Technical Note: Hydrology of the Lake Urema wetland, Mozambique

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Description

Lake Urema is a shallow lake located on the floor of the Rift Valley, just to the south of the Zambezi River in Gorongosa National Park in Mozambique. Located at 18°52' S and 34°39'E at an altitude of approximately 20 masl, the lake is part of the Lower Zambezi-Gorongoza-Buzi-Pungwe floodplain system (Breen *et al*., 1997). The floodplains surrounding the lake are highly productive and crucial to the ecological well being of the National Park. The periodic inundation of the floodplains creates a dynamic ecotone supporting a range of diverse temporal habitats with the capacity to support large numbers of herbivores and associated predators (Tinley, 1977). The lake itself supports large numbers of hippopotamus, crocodiles and water birds and is an important source of fish for several communities living close to it.

Several rivers drain onto the Rift valley floor from the both the east and west. The primary inflowing river is the River Nhanduge which rises to the north-west of the lake on the Barue platform which forms the highlands on the western side of the Rift Valley (Figure 1). The river source is close to the city of Macosse and not far from the border with Zimbabwe. Other rivers originate on the flanks of Mount Gorongosa. Mount Gorongosa is a younger intrusive granite massif (30km (N-S) by 20 km (E-W)) rising 1,400m above the Barue platform immediately to the north-west of the lake (Figure 1). The Chirengoma plateau forms the highlands on the eastern side of the Rift Valley. Although the major rivers from this plateau drain east into the Indian Ocean, some smaller rivers flow west and converge with the rivers flowing from the Barue Platform and Mount Gorongosa. As a result there are two primary inflows into the lake; the Sungue River and the Mucambeze river, both of which enter the northern end of the lake (Figure 1).

The main outflow from the lake is the Urema River which flows south to a confluence with the Pungwe River, which originates on the Barue Platform in Zimbabwe and flows into the Indian Ocean close to Beira (Figure 1; Box1). The total catchment area of the lake is estimated to be approximately 8,000 km^2 [1]. The total catchment area of the Urema river at its confluence with the Pungwe is 8,402 km^2 (i.e. 27 % of the total Pungwe catchment area of 31,105 km^2) (SWECO and Associates, 2004).

The average depth of the lake is estimated to be less than 2.0m (Bőhme, 2005). The areal extent of the lake varies from year to year. Supervised classification of satellite images (primarily from the dry season) and analyses of historic topographic maps indicates that between 1960 and 2000 the lake area varied from a minimum of 7.9km^2 (1960) to a maximum of 104.1 km^2 (1997). However, the 1997 image was one of the few obtained at the end of the wet season and the 1960 image was simply derived from a map. Ignoring these two extremes, on average the dry season area of the lake is 20.5 km^2 with a standard deviation of 2.8 km^2 (Bőhme, 2005). It is probable that the wet season area is significantly greater, but varies considerably depending on the volume and temporal distribution of rainfall.

[1] This is smaller than the 8,755 km^2 estimated by Bőhme (2005) but is slightly less than the area (8,060km^2) to the gauging station E81, located immediately downstream (Figure 1).

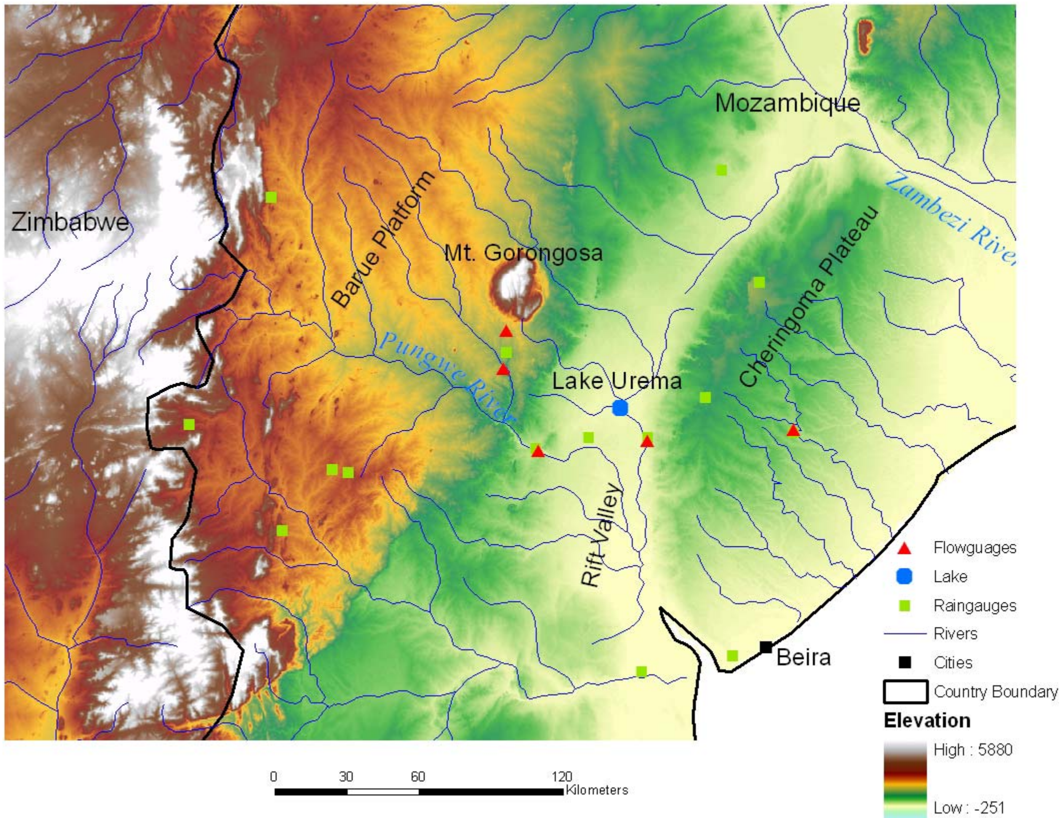


Figure 1: *Map showing the location of Lake Urema as well as rain and flow gauges.*

Box 1: The Pungwe River (source: SWECO and Associates, 2004)

The Pungwe River stretches for 400 kilometres, flowing eastwards from Zimbabwe's Eastern Highlands, through Manica and Sofala provinces in Mozambique, to the Indian Ocean at Beira. The main river and its tributaries drain a total catchment area of 31 151 km^2, of which approximately 5% is within Zimbabwe and 95% is within Mozambique. Nonetheless, the Zimbabwean part of the basin is estimated to produce approximately 28% of the natural runoff. The mean annual flow to the sea at Beira is estimated to be 4,195 Mm^3. However, there is significant annual variation in the Pungwe's flow, with frequent recurring periods of flooding and drought. Currently the main economic activity in the catchment is agriculture. This is primarily rainfed. In Mozambique 8,798 ha are equipped with irrigation infrastructure, mostly for sugar cane production. Annual irrigation consumption is estimated to vary between 190 Mm^3 in the driest years to 84 Mm^3 in the wettest years. Currently there is very little hydraulic infrastructure on the river, and that which does exist (i.e. small diversions for water supply and irrigation) does not have a significant effect on the natural flow regime. To improve flow regulation for irrigation expansion, hydropower production and flood mitigation a number of potential large dam sites (13 in total) have been identified in Mozambique on both the main stem and tributaries. In addition 28 small dam sites have been earmarked for development.

Climate

The climate of the region is largely controlled by the movement of air masses associated with the inter-tropical convergence zone (ITCZ). This results in a distinct rainy season from November to April. Table 1 summarizes details of the climatic data obtained for this study.

Rainfall over the catchment varies considerably and is primarily controlled by altitude and aspect (Owen, 2004). There is considerable variation over relatively small distances, but generally mean annual rainfall on the Rift Valley floor (600 – 1000 mm) is lower than on the higher ground both to the west (i.e., the Barue Platform) and to the east (i.e. the Cheringoma Plateau) (Table 2; Figure 2). The Gorongosa Mountain generates its own microclimate. Orographic effects result in increased annual precipitation and an extended seasonal distribution, particularly on the summit and the mountain slopes facing east. Although there is no gauge it is estimated that mean annual precipitation on the peak is approximately 2,000 mm. This compares to mean annual precipitation of approximately 1,000-1,200 mm on the surrounding Barue platform and perhaps as high as 1,600 mm close to the headwaters of the Nhandugue River. Mean annual rainfall on the Cheringoma plateau is higher on the eastern flank, but is typically 900-1,000 mm even on the western side.

The rainfall pattern is irregular with significant variation from one year to the next throughout the catchment (Figure 3). Coefficients of variation for annual rainfall are typically in the range 0.21-0.48. Potential evaporation is approximately 1500 mm and on the Barue Platform (at Chimoio) and 1700 mm on the Chirengoma Plateau (at Inhaminga). In both cases mean monthly potential evaporation exceeds mean monthly rainfall except in the months December to March (Figure 3). In the Rift Valley, where rainfall is lower, mean monthly potential evaporation is believed to higher than mean monthly rainfall in all months except February (Owen, 2004).

SWECO and associates (2004) provide areal estimates of average annual precipitation and potential evaporation (based on pan evaporation data) over the upper (Nhandugue) catchment and the lower (Urema) catchment (Table 3). Unfortunately none of the raingauge data series are sufficiently long to enable investigation of any correlation between the area of Lake Urema and rainfall.

Table 1: *Climate stations for which data obtained*

Nos.	Name	Latitude	Longitude	Altitude (masl)	Distance from the lake(km)	Rainfall data	Temperature data	Potential Evaporation
MZ94VLMC	Vila-Machado	19.26^{o}S	34.20^{o}E	57	58 (SW)	Monthly total 1912-1968	Mean monthly	Mean monthly
MZ84VLPR	Vila-Pairade-And*	18.66 ^{o}S	34.05 ^{o}E	375?	60 (NW)	Monthly total 1916-1968	Mean monthly	Mean monthly
MZ85NHMN	Inhaminga	18.40 ^{o}S	35.00 ^{o}E	316	69 (NE)	Monthly total 1929-1968	Mean monthly	Mean monthly
MZ74MPOO	Mopeia	17.98 ^{o}S	34.86 ^{o}E	51	104 (N)	Monthly total 1891-1968	Mean monthly	Mean monthly
MZ94BROO	Beira	19.80 ^{o}S	34.90 ^{o}E	16	109 (S)	Monthly total 1908-1997	Monthly average 1913-1991	Mean monthly
MZ94VLGL	Vila-Guilherm	19.86 ^{o}S	34.56 ^{o}E	10	110 (S)	Mean Monthly	Mean monthly	NA
MZ94BRBS	Beira Observatory	19.83 ^{o}S	34.85 ^{o}E	7	111 (S)	Monthly total 1979-1997	Mean monthly	Mean monthly
MZ93CHMO	Chimoio	19.11 ^{o}S	33.46 ^{o}E	732	120 (W)	Monthly total 1951-1997	Mean monthly	Mean monthly
MZ03VLPR	Vila-Pery	19.10^{o}S	33.40 ^{o}E	N/A	126 (W)	Monthly total 1912-1974	N/A	Mean monthly
MZ93SSSN	Sussendenga	19.33 ^{o}S	33.21 ^{o}E	635	152 (W)	Mean Monthly	Mean monthly	Mean monthly
MZ83CTND	Catandica	18.08 ^{o}S	33.17 ^{o}E	611	174 (W)	Mean Monthly	Mean monthly	Mean monthly
MZ82MNCO	Manica	18.93 ^{o}S	32.86 ^{o}E	723	180 (W)	Mean Monthly	Mean monthly	Mean monthly
P365	Urema E.N. 128+	18.98 ^{o}S	34.58 ^{o}E	36	11 (SE)	Monthly total 1955-1982	NA	NA
P373	Chitengo O.P+	18.98 ^{o}S	34.36 ^{o}E	43.0	17 (SW)	Monthly total 1956-1970	NA	NA
P169#	Bue Maria+	-19.02^{o}S	34.18 ^{o}E	100	35 (SW)	Monthly total 1957-1977	NA	NA
NA	Muanza+	18.83 ^{o}S	34.80 ^{o}E	242	35 (E)	Monthly total 1971-1979	NA	NA
P723	Chinizuia+	18.96 ^{o}S	35.13 ^{o}E	190	69 (E)	Monthly total 1972-1980	NA	NA

Sources: FAO databases FAOClim and LocClim.

+ Provided by Richard Owen (largely from DNA (the National Department of Water) and INAM (the state meteorological institute)

* Combination of FAO database and from Richard Owen (RO data used to extend 1969-1977)

Station number deduced from Pungwe Monograph Report Annex II - hydrometric networks. Location estimated from Pungwe Monograph report Annex I – surface water resources of the Pungwe River Basin

Table 2: *Mean monthly rainfall for selected gauges representative of the three major landforms in the catchment*

Station	Altitude (masl)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
		Mean Monthly total (mm)												
	Barue Platform													
Chimoio	732	236	216	140	57	24	18	17	20	18	40	99	204	1,089
Catandica	611	370	335	212	101	29	21	11	18	15	28	149	302	1,591
Vila Pairade And+	350	227	249	197	75	29	27	25	27	25	33	127	245	1,287
	Rift Valley													
Chitengo O.P.	43	184	188	108	47	23	22	10	24	14	22	78	185	906
Urema	36	94	115	67	32	14	15	10	13	6	19	45	98	529
Bue Maria	100	220	229	129	60	32	23	12	26	14	38	114	202	1,098
	Cheringoma Plateau													
Muanza	242	176	127	129	57	36	43	19	25	14	20	100	182	927
Inhaminga	316	225	192	171	56	28	34	20	19	15	25	94	191	1,068
Chinizuia*	190	153	208	409	163	43	79	55	32	21	27	76	217	1,484

+ lower slopes of Mt. Gorongosa
* based on few years of data and located on the eastern slopes of plateau

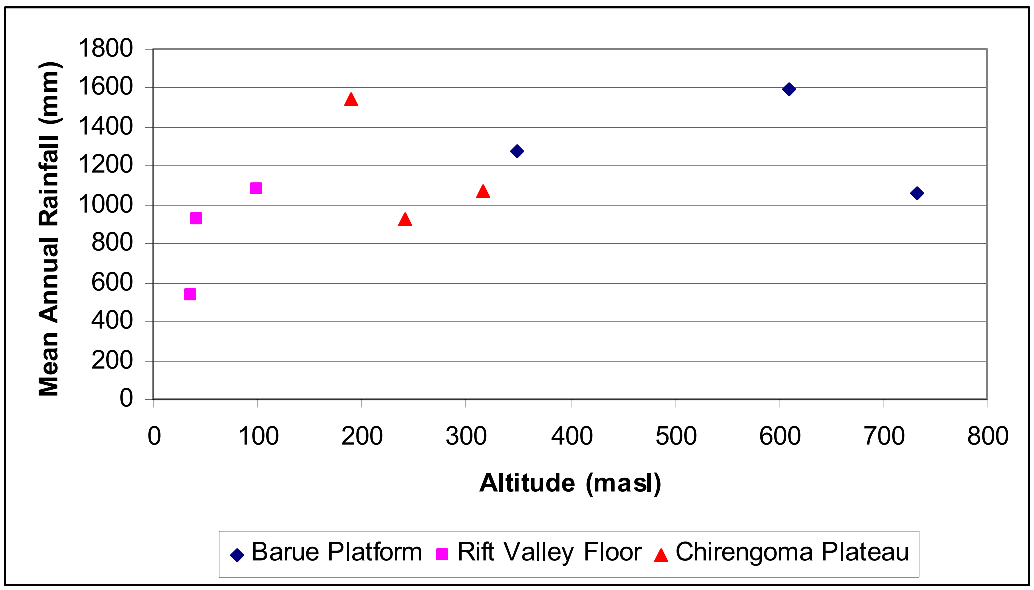
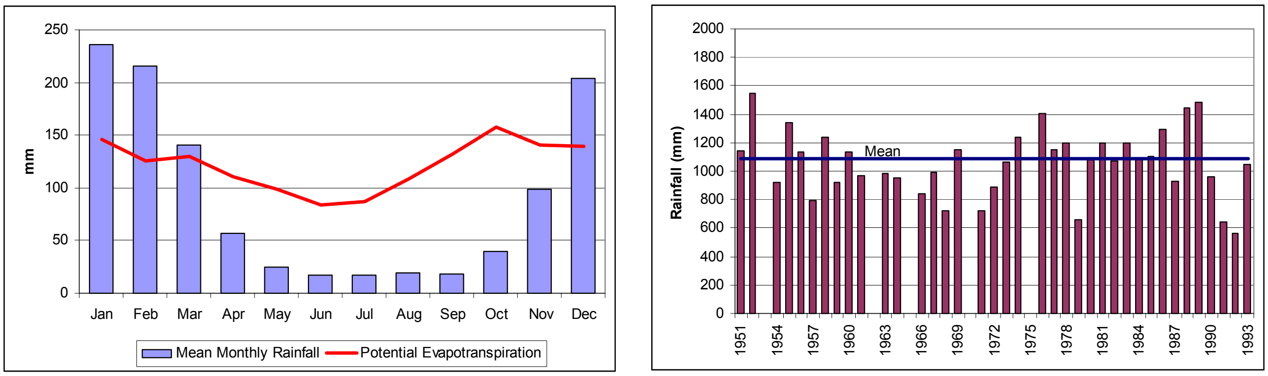


Figure 2: Mean annual rainfall for selected raingauges, representative of different regions.

Table 3: *Areal estimates of mean annual precipitation (MAP) and mean annual evaporation (MAE)*

Catchment	**Area**	**MAP (mm)**	**MAE (mm)**
Nhandugue	2,830	850	1450
Urema	5,572	900	1,590

a)



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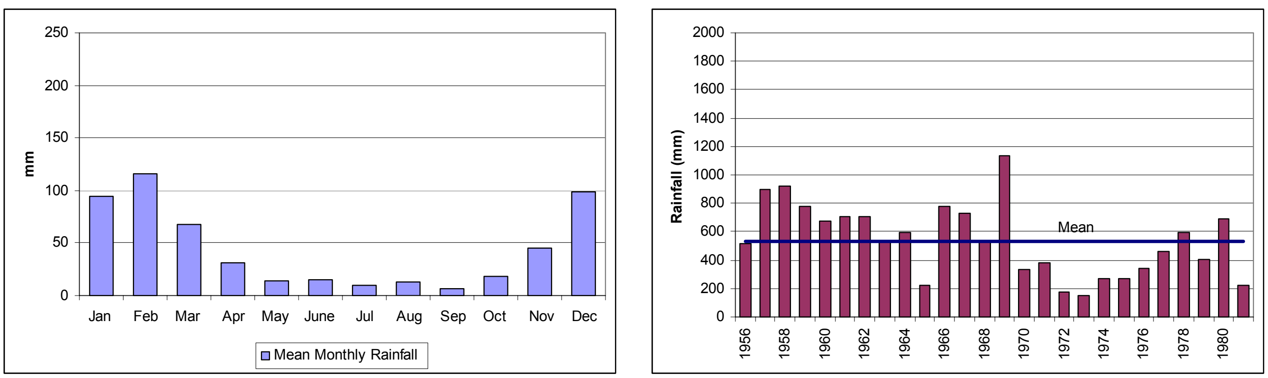

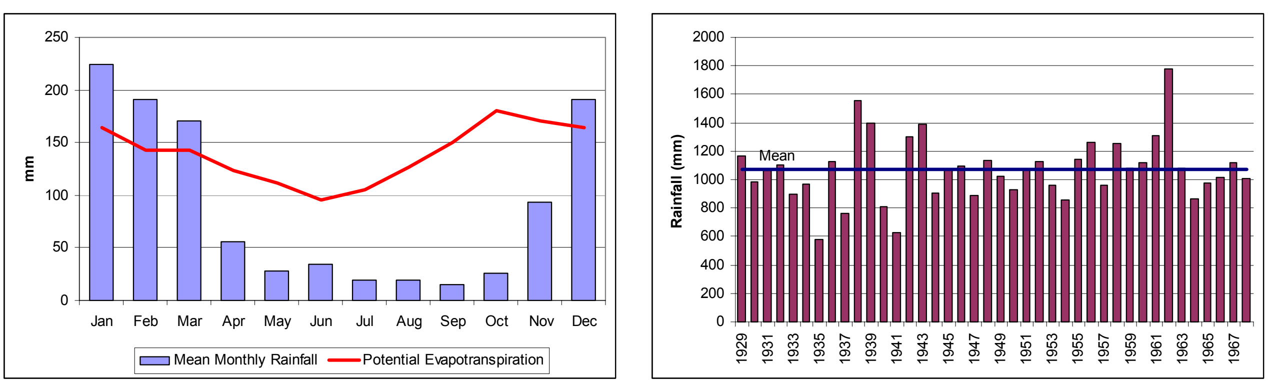

Figure 3: *Mean Monthly Rainfall and Potential Evapotranspiration (where available) and time series of annual rainfall for three locations: a) Chimoio (on the Barue Platform) b) Urema (in the Rift Valley) and c) Inhaminga (on the Chirengoma Plateau)*

River Flows

The hydrology of the region is strongly controlled by the underlying geology. The nature of the bedrock, the thickness of the weathered regolith and the degree and density of fracturing are all critical factors that control drainage patterns and the division of rainfall into runoff and infiltration (Owen, 2004). There are very few flow gauges in the area and data could only be obtained for one actually located in the Urema catchment (i.e., E81 on the outflow from the lake). Other flow data were obtained for (Table 4):

- the main Pungwe River, upstream of the confluence with the Urema;
- the Vanduzi which drains from the Barue Platform;
- the Nhadare which drains from Mount Gorongosa;
- the Chiniziua which drains the eastern slopes of the Chirengoma Plateau

Table 4: *Flow gauging stations for which data were obtained*

Station No.	River	Location	Latitude	Longitude	Catchment Area (km^2)	Record+	Nos. of complete years*
E66	Pungwe	Bue Maria	-19.03 °S	34.17 °E	15,046	HY1957-HY1982	26
E80	Vanduzi	Villa Paiva de Andrada	-18.72°S	34.04 °E	9,401	HY1963-HY1983	20
E42	Nhadare	Gorongosa	-18.58°S	34.05 °E	121	HY1969-HY1983	14
E81	Urema	Urema	-18.99°S	34.58°E	8,060	HY1956-HY1979	23
E464	Chiniziua	Muanza Serra	-18.95 °S	35.13 °E	905	HY1971-HY1983	11

+ As a result of seasonality, Mozambiquan flow data are usually presented in a hydrological year that extends from 1 October to 30 September. The standard convention of naming hydrological years after the year in which the month of October occurs has been adopted in this study. Thus hydrological year 1957 (HY1957) extends from 1 October 1957 to 30 September 1958.

The data for gauge E42 appear to be incorrect. For this station the data suggest that runoff exceeds rainfall in some years, which is, of course, impossible. It is possible that the catchment area is simply incorrect. However, with no way to validate them, these data were not used. Table 5 summarizes mean monthly flows and runoff for the four stations for which seemingly reliable data are available. Figure 4 shows the time series of available monthly flow for the same four stations. These data highlight:

i) the high seasonal variation in flow (reflecting the seasonal variation in rainfall)
ii) the considerable inter-annual variation in flow
iii) the difference in the flow regime of the Vanduzi and Urema catchments, both of which are of similar size and orientation

Annual flows in the 23 year record of the Urema River at Urema range from 1,492.2 Mm^3 (HY1978) to 176.4 Mm^3 (HY1972). On average the catchment contributes 19 % of the estimated average annual outflow in the Pungwe (4,195 Mm^3) (SWECO and Associates, 2004). Assuming an average annual rainfall over the catchment of approximately 900 mm the average annual runoff (97.8 mm) equates to a coefficient of runoff of 11%. The flow from the Urema catchment

is significantly greater (54%) and also less "flashy" than that from the slightly larger Vanduzi catchment.

Table 5: *Mean monthly flow and runoff*

Gauge	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
	Flow (Mm^3)												
E66	43.5	68.3	230.0	437.2	497.6	521.4	288.2	155.9	99.3	71.4	56.4	44.7	2,513.9
E80	4.2	9.4	35.6	69.7	136.2	103.7	22.4	12.8	8.9	7.9	6.4	4.7	421.9
E81	2.9	3.6	24.1	88.8	110.3	159.6	212.1	138.3	22.7	11.4	10.1	4.4	788.3
E464	0.4	0.4	2.9	7.6	12.3	7.1	6.9	1.8	1.0	0.8	0.7	0.5	43.3
	Runoff (mm)												
E66	2.9	4.5	15.3	29.1	33.1	34.7	19.2	10.4	6.6	4.7	3.7	3.0	167.1
E80	0.5	1.0	3.8	7.4	14.5	11.0	2.4	1.4	1.0	0.8	0.7	0.5	44.9
E81	0.4	0.5	3.0	11.0	13.7	19.8	26.3	17.2	2.8	1.4	1.3	0.6	97.8
E464	0.4	0.4	3.2	8.4	13.6	7.9	7.6	2.0	1.1	0.9	0.8	0.5	46.7

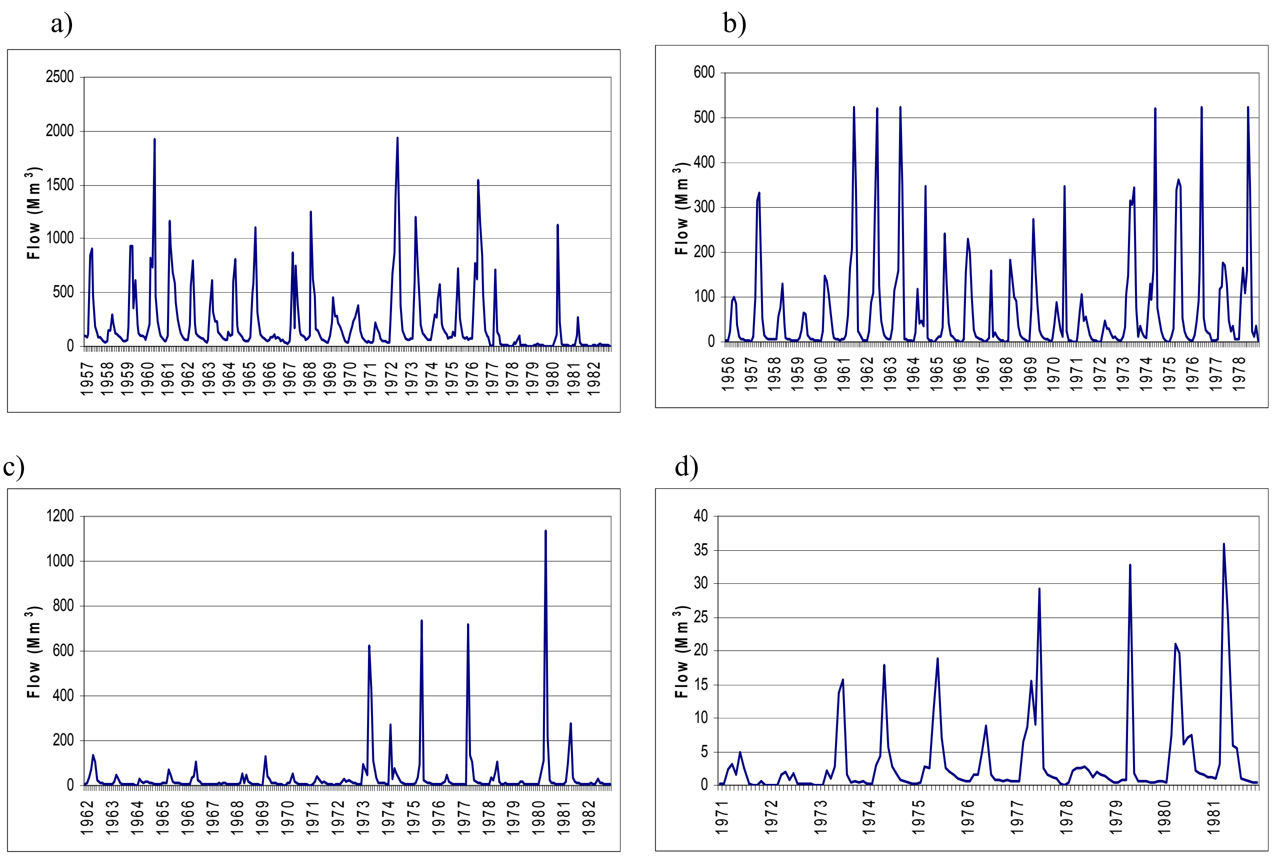

Figure 4: *Flow measured for: a) the Pungwe at Bue Maria b) the Urema at Urema, c) the Vanduzi at Villa Paiva de Andrada and d) the Chiniziua at Muanza Serra*

Figure 5 compares the runoff from the four catchments. This illustrates the different pattern of runoff from the Urema, which peaks in April rather than February on the Vanduzi. The dry season runoff from the Urema is also significantly greater than that from the Vanduzi. In the Urema average dry season runoff equates to 24% of the total annual runoff, whilst in the Vanduzi it equates to just 11%. These differences most likely reflect differences in geology between the two catchments and greater flow contributions from the eastern flanks of Goronogosa Mountain

to the Urema. It is likely that for the rivers flowing into the rift valley there is considerable infiltration of water to the valley floor sediments, particularly at the slope break, close to the edge of the Barue Platform escarpment (Owen, 2004). Although no research has been conducted it is possible that it is resultant lateral subsurface flow that maintains Lake Urema and the dry season flow in the Urema River. If this is the case, it would in part explain the relatively small inter-annual variation in the dry season area of the lake. The role of Lake Urema in regulating flow from the catchment also needs to be investigated. By contrast the Vanduzi catchment has crystalline basement geology that provides considerably less buffering and explains the generally earlier peak flow and considerably lower dry season flows than in the Urema catchment (Owen, 2004).

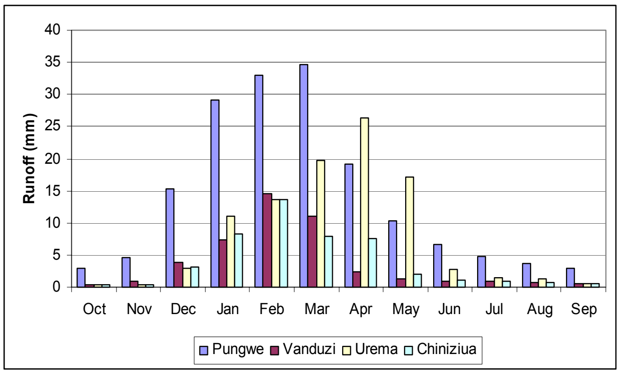

Figure 5: *Comparison of runoff in four catchments*

Electrical conductivity (EC) measurements indicate low mineralization of Lake Urema water and its tributaries. Towards the outlet of the lake and in the Urema River the EC values are higher than further upstream. However, the results indicate that overall there is relatively little salinity enrichment as a consequence of either evaporation or inflows of groundwater (Bőhme, 2005). The lack of evaporative enrichment in a climate of high potential evaporation (see above) indicates relatively short residence times for water in the lake. Based on an assumed volume of the lake and from surface water runoff estimates, typical residence times of between 3 and 30 weeks have been estimated (Bőhme, 2005). The lack of groundwater enrichment indicates that either groundwater inflows into the lake are small, even in the dry season, or alternatively groundwater inflows are not transporting significant quantities of solutes into it. Low salinity groundwater is not uncommon from crystalline catchments with well leached soils. However, these results do suggest that groundwater residence times are also relatively short and that significant volumes of deep groundwater (which would be highly mineralized) are definitely not contributing significantly to the lake water budget, even in the dry season. This adds evidence to the hypothesis that it is relatively shallow lateral movement of groundwater that is feeding the lake.

There is some speculation that in years of high flow the Zambezi River connects with the Pungwe via the Urema catchment (Ref.). This speculation arises because within the Rift Valley, the catchment divide between the two catchments is relatively low and has not been properly demarcated. However, although the Urema flow varies significantly from year to year there is no evidence, in the short record available, of the massive increases in flow that would be associated with such a connection. It is believed that there was no connection during the Zambezi floods of 2000. Therefore it seems that, although it may well have occurred in the distant past (Tinley, 1977) if it does occur now, it is only during very rare, extreme events. However, the extent to

which there is groundwater interaction between the two catchments is unclear and warrants further investigation.

Potential threats to the system hydrology

There is concern that land-use change on Gorongosa Mountain will modify the flow regime of rivers discharging into the Rift Valley from the eastern side mountain. In recent years rising population and other socio-economic pressures have resulted in increased deforestation for agriculture. There is also increasing diversion of water for irrigation, though currently abstractions are believed to be relatively small. Currently the impacts of these anthropogenic changes on the water budget of the lake and surrounding floodplains is unclear, but the concern is that if allowed to go unchecked they will result in lower flows to the lake, particularly in the dry season.

The potential impact of dams on the Pungwe river, particularly the one proposed at Bue Maria, approximately 75 km upstream from the Urema confluence, are also a cause for concern. It is not known exactly how such dams will affect the Pungwe flow regime, but since the purpose of dams is to regulate flows, they would definitely result in lower wet season floods and higher dry season base flows. Such changes could affect the flow regime of the Urema River and the outflow from the lake. The dams could influence groundwater recharge in the vicinity of the Urema-Pungwe confluence which could in turn result in changes in hydraulic gradient between Lake Urema and the downstream drainage area. If Lake Urema is largely maintained by groundwater in the dry season (see above) this could have dramatic implications for lake water levels. However, significant further study is required to determine the exact hydrological impacts and the likely subsequent ecological consequences of such changes.

Future work

The importance of Lake Urema and the surrounding floodplain wetlands to the well-being of the Gorongosa National Park is recognized. However, not withstanding the research that has been done to date, current understanding of the system functioning is limited and constrained by lack of data. Greater knowledge of the system hydrology and quantification of water inputs and outputs is a necessary prerequisite to understanding how the system functions, its role in supporting the diverse ecology of the Park and its vulnerability to possible changes resulting from human activities. To this end, the following suggestions[2] are made to enhance hydrological understanding and assist with the adaptive management of the National Park:

i) Establish an improved hydrometric monitoring network, with flow gauges installed on the principal inflowing rivers. This would enable the relative contribution of surface water from the Barue Platform, Mount Gorongosa and the Chirengoma Plateau to be determined[3]. If correctly located such gauges would provide information on transmission losses as the rivers debouch into the Rift Valley. Efforts should be made to obtain data from E414 located on the River Nhanduge upstream of Lake Urema and to determine if data from E42 can be salvaged for analyses.

ii) Install shallow observation wells and piezometers in transects from the edge of the Rift Valley over the plains. This would provide useful information on hydraulic gradients and the movement of shallow groundwater beneath the floodplain. Whether

[2] These suggestions for future work were identified and discussed at a workshop held at Chitengo 20 - 22 August, 2007. More details of this and other work proposed are presented in Beifuss et al. (2007).

[3] ARA-Centro, the regional water authority, is in the process of establishing such a network.

shallow groundwater moves towards or away from the lake and seasonal variation could be ascertained.

iii) Conduct hydrochemical monitoring to increase understanding of catchment hydrology and identify flow paths. Such studies using natural tracers to separate stream flow into different runoff components have been widely used in many different environments, including wetlands. The use of naturally occurring isotopes (e.g. deuterium (D) and oxygen-18) to investigate the relative age of water is also common practice. If conducted in Gorongosa such studies would provide valuable insights into flow pathways and the relative contribution of deep and shallow groundwater to the lake.

iv) Use remotely sensed data to gain understanding of the inter- and intra-annual variation in the inundated area. Synthetic Aperture Radar (SAR), which is not restricted by cloud cover, would enable both dry season and wet season inundation to be mapped. If combined with data derived from the hydrometric monitoring, the relationship between wetland area and inflows could be established. Knowledge of periodicity and duration of inundation would also almost certainly provide useful insights into the likely cause of spatial variation in the patterns of vegetation observed on the floodplains.

v) Develop a physically-based hydrological model of the system. Such a model would undoubtedly provide useful insights into system dynamics and hydrological functioning. It would also provide a useful management tool that, if correctly configured, would enable the hydrological implications of land-use changes and diversion of water for irrigation to be ascertained.

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