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# The sensitivity of East African rift lakes to climate fluctuations

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**Abstract** Sequences of paleo-shorelines and the deposits of rift lakes are used to reconstruct past climate changes in East Africa. These recorders of hydrological changes in the Rift Valley indicate extreme lake-level variations on the order of tens to hundreds of meters during the last 20,000 years. Lake-balance and climate modeling results, on the other hand, suggest relatively moderate changes in the precipitation-evaporation balance during that time interval. What could cause such a disparity? We investigated the physical characteristics and hydrology of lake basins to resolve this difference. Nine closed-basin lakes, Ziway-Shalla, Awassa, Turkana, Suguta, Baringo-Bogoria, Nakuru-Elmenteita, Naivasha, Magadi-Natron, Manyara, and open-basin Lake Victoria in the eastern branch of the East African Rift System (EARS) were used for this study. We created a classification scheme of lake response to climate based on empirical measures of topography (hypsometric integral) and climate (aridity index). With reference to early Holocene lake levels, we found that lakes in the crest of the Ethiopian and Kenyan domes were most sensitive to recording regional climatic shifts. Their hypsometric values fall between 0.23–0.29, in a graben-shaped basin, and their aridity index is above unity (humid). Of the ten lakes, three lakes in the EARS are sensitive lakes: Naivasha (HI = 0.23, AI = 1.20) in the Kenya Rift, Awassa (HI = 0.23, AI = 1.03) and Ziway-Shalla (HI = 0.23, AI = 1.33) in the Main Ethiopian Rift (Main Ethiopian Rift). Two lakes have the graben shape, but lower aridity indices, and thus Lakes Suguta (HI = 0.29, AI = 0.43) and Nakuru-Elmenteita (HI = 0.30, AI = 0.85) are most sensitive to local climate changes. Though relatively shallow and slightly alkaline today, they fluctuated by four to ten times the modern water depth during the last 20,000 years. Five of the study lakes are pan-shaped and experienced lower magnitudes of lake level change during the same time period. Understanding the sensitivity of these lakes is critical in establishing the timing or synchronicity of regional-scale events or trends and predicting future hydrological variations in the wake of global climate changes.

**Keywords** East African Rift · Tectonics · Geomorphometry · Aridity index · Sensitive lakes

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## Introduction

The sedimentary sequences of equatorial African lakes have been used widely as archives of past climate changes in the low latitudes on diverse time scales

(Verschuren et al. 2000; Gasse 2000; Barker and Gasse 2003; Trauth et al. 2005; Legesse et al. 2002). In these studies, biological and geochemical proxies, and sequences of paleoshorelines have been used to study past climate fluctuations (Gasse 2000; Barker and Gasse 2003). A crucial prerequisite for paleoclimate interpretation of lacustrine sedimentary sequences, however, is an understanding of the lake system under investigation, such as the: (a) response to changes in climate and catchment activities, (b) response of biological and physico-chemical properties to moisture changes, and (c) site-specific processes governing the incorporation of environmental signals into the sediments (Street-Perrott and Harrison 1985; Legesse et al. 2002). Complexities, however, also arise in inferring climate from these records, especially in tectonically active settings, because responses of lakes to climate are also mediated by the geomorphic and hydrologic setting of basins thus creating non-linearity and spatial heterogeneity in the pattern and timing of inferred change.

Large lakes in East Africa experienced large hydrologic fluctuations, driven by insolation changes, during the late Pleistocene and early Holocene (15–5 ka BP). Although the timing and magnitude of the hydrological shifts in the basins are known, the climate conditions at those times are not well defined. Lake water-balance modeling results for some East African lakes show only moderate changes in effective moisture ($\sim$25% more rain) that cannot account for the high lake stands (Hastenrath and Kutzbach 1983; Bergner and Trauth 2004; Dühnforth et al. 2006). Street-Perrott and Harrison (1985) explained this response of East African Rift System (EARS) lakes to climate changes using a Precipitation-Evaporation balance in the catchment and introduced the term "amplifier lakes." Their classification of lake sensitivity showed closed lakes are more sensitive 'amplifiers' than open lakes with large outflows. They suspected the graben morphologies of the EARS lakes had an influence on whether a basin was an "amplifier lake," but did not pursue the idea. Another common ratio used in sensitivity studies has been catchment/lake area ratio. Basins with large catchment-to-lake-surface area ratios have demonstrated large amplification factors (Burrough and Thomas 2009).

Basic morphometric features such as volume, surface area, and mean depth, as well as information related to hypsographic curves, are increasingly being used to describe limnological changes that occur as lake volume changes (Johansson et al. 2007). In very flat basins, changes in lake volume cause horizontal oscillations rather than vertical changes in shoreline position, making lakes that are steep over a wide range of water depths more suitable for sensitivity studies. Morphometric variables in basins can be determined by hypsometric analysis of Digital Elevation Models (DEM). In the past, routine hypsometric analyses were limited by computer power. With advances in computing and GIS technology since 1952, hypsometry is being reinvestigated to improve understanding of geomorphologically controlled dynamics of sediment proxies. A combination of lake bathymetric maps and hypsometric curves can provide visual representation of 2D and 3D properties of a lake (Johansson et al. 2007). The integral of the curve provides a simple index of the depth distribution within the lake/area under consideration, which can be used to quantify the size and form of a lake.

This paper investigates the sensitivity of EARS lakes as climate recorders by incorporating variables that describe lake form and hydrology, and is a continuation of the work by Street-Perrott and Harrison (1985) who first introduced the term "amplifier lake." We investigated nine closed-basin rift lakes between 5°S and 10°N latitude and 30°E and 40°E longitude, from Ethiopia through Kenya to Tanzania. The study included Lakes Ziway-Shalla, Awassa, Turkana, Suguta, Baringo-Bogoria, Nakuru-Elmenteita, Naivasha, Magadi-Natron, Manyara, and one open non-rift lake, Victoria, which is situated in the plateau region between the eastern (Gregory Rift) and the western arms (Albertine Rift) of the EARS. The latter basin was included for comparison. Results from our analysis can be used to better constrain climate interpretations from lakes.

## Tectonic setting and climate

The EARS has two main branches, the eastern and the western branches that crosscut Eastern and Central Africa, beginning at the triple junction of the Red Sea and Gulf of Aden oceanic ridges, and the Afar Rift at about 10°N latitude to more than 30°S latitude, terminating on land with the Lake Malawi basin. It is structurally and magmatically controlled, creating complex relief and drainage conditions that are highly variable through time, initiated about 45 Ma and continuing to present (Baker et al. 1972; Strecker et al. 1990; Ebinger et al. 2000; Chorowicz 2005). We studied lakes in the Eastern branch, which extends over a distance of 2,200 km, from the Afar triangle in the north, through the Main Ethiopian Rift (MER), the Turkana-Omo lows, the Kenyan (Gregory) rift, to the basins of the North-Tanzania divergence. The EARS is generally <100 km wide, with the exception of the region between southern Ethiopia and Northern Kenya, and the region in Northern Tanzania, where the Kenyan (Gregory) rift terminates. In these regions, the rift is more than 300 km wide (Chorowicz 2005).

The NE-striking MER (330 km long, 50 km wide) floor rises progressively from the northeast with elevations of 750–1,700 m southwestwards, and finally downgrades to 1,100 m in the south (Ayenew et al. 2007; Chorowicz 2005). The Kenyan (Gregory) rift region corresponds to the Kenyan dome. Elevations in this rift floor rise from about 1,050 m in the north around the Baringo-Bogoria Basin to about 2,000 m in the middle, and step down progressively southwards to about 600 m asl in the Natron basin (Chorowicz 2005). The floor of the rift is highest in the central portion, between Lake Nakuru and Lake Naivasha, and decreases in altitude in both directions along the rift. The basins in the rift are generally bordered on both sides by high relief, comprising almost continuous parallel mountain lines and plateaus, and sometimes, volcanic massifs. Between these domes are the Turkana-Omo lows, with significantly lower (250 m asl) elevations than the dome regions. This low area has no pronounced rift shoulders, but there are several N- to NE-striking half-graben basins, e.g. Omo Valley, Lake Turkana and Chew Bahir.

Late Cenozoic tectonic activity in the EARS commenced with southward propagation of rifting and magmatic activity and progressive formation of faulted troughs throughout the length of the rift, in which lakes have formed (Tiercelin and Lezzar 2002; Trauth et al. 2007). These troughs are generally half-grabens bounded by major high-angle boundary faults on one side and a faulted flexural margin on the other, or less frequently, grabens bounded by two faults of similar importance. These lakes are typically elongate, following the dominant trend of the faults: NNE-SSW-trending lakes within the MER, NS-trending within the Turkana-Omo lows. Further south in the Kenyan rift they assume a NNW-SSE to NS trend and NS to NNW trend in Northern Tanzania, at the termination of the rift (Le Turdu et al. 1999). In contrast to the large ($\sim$30,000 km$^2$) and deep ($\sim$1,000 m) lakes of the western rift, the lakes in the eastern rift are small (about 100–200 km$^2$ surface area), shallow (<10 m deep) and mostly of the closed-basin type, with internal drainage (Ebinger et al. 1993; Singer and Stoffers 1980). Few of the lake basins in the EARS contain fresh water, and most are quite saline.

Rifting of the EARS was preceded by doming of the Ethiopian and the Kenyan domes. This morphotectonic evolution contributed significantly to creating important orographic barriers and environmental changes (Sepulchre et al. 2006; Spiegel et al. 2007). Modern climate is governed by the seasonal influence of several major air streams and convergence zones that interact with regional orography, large inland water bodies and sea-surface temperature fluctuations in the Indian and the Atlantic Oceans (Nicholson 1996). Meridional moisture transport shows the Ethiopian Highlands deflect the northeast monsoon flow southward along the Somalian coast during winter and the Kenyan highlands deflect the southeast flow northward during summer (Sepulchre et al. 2006). As a result, climate patterns are highly complex and variable. In general, highlands flanking the Rift Valley intercept most of the monsoonal rainfall in the region, resulting in a strong moisture deficit at the rift floor, particularly near the lakes.

## Lake basins

The location and key characteristics of the ten study basins are summarized in Table 1. Each basin contains at least two modern lakes owing to fragmentation caused by faulting and volcanic eruptions within the basins that diverted or dammed surface drainage, hence multiplying the number of basins within a tectonic depression. The catchment areas of most of these basins are within the rift, most areas being supplied by streams descending from high marginal escarpments. Basin sizes range from a few hundred to thousands of square kilometres. Major rivers such as the Ewaso Ngiro which feeds Lake Natron, and the Kerio River which feeds Lake Turkana, are channeled N or S along fault-angle

**Table 1** East African rift lakes mentioned in the text, their location and key characteristics

| | Longitude (deg) | Latitude (deg) | Altitude (m) | Lake area ($km^2$) | Basin area ($km^2$) | Basin area/ Lake area | Hypsometric integral | Precipitation | Potential evaportrans piration | Aridity index | Holocene lake level rise | Normalized Holocene lake level rise | Normalized Holocene lake level rise | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nakuru-Elmenteita | 36.08 | −0.37 | 1,770 | 60 | 2,390 | 39.83 | 0.30 | 1,200 | 1,400 | 0.85 | 180 | 3.0000 | 0.0753 | Dühnforth et al. (2006), Washbourn-Kamau (1970) |
| Naivasha | 36.34 | −0.77 | 1,885 | 180 | 3,200 | 17.78 | 0.23 | 1,500 | 1,250 | 1.20 | 110 | 0.6111 | 0.0344 | Ase et al. (1986), Verschuren (1999), Washbourn-Kamau (1975) |
| Awassa | 38.43 | 7.03 | 1,680 | 129 | 1,455 | 11.28 | 0.23 | 1,028 | 1,000 | 1.03 | 40 | 0.3101 | 0.0275 | Alemayehu et al. (2006), Ayenew and Greegziabher (2006), Makin et al. (1976), Telford et al. (1999) |
| Suguta | 36.55 | 2.22 | 275 | 80 | 12,800 | 160.00 | 0.30 | 1,000 | 2,309 | 0.43 | 300 | 3.5000 | 0.0219 | Castanier et al. (1993), Garcin et al. (2009), Nyenzi et al. (1981) |
| Ziway-Shala | 38.76 | 7.59 | 1,558 | 1,222 | 14,600 | 11.94 | 0.23 | 1,200 | 900 | 1.33 | 120 | 0.0982 | 0.0082 | Alemayehu et al. (2006), Legesse et al. (2002) |
| Magadi-Natron | 36.26 | −2.33 | 600 | 440 | 10,930 | 24.84 | 0.36 | 1,000 | 1,750 | 0.57 | 48 | 0.0409 | 0.0016 | Barker (1990), Bessems et al. (2008), Darling et al. (1996), Knight Piesold and Partners (1992), Tiercelin (1990) |
| Baringo-Bogoria | 36.06 | 0.63 | 967 | 215 | 6,200 | 34.98 | 0.37 | 1,000 | 2,309 | 0.43 | 9 | 0.0419 | 0.0015 | Burrough and Thomas (2009), Nyenzi et al. (1981), Owen et al. (2004), Rowntree (1990), Tarits et al. (2006), Tiercelin (1990) |
| Manyara | 35.80 | −3.62 | 960 | 12,000 | 23,207 | 1.93 | 0.13 | 1,000 | 2,000 | 0.50 | 23 | 0.0019 | 0.0010 | Casanova and Hillaire-Marcel (1992), Ring et al. (2005) |
| Turkana | 36.05 | 3.66 | 375 | 7,300 | 130,860 | 17.92 | 0.13 | 1,400 | 2,560 | 0.55 | 80 | 0.0110 | 0.0006 | Ferguson and Harbott (1982), Nicholson (1996), Nyenzi et al. (1981), Odada et al. (2003) |
| Victoria | 36.26 | −2.33 | 1,134 | 68,800 | 184,000 | 2.67 | 0.18 | 2,400 | 1,690 | 1.40 | 18 | 0.0007 | 0.0027 | Odada et al. (2003), Spigel and Coulter (1996) |

depressions. These basins are all closed and their chemistry ranges from fresh, alkaline to saline, depending on the input–output balance of each system. The fresh lakes are Naivasha, Awassa, Baringo, Ziway, Langano and Victoria, while the alkaline to saline lakes are Turkana, Suguta, Bogoria, Nakuru-Elmenteita, Magadi- Natron and Manyara.

Two of the basins, Ziway-Shala and Awassa, are located within the MER. The Ziway-Shala is a system of four interconnected, internally drained basins (Ziway, Langano, Abiyata, and Shala) in a NNE-SSW down-faulted structure, with the Somalian Plateau on the east and the Ethiopian Plateau on the west. Three of these sub-basins formed in tectonically controlled basins, whereas Shala occupies a deep caldera (Le Turdu et al. 1999; Legesse et al. 2002). Mean annual precipitation varies from 600 mm/year close to the lakes to 1,200 mm/year on the humid plateaus and escarpments. Ziway and Shalla receive water principally from the west escarpment. Langano is fed from the east escarpment, while Abiyata is mainted by overflow from Ziway and Langano (Alemayehu et al. 2006; Ayenew 2003). Basin evapotranspiration has been estimated at 900 mm/year (Ayenew 2003). Evaporation ranges from 2,500 mm/year in the rift floor to <1,000 mm/year in the highlands (Le Turdu et al. 1999). South of the Ziway-Shala basin, at the southern edge of the MER, is the Awassa basin, located within a pair of collapsed Pliocene calderas, Awassa and Corbetti (Ayenew and Greegziabher 2006). The catchment area is smaller (1,455 km$^2$) and the lake area is 129 km$^2$. Maximum and mean depths are 21 and 10 m. Awassa receives surface input intermittently from the Shallo swamp, fed from the eastern wall of the rift valley. The lake has no surface outlet and is a freshwater system maintained by significant outflow of groundwater northwards (Darling et al. 1996). Rainfall is about 960 mm/year (Ayenew and Greegziabher 2006) and pan evaporation estimates over the lake range from 1,600 to 2,140 mm/year (Makin et al. 1976; Telford et al. 1999).

The Turkana and Suguta basins (375 m asl) lie in the Turkana-Omo lows region, located between the Ethiopian and the Kenyan domes (Chorowicz 2005). Turkana is the largest lake in the eastern rift, with a catchment covering 130,860 km$^2$. The mean and maximum depths are 35 and 120 m, respectively. In this bottom rift setting, the lake receives about 300 mm/year of rainfall (Nicholson 1996; Odada et al. 2003). The annual evaporation rate is about 2,300 mm/year and evapotranspiration is about 2,500 mm/year (Nyenzi et al. 1981; Ferguson and Harbott 1982). Lake Turkana is saline-alkaline and receives 90% of its water via the Omo River from Ethiopia, with minor inputs from the Turkwell and Kerio river systems to the south (Odada et al. 2003). Directly south of the Turkana basin lies the Suguta basin, separated by a transverse volcanic barrier currently occupied by Lakes Logipi and Alablab (Dunkley et al. 1993). In the dry season, the water body is reduced to salt pans that are restricted to the deepest parts of both lakes. At its maximum extension, the lake depth varies between 3 and 5 m. Together the lakes cover 80 km$^2$ and the catchment covers 12,800 km$^2$. Rainfall varies from <300 mm/year over the lake to 1,000 mm/year in the headwaters of the Suguta River, located in the south. There is considerable subsurface water inflow from the north as well (Castanier et al. 1993). Evapotranspiration is 2,309 mm/year (Nyenzi et al. 1981).

Baringo-Bogoria basin lies in the northernmost part of the Kenyan dome and developed in the main region with half-grabens. It has two closed lakes, Baringo and Bogoria. Baringo is fresh, whereas Bogoria is saline and alkaline. The entire basin covers 6,200 km$^2$ and is drained by five rivers. Lake Baringo is currently very shallow, with a mean depth of $\sim$1.6 m and a maximum depth of 2.1 m. It is fed perennially by the Perkarra and Molo rivers from the south. The ephemeral rivers, Ol Arabel and Mukatan, enter it from the east and from the west, and several ephemeral rivers drain the Kamasia highlands (Tarits et al. 2006; Bessems et al. 2008). Lake Bogoria is deeper (10 m) and is fed by nearly 200 hydrothermal springs along the lakeshore, as well as four seasonal rivers (Waseges-Sandai, Loboi, Emsos and Mogun). The entire basin receives between 600 and 900 mm/year of rainfall on the rift floor and >1,000 mm/year in the adjacent uplands. Potential evaporation exceeds 2,500 mm/year (Nyenzi et al. 1981; Rowntree 1989; Owen et al. 2004).

The Nakuru-Elmenteita basin contains two shallow alkaline lakes, Nakuru and Elmenteita. The basin is set between east-dipping normal faults of the Mau escarpment and west-dipping faults to the east in the intra-rift Bahati-Kinangop plateau. The northern boundary comprises the Menengai Caldera, and to the south, the Eburru volcano separates it from the Naivasha basin. The catchment is about 2,390 km$^2$ in area. Mean annual rainfall is up to 1,200 mm/year in the catchment and potential evapotranspiration is 1,400 mm/year, whereas evaporation over the lake is about 1,736 mm/year. Both lakes are shallow, with an average water depth of <3 m (Dühnforth et al. 2006). The basin is fed mainly by streams from the Mau escarpment. Naivasha basin (1,885 m asl) is the highest point of the Kenyan Rift. Naivasha is fed by three rivers that drain the Bahati-Kinangop ramp highlands, which receive up to 1,500 mm/year of rainfall and have evapotranspiration of about 1,250 mm/year. Rainfall over the lake is about 600 mm/year while evaporation is ~1,800 mm/year. The basin is confined by volcanoes that create three connected satellite basins, the main lake, Crescent crater and Oloidien. Crescent Crater Lake in the southeastern sector represents the deepest part of the lake (18 m) and a permeable sill separates the main lake from more alkaline Lake Oloidien in the southwestern sector (Ase et al. 1986; Verschuren 1999). The volcanic-tectonic origin of the lake accounts for its relatively circular shape.

The Victoria basin straddles the equator and is the second largest lake in the world, covering 68,800 km$^2$. The catchment area is 184,000 km$^2$. Lake Victoria formed as a result of river reversal and ponding as a consequence of rift margin uplift along the western branch in the late Pleistocene (~14.6 ka BP) (Scholz et al. 1998) and can thus be described as a tectonically induced lacustrine system. It is an open lake, receiving water from several rivers, the largest being the Kagera and the Katonga in the west and draining to the north through the Nile. Rainfall over the lake is about 1,200 mm/year and up to 2,400 mm/year in the catchment. Evapotranspiration is about 1,690 mm/year and river inflow makes a minor contribution (Spigel and Coulter 1996).

At the southern tip of the Kenya Rift is the Magadi-Natron basin that contains two lakes, Magadi and Natron, whose catchment covers 23,207 km$^2$. Annual rainfall in the catchment is about 1,000 mm/year and evaporation is about 1,750 mm/year (Burrough and Thomas 2009). Lake Magadi is formed by an assemblage of several small basins defined by a complex system of N–S-, NNW-SSE- and NNE-SSW-trending faults. Magadi has no perennial inflowing streams at present and is fed by numerous (partly hot) springs as well as rainfall (Barker 1990). Lake Natron is a shallow water body covered by eight saline lagoons, with a maximum depth of about 2 m. It is fed mainly by two rivers, Peninj and Ewaso Ngiro, and some perennial streams (Knight Piesold and Partners 1992). Both lakes have extensive trona crusts that dissolve during the rainy season. Manyara basin lies in the Manyara Rift at the southern termination of the eastern branch of the East African Rift in the Tanzanian Divergence Zone. This basin contains Lakes Manyara and Burungi (Ebinger et al. 1997; Chorowicz 2005; Ring et al. 2005). The lakes cover a surface area of about 440 km$^2$ with a maximum depth of 4 m. Mean rainfall ranges between 500 and 600 mm/year. The catchment area is 10,930 km$^2$ and receives annual precipitation between 800 and 1,000 mm/year and potential evapotranspiration is 2,000 mm/year (Casanova and Hillaire-Marcel 1992; Nyenzi et al. 1981). The main perennial rivers are located west of the lake.

## Methods

We assessed the basin factors that can cause significant heterogeneity in paleoclimate records within the EARS: (1) geomorphic characteristics that best describe basin form and the accommodation space available for storage and preservation of sediment records, and (2) the aridity index (AI), which is an indicator of the effective moisture available to a basin relative to the demand under prevailing climatic conditions.

### Geomorphic analyses

Hypsometric analysis describes the elevation distribution across an area of land surface, therefore it is an important tool for assessing and comparing geomorphic evolution of various landforms, irrespective of factors such as tectonics, climate, and lithology, which may be responsible for their creation (Hurtrez et al. 1999; Montgomery et al. 2001). Two products of these analyses are the hypsometric curve and the hypsometric integral (HI). The latter is a dimensionless parameter that allows different catchments to be compared. The absolute and relative vertical resolutions of the Shuttle Radar Topography Mission (SRTM) DEM in Africa are estimated as ± 5.6 m and ± 9.8 m, respectively (Rodriguez et al. 2006). This low error has little effect on hypsometric analyses of large catchments. Moreover, studies show that hypsometry is largely insensitive to grid scale, through comparison of results from a 10, 20 and 90 m DEM (Hancock et al. 2006).

We used the 3 arc second or 90-m DEMs from the SRTM and processed 52 SRTM tiles covering the EARS. Where necessary, various tiles were "mosaiced" into larger grids and the larger DEMs were resampled into a coarser grid before processing to save on computing time. Existing data gaps were filled by interpolation and data were smoothed using a 9 × 9-pixel moving average filter. We conducted watershed analyses for each basin, then carried out morphometric analyses, developing hypsometric curves and integrals and swath profiles of East–West sections from the data.

The hypsometric curve for each basin was created by dividing into equal elevations the range of elevations and calculating the proportion of basin area within each interval. Elevations were normalized to the relief of the catchment so that they ranged from 0 to 1. The two ratios are plotted against each other. The hypsometric integral (HI) is the area under the curve obtained by numerically integrating this area. An alternative method uses the simple equation introduced by Pike and Wilson (1971):

$$HI = \frac{Mean\,Elevation - Minimum\,Elevation}{Maximum\,Elevation - Minimum\,Elevation} \qquad (1)$$

This equation is widely used because it does not require rigorous computation of the hypsometry of the basin, but rather, relies on three easily obtainable values, mean, maximum and minimum DEM values. This approach, however, is very sensitive to noise and outliers in the DEM. We compared both approaches by using the equation and integrating the area under the curve using the trapezoidal method "trapz," developed in *MATLAB*®.

## Swath analysis and basin characteristics

To assess the topographic variations for each basin, we took swath profiles oriented approximately perpendicular to the main axis of the lake basins, from the resampled SRTM data. The area of the swath is defined by the rectangular grid sections that envelope each lake basin. For uniformity, we defined the extent of the swath as 300 m above the altitude of the current lake level because this is the highest inferred early Holocene lake level, which is observed in the Suguta Valley (Garcin et al. 2009). For each swath area, we calculated the maximum, mean and minimum elevations. Swath profiles provide valuable insights into the geomorphologic means and variances of a basin and show depths and lake basin extent. These help define the graben- and pan-shaped basins in this study.

Table 1 shows the key characteristics of the lakes in the study. Because we are comparing several basins of various sizes, surface areas and volumes, we scaled them for comparison by their early Holocene lake level to basin size and lake size. Early Holocene lake levels used were based on published paleoshoreline levels that had been identified by wave-cut notches, as shoreline cliffs, beaches, or shallow-water sediments with dated organic matter and stromatolites (References in Table 1).

## Aridity index

The aridity index is used to define the moisture availability in a basin based on meteorological variables such as precipitation and air temperature. There are several indices currently in use. The De Martonne's aridity index is defined by the ratio between the mean annual precipitation (P) and temperature plus 10°C [P/(T + 10)] (Paltineanu et al. 2007). The Thornthwaite index is defined by the ratio of the difference between precipitation and evapotranspiration to the potential evapotranspiration and given by 100((P/PE)−1). The water deficit (WD) is simply the difference between precipitation and evapotranspiration (P−ET), and the UNESCO aridity index is the ratio between precipitation and evapotranspiration. All these terms have some value in studying the potential impact of climatic change on water resources. The potential evapotranspiration according to the definition used by the UNESCO is calculated using the Penman formula, which requires meteorological data that are difficult to acquire for most basins in the world. This led to the introduction of a more simplified approach for calculating the potential evapotranspiration using the Thornthwaite formula. This index is widely known as the UNEP aridity index (Tsakiris and Vangelis 2005) and is defined as:

$$AI = \frac{P}{PE} \quad (2)$$

Where $P$ is the total annual precipitation (mm/year) and $PE$ is the potential evapotranspiration (mm/year). According to this concept, regions where the aridity index is lower than unity are broadly classified as dry since the evaporative demand cannot be met by precipitation. Regions with an aridity index higher than unity are broadly classified as wet. We used published and known meteorological data of annual rainfall and potential evapotranspiration values for the lake basins in our study. Their areas are between 1,455 to 184,000 km$^2$, and annual rainfall over the catchments varies from 500 to 2,400 mm/year. Potential evaporation ranges from 1,690 to 2,600 mm/year, and the values were used as inputs to compute the UNEP aridity index (Table 1).

## Results

### Morphometric analyses and lake features

Averaged statistics for each E-W-oriented swath section, plotted against longitude (Fig. 2a), illustrate the relationship between specific basin geometry and location along the EARS. The basins range from symmetric to asymmetric. The lowest mean and minimum elevation values are for the Turkana basin, and values increase significantly from the Turkana-Omo lows in both directions, southward to the Kenyan dome and northward to the Ethiopian dome. The swath profile reliefs gradually increase southward to the Suguta basin, through the Baringo-Bogoria, Nakuru-Elmenteita basins and peak at the Naivasha basin. From there, southward along the rift, the mean and minimum values decrease through the Magadi-Natron basin to the Manyara basin. A similar pattern is observed north of the Turkana-Omo lows, the average minimum and mean elevations increase through the Awassa basin and terminate at the Ziway-Shalla basin. There is, however, a great variability in averaged maximum elevations for each swath profile caused by the existence of volcanoes and features related to the *en-echelon* faults that influence the local topography, but have no distinguishing characteristics.

The swath profiles also show strong topographic differences, creating two main morphological shapes, distinct grabens and pan-shaped depressions. Examples of pan-shaped morphologies with gentle slopes are the Victoria, Turkana, Manyara, Magadi-Natron and Baringo-Bogoria basins. The Ziway-Shalla, Awassa, Suguta, Nakuru-Elmenteita, Naivasha basins show graben or half-graben morphologies with steeper slopes (Fig. 2a).

Figure 2b shows results of hypsometric analyses. The hypsometric curves are typically sigmoidal or concave up, which can be grouped broadly into three categories of landmass distribution. The first category includes Lakes Manyara, Turkana and Victoria, which have relatively flat basins, and hence low hypsometric integral values. These lakes have low gradients and most of their relief occupies less than 50% of the highest altitude, giving them a lower local elevation range. The second category includes basins with pronounced step-like features in the higher altitudes and relatively higher hypsometric integrals. Examples in this category are Lakes Naivasha, Awassa, Ziway-Shalla and Suguta. The Ziway-Shalla, Suguta and Awassa catchments have shoulders in the hypsometric curve. The shoulders characterize abrupt rises in land surface as a series of fault steps that point to the tectonic activity of the EARS. Lakes in the third category have the highest topographic gradients and include Lakes Nakuru–Elmenteita, Magadi-Natron and Baringo-Bogoria. Lakes Nakuru-Elmenteita and Baringo-Bogoria have a high gradient in the hypsometric curve, i.e. they are characterized by a higher local elevation range. At 30% altitude, the hypsometric curves of lakes in the second category (Fig. 2b) are comparable to the full profile of lakes Baringo-Bogoria, Magadi-Natron and Nakuru Elmenteita.

Hypsometric integrals for these basins range from 0.13 to 0.37 (Table 1). These values are relatively low, indicating that a greater proportion of the landmass within the catchment is at low or intermediate elevations. The results fall into three categories, similar to the hypsometric curve classification (Fig. 2b): 0.1–0.2, 0.21–0.3, and 0.31–0.4. The 0.1–0.2 category basins occupy the terminal end of the rift valleys. Both lakes Manyara and Turkana have hypsometric integrals of 0.13. Lake Victoria is a non-rift lake, but also falls in this category with a value of 0.17. Category II with HI values of 0.21–0.3, occupy the highest elevation in the EARS dome. Naivasha, Awassa, and Ziway-Shalla have integrals of 0.23, Suguta has an HI of 0.29 and the Nakuru-Elmenteita basin has a value of 0.3. Category III comprises the lakes in the intermediate area between the termination of the Kenyan rift and the dome. Examples are Lakes Magadi-Natron and Baringo-Bogoria, which have higher HI values of 0.36 and 0.37, respectively, and their hypsometric curves are almost linear. An exception to this rule, but also a member of this group, is the Suguta basin, which is located in an intermediate region, but has a lower integral (0.29). A plausible explanation for this lower value is its location. It is surrounded by volcanic formations to the north (the Barrier) and east (Tirr Tirr Plateau, Emuruangogolak), giving it high gradients similar to those of the Category II basins.

A strong correlation exists between relief and hypsometric integrals for the study area. The intermediate HIs of $\sim$0.23–0.29 are typical for basins characterized by distinct graben morphology and a tectonically active rift setting, whereas the lower and higher values describe pan-shaped basins in highly eroded, or tectonically less active settings.

Scaling by Holocene lake level rise to basin area enabled comparisons. Nakuru-Elmenteita emerges as having the largest change (0.0753) and the Turkana Basin had the least change (0.0006). Table 1 is arranged in descending order of normalized values. Victoria is last because it is a non-rift lake. By this classification, five lakes, Nakuru-Elmenteita, Naivasha, Awassa, Suguta and Ziway-Shalla, emerge as "sensitive." This finding is in agreement with the hypsometry and aridity index classification. Lakes Victoria, Baringo-Bogoria, Manyara, Turkana and Magadi-Natron experienced relatively minor increases in water levels during the early Holocene wet episode in East Africa (Table 1).

### Aridity index

Results for the study area range from 0.50 to 1.42. Lower values denote arid basins and higher values denote humid basins. There is a striking spatial pattern of the aridity index along the N–S axis of the eastern branch of the EARS (Fig. 3). The lowest AI values occur in the low-elevation basins in the Omo-Turkana lows and at the southern termination of the Kenya Rift, i.e. in the catchments of Lakes Turkana, Suguta, Baringo-Bogoria, Magadi-Natron and Manyara, with values of 0.55, 0.43, 0.43, 0.57 and 0.50, respectively (Fig. 3). The AI values for lake basins at the domes of the Kenyan and Ethiopian rifts are higher (wet), e.g. the Ziway-Shalla, Awassa and Naivasha basins, which have indices of more than unity, 1.33, 1.03 and 1.20, respectively. The catchment of the Nakuru-Elmenteita basin, however, which also lies in the Kenyan dome, has an aridity index of 0.85. We explain the exceptionally low value of this basin by the relatively small catchment area of the basin and its location north of Naivasha, lacking the high-elevation topography that captures high precipitation winds.

The spatial distribution of AI is a result of orographic effects. The rift flanks deflect moist air upward causing rain in the highlands. The air descends into the valleys devoid of moisture. Thus higher AI corresponds to high elevation and vice versa. Lake Victoria has an AI of 1.42, which is the highest value of all lakes in the study. This lake receives an enormous amount of rainfall in the 184,000-$km^2$ catchment that is not compensated for by high evapotranspiration in the lake area.

## Discussion

In this study we used empirical measures to scale the sensitivity of EARS lakes with respect to their ability to record climate shifts. Using the geomorphologic and hydrologic settings of ten lake basins, we determined the key factors that amplify their sensitivity. The geomorphologic setting is described here by the hypsometry, whereas the climate setting is characterized by the aridity index. Traditionally, morphometric studies have been applied to sections of topography and individual drainage basins. To our knowledge, this is the first attempt to apply the approach in lakes of the East African rift system to classify them with respect to climate sensitivity.

Swath profiles of mean elevation show the topographic differences that exist east and west of the basins (Fig. 2). In general, the mean elevations from the swath profiles of the lakes display either graben or half-graben shapes or pan-shaped basins. The shape affects the response and the preservation of the lake sediment record, and we used it to identify the potential for lake level amplification. No direct correlation exists between the swath profile shapes and the hypsometric analyses. The swath profiles,

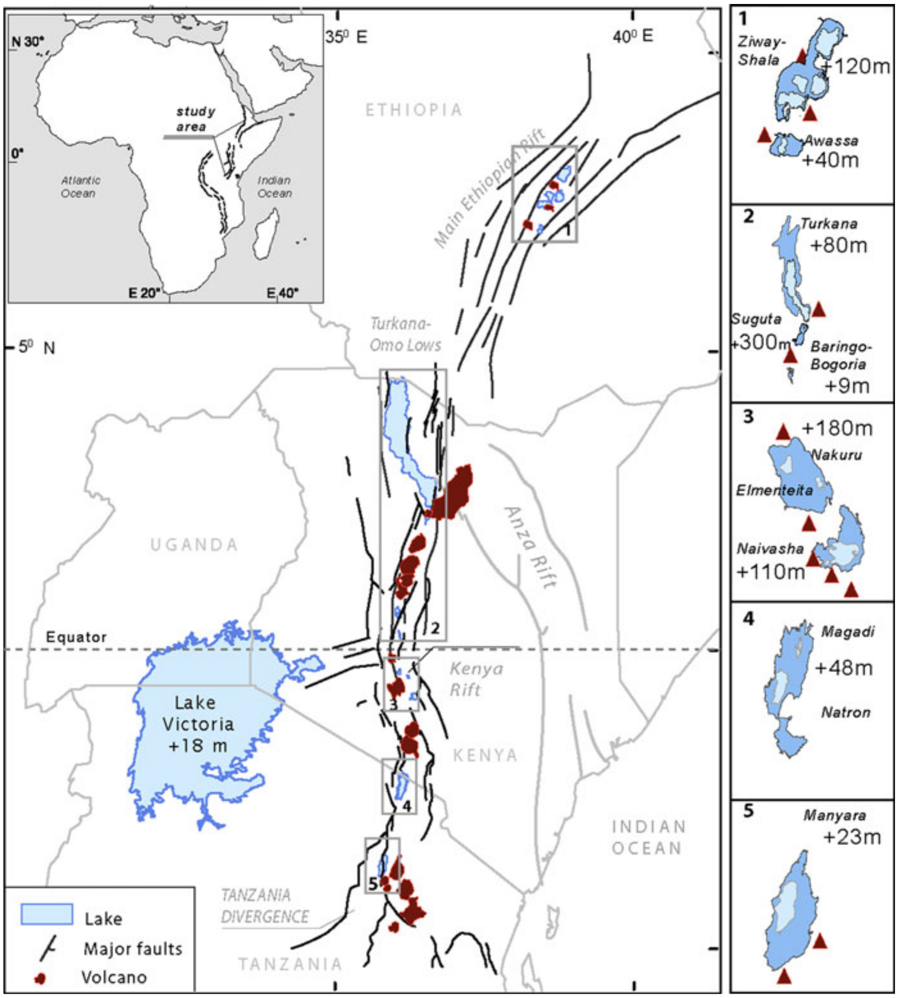


**Fig. 1** Map of the eastern branch of the East African Rift System (EARS) showing the lake basins of the study and the main faults and volcanic centers defining them. Insets 1–5 show the extent of the early Holocene lakes and their height above the modern lake (see Table 1 for references)

however, provide information about the slope and shape of lake basins and their catchments, both of which influence orographic rainfall distribution. From the swath profiles, we classified lakes as pan-shaped or graben-shaped. The former have greater oscillations in surface area relative to depth, while the latter have greater oscillations in lake level relative to surface area due to the constraining steep walls that bound them. The latter have high potential to yield good sediment records for paleoclimate studies, however the presence and preservation of biological and geochemical indicators of such climate changes depends on the chemistry of the lake.

The spatial distribution of HI values within the rift follows the general trend of the absolute elevation of basins above sea level (Fig. 4), with the exception of the Victoria basin. High values are found within the Kenyan and Ethiopian domes, whereas low values are observed in the intermediate zones of the Turkana-Omo lows and Tanzania divergence. This finding points to tectonic control because both the domes and the basin-and-range-type tectonic setting of the Turkana-Omo area relate to the thermomechanical state of the lithosphere at the time of rifting and basin formation (Buck 1991; Ebinger et al. 2000). Hot, weak lithosphere over the Turkana-Omo basin area developed broad rift zones bounded by low-angle border faults, creating pan-shaped basins with large basin areas (Fig. 1), while cold, strong lithosphere developed narrow rift zones bounded by high-angle border faults at the crest of the domes, creating graben-shaped basins in, for example, the Nakuru-Elmenteita, Naivasha, Ziway and Awassa basins (Fig. 4), with smaller basin areas (Table 1). A similar

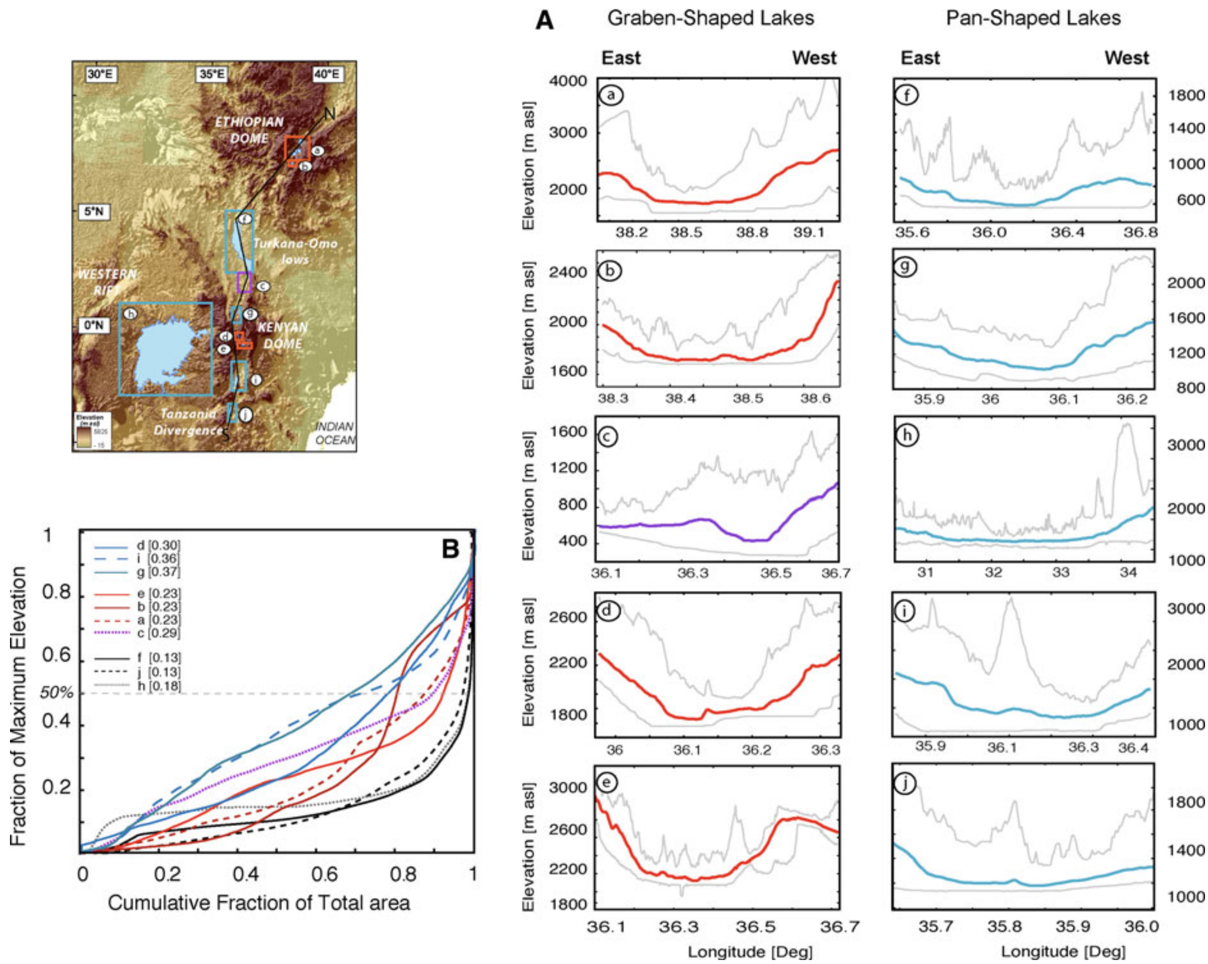


**Fig. 2** Morphometric characteristics from the SRTM (a) EW-oriented sections of swath profiles across the lake basins along the EARS derived from Shuttle Radar Topography Mission (SRTM) data. Each swath profile includes the lowermost 300 m of the lake basin. Bold lines indicate mean values of topography, thin grey lines are maximum (top) and minimum (bottom) elevations. Blue lines correspond to typical pan-shaped morphologies, whereas red profiles represent graben morphologies and the purple profile represents distinct half-graben morphology in lake basins (b) Hypsometric curves and hypsometric integrals of basins. The lowest values are for the lakes that lie at the northern and southern termination of the Kenya rift, while the intermediate values represent lakes in the Ethiopian and Kenyan domes. High values belong to the lakes in the intermediate elevations

study by Hurtrez et al. (1999) found tectonic control to be dominant on drainage basin hypsometry in regions subjected to rapid tectonic uplift rates, in the Siwalik Hills of the Himalayas.

Using size and basin morphology to define sensitivity of lakes, various studies have shown that basins with large catchment-to-lake-surface area ratios have large amplification factors. Thus, they do not require a high input of water to maintain a positive hydrological balance (Burrough and Thomas 2009). In our study, it could explain the magnitude of paleolakes in the Suguta, Ziway-Shala, Naivasha, Awassa and Turkana basins (Table 1). However, we see exceptions to this rule in the Magadi-Natron and Baringo-Bogoria basins. For instance, Lake Manyara has a catchment-to-lake-surface area ratio of 24, but the highest lake level recorded was only 23 m above the current lake level. In some of these examples, overflow toward adjacent basins explains relatively low lake levels during periods of wetter climate. While important for some regions, size ratio is not the sole determinant of response to climate change for

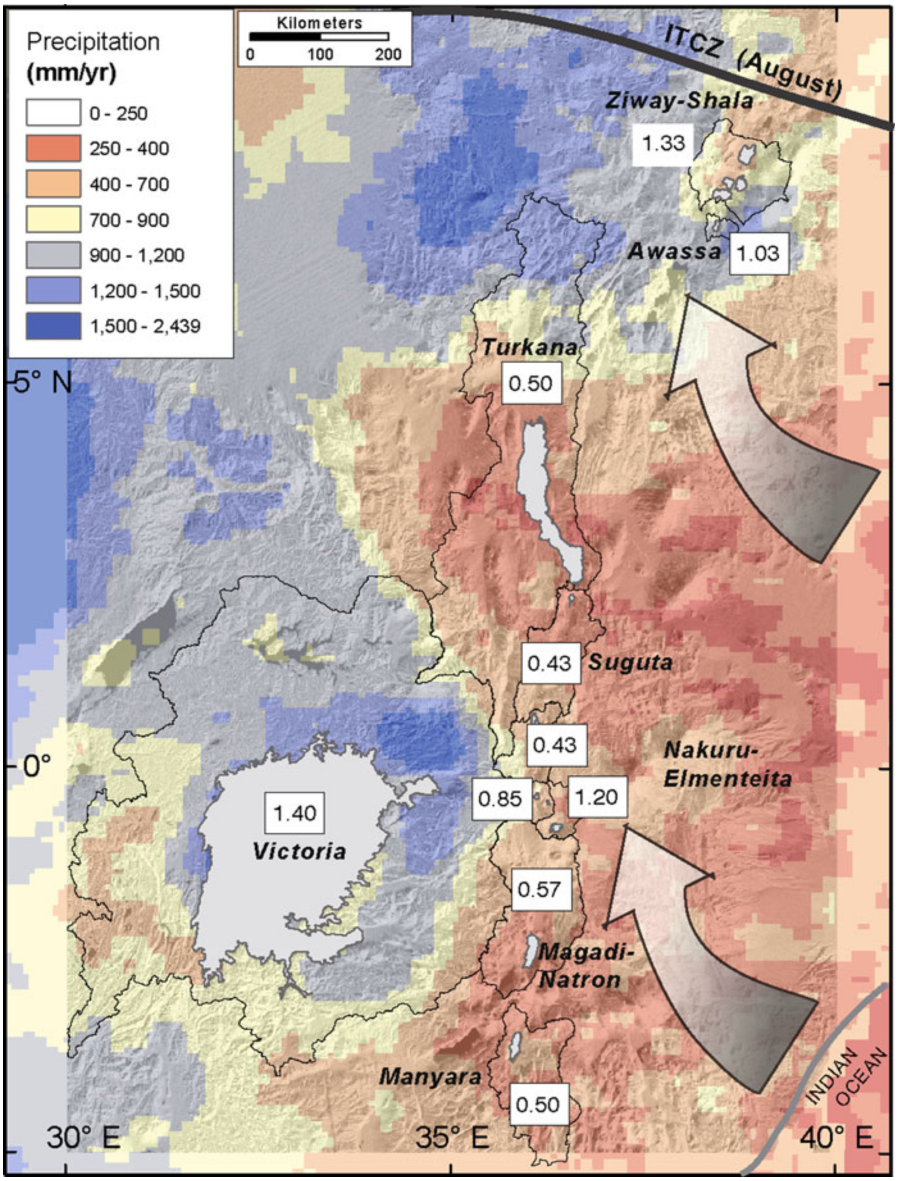


**Fig. 3** Spatial distribution of aridity index values. The arrow shows wind direction from the Indian Ocean. High aridity index values are seen in the domes of Ethiopia and Kenya, which capture moisture-laden air from the Indian Ocean. Victoria is a large water body that is dominated by convective rainfall

the lakes of the EARS (Table 1). Lakes with larger groundwater catchments than surface-water catchments cannot be classified with this method. These include such EARS lakes as Nakuru-Elmenteita, Magadi-Natron, Baringo-Bogoria. Thus both surface and subsurface input must be considered, along with information on size and morphology of the lake basins.

We used the aridity index to describe the effective moisture within basins. Using the UNEP classification scheme, regions with an aridity index >0.65 are classified as humid, while those <0.65 are divided into four arid subclasses, from dry sub-humid to hyper-arid. Sub-humid to sub-arid basins in the EARS are Suguta (0.43), Baringo-Bogoria (0.43), Manyara (0.50), Turkana (0.54) and Magadi-Natron (0.57). Humid basins are Nakuru-Elmenteita (0.85), Ziway-Shalla (1.33), Awassa (1.03), Naivasha (1.20) and Victoria (1.40). Because aridity indices correlate directly with precipitation and inversely with potential evapotranspiration, a low aridity index for a region means low rainfall because rainfall is hindered by greatly heated land surfaces and presence of dry descending air. Lower elevations (<1,500 m asl),

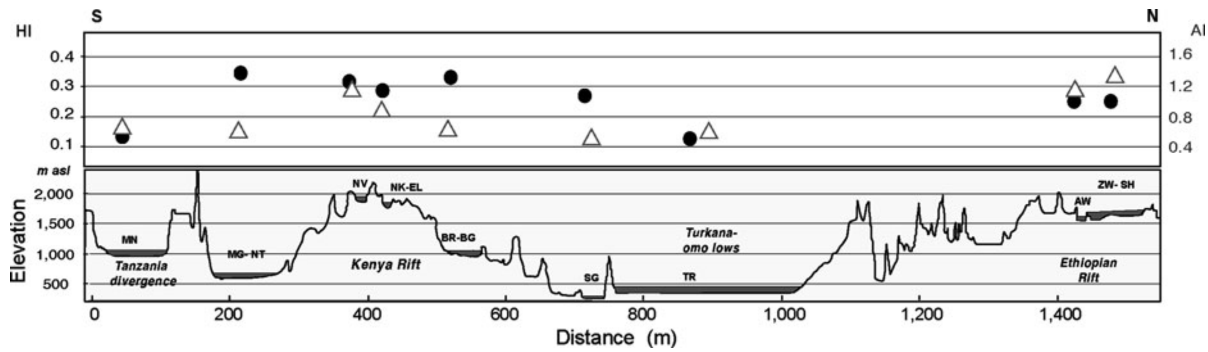


**Fig. 4** Topographic cross-section through the lake basins from south to north and the corresponding hypsometric integral (HI; circles) and aridity index (AI; triangles) values of lake basins. The high values of HI and AI correlate with Ethiopian and Kenyan domes, whereas low values appear at the terminal end of the Kenya rift ( ~4°S latitude) and between the Kenyan and Ethiopian rift at the Turkana-Omo lows ( ~4°N latitude). The basins are labeled as follows: MN -Manyara, Mg-NT -Magadi-Natron, NV- Naivasha, NK-EL- Nakuru-Elmenteita, BR-BG -Baringo-Bogoria, SG -Suguta, TR -Turkana, AW -Awassa, Zw-SH -Ziway-Shalla

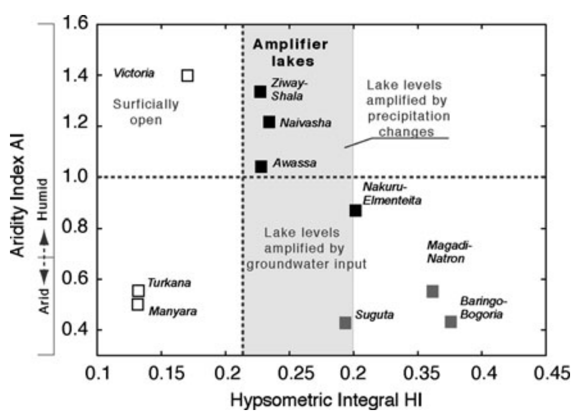


**Fig. 5** Hypsometric integral (HI) plotted against the aridity index (AI) of the basins of the EARS. Sensitive lakes plot in the top center, an ideal combination of a hypsometric integral of 0.23–0.30 and an aridity index > 1. The most sensitive lakes lie at the highest point of both the Kenyan and Ethiopian domes

such as the intermediate zones between the domes and the flanks of the domes, correspond to lower aridity indices (drier conditions) due to rain shadowing from the Indian Ocean moisture and relatively high air temperatures. The Victoria basin, though only 1,100 m asl, is relatively humid as it is not influenced by orographic rain shadowing and receives rainfall from the plateaus in both the western and eastern arms of the EARS, both at high elevations ( ~3,200 m). High-elevation lakes include the Nakuru-Elmenteita, Naivasha, Awassa and Ziway-Shalla basins, which have high aridity indices (Fig. 5). Their landmass is distributed across the high-elevation plateaus (>2,500 m), which capture most of the moisture coming from the Indian Ocean.

Climate in the EARS is influenced greatly by topography. Plotting the hypsometric integral (HI) and aridity index (AI) values against altitude illustrates this relation. The aridity index of the lakes increases with altitude (Fig. 4). The Ethiopian and Kenyan domes create an orographic barrier that captures the moisture-laden air from the Indian Ocean and the highlands receive high rainfall, as observed in high-elevation (>1,500 m asl) lakes such as Naivasha (1,885 m asl), Awassa (1,680 m asl) and Ziway-Shala (1,636–1,557 m asl). The intermediate zones are in the rain shadow, thus their aridity index values decrease away from the crest of the domes in the Suguta, Turkana, Baringo-Bogoria, Magadi-Natron and Manyara basins. The AI of Lake Victoria (1.4) reflects high rainfall and relatively low evapotranspiration in a catchment that includes the plateau areas of both arms of the rift and the large lake area of 68,800 km$^2$, which is more humid as a result of local convectional rainfall.

We used early Holocene lake levels from published paleoshoreline studies (Table 1) to explore the sensitivity of lakes to climate change. In some basins, preservation of the sediment record is not perfect, especially in the pan-shaped basins, because of reworking and erosion of sediments during arid-to-humid transitions. The most dramatic change was observed in the Nakuru-Elmenteita and Suguta basins, where early Holocene lake levels were 45× and 75× higher than today, respectively. Both have graben shapes and HI of 0.23 and 0.29, respectively. Their basins receive lower rainfall (AIs of 0.85 and 0.45), and we suspect a significant contribution of groundwater from neighboring basins kept water levels high. In the Kenyan rift, studies have shown that groundwater flows from the Naivasha basin to the north and south, following the hydraulic gradient created by the up-doming of the central section. Therefore, the amplifier effect of Lake Naivasha also contributes to the Lake Nakuru-Elmenteita system. Analogously, high-elevation Suguta lake received significant groundwater inflow or even surface overflow from the high Baringo-Bogoria system during the early Holocene (Garcin et al. 2009) that compensated for the extremely low aridity index of these basins.

The EARS's diverse lakes were valuable for sensitivity studies using empirical measures. According to this approach for evaluating sensitivity of lakes to climate fluctiations, lakes with a combination of an aridity index >1 and a hypsometric integral $\sim$0.23 plot as the most sensitive (Fig. 5) to local and regional climatic changes. These are rift lakes with graben morphologies and humid conditions, such as Naivasha, Awassa and Ziway-Shala. Their water balance is dominated by rainfall and surface inflow. Other lakes, such as Nakuru-Elmenteita and Suguta have graben morphologies and ideal hypsometry values, however, they receive low rainfall, and thus do not make good archives of local arid-humid transitions, because they receive significant groundwater from neighboring basins. They do however, archive regional climate changes. This helps explain why lake level changes during the early Holocene varied in magnitude among the lakes of the EARS. Because both basin morphology and climate are the consequence of up-doming and rifting in East Africa, this study highlights the importance of site-specific morphometry in tectonically controlled basins for unraveling climate histories from sediment records.

## Conclusions

Previous shoreline studies of lakes in the EARS showed high water levels during the Holocene, though modeling results show only 25% more rainfall, which cannot account for the high lake levels. The "amplifier lake" concept was introduced by Street (1980) and Street-Perrott and Harrison (1985) to explain this phenomenon. We expanded upon this concept in our study by including a detailed morphometric analysis of basins using SRTM Digital Elevation Model and climate data. Considering the early Holocene high lake levels, we found that a lake basin with a hypsometric integral (HI) value between 0.23 and 0.30 and an aridity index (AI) > 1 responds sensitively to climate changes. Both of these variables are directly linked to tectonics in the EARS. The rift lakes have distinct graben morphologies related to up-doming, rifting and volcanism within the EARS. The steep walls of such grabens inhibit wind-driven mixing, as opposed to the situation in pan-shaped basins. Of the ten lakes we examined, three are "amplifiers" and have provided adequate sediment records for paleoclimate studies. The non-uniform responses of lakes to climate change because of morphometric differences, dictates that caution be used in generalizing about climate inferences derived from a single lake in the EARS. Careful calibration of basins and modeling of lake responses can be used to better constrain the nature of lake responses to climate. Studies of modern lake responses to climate shifts is of interest to planning and management authorities who must deal with future climate-change scenarios. Our findings come from study of the lakes in the eastern arm of the EARS, but may also apply to similar geomorphologic and climatic settings elsewhere.

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