest export earner for Kenya, employing
157 50,000 - 60,000 people directly and 500,000 others indirectly through affili-
158 ated services (KFC, 2011). Although flowers are now grown in many areas
159 with temperate climate and an altitude above 1,500 m in Kenya, the region
160 around Lake Naivasha still remains the nation's main floriculture farming
161 center. The foremost categories of cut flowers exported from Kenya include
162 roses, carnations, statice, alstromeria, lilies and hypericum. Indeed, Kenya
163 is arguably the largest exporter for flowers in the world, supplying over 35%
164 of cut flowers to the world's largest market - the European Union (KFC,
165 2011).

FIGURE 2

166 **3. Datasets and Methodology**

167 *3.1. Gravity Recovery and Climate Experiment (GRACE) Data*

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

170 89.5°. The separation between the two satellites is measured by a K-Band
171 range rate system (KBRR) and the locations of the satellites are determined
172 by Global Positioning System (GPS) receivers on-board the spacecraft and
173 satellite laser ranging (Tapley et al., 2004). Other information are provided
174 by accelerometers that help to correct for non-gravitational effects such as
175 atmospheric drag (Tapley et al., 2004).

176 One of the GRACE main products is its level-2 time-variable gravity
177 fields (Flechtner, 2007). There are a number of institutions that provide
178 various GRACE level-2 products, each employing different processing proce-
179 dures, background models and assumptions. The products employed in this
180 work are the Release 2 from the Centre National d’Etudes Spatiales/Groupe
181 de Recherche de Geodesie Spatiale, France (CNES/GRGS, Bruinsma et al.,
182 2010), Release 4 of the Centre for Space Research, University of Texas at
183 Austin, USA (CSR, Bettadpur, 2007), and Release 4 of the German Re-
184 search Centre for Geosciences (GFZ, Flechtner, 2007). The CSR and GFZ
185 time series have a monthly temporal resolution, while the CNES/GRGS is
186 for every 10 days.

187 GRACE results have been used for assessing the relationships between
188 water storage changes and climate change in a number of cases (e.g., Becker
189 et al., 2010, Forootan et al., 2012). Awange et al., (2008b) and Swenson and
190 Wahr (2009) used multi-satellite data to study the water storage changes of
191 Lake Victoria. However, we will only use the GRACE products to exam-
192 ine the area covering the Lakes Naivasha and Victoria basins to determine
193 whether the climatic behaviour there correlates with that over Lake Victoria.
194 This is because the area of Lake Naivasha is much too small for it to be ade-

195 quately assessed by GRACE, where areas of the order of 200,000 to 400,000
196 km² are necessary (Swenson et al., 2003; Rowlands et al., 2005), as opposed
197 to the 140 km² that Lake Naivasha covers (Becht et al., 2005). Lake Vic-
198 toria basin covers an area of more than 250,000 km² (see, e.g., Awange and
199 Ong’ang’a, 2006), which, when combined with Lake Naivasha basin, suffices
200 for GRACE satellite analysis.

201 In order to derive TWS maps, first, monthly products were filtered us-
202 ing a Gaussian filter (Jekeli, 1981) of 500 km radius. Then, residual gravity
203 field solutions were computed with respect to the temporal average (assumed
204 static) over the considered study period (2002-2010). The residual coefficients
205 were transformed into monthly TWS values using the approach of Wahr et al.
206 (1998). Note that there are alternative filters for de-noising GRACE prod-
207 ucts, e.g., non-isotropic filters discussed in Kusche et al. (2009). However,
208 this study used the Gaussian filter due to the simplicity of its implementation.

209 3.2. *The Princeton African Drought Monitor (ADM) model*

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

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

215 where S stands for soil moisture, P for precipitation, E for evaporation and
216 R for discharge measured in time (t). For assessing GRACE-TWS results,

217 and also to extract more information about each of the water balance compo-
218 nents, therefore, we used the outputs of the African Drought Monitor (ADM)
219 model (<http://drought.icpac.net/>) for the period of 2002 to 2012, which con-
220 tains data from both historic reconstruction (1950 to 2008) and real-time
221 monitoring (2009 to Present) of the hydrological cycle and drought events
222 over Africa (Sheffield et al., 2006). The outputs of the model has been used
223 for monitoring drought in Africa (see, e.g., Sheffield et al., 2009), while the
224 performance of the model for monitoring droughts in the USA and Africa is
225 discussed in Luo et al. (2008).

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

235 *3.3. Tropical Rainfall Measuring Mission (TRMM) Data*

236 TRMM is a joint mission between the United States (NASA) and Japan
237 (Japan Aerospace Exploration Agency) (Kummerow et al., 1998; Kummerow
238 et al., 2000). TRMM is designed to monitor tropical rainfall in the latitude
239 range $\pm 50^\circ$. The primary instruments are the TRMM Microwave Imager
240 (TMI), the Precipitation Radar (PR), and the Visible and Infrared Radiome-
241 ter System (VIRS) (Kummerow et al., 1998). There are a number of products

242 based on the TRMM observations, whose use is dependent upon the sub-
243 ject of interest. In this work, we used monthly averaged 3B43 rainfall rate
244 products over the latitude range $\pm 50^\circ$, which is inferred from not only the
245 TRMM observations, but also employs data from a number of other satellites
246 and ground-based rain gauge data (Huffman et al., 2007). TRMM observa-
247 tions have been used in several studies of rainfall over Africa (e.g., Adeyewa
248 and Nakamura, 2003; Nicholson et al., 2003). In particular, Awange et al.
249 (2008b) investigated the falling levels of Lake Victoria using a combination
250 of TRMM, GRACE and CHAMP satellite data. TRMM rainfall maps are
251 filtered using a Gaussian 500 km filter to be consistent with GRACE-TWS
252 and ADM products.

253 *3.4. Landsat Images*

254 The Landsat series of Earth observations provide a unique historical data
255 set for land surface and climate change studies covering almost 40 years.
256 In this study, four Landsat images were used, gathered by the Landsat 5
257 spacecraft using its Thematic Mapper (TM) and Multispectral scanners. The
258 acquired imagery were for the 30th March in the years 1989, 1995, 2000, and
259 2006. All images are made available from the Global Land Cover Facility
260 (GLCF) of the Maryland University (USA) and constitute part of NASA's
261 global orthorectified Landsat data set (Tucker et al., 2004). Landsat TM has
262 seven spectral bands that cover the visible, near infrared, short-wave infrared
263 and thermal infrared regions of the electromagnetic spectrum (Mather, 2004).
264 Ancillary data for validating remote sensing measurements usually consists
265 of topographical (digital elevation model) and soil data. These were mainly
266 used to assist in the interpretation of the imagery, with supervised image

267 classification employing the minimum distance classifier.

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

279 *3.5. Satellite Altimetry Data*

280 Observing water level fluctuations provided by existing altimetry mis-
281 sions is of major importance in monitoring water reservoirs, as they provide
282 additional information besides the traditional in-situ data sets (Becker et al.,
283 2010; Crétaux et al., 2011; Sharifi et al., 2012). From the available satel-
284 lite altimetry missions, TOPEX/Poseidon (T/P) and its follow-on mission
285 Jason-1 have provided observations for Lake Naivasha. During 1993 to 2002,
286 we used data provided by the NASA Physical Oceanography DAAC (PO-
287 DAAC) at the Jet Propulsion Laboratory, California Institute of Technology,
288 which is in a format termed the Merged Geophysical Data Record (MGDR)
289 (Benada, 1997). Over this time period, we found that 273 of the 369 T/P's
290 cycles contained one valid observation over Lake Naivasha (See Figure 4). To
291 cover the remaining period of the study, we examined the Jason-1 Interim

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

297 *3.6. Other Data Sets Employed*

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

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

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

315 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

316 4. Results and Discussions

317 4.1. Lake Level Analysis

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

327 0.69 between smoothed altimetry data and tide gauge observations (Figure
328 4,(Bottom)). Figure 4,(Top) confirms that although the lake level has been
329 fluctuating both annually and seasonally over time up to around the year
330 2000, thereafter, a general downward trend at a rate of -10.2 cm/year before
331 the onset of the 2007 ENSO rains is visible.

FIGURE 4

332 *4.2. GRACE Analysis*

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

FIGURE 5

346 Figure 6 (a) shows the TWS changes as described by the three GRACE
347 products considered; CSR, CNES/GRGS and GFZ. Evidently, all GRACE

348 solutions indicate water loss in both Lakes Naivasha and Victoria regions
349 from 2002 to late 2006. The increase in late 2006 is attributable to the
350 ENSO effect, with water loss continuing again after an increase in late 2006-
351 early 2007. Previous studies have demonstrated that the fall in Lake Victoria
352 during that period was due to anthropogenic factors such as the expanded
353 Nalubale dam (see, e.g., Awange et al., 2008a,b; Swenson and Wahr, 2009).
354 Similar findings are shown by the cumulated water as illustrated in Figure 6
355 (b). The cumulative annual TWS of the Naivasha catchment lost water at a
356 rate of 72 cm/yr from 2003 to May 2006. From January 2007 to December
357 2009, this loss was 41 cm/yr.

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

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

FIGURE 6

FIGURE 7

385 4.3. ADM Analysis

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

394 1700 mm/year. Since the runoff parameter is not available after the year
395 2000 for Lake Naivasha (see also Ayenew and Becht, 2008) and the fact that
396 Ojiambo et al. (2001) suggest that yearly R is negligible for the lake, we did
397 not include it in our computations.

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

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

411 Comparing the modeled precipitation (the green line in Figure 8 (D))
412 with in-situ precipitation (the cyan line in Figure 8 (D)), shows some incon-
413 sistencies, mainly in terms of the differences in the amplitudes between the
414 modeled and in-situ values. A phase difference of one month is also evident
415 between the two data sets. The dark-blue line in Figure 8 (D) represents
416 the amount of evaporation changes for the period of July 2002 to 2012 show-
417 ing almost steady range when compared to precipitations and soil moisture
418 changes. As a result, one can see that the water capacity corresponding to

419 soil moisture layers and rainfall is declining within the basin.

FIGURE 8

420 *4.4. Rainfall Analysis*

421 From the in-situ rainfall observations, the rainfall regime over the Naivasha
422 basin has seen a downward trend since 1960 (see Figure 9). For instance,
423 Figure 9 (bottom) shows a time series of the annual total (the black line),
424 March-May (MAM, the blue line), June-August (JJA, the red line) and
425 October-December (OND, the green line) rainfall seasons over Naivasha. In
426 this study, we employed both graphical and statistical methods (described
427 in WMO, 1966) to superficially test the significance of the observed trends
428 (see also discussions in Wilks (1995) and Omondi et al. (2012; 2013a)). The
429 data were analysed for trends using linear regression, and the significance of
430 trends was tested using the non-parametric Mann-Kendall tau test (Sneyers,
431 1990). An overview of the total amount of annual rainfall variation derived
432 from the four stations is summarized in Figure 9, while their corresponding
433 linear rates are reported on each graph. However, although the derived long-
434 term linear trend values were negative, they were not large enough to pass
435 the tau test (see also Omondi et al., 2013b).

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

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

FIGURE 9

452 Figure 10 illustrates the total rainfall of the catchment and its accumu-
453 lated values as described by the TRMM 3B43 product over the 4×4 degree
454 windows defined in Figure 5. The larger rainfall over Lake Victoria is seen
455 both in terms of the time series, and also in the greater rate of increase
456 in the accumulated values. Comparatively, while there seems to have been
457 an increase in the precipitation rate over the Lake Victoria basin after late
458 2006, there seems to be little change in the rainfall over the Lake Naivasha
459 basin. Comparing the TRMM results in Figure 10 with the GRACE results
460 in Figure 6 for period 2002-2010, while no significant change is visible in
461 the TRMM results, those from GRACE show a loss of water from the Lakes
462 Naivasha and Victoria basins. This could therefore mean that the drop in
463 Lake Naivasha's water level (as is the case for Lake Victoria) may be more
464 influenced by anthropogenic factors compared to climatic factors.

FIGURE 10

465 *4.5. Comparing TWS Changes Across Lake Naivasha with Rainfall*

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

FIGURE 11

477 *4.6. Image Analysis*

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

480 *Image classification:* To validate the results obtained from using GRACE
481 and TRMM data sets, satellite remote sensing and GIS analysis were per-
482 formed. Landsat imagery of the study area acquired from different epochs
483 was employed and different land use / land cover types were discriminated.
484 The interpretation of Landsat imagery was undertaken using the minimum

485 distance supervised classifier. The overall accuracy of the land use / land
486 cover map was estimated to be 85.0% with a kappa statistic of 0.79. This
487 meets the minimum threshold established by the United States Geological
488 Survey (USGS) classification scheme (Anderson et al., 1976). As an example,
489 the classification results for the first epoch (1989) are shown in Figure 12 (a).
490 The classified image depicts a clear demarcation between land/vegetation
491 and water, hence revealing a clear picture of the shoreline position. The red
492 colour depicts water, yellow represents general vegetation cover while green
493 represent general bare land. There is a significant intrusion onto the northern
494 shoreline by vegetation, indicating a positional change of the shoreline. Fig-
495 ure 12 (b), showing the second epoch examined (1995) shows a significant
496 departure from Figure 12 (a), especially in the north, where vegetation has
497 significantly receded, leaving only scattered traces in contrast to the 1989
498 image that showed a thick vegetation cover around the same area. There is
499 also a change around Crescent Bay (formerly Crescent Island, see Figure 2).
500 While the 1989 image shows a near excision of the bay from the main lake,
501 the situation is different in the 1995 image. This is because of the general
502 increase in water volume caused by increased rainfall over the same period.

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

510 2000. However, there are some traces of vegetation at the centre of the lake.
511 These might be due to the presence of water lillies in the lake or traces
512 of leaves transported by run-off into the lake. Figure 12 (d) shows that
513 the scattered traces of vegetation in the middle of the lake that were part
514 of the preceding images have disappeared. However, the Crescent Bay has
515 receded and a section of it is almost cut-off from the main lake to form an
516 independent lake. There is also a significant change in the shape of the island
517 when compared to the previous images. The amount of grassland cover has
518 also increased along the shoreline compared to the 2000 image, indicating a
519 relationship between vegetation and the lake's surface area.

FIGURE 12

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

527 This was done by digitizing the shoreline from the respective classified im-
528 ages in a Geographic Information System (GIS) environment using ArcGIS
529 version 9.3. The shorelines from each epoch were then overlaid to reveal the
530 general change trend. To allow for a detailed analysis, the overlay result
531 was further divided into five segments as shown in Figure 13. In general,
532 the results show that there was an increase in water level in Lake Naivasha

533 between 1989 and 1995. This increase continued until 2000, however, the
534 2006 shoreline shows a decline in water level between 2000 and 2006. De-
535 tailed scrutiny shows that there was a steady northern (outward) shift of the
536 shoreline from 1989 to the year 2000, indicating an increase in water level.
537 This was followed by an inward shift in 2006, indicative of a drop in water
538 level. However, the magnitude of the shoreline change is not uniform over
539 the different epochs. The lack of uniformity can be attributed to variations
540 in the local terrain, resulting in, obviously, the shoreline changing more in
541 flatter terrain as opposed to steeper areas.

FIGURE 13

542 *Shoreline change and variation:* The surface area of the lake in each
543 epoch was computed in the GIS environment. A summary of the changes in
544 the surface area between different epochs for the different land cover classes,
545 with 1989 as the reference year, is shown in Table 2, which indicates a direct
546 relationship between the lake's level and surface area. The increase in area
547 in 1995 compared to 1989 (i.e., 14.8%) is represented by an increase in water
548 level (1.19 m). The situation is even more apparent between 1989 and 2000
549 where there is an increase of 20% in surface area and a corresponding increase
550 of 2.33 m in water level. There was a drop in surface area of the lake between
551 2000 and 2006 (i.e., a drop of about 4.7%) and again this is shown by a
552 drop of 1.92 m in the water level during this period. This general trend is
553 corroborated by results obtained from both satellite altimetry and GRACE
554 illustrated in Figures 4 and 7, respectively. Figure 14 shows the variation of
555 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

556 and 2010.

FIGURE 14

557 From the above results, it is clear that Lake Naivasha has experienced
558 shoreline variations over the last 17 years as indicated by the changes in
559 surface area. There was a positive gain in area by 16.80 km² between 1989
560 and 1995 (i.e., 14.8%), with a further gain by the year 2000 of 5.95 km², due
561 largely to the 1997 ENSO rainfall. However, there was a drastic decline in
562 the surface area between 2000 and 2006, with the lake losing 6.35 km² of its
563 surface area (i.e., 4.7%), indicating a recession in its shoreline. The surface
564 area of the lake in 2006 is comparable to that of 1995 (both \sim 130 km²).
565 After 2006, the lake continued shrinking with a surface area of 126.01 km²
566 in 2010 (i.e., a reduction of about 7.6%). In general, from these images, it
567 was calculated that the lake's area is shrinking at a rate of 1.04 km²/year.

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

578 *4.7. Comparing Lake Levels with Rainfall and Flower Exports*

579 In light of the previous results, the relationship between the decline of
580 WS within the catchment, the lake itself, and the local and catchment pre-
581 cipitation were explored. To finalize this study, a simple comparison is made
582 between the level of lake (one of the main water sources of the catchment)
583 and other data sets considered in this work, including rainfall recorded by
584 the Naivasha station (a representation of climate variability) and flower pro-
585 duction (a representation of human use) (see Figure 15). Considering first
586 rainfall and the lake's levels (Figure 15 (A)), where we plot annual rainfall
587 against annual average lake level, a correlation coefficient of -0.24 is obtained,
588 suggesting no statistically significant correlation between these quantities.
589 On the other hand, considering lake levels with flower production (Figure 15
590 (B)), where we have plotted tonnage of flower production against the annual
591 averages of the lake levels for the years where the tonnage data were avail-
592 able, we find a strong statistically significant correlation, with a correlation

593 coefficient of -0.68. This suggests strongly that flower exports could have
594 influenced the reduction in Lake Naivasha's water level. Finally, Figure 15
595 (C) shows an insignificant correlation coefficient of -0.19 between rainfall and
596 flower production.

597 Caution should be exercised, however, when one is interpreting the corre-
598 lation results above. This is due to the fact that flower production, though it
599 is a useful proxy for estimating water consumption in the Lake Naivasha re-
600 gion, and indeed constitutes the main cause of water consumption, depends
601 on other factors unrelated to water withdrawal from the lake, e.g., in-put
602 fertilizers. Therefore, an analysis of other factors that influence flower pro-
603 duction, e.g., the amount of water withdrawn and used to irrigate the flowers,
604 would be desirable. Along these lines, Mekonnen et al. (2012) quantified the
605 water footprint within the Lake Naivasha Basin related to cut flowers and
606 analysed the possibility of mitigating the footprint by involving cut-flower
607 traders, retailers and overseas customers. Hagos (2008) assessed the pos-
608 sibility of using shallow and deep underground water, while Reta (2011)
609 simulated a long term groundwater and lake water balance of Lake Naivasha
610 in an attempt to establish the relationship between water consumption and
611 water levels. Both Hagos (2008) and Reta (2011) highlighted the importance
612 of underground water in the dynamics of Lake Naivasha's water levels. Such
613 influence has been investigated, e.g., by Becht et al. (2002) and Becht and
614 Nyaoro (2005), who considered the influence of groundwater fluctuations on
615 Lake Naivasha and found it to have an important effect on the water balance
616 of the Lake. In fact, Becht and Nyaoro (2005) deduced that the interaction of
617 the groundwater and the Lake dynamics introduces a degree of inertia to the

618 lake groundwater system, resulting in delayed reactions to external (meteo-
619 rological) stresses where the groundwater acts as an extra reservoir absorbing
620 water during wet periods and releasing water during droughts. Evaporation
621 also plays a key role in Lake Naivasha's water balance as evident by the
622 results of Farah et al., (2004), who obtained in-situ evaporation values at a
623 grassland and woodland site in the Lake Naivasha basin for about a year.
624 Another example of extraneous factors affecting Lake Naivasha's water levels
625 is presented, e.g., in Olago et al. (2009), who showed that the hydrology of
626 the Rift Valley is controlled mainly by climate and water table variation,
627 among other factors.

FIGURE 15

628 **5. Conclusions**

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

- 636 1. During the study period 1989 to 2010, Lake Naivasha experienced vari-
637 ation in its spatial extent and significant fluctuations in its level. How-
638 ever, from around the year 2000, a steady decline in its spatial extent

639 has been observed with the lake receding at a rate of $1.41 \text{ km}^2/\text{year}$, ac-
640 companied by a corresponding drop in water level of about $33 \text{ cm}/\text{year}$.

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

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

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

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

679 Remedial measures for the conservation and management of Lake Naivasha
680 should thus be seriously considered before this Ramsar wetland becomes ex-
681 tinct. Already, the potential seriousness of the consequences arising from the
682 decline of Lake Naivasha has finally been appreciated by the Government of
683 Kenya, who has appointed an administrative body known as the Imarisha
684 Lake Naivasha Management Board, for managing the Lake Naivasha Catch-
685 ment Restoration Programme, whose aim is to restore Lake Naivasha and its
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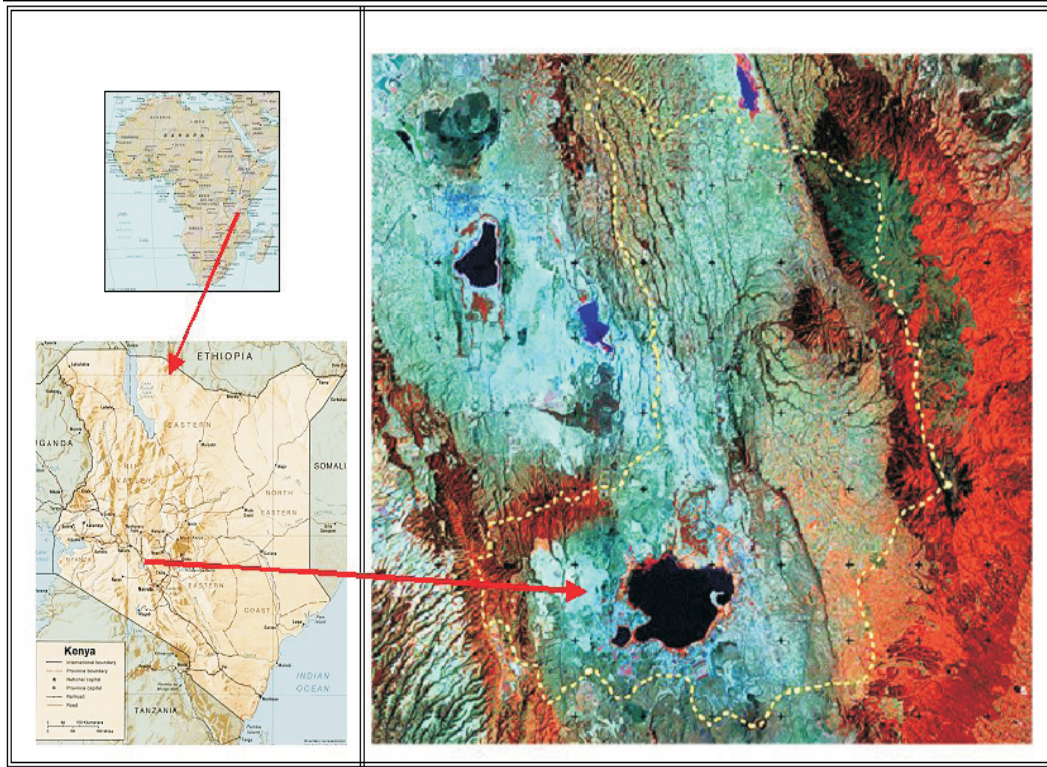


Figure 1: Location map of the Lake Naivasha Basin (Becht et al., 2005).

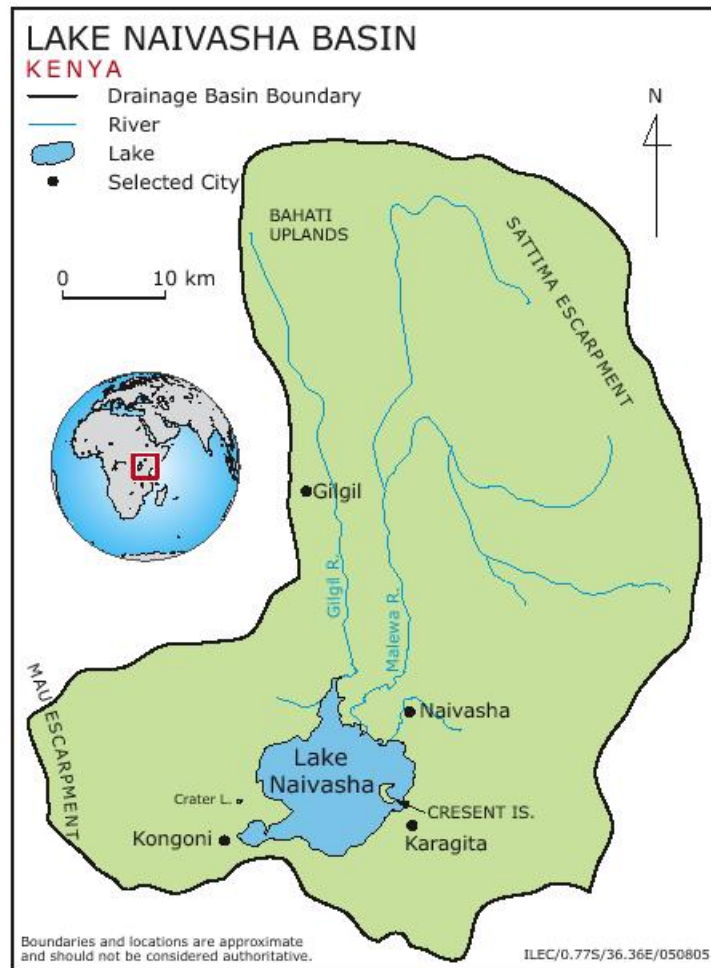


Figure 2: Lake Naivasha drainage system (Becht et al., 2005).

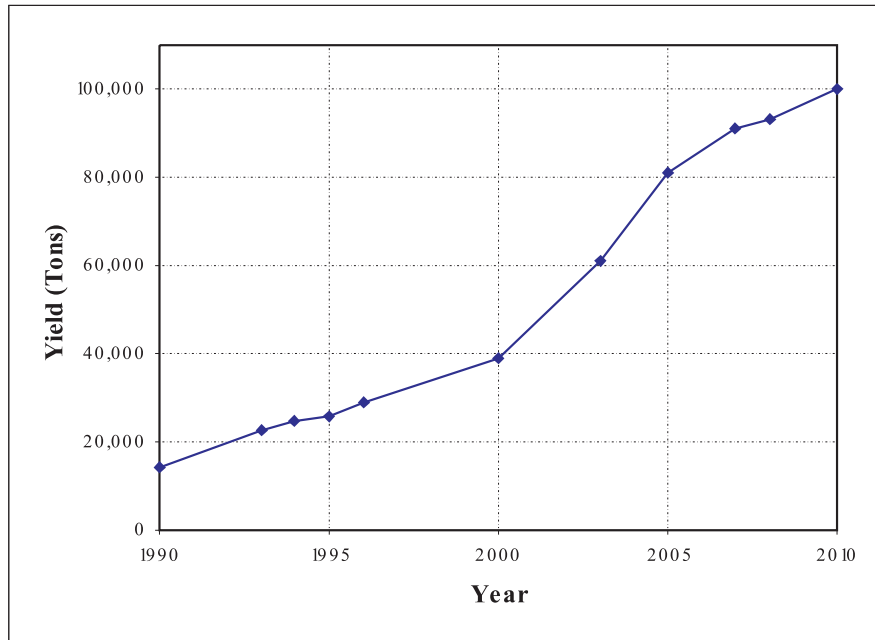


Figure 3: Annual flower exports from Kenya (KFC 2011).

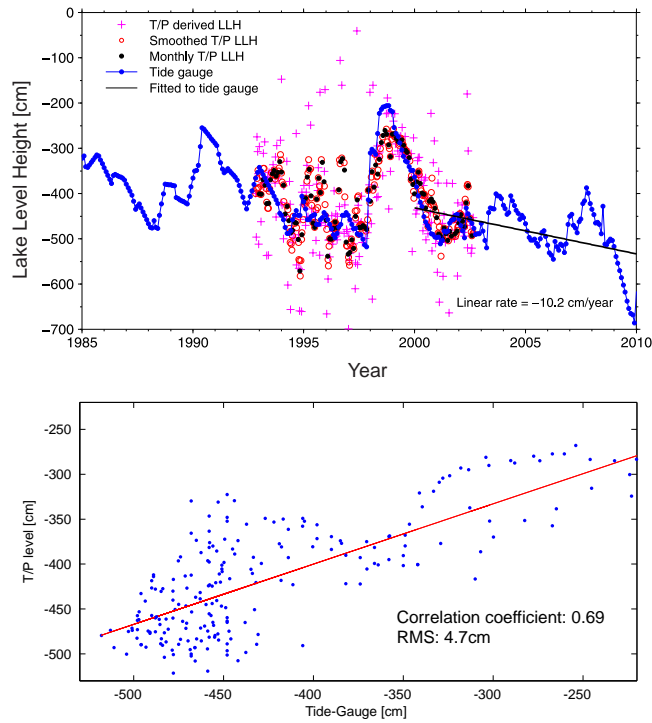


Figure 4: (Top) Time series of lake level height changes for Lake Naivasha as provided by satellite altimetry (T/P) and a tide gauge. (Bottom) Correlation between the lake level heights given by the tide gauge and the T/P altimetry.

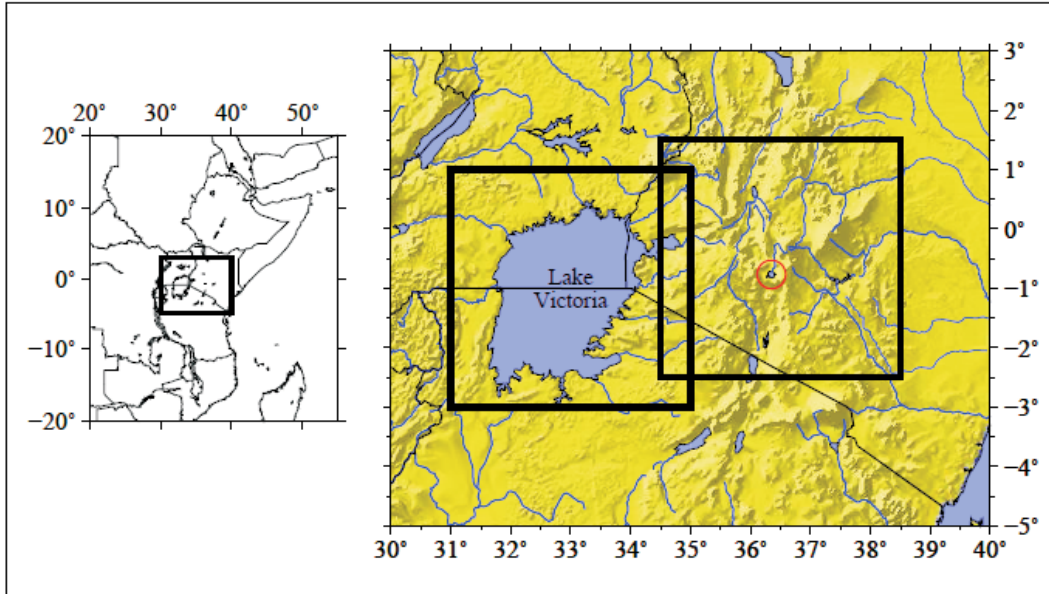


Figure 5: The areas defined over the Lakes Naivasha and Victoria basins considered in the GRACE and TRMM analysis (see Figures 6 and 10). The red circle marks the location of Lake Naivasha.

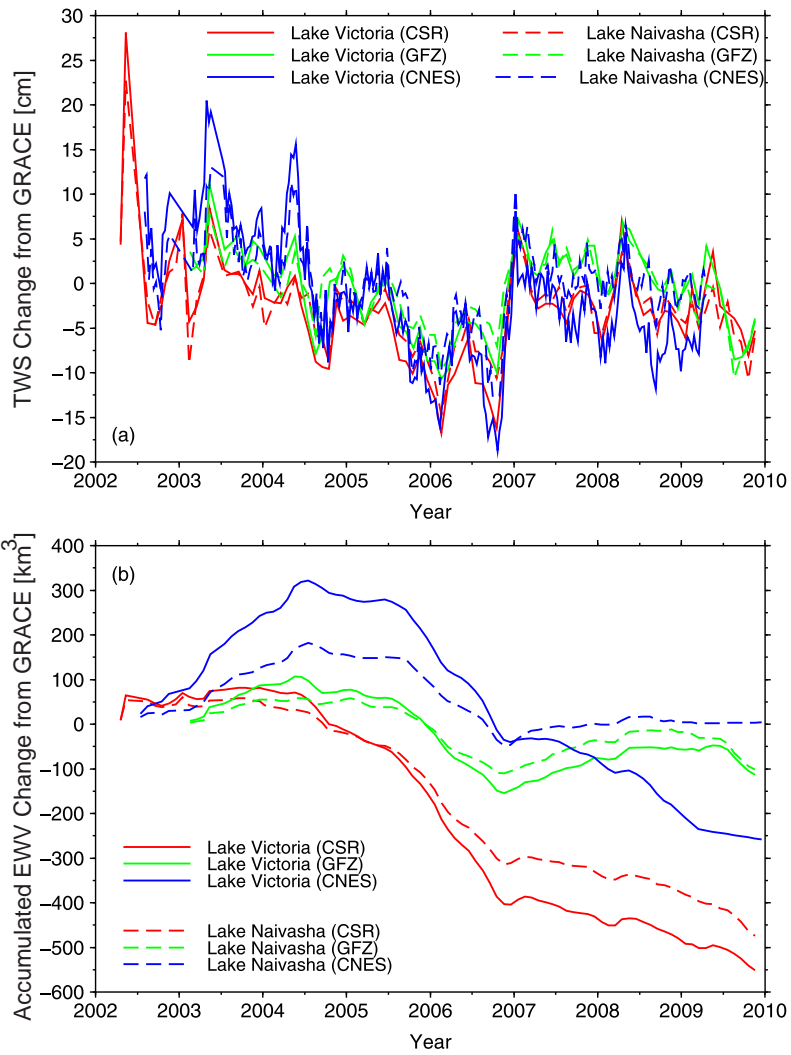


Figure 6: Variations in stored waters (an integration of surface and terrestrial water storage changes) over Lakes Naivasha and Victoria derived from GRACE products. (a) Change in TWS and (b) accumulated changes of TWS in equivalent water volume (EWW) (see Figure 5, for the Victoria and Naivasha catchments).

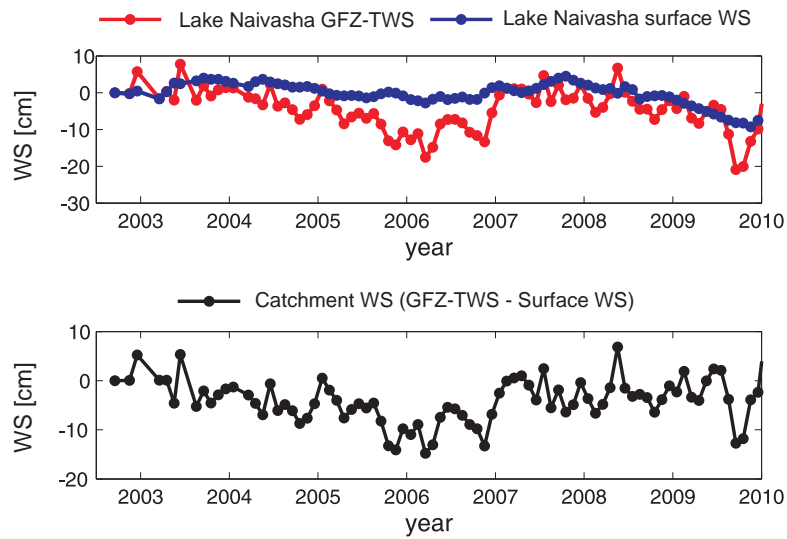


Figure 7: Top, the red line shows the average TWS computed from the GFZ GRACE data (related to Figure 5, the black box on the right-side). The blue line is surface WS belonging only to Lake Naivasha. The catchment terrestrial WS signal is then obtained from the difference between GRACE-TWS signal (red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

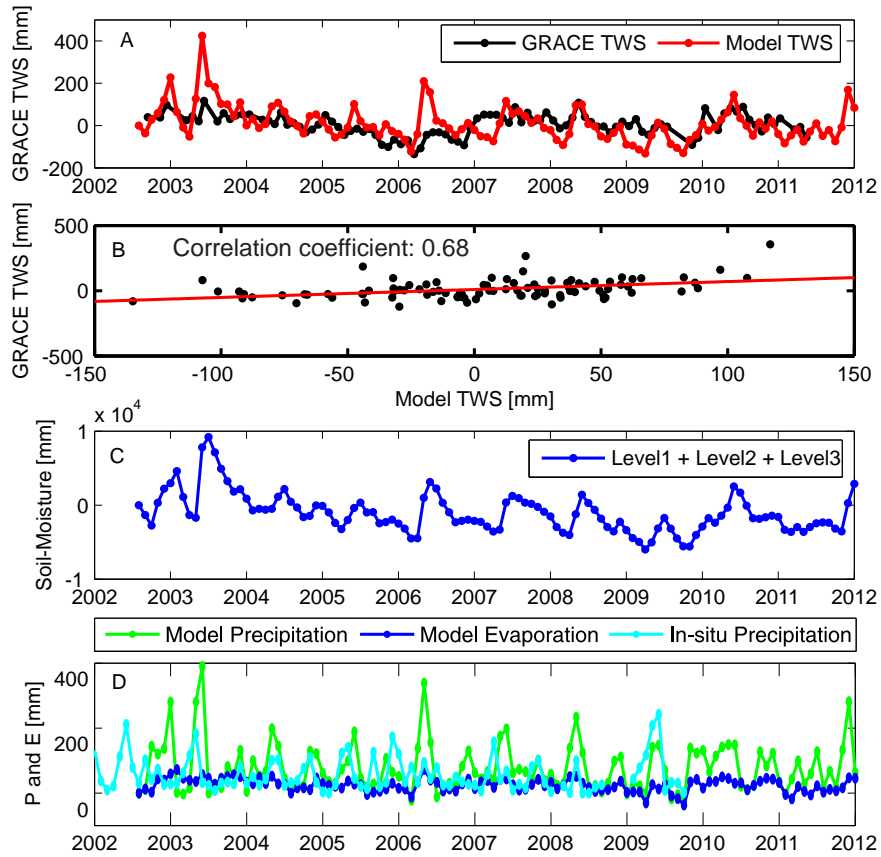


Figure 8: (A) A comparison between the calculated TWS from the ADM TWS and the GRACE TWS, (B) shows the GRACE TWS against ADM TWS changes, (C) a basin averaged soil moisture layers over Naivasha, and (D) a comparison between model-derived precipitation and in-situ measurements along with the temporal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

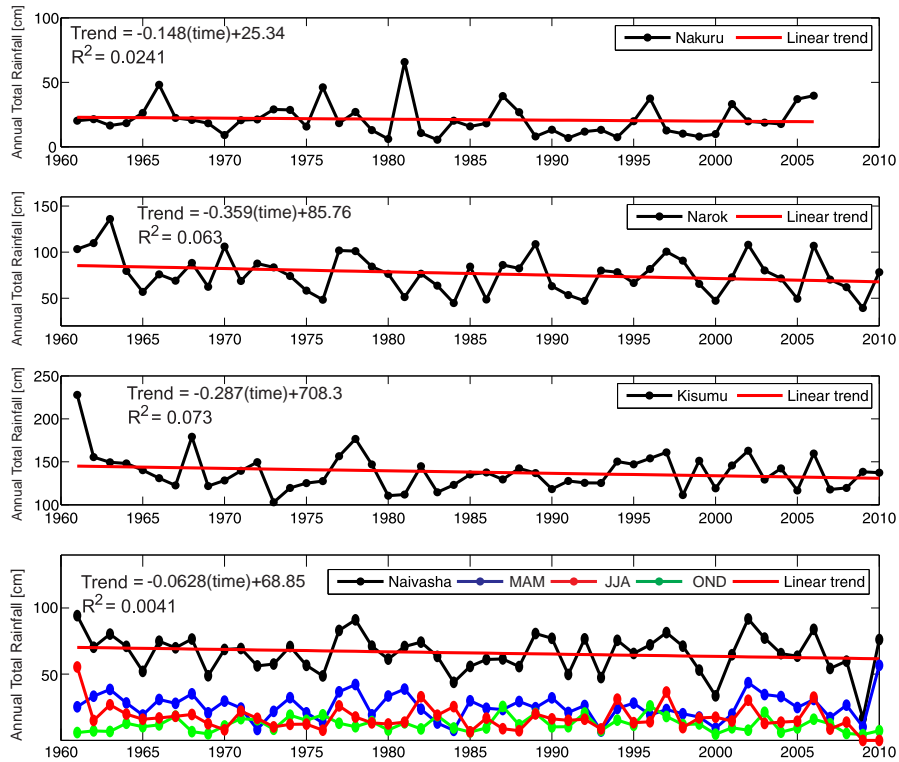


Figure 9: Annual rainfall time series over four stations in the region of Lake Naivasha. From top, Nakuru (0.28°S, 36.1°E), Narok (1.1°S, 35.9°E), Kismu (0.1°S, 34.8°E) and Naivasha (0.72°S, 36.4°E) stations. For Naivasha, MAM [blue], JJA [red] and OND [green] yearly values are also provided.

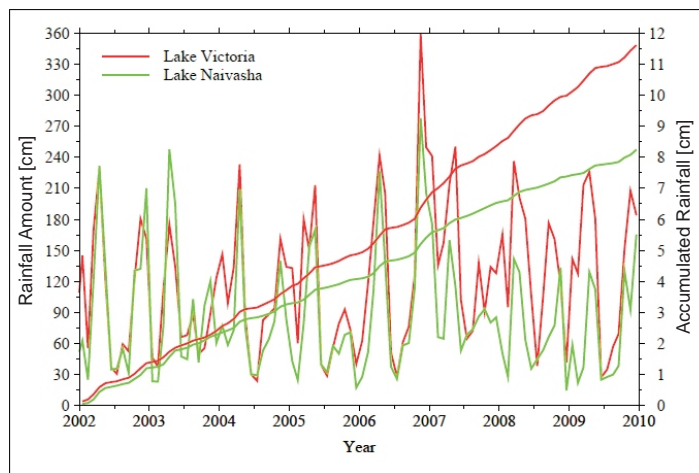


Figure 10: Rainfall over the Lakes Naivasha and Victoria basins (see Figure 5) as provided by the TRMM 3B43 product. Rainfall amounts are shown by the solid lines and the accumulated values are dashed.

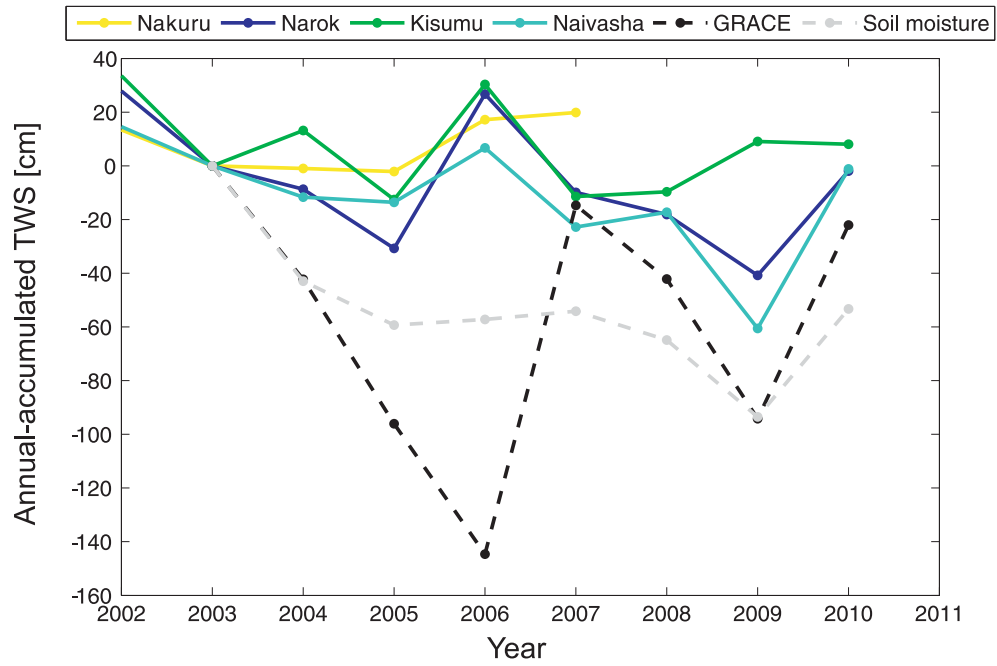


Figure 11: Comparing annual total water storage variations derived from GRACE with annual soil moisture contents (from ADM) and annual rainfall (from in-situ stations).

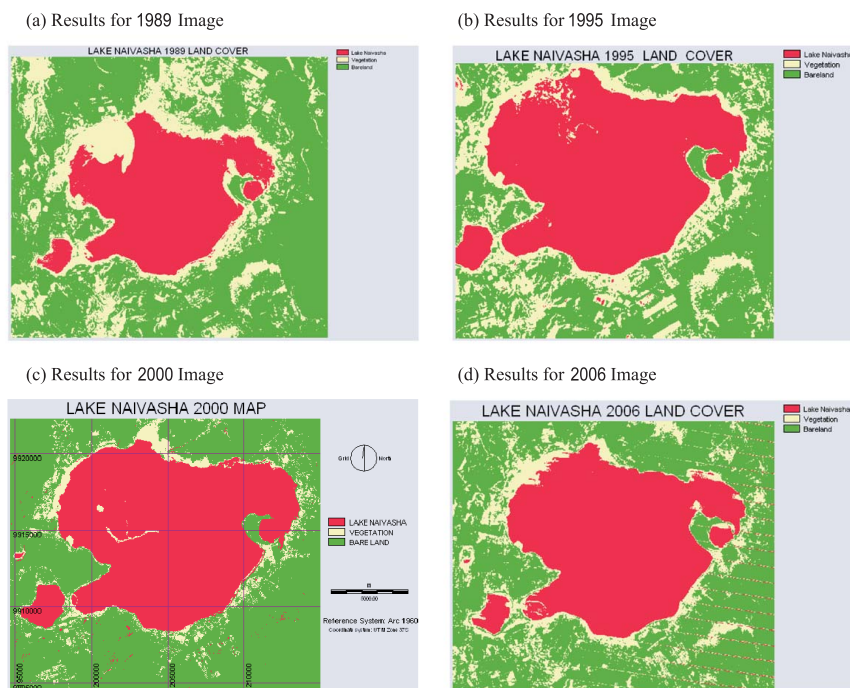


Figure 12: Surface-type classification results for the considered Landsat images. (a) 1989, (b) 1995, (c) 2000 and (d) 2006.

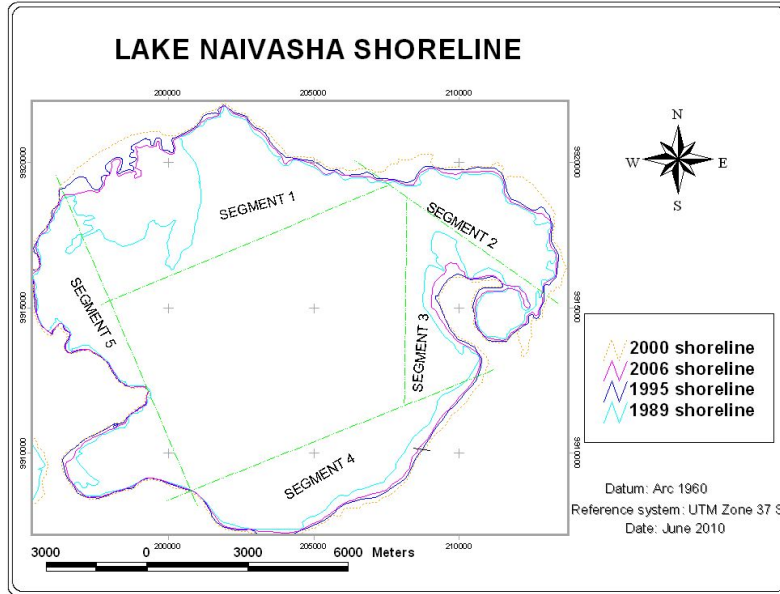


Figure 13: Segmentation of the changes in the Lake Naivasha shoreline for the years 1989, 1995, 2000 and 2006.

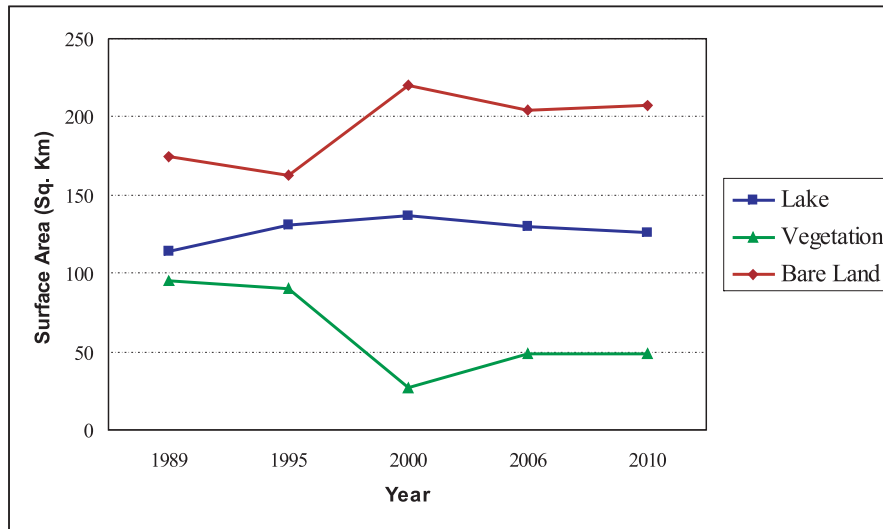


Figure 14: Variation in the area of the different land types around Lake Naivasha.

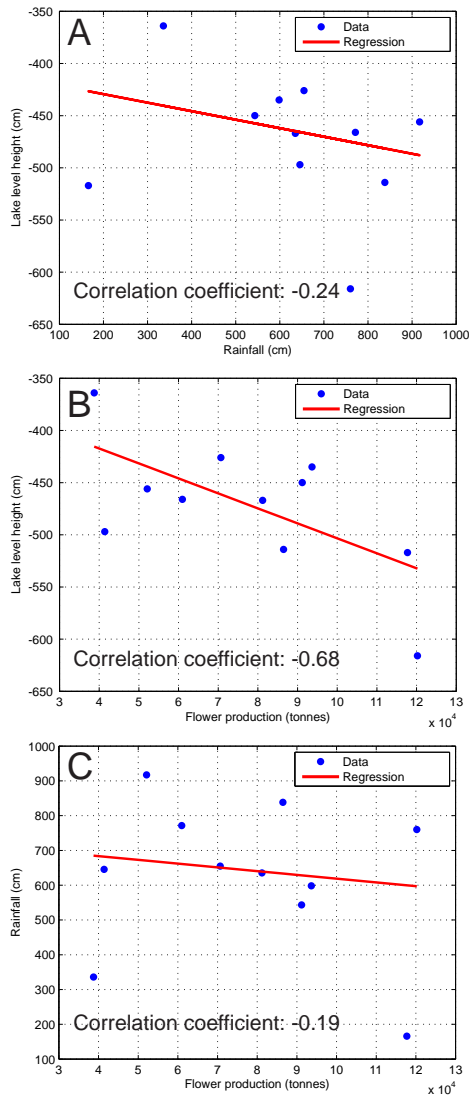


Figure 15: Comparing annual average lake levels with (A) rainfall observed at the Naivasha station and (B) flower exports. (C) Comparing annual average rainfall of the Naivasha station and flower exports. The solid lines are fitted linear trends, along with the correlation coefficients.