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Geomorphology, hydrology, and ecology of Lake Urema, central Mozambique, with focus on lake extent changes

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Abstract

Lake Urema is one of the most important ecological features of Gorongosa National Park, located in central Mozambique, in the East African Rift System. Understanding hydrology and ecology of the lake and its tributaries is particularly important for the conservation of the Park's floodplain habitats and its biodiversity. There are concerns that hydrological boundary conditions and ecology of Lake Urema have changed in recent years. Possible causes for this change include climatic and land use changes as well as tectonic and geomorphological processes. In this study, a multi-temporal and multi-disciplinary approach was applied to investigate the dynamics and control mechanisms of Lake Urema. Principal methods comprised remote sensing analyses of time series of Landsat and ASTER data, geomorphological interpretations of a Digital Terrain Model (DTM) as well as field investigations such as analyses of water quality and sediment composition. The waters of Lake Urema have a low mineralization and pH values approximately neutral. The spatially dominant sediment type has a pure clay texture consisting of kaolinite and smectite. The sandy type consists of quartz, kali felspar, and plagioclase. The results of the supervised classifications for the satellite images from 1979 to 2000 showed that the lake's extent ranged between 17 km^2 (09/1995) and 25 km^2 (08/1979). Above average rainfall was responsible for the extreme lake size in May 1997 (104 km^2). The interpretations of the Digital Terrain Model demonstrated that alluvial fans limit the Urema basin from all sides and make Lake Urema a form of "reservoir lake". The control mechanisms of the hydrological regime of Lake Urema, such as the contribution of groundwater, are not yet fully understood. The lake's condition during the rainy season was not investigated. In the future, investigations of the sources and amounts of sediment input into the lake should be conducted.

Keywords: Floodplain; Remote sensing; Reservoir lake; Sediment composition; Savanna; Water quality

1. Introduction

Lake Urema (LU) and the surrounding floodplain grasslands are an important, if not the most important, ecological feature of Gorongosa National Park (GNP), which was called the "jewel in the crown of Mozambique's National Parks" (Tinley, 1977) prior to the civil war in Mozambique (1976–1992). At that time the Urema floodplains were inhabited by a variety of wildlife

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including hippopotamus, buffalo, elephant, wildebeest, zebra, water buck, impala, oribi, sable and eland (Tinley, 1977).

There have been concerns that LU's extent has been decreasing for the last 20 years. The drying-up of these wetland habitats could then lead to bush encroachment with consequences for the ecosystem such as a shift from grassland species towards savanna woodland species (Tinley, 1977). Burlison et al. (1977) investigated whether a drying-up of the wetland areas of GNP is taking place. A related concern is that siltation of the lake is occurring due, presumably, to increased soil erosion.

Reasons for a change of the lake's extent can be diverse, including impacts of climate change, neo-tectonic movements, geomorphologic and anthropogenic causes. The latter include land use changes in the catchment area (deforestation) located outside GNP and the near eradication of hippopotamus, which are considered to act as an ecosystem engineer through their ability to open and maintain channels (McCarthy and Ellery, 1998).

After a comprehensive study of Tinley in 1977 about the Gorongosa ecosystem, SWECO & Associates (2004) investigated the hydrological regime of the Pungoe River Basin and Owen (2004) looked at that of the Gorongosa Ecosystem. However, hydrology and ecology of LU was never the subject of an in-depth scientific study.

An interdisciplinary and integrated approach was applied to (a) quantify LU's size variations over the last 20 years and (b) investigate the controlling factors of LU's hydrological regime, its hydrogeochemistry and sediment composition.

2. The Lake Urema area

LU and the adjacent floodplains are located in the Sofala Province/central Mozambique (cf. Fig. 1, left). They are part of the GNP (6330 km^2), (Legal Diploma 27/50, 2767, 2935) which is situated in the Urema Rift, the southern end of the East African Rift System. West of the Rift Valley are the Báruè Midlands, consisting of Precambrian gneisses and migmatites with an altitude of 300 to 800 m a.s.l. (Edição Dos Serviços de Geologia e Minas, 1968; Lächelt, 2004). Gorongosa Mountain (1863 m a.s.l.), an isolated Cretaceous granitic intrusive complex, is located within the Midlands. To the East of the Rift Valley, the Cheringoma Plateau (300 m a.s.l.) consists of a sequence of Cretaceous to Pleistocene sandstones and limestones. The Rift floor is covered by unconsolidated Pleistocene to recent alluvial deposits and has elevations below 100 m a.s.l. The deepest part of the Rift floor is occupied by LU (14 m a.s.l.).

Central Mozambique is influenced by the monsoon circulation and the impact of El Ninõ/Southern Oscillation (ENSO) events. ENSO occurred in 1982–1983, 1986–1987, 1991–1992 and 1994–1995, and caused collateral droughts in Mozambique (Eastman et al., 1996). In 1997, an excess of rainfall was reported (NOAA, 2005). A cold ENSO event in February 2000 triggered heavy floods in southern and central Mozambique (UCAR, 2005), which however had no impact on LU's catchment area. Following Köppens Climate Classification System the study area is designated as a Wet-Dry Tropical Savanna Climate (Aw) with a moist, warm season from November to April and a cool, dry period from May to October (COBA & PROFABRIL, undated). The climate station in Chitengo, situated in the Urema Rift, has registered an annual

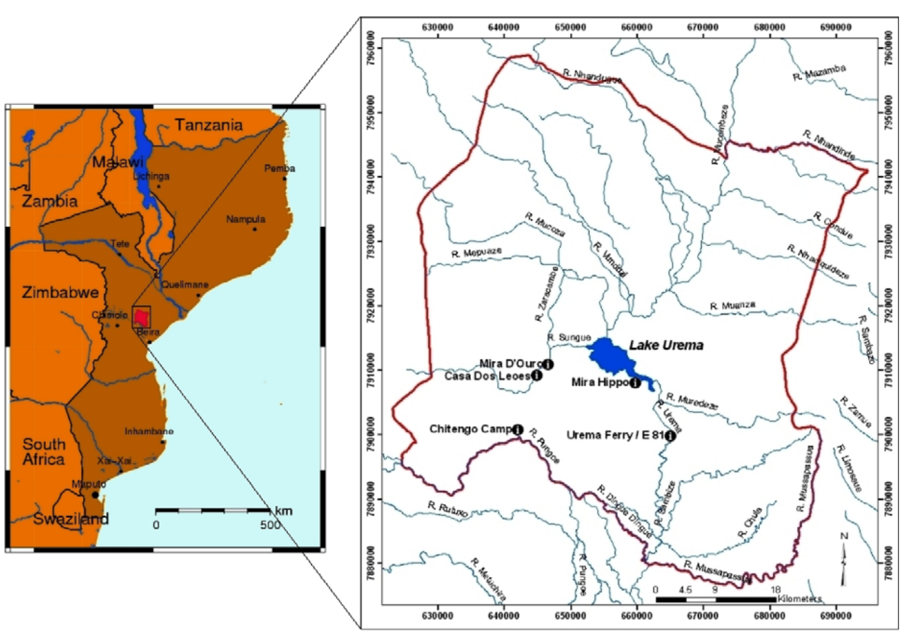

Fig. 1. Location of Gorongosa National Park (black frame in the left image) in central Mozambique; left image Wobbe (2005), right image based on IGN.FI CENACARTA (1999) and DINAGECA (1997/98).

precipitation of about 900 mm (ARAC, 2004). According to global climate estimators, there exists an annual water deficit of 600–800 mm in the Rift (Owen, 2004). Gorongosa Mountain receives an annual precipitation of up to 2000 mm due to orographic rainfalls (Tinley, 1977). Between these two precipitation extremes are the Báruè Midlands and the Cheringoma Plateau with 800–1200 mm and 1000–1400 mm, respectively (Owen, 2004).

The low elevation gradient of the Rift floor causes the meandering and retarding of streams in wetlands. The Urema wetland system receives water from the Rift escarpments to the East and to the West, as well as from the Rift Valley floor (see Fig. 1, right). The Vunduzi River, which originates on Gorongosa Mountain, is an important tributary during the dry season (Tinley, 1977). The Urema River is the only surface outflow of LU and drains into the Pungoe River.

3. Methodology

Eleven satellite scenes from different sensor types were available for the period 1979–2000 (Landsat MSS, TM, ETM+ and ASTER). They were used to describe the intra- and inter-annual variations of the extent of LU. Image analyses were conducted with PCI Geomatica V9.1.x. Preprocessing comprised geometrical and atmospheric correction (Richter, 2005). Gaps in the spectral coverage due to missing or not assignable bands limited the image interpretation. To distinguish open water from other habitats a supervised Maximum Likelihood Classification with null classes and additional processes, such as PCA (Principal Component Analysis), NDVI (Normalized Difference Vegetation Index) and Tasseled-Cap-Transformation was used. The Tasseled-Cap-Transformation proved to be a suitable instrument for the intra- and inter-annual comparison of the vitality of the floodplain grasslands and therefore for the evaluation of areas under shifting water supply.

The drainage network, the catchment area of LU as well as the geomorphology were derived from the SRTM-Digital Terrain Model (Shuttle Radar Topography Mission, USGS), (Jenson and Domingue, 1988), which has a horizontal resolution of 90 m and a vertical resolution of 1 m (SRTM, 2004).

During fieldwork conducted between September and November 2004 water temperature, pH-values, electrical conductivity, concentration of dissolved oxygen and redox potential at a nominal depth of about 20 cm in the inflow, outflow and in the lake water was measured. Additionally, Secchi-disc transparency was determined. Water samples for the laboratory analyses via Ion-Chromatography and for the determination of Total Inorganic Carbon (TIC) and Dissolved Organic Carbon (DOC) were taken in October 2004.

In order to describe the sedimentation pattern in LU five sediment cores of 0.3 m length (see Fig. 4) were taken. The sampling was restricted to shallow sites at the southwestern shoreline as only a simple Polyacryl-core for manual coring was available. Grain size distribution of the samples and their mineralogical composition was determined in a laboratory. For the latter XRD (X-ray diffractometry) was utilized separately for the silt-clay fraction (smaller than 63 μm) and the sand fraction (63–2000 μm).

4. Results

4.1. Delineation of the catchment area and modeling of the drainage network

The entire catchment area of the Lake Urema derived from SRTM90 comprises 8755 km^2 and forms three major subcatchments (see Fig. 2) with the Nhandugue-Mucombeze subcatchment covering about 68% of the total catchment area. The lake catchment/lake ratio (lake's extent extracted from satellite scene acquired in October 2000) is about 460, the shoreline development (ratio of length of shoreline to length of circumference of a circle with the same area as the lake) is 3.1.

4.2. State of the Lake Urema in the dry season 2004

In October 2004 the lake's extent was estimated with the tracking function of a handheld GPS (positional accuracy about 10 m). The resulting contour line was then compared with those extracted from the satellite images of the previous 10 years of dry season. The lake's extent in October 2004 was in the same order as the years before. Four depth profiles in the central part of the lake and in the narrowing lake arm were taken with sonar giving an average depth of 1.64 ± 0.13 m. The water volume of LU at that time was estimated at 30.3×10^6 m^3.

Between the 4th of September and the 28th of October 2004 the lake level decreased by 32 cm. An estimate of the water balance of LU for that time was conducted. It is assumed that the fluctuation of the lake level over time is related to the change in the lake's water volume and therefore Eq. (1) can be applied

$$dV/dt = (R + P + G_i) - (D + E + G_O) \quad \text{(Mercier et al., 2002)} \tag{1}$$

where

V = lake's volume,
t = period of change of the lake's water volume,
R = rate of surface runoff,
P = rate of precipitation on the surface of the lake,
G_i = rate of incoming groundwater seepage,
D = rate of discharge,
E = rate of evaporation from the surface of the lake,
G_O = rate of outgoing groundwater seepage.

Measurements of precipitation were conducted by the responsible water authority (ARA Centro, Beira) on the

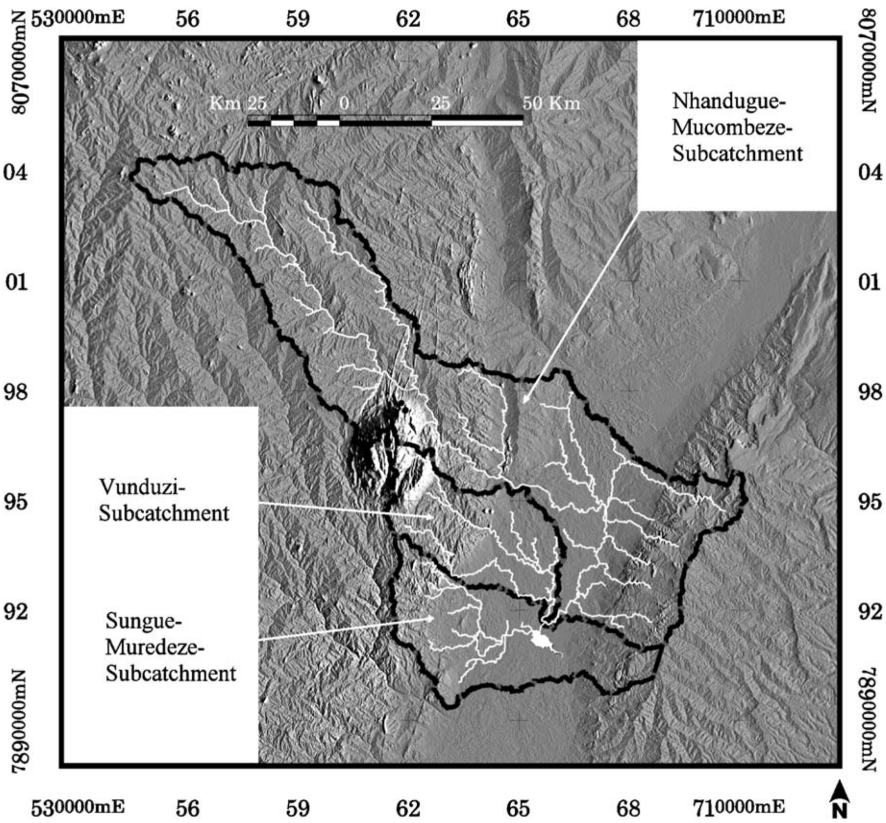

Fig. 2. Catchment area of the Lake Urema with sub-catchments and drainage system as derived from SRTM-DTM, sun elevation angle 30°, sun azimuth angle 90°.

Rift floor in Chitengo, approximately 18 km southwest of the lake. Rainfall was noted only twice in the period from September to October (0.8 mm and 1.6 mm). Water stagnated in the Urema River; the only surface outflow of the lake, and in large areas the river was covered by vegetation.

There is no available information for groundwater, therefore this component had to be discarded for the calculation of the water balance. Historical data of the potential evaporation in Chitengo, calculated with the energy balance method, were available (ARAC, 2004). A discharge of 1.65 m^3/s was measured in the Vunduzi River approximately 60 km upstream of the lake.

After interpolation of all components of the water balance equation, and considering that no surface outflow was observed, the lake level should have risen by 0.24 m during the period of September to October 2004.

The pH of the surface water samples varied locally between 5.9 and 9.1 with the lowest values in areas with little water circulation or stagnant conditions such as in bays or close to the littoral.

The majority of the measurements indicated neutral to slightly alkaline conditions. The electrical conductivity in the Vunduzi River (32 μS/cm) was comparable to that of rainwater sampled in Beira City (30 μS/cm) approximately 160 km from the Vunduzi River sampling site. The lake's average electrical conductivity was approximately 140 μS/cm. These low values coincide with the low concentrations of major anions and cations. Hydrogen carbonate was the dominant anion while sodium was the dominant cation (see Fig. 3). Measurements of the redox potential indicated predominantly oxidizing to partly oxidizing conditions (on average 400 mV_h).

A striking characteristic of LU is its low Secchi-disc transparency (0.44 ± 0.11 m).

According to local fishermen (pers. comms.) and our observations, the majority of the lake basin is covered with very fine-grained sediments. Three sediment cores were dominated by a pure clay texture (grain size < 0.002 mm) or showed a layer of medium sandy clay over a layer of pure clay (S02, S03, S04, see Figs. 4 and 5). Another two cores, sampled in the narrower part of the lake (S00, S01) consisted of pure sand (dominant grain size 0.2–0.63 mm). The mineral composition of four samples is shown in Fig. 4. The organic rich top layer was determined as gyttja, a coprogenous subhydric sediment containing inorganic precipitates and particulate organic matter (Wetzel, 2001).

4.3. Size of Lake Urema from 1979 to 2000

Results from the satellite image processing, i.e., classifications and threshold for the NDVI, do not indicate any trend in the variation of the lake's size. The area of the lake ranged from 17.4 km^2 in September 1995 to 25.1 km^2 in August 1979 (mean 20.5 ± 2.8 km^2, see Fig. 6). The lake's

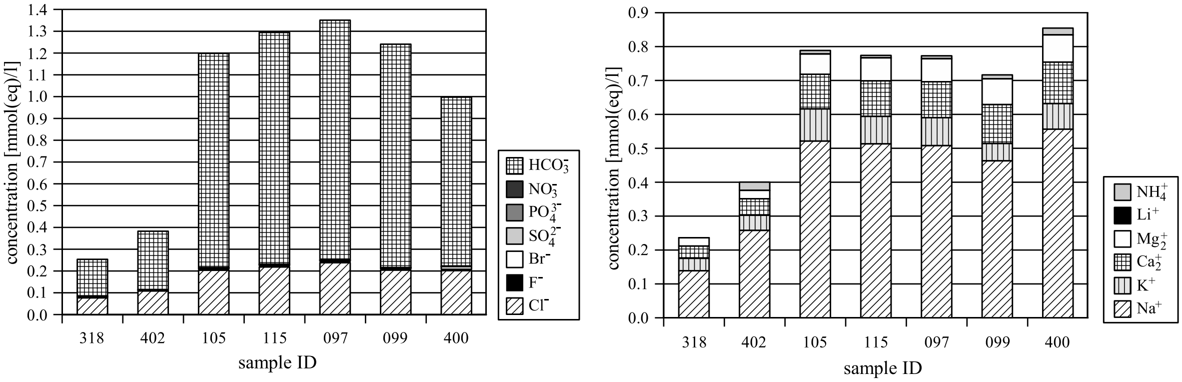

Fig. 3. Major anions (left) and cations (right) in the Vunduzi River (site 318), in the Urema River (site 400) and in the lake; site 402 in the inflow region of the lake.

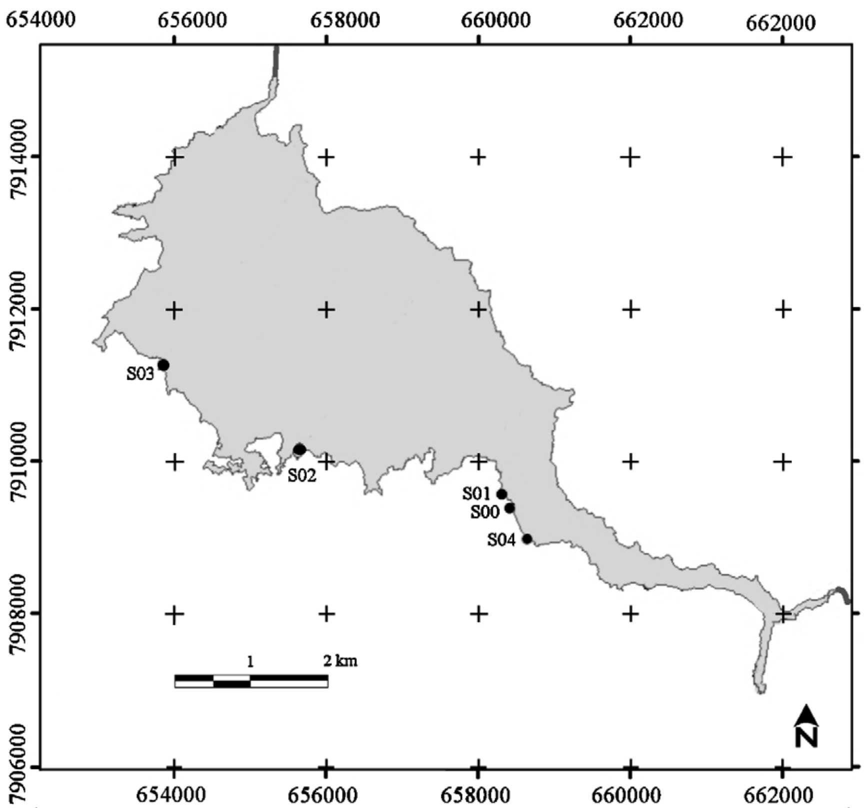

Fig. 4. Location of sediment sampling sites; S03-2 and S03-3 represent the same sample site with S03-3 lying below S03-2.

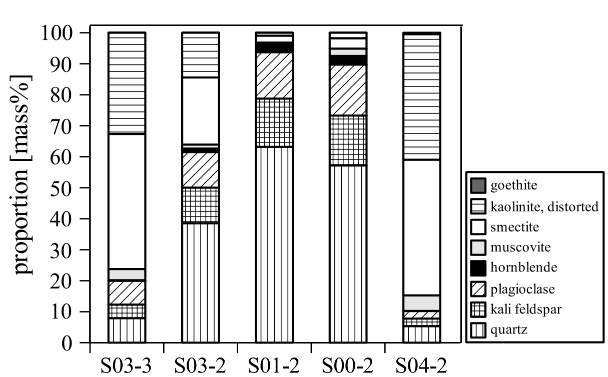

Fig. 5. Mineral composition of sampled sediment cores.

extent from the Landsat TM scene of May 1997 was excluded from calculation of the mean size to avoid an overestimation of the lake's extent because in 1997 the flooded area measured 104.1 km^2 and was associated with a periodic climate event. The intra-annual variation of the lake's size in 1994 (scenes from May and July), 1995 (May and September) and 2000 (October and December) is less than one square-kilometer.

Using the SRTM-DTM and the extent of the lake in May 1997 the difference between the water volume of LU under "normal precipitation" conditions (such as in October 2000) and during "above average rainfall" (May 1997) amounts to $248.9 \times 10^6\ m^3$. The difference in the

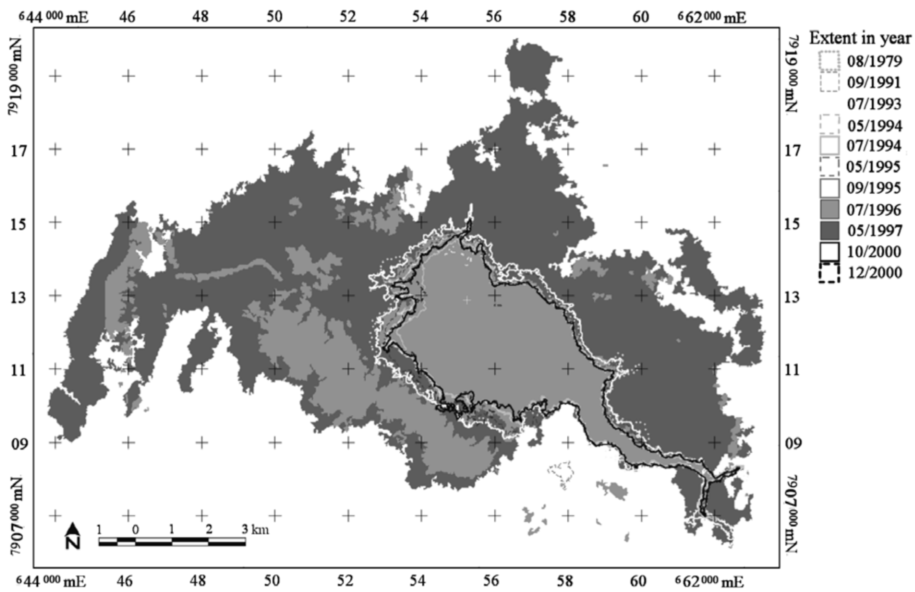

Fig. 6. Sizes of LU from 1979 to 2000 and occurrence of flooded areas around the lake.

lake's volume is equal to 50% of the Mean Annual Runoff (MAR) and 3% of the Mean Annual Precipitation (MAP) in the catchment area (data for MAR and MAP from SWECO & Associates, 2004).

4.4. Regulation of the hydrological regime of Lake Urema

Analysis of earthquake data from the Harvard Seismology CMT catalog (CMT, 2005) shows that earth tremors occur frequently in the Rift and indicates high tectonic activity (see Fig. 7). The Centroid Moment Tensor

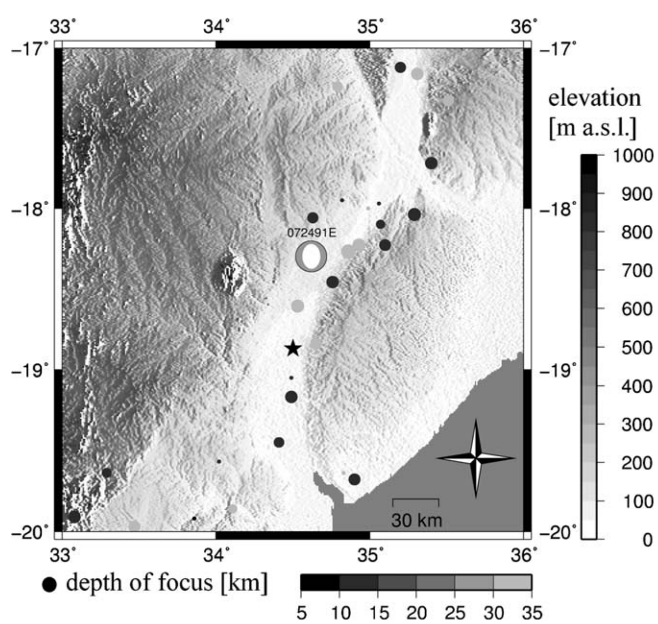

Fig. 7. Seismic activity in the Urema Rift between 1973 and 2004. Star symbol indicates location of LU. Data acquired from Harvard Seismology CMT catalog (CMT, 2005), underlying relief from GTOPO30 (USGS, 2005).

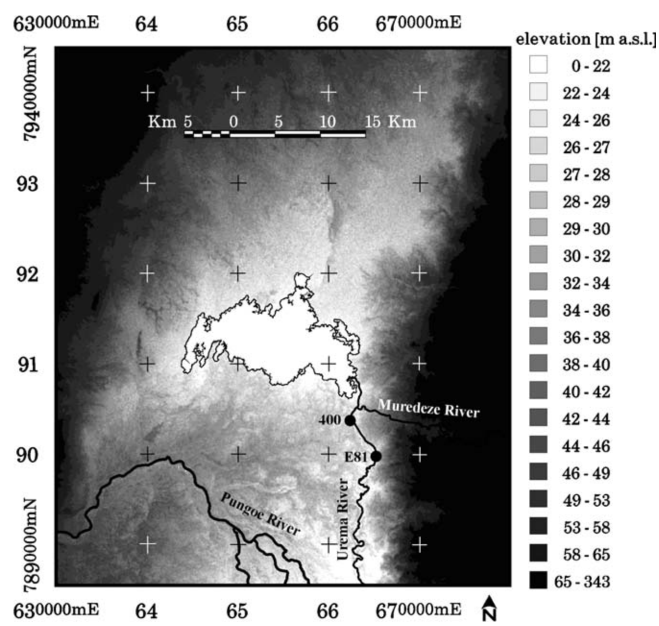

Fig. 8. Detail of the Urema basin from SRTM-DTM, showing flooded areas (in white) in May 1997.

(CMT) focal mechanisms indicate an east–west extension of the Rift. Four shallow earthquakes occurred in the vicinity of the lake in the 1980 s. The impact of seismicity on the hydrological regime of the lake and its catchment area has not been determined.

The analysis of the Digital Terrain Model demonstrated that the extent of LU is delimited by alluvial fans formed by rivers originating from the Rift escarpments (see Fig. 8).

5. Conclusions and recommendations

This study shows that significant variations of the extent of LU and flooded areas in its vicinity are related to extraordinary flood events. The flood of 1997 is linked with three tropical storms which contributed to abundant rains over south-eastern Africa during the 1996/1997 wet season (NOAA, 2005). The variance of the open water surfaces of LU is relatively low (standard deviation of 2.8 km^2) between 1979 and 2000. Using the SRTM-DTM it is demonstrated, that the structure of the drainage system of LU is morphologically controlled. LU is therefore classified as a reservoir lake, which in accordance with Wetzel (2001), owes its existence to an impounding structure, in this case the alluvial fans. Flooded river valleys are characterized by a narrow, elongated shape and a shore line development clearly larger than 2 (Wetzel, 2001). For LU this parameter is 3.1. As was illustrated during an extraordinary flood event in May 1997, these fans are both a morphological barrier for the extension of the lake and a natural dam, controlling its surface outflow. At the time the lake's extent was five times greater than mean size (104.1 km^2 vs. 20.5 km^2) and completely bounded by the fans structures (see Fig. 8).

The water of LU, its tributary Vunduzi River and its outflow Urema River show a low mineralization indicating both the influence of low mineralized groundwater (gneiss, granite, sandstones dominating in the catchment area) and/or the supply of surface waters. The low concentration of dissolved minerals implies that the lake water is not significantly enriched by evaporation and must have a very short retention time. Since we did not detect any direct surface outflow during the dry season of 2004 we assume that a significant amount of the lake's water is channeled through groundwater.

The widespread distribution of clayey sediments over large parts of the lake and the evidence of sandy sediments in the narrowing part of the lake, towards its outflow, suggests a temporally and spatially constrained pattern of transport and deposition. The deposition configuration and types, as well as the incised lake floor (shown by bathymetric profiles), correspond with the hypothesis that the axial part of the lake is characterized by a more energetic flow and the lateral areas by quiescent conditions.

Our evaluation of a 20 year time-series of satellite images suggests that the disappearance of LU is not a concern under current conditions. A major threat to the wetland system is, however, the siltation of the lake through increased sediment input from the catchment area, which is probably caused by non-sustainable land-use practices. Soil erosion could also contribute to the alteration of the water availability in the catchment area through decreased infiltration and accelerated surface runoff. If the envisaged dam at Buè Maria is to be constructed its influence as a significant agent of change to the hydrological regime must be very carefully studied.

Our integrated study shows that the lake's extents and dynamics are predominantly controlled by geomorphological barriers, which buffer drainage and in turn influence the entire surrounding Urema ecosystem.

Further work should focus on:

(1) Contribution of groundwater to the lake's water balance. Groundwater and lake level measurements, chemical analyses and the use of stable isotopes ^{18}O and ^{2}H can help to separate the groundwater

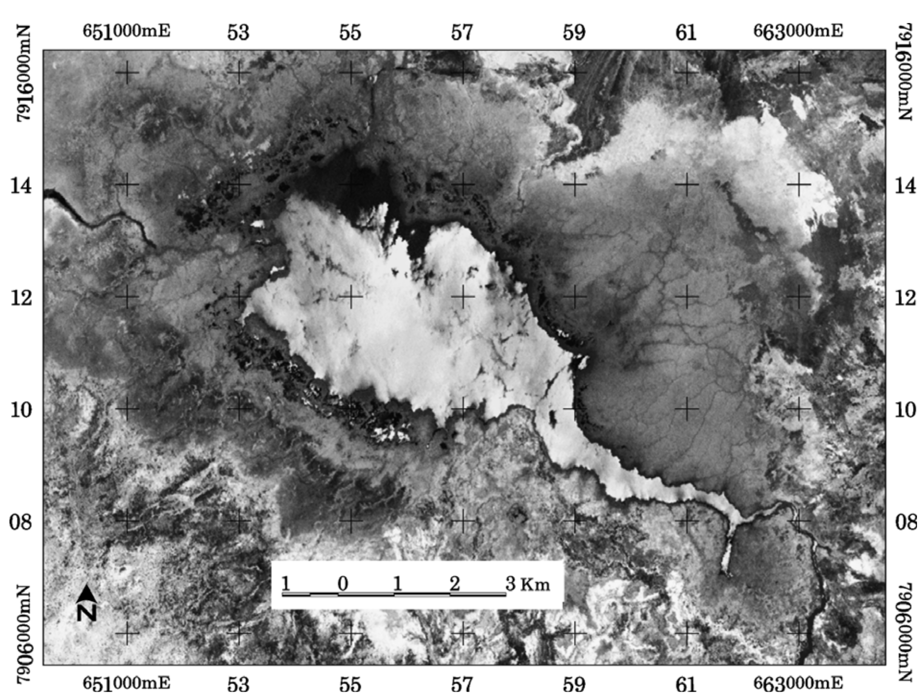

Fig. 9. ASTER scene from 2nd of October 2000, band 1–2–3 showing LU in the center, dark areas in the water body indicate lower concentrations of suspended matter than lighter areas.

component from the surface water component and to correlate groundwater level fluctuations to variations in lake level height.

(2) Improvement of the data base of main climate and hydrological parameters in the catchment area. Flow measurements at the major inflows and at the outflow of the lake are recommended.

(3) Investigation of the pattern of sediment deposition, which can be monitored with bathymetric measurements.

(4) Turbidity measurements in the inflows throughout the year. We estimate that there is a considerable difference between the sediment load in the dry season and in the wet season. The monitoring of suspended loads in the water body of LU is possible using a remote sensing approach. Concentrations of suspended solids/water clarity are positively correlated with the reflectance in the visible and near-infrared wavelengths (see Fig. 9, also Nellis et al., 1998).

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