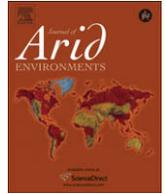




Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Non-climatic growth of the saline Lake Beseka, Main Ethiopian Rift

Anna Goerner*, Egbert Jolie, Richard Gloaguen

Remote Sensing Group, Institute of Geology, TU Bergakademie Freiberg, Bernhard-von-Cotta-Str. 2, 09599 Freiberg, Germany

ARTICLE INFO

Article history:

Received 26 May 2006

Received in revised form 12 August 2008

Accepted 24 September 2008

Available online xxx

Keywords:

Lake level change

Main Ethiopian Rift

Remote sensing

Surface temperature

ABSTRACT

When using rift lakes as proxies for palaeoclimate it is essential to know if water level changes are of geological or climatic origin, and whether a reinterpretation of palaeo-lake levels derived from lithostratigraphic sequences is required. The saline, endorheic Lake Beseka is located in the tectonically active Main Ethiopian Rift. Despite the aridity of the rift valley the lake's surface area quadrupled from 11.1 km² in 1973 to 39.5 km² in 2002. We quantify the lake growth by means of a detailed bathymetric model and high-resolution satellite time series. We analyse the potential climatic, anthropogenic, and tectonic agents of Lake Beseka's growth. Multitemporal remote sensing data and meteorological records were compared with in-situ measurements of hydrochemical parameters and water depth to address the reason for the lake level rise. Our results suggest that Lake Beseka's expansion originates from an increased discharge of the hot springs. The combined analysis of satellite data and in-situ measurements proved to be a valid tool for the quantification of lake level changes and can help to detect the causes of these variations.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

Past lake levels are used as proxy for palaeoclimate in numerous studies (e.g., Kiage and Liu, 2006; Stager et al., 2005; Verschuren et al., 2000). For a meaningful interpretation, signals derived from bio- and lithostratigraphic data need to be corrected for influences other than climate variations. Our study aims to determine these factors taking Lake Beseka as an example for a rift lake in a tectonically active environment. The endorheic Lake Beseka, in the centre of the semi-arid rift valley of the northern Main Ethiopian Rift (nMER, cf. Fig. 1), has rapidly expanded over recent decades (e.g. Williams et al., 1981).

East Africa is a region of extremely complex meteorological and climatological phenomena and coupling-mechanisms, possibly one of the most complicated of the continent. The topography of the rift exerts a strong influence on microclimate, drainage systems, and local ecosystems (e.g. Seleshi and Zanke, 2004; Gissila et al., 2004). The lakes occupying the rift valley are either dominated by highland runoff and riverine delivery or by groundwater and local runoff (Brandt, 1982). In arid areas like the one exemplified in this study, a high fraction of lakes will be endorheic and thus more susceptible to slight perturbations of the water balance. According to Mercier et al. (2002) height changes of a lake's water column may be caused by

- (i) Changes in surface pressure;
- (ii) Wind-driven events (i.e. seiches) and tides;
- (iii) Fluctuations in the volume of this column due to an alternating temperature or composition;
- (iv) Modifications of the hydrologic cycle (i.e. recharge, outflow, evaporation).

Items (iii) and (iv) will ultimately result in lake water volume changes.

The first three factors may be relevant for larger rift lakes, but cannot explain a water level increase of more than 4 m within less than three decades (Ayenew, 2004) of the comparatively small Lake Beseka. Cause (iv) can be directly triggered by non-climatic factors, for example tectonically induced alteration of flow patterns, changes in the heat budget due to geothermal effects, and artificial regulation. Anthropogenic influence on rift lake levels can also be exerted indirectly through water withdrawal (Ayenew, 2004) or an increased sediment input as a result of inadequate agricultural practices (Geremew, 2000; WWDSE, 2001). Lakes also fluctuate in accordance to climatic variations (Street and Grove, 1976; Chernet, 1982; Chalié and Gasse, 2002), especially when they are terminal (Ayenew, 2004). All these potential contributors to lake level change must be quantified in order to understand the hydrological setting of a drainage area.

Changes in the level of continental lakes can be assessed by measuring the absolute or relative elevations of the water level by continuous gauge records. However, in many settings it might be difficult to use standard hydrological survey data. A historical data record might not exist or not be accessible. Archives of satellite data

* Corresponding author. Tel.: +49 3731392770; fax: +49 3731393599.

E-mail addresses: anna.goerner@web.de (A. Goerner), egbert.jolie@gmx.de (E. Jolie), gloaguen@geo.tu-freiberg.de (R. Gloaguen).

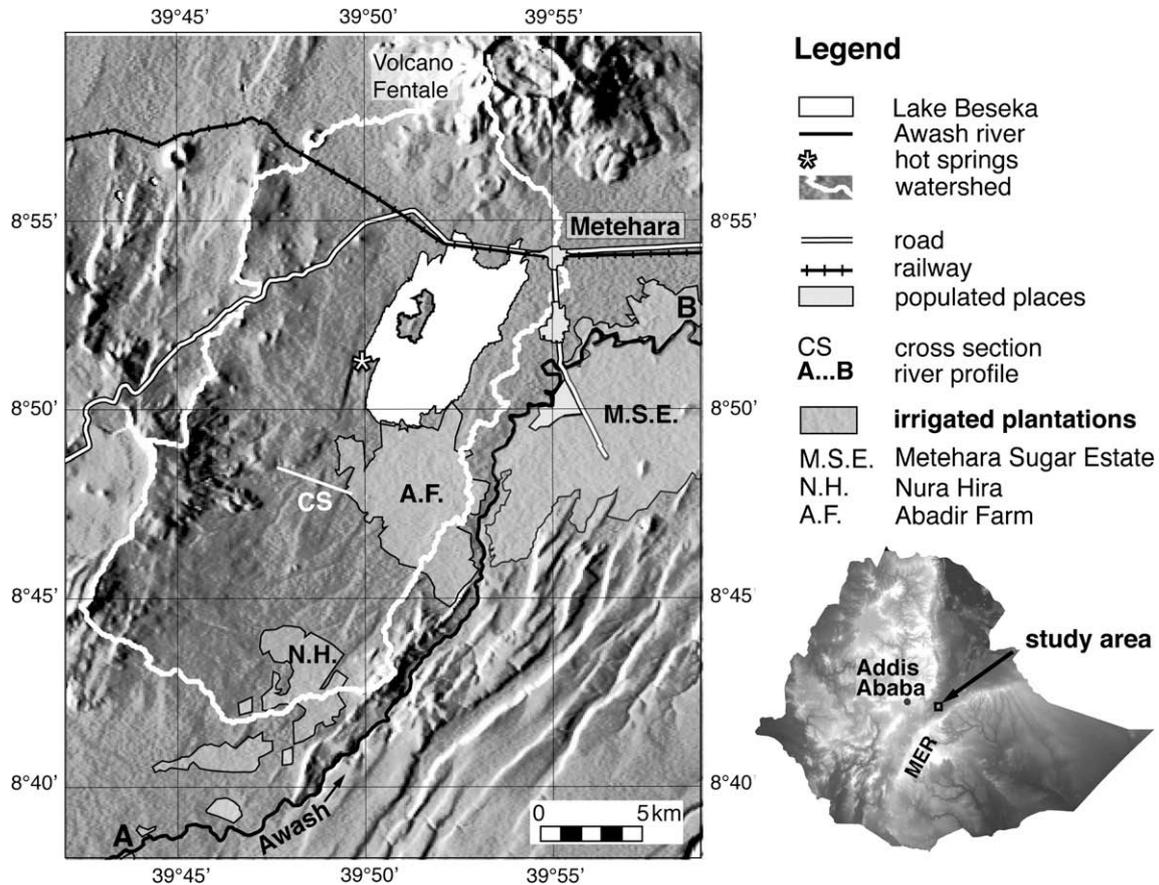


Fig. 1. Lake Beseka and its surroundings plotted over a digital elevation model (SRTM, 90 m resolution, shaded relief). The cross section and the elevation profile of the Awash River indicated here are displayed in Figs. 2 and 10.

covering up to 35 years can provide an inexpensive alternative or addition to incomplete ground measurements. RADAR altimeters were shown to yield reasonably accurate measurements of variations in water surface elevation (e.g., Mercier et al., 2002). However, they are only applicable for lakes situated along the satellite altimeter's ground track. In addition, the lakes need to be wider than 500 m and need to have a surface area of more than 100 km² (Crétaux and Birkett, 2006). In this study we quantify the expansion of Lake Beseka over the past decades with multitemporal optical remote sensing data, a bathymetric model, and lake level records. Moreover, we apply hydrochemical analyses and temperature measurements to contribute to the study of Beseka's rapid lake level change.

2. Study area

The East African Rift System (EARS) cuts through the Ethiopian highlands (Fig. 1). One of its subsystems, the nMER, is among the few sites worldwide featuring a transition from continental to oceanic rifting (Ebinger and Casey, 2001). Present-day volcanic and seismic activity and faulting (Keir et al., 2006; Keranen et al., 2004; Kurz et al., 2007) are phenomena linked to this geologic process. Located within an active tectono-magmatic segment (e.g. Kurz et al., 2007), Lake Beseka's basin is shaped by numerous normal faults trending N10–20°, which also form the shoreline of the lake and its watershed (Figs. 1–3). Due to a relatively high temperature gradient of 0.17 K/m (Tamiru, 2003), thermal groundwaters circulate even at shallow depths. Since the normal faults also act as preferred pathways for hydrothermal fluids, hot springs are abundant in this area (Mamo and Getaneh, 2003). In the west, the

deepening basin of Lake Beseka is bordered by NNE-trending escarpments (max. 1850 m); in the east the watershed runs along lower escarpments. The conical volcano Fentale with its elliptical caldera is the most significant elevation (2007 m asl) in the vicinity of the lake and limits the basin to the north. The lithology of the study area is another indicator of recent tectonic activity. No geological feature is older than 2 Myr (Pleistocene) (Buchwitz, 2006). The majority of rocks are of volcanic origin. The area south of Lake Beseka and within the sugar cane plantation is covered by Pleistocene to recent sediments (Buchwitz, 2006).

For the past decades, the alkaline (pH = 9.5) and saline (electrical conductivity: 6.3 mS/cm) Lake Beseka has undergone a major water level rise (e.g. Williams et al., 1981; Ayenew, 2004), the onset of which has not been dated. The Ministry of Water Resources of Ethiopia started recording the lake level in July 1976. The rapid expansion of the lake has severe implications: Since 1993 Lake Beseka has partially flooded and salinized the Abadir Farm. Damages

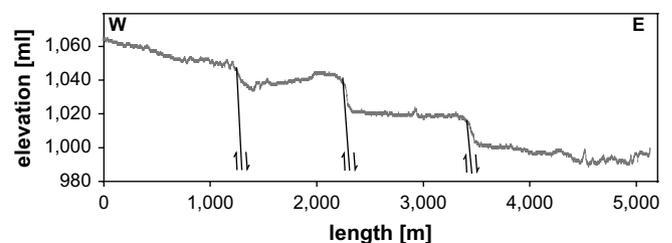


Fig. 2. Cross section showing the extent of vertical displacement due to active faulting in the vicinity of Lake Beseka (cf. Fig. 1). Horizontal resolution of the digital elevation model (obtained from photo-stereogrammetry) used: 4 m.

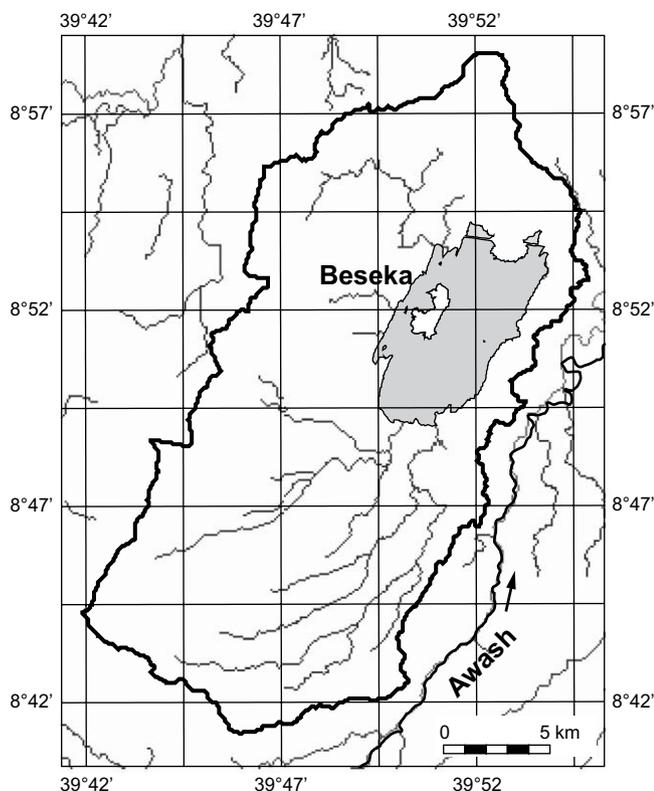


Fig. 3. Watershed of Lake Beseka with preferred flow paths calculated from a 90 m resolution digital elevation model according to algorithms developed by Jensen and Domingue (1988). This drainage system is only active during precipitation events. At present there is no superficial link between Lake Beseka and the Awash River.

on the farm as well as on the nearby railway line and highway caused a loss amounting to 2.6 million US\$. In response to this threat, an embankment has been built to prevent further damage to crops. The road on the northern shore, Ethiopia's sole access to the seaport in Djibouti, needed to be raised twice (Tessema, 1998; Ayenew, 2004). Currently, the lowest part of the watershed is only 1 m above the lake level (955 m asl in October 2004). Since the small towns on the eastern shore and the road are threatened by flooding, it is planned to lower the lake level from 955 m to 948 m asl within 5 years (2004–2009; personal communication Eshete, 2004). A pumping station situated on the northeastern shore is planned to conduct lake water into the Awash River (MWR, 1999). The Ethiopian authorities intend for this water level control centre to become fully operational early in 2004 (WIC, 2003), although it was not working during a field check in October 2004.

The study area is situated about 150 km east of Addis Ababa, at the boundary to the Afar region (Fig. 1). There is a distinct anthropogenic influence on the hydrology of the region of interest. The Awash, a major Ethiopian river emanating west of Addis Ababa and, after 2000 km, emptying into Lake Abbe in the Danakil depression, runs south-east of Lake Beseka's water divide. The Koka dam was constructed 152 km upstream of the study area in 1960 to regulate a steady flow of the river Awash (Tessema, 1998). Tessema (1998) argues that increased transmission losses resulting from the perennial flow of the Awash River resulted in increased groundwater inflow into Lake Beseka. As a result of the dam construction, an irrigation project became operational in 1964 and, at present, three sugar cane plantations in the surroundings of the lake rely on the Awash River for irrigation water (Tessema, 1998). The plantations Nura Hira and Abadir Farm are mainly situated within the lake's watershed (Fig. 1). A network of open channels covering all areas under cultivation regulates water distribution. About 5 m³

river water per second are pumped to the Abadir Farm (personal communication Eshete, 2004). Based on a hydrochemical analysis by Tessema (1998) some studies (e.g., Ayenew, 2004; Alemayehu et al., 2006) argue that poor irrigation efficiency is an important contribution to Lake Beseka's level rise.

3. Materials and methods

3.1. Quantification of the growth of Lake Beseka

Data from Landsat (180-054, 168-054: 1973, 1986, 1989, 2000, 2001, 2002) and ASTER (2000, 2001) were investigated in order to describe temporal variations in the surface area of Lake Beseka. To avoid obscuration by clouds, these data were acquired in the dry season. Due to a similar spectral signature of the littoral and recent basalt flows on the northern shore, the precise shoreline of Lake Beseka is difficult to map. Hence, two methods were applied on the satellite data to measure the surface area of Lake Beseka at different times: (a) we digitised polygons of the lake area according to visual differentiation of land and water, and (b) used supervised classification of digital pixel values to extract the water surface. The results of both techniques differ by 4.3%. To minimise misassignment of pixels along the water–land border, the average surface areas from both approaches were used for analysis.

To quantify the increase in Lake Beseka's water volume, bathymetric data were collected using a sonic depth finder in combination with GPS positioning. The sonar depth was continuously verified by means of a plumb line. Two separate basins north of the railway have not been mapped due to their minor extent and poor accessibility. Discrete smooth interpolation (Mallet, 2002; gOcad 2.0.8) was applied to the dataset to generate a digital terrain model (DTM) of the lake floor. Lake Beseka's boundary was digitised from the most recent Landsat scene available (December 2002) to mark the shore in the bathymetric dataset. The lake floor DTM was then used to calculate water volumes and surface areas of the 2004 state and for ten former lake levels each 1 m below the other (Table 1). Since the absolute elevation of the gauge is not known, the 1977-to-1998 water level record could not be linked to the lake floor DTM. The strong influence of faults generates nested sub-basins, which cause a stepwise filling of the lake. Therefore, surface areas of Lake Beseka are only partially correlated to its water volume, i.e. for each fault-induced step. We applied linear regression on lake areas measured from satellite scenes to date the most recent stages of lake growth derived from the DTM (Table 1).

For a sound assessment of the changes in Lake Beseka's volume, the effect of neotectonic activity must be considered. A geodetic survey conducted by Bilham et al. (1999) from 1969 to 1997 notes that the average spreading rate of the nMER is 0.45 ± 0.10 cm/yr. The same report indicates that half of this deformation is concentrated within a central 33 km wide stripe. We thus apply a deformation rate of 0.23 cm/yr for the Lake Beseka area. The maximum subsidence rate for a basin formed by two normal faults calculates as:

$$\text{sub} = (\tan(\text{dip}) \times \text{sr})/2$$

where sub = subsidence rate; sr = spreading rate.

Our field measurements show that the faults bordering Lake Beseka dip from 70° to 85°. To compute the subsidence rate, we chose an average value of 80°. To calculate the increase in basin volume caused by subsidence, we refer to the surface area of November 1989 (31.19 km²).

3.2. Multi-method assessment of potential sources of increased water

We have a comprehensive meteorological dataset at hand that allows examining the influence of climate change on the unusual

Table 1
Stages of Lake Beseka's growth as calculated from the digital terrain model (DTM) of the lake floor.

Level m below 2004	Lake floor [masl]	Volume [m ³]	Area [m ²]	Average depth [m]	Date
0	955	2.436 e+8	4.404 e+7	5.5	July 2004
1	954	2.057 e+8	4.012 e+7	5.1	May 2000
2	953	1.306 e+8	3.074 e+7	4.2	June 1990
3	952	1.12 e+8	3.052 e+7	3.7	–
4	951	7.714 e+7	3.035 e+7	2.5	–
5	950	5.35 e+7	2.21 e+7	2.4	–
6	949	3.649 e+7	1.639 e+7	2.2	–
7	948	2.181 e+7	1.29 e+7	1.7	–
8	947	1.096 e+7	8.704 e+6	1.3	–
9	946	4.125 e+6	5.232 e+6	0.8	–
10	945	6.996 e+5	1.559 e+6	0.4	–

growth of Lake Beseka. The dataset comprises minimum and maximum precipitation, minimum and maximum temperature, number of rainy days, humidity, Pan A evaporation, duration of sunshine, wind direction, and wind speed. These climate data were recorded on behalf of the sugar cane plantation on the eastern shore of the lake and extend from 1966 to 2004 (precipitation until December 2000). Water level measurements cover the time span from July 1976 to December 1998. For 1989, all hydrologically relevant data except for the discharge of the hot springs are available and satellite data are also at hand. These records served as a basis for calculating a water balance. During fieldwork in October 2004 we rated the output of the hot springs to be 0.05 m³/s. However, as we have no information about how the discharge varies with time, we could not employ this value in the 1989 water balance.

In this water balance, the total inflow into the lake must at least be equal to the water loss due to evaporation if a constant lake level is to be maintained. In addition, we incorporated the lake level rise in our calculation to account for Lake Beseka's expansion. To obtain a flow rate, we refer to the lake's surface area in 1989: minimum inflow = surface area × (evaporation + lake level rise). This theoretical minimum inflow was then related to known sources of water input, namely precipitation on the lake and superficial runoff from the drainage area. The size of the surface catchment area of

Lake Beseka was calculated from a 90 m resolution digital elevation model using algorithms developed by Jenson and Domingue (1988). Since little information on soil parameters of the catchment area is available, general runoff coefficients representing a typical range for sparsely vegetated unsealed land were applied (according to Maidment, 1993: 0.05 and 0.10).

To obtain further information about the origin of lake water, we examined its chemical composition. During and subsequent to fieldwork in 2004, water samples from the study area were analysed with respect to Na⁺, Ca²⁺, K⁺, Li⁺, Mg²⁺, Cl⁻ and SO₄²⁻ using ion chromatography; the NH₄⁺ and NO₃⁻ concentrations were determined photometrically and the fluoride concentration with an ion sensitive electrode. Moreover, total inorganic carbon (TIC), dissolved organic carbon (DOC), pH, and electrical conductivity were measured. Fig. 4 shows the sampling locations: 2 samples are from the Awash River, 2 were taken from irrigation channels within the sugar cane plantation, 4 samples are from the lake itself, and 2 more are from the hot springs on the south-western shore. We averaged the latter due to their very similar chemical composition.

For further information on the origin of lake water we investigated the spatial distribution of water temperature. Lake Beseka's surface temperature was measured from multitemporal Landsat ETM+/TM data. The radiance signal recorded in the thermal infrared channel 6 was corrected for atmospheric distortions and then converted into brightness temperature as described by Richter (1996). We compared the pattern of surface temperature derived from several scenes and with in-situ measurements obtained during fieldwork in September and October 2004.

To test the potential causes of the lake's expansion (see above) and their special contribution, further hydrochemical modelling was applied on several samples. We simulated the effect of evaporation on the water samples collected at the hot springs and in the irrigation channels (PHREEQC, Parkhurst and Appelo, 1999). Since sodium is little affected by precipitation, ionic exchanges and other bio-geochemical processes (Chernet et al., 2001), the ratios Na⁺(Lake Beseka)/Na⁺(hot springs) and Na⁺(Lake Beseka)/Na⁺(irrigation water) were chosen as evaporation factors. During the simulation all analysed elements and compounds were allowed to react with each other (e.g. precipitate) according to the temperature and pH recorded on-site.

Due to a lack of boreholes within the watershed (Tessema, 1998), a valid groundwater flow model could not be established. We computed a 55 km long elevation profile of Awash from a 90 m resolution DEM. Related to the absolute level of other waterbodies; this yields the general characteristics of the underground water system.

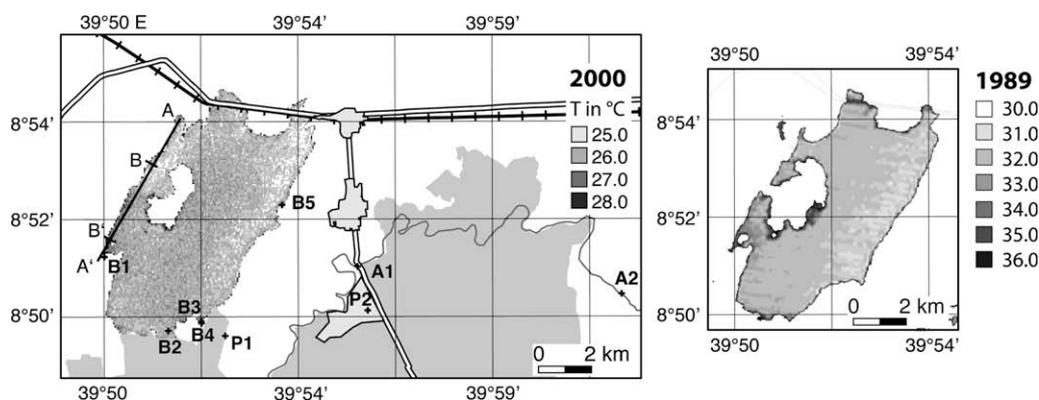


Fig. 4. Temperature distribution on the lake surface obtained from Landsat ETM+ (December 2000) and Landsat TM (November 1989). BB' & AA': cf. Fig. 8. B1–B5, P1–P2, A1–A2: water samples taken from Lake Beseka (B), irrigation channels within the plantation (P) and the Awash (A) River.

4. Results

The time series of satellite data documents that Lake Beseka's surface area quadrupled from 11.1 km² in January 1973 to 39.5 km² in February 2002 (Fig. 5). Aerial photographs from 1957 and 1964 show a lake area of about 3 km² (Tessema, 1998). Putting aside seasonal fluctuations the lake has been steadily rising at an average rate of approximately 18 cm/yr (Fig. 6). In total the water level increased by about 8 m from 1976 to reach 955 m asl in September 2004.

The striking similarity between the shapes of the DTM-derived past lake surfaces and the areas obtained from satellite scenes appears to confirm the accuracy of the bathymetric DTM (cf. Figs. 5 and 7). According to our measurements, the northern part of the basin is the deepest – about 12.4 m. Two more relatively deep sections of the basin are located south of the main island. The southernmost part of the basin and the section close to the northeast were submerged only recently (cf. Fig. 5) and are hence comparatively shallow. For the vicinity of Lake Beseka, we computed a maximum subsidence rate of ~1 cm/yr. The increase in volume during the year 1989 consequently accounted for 322,948 m³. This is equivalent to 0.2% of the 1989 lake water volume or to 6.9% of the water volume increase caused by lake level change in the year 1989. Although deformation is concentrated in the rift centre (e.g. Ebinger and Casey, 2001), the spreading rate applies not only to Lake Beseka's basin but to a band of about 30 km width (Williams et al., 2004). The impact of subsidence on the lake basin volume is therefore likely to be smaller than calculated here. With sonar we detected no fresh sediment layer on the lake floor. Hence, we assume that the impact of sediment deposition and erosion within the rather short time span of interest is negligible for the calculation of the water balance.

The meteorological parameters recorded over 39 years indicate a generally constant climate (Fig. 6): The mean annual precipitation amounts to 600 mm; on average, evaporation exceeds precipitation in eleven months out of twelve. Regression models of precipitation, evaporation and temperature were assessed with a chi-squared test; no significant anomalies were revealed for the 95% confidence limit. Despite small interannual variations, the water level has been

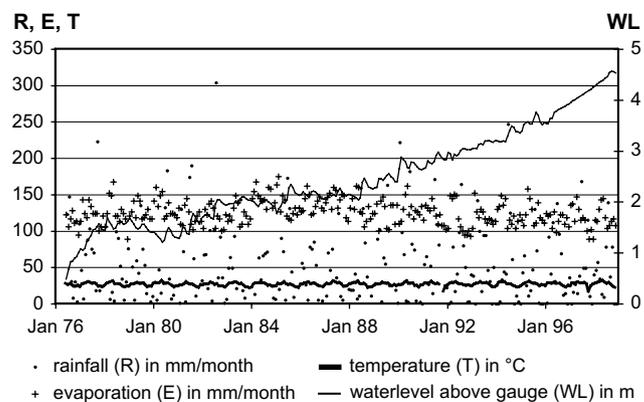


Fig. 6. Lake level development in relation to climatic factors. Temperature, precipitation, evaporation, and relative lake level were recorded on the eastern lakeshore.

rising for more than three decades; it is thus not a product of climatic variations.

Our calculation of Lake Beseka's water balance shows that at least 1.59 m³/s of water (1989 average) must flow into the lake to compensate for evaporation (92% of the 1.59 m³/s) and to allow for water level rise (8% of the 1.59 m³/s). Rainfall on the lake contributes only 41% of this theoretical inflow. The superficial runoff from the 400 km² large catchment area supplies another 24–48% of the minimum inflow, depending on the runoff coefficient applied (Table 2). There is still an unexplained remainder of 11–35%. As a consequence, water sources other than local precipitation amount to at least 0.17–0.56 m³/s. The contribution of these other sources is even higher after 1989, when a larger water surface resulted in additional evaporation.

Irrigation on the Abadir Farm, surface and subsurface runoff, and underground water systems discharging from springs might be considered as potential sources of that water. To examine their influence, we analysed remote sensing and hydrochemical data.

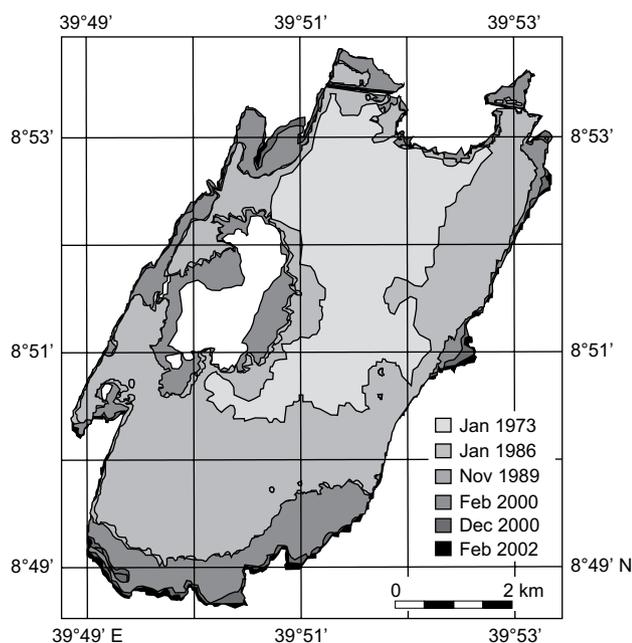


Fig. 5. Temporal variations of Lake Beseka's extension. The lakeshore was digitised from aerial photographs (1973) and satellite scenes (Landsat TM & ETM+).

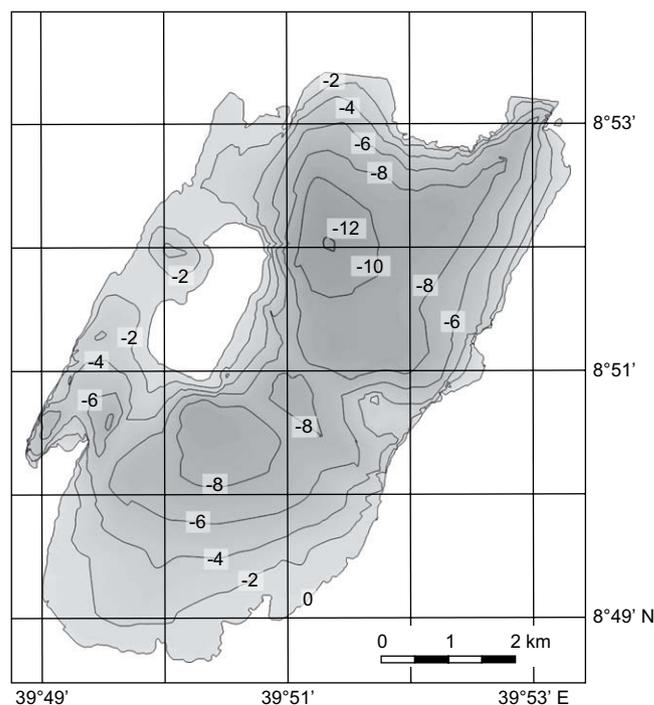


Fig. 7. Bathymetric map of Lake Beseka's main basin as obtained from discrete smooth interpolation of sonic depth measurements.

Table 2
Water balance of Lake Beseka for 1989.

	$K_{RO} = 0.05$		$K_{RO} = 0.1$	
Evaporation			–1.47 m ³ /s	
Lake level increase			–0.12 m ³ /s	
Minimum inflow	1.59 m ³ /s	100%	1.59 m ³ /s	100%
Precipitation	0.65 m ³ /s	40.88%	0.65 m ³ /s	40.88%
Surface runoff	0.38 m ³ /s	23.90%	0.77 m ³ /s	48.43%
Unknown sources	0.56 m ³ /s	35.22%	0.17 m ³ /s	10.69%

K_{RO} = surface runoff coefficient.

Measurements of the kinetic temperature from satellite data show that Lake Beseka's surface temperature is lowest near the eastern shoreline and increases towards the south-western bay where the hot springs are located (Fig. 4). The absolute temperature values depend on local meteorological conditions and therefore vary among scenes. However, all but one of the investigated Landsat-scenes display the same temperature pattern. The distribution of surface temperature is not correlated with water depths (cf. Figs. 4 and 7). This suggests that other factors, most likely inflowing water, govern the thermal characteristics of Lake Beseka. Surface temperature measurements contradict the assumption that the enlargement of Lake Beseka is caused by transmission losses from irrigation channels. Since the irrigation water is relatively cold (27–28 °C during a field check in November 2004) compared to the lake water (32 °C on the southern shore in November 2004), we would expect lower temperatures in the vicinity of the southern shoreline if there were significant transmission losses from the irrigation system. Surface temperature measurements suggest that the water dispersing from the hot springs spreads over large parts of the lake and hence dominates Lake Beseka's surface thermal properties. In-situ measurements of water temperature and electric conductivity are consistent with the results obtained from remote sensing data (Fig. 8). Surface water temperature increases towards the hot springs (Fig. 8a and b) as other factors decrease, such as electrical conductivity (Fig. 8b) and pH. The northern part of the lake is quite homogeneous with an average pH of 9.5 and an electrical conductivity of around 7.15 mS/cm. In the vicinity of the hot springs the values drop to a pH of 8.4 and an electrical conductivity of 1.65 mS/cm. Although water properties are very heterogeneous in the immediate surroundings of the hot springs (e.g. Ia, Ib in Fig. 8c), vertical temperature profiles in most other parts of the lake (e.g. IIa, IIb in Fig. 8c) show no stratification. This implies that the lake is thoroughly mixed and measurements at the surface are correlated to water attributes in greater depths.

Similar to other lakes in the MER, Beseka is alkaline and saline due to the geology of the basin and the concentration of soluble

materials as a consequence of high evaporation rates (Gizaw, 1996). High total inorganic carbon (TIC) as well as low calcium (Fig. 9), which is still present in water flowing into Lake Beseka, indicate the precipitation of calcite in the lake that goes along with high fluoride concentrations (Chernet et al., 2001; Gizaw, 1996). The chemical compositions of irrigation water from the plantation and of the water coming from hot springs were used to model evaporation (Table 3). The TIC calculated for the evaporated spring water yields 127% of the average Lake Beseka TIC while the total inorganic carbon of the evaporated irrigation water equals 384% of the Lake Beseka value. Being a major constituent of the lake water, TIC is a meaningful indicator. The correspondence between the original lake water and the evaporated samples is limited by an incomplete registration of factors affecting the chemical equilibria, such as composition of precipitates on the lake floor and biological activities, which could consequently not be incorporated in the evaporation model. Our simulation shows that modelling the evaporation of hot spring water can reproduce the hydrochemical composition of Lake Beseka's water with good accuracy. We can show that irrigation water has little influence on the lake's hydrochemistry.

Some of the rift lakes are known to receive a large part of their inflow from groundwater systems from outside the surface area of the catchment, in this case, from rainfall in the highlands (Ayenew, 2003). Therefore we considered factors beyond the catchment basin. The elevation of Awash's and Beseka's (955 masl in November 2004) water surfaces within the area of investigation differ by about 200 m (Figs. 1 and 10). Since levels of local water-bodies tend to coincide with local minima of the groundwater table, the gradient in elevation of the water table indicates a general northeastward groundwater flow.

5. Discussion and conclusions

We used several methods to examine the growth of Lake Beseka and establish the contribution of various potential water sources. The influence of neotectonic activity has rarely been taken into account. Previous approaches did consider the basin morphology only to a very limited extent (Tessema, 1998; MWR, 1998; Engida and Russom, 2004). In this study, we present the most detailed model of the lake floor yet considered. In combination with measurements from optical satellite data and digital elevation models of the catchment area this DTM strongly suggests that there is a close relationship between recent tectonic activity and the shape of the lake. The DTM also enabled us to quantify Lake Beseka's expansion for the first time with reasonable accuracy.

Our study suggests climatic change is an unlikely cause of Lake Beseka's recent growth. We can neither observe a trend in

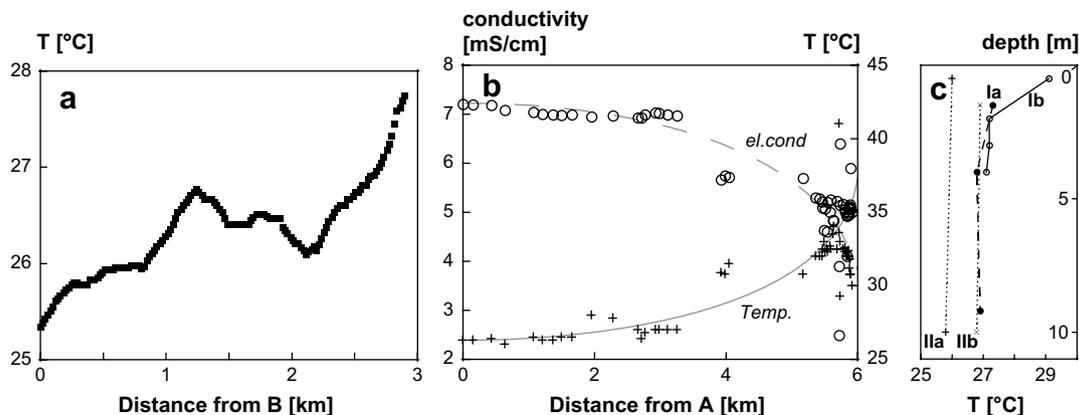


Fig. 8. (a) Profile of surface temperature as calculated from a Landsat ETM+ scene (cf. BB' in Fig. 4). (b) In-situ profile of temperature and electrical conductivity (cf. AA' in Fig. 4). (c) Exemplary in-situ vertical temperature profiles in the vicinity of the hot springs (Ia, Ib) and in the main basin (IIa, IIb).

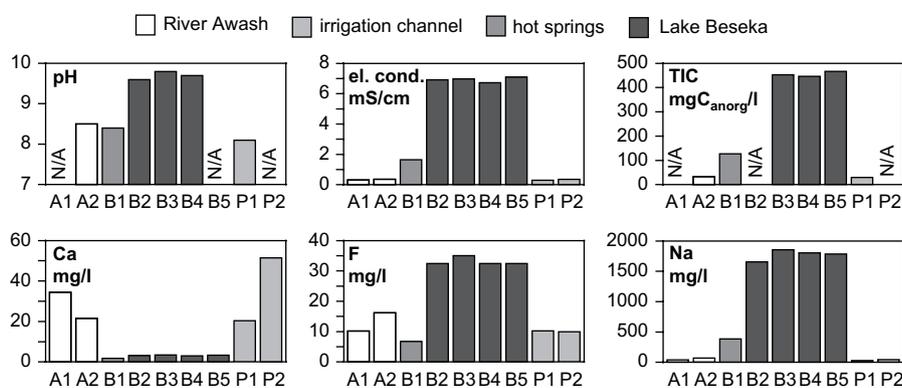


Fig. 9. Major hydrochemical parameters of Lake Beseka, water in the vicinity of the hot springs, water from irrigation channels and from the Awash River (cf. sampling locations indicated in Fig. 1).

meteorological parameters nor do adjacent rift lakes show comparable water level increase (e.g. Ayenew, 2004). The absence of a climatic trend is consistent with general findings for northern and central Ethiopia (Seleshi and Zanke, 2004). Sediment deposition and water withdrawal are also insignificant in regard to Lake Beseka's lake level change.

Sediment deposits south of Lake Beseka suggest that Lake Beseka was much larger during previous lake stages and was possibly connected to the Awash River. Lithostratigraphic sequences and radiocarbon measurements date the two main lake highstands at 11,000–12,000 yr b.p. (10 m above the January 1974 lake level), and approximately 10,000 years before that (Williams et al., 1981). Archaeological records of terminal Pleistocene/early Holocene gathering–hunting–fishing communities also support these findings (Brandt, 1982). Core records from other lakes in the main Ethiopian rift indicate that conditions wetter than today prevailed from 11,000 to 6000 yr b.p. (Umer et al., 2004). Water level fluctuations of this magnitude and spatial extent were interpreted as reflections of natural climatic change during the Quaternary (Verschuren et al., 2000; Gasse, 2000). We show that factors other than climate can also trigger such variations.

Several studies (Halcrow and Partners, 1979; IAEA, 1999; Ayenew, 2004) conclude that the irrigation of sugar cane plantations is responsible for the lake's expansion. However, the coherent area-wide measurements from satellite images and on-site findings we present (distribution of surface temperature, stratification of water, chemical analysis of water samples and simulated evaporation) indicate little if any influence from the irrigated plantations.

Since the lake has no perennial superficial inflows, most of the increased inflow of water must enter the lake underground. As basaltic rocks are largely non-porous, the waterflow is bound to fissures and faults. The general groundwater flow direction we derived from the elevation profile of the Awash River is north-eastwards. This corresponds to the conclusions Engida and Russom (2004) derived from the integration of previous studies and simple

groundwater modelling. They proposed that an increased groundwater discharge into the lake near the south-western shore is the main cause of Lake Beseka's level rise. The bulk of the groundwater inflow will most likely occur at the (now submerged) springs. We rated the discharge of the hot springs to be 0.05 m³/s (on-site findings October 2004), which is consistent with the estimations of Halcrow and Partners (1979). Tessema (1998) reports 1.2 m³/s. However, the discharge of the hot springs is likely to vary seasonally. Other submerged springs exist along the faults. For instance, Tessema (1998) mentions two cold springs on the northern end of the large island. Though we found no discernible flow there, a temperature difference (5 °C) between Lake Beseka itself and a small lagoon was obvious in 2004. As the presence of these cold springs is not manifested in our in-situ and remote sensing measurements of physico-chemical parameters, they probably have no significant influence. We thus assume that the bulk of underground inflow into the lake enters via the hot springs. This is supported by the results of the hydrochemical modelling: The similar chemical composition of the evaporated spring water and the original mean lake water is large enough to support the assertion that a significant fraction of Lake Beseka's inflow is contributed by discharge of the hot springs.

In summary, our results suggest that neither a change in local climate nor diversion of surface water for irrigation of the nearby sugar cane plantation is a major contributor to Lake Beseka's level rise. The principal source of water that is sufficient to explain the rise in lake level is groundwater entering the lake via the hot springs. Our findings do not provide a definite reason for the increased groundwater discharge. Two potential triggers are still to be considered:

- (1) Tessema (1998) suggests that the perennial flow of the Awash River due to the construction of the Koka dam altered the groundwater regime by raising the groundwater table. The simultaneous construction of the dam and the onset of Lake

Table 3

Hydrochemical modelling of evaporation: removal of 78.1% of spring water (B1) and 98.3% of irrigation water (P1). Results: B1 evaporated, P1 evaporated, evaporated B1 and evaporated P1 in relation to the original lake water.

	pH	T [°C]	TIC [mgC/l]	Na [mg/l]	NH ₄ [mg/l]	K [mg/l]	Ca [mg/l]	Mg [mg/l]	Cl [mg/l]	SO ₄ [mg/l]	F [mg/l]	NO ₃ [mg/l]
B1	8.4	43	127	389	0.13	22.2	1.87	1.37	110	114	6.8	5.3
P1	8.1	27	29.9	30.1	0.28	6.35	20.4	2.95	9.2	8	10.3	7.1
Beseka (mean)	9.7	28	455.7	1776	0.59	65.9	3.26	1.31	583.3	538	33.1	6.7
B1 evaporated	8.2		580.1	1778	0	100	5.25	3.9	502.4	521	30.1	34.8
P1 evaporated	7.7	27	1752.4	1765	0	370	661	73.9	539.2	469	527	372
B1 evaporated [%]			127	100	0	152	161	298	86	97	91	519
P1 evaporated [%]			385	99	0	561	####	5644	92	87	1593	5552

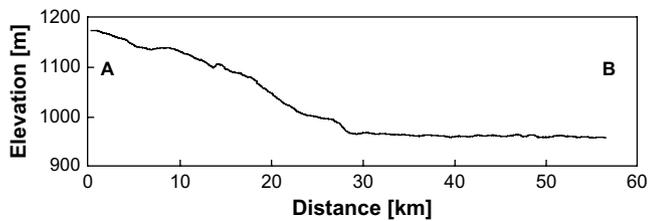


Fig. 10. Elevation profile of the Awash River (cf. AB in Fig. 1) extracted from a 90 m resolution DEM (SRTM).

Beseka's expansion argue in favour of that theory. It is however contradicted by the course of Awash River in relation to faults that act as preferential flow path.

- (2) Although our study proved that subsidence is of little importance for Lake Beseka's water balance, we propose that abundant neotectonic activity (faulting, fracturing) in the study area has resulted in a change in groundwater flow patterns. This in turn would have enlarged the underground catchment area and thus contributed to the rapid growth of Lake Beseka. The shape of the lake, nearby faults, and seismic measurements (Keir et al., 2006) document recent neotectonic activity in the region. Moreover, an increased discharge of springs due to tectonic activity has been observed in the vicinity of Lake Langano, MER (Ayenew, 1998).

To evaluate these two hypotheses a more detailed water balance is necessary. Soil properties such as permeability must be established in order to approximate the superficial runoff more precisely. This study illustrates the need for a better understanding of the underground water system. Existing attempts to draw conclusions about Lake Beseka's level rise from isotope analysis are ambiguous. IAEA (1999) investigated stable water isotopes, tritium and C14 in dissolved organic carbon in Lake Beseka and its surroundings in 1998–1999. Due to a lack of data, we could not establish a tritium model. It remained unclear, whether the lake level rise is to be attributed to a decreased outflow (because of a rise in groundwater level beneath irrigated areas) or an increased inflow via the thermal springs. Tessema (1998) concludes from an isotopic similarity of Awash water and groundwater adjacent to the river that transmission from the Awash River is recharging Lake Beseka. This interpretation is not supported by the IAEA data. Also, according to our findings, data scarceness within the study area (only few active boreholes, no reliable groundwater model so far) does not allow any safe conclusions. The magnitude of groundwater discharge into Lake Beseka can only be assessed with a broader dataset at hand. Future research should therefore include the drilling of several boreholes and precise groundwater flow modelling.

We could show that an approach based on both in-situ measurements and remote sensing data is useful to quantify changes in lake extension over time. The methods described in this study also turned out to be a convenient tool to obtain a better understanding of potential causes for lake level rise. For rift lakes to serve as useful proxies for palaeoclimate it is essential to know if the 10 m water level change in the recent history of Lake Beseka is of geological or anthropogenic origin. If the water level rise is triggered by tectonics, a similar phenomenon could also have occurred in the past. This would call for a new interpretation of palaeo-lake levels derived from lithostratigraphic sequences. A considerable number of palaeoclimatological lake level studies have been conducted in rift lakes without considering tectonic influences. Kiage and Liu (2006) review palaeohydrological records from several East African Lakes that are situated in tectonic active regions. For instance, Lake Albert, Lake Abiyata, and Lake Rukwa are tectonically controlled (Karner et al., 2000; Le Turdu et al., 1999;

Kervyn et al., 2006). For other lake level records subject to palaeoclimatic interpretation (Lake Naivasha, Verschuren et al., 2000; Lake Victoria, Stager et al., 2005), tectonic influence cannot be completely excluded (Johnson et al., 2000; Trauth et al., 2003).

Acknowledgements

The realisation of this project would never have been possible without the logistical support of the staff of the Department of Biology (Addis Ababa University) and the kind assistance of K. Adem, T. Ayenew, H. Hagos, Z. Shiferaw and M. Umer (all Department of Geology, AAU). T. Eshete, M. Adem and L. Gurmu (Metehara Sugar Plantation) helped us with detailed information on the sugar plantations near Beseka. M. Buchwitz (TU Bergakademie Freiberg) supported us with detailed geologic knowledge of the surroundings of Lake Beseka. H.-J. Peter and B. Merkel (TUBAF) provided assistance with hydrochemical analysis. We are grateful to L. Ratschbacher, the anonymous reviewers, and the editor C.F. Hutchinson for their help in improving the manuscript. We also owe a sincere debt of thanks to S. Kaessner who kept our boat running, and to all the other participants in the field trip.

Software used: Geomatica 9 by PCI Geomatics; gOcad 2.0 by the gOcad research consortium; PHREEQC – Version 2.11 2005/02/13.

References

- Alemayehu, T., Ayenew, T., Kebede, S., 2006. Hydrogeochemical and lake level changes in the Ethiopian Rift. *Journal of Hydrology* 316, 290–300.
- Ayenew, T., 1998. The Hydrogeological System of the Lake District Basin. Central Main Ethiopian Rift. PhD thesis, Free University of Amsterdam, The Netherlands, 259 pp.
- Ayenew, T., 2003. Environmental isotope-based integrated hydrogeological study of some Ethiopian rift lakes. *Journal of Radioanalytical and Nuclear Chemistry* 257 (1), 11–16.
- Ayenew, T., 2004. Environmental implications of changes in the levels of lakes in the Ethiopian Rift since 1970. *Regional Environmental Change* 4, 192–204.
- Bilham, R., Bendick, R., Larson, K., Mohr, P., Braun, J., Tesfaye, S., Asfaw, L., 1999. Secular and tidal strain across the Main Ethiopian Rift. *Geophysical Research Letters* 26, 2789–2792.
- Brandt, S.A., 1982. A Late Quaternary Cultural/Environmental Sequence from Lake Beseka, Southern Afar, Ethiopia. PhD thesis, University of California, Berkeley, 388 pp.
- Buchwitz, M., 2006. Field work report, TU Bergakademie Freiberg. http://www.geo.tu-freiberg.de/fernerkundung/MER_Beseka/beseka_geo.html.
- Chalié, F., Gasse, F., 2002. Late Glacial–Holocene diatom record of water chemistry and lake level change from the tropical East African Rift Lake Abiyata (Ethiopia). *Palaeogeography, Palaeoclimatology, Palaeoecology* 187, 259–283.
- Chernet T., 1982. Hydrogeology of the Lakes Region, Ethiopia. Memoir No. 7, Ministry of Mines and Energy, Addis Ababa, 97p.
- Chernet, T., Travi, Y., Valles, V., 2001. Mechanisms of degradation of the quality of natural waters in the lakes region in the Main Ethiopian Rift Valley. *Water Research* 35, 2819–2832.
- Créteaux, J.-F., Birkett, C., 2006. Lake studies from satellite radar altimetry. *Comptes Rendus Geoscience* 338, 1098–1112.
- Ebinger, C.J., Casey, M., 2001. Continental breakup in magmatic provinces: an Ethiopian example. *Geology* 29, 527–530.
- Engida, Z.A., Russom, G.E., 2004. Determination for the cause of rising water levels in Lake Beseka and design of remedial measure. *Ethiopian Engineers Association Journal* (August issue).
- Eshete, T., 2004. Chief of agriculture at the Metehara Sugar Factory, personal communication.
- Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. *Quaternary Science Reviews* 19, 189–211.
- Geremew, Z., 2000. Engineering Geological Investigation and Lake Level Changes in the Awassa basin. M.Sc. thesis, Department of Geology and Geophysics, Addis Ababa University, Addis Ababa, Ethiopia.
- Gissila, T., Black, E., Grimes, D.I.F., Slingo, J.M., 2004. Seasonal forecasting of the Ethiopian summer rains. *International Journal of Climatology* 24, 1345–1358.
- Gizaw, B., 1996. The origin of high bicarbonate and fluoride concentrations in waters of the Main Ethiopian Rift Valley, East African Rift system. *Journal of African Earth Sciences* 22, 391–402.
- Halcrow and Partners, 1979. Master Plan for the Development of the Surface Water Resources in the Awash Basin, vol. 6. Ministry of Water Resources, Addis Ababa, Ethiopia.
- IAEA, 1999. Water and Environment News. Isotope Hydrology Section, International Atomic Energy Agency, Vienna. Quarterly No. 8/9.

- Jenson, S.K., Domingue, J.O., 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering and Remote Sensing* 54, 1593–1600.
- Johnson, T.C., Kelts, K., Odada, E., 2000. The Holocene history of Lake Victoria. *AMBIO: A Journal of the Human Environment* 29, 2–11.
- Karner, G.D., Byamungu, B.R., Ebinger, C.J., Kampunzu, A.B., Mukasa, R.K., Nyakaana, J., Rubondo, E.N.T., Upcott, N.M., 2000. Distribution of crustal extension and regional basin architecture of the Albertine rift system, East Africa. *Marine and Petroleum Geology* 17, 1131–1150.
- Keir, D., Stuart, G.W., Jackson, A., Ayele, A., 2006. Local earthquake magnitude scale and seismicity rate for the Ethiopian Rift. *Bulletin of the Seismological Society of America* 96, 2221–2230.
- Keranen, K., Klemperer, S., Gloaguen, R., EAGLE Working Group, 2004. Imaging a proto-ridge axis in the Main Ethiopian Rift. *Geology* 39, 949–952.
- Kervyn, F., Ayub, S., Kajara, R., Kanza, E., Temu, B., 2006. Evidence of recent faulting in the Rukwa Rift (West Tanzania) based on radar interferometric DEMs. *Journal of African Earth Sciences* 44, 151–168.
- Kiage, L.M., Liu, K.-B., 2006. Late Quaternary paleoenvironmental changes in East Africa: a review of multiproxy evidence from palynology, lake sediments, and associated records. *Progress in Physical Geography* 30, 633–658.
- Kurz, T., Gloaguen, R., Ebinger, C., Casey, M., Abebe, B., 2007. Deformation distribution and type in the Main Ethiopian Rift (MER); a remote sensing study. *Journal of African Earth Sciences* 48 (2–3), 100–114.
- Le Turdu, C., Tiercelin, J.J., Gibert, E., Travi, Y., Lezzar, K.E., Richert, J.P., Massault, M., Gasse, F., Bonnefille, R., Decobert, M., Gensous, B., Jeudy, V., Tamrat, E., Mohammed, M.U., Martens, K., Atnafu, B., Chernet, T., Williamson, D., Taieb, M., 1999. The Ziway–Shala lake basin system, Main Ethiopian Rift: influence of volcanism, tectonics, and climatic forcing on basin formation and sedimentation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 150, 135–177.
- Maidment, D.R. (Ed.), 1993. *Handbook of Hydrology*. McGraw-Hill, New York.
- Mallet, J.-L., 2002. *Geomodelling*. Oxford University Press.
- Mamo, T., Getaneh, E., 2003. The Geology and Surface Hydrothermal Alteration Mapping of Fentale Geothermal Prospect. Intern report of the Geological Survey of Ethiopia. Hydrogeology, Engineering Geology and Geothermal Department, 29 pp.
- Mercier, F., Cazenave, A., Maheu, C., 2002. Interannual lake level fluctuations (1993–1999) in Africa from Topex/Poseidon: connections with ocean-atmosphere interactions over the Indian Ocean. *Global and Planetary Changes* 32, 141–163.
- MWR, 1998. Inception report. Study of Lake Beseka, vol. 1. Ministry of Water Resources, Addis Ababa, Ethiopia.
- MWR, 1999. Main report. Study of Lake Beseka, vol. 1. Ministry of Water Resources, Addis Ababa, Ethiopia, 203 pp.
- Parkhurst, D.L., Appelo, C.A.J., 1999. User's Guide to PHREEQC (Version 2)—a Computer Program For Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations, U.S. Geological Survey Water-Resources Investigations Report 99-4259, 310 pp.
- Richter, R., 1996. Spatially adaptive fast atmospheric correction algorithm. *International Journal of Remote Sensing* 17, 1201–1214.
- Seleshi, Y., Zanke, U., 2004. Recent changes in rainfall and rainy days in Ethiopia. *International Journal of Climatology* 24, 973–983.
- Stager, J.C., Ryves, D., Cumming, B.F., David, M.L., Beer, J., 2005. Solar variability and the levels of Lake Victoria, East Africa, during the last millenium. *Journal of Paleolimnology* 33, 243–251.
- Street, F.A., Grove, A.T., 1976. Environmental and climatic implications of late Quaternary lake-level fluctuations in Africa. *Nature* 261, 385–390.
- Tamiru, A., 2003. Controls on the occurrence of cold and thermal springs in central Ethiopia. *Africa Geoscience* 10, 245–251.
- Tessema, Z., 1998. Hydrochemical and Water Balance Approach in the Study of High Water Level Rise of Lake Beseka. M.Sc. thesis, University of Birmingham, UK.
- Trauth, M.H., Deino, A.L., Bergner, A.G.N., Strecker, M.R., 2003. East African climate change and orbital forcing during the last 175 kyrBP. *Earth and Planetary Science Letters* 206, 297–313.
- Umer, M., Legesse, D., Gasse, F., Bonnefille, R., Lamb, H.F., Leng, M.J., Lamb, A.L., 2004. Late Quaternary climate changes in the Horn of Africa: past climate variability through Europe and Africa. *Developments in Paleoenvironmental Research* 6, 159–180.
- Verschuren, D., Laird, K.R., Cumming, B.F., 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* 403, 410–414.
- WIC (Walta Information Center), October 01, 2003. Over 230 Million Birr Water Projects Nearing Completion Available from: http://www.waltainfo.com/ennews_old/2004/oct/01oct03/oct01e10.htm.
- Williams, M.A.J., Williams, F.M., Bishop, P.M., 1981. Late Quaternary history of Lake Beseka, Ethiopia. *Palaeoecology of Africa and the Surrounding Islands and Antarctica* 13, 93–104.
- Williams, F.M., Williams, M.A.J., Aumento, F., 2004. Tensional fissures and crustal extension rates in the northern part of the Main Ethiopian Rift. *Journal of African Earth Sciences* 38, 183–197.
- WWDSE., 2001. The study of Lake Awassa level rise (Main Report, Vol II). Unpublished report of Water Works Design and Supervision Enterprise, Addis Ababa, Ethiopia, 291.