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Analysis of water stable isotopes fingerprinting to inform conservation management: Lake Urema Wetland System, Mozambique

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ABSTRACT

The present study focusses on the analysis of water stable isotopes to contribute to understanding the hydrology of the Lake Urema wetland system in central Mozambique towards conservation management.

Lake Urema Wetland is located in the Gorongosa National Park at the southernmost extent of the East African Rift System and is situated entirely within the Urema catchment. Of particular concern to the park's management is the understanding of hydrological processes as these may trigger transformations of ecosystems, habitat losses and wildlife migrations. Concerns over the Lake Urema wetland's drying up and the trapping of sediments in the floodplain have been raised for some time by conservationists.

Water samples were collected for stable water isotope analyses during the wet and the dry seasons for the period 2006–2010 from springs, boreholes, rivers, and Lake Urema. In addition monthly composite precipitation was collected at two rain gauges.

The results show that Lake Urema is maintained throughout the dry season merely from water generated during the wet season. It receives water from wet season precipitation and the runoff generated from this precipitation. The water source areas of the lake are the Gorongosa Mountain and the Barue Basement geomorphological units. Consequently, the source of the sediments which have been trapped into the lake and the floodplain has to be identified in these two catchment areas and urgent action is required to rescue the lake. This water body constitutes a groundwater buffer system which supports a unique wetland landscape. The annual inundations' processes leading to the recharge-drainage cycle in the floodplain are most sensitive to the deposition of sediments, changing hydraulic gradients, and reducing wet season inflows and increasing drainage rates.

1. Introduction and background

Lake Urema Wetland is located in the Gorongosa National Park in Mozambique at the southernmost extent of the East African Rift System and is situated entirely within the Urema catchment (Fig. 1). The Gorongosa National Park Management has adopted the adaptive management principle acknowledging the need for conservation management based on incomplete knowledge of the ecosystems. Of particular concern is the understanding of hydrological processes as these may trigger transformations of ecosystems, habitat losses and wildlife migrations. The Lake Urema wetland forms a distinct ecosystem at the terminal end of the Urema catchment that has a major influence on the biological productivity of the landscapes (Tinley, 1977; Burgess et al., 2004; Beilfuss et al., 2007; PNG, 2011). Moreover it is the only permanent water source for wildlife located entirely inside the Gorongosa National Park. Concerns over the Lake Urema wetland's drying up have been raised for some time by conservationists.

The park has five important landscape units: the Urema Graben floor (15–80 m above mean sea level – m amsl), the Gorongosa Mountain inselberg (1863 m amsl), the metamorphic Barue Basement west of the graben, the limestone/sandstone formations of the Cheringoma Plateau to the east, and the fault-dominated Graben transition zones (Beilfuss et al., 2007; Steinbruch, 2010). The park is drained in a southerly direction through the Lake Urema Wetland. Lake Urema is fed by several rivers and has one outflow called Urema River which drains into the Pungwe River, which ends in the Indian Ocean. The Urema catchment is, with about 9300 km^2 the largest sub-basin of the Pungwe River Basin. All rivers in the park are perennial before entering the Urema Graben however, during the dry season the surface water flowing towards

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and from the lake stop as the water infiltrates into aquifer systems at the transition of the escarpments of the Urema Graben to the graben bottom (Fig. 1) (Steinbruch, 2010; Arvidsson et al., 2011). The Urema Graben floor is characterized by extensive swamps, pans associated with termite activity, and other features indicative of impeded drainage.

Wetland Systems are important ecosystems because of the rich biodiversity associated with them as a result of the seasonal fluctuations of water levels. Changing water levels cause wetlands to expand and shrink, therefore creating seasonally changing patches of habitats with high biological productivity. Many wetland systems are maintained not only by surface water but also by groundwater. In such wetlands, the interactions between surface water and groundwater are important for the functioning of the wetland system (Winter, 1999; Mitsch and Gosselink, 2000; MA, 2005).

Water stable isotope ratios reflect the meteorological conditions of the geographical region in which water molecules were formed, i.e. processes constituting equilibrium or non-equilibrium conditions. The climate of Central Mozambique is influenced by the migration of the Inter-Tropical Convergence Zone (ITCZ) which results in a warm wet season from December to March with moisture originating from the Indian Ocean. Some rainfall occurs throughout the cooler dry season during June and July as a result of inflow of sub-polar moist cold air and continental depressions (Benessene, 2002). ITCZ is a belt between the 30° latitudes north and south of the equator, where prevailing so-called trade winds of the northern and southern hemisphere meet, heat up over the continents and are forced to rise. As a result moist air is pulled from the oceans to the continents generating monsoon precipitation (Valimba, 2004). Thus, wet and dry season have precipitations of different origin and of different water vapour source areas, which can be differentiated based on their stable water isotope ratios.

The Urema Catchment climate is marked by the Gorongosa Mountain inselberg that generates orographic rain, while the afromontane forests and alpine grasslands on top of the mountain increase the amount of rainfall due to the lower albedo, and acting as buffer to the surface runoff (Kirschbaum et al., 2011). The Urema Graben is a rain shadow area about 110 km from the Indian Ocean (Fig. 1c).

The lighter stable water isotopes begin to evaporate preferentially from the precipitation on its way to the ground. As some precipitation infiltrates and recharges local aquifers, this groundwater will maintain the stable water isotope composition of the precipitation, if the aquifer is not influenced by evaporation or biological activity. Rainfall that forms the runoff component is subjected to evaporation which results in the relative enrichment in the heavier isotopes of water. The rivers on Gorongosa Mountain flow through deep narrow cracks from which little water can evaporate (Steinbruch, 2010) and therefore, it is expected that stable water isotope signatures of the local precipitation are preserved. Lakes without outflow can be seen as an evaporation pan, in which the heavy stable water isotopes will remain in the water the longest. Any lake subsurface inflow or outflow will be noticed in the deviation of the lake's stable water isotope signatures from the local evaporation line (Clark and Fritz, 1997; Kendall and McDonnell, 1998; Cook and Herczeg, 1999; Geyh, 2000; Leibundgut et al., 2009).

The source areas of water of the Lake Urema wetland system were thought to be the Gorongosa Mountain runoff (Tinley, 1977) or the Zambeze river by bridging the water divide to the Pungwe Basin along the Urema Graben (Timberlake, 2000) (Fig. 1c).

Several studies were conducted to understand the hydrological processes of the Lake Urema wetland and combined with ecological monitoring. Evidences for apparent changes in the floodplain hydrology came from the monitoring of this environment‘s key indicator species, *Hippopotamus amphibius*, a water-dependent large herbivore. Wildlife observations conducted during the dry seasons in 2007 and 2010 revealed that this large mammal has abandoned the lake and migrated into areas distant from this zone (PNG, 2008, 2011). This suggested an irreversible change in the geo-ecology of the area warranting special conservation efforts.

Hydrograph analyses of the outflow from the lake revealed a memory effect that is disconnected from the seasonal flooding-drying cycle suggesting surface–ground water interactions in the floodplain (Owen, 2004; MA, 2005). Remote sensing change analyses of the Lake Urema‘s surface area size during the dry season showed a fluctuation between about 7 km^2 and 22 km^2 as a response to climate phenomena such as El Niño (Böhme et al., 2006; Brodin, 2010). A trough was found with medium to coarse sands at the bottom during a bathymetric and lithological survey in the year 2004. The water body's volume during the dry season consisted of about 99 million cubic meters (Böhme, 2005). This suggests that the lake might be recharged not only by surface water but also by groundwater. The lake's volume was surveyed again in 2009. A thick layer of clay was found at the bottom and the volume had reduced to 13 million cubic meters (Fig. 2) (Bűrmann, 2012). As the lake has trapped clay, its surface storage capacity reduced dramatically and the impermeable clay layer prevented groundwater–lake water interactions. This sedimentation alone may provide the explanation for the migration of hippopotami, because this species requires water that is deep enough to dive and ground sediments which allow these animals to stand or walk. However little is known about the wetland's water source.

This paper presents the findings of the investigation of the sources of water and the catchment areas which feed the Lake Urema wetland system by analysing water stable isotopes fingerprinting of surface water, groundwater and precipitation, for conservation management.

2. Methods

Water samples were collected at 48 locations spread across all geomorphological units viz.; Urema Graben, Barue Basement, Gorongosa Mountain and Cheringoma Plateau (Figs. 1 and 2 and Table 1). A total of 89 water samples were collected during the dry and wet seasons during 2006 to mid-2010 from rivers, springs, Lake Urema and a few boreholes (Table 4). Sample UG5 (Table 1) is special, in that it is from a water-filled pan, called Sungue-Picada 10, located in the Urema Graben about 5 km west of Lake Urema. This pan gets refilled and connected with the graben's inflows and the Lake Urema wetland during the wet season when the wetland expands and remains isolated from any inflows for the rest of the year. This open water body acts as a natural evaporation pan and the obtained stable water isotope composition from a sample taken before the onset of the wet season rains, was considered as an evaporation end point. A local evaporation line (LEL) was established for the Lake Urema wetland by combining this evaporation end point with the mean weighted stable water isotope composition of the wet season's precipitation (Fig. 3). Five water samples were at the top of Gorongosa Mountain at altitudes above 1000 m (Table 1; MG1, MG3, MG4, MG10, MG13). Monthly composite precipitation was collected from 2007 to 2009 at the "Vila Gorongosa" (within the Barue Basement unit; 346 m amsl) and "Chitengo" (within the Urema Graben unit; 34 m amsl) rainfall gauges (Fig. 2, Tables 1–3). The depth-weighted (precipitation weighted) water stable isotopic data of 41 precipitation samples, obtained from these two stations, were used to establish the Local Meteoric Water Line (LMWL) for the Urema catchment in a conventional δ^2H–δ^{18}O diagram. In the analysis the samples were grouped according to the sampled month into dry and wet season,

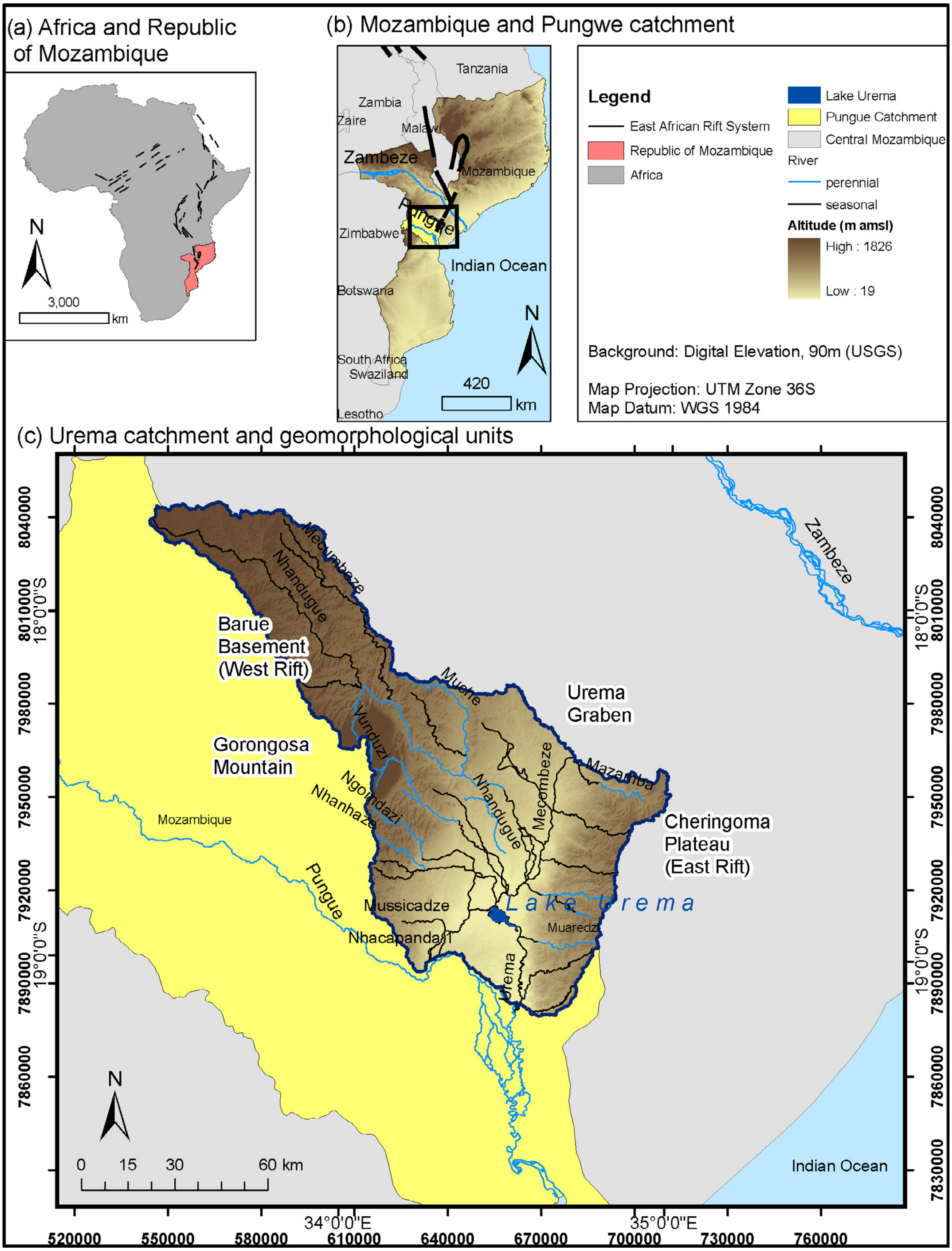

Fig. 1. Location map. (a) Map of Africa Map and Republic of Mozambique, (b) Republic of Mozambique, East African Rift System, Pungwe catchment, and study area and (c) Urema catchment, Gorongosa National Park, and geomorphological units.

whereby 28 samples from April to September formed the dry season group and 13 samples during October to March formed the wet season group.

Water samples were collected in 50 mL narrow-necked bottles with an additional inlet cap to avoid evaporation from the bottle during storage and shipping to the laboratory. At the laboratory a sample of each doublet of 4 mL was injected into glass vessels of a 48-port HDO-equilibration line, where the ports were occupied by a total of doublets of 18 samples consisting of four times two work standards and four standard water samples as control. In some aspects the equilibration line differed from the model presented by Horita et al. (1989). The Hokko beats are kept in steel meshes above the water sample which is stirred at 18 °C (±0.01 °C). After its equilibration the hydrogen and CO_2 gases are

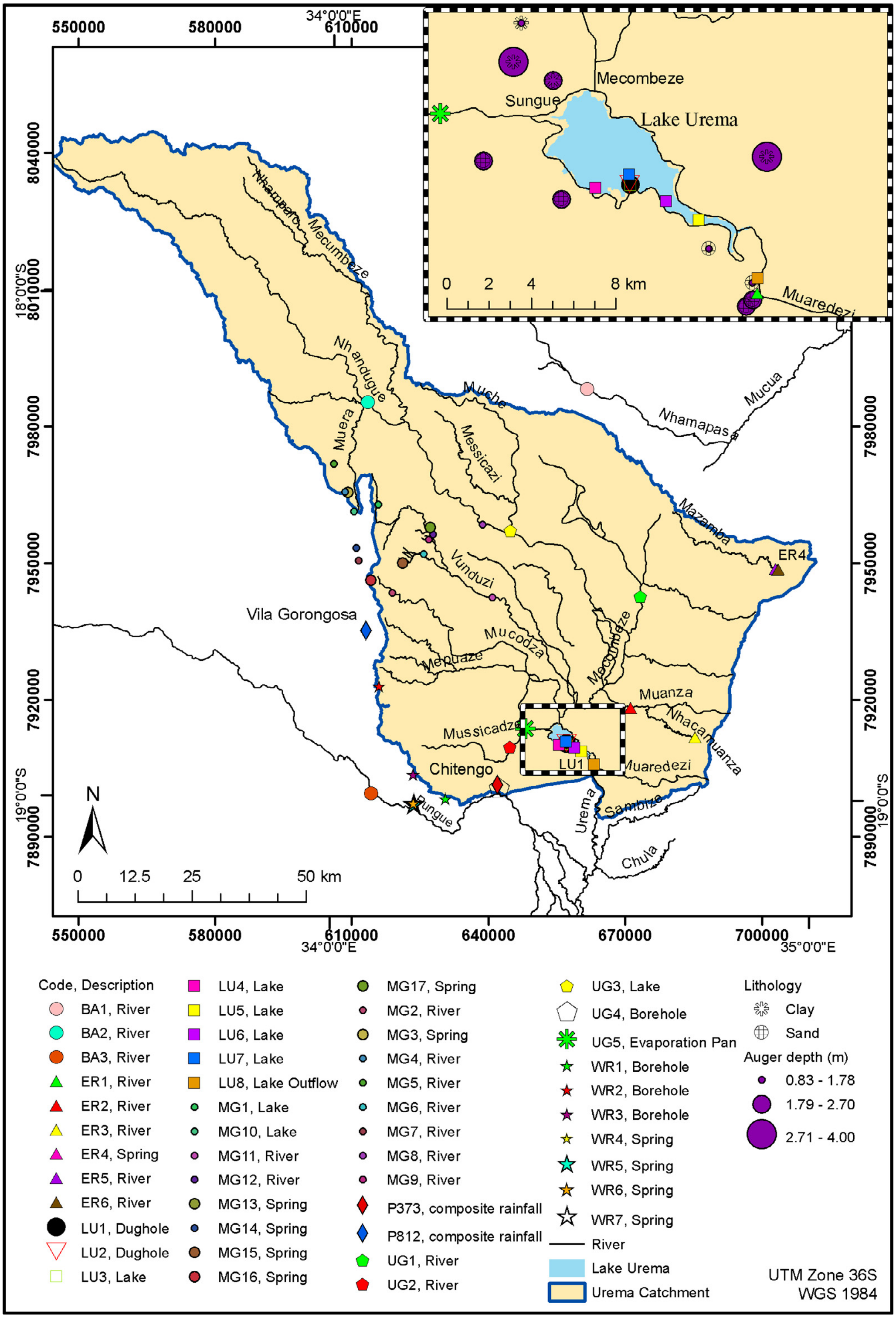

Fig. 2. Map of the locations of the sample sites.

step-by-step introduced via a double inlet system for measurement into an isotope ratio mass spectrometer (Thermo Finnigan Delta S). With the standard waters integrated into the run, the samples were matched with the common VSMOW-SLAP scale (Vienna Standard Mean Ocean Water – Standard Light Antartic Precipitation) (Gonfiantini, 1978), and expressed as abundance ratio, δ values in permil (‰), defined as: $\delta = 1000\,(R_s - R_p)/R_p$ ‰, where δ is the isotopic deviation in ‰; S is the sample; P is the international reference; and R is the isotopic ratio ($^{2}H/^{1}H$, $^{18}O/^{16}O$). The analytical uncertainties were ±0.1‰ for $\delta^{18}O$ and ±0.8‰ for $\delta^{2}H$ (δD).

3. Results

The derived LMWL of the Urema Catchment is given by the equation δD ($\delta^{2}H$) = 8.7 δ18O + 15.5 ($R^2 = 0.97$) (Figs. 3–5). The weighted stable isotope compositions for precipitation of the Vila

Table 1
List of sample sites (GPS positions).

Code	Longitude	Latitude	Altitude (m amsl)	Location	Geomorphologic unit
BA1	661633	7988172	117	Nhamapaza River EN1	Barue Basement
BA2	613571	7985320	364	Nhandungue River EN1	Barue Basement
BA3	614218	7899455	194	Pungue River/EN1	Barue Basement
ER1	663176	7905182	13	Muaredzi River	Cheringoma Plateau
ER2	671229	7918275	49	Muanza River	Cheringoma Plateau
ER3	685386	7911840	198	Nhacamuanza River	Cheringoma Plateau
ER4	703403	7948516	185	Mazamba Spring	Cheringoma Plateau
ER5	703034	7948741	174	Mazamba River Campira	Cheringoma Plateau
ER6	703563	7948635	203	Nhamatope River	Cheringoma Plateau
LU1	657155	7910343	19	Lake Urema Dughole 1 (0.5 m)	Lake Urema
LU2	657127	7910336	20	Lake Urema Dughole (0.5 m)	Lake Urema
LU3	657155	7910343	19	Lake Urema	Lake Urema
LU4	655495	7910192	19	Lake Urema near inflow	Lake Urema
LU5	660401	7908682	20	Urema GPS 7	Lake Urema
LU6	658847	7909559	20	Urema GPS 31	Lake Urema
LU7	657088	7910822	19	Urema 52	Lake Urema
LU9	663202	7905892	18	Lake Urema	Lake Urema
LU8	663202	7905892	17	Urema River	Lake Urema
MG1	615748	7962927	1298	Pool in Vunduzi River	Top of Gorongosa Mountain
MG10	610428	7961325	1707	River Gorongosa Mountain	Top of Gorongosa Mountain
MG11	640819	7942505	79	Vunduzi R. (Bunga)	Gorongosa Mountain
MG12	627831	7956305	279	Vunduzi River	Gorongosa Mountain
MG13	609098	7965496	1457	Vunduzi Spring	Top of Gorongosa Mountain
MG14	610953	7953321	727	Nhambamba Spring Gorongosa Mountain	Gorongosa Mountain
MG15	621107	7950021	381	Nhamucunga Spring Gorongosa Mountain	Gorongosa Mountain
MG16	614142	7946241	447	Spring	Gorongosa Mountain
MG17	627224	7957877	319	Spring Mountain foothill	Gorongosa Mountain
MG2	618836	7943448	360	Mucodza river	Gorongosa Mountain
MG3	609098	7965496	1457	Muera Spring	Top of Gorongosa Mountain
MG4	608494	7965672	1236	Muera River Mountain	Top of Gorongosa Mountain
MG5	606067	7971800	510	Muera River Mountain foothill	Gorongosa Mountain
MG6	625757	7952005	260	Ngomadzi River	Gorongosa Mountain
MG7	611516	7950568	490	Nhandare River	Gorongosa Mountain
MG8	638655	7958428	132	Nhandungue River old EN1	Gorongosa Mountain
MG9	626825	7955212	275	Nhanhaze River	Gorongosa Mountain
UG1	673330	7942658	40	Mecombedze River	Urema Graben Floor
UG2	644725	7909611	17	Mussicadze River	Urema Graben Floor
UG3	644806	7957152	93	Lake Catonze/Casa Banana Road	Urema Graben Floor
UG4	642360	7900708	34	Chitengo borehole	Urema Graben Floor
UG5	648147	7913723	24	Sungue-Picada 10	Urema Graben Floor
WR1	630573	7898286	75	Boma Groundwater	Barue Basement
WR2	615959	7922929	341	Matacamacha Borehole	Barue Basement
WR3	623499	7903576	181	Site one Borehole	Barue Basement
WR4	623683	7897316	54	Cold spring1 near Nhambita hotspring	Barue Basement
WR5	623615	7897062	56	Cold spring2 near Nhambita hotspring	Barue Basement
WR6	623555	7897184	45	Cold spring4 near Nhambita hotspring	Barue Basement
WR7	623646	7897237	51	Nhambita Hot spring	Barue Basement
P812	613094	7935149	346	Composite rainfall	Vila Gorongosa
P373	641953	7901378	34	Composite rainfall	Chitengo

Gorongosa and Chitengo rainfall gauges ranges from −7.84‰ to 2‰, with a mean value of −2.4‰ for $\delta^{18}O$ and from −51.1‰ to 19‰, with a mean value of −6.41‰ for δ^2H. Remarkable is that the d-excess of the wet season precipitation's samples of Vila Gorongosa is close to the d-excess of mean ocean water (9.37‰; $\delta D = 7.23\ \delta^{18}O + 9.37$, $R^2 = 0.98$). The dry season's d-excess for the precipitation's samples of Vila Gorongosa is 17.67‰ ($\delta D = 9.13\ \delta^{18}O + 17.67$, $R^2 = 0.94$). The weighted $\delta^{18}O$ composition of the dry season precipitation ranges from −5.03‰ to −0.41‰, with an average of −3.27‰ and weighted ranges from −28.49‰ to 5.95‰, with an average of −14.55‰ for δ^2H. On the other hand, the weighted $\delta^{18}O$ composition of the wet season's precipitation ranges from −5.0‰ to 0.22‰, with an average of −2.07‰ and from −0.76‰ to 5.9‰, with an average of −2.09‰ for δ^2H (Fig. 3, Table 2).

For dry season runoff stable water isotope signatures of $\delta^{18}O$ range from −6.5‰ to 3.62‰, with an average of −3.58‰ and from −37.7‰ to 20.20‰, with an average of −22.19‰ for δD. The wet season signatures of runoff range for $\delta^{18}O$ from −9.34‰ to 7.28‰, with an average of −3.96‰ and from −64.3‰ to 36.5‰ for δD, with an average of −22.38‰.

The water sample collected from the natural evaporation pan (UG5) had a $\delta^{18}O$ of 11.84‰ and 55.4‰ for δ^2H and therefore is highly enriched in the heavy stable isotopes of water. The mean stable water isotope ratio of the wet season's precipitation, with $\delta^{18}O$ of −3.5‰ and −16.0‰ for δ^2H and the stable water isotope composition of UG5 provided a local evaporation line (LEL) given by the equation $\delta D = 4.65\ \delta^{18}O + 0.29$ (Fig. 3).

From plotting the stable water isotope ratios of all samples collected from Lake Urema and its outflow (Table 4, LU1–LU8) it was possible to construct a line by the equation $\delta D = 5.1\ \delta^{18}O + 1.46$ ($R^2 = 0.99$) (Fig. 3; Lake Mixing Line – LML). These samples have values ranging from −2.1‰ to 7.28‰, with a mean value of 1.92‰ for $\delta^{18}O$, and from −11.5‰ to 36.5‰, with an average value of 11.27‰ for δ^2H. The stable water isotope compositions of the wet season's samples (Table 4; LU1, LU3, LU8/5, LU8/6) fall on an evaporation line by the equation $\delta D = 4.95\ \delta^{18}O + 0.83$ ($R^2 = 0.99$), while the dry season's samples (Table 4, LU2, LU4–LU8/4) follow the regression line $\delta D = 5.73\ \delta^{18}O + 1.22$ ($R^2 = 0.98$).

The rivers of the Cheringoma Plateau have stable water isotope compositions ranging from −5.24‰ to −3.1‰ for $\delta^{18}O$, with a

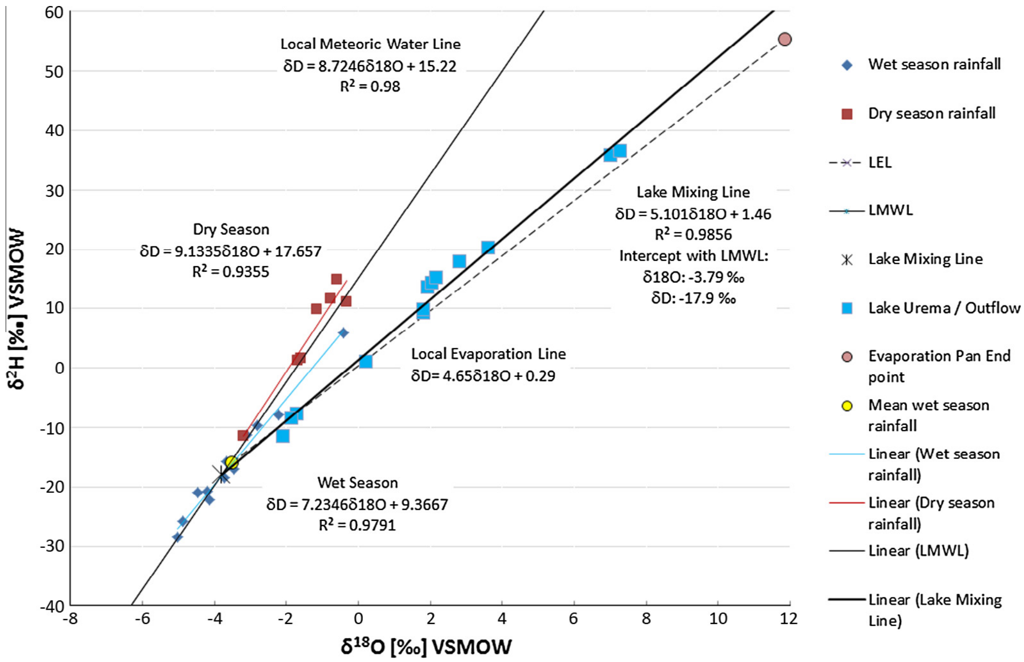

Fig. 3. δD–δ^{18}O plot of the Local Meteoric Water Line, Local Evaporation Line, linear regression lines of the wet and dry season precipitation, and lake mixing line.

Table 2
List of stable water isotope ratios of precipitation collected at station P812 (Vila Gorongosa) and P373 (Chitengo).

Sample date	Gorongosa/Barue Basement			Chitengo/Urema Graben Floor		
	$\delta^{8}O_{H2O}$ ($‰_{VSMOW}$)	$\delta^{2}H_{H2O}$ ($‰_{VSMOW}$)	δ^{2}H excess ($‰_{VSMOW}$)	$\delta^{18}O_{H2O}$ ($‰_{VSMOW}$)	$\delta^{2}H_{H2O}$ ($‰_{VSMOW}$)	δ^{2}H excess ($‰_{VSMOW}$)
February-07	−7.18	−46.1	11.3	−3.55	−19.6	8.8
March-07	−1.95	−1.6	14.0	−2.06	−5.2	11.3
April-07	−1.98	−1.0	14.8	−3.24	−14.3	11.6
May-07	[a]	[a]	[a]	[b]	[b]	[b]
June-07	−1.83	11.9	26.5	[b]	[b]	[b]
July-07	−1.01	10.4	18.5	[b]	[b]	[b]
August-07	−0.35	12.6	15.4	[b]	[b]	[b]
September-07	[a]	[a]	[a]	[b]	[b]	[b]
October-07	−0.60	7.7	12.5	−3.45	−16.9	10.7
November-07	−3.36	−14.7	12.2	−3.10	−11.2	13.6
December-07	−3.33	−14.8	11.9	−2.85	−10.8	12.0
January-08	−3.01	−12.0	12.1	−1.70	−1.6	12.0
February-08	−1.69	2.5	16.0	−1.23	6.6	16.5
March-08	−3.12	−7.5	17.5	−2.75	−3.9	18.1
April-08	[a]	[a]	[a]	2.00	19.0	3.0
May-08	[a]	[a]	[a]	[a]	[a]	[a]
June-08	[b]	[b]	[b]	[b]	[b]	[b]
July-08	[a]	[a]	[a]	[a]	[a]	[a]
August-08	[b]	[b]	[b]	[b]	[b]	[b]
September-08	[b]	[b]	[b]	[b]	[b]	[b]
October-08	−0.03	−0.2	0.0	[b]	[b]	[b]
November-08	−1.93	−14.2	1.2	[b]	[b]	[b]
December-08	−7.84	−51.1	11.6	−6.62	−43.4	9.5
January-09	−1.69	−5.3	8.2	−6.52	−42.4	9.8
February-09	−2.03	−2.9	13.3	−1.76	−1.1	13.0
March-09	−5.72	−32.2	13.5	−3.81	−19.5	11.0
April-09	−1.23	4.0	13.8	−2.00	−5.4	10.6
May-09	−1.43	1.9	13.4	[b]	[b]	[b]
June-09	−0.45	11.5	15.1	[a]	[a]	[a]
July-09	−0.47	18.4	22.1	[a]	[a]	[a]
August-09	−1.08	11.1	19.7	[a]	[a]	[a]
September-09	−0.32	11.1	13.6	[a]	[a]	[a]
October-09	−0.18	5.0	6.4	[a]	[a]	[a]
November-09	−1.97	2.1	17.9	[a]	[a]	[a]

[a] Not sampled.
[b] No rainfall.

Table 3
List of rainfall weighted stable water isotope ratios of rain gauges P812 (Vila Gorongosa) and P373 (Chitengo) for the period of 2007–2010.

Month	Weighted $\delta^{18}O_{H2O}$ (‰$_{VSMOW}$)	Weighted $\delta^{2}H_{H2O}$ (‰$_{VSMOW}$)	Weighted δ^{2}H excess (‰$_{VSMOW}$)	Mean Precipitation (mm)	Season
Vila Gorongosa/Barue Basement (346 m asl)					
January	−2.23	−7.88	9.93	142	Wet
February	−4.87	−25.80	13.18	260	Wet
March	−4.45	−20.88	14.71	97	Wet
April	−1.69	1.26	14.75	92	Dry
May	−1.58	1.57	14.21	39	Dry
June	−1.15	9.92	19.10	13	Dry
July	−0.57	14.88	19.47	33	Dry
August	−0.77	11.74	17.88	14	Dry
September	−0.32	11.06	13.61	27	Dry
October	−0.41	5.95	9.26	21	Wet
November	−2.81	−9.64	12.84	123	Wet
December	−5.03	−28.49	11.76	474	Wet
Chitengo/Urema Graben Floor (34 m asl)					
January	−4.14	−22.23	10.89	135	Wet
February	−4.19	−20.73	12.77	207	Wet
March	−3.67	−15.69	13.64	128	Wet
April	−3.19	−11.44	14.06	59	Dry
May	−1.38	1.96	13.03	52	Dry
June	0.22	17.17	15.38	11	Dry
July	−5.00	−30.76	9.25	18	Dry
August	n/a	n/a	n/a	0	Dry
September	n/a	n/a	n/a	0	Dry
October	−3.45	−16.94	10.66	2	Wet
November	−3.10	−11.19	13.58	170	Wet
December	−3.74	−18.51	11.39	243	Wet

mean value of −4.58‰ and from −36.6‰ to −21.0‰, with an average value of −29.6‰ for δ^{2}H (Table 4, ER1–ER6, Fig. 5).

The rivers draining the Barue Basement, such as the Nhandugue and the Pungwe River have stable water isotope signatures ranging from −9.034‰ to −3.17‰ for δ^{18}O, with a mean value of −4.95‰ and from −64.3‰ to −19.0‰, with an average value of −28.09‰ for δ^{2}H (Table 4, BA1–BA3, Fig. 5).

The samples collected in the Urema Graben have stable water isotope compositions ranging from −7.56‰ to −0.97‰ for δ^{18}O, with a mean value of −4.44‰ and from −53.2‰ to −7.5‰, with an average value of −29.46‰ for δ^{2}H (Table 4, UG1–UG4).

The Gorongosa Mountain's samples have stable water isotope compositions ranging from −6.45‰ to 2.0‰ for δ^{18}O, with a mean value of −4.62‰ and from −37.7‰ to 2.9‰, with an average value of −25.1‰ for δ^{2}H (Table 4, MG1–MG17, Fig. 5).

Separate evaporation lines can be constructed for karst water from the Cheringoma Plateau and other surface waters of the graben as follows: Cheringoma Plateau (ER): $\delta D = 6.42\ \delta^{18}O - 0.26$ ($R^2 = 0.85$); Urema Graben (UG): $\delta D = 6.61\ \delta^{18}O + 0.91$ ($R^2 = 0.97$); Barue Basement (BA): $\delta D = 7.67\ \delta^{18}O + 9.91$ ($R^2 = 0.94$); Gorongosa Mountain (MG): $\delta D = 4.84\ \delta^{18}O - 2.75$ ($R^2 = 0.92$) (Fig. 4). The groundwater samples collected from the boreholes and a hotspring in the fractured aquifer on the west side of the Urema Graben have stable water isotope compositions ranging from −5.77‰ to −3.53‰ for δ^{18}O, with a mean value of −5.06‰ and ranging from −34.3‰ to −20.8‰ for δ^{2}H, with an average value of −30.63‰ (Table 4, WR1–WR7, Fig. 5).

4. Water sources of Lake Urema wetland system

For the Urema catchment, the high deuterium excess value (15.22‰) observed in the precipitation is attributed to the kinetic fractionation processes which the water vapor had undergone during the rain's formation. In the case of the wet season's rainfall (d-excess: 9.4‰), this was formed over the Indian Ocean without undergoing major fractionation. Nevertheless, the dry season rainfall's d-excess value (17.7‰) pointed to an orographic precipitation as result of the sudden rise of moist air on the eastern slopes of the Gorongosa Mountain coming from the Indian Ocean as well as from locally evaporated or recycled waters from the floodplains of the Urema Graben (Fig. 3).

The LML intersects the LWML at δ^{18}O of −3.7‰ and δD of −17.6‰, close to the stable water isotope signature of the mean weighted wet season precipitation (Figs. 3 and 4). As can be seen in Fig. 3, the dry season precipitation is not reflected in the water stable isotope signatures of the dry and wet season runoff, hence it can be inferred that the surface runoff component in the dry season is small. Hence, the water sources for the Lake Urema are the wet season precipitation and its corresponding runoff. During the wet season flows, soils are transported into the floodplain. Along the course of the flow the sediments get graded and the finest are found in the Lake Urema Wetland. Changes in the runoff characteristics, soil cover and river banks will increase the amount of sediments removed during precipitation events.

Local lithological characteristics of the lake suggest that some parts of the dry season's lake inflows merely contribute to its recharge and are from runoff, and precipitation generated during the wet season (Fig. 2, soil auger locations). This is because the Urema wetland area stores part of the wet season rainfall during annual inundations in the floodplain's shallow aquifers, preserving its specific stable isotope signature, and slowly releases this water into the lake throughout the dry season.

Stable water isotope signatures of wet season's (LU1, LU3, LU8/5-6) and dry season's samples (Table 4; LU2-, LU4-7, LU8/1-4) of Lake Urema and Urema River appear to be desynchronized from the respective sampling season as some of the wet season samples are slightly more enriched in the heavier stable water isotopes than the lake's dry season's samples and vice versa (Fig. 4). It can be explained by the delayed hydrological response of the lake to runoff generated from precipitation events in the upper catchment. It also suggests that the lake's surface water–groundwater interactions are fairly dynamic. For example, when the upper catchments of the Barue Basement receive high amounts of precipitation earlier than the Gorongosa Mountain catchment, then the

Table 4
List of stable water isotope ratios ($\delta^{18}O$ and $\delta^{2}H$) of the sampled catchment waters.

Code	Sample	Location	Sample date		$\delta^{18}O_{H2O}$ (‰)$_{(VSMOW)}$	$^{18}O_{H2O}$ error (‰)$_{(VSMOW)}$	$\delta^{2}H_{H2O}$ (‰)$_{(VSMOW)}$	$^{2}H_{H2O}$ error (‰)$_{(VSMOW)}$	$\delta^{2}H$ excess (‰)
			Wet season	Dry season					
BA1	1	Surface inflow from Barue basement into Urema Graben (baseflow/groundwater)	24-10-2007		−5.77	0.1	−36.9	0.8	9.3
BA1	2		11-01-2008		−4.05	0.1	−20.4	0.8	12.1
BA2	1	Surface inflow from Barue basement into Lake Urema (seasonal flow)	24-10-2007		−3.72	0.1	−24.8	0.8	5
BA2	2		11-01-2008		−4.85	0.1	−27.1	0.8	11.7
BA2	3		06-01-2009		−9.34	0.1	−64.3	0.8	10.5
BA2	4		19-02-2010		−5.31	0.1	−26.5	0.8	15.9
BA3	1	Surface flow from Barue Basement (connected with Lake Urema Wetland during wet season)		06-06-2006	−4.95	0.1	−26.3	0.8	13.4
BA3	2			21-06-2006	−4.95	0.1	−25.6	0.8	14
BA3	3		11-01-2008		−4.4	0.1	−22.6	0.8	12.7
BA3	4		05-11-2008		−3.17	0.1	−19	0.8	6.3
BA3	5			15-09-2009	−4.4	0.1	−24.2	0.8	11
BA3	6			15-05-2009	−4.98	0.1	−27.9	0.8	11.9
BA3	7		15-10-2009		−4.28	0.1	−21.9	0.8	12.4
BA3	8		15-11-2009		−4.15	0.1	−21	0.8	12.2
BA3	9		13-01-2009		−6.08	0.1	−38	0.8	10.7
BA3	10		15-03-2009		−5.19	0.1	−28.9	0.8	12.7
BA3	11			17-04-2009	−5.1	0.1	−29.4	0.8	11.4
BA3	12			30-06-2009	−4.87	0.1	−26.9	0.8	12.1
BA3	13			15-07-2009	−4.82	0.1	−25.9	0.8	12.6
BA3	14			16-08-2009	−4.73	0.1	−26.6	0.8	11.2
BA3	15			12-07-2010	−4.88	0.1	−25.8	0.8	13.2
ER1	1	Surface inflow of karst springs from Cheringoma plateau		19-09-2007	−3.79	0.1	−24.4	0.8	5.9
ER2	1		03-10-2007		−3.1	0.1	−21	0.8	3.8
ER3	1		03-10-2007		−4.67	0.1	−28.2	0.8	9.1
ER4	1			22-07-2006	−5.24	0.1	−36.6	0.8	5.3
ER4	2			25-08-2007	−5.12	0.1	−35.9	0.8	5.1
ER5	1			21-07-2006	−5.06	0.1	−30.3	0.8	10.2
ER6	1			01-07-2008	−5.07	0.1	−31.1	0.8	9.5
LU1	1	Lake Urema	28-11-2008		7.01	0.1	35.9	0.8	−20.2
LU2	1			26-09-2008	−2.1	0.1	−11.5	0.8	5.4
LU3	1		17-02-2010		1.81	0.1	9.9	0.8	−4.6
LU4	1			27-09-2009	2.8	0.1	18	0.8	−4.4
LU5	1			20-09-2009	1.91	0.1	13.6	0.8	−1.7
LU6	1			20-09-2009	2.05	0.1	14.3	0.8	−2.1
LU7	1			20-09-2009	2.16	0.1	15.2	0.8	−2.1
LU9	1		19-11-2008		7.28	0.1	36.5	0.8	−21.7
LU8	1	Lake Urema outflow		14-07-2006	−1.7	0.1	−7.6	0.8	13.6
LU8	2			23-08-2007	0.2	0.1	1.1	0.8	−0.8
LU8	3			22-09-2007	1.81	0.1	9.3	0.8	−13.7
LU8	4			26-09-2008	3.62	0.1	20.2	0.8	−28.9
LU8	5		17-02-2010		−1.85	0.1	−8.4	0.8	6.4
MG1	1	Surface Runoff from Gorongosa Mountain into Urema Graben (perennial)		16-07-2006	−5.36	0.1	−26.9	0.8	16
MG10	1			16-07-2006	−6.05	0.1	−32.7	0.8	15.7
MG11	1			28-06-2009	−4.58	0.1	−24.1	0.8	12.5
MG11	1			01-07-2010	−4.63	0.1	−22.8	0.8	14.3
MG12	4			06-06-2006	−5.02	0.1	−25.7	0.8	14.5
MG12	3			21-06-2006	−5.04	0.1	−25.7	0.8	14.6
MG12	1			22-07-2006	−5.1	0.1	−25.8	0.8	14.9
MG12	2			22-07-2006	−5.1	0.1	−25.8	0.8	14.9
MG12	5			24-08-2007	−4.9	0.1	−26.2	0.8	13
MG12	6		11-01-2008		−4.74	0.1	−23.3	0.8	14.6
MG13	1			22-05-2008	−5.67	0.1	−30.2	0.8	15.1
MG13	2			24-05-2008	−5.71	0.1	−30	0.8	15.7

MG14	1			01-07-2008	−4.63	0.1	−23	0.8	14
MG15	1			01-07-2008	−5.09	0.1	−27.3	0.8	13.4
MG16	1			01-07-2008	−4.99	0.1	−28.7	0.8	11.2
MG17	1			01-07-2008	−5.14	0.1	−30.3	0.8	10.8
MG2	1			06-06-2006	−4.62	0.1	−24.6	0.8	12.4
MG2	2			24-08-2007	−4.69	0.1	−25.7	0.8	11.8
MG2	3			11-01-2008	−4.36	0.1	−21.6	0.8	13.3
MG3	1			01-07-2008	−6.45	0.1	−37.7	0.8	13.9
MG4	1			01-07-2008	−6.44	0.1	−37.7	0.8	13.8
MG5	1			01-07-2008	−5.64	0.1	−35.4	0.8	9.7
MG6				24-08-2007	−4.46	0.1	−23.2	0.8	12.5
MG6	2		11-01-2008		−4.27	0.1	−20.8	0.8	13.4
MG7	1			01-07-2008	−5.02	0.1	−25.9	0.8	14.3
MG8	2			06-06-2006	−3.9	0.1	−21.1	0.8	10.1
MG8	3			21-06-2006	−4.04	0.1	−21.5	0.8	10.8
MG8	4			24-08-2007	−2.62	0.1	−16.3	0.8	4.7
MG8	6		17-11-2008		2	0.1	2.9	0.8	−13.1
MG8	7		12-12-2008		−1.44	0.1	−7.5	0.8	4
MG8	1		12-01-2009		−5.13	0.1	−30.9	0.8	10.1
MG8	8		23-03-2010		−4.94	0.1	−27.2	0.8	12.4
MG9	1			24-08-2007	−4.68	0.1	−25.6	0.8	11.8
UG1	1	Urema Graben Springs/runoff (connected with Lake Urema Wetland during wet season)		27-05-2008	−0.97	0.1	−7.5	0.8	0.2
UG2	1		13-01-2009		−7.56	0.1	−53.2	0.8	7.3
UG3	1		12-12-2008		−2.5	0.1	−16.7	0.8	3.4
UG3	2			19-08-2010	−2.7	0.1	−15	0.8	6.6
UG4	1	Groundwater in Urema Graben		07-06-2006	−5.83	0.1	−34.5	0.8	12.1
UG4	2			21-06-2006	−5.84	0.1	−36.3	0.8	10.4
UG4	3			29-09-2008	−5.7	0.1	−36	0.8	9.6
UG5	1	Isolated Pan in Urema Graben	25-11-2008		11.84	0.1	55.4	0.8	−39.3
WR1	1	Groundwater in Barue Basement	18-10-2007		−5.17	0.1	−32.8	0.8	8.6
WR2	1			05-06-2009	−5.2	0.1	−31.1	0.8	10.5
WR3	1			03-06-2008	−5.01	0.1	−30.2	0.8	9.9
WR4	1			01-07-2008	−4.99	0.1	−30.6	0.8	9.3
WR5	1			01-07-2008	−5.22	0.1	−31.6	0.8	10.2
WR6	1			01-07-2008	−3.53	0.1	−20.8	0.8	7.4
WR7	1			18-07-2006	−5.77	0.1	−33.7	0.8	12.5
WR7	2			23-08-2007	−5.61	0.1	−34.3	0.8	10.6

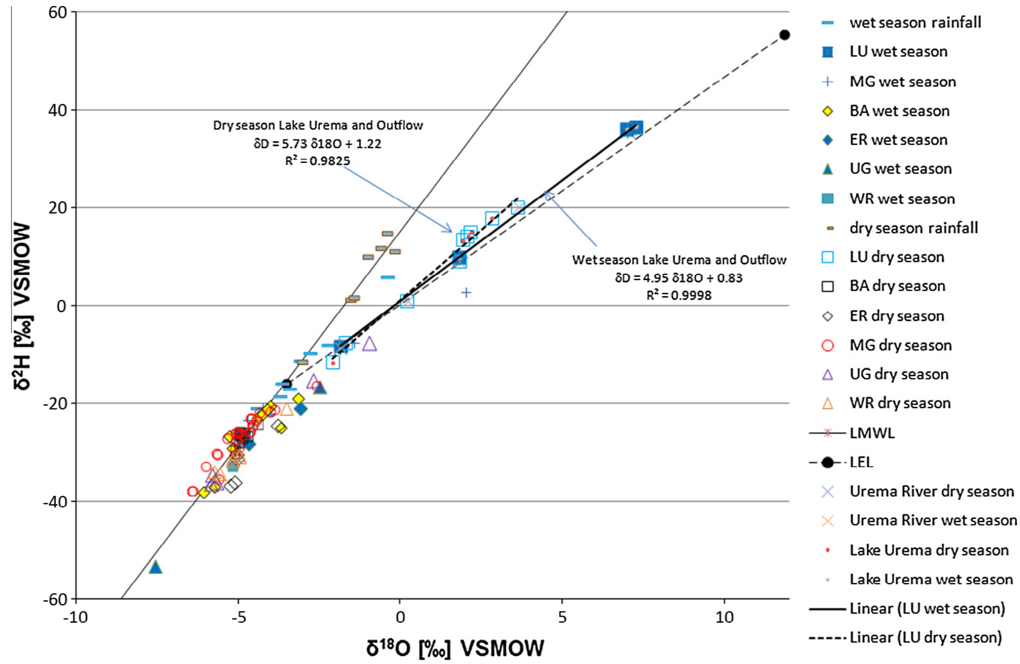

Fig. 4. δD–δ18O plot of the sampled water grouped into wet/dry season precipitation and wet/dry season runoff of each geomorphological unit.

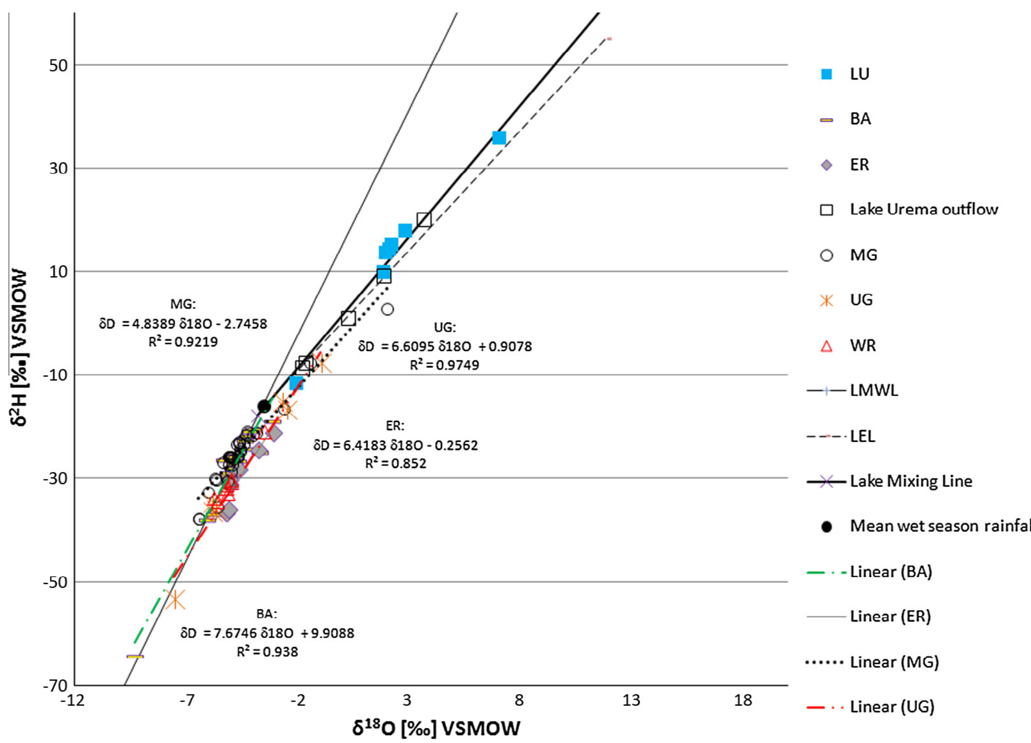

Fig. 5. δD–δ18O plot of the sampled water grouped into the main geomorphologic and catchment areas with linear regression line, in relation to the LMWL, LEL and the lake mixing line.

increased flow in the Pungwe River will prevent the outflow from the lake. Consequently, reverse flows occur in the Urema River and the Pungwe spills over into the Lake Urema wetland. The stable water isotope compositions of the lake's outflow compare well with the lake's signatures. The rivers draining the Cheringoma Plateau do not influence the stable water isotope signature of the lake. This suggests that the Cheringoma Plateau recharges some other aquifers associated with the rift transition zone.

As Fig. 5 shows, the water stable isotope composition for the Barue Basement follow the local meteoric water line of the wet season. Samples collected on the Gorongosa Mountain's top are slightly offset from the LMWL, which can be attributed to the altitude effect, however generally, plot around the LMWL. The stable water isotope compositions of mountain runoff show the effect of evaporation trending along an own evaporation line, however differing from the LEL only by its deuterium excess value. These runoff samples have their origin in wet season precipitation that was more depleted in the heavier stable water isotopes than the source waters of Lake Urema. Nonetheless, the Cheringoma Plateau follow an evaporation line which also differs from the LEL only in the d-excess value. Waters of the Cheringoma Plateau intersect the LMWL at a $\delta^{18}O$ value of −6.72‰ and a $\delta^{2}H$ value of −43.38‰, developing the evaporation line out of the wet season precipitation (Figs. 4 and 5). The Urema Graben' dry season's drainage has a slope between the LMWL and LEL, and intersects the LMWL at a $\delta^{18}O$ value of −7.67‰ and a $\delta^{2}H$ value of −43.81‰, having its origin in the Gorongosa Mountain, the Barue Basement, and the Cheringoma Plateau catchment areas (Figs. 4 and 5). Therefore, neither the water from the Cheringoma Plateau nor the Urema Graben dry season's drainage feed the Lake Urema. The stable water isotope ratios of individual water samples falling on the same evaporation line have their origin in similar meteoric conditions and from the same source area. In this case the stable water isotope signatures of Lake Urema and its outflow follow a line, which intersects the local meteoric water line close to the isotopic signature of the mean wet season precipitation with a slope between LMWL and LEL indicating that the curve constitutes a mixing line formed by waters of the same origin that underwent different levels of evaporation. This water body's stable isotope signature links the lake with the Gorongosa Mountain and the Barue Basement as catchment source areas, which supply the lake with runoff of the wet season's precipitation. Regarding the mixing line of the Lake Urema (Figs. 4 and 5), the water supply from these two geomorphological units' source areas, produced under the same climatic conditions and with similar stable isotope ratios, has to be occurred in such a way that *minimal isotopic fractionation* could have taken place between these water source areas and the lake. The possible mechanism is a single annual flooding event with a subsequent evaporation process.

Finally, the stable water isotope compositions of groundwater from the Barue Basement suggest a recharge mechanism from wet season precipitation that is relatively depleted in the heavier stable isotopes of water, generated possibly on Gorongosa Mountain (Figs. 4 and 5). A link between these fractured aquifers and Lake Urema could not be established.

5. Conclusions

The Lake Urema's permanent water body is maintained throughout the dry season merely from water generated during the wet season. This lake receives its water from wet season precipitation and the runoff generated from this precipitation. The water source areas of the lake are the Gorongosa Mountain and the Barue Basement geomorphological units. Consequently, the source of the sediments which have been trapped into the lake and the floodplain has to be identified in these two catchment areas and urgent action is required to rescue the lake. This water body constitutes a groundwater buffer system which supports a unique wetland landscape. The annual inundations' processes leading to the recharge-drainage cycle in the floodplain are most sensitive to the deposition of sediments, changing hydraulic gradients, and reducing wet season inflows and increasing drainage rates.

Conflict of interest

There is no conflict of interest.

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