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Geology and geomorphology of the Urema Graben with emphasis on the evolution of Lake Urema

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ABSTRACT

The Lake Urema floodplain belongs to the Urema Catchment and is located in the downstream area of the Pungwe River basin in Central Mozambique. The floodplain is situated in the Urema Graben, which is the southern part of the East African Rift System. Little geological information exists about this area. The circulated information is not readily available, and is often controversial and incomplete. In this paper the state of knowledge about the geology and tectonic evolution of the Lake Urema wetland area and the Urema Catchment is compiled, reviewed and updated. This review is intended to be a starting point for approaching practical questions such as: How deep is the Urema Graben? What controls the hydrology of Lake Urema? Where are the hydrogeological boundaries? Where are the recharge areas of the Lake Urema floodplain? From there information gaps and needs for further research are identified.

1. Introduction

The Lake Urema floodplain belongs to the Urema Catchment and is located in the downstream area of the Pungwe River basin in Central Mozambique (Fig. 1). It is situated in the southern part of the East African Rift System (EARS) – here called Urema Graben (UG). This graben structure and Mount Gorongosa just west of it are considered as the main features generating conditions for an ecological hotspot with potential of wildlife abundance and diversity. The southernmost part of the Urema Catchment is host to Gorongosa National Park (GNP), whose administration's aim is to restore the past biodiversity. The wildlife was sustained from natural water sources such as Lake Urema. Geology and tectonic settings are the underlying factors, which influence soil properties, landscape morphology, hydrological patterns, type of aquifers and consequently biodiversity and habitats of the Urema Catchment area.

Controversial and incomplete information about the geology of the area containing the Lake Urema floodplains, is found in publications often uncritically copied from author to author. Also the role of groundwater in sustaining the Lake Urema wetland ìs left aside or negliged, because little is known about hydrodynamic properties of rock formations in the study area. This paper is intended to compile, review and update knowledge about the geology and tectonic evolution of Lake Urema wetland area and the Urema Catchment as well as to pinpoint needs for further research.

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2. Regional geology and tectonic evolution

2.1. Precambrian basement evolution

The geological past of UG reaches as far back as to Archaean age. The oldest geological element, which influences geotectonic processes in the region until today, is the Archaean–Proterozoic Zimbabwe Craton, which belongs to the larger Kalahari Craton (review in Lächelt, 2004). It is made of granite–gneiss–migmatite complexes and several greenstone belts. Windows of Archaean rocks in Proterozoic rocks were mapped close to the Zimbabwean border in Manica Province by Hunting (1984). The linkage of Precambrian with cross-bordering geological units in the surrounding countries was made by Hartzer (1998). Details on the geotectonic evolution from the Archaean to the Neoproterozoic period in a modern view and a revision of former subdivisions was produced by the GTK Consortium (2006). The Urema Catchment area belongs to the so-called South Gondwana Terrane made of Archaean and overthrusted Proterozoic tectono- and lithostratigraphical elements, such as the Bárué Complex (GTK Consortium, 2006, p. 117).

The northwestern part of the Urema Catchment consists of the W–E stretching Mutare-Manica Greenstone Belt. The ENE–WSW striking Mutare Segment of this belt is an asymmetric syncline–anticline–syncline succession. The northern part is called Penhalonga syncline, which has a shallow, eastwards plunging dip. Two generations of Archaean granitoids occur in the area of interest, whereas only the younger granitoids were mapped at a scale of 1:250,000 (GTK Consortium, 2006, p. 122). The granitoids, together with felsic metamorphic rocks, are lumped under the term

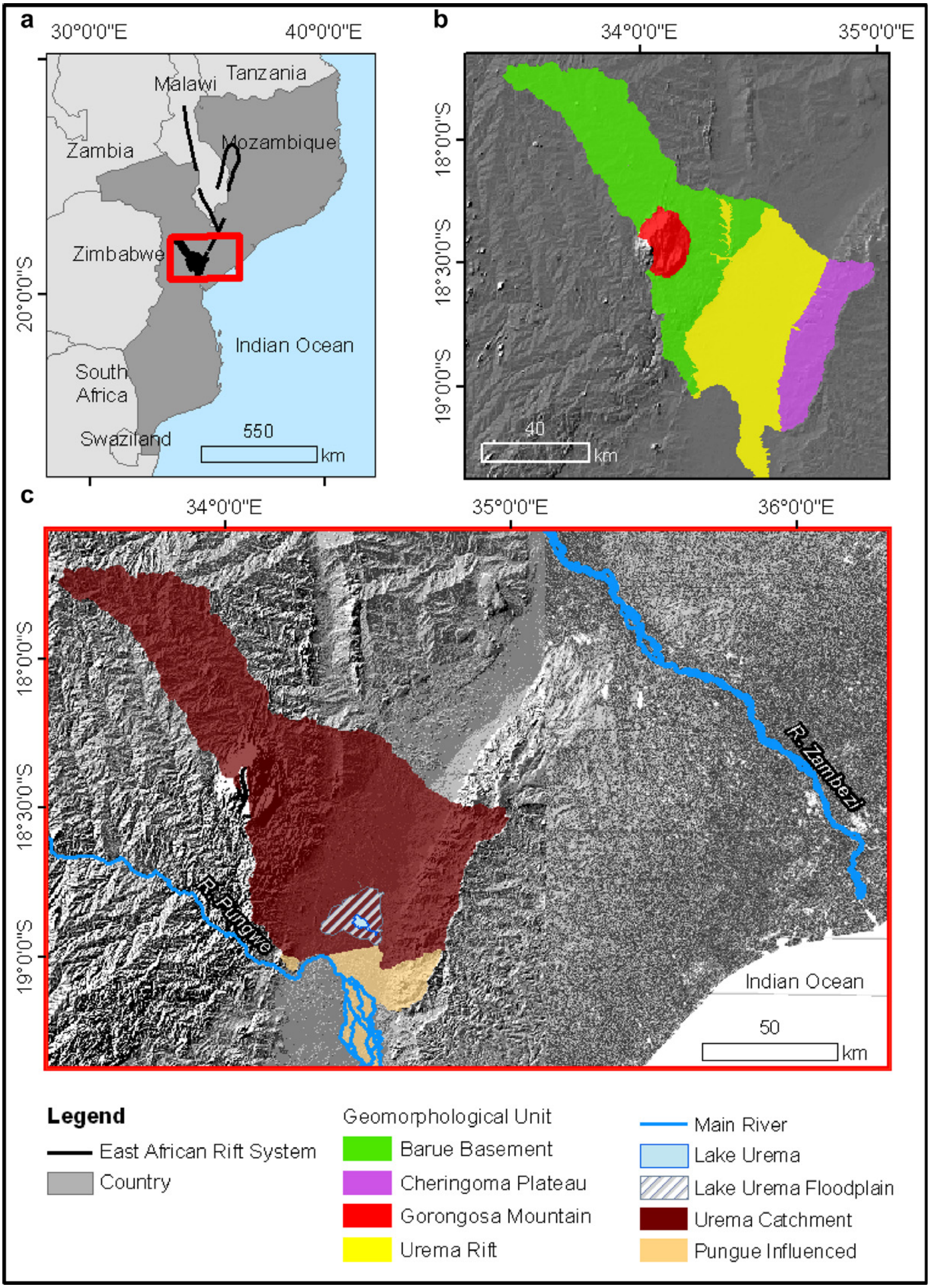

Fig. 1. Overview maps: (a) Location in Africa. (b) Geomorphological units. (c) Urema Catchment (ESRI and USGS basemaps, background hillshade derived from USGS SRTM 90 m).

Mavonde Complex and have generally a Neo-Archaean age (2.5–2.8 Ga), (GTK Consortium, 2006, p. 129). A fault with an east-dipping slope, which is thought to be caused by the evolution of the East African Rift System (EARS), separates the smoother eastern part of the Mavonde Complex from the rougher, high-altitude western part (GTK Consortium, 2006, p. 219). The Mutare-Manica

Greenstone Belt and Mavonde Complex were intruded by Palaeoproterozoic NNW–SSE striking dolerite dykes.

Mesoproterozoic (1.1 Ga), fluvial to shallow marine sediments cover unconformely the older basement. The Mesoproterozoic rocks, the so-called Umkondo Group, can be subdivided, into a facies in eastern Zimbabwe and the Gairezi Facies in western Mozambique (GTK Consortium, 2006, p. 160). The Gairezi Facies, a deep water facies, consists of quartzites, silt- and sandstones with synsedimentary dolerite sills and gabbro flows referred to as Umkondo Igneous Province (Lächelt, 2004). The eastern most metadolerite dyke swarm occurs within the mylonite zone, which forms the boundary between the Archaean basement and the Báruè Complex (GTK Consortium, 2006, p. 162). It has been assumed, that the N–S striking metadoleritic dikes reflect the eastern boundary of the Zimbabwe Craton.

At the end of the Mesoproterozoic, the Kibarian or Irumide Orogenesis led to the formation of the Rhodinia Supercontinent. In Southern Africa the Irumide suture zones were largely obscured by younger formations (GTK Consortium, 2006, p. 102).

The Neoproterozoic time is characterized by the development of a passive margin and the Mozambique Ocean along the eastern boundary of the Zimbabwe Craton. The collision of several oceanic island arcs and microcontinents resulted during the East African Orogenesis in the formation of the N–S striking Mozambique Belt. At the same time the Zambezi Mobile Belt developed along the northern boundary of the Zimbabwe Craton. During the so-called Pan-African orogenesis, the closure of the Mozambique Ocean resulted in the amalgamation of the East, West and South Gondwana Terranes, whereby the recent Central Mozambique became part of the Gondwana or Pangea Supercontinent.

The continuation of the Precambrian basement to the east beneath Paleozoic to Cenozoic geologic formations is unknown (Lächelt, 2004). However, basaltic Karoo volcanism originating from the underplating of basic mantle magmas underneath continental crust, occurs as far east as Nhamatanda and the Lupata trough. It has been speculated, that those volcanic spots are the result of a west-verging thrust event (GTK Consortium, 2006, p. 119). Further to the east the Precambrian basement is buried at an unknown depth (Salman and Abdula, 1995).

2.2. Evolution during Phanerozoic Eon

An overview about the Phanerozoic geology of Mozambique was published by Afonso et al. (1998). The most recent comprehensive description on the geology of Mozambique was compiled by Lächelt (2004).

The Phanerozoic geologic evolution of Mozambique can be divided into two periods: the Gondwana or Karoo Period (300–157 Ma), and the Post-Gondwana Period (157–118). Two main phases have been distinguished in the Gondwana Period (Lächelt, 2004): the Gondwana Rifting Phase (from Upper Carboniferous) and the Final Phase (from Middle Jurassic) (Lächelt, 2004). The Gondwana Rifting Phase initiated the breakup of the Gondwana Supercontinent. This was associated with denudation and the deposition of continental and marine-clastic sediments over the southern part of the Gondwana Supercontinent. Large intracratonic Karoo basins formed in association with rift structures (Watkeys, 2002). Some of those tectonic structures became early rift faults of the later EARS (Salman and Abdula, 1995), e.g. the UG. Volcanism resulted in the deposition of basalts, rhyolites and ignimbrites. Older sediments were resembled, fluvial, shallow water and deltaic sediments were deposited. Coal seams and uranium deposits have been formed.

The Late Mesozoic to Cenozoic Post-Gondwana Period began with the disintegration of Precambrian and Phanerozoic units (from 157 to 118 Ma) characterized by sea-floor spreading. Several spreading centres – recognized as magnetometric anomalies –, with varying activity and location were identified in southern Mozambique, the Natal Valley and the Mozambique Ridge in the southwest Indian Ocean (Tikku et al., 2002; review Lächelt, 2004, p. 165). Between Kimmeridgian and Tithonian, a first transgression reached the Rovuma Basin in northern Mozambique and was related to the Tethian transgression in northeastern Africa. The second transgression was related to the opening of the Southern Atlantic Ocean 130 Ma ago (Lächelt, 2004). During Aptian to Eocene taphrogenesis dominated the region leading to the expansion of continental margin basinsalong with the deposition of marly-argillaceous, shallow water sediments (Lächelt, 2004). Coastal basins and shallow water shelves developed accompanied by transgressions and regressions as well as rift-border magmatism/volcanism. At this time the Mozambique Basin developed in Southern and Central Mozambique. Cenomanean intra-plate magmatism led to the emplacement of carbonatites and kimberlites. Example is the Xiluvo Mountain near Nhamatanda just south of the Pungwe River. Neo-rifting, during Miocene was related to the south propagation of the East African Rift System (EARS). The Tertiary UG system cuts across the Mesozoic rifts such as the Zambezi Rift (Bosworth, 1992). Neo-rifting resulted in the uplifting of blocks, the formation of half grabens, and the deposition of thick sediment layers in subsidence zones. During Oligocene a regression occurred, which was followed by a transgression in Miocene.

The Quaternary of Mozambique was only studied in the southern part of Mozambique by Foerster et al. (1982), Momade and Lächelt (2002) and Lächelt (2004). The Quaternary is characterized by a general eastwards regression of the Indian Ocean. According to local evidences transgressions may have reached as far as 100 km westwards.

2.3. Tectonic setting of the East African Rift System

The East African Rift System (EARS) initiated in the Ethopian Plateau at around 30–35 Ma and has since been propagating southwards at mean rift spreading rates of 2.5–5 cm/year (Chorowicz, 2005; GTK Consortium, 2006). Indicators of rifting, such as CO_2-exhalations, hot springs and high seismic activity occur as far south as Lesotho and KwaZulu Natal in South Africa (Hartnady, 1985; Fenton and Bommer, 2006). Rift segments of the EARS continue developing at differing spreading rates. Rift segments may propagate to the north and south, and eventually connect with other isolated parts (Frisch and Loeschke, 1993; Chorowicz, 2005). Rifting largely follows the Proterozoic mobile belts surrounding the Archaean cratons. Rifting of the EARS is related to diverging plate movement caused by uplifting asthenosphere. It is associated with high seismic activity and negative high thermal flux gravity in the graben structures. The western branch of EARS has less volcanic activity than the eastern branch, which took mainly place before and during the initial faulting and subsidence. Different models exist with regard to the evolution of the EARS: (1) emphasizing active rifting associated with one or several mantel plumes with lateral tensions and fracturing and (2) defending passive rifting with localized thinning of crust and pressure-released melting. The conclusion might be a combination of both, active and passive rifting influenced by lithospheric regional patterns of tensions, stress propagation through rigid cratons and convection in the asthenosphere (Logatchev et al., 1972; Ebinger, 1989; Pavoni, 1992; Nyblade and Brazier, 2002). The UG is part of the western branch of EARS. This branch has developed along a Mesozoic rift structure (Logatchev et al., 1972; Kampunzu et al., 1998; GTK Consortium, 2006). The typical graben structure in the EARS consists of two major normal faults forming the rift flanks. The main grabens are all asymmetric to the west and reach vertical throws of 3–4 km (Chorowicz et al., 1987). Four successive stages of rift development were

Table 1
Phases of rifting in the East African Rift System (derived from Chorowicz et al., 1987).

Phase	Main processes
1. Pre-rift evolution	Horizontal, slightly diverging slip movement along existing fracture zones and lineaments forming tension gashes
2. Initial rifting	Rifts are bordered by one normal fault and one faulted flexure, and are separated within the rift by basement highs. The width between the rift flanks is usually between 60 and 70 km
3. Typical rift formation	Strike-slip movement and development of normal faults. Tension gashes turn rift parallel and are characterized by high subsidence rates along the main rift fault while the rift flanks are uplifted
4. Advanced rifting	Motions result from alternatively or simultaneously acting stresses accompanied by alkaline volcanism and high subsidence

distinguished by Chorowicz et al. (1987), which are (1) Pre-rift evolution or preliminary subsidence, (2) Initial rifting: (3) Typical rift formation, (4) Advanced rifting (Table.1). UG has undergone phase (1) and initiated (2) of rift development (Chorowicz, 2005). As a result of rifting, regional drainage systems are altered. Deep lakes occur, where small erosion catchments develop along high-angle boundary faults with high vertical to horizontal displacement ratio and low sediment input, e.g. Lake Niassa in Northern Mozambique (Wescott et al., 1996). Incontrary, rifting can course the increase of a drainage system by connecting adjacent basins with each other, thereby generating large sediment volumes, which are consequently deposited in the graben structure. Crustal extension is less than 10 km and restricted to the widths of the rift basin (Ebinger, 1989; Nyblade and Brazier, 2002).The amount of subsidence is almost equal to the amount of uplift of the rift flanks above the local topography (Ebinger, 1989; Contreras et al., 2000).

2.4. Tectonic setting of the Urema Graben

The UG (UR) is the southern extension of the western branch of the EARS forming the prolongation of the Rukwa – Niassa/Malawi – Shire Rift System. Further south the UG branches into the Chissunga Graben to the east and to the west into the Lucite/Dombe – Buzi – Limpopo fault zone (Vail, 1967; Chorowicz, 2005). The development of the UG began in Eocene by re-activating an older tectonic zone. It cuts the Precambrian S–N oriented tectonic setting as well as the W–E striking Mesozoic Zambezi Rift. The up-to-day active Zambezi Rift acts as a dextral intracontinental transform fault that connects the UG with the Malawi Rift (Chorowicz et al., 1987; Chorowicz, 2005).

Rifting propagated during Eocene to Early Miocene to the SE and SW resulting in the propagation of the EARS from UG through the Chissenga Graben along the coastal area south of the Pungwe River mouth. Strike-slip and diverging movement resulted in the development of tectonic blocks in the sedimentary rock formations. Consequently blocks in pull-apart structures sank while others in constraining zones were tilted upwards and/or moved horizontally. The outcrops in the UG floor and the reversed order of sedimentary rocks along the edge of the Cheringoma Plateau (Geol. Map 1:250,000, 1968) might be evidence for zones of differentiated uplift/downdrop. It is important to mention that the map produced in 2006 does not contain those areas of reversed order on the Cheringoma Plateau. Uplifting of the Inhaminga Block along the Inhaminga Fault took place after the deposition of Miocene conglomerates of the Mazamba Formation now exposed on top of the Inhaminga Block. These continental conglomerates have their source area west of today's UG. The Inhaminga Horst and Nhamatanda Block are bound by NE–SW oriented fault lines and are separated by the Chissenga Graben. Van Solen (1928) found that rocks of the Sena Formations, which are at similar altitude on the western rift scarp, are younger than on the eastern side. This indicates that the rift has an asymmetric shape towards the east. The eastern side was uplifted, and the hanging wall was removed by erosion. The width of the UG is about 60 km. There is no data available about the amount of uplift or vertical throw for the UG, however the adjacent Shire Rift might serve as the nearest example in the EARS. A decrease is observed from the Malawi Rift with 6 km downdrop to less than 1 km in the Shire Rift (Ebinger et al., 1984; Specht and Rosendahl, 1989). Because UG was not disconnected from a large sediment source, i.e. river catchment, it is speculated that sediment thicknesses in UG are in the order of 1–6 km. The two main tectonic directions NE–SW and SE–NW are also depicted in the about 30 known limestone caves on the Cheringoma Plateau (Laumanns, 1998).

Fig. 2 provides an overview about tectonic data available of the area and mapped in different years. The oldest map of 1968 was published as provisional map. Data were derived from aerial photography. The tectonic information of 1984 was obtained from detailed fieldwork and aerial photography (Hunting, 1984). The map published in 2006 is based on satellite image interpretation (DNG, 2006). It is obvious, that the major dykes and faults appear in all three versions, however smaller faults and veins are speculative. Detailed ground check is required firstly, to improve the quality of the map and secondly, to enable meaningful studies on groundwater flow paths in the fractured rocks. Additional structural-tectonic information could be obtained for the rift floor from the combination of seismic data and a hydrogeological interpretation of Landsat 5 TM images (Fig. 5).

Earthquakes are signs of tectonic activity. The UG is characterized by frequent seismic activity in magnitudes between 4 and 8 and depths of epicenters of mostly between 26 and 33 km. The Centroid Moment Tensor focal mechanism indicates an E–W expansion (ANSS database, Fig. 3). The occurrences of earthquakes seem to delineate the flanks of the UG, e.g. the line connecting the locations of the volcanic rocks on Cheringoma Plateau as well as the limits of transform faults, e.g. along the Nhandugue River. Elevated thermal gradients indicate crustal thinning or mantel plumes.

Thermal gradients obtained from oil exploration drillings in the Mozambique Basin are in the order of 28.5 mK/m and are not especially high. Heat was estimated at 57 mW/m^2 (Martinelli et al., 1995). However, the occurance of a hotspring in the southern part of the UG indicates higher thermal fluxes (Steinbruch and Merkel, 2008).

3. Geomorphology and lithology of the Urema Catchment

The Urema Catchment has four distinct geomorphological units, which are from west to east: Báruè Basement, Mount Gorongosa, Urema Graben valley and Cheringoma Plateau (Fig. 1). The first geological mapping with focus on hydrocarbons prospection was undertaken by van Solen (1928) and concentrated on the sedimentary formations partly covering the Báruè Basement and the formations of the Cheringoma Plateau. A provisional geological map at a scale of 1:250,000, derived from aerial photographs was produced in 1968 (DNG, 1968). The geology of the western most part of the Urema Catchment was mapped in more detail by Hunting (1984). A revised geological map of the area was published in 2006 updating the stratigraphy based on latest chronological data and applying international standard naming conventions (DNG, 2006; GTK

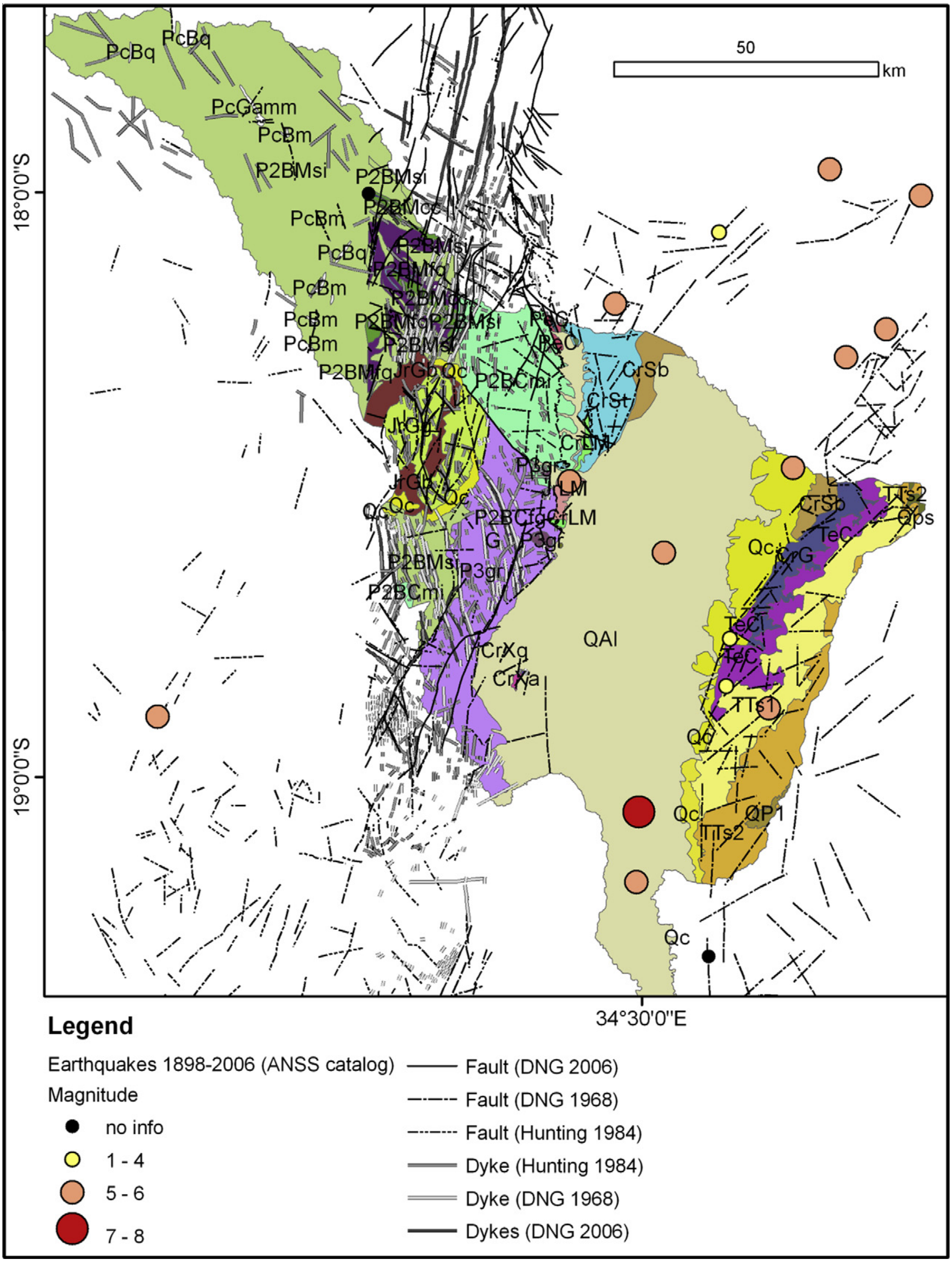

Fig. 2. Map of geology, tectonic elements and seismic activities of the Urema Catchment (dervided from DNG, 1968; Hunting, 1984; DNG, 2006, ANSS catalog).

Consortium, 2006). It is worth mentioning that the updated geological map has gained information in the basement areas, however lost details in regions with formations younger than Mesozoic. Aeromagnetic surveys, conducted in 1984 and 2004 on behalf of the Ministry of Mineral Resources of Mozambique, do not cover the central part of the Urema Graben (UG). In 2008 aero-

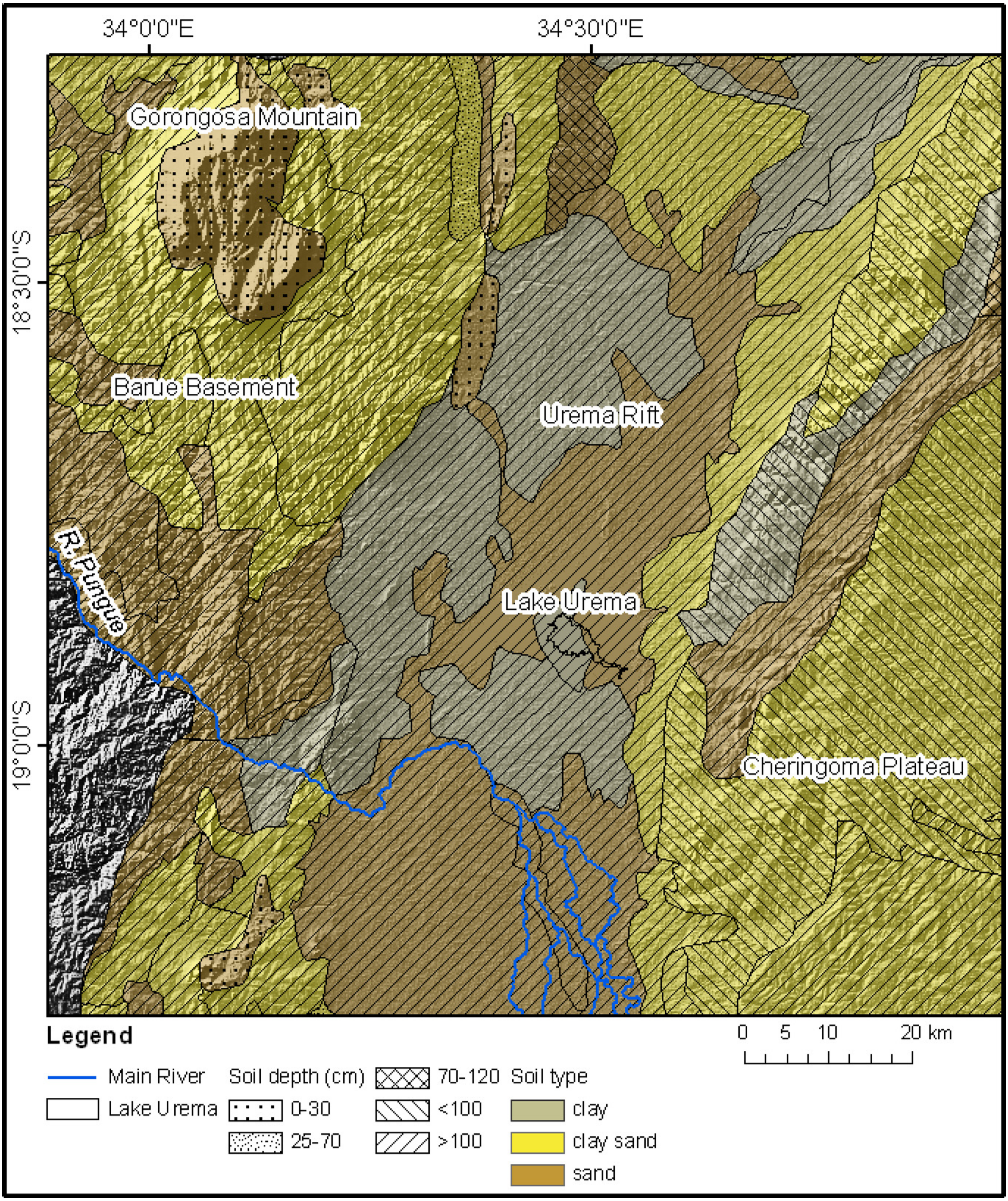

Fig. 3. Map of soils of the Urema (background hillshade derived from USGS SRTM 90 m, DINAGECA, 1995).

magnetic surveys were conducted on behalf of the National Hydrocarbons Company of Mozambique (ENH) to fill the data gap. However, these data are not yet available to the public.

The geomorphology of the area is described in Real (1966, p. 11) and Tinley (1977, p. 15), and with focus on Lake Urema in Böhme et al. (2006).

3.1. Bárué Basement

The Bárué Basement is the area west of the UG with altitudes between 400 and 600 m asl. The terrain has slopes of less than 5° with some inselbergs rising above the surrounding area. The geological term Bárué Complex corresponds in its latest understanding

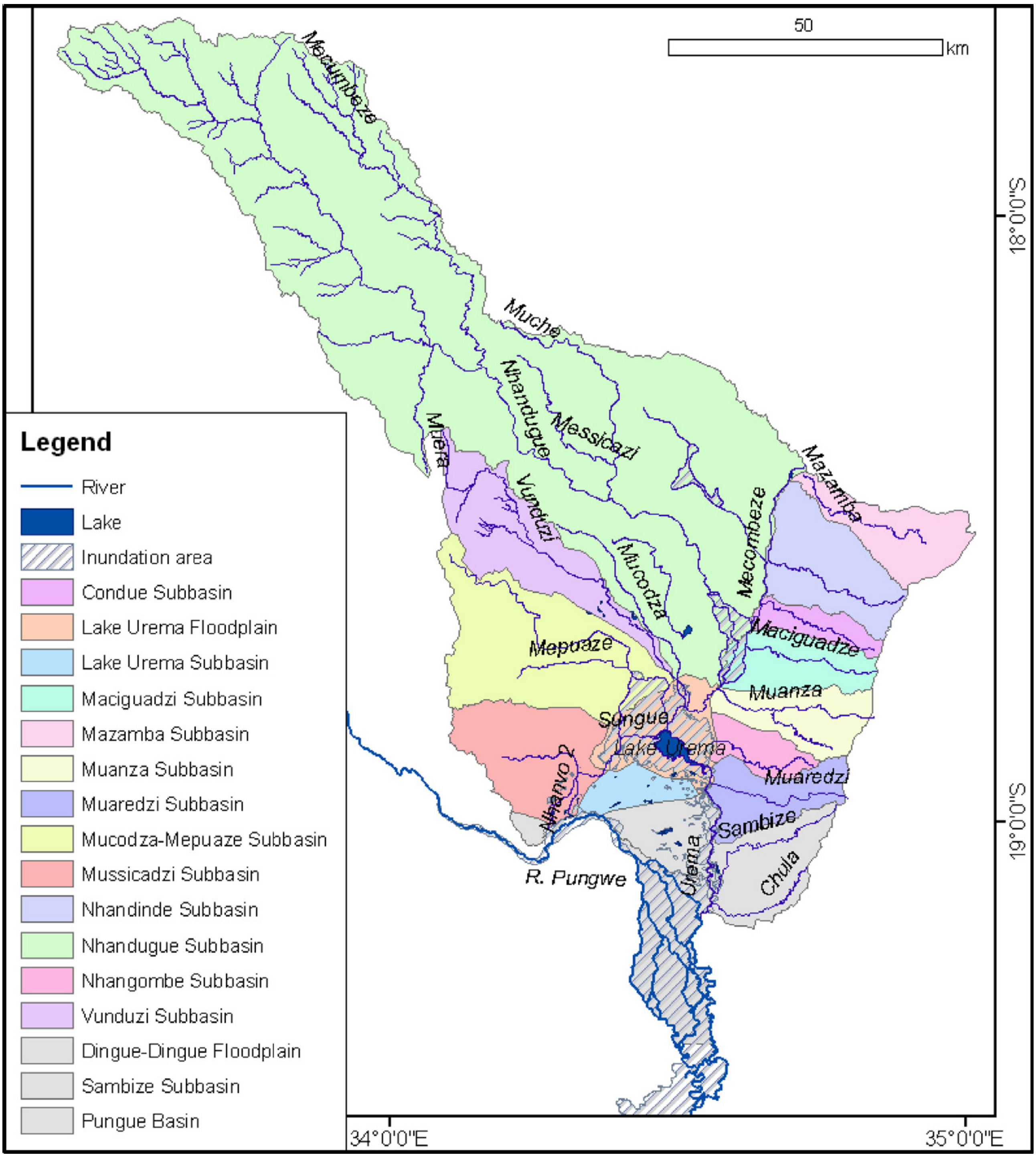

Fig. 4. River basins, rivers, lakes and inundation areas of the Urema Catchment.

to the area, bounded to the west by a major sinistral shear zone along the Archaean Zimbabwe craton, the south buried by phanerozoic formations, the north by a northward-directed thrust and the east by the Gorongosa Intrusive Complex (GTK Consortium, 2006). The Bárué Complex consists of Precambrian gneisses, migmatites, granitoides and metagreywackes. Lenses of marble and calcsilicates occur in the metamorphites. Calcsilicates were found in three boreholes drilled by GNP on the Bárué Basement – Urema Graben transition at a depth of 2 m, 16 m and 40 m depth and with thicknesses ranging from 4 m to 10 m (GNP, 2006). This is an important geological element affecting groundwater qualities. Because calcsilicates act as a geochemical trap for heavy metal fluids, interactions between groundwater and calcsilicates can cause elevated concentrations of dissolved metal ions or metal complexes in groundwater resulting in water, which is unsuitable for domestic consumption.

Lächelt (1990, p. 54) arrived at the conclusion, that the chronological position of the Bárué Complex is of Archaean age and was tectonically reactivated during Meso-/Neoproterozoicum. Age-dating of deformated plutonic bodies in the metasedimentites of the Bárué Complex conducted by GTK Consortium (2006) arrived at ages between 1.1 and 2.5 Ga. Pegmatite, quartz breccia and doler-

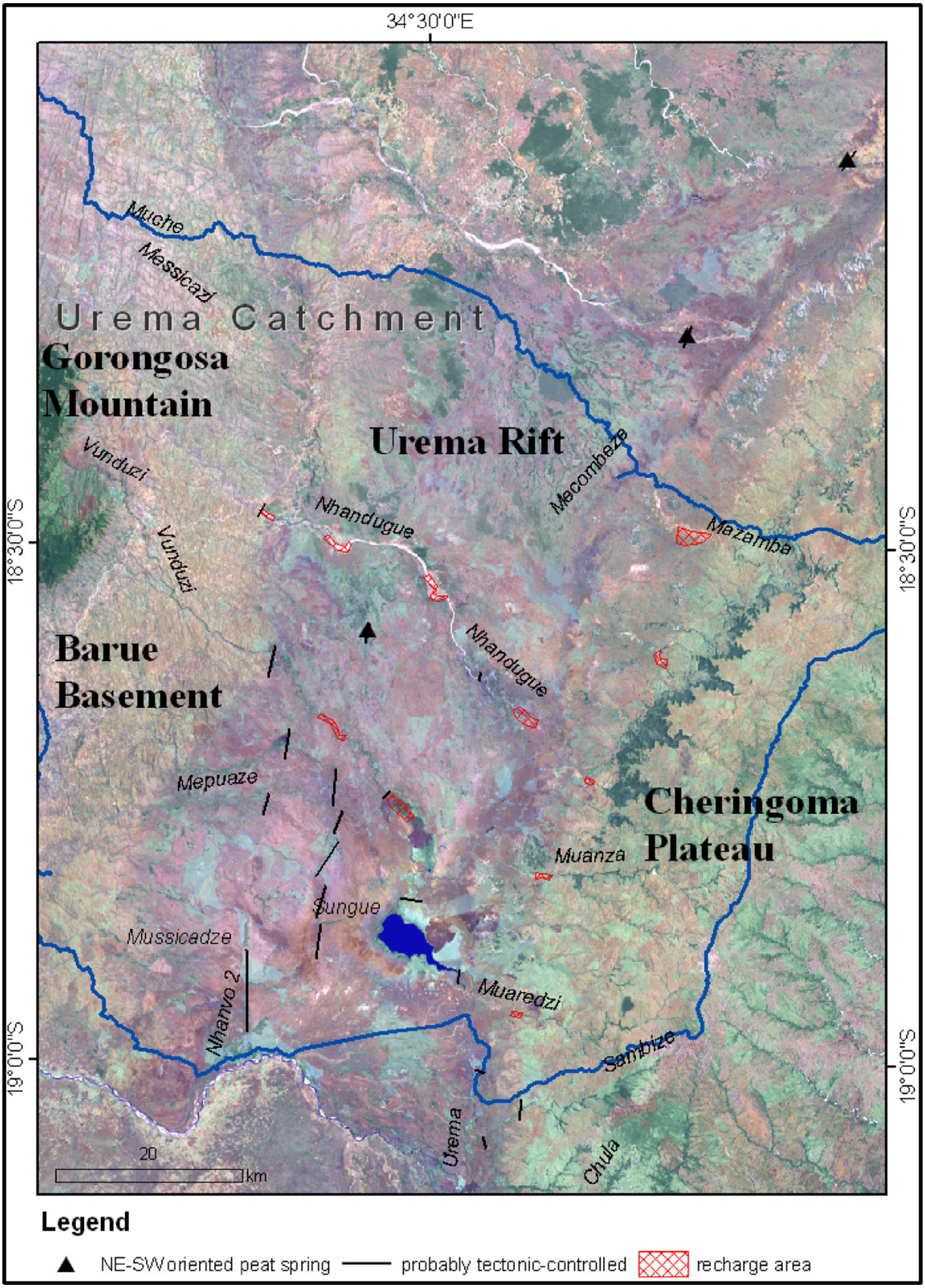

Fig. 5. Map of important recharge zones and tectonical controls influencing the hydrology of Lake Urema (background Landsat TM, 5 October 2005, bands 7–5–3).

ite intrusions intersect the Precambrian metamorphites, which Lächelt (2004) relates to the East African Rift System (EARS) tectonics. Older publications positioned these intrusions at Karoo age. According to GTK Consortium (2006, p. 31) there is insufficient data available for a stratigraphical grouping of the plutonic intrusions and geochronological investigations are required. Pegmatites, quartz breccia and dolerites are important structural elements in the region, because they act as hydraulic conduits or barriers of groundwater. Remnants of Upper Senonian conglomerates and greywacke occur along the Báruè Basement – Urema Graben transition.

3.2. Mount Gorongosa

Mount Gorongosa forms an inselberg west of the UG and east of the Báruè Basement. Mount Gorongosa has a size of 30 km in N–S and 25 km in E–W direction. It has three summits of which the so-called Mount Gogogo is with 1863 m asl the highest.

Mount Gorongosa rocks show a ring structure. Rock formations consist of older gabbros, which outcrop on the western side of the mountain and younger microgranites, which intruded into the gabbro and are outcropping on the eastern side. In aeromagnetic data is a second, younger gabbro visible, which is emplaced in the centre of the syenites (GTK Consortium, 2006). Remnants of contact metamorphic rocks such as quartz hornfels and amphibole hornfels occur in the vicinity of the plutonic rocks. Chemical properties of these rocks are described in Coelho (1959), Afonso (1977), and GTK Consortium (2006). The morphology on the surface of the gabbros is undulated with slopes of less than 15°. Microgranites on the mountain form up to 35° steep, often bare-soiled slopes and are deeply eroded along radial shrinkage fractures.

Coelho (1959) positioned the Mount Gorongosa pluton based on comparative lithological studies at Karoo age, whereas Lächelt (2004, p. 166) relates the emplacement of the pluton to the beginning of the rifting at Lower Cretaceous/Upper Jurassic age. Dating of a syenite sample of Mount Gorongosa conducted by GTK Consortium (2006, p. 272) determined an age of 181 ± 2 Ma, which corresponds to Lower Jurassic age. GTK Consortium (2006) introduces a new structural feature to the geo-tectonic interpretation of the region – the so-called Gorongosa Intrusive Suite. The term Gorongosa Intrusive Suite describes a 240 km long and up to 20 km wide NNW–SSE striking fault/dyke swarm, which includes Mount Gorongosa as well as the so-called Gorongosa Fault/Fracture Corridor that extends SSW of Mount Gorongosa to the Pungwe River and NNE of Mount Gorongosa to the Zambezi River. This area is characterized by anomalies in geochemical background values, which are typical in rift tectonics (Korkiakoski, 2008).

3.3. Urema Graben

The 180 km long Urema Graben (UG) located between Zambezi River to the north and Pungwe River to the south has altitudes between 14 and 70 m asl. It is almost plane with slopes of less than 5° and forms a water retention area hosting lakes, wetlands, and pans. The largest lake is Lake Urema.

The UG is according to the old, and more detailed geological map, covered by colluvium and fluvial sediments along the foot of the rift flanks and by eluvium in the centre (DNG, 1968). Sediments consist of heavy montmorillonite-rich clays and leached sands of varying grain size documented in the soil map and description by Fernandes (1965), DNA (1987) departs from the assumption that coarser sediments are deposited close to the rift flanks, because of the sudden loss of transport energy, and finer sediments are encountered towards the rift centre. Yet, the latest soil map produced by DINAGECA (1995) shows a variety of deep Pleistocene and Holocene sands, clay-sands and clays, whereby medium to coarse sands occur along the central rift drainage line and clays/clay-sands form fans from the rift flanks towards the centre (Fig. 2). Fernandes (1965) already differentiates two soil types in the rift centre, namely hydromorphic alluvium consisting mainly of clay, and non-hydromorphic alluvium composed of coarse sand. Tinley (1977, p. 41) confirmed the occurrance of clay in the centre of the rift and founded his theory of the hydrological dynamics on the existence of an extensive, impermeable top layer.

In two boreholes drilled by GNP, clay of at least 18 m and 26 m thickness was found (GNP, 2006). Clay deposits act as a preservative and provide a window to past hydrologic and climate conditions. One would expect different types of pollen and laminations of organic-rich and organic-poor sequences deposited in a calm, deep water environment over a long period of time. Seeking for water only, neither sampling nor a detailed lithological documentation took place. Böhme et al. (2006) found coarse to medium sand in four sediment cores taken from the bottom of Lake Urema, whereas it was expected to find clay acting as a sealing to hold the water. Following up on this finding well-sorted sands underneath a thin clay layer were observed by the author in various locations in the central parts of the rift, e.g. in the downstream end of the Mussicadzi River and south of Lake Urema. Plane clay-covered areas show distinct, up to 2 m deep sink–slump structures indicating the existance of sandy layers with varying water tables underneath the clay. In addition, all permanent water pans and drainage channels visited by the author are located in coarse sands. These findings suggest that permanent lakes and pans in UG are sustained by a shallow unconfined aquifer. This information is fundamental, because groundwater-dependent wetlands and lakes require different water resources management approaches than pure surface-fed water bodies (Fig. 3).

Close to the western rift flank occur three distinct mountains, which in the old map are described as trachytes of Karoo age and in the most recent geological map as remnants of Cretaceous phonolitic lava (DNG, 1968; GTK Consortium, 2006). Pieces of fossil trees, an evidence of volcanic activity, were found during excavations about 20 km east of the national road number 1 and about 2 km north of the Pungwe River. In the southwestern part of the UG occur two outcrops, which in the old geological map are described as Precambrian gneisses (DNG, 1968). The most recent geological map labels those outcrops as dykes of Cretaceous granite breccies (GTK Consortium, 2006). Various cross-sections were published (Flores, 1973 – reprinted in Steiner (1992) and Lächelt (2004); Tinley, 1977; DNA, 1987; Cilek, 1989). The general sediment sequence in the pre-rift stage consists of sandy-fluviatile deposits on top of the basement followed by clay and organic rich sediments of a lacustrine facies (Chorowicz, 2005). However the geology, e.g. whether karstified rocks of the Cheringoma Formation occur underneath the alluvial cover in UG, the sediment types and thicknesses determining aquifer properties, and tectonic structures, which may enable hydraulic links between aquifers remains speculative.

3.4. Cheringoma Plateau

The Cheringoma Plateau, east of the UG and west of the current coastline of the Indian Ocean, comprises the Inhaminga Horst also called Inhaminga Block as the main tectonic element. The Inhaminga Block is limited to the north by the Zambezi Graben and to the south by the Chissenga Graben, which is well visible on seismic profiles (published in Lächelt, 2004).The geological formations of the Cheringoma Plateau are dipping 5–7° SE. The seawards slope of the plateau is less than 5°, while the rift-oriented slope is mainly between 5° and 10°. It reaches elevations of 352 m asl with outcrops of arkose sandstones, nummulitic limestones, and continental sandstones of Cretaceous to Miocene age. The arkose sandstones and limestones were intensively karstified during Eocene and re-filled during Miocene (Laumanns, 1998). Head erosion along the eastern rift flank has partly removed the sediment fill from the fossil karst systems and created canyons and rock arches. Several remnants of rhyolites and nepheline basalts of Oligocene to Pliocene age occur on the Cheringoma Plateau forming distinct hills (Foerster et al., 1982). The stratigraphy in this area is based on fossil records (Van Solen, 1928), geological and geophysical mapping for hydrocarbon exploration (Campos, 1927; Salman and Abdula, 1995) and deep-borehole records of the late 1930s (published in Coba and Profabril, 1987). Geochemical analyses of the limestones are presented by Cilek (1989). General stratigraphic profiles of the Mesozoic in Mozambique are published in Foerster et al. (1982) and Lächelt (2004). Several cross-sections using the drilling results were produced (Tinley, 1977; DNA, 1987; Coba and Profabril, 1987; Cilek, 1989; Salman and Abdula, 1995). However none reflects the tectonics of the area such as the volcanism along tectonic lines, block faulting or the secondary permeability as a result of the karstification of the limestones.

4. The Evolution of Lake Urema

Hydrological patterns are controlled by geological, geomorphological and climatic conditions of an area. The climate of the Urema Catchment is characterized by a warm wet season from December to March and a cool dry season from April to November. Groundwater and hydological assessments for the Pungwe River Basin and/or parts of it were conducted by Coba and Profabril (1987), SWECO and Associates (2003) and Owen (2004). The studies of 2003 and 2004 are pure desktop studies. A hydrogeological map of Mozambique exists at a scale of 1:1Mio accompanied by an explanatory text (DNA, 1987).

The total size of the Urema Catchment is 9295 km^2. The hydrological sub-basins of the Urema catchment reflect the asymmetric shape of the UG. The sub-basins in the western part of the Urema Catchment are large and elongated, while those of the Cheringoma Plateau are small and round-shaped (Fig. 4). Remarkable is that all rivers coming off Mount Gorongosa and Cheringoma Plateau are perennial, and by entering UG infiltrate into the subsurface. thus becoming seasonal (Fig. 5). This suggests that the flanks ofUG act as regional groundwater recharge areas. Further investigations, especially quantifications are necessary using geophysical methods and conducting recharge measurements.

4.1. Palaeohydrological evolution of the Urema Graben

The evolution of the palaeohydrology of the Lake Urema Floodplain is driven by geotectonic processes and can, especially in the absense of borehole and geophysical data, provide clues about today's hydrogeological conditions. UG is an active tectonic element, which has shaped hydrological properties of the Urema Catchment including Lake Urema. The hydrological evolution of the UG is often believed to be a part of the evolution of the lower Zambezi River (Real, 1966; Flores, 1973; Tinley, 1977). Although this may not be correct the sediment history of the Zambezi River, which has been studied manifold especially in the course of petroleum explorations, provides insights into the sediment formations found in the adjacent UG and Cheringoma Plateau.

The Palaeo-Zambezi Valley was formed during Karoo age (Pre-Jurassic/Jurassic). It followed the W–E oriented Zimbabwe Craton – Zambezi Mobile Zone – contact. The Mesozoic-Cenozoic-aged Shire Rift crosses the Zambezi Rift and extents into the UG. Both, the Zambezi Rift as well as the UG were reactivated during Miocene. An intracratonic depression, called Mozambique Basin developed in the area between the Lower Zambezi River and the Save River during Cretaceous. A Cretaceaous palao-delta of the Shire-Zambezi River was identified in the Caia-Chemba region (Lächelt, 2004; Salman and Abdula, 1995). At the same time shallow water and shelf sediments of the Sena, Domo, and Grudja Formations were deposited on top of Precambrian basement formations all over the UG area and the Cheringoma Plateau. Several transgression–regression cycles occurred from Paleaocene to Miocene causing the shifting of the palaeo-coastline from west to east and vice verse. Thick sediment sequences of these periods occur in the area between the Zambezi and the Buzi River with facies changes from west to east, typically terrestrial, and shallow water to deep water. During the regression phase the arkose sandstones and nummulitc limestones underwent intensive karstification resulting in the formation of caverns and cave systems, today known from the Cheringoma and the Buzi regions. During the transgression phase these caverns and caves became filled with sediments (Laumanns, 1998).

The largest rivers on the Bárué Basement such as the Pungwe, Nhandugue and Nhamapassa River are residing in deep W–E draining valleys, which suggests their pre-UG history and their individual significant sediment contribution to the Mozambique Basin. The so-called Zambezi Delta sediments however, deposited during Oligocene to Early Miocene had their origin in Northern Mozambique and were delivered through the Serpa Pinto Valley to the Indian Ocean. The contribution of Zambezi River sediments was minimal, and the sediments were deposited through a system of shallow channels about 200 km NE of today's Zambezi River mouth (Droz and Mougenot, 1987). The arguments that the Zambezi River was during Cenozoic temporarily flowing through the UG into the Pungwe estuary and for this reason accounting for the large alluvial UG floodplain and the sinuosity of UG rivers, could not be sustained. The river diversion would have caused an unconformity in the Zambezi delta stratigraphy and a deposition of Zambezi delta sediments in the Pungwe area, which both are absent (Walford et al., 2005). During Neogene to recent the Zambezi Valley became the major source of large volumes of sediments deposited in the Zambezi Delta. This was the result of the enhancement of the Zambezi catchment by joining the Upper and Middle Zambezi River systems with the Shire River basin during Pliocene or Neo-Pleistocene (Thomas and Shaw, 1988; Goudie, 2004) due to the development of the EARS. As the Inhaminga Horst was uplifted the Zambezi River drainage became confined to the graben structures of the Zambezi Rift. Because of subsidence in UG and uplift of surrounding blocks, old aquifers got fragmented. Consequently the hydrodynamic regime changed. In Pliocene/Pleistocene the Cheringoma Plateau became the surface water divide between inland rivers and the Indian Ocean. However, contrary to Tinley (1977), no continuation of ancient river courses across the Cheringoma Plateau can be delineated from today's drainage.

The neo-rifting caused a sudden decrease in sediment volumes and river flows, which are not yet understood in detail. Also the W-E oriented fault accommodating the Pungwe River valley east of UG became intersected by NNW–SSE striking faults, which in some places have caused horizontal slip movement of up to 70 m. Among the large Bárué Basement rivers in the area of the UG only the Pungwe River has a sufficiently high hydraulic gradient and run-off to develop its own drainage south-southeastwards along a tectonic line to the Indian Ocean. The Nhamapassa River has developed the largest fan in the UG. The active channels propagated northeastwards changing from the direct discharge into the Indian Ocean to a drainage through the Zambezi River, and with this created the surface water divide between Zambezi and Pungwe River. The deposition of sediment fans resulted in the creation of large floodplains and lakes in the UG, such as the Lake Urema floodplain (Fig. 5).

4.2. Current hydrological patterns and catchment properties

4.2.1. Nhandugue River Catchment

The Nhandugue River originating on the Bárué Basement forms the main sub-basin of the Urema Catchment with a size of 4200 km^2 and drains rivers through a dentritic drainage system. The Nhandugue River is following the Eocene transverse WNW–ESE striking tectonic setting and has a dentritic drainage. The river turns in some parts suddenly NE following another tectonic print resulting from horizontal strike-slip movements along the major fault direction as well as from rift expansion. In the UG the river flows to the SE. A sediment fan spreads from the western rift flank into the rift floor and the valley meanders for a distance of some 17 km in a wide channel with coarse, well-sorted sands. Then the valley becomes narrow and finally dissolves within the rift axial drainage. Run-off on the Báruè Basement is characterized by a fast-on-set and dry-fall as results of local rainfall and an absence of local aquifers. Muera River and some smaller tributaries from Mount Gorongosa bring run-off to the Nhandugue River all year. The diversion of those rivers for the irrigation of semi-commercial farms creates a serious threat to the health of rivers and the floodplain ecosystems. The mean annual run-off from the Nhandugue catchment is estimated at 60 mm (SWECO and Associates, 2003), which corresponds to 50% of the total mean annual run-off to Lake Urema. Yet, the importance of this subcatchment for the Lake Urema wetland is totally negliged. In the past this river was classified as clear river suggesting low mineralization and low siltation (Tinley, 1977). Because of landuse changes in the upper catchment, this river is now transporting huge amounts of silt into Lake Urema. The sediments carried by the Nhandugue River into the Lake Urema floodplain are deposited there. This forms a serious threat to the floodplain, because supply of water from shallow aquifers gets sealed off and Lake Urema is quickly filled up with sediments (Fig. 5).

4.2.2. Mount Gorongosa Catchment

Mount Gorongosa Catchment has a size of 1280 km^2. Mount Gorongosa receives orographic rainfall throughout the entire year releasing the perennial run-off from the mountain. A NE–SW oriented watershed on Mount Gorongosa divides the Nhandugue from the Vunduzi basin. The mountain precipitation is stored in thick moos and sponges vegetation growing on the granites. The water is seeping permanently from the rock–soil interflow feeding into small rivers. These small rivers follow deeply eroded caverns and channels of radial shrinkage fractures in the granite forming zigzag-shaped watercourses. The river channels are often only a few centimeters wide at the surface. This results in reduced water loss due to evaporation and causes the relatively low and constant water temperature throughout the year. Fracture junctions are in some places eroded forming crystal clear, cold water pools of about 2 m depth and 10 m diameter. It is yet unknown, how much water infiltrates into deep-reaching fracture controlled groundwater aquifers running parallel to the main UG structures. However, hydrochemical and isotopic studies conducted in the area provide some evidence of such deep paths of groundwater circulation (Steinbruch and Merkel, 2008).

Around the foot of Mount Gorongosa occur more than 40 springs feeding into small rivers. These are located at the interface between weathered rock (colluvium), gneisses and gabbros. Though yields are increasing after rainy days the springs are not falling dry during the dry season. The largest river having its sources in a spring on the mountain's foothills is Mucodza River. The largest mountain run-off forms Vunduzi River. The moment the river enters the UG it flows in a fairly deep and sharply meandering SE oriented valley. This course changes after about 19 km to a straight, narrow river channel terminating in an inundation area close to the rift axial drainage.

Mount Gorongosa was considered as the most important source of water for Lake Urema since the studies of Tinley (1977). The mean annual run-off is estimated at 59 mm, which is almost the same as for the Nhandugue basin (SWECO and Associates, 2003). Thus the Mountain catchment is as important for run-off generation into Lake Urema as is the Nhandugue catchment. Deforestation and fires on Mount Gorongosa are forming a major threat to the mountain catchment. With the exponentially progressing deforestation the mesoclimate of the region and hydrological regimes become altered. The likely scenario is less rainfall and less water retention capacity resulting in an increase in flashfloods with increased soil erosion and the decrease in water availability in the Lake Urema floodplain.

4.2.3. Cheringoma Plateau Catchment

The Cheringoma Plateau is characterized by small sub-basins with karst features as well as deeply-drained sandstones with pronounced head erosion from the rift escarpment. Rivers draining towards the UG are following faults and rock beddings. The faults and beddings framework is dense. Run-off enters deep karst canyons or flows some distances entirely underground. Mean annual rainfall in the riftwards catchment is only 800 mm whereas it is 1200 m in the coastal catchment. Remarkable is that all main rivers are fed by small perennial karstsprings. The largest is the artesian Nhamatope spring, which drains into the Mazamba River. The discharge behavior of the Nhamatope spring lets assume, that the groundwater recharge area reaches eastwards beyond the surface water divide. Further investigations are required to delineate the groundwater division and to understand, how much of the rain on the east slopes of the Cheringoma Plateau infiltrates into the karstified limestones and contributes, through fractured aquifers beneath the alluvial sediment cover of UG, actively to the water balance of the Urema Catchment, i.e. is not draining directly into the Indian Ocean.

4.2.4. Urema Graben Catchment

The UG is receiving all waters from the three other morphological units and drains those through an asymmetric NE–SW oriented run-off called Mecombeze River upstream and Urema River downstream of Lake Urema into the Pungwe River. The Mecombeze River originates in a swamp area north of Lake Urema. Remarkable is, that this swamp area has a second northeast oriented outflow, which is the Zangue River draining into the Zambezi River. During past times of severe floods Zambezi River floodwater used to drain through the UG into the Pungwe River. This event was last observed before the closure of the Kariba dam in 1958. Because sediments are trapped in the Cahora Bassa dam increased channel erosion and consequent drawdown of groundwater levels to up to 6 m are observed.

This results in an increase of hydraulic gradients in the UG towards the Zambezi basin causing a southeast-oriented propagation of head erosion. This results in the interruption of the hydraulic connection and the creation of a sharp catchment division between Pungwe and Zambezi basin. The consequences of the faster drainage and lower watertables are a drying of the floodplain followed by a replacement of floodplain grasslands by woody vegetation and a loss of the carrying capacity for large herbivores.

The area of the lowest elevation in the UR is host to the perennial Lake Urema, which receives surface inflows only during the rainy season. The lake collects run-off and groundwater from all sides. The lake outflow, located in the southeast of the lake on the axis of the UG, appears to be structural controlled. The Urema River is characterized by a narrow, 4–5 m deep straight valley of about 10 km length, which then suddenly becomes wide and meandering until it meets the currently active Pungwe River channel. This change in river morphology seems to be the knickpoint from where UG drainage flows permanently into the Pungwe River. During the peak of the rainy season Lake Urema annually receives Pungwe River water through oxbows of an earlier Pungwe channel. This NE directed breeching zone accommodates the channels of the Nhacapanda and Nhanvo River. Those rivers join the Mussicadzi River located in the centre of the UG draining through the Sungue River into Lake Urema. Though the catchment of the Mussicadzi River is relatively small and entirely depending on local rainfall the river has got a 4–

5 m deep and about 15 m wide valley, which near the Sungue confluence suddenly dissolves in the open floodplain. This feature seems to be a tectonic zone with merit for more attention.

Termite hills are indicators of groundwater levels. Since the area is flat these hills have an influence on surface flow directions and are zones of higher water infiltration. The hills often serve as first ground for woody species. The involvement of these plants in reverse osmotic processes, which would explain the reduced mineralization of lake water during the dry season needs to be investigated. The UG used to be covered by termite hills at a density of 3 hills/ha (Tinley, 1977). Today the landscape does not have this high density in termite hills anymore, which may indicate changes in the water availability in the UG. Eroded termite hills turn into pans, which hold water for several weeks after the occurrence of rain events have (Tinley, 1977). Soils around the pans accumulate salt and form bare-soil circles seeked for by animals.

In at least three locations around the Nhandugue River in the UG occur peat wetlands fed by perennial springs. All the observed peat swamps have a NE–SW stretching narrow shape. The fact of having an environment that supports the evolution of peats suggests the linkage to active tectonic structures. Those tectonic windows should be subject to further investigations.

4.3. Lake Urema characteristics and consequences for management

The first detailed study about Lake Urema was conducted by Böhme et al.(2006) and provides information on the dry season characteristics of the lake including an analysis of the lake's dry season extent from 1974 to 2000. The dry season mean area of the open water for the period of 1974–2000 is 20.5 ± 2.8 km^2, the average depth is 1.64 m with no significant stratification and a volume of the open water body of 30.34 Mio m^3 (Böhme et al., 2006). From this 30-year time series was concluded that the dry season size of Lake Urema is not influenced by periods of droughts or floods. However, exemptions in dry season lake sizes are seen in aerial and satellite images of 1958 and 2008, when the lake shrank to about 10 km^2. This suggests that Lake Urema, in addition to the immediately observable seasonal patterns, is mirroring climate events (e.g. El Niño/La Niña), yet retarded by an unknown time interval. This requires more investigations as it potentially determines a threshold of concern in water resources management.

Also the bathymetric survey by Böhme et al. (2006) shows that the lake forms a trough meaning that the dry season lake size will not be affected by in- and outflows, whereas the lake level and consequently volumes will. Lake Urema has a floodplain of 305 km^2 size, which floods annually reaching water levels of up to 3 m above the dry season surface (Steinbruch and Merkel, 2008).

The shoreline development is typical for flooded river valleys. The annually observed hydraulic linkages between Lake Urema and the currently active Pungwe channel suggest that Lake Urema may have developed from being the concluence of the central UG drainage with the Pungwe River to an oxbow of the Pungwe River and finally today's lake. The lake has a radial seasonal inflow drainage pattern and one seasonal surface outflow. The outflow area is confined by a fan of the Pungwe River.

Sediment columns of 0.5–0.9 m lengths sampled in four locations in the lake varied between pure sand, pure clay and medium sandy clay, whereas pure sand occurs towards the lake outflow (Böhme et al., 2006). Coarse or medium sands are not transported under the current climatic and catchment conditions. Those sands must therefore be associated with conditions of high run-off gradients and flow rates, which probably existed during Pleistocene age. The source and thickness of the sands is unknown and subject to further investigation. The clay fraction consists of minerals of metamorphic origin such as hornblende, plagioclases, muscovite and corresponding secondary minerals. The main source area of the clay fraction is the Precambrian gneisses of the Báruè Basement. These findings suggest that the lake is located in a shallow, unconfined aquifer of yet unknown dimensions.

In the past, surface flows were considered as the main water source of the lake with the so-called Muaredzi Plug as a physical barrier that regulates the lake waterlevels and outflow (Tinley, 1977). The Muaredzi Plug is actually a sediment fan of the Muaredzi River coming from the eastern rift escarpment consisting of coarse, well sorted quartz sands reaching into the Urema River valley. As a suitable aquifer it might act as a hydraulic barrier of the lake outflow with groundwater discharging into the lake. The analysis of the historical hydrometric data covering the period of 1956–1982 was conducted by Owen (2004). The results show a mean annual water deficit of 700 mm in UG however, Lake Urema does not dry up. The lake must be a mixed surface water–groundwater flow system receiving surface run-off during the rainy season and groundwater during the dry season. Electrical conductivities of the lake vary from 101 to 230 μS/cm, which suggests that most groundwater has its origin in the low-mineralized waters of Mount Gorongosa and Báruè Basement rivers.

The lake was home to thousands of hippopotamus in the past. Their habit of moving along drainage channels caused the creation of hydraulic linkages of otherwise disconnected watercourses. Hippopotamus may also have contributed to maintaining the lake's depth and groundwater inflows by preventing sediment deposition and sealing of the lake's bottum. The role of these animals as so-called ecological engineers is only poorly understood but seems to be underestimated. The concept of the plug culminated in the handy but misleading advice (SWECO and Associates, 2003) to construct a dam or weir at the lake outflow to manage waterlevels. The groundwater-dependence of Lake Urema however, makes the system more vulnerable to a complexity of factors such as water abstractions from rivers and aquifers, processes of siltation in the UG, and evaporation from shallow aquifers due to vast wildfires.

5. Conclusions

This review summarizes and discusses the current level of knowledge about geological and tectonic processes in the Urema Catchment as well as some implications to the hydrological management of the Lake Urema floodplain. The geological and tectonic map needs to be improved in scale through detailed fault analyses, detailed mapping in the field and ground truthing of remote sensing data. Also the discrepancies between official soil maps have to be reviewed. It is important to learn more about the shallow aquifer in which Lake Urema is embedded, e.g. by using stable isotopes and by installing a piezometer network around the lake. Hydrological modelling must account for surface–groundwater interactions. Qualified borehole logging and geological interpretation is crucial to improve the understanding of the geology and to better manage water resources of the region. Geophysical surveys, e.g. conducted along selected transects would provide key information for a follow up by more expensive field methods such as drilling.. For a good water balance analysis the volume of the lake needs to be determined accurately for the dry and wet season status. For lake change analyses a study of the evolution of sediment fans (terraces, morphology, erosion) from aerial photo and satellite image time series would provide fundamental information.

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