PARQUE NACIONAL DA GORONGOSA, MOÇAMBIQUE LONG-TERM PLAN FOR HYDROLOGICAL...

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LONG-TERM PLAN FOR HYDROLOGICAL RESEARCH: ADAPTIVE MANAGEMENT OF WATER RESOURCES AT GORONGOSA NATIONAL PARK

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SUMMARY

The future of Gorongosa NP depends on the sustainable management of its water resources. Hydrological research and monitoring is thus an essential component of the adaptive management system for Gorongosa NP. This plan aims to generate the data, knowledge, and capacity necessary to address the most important challenges to effective water resource management in the Gorongosa system, including:

- Maintenance of Lake Urema and associated floodplain wetlands;
- Deforestation in the catchment;
- Large dams on the Pungwe and Zambezi Rivers;
- Water withdrawals and diversions
- Mercury contamination associated with gold mining;
- Fertilizer and pesticide runoff from agricultural development schemes;
- Climate change.

The plan serves as the foundation from which research proposals will be developed for hydrological research and management in the Park, with emphasis on creating opportunities for Mozambican students, faculty, and institutions to conduct research that leads to biodiversity conservation, sustainable development, and adaptive management of natural resources.

Highest priority is to establish a research and monitoring network for the greater Gorongosa region. The hydrometric network will enable quantification of the water budget of the Lake Urema-floodplain system, including the relative magnitudes and temporal fluxes of rainfall, evapotranspiration, surface water inflows and outflows, groundwater dynamics, lake and floodplain storage volumes, and Pungwe River interactions. The water quality network, closely linked to this hydrometric network, will provide spatial and temporal data for evaluating changes in water quality associated with soil erosion, gold mining, and agrochemical applications in the catchment in particular. Building on data generated by the research and monitoring network, synergistic approaches are recommended to provide a more comprehensive assessment of the underlying hydrological process at Gorongosa NP, including:

- Isotope differentiation of rainfall, surface water, and groundwater inputs to Lake Urema;
- Comprehensive analysis of Lake Urema hydrodynamics;
- Status assessment of the Muaredzi plug as a constriction to Lake Urema;
- Long-term changes in sediment aggradation on the Rift floor;
- Finite Element or Finite Difference modeling of the Rift Valley hydrogeologic system;
- Environmental Flow Requirements for the Pungwe River system.

The Gorongosa Research Center maintains a central database and information management system for generating, compiling, integrating, analyzing, and disseminating data resulting from hydrological research and monitoring, and for ensuring data quality. The database is managed to provide key information to decision-makers for the adaptive management of Gorongosa NP.

1. BACKGROUND

Gorongosa National Park lies at the southernmost extent of the Great Rift Valley of East Africa (Figure 1). The park is situated entirely within the Urema drainage basin, an area of approximately 9300 square kilometers that includes five important landscape units: the Rift Valley floor, the Gorongosa Mountain massif (1863 m amsl), the Midlands or Barue platform rising to the west of the Rift Valley, the Cheringoma escarpment rising abruptly to the east, and the Rift Valley flanks (the westward and eastward facing flanks of the Rift Valley draining to the Rift floor) (Figure 1). The Rift Valley (also known as the Urema Trough) is a broad lowland alluvial plain, about 35-40 km wide, traversed by meandering perennial and seasonal streams. The trough drains in a southerly direction to Lake Urema, a vast freshwater lake with a permanent surface area of 10-15 square km that swells to more than 200 square km during wet years. Lake Urema outflows through the Urema River to the Pungwe River, which in turns drains to the Indian Ocean near the port city of Beira. The Rift Valley floor is characterized by extensive swampy areas, shallow lakes and pans, extreme meandering, and other features indicative of impeded drainage (Figure 2).

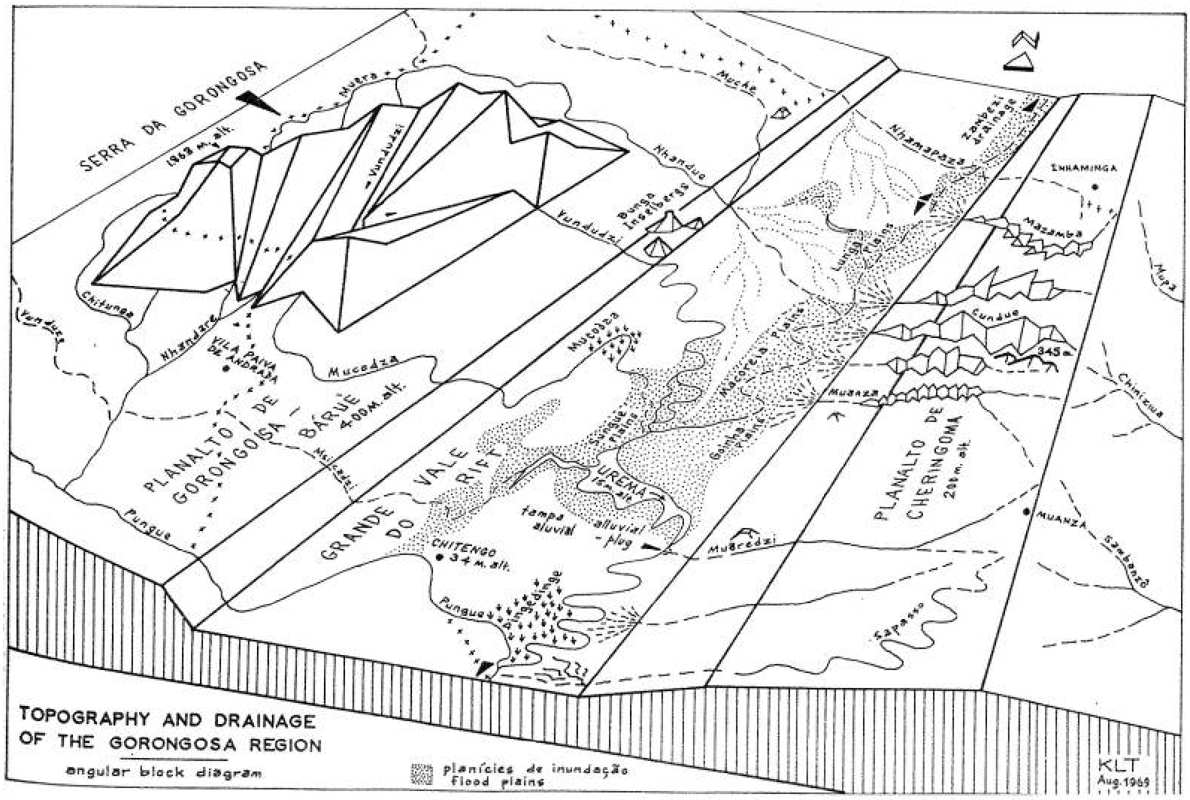

Figure 1. Block diagram showing landscape units of the Greater Gorongosa region and drainage pathways to the Rift Valley floor (from Tinley 1977).

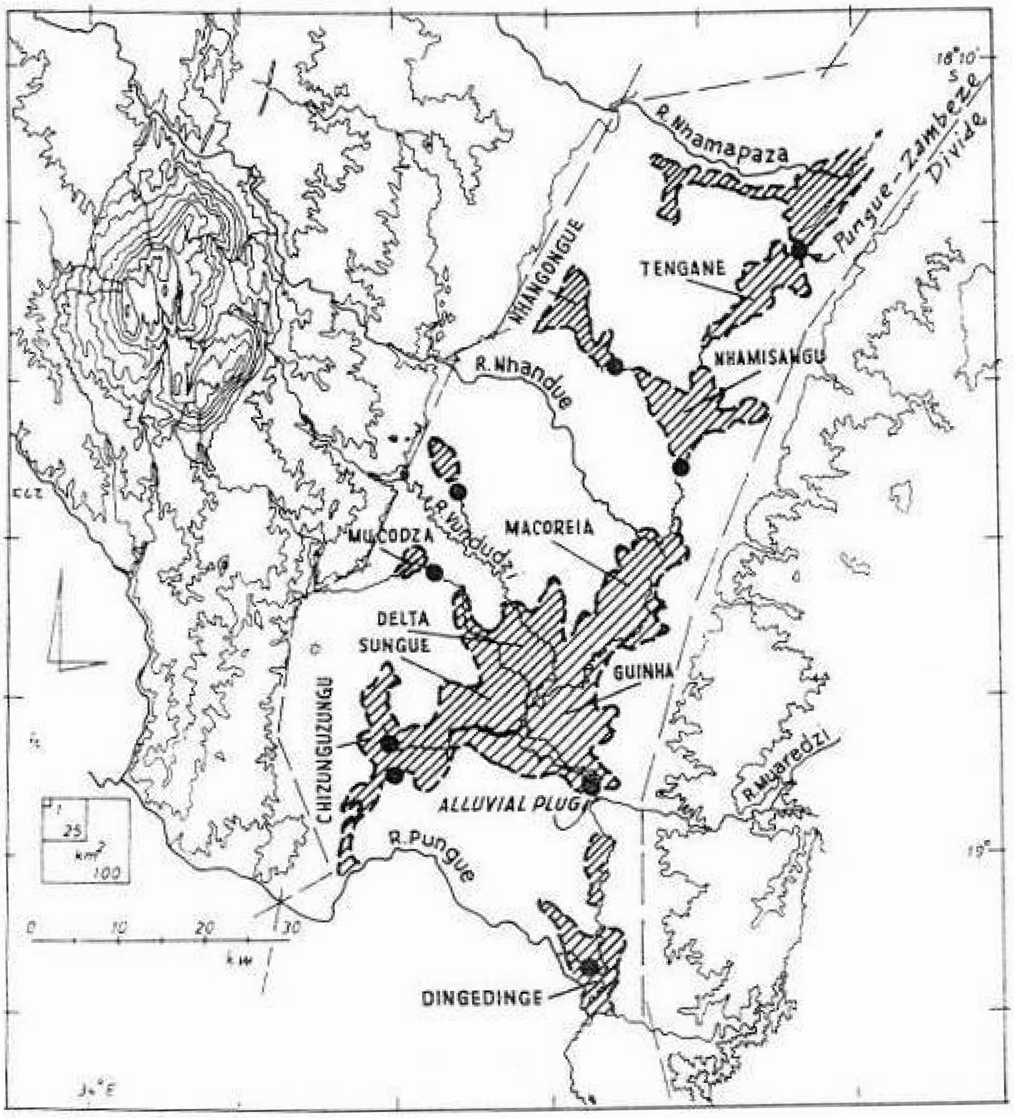

Figure 2. Floodplain swamps on the Rift Valley floor, in association with drainage from Gorongosa Mountain and the Rift Valley escarpment (from Tinley 1977).

Three studies in particular provide a useful foundation for future research on the water resources of the Gorongosa region. Tinley (1977) described the hydrology of Gorongosa National Park in his comprehensive dissertation on the Greater Gorongosa Ecosystem. Owen (2004) described hydrogeological conditions and trends within the Gorongosa–Marromeu region for the Southern African Millennium Ecosystem Assessment (SAfMA), with emphasis on water availability and water quality for human and ecosystem use over the next twelve years. Bohme (2005) described the geo-ecology of the Lake Urema system and patterns of change over time.

The mean annual rainfall in the Rift Valley is 600-1000 mm/annum (Owen 2005). Rainfall is strongly seasonal, with a pronounced dry season from May through November. The climate ranges from hot (20-25º C average winter temperatures) to torrid (25-30º C average summer temperatures). On an annual basis, potential evapotranspiration exceeds rainfall by 500 to 1000 mm, resulting in a water deficit during the dry season. However, very high orographic rainfall on Gorongosa Mountain (1800-2200 mm per annum), combined with steep slopes and areas of bare rock, generates substantial runoff. The mountain gives rise to five perennial rivers: the Vunduzi, Muera, Mucodza, Nhandare, and Chitunga. The Vunduzi is the largest river draining into the park from Gorongosa Mountain. It cuts down from the massif through the Midlands and, together with the Mucodza River, meanders across the Rift Valley floor until it empties into Lake Urema. The Muera River is captured by the Nhandugue River system that rises to the north of Gorongosa Mountain, and drains across the northern portions of the Urema Trough together with the smaller Muche River. The Nhandare and Chitunga Rivers drain directly to the Pungwe River upstream of the Urema confluence.

On the opposite eastern side of the Urema Trough, smaller seasonal streams, some supported by prolific springs, drain the Cheringoma flanks—including the Muaredzi, Mutsambizi, Cundue, and Mazamba Rivers—and fan out along the eastern margin of the floodplain. The majority of runoff from the eastern escarpment drains eastwards away from the Rift Valley across the gentle Cheringoma backslope to the Zambezi Delta and Indian Ocean coastline. Cumulatively, these perennial and seasonal rivers are the lifeline of the Rift Valley floodplain system, providing extensive flooded areas during the wet season and high water table conditions during the dry season.

During periods of peak runoff in the Pungwe catchment, Pungwe River floodwaters spread across vast seasonally-flooded grassy pans along the southern boundary of the Park via a series of grassy distributary slacks. As Pungwe floodwaters recede, these channels reverse flow and drain back to the river, leaving pockets of standing water and high water table conditions in low-lying areas. Most important among these seasonal floodplains are the lowland areas of the Gorongosa Wildlife Sanctuary at the southwestern corner of the park, and the vast DingeDinge marshes at the confluence of the Pungwe River and Urema outflow channel.

Historically, the Gorongosa-Urema system received floodwaters directly from the Zambezi River system, but a drainage divide built up naturally over time and now separates the Zangue River system—which flows north along the Rift Valley floor to the Zambezi River—from the south-flowing Urema system that drains to the Pungwe River. The current hydrological and hydrogeologic connections between the Zambezi River and Urema trough are further affected by the regulation of Zambezi River flows.

2. OBJECTIVES

Biodiversity conservation and sustainable development in the Greater Gorongosa region is based on the principles of *Adaptive Management* (Beilfuss 2006). This is a systematic, iterative approach to management that acknowledges that, from an ecological and socio-economic perspective, one is working with incomplete knowledge of the Gorongosa ecosystem. The process starts with clearly defined mission, goals, and measurable objectives, based on agreed-upon target states, and implements management practices based on best current knowledge to achieve the desired outcomes. Because the outcomes of management are not always guaranteed, each management action is carefully monitored to evaluate whether desired outcomes are indeed being achieved. The underlying principle in adaptive management of water resources is to establish and monitor hydrological components and processes of the system, and to study changes in historical conditions over time as a basis for understanding current status and providing perspective on future change.

Hydrological research and monitoring is thus an essential component of the adaptive management process for Gorongosa NP, implemented through the Gorongosa Research Center. Of particular concern to long-term adaptive management of the Greater Gorongosa region are the following challenges:

- Maintaining Lake Urema and floodplain wetlands on the Rift Valley floor, especially with respect to geomorphic processes constricting outflows;
- Mitigating against the effects of deforestation and land clearing on water resources of the Urema catchment;
- Ensuring sustainable development of water resources in the Urema catchment, especially with respect to small dams, diversions, groundwater extractions, and illegal gold mining;
- Mitigating against the effects of land use changes on water quality in the Pungwe catchment, including contaminants related to gold mining, agriculture, and urban development;
- Ensuring sustainable development of the Pungwe River basin, especially with respect to planned large dams (hydropower and water supply);
- Mitigating against the effects of Zambezi River basin development on the water resources of the Rift Valley (surface and groundwater interactions);
- Mitigating against hydrological changes associated with global warming, which may include more concentrated runoff during rainfall events, reduced groundwater infiltration, and higher rates of evapotranspiration.

This long-term plan for hydrological research and monitoring aims to generate the knowledge and information needed for sound management decision-making about water resources in the Greater Gorongosa system. The plan should serve as the foundation from which research proposals are developed for hydrological research and management in the Park. This plan also provides the basis for prioritizing projects for the purpose of research permitting, securing and allocating funding, and managing logistics.

An important objective of the Gorongosa Research Center is to increase the capacity of Mozambican students, faculty, and institutions to conduct innovative and integrated research that leads to biodiversity conservation, sustainable development, and adaptive management. We envision a key role for Mozambican students in conducting many of the research and monitoring activities outlined in this plan, under the direct supervision of Gorongosa Research Center staff and university faculty from Mozambique and abroad.

As most of the water resources of Gorongosa National Park originate outside the park's boundaries, water resources management must be integrated with regional planning and development efforts, especially the Regional Water Authority of Central Mozambique and various stakeholders of the Pungwe Basin. The park is a member of the Pungwe Basin Stakeholder Committee, which is a platform for the coordination of water issues between Zimbabwean and Mozambican stakeholders and government authorities.

This hydrological research plan was developed with the advice of an expert team specialized in hydrology, hydrogeology, water chemistry, isotope hydrology, geophysics, and remote sensing/GIS, and in consultation with experts that have worked in the park spanning a period of 40 years. This group will also form the core of an expert advisory panel aimed at ensuring the implementation of strategies proposed in this plan.

3. RESEARCH PRIORITIES FOR ADAPTIVE MANAGEMENT

3.1. What maintains the Lake Urema floodplain system?

Lake Urema is located in the heart of Gorongosa NP, on the valley floor of the southern extent of the Great East African Rift Valley. Lake Urema is a shallow, perennial, natural lake that expands to more than 200 km^2 in high flood seasons and recedes during the dry season to an area between 12-15 km^2. The flush of grassy vegetation on the Lake Urema plain as floodwaters recede provides the key pasture for large concentrations of wildlife (once supporting among the highest game populations in Africa).

The persistence of perennial surface water and high water table conditions on the Rift Valley floor throughout the dry season, despite conditions of high evapotranspiration relative to rainfall, is attributed to substantial surface and groundwater inputs originating from higher rainfall areas on Mount Gorongosa and the Rift Valley escarpment. The relative importance of surface water and groundwater processes for maintaining the lake and associated floodplains has significant implications for management of the lake-floodplain system.

Tinley (1977, 1994) asserted that Lake Urema and its associated floodplains are maintained during the dry season by alluvial "plugs", deposited where escarpment drainage lines intersect the Rift floor, that impede drainage from the system. Tinley attributed alluvial plugs to the formation and maintenance of seven floodplain systems with high watertable conditions (Figure 2):

- The Tengane, Nhamisangu, and Nhangongue floodplains in the Urema basin of Regime de Vigilancia da Extincta Coutada 1;
- The higher elevation floodplains associated with the Vunduzi and Mucodza Rivers east of Mount Gorongosa;
- The DingeDinge marshes at the confluence of the Urema with the Pungwe River;
- The vast Lake Urema and associated floodplain system.

Of particular management concern is the potential role of sediment deposited by the Muaredzi River into the Urema River (Figure 3). Tinley suggested that these deposits block drainage from Urema Lake resulting in a perennial surface water body. Based on the theory of the Muaredzi plug, Tinley felt that the timing of the first floods was of great significance. If the Muaredzi flooded first and established the "plug," then the lake would remain full. However, if the first floods come from the western platform and the Urema drainage, then the plug would not be able to form and Lake Urema would experience much greater drainage losses.

Tinley argued that Lake Urema and Rift Valley floodplains are most threatened by loss of this and other alluvial plugs due to gradual headward erosion of nickpoints or rapid incision during large runoff events or (in the past) hippo movements. He recommended the reinforcement of these plugs (or their reestablishment where breached by gullied outlets) using permanent weirs to restrict flows at critical base levels.

The physical evidence shows a constriction of the Urema drainage at the Muaredzi confluence, but no measurements have shown that water levels differ on either side of this constriction and the constriction does not close the Urema River. The plug consists of Muaredzi alluvial material, which is coarse permeable channel material, rendering it ineffective as an impermeable plug. In addition, there is no "dam" effect visible on air photos at the site of the plug, and there is no evidence that Urema Lake has emptied frequently historically, as would be expected if it has been kept full by the presence of an annually replaceable sediment plug.

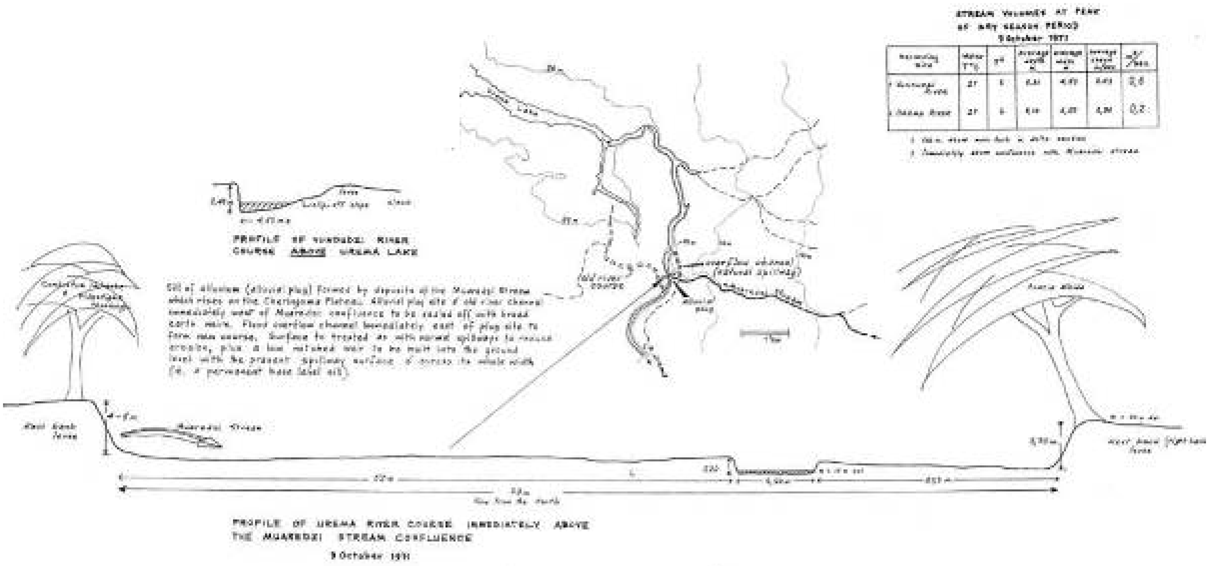

Figure 3. Profile of the "Muaredzi plug" at the outlet of Lake Urema (Tinley 1977).

Alternatively, the maintenance of Lake Urema may more related to the presence of a tectonically controlled, physical depression some hundreds of meters upstream rather than the effect of any impermeable plug at the Muaredzi confluence. The perennial nature of Urema Lake could be explained if the significant inflows into the rift floor infiltrate into the groundwater zone, and fill the rift floor sediments as groundwater rather than as surface run-off (Owen 2005). It is suggested that Urema Lake occupies a topographically lowered section of the Urema drainage that intersects the piezometric surface and is thus fed by perennial upwards groundwater discharge from the valley floor sediments.

Several factors support the scenario of a groundwater fed Urema Lake:

- The flat topography in the valley floor;
- The marked change in stream pattern from straight incising to meandering depositional streams at the junction between the rift flanks and the valley floor, indicating groundwater recharge;
- The anticipated depositional wedge of coarse clastic materials at the rift margin, promoting groundwater recharge at that point;
- The ephemeral nature of the surface flows in the valley floor;
- The lack of integrated surface drainage on the rift floor;
- The negative balance between potential evapotranspiration (~2000mm) and precipitation (~500mm) in the valley floor.

In addition Urema Lake is probably fed by slow draining surface water that has been detained in the wetlands upstream within the rift valley. Following this logic, Lake Urema and associated floodplains are most threatened by structures that modify groundwater levels and create a gradient for increased subsurface drainage from the shallow lake.

Tinley noted that siltation of Urema Lake is a natural phenomenon that is a long-term threat to the continued existence of the Lake. He highlighted the potential of agriculture to increase the amount of sediment in the streams and thus exacerbate the siltation threat to Urema Lake. It is also noted that the hippo population in Urema Lake may have been be responsible for ensuring that the lake bottom did not become filled with silt, and the destruction of the hippos during the war period may be responsible for an increase in silt in Urema Lake.

Further research must quantify the water and sediment budgets of the Urema floodplain system in detail, and definitively establish the underlying processes, such as neotectonics and sources that maintain the Lake Urema system and its vital wetlands. Research must lead to management actions that will secure perennial surface waters and high watertable conditions for the Lake Urema- floodplain system into the future.

3.2. How does land clearing and deforestation affect Gorongosa NP

Gorongosa Mountain and the Rift Valley escarpment provide a significant amount of the inflow water into the Urema drainage on the Rift Valley floor, and it is important to consider the possible effects on the Urema drainage of land use changes in the surrounding landscape. Land clearing on and around Gorongosa Mountain in particular is expanding rapidly, due in part to population growth, in-migration as a result of the new tar road joining Gorongosa to the existing tar road network, and various socio-cultural and economic changes in the region. Figure 4 shows the extent of recent clear-cutting on Gorongosa Mountain between 1992 and 2005. The likely effect on the hydrology of land clearing and deforestation will be to reduce the total evapotranspiration and to increase the direct runoff while decreasing the baseflow. The expected hydrological effects can be summarized as increased volume of surface runoff, increased peak flows in surface runoff, decreased dry season flows, and decreased groundwater recharge. As a result, some perennial streams may become seasonal.

If surface flows are responsible for maintaining Lake Urema and wetland areas during the dry season, then the changes to the flow regime identified above could result in partial drying out of wetlands and the lake in the late dry season. If the lake and wetlands are mainly fed by groundwater flows, then the effects of land clearing on Gorongosa Mountain may not be as severe if some of the additional surface runoff is captured as groundwater recharge at the rift margins. Reduced groundwater infiltration on the upper reaches of the mountain may affect more distant groundwater discharge points.

Urema river flow data indicate that there is a time lag between rainfall and surface runoff. This suggests that external surface runoff from the Barue and Cheringoma into the rift valley drainage does not immediately flow through the rift but is detained. Surface detention features such as lakes and wetlands may detain this external water, or it may be detained as groundwater, before later appearing as runoff in the Urema hydrograph. In either case, the Rift Valley system acts to extend the duration of flows from the lower Urema, and may mitigate the effects of increased peak run-off from the Gorongosa Mountain.

Further research must determine the degree and mechanisms by which land use changes on Gorongosa Mountain are affecting the Lake Urema-floodplain system. Research must lead to management actions aimed at mitigating land use changes in the catchment that have a deleterious effect on the hydrological system.

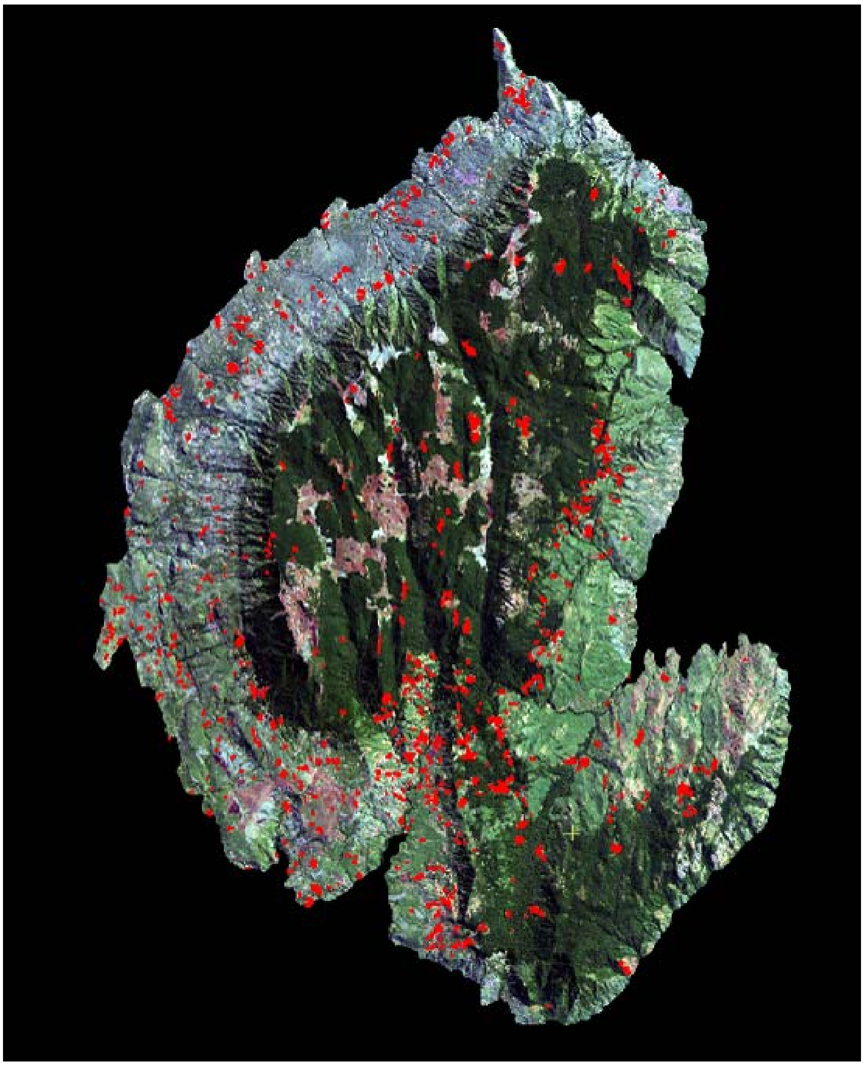

Figure 4. Afromontane forest and wet miombo woodland loss (areas shown in red) on Gorongosa Mountain above 700 meters, 1992-2005 (Woods Hole Research Center 2006).

3.3. How does Pungwe River Basin development affect Gorongosa NP?

The Pungwe River is shared between Mozambique (95% of the basin, generating 65-70% of the runoff) and Zimbabwe (5% of the basin, generating 30-35% of the runoff). At present, there are no significant water resources development projects in the Pungwe River basin in Mozambique. However, demand to harness Pungwe waters for inter-basin water transfer, municipal water supply, salinity control, hydropower, flood mitigation, large irrigated agriculture (sugar) schemes, and other uses is increasing. A basin-wide water development and management strategy has been launched, the *Pungwe River Basin Joint Integrated Water Resources Management Strategy* (SWECO & Associates 2004), which includes the elaboration of investment projects for large dams and water transfer schemes. Six large dam sites have been identified on the mainstem Pungwe, at Monte Hombe, Chibandulire, Pungwe3, Tacuraminga, Pavua, and Bue Maria, with an additional 38 small/medium dam sites in the catchment (Figure 5).

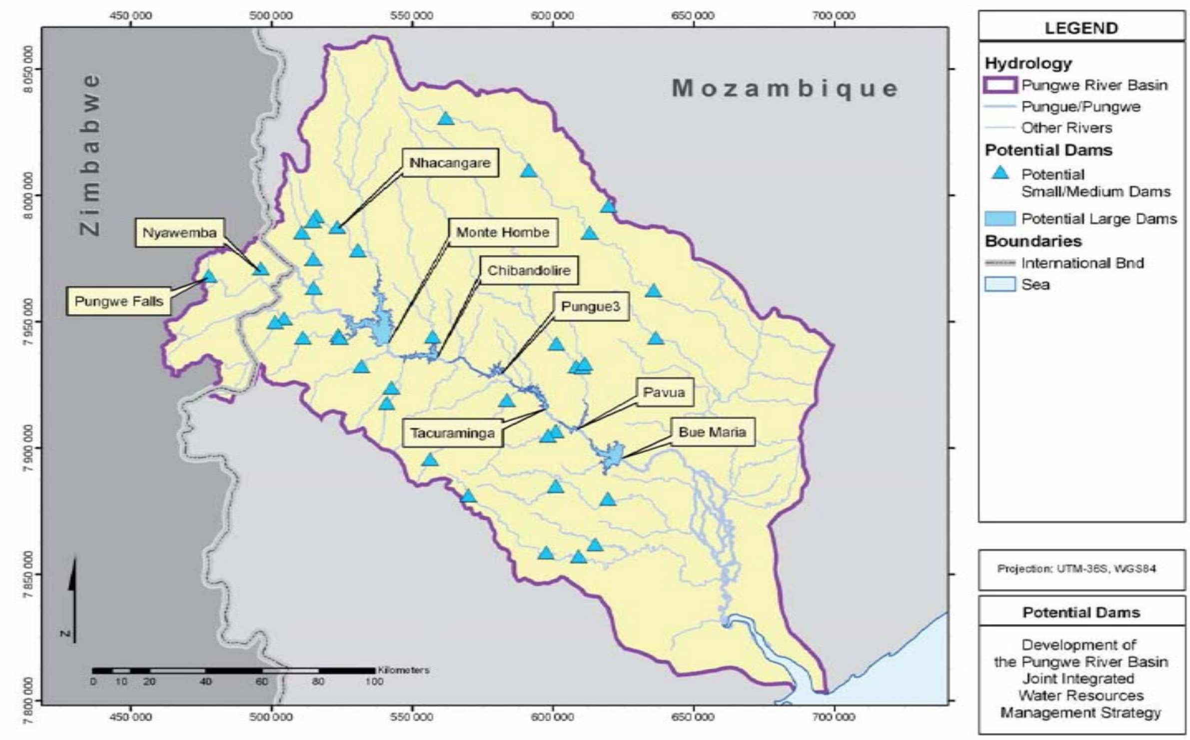

Figure 5. Proposed water resources development in the Pungwe River basin (SWECO & Associates 2004).

The Pungwe River marks the southern boundary of Gorongosa NP from Bue Maria to its confluence with the Urema River. Seasonal flooding from the Pungwe inundates shallow pans and oxbow channels on the Rift Valley plain at the southern end of the park. This flooding is vital for the newly constructed 6200 ha wildlife sanctuary near Chitengo-- more than 20% of which is directly inundated by Pungwe waters that provide critical water supply and sustain high carrying-capacity grasslands for reintroduced wildlife—and the DingeDinge Marshes at the confluence of the Pungwe and Urema rivers.

Any large dams or water extraction projects that alter natural runoff patterns in the Pungwe River pose a significant threat to Gorongosa NP. Of particular concern are the proposed Bue Maria and Pavua Dams, located immediately upstream of the park, which would reduce or eliminate the influx of floodwaters from the Pungwe River, lowering water tables and reducing the carrying capacity for wildlife in the southern part of the Park where tourism and wildlife are concentrated. DingeDinge Marsh at the confluence of the Urema and Pungwe Rivers would experience significant water table decline without regular annual flooding. Downstream groundwater level declines are expected in the Pungwe valley and the partial desiccation of the Pungwe floodplain at the southern end of the rift valley. This floodplain forms the local base level for the Urema drainage, and the drying out of the floodplain will cause an increase in the hydraulic gradient between the Urema drainage and the Pungwe floodplain, resulting in increased groundwater flow velocities and increased drainage of the Urema groundwater. If the shallow (1 to 1.5m) Urema Lake is groundwater fed as proposed above, then the lowering of groundwater levels due to Pungwe dam development will have a direct impact on Urema Lake water levels. Tinley also noted that high Pungwe flows tended to decrease the rate of drainage from the Urema catchment.

The Bue Maria will have the additional impact of flooding the best agricultural lands of the Candeeiro and Nhambita community, and flooding their proposed hot springs development site—both of which will cause economic hardship for the community and will increase pressure on Gorongosa NP for resources.

Research must model changes in the downstream hydrological regime of the river and its floodplain (in terms of the timing, magnitude, duration, extent, and frequency of flooding events and sediment deposition) associated with the operation of proposed large dams on the Pungwe River. Environmental Flow Requirements for the Pungwe River must be determined, using specialists in the biophysical and socio-economic sciences to assess the potential impacts of river changes on ecological conditions and subsistence users, including not only the mainstem Pungwe and its floodplain, but also the entire Lake Urema floodplain system. The Environmental Flows Assessment for the Zambezi Delta, using the DRIFT (Downstream Response to Imposed Flow Transformations) methodology, may serve as a model for this approach (Beilfuss and Brown 2006).

3.4. How do land use changes affect water quality in Gorongosa NP?

In addition to hydrological changes resulting from large-scale development of the Pungwe basin, a range of smaller-scale activities may threaten water quality in Gorongosa NP, including artesanal and illegal gold mining, commercial farming, and village wastewater systems. Heavy sediment loads in Pungwe River baseflows in-between storm events indicate the extent of gold panning on the river. Gold mining is of particular concern due to the potential for mercury availability and contamination of the food chain, threatening the park and surrounding communities. The rise of commercial farming development in the Urema catchment including cotton, bananas, and biodiesel) gives rise to increasing application of fertilizers and pesticides that may negatively affect the downstream ecosystem, including the contamination and eutrophication of water bodies. In addition, rural areas around the Park are progressively transforming into semi-urban settlements that discharge untreated sewage directly into catchment streams, raising concerns about faecal contamination, grease slicks, and other pollutants in downstream waterbodies. Industrial development at present is minimal.

Tropical wetlands such as the Lake Urema system are especially efficient nutrient sinks and pollution with heavy metals can be tolerated to a certain degree. Limits must be understood, however, to avoid toxic accumulation levels in the wetland system that could threaten biota.

A water quality monitoring network (described below) is being developed in cooperation with the Regional Water Authority for Central Mozambique (ARA-Centro) to assess the status and changes in catchment water quality over time. Ongoing monitoring activities should be coupled with more detailed studies of the hydrological and water quality processes associated with, and ecosystem threats resulting from, gold mining, pesticides and fertilizers, and wastewater discharge.

3.5. How do water abstractions in the Urema catchment affect Gorongosa NP?

Efforts to reduce slash-and-burn agriculture development in the Urema catchment will require development of extensive areas of irrigated agriculture and agro-forestry schemes on red loam permanently cultivable soils. Water-intensive cotton production areas in the Gorongosa region were widespread historically and may be re-established. These and other irrigation projects may include dams on perennial and seasonal rivers, and groundwater extraction. Although the present extraction of water from the catchment is insignificant (<1%) and likely to remain minor relative to the total annual inflow volume to the Urema floodplain for some time, the impact of water extraction may be significant at certain specific locations, especially at the end of the dry season or during prolonged drought periods. Little is known about groundwater recharge rates. First results from isotope studies indicate, that groundwater in the downstream area of the Urema catchment is older than 10 000 years (Merkel and Steinbruch 2006). This implies that groundwater recharge is taking place at very low rates and current hydrological processes (such as droughts and siltation) may not be reflected in the observed yields.

Of immediate term concern is the impact of water withdrawals on the unique hydrogeological features of the region. At the Gorongosa NP boundary with Nhambita community occurs the only thermal spring of Sofala Province. Gorongosa NP and its buffer zone include the largest accessible karst region of Mozambique, including the three largest known karst caves, deep karst canyons, large tunnels, rock arches, and artesian perennial springs which provide great recreational potential. However, these systems are especially sensitive to physical destruction and changes in the hydraulic system caused by water abstraction. Research is needed to provide guidelines for the sustainable use of these areas for tourism and other developments (e.g. bottling of mineral water).without degrading their unique qualities.

Over the longer-term, integrated, multi-disciplinary research is needed to provide scientific guidance for water resources development in the Urema catchment, ideally aimed at establishing Thresholds of Potential Concern (TPCs) for water abstraction. This would involve a series of complicated steps at the forefront of current hydro-ecological knowledge, including

- Calculating the water balance for the Lake Urema system and relative importance of surface and groundwater inputs (note—water balance analysis is at the core of all research and monitoring activity, and methods are described in detail in section 4);
- Assessing potential changes in hydrological conditions associated with water resources development—the magnitude, timing, duration, extent, and/or frequency of conditions on the Lake-floodplain system;
- Identifying indicator species and/or ecosystem processes that are sensitive to hydrological change and can be readily monitored;
- Determining the approximate range of acceptable hydrological conditions for selected indicator species and/or ecosystem processes;
- Defining Thresholds of Probable Concern (TPCs) associated with the upper and lower limits of acceptable hydrological changes for indicator species and ecosystem processes;
- Estimating allowable water extractions prior to crossing TPCs—with specific attention to spatial and temporal opportunities and constraints;
- Providing management protocols for sustainable water resource development in the Urema catchment; and
- Monitoring hydrological conditions and ecosystem response relative to TPCs for adaptive management.

3.6. How does Zambezi River basin development affect Gorongosa NP?

Tinley (1977) indicates that the Zambezi used to drain into the Pungwe before it was captured by coastal drainage. The divide between the two drainages occurs on the rift valley floor, a low ridge of alluvial deposits (sediment fans propagating from the Rift flanks) between the

Nhamapaza River tributary of the Zambezi and the Nhandugue River tributary of Lake Urema, to the north of Gorongosa NP, at an elevation of 59 masl. The Zambezi / Rift intersection is at 25 masl, while the Pungwe / Rift intersection lies at just 12 masl. Theoretically, in an extreme flood event, Zambezi water could flow over the divide into the Pungwe drainage, and erode the divide below the 25 m elevation level so that the Pungwe re-captures the Zambezi drainage. Such events could result in the input of significant additional surface water to the Lake Urema system, increasing the flooded extent of the lake-floodplain system and the availability of dry season pasture for wildlife.

Beilfuss (2001, *in prep*) provided a detailed record of the patterns of long-term hydrological change in the Zambezi Delta region due to river regulation for hydropower and flood control. There has been a significant reduction in the magnitude, duration, and extent of annual flooding events, a down-cutting of the mainstem Zambezi channel, and a steady decrease in shallow groundwater levels across the floodplain. Possible consequences of these hydrological changes for Gorongosa NP include a reduction of the magnitude and frequency of large flooding events that may bridge the Zambezi-Pungwe drainage divide, and increased subsurface drainage gradients from the Urema trough to the Zambezi River. Bolton (1983) argued that the record 1958 Zambezi River flood drained in part through the Urema trough and discharged via the Pungwe River. Subsequent to the construction of Kariba Dam (1959) and Cahora Bassa Dam (1974), however, there is no further evidence of this hydrological connection. Various water resource managers and consultants have speculated that recent flooding events on the Zambezi, including 1978, 1997, and 2001 floods, over-topped the catchment divide, but no direct evidence is available from field observations and subsequent evaluation of satellite imagery does not support this claim.

A geodesic survey is needed to link the Zambezi River stage at the Caia gauging station with the lowest breach point at the catchment divide, coupled with field observations of the catchment divide during large flooding events. The exchange of surface waters between the Zambezi and Urema trough (via the Zangue-Mecombeze River) should be further verified by comparing Zambezi discharge measurements above and below the Zangue confluence once the river gauging network for the Zambezi River is established, and by using isotopes and indicative species (e.g. fish) as tracers.

3.7. How will climate change affect Gorongosa NP?

The adaptive management of water resources of Gorongosa NP requires mitigating against the potential adverse affects of land uses that alter the magnitude, timing, duration, and/or frequency of runoff from the catchment, including large dams, deforestation, and water extractions and diversions. Hydrological changes related to global warming and associated climate change will likely exacerbate these threats and require additional management interventions

The El Nino Southern Oscillation (ENSO) is the primary cause of interannual climate patterns in southern Africa, with specific influence on rainfall. Current climate change models suggest ENSO changes within this century may range from no increase to a small increase in amplitude (Brew and Washington 2004). Other anticipated regional hydrological consequences of global warming, already observed in the region, include an increasing concentration of precipitation in large storm-related runoff events, and an increase in net evaporation (negative balance between potential evapotranspiration and precipitation) due to higher regional temperatures. To effectively manage the water resources of Gorongosa NP over the long-term, the net effect of these changes on the Lake Urema floodplain system must be understood and mitigated.

A predictive, site-specific model is needed to forecast future climate change in the Gorongosa region and generate a range of scenarios for hydrological change and associated ecological consequences. The quality of this model will depend in large part on data generated through the development of the monitoring network described in the following section. Important insights about historical patterns of climate change and hydrological fluctuations may also be gained by reconstructing past climates and major ecological events in the region through sediment and pollen analysis of Lake Urema.

4. RESEARCH AND MONITORING NETWORK

The adaptive management of water resources at Gorongosa NP depends on an effective research and monitoring system that provides timely and reliable data on status and trends for water quantity and quality. Highest priority is to establish a hydrometric network through which we can quantify the water budget of the Lake Urema-floodplain system on the Rift Valley floor -- including the relative magnitudes and temporal fluxes of rainfall, evapotranspiration, surface water inflows and outflows, groundwater inflows and outflows, and lake and floodplain storage volumes. Managers need to understand changes in water budget components (in terms of timing, magnitude, duration, frequency) associated with water resources development activities. A water quality network is equally important, and closely linked to this hydrometric network, to evaluate changes in water quality associated with soil erosion, gold mining, and agrochemical applications in the catchment in particular. Data are needed to establish current (baseline) conditions and evaluate change over time, especially for Lake Urema and the Pungwe River, the water bodies most vulnerable to the cumulative impacts of unsustainable land use practices in the Greater Gorongosa region.

4.1 Hydrometric network

This section reviews time series and spatial extent of available data, and provides recommended actions to quantify each water budget component, recognizing that any proposed monitoring station locations must address year-round accessibility, data collection protocols (who, what, where, when), and theft protection among other considerations.

Rainfall

Owen (2004) reviewed the historical data available from rainfall gauging stations in the Greater Gorongosa region. Time series monthly rainfall data, ranging from 9 to 26 years record length, are available generally in the time period ranging from 1956 to 1982, from 6 stations. The geographic distribution of these rainfall records includes two are on the Barue Platform (Vila de Gorongosa, Bue Maria), 2 in the Rift Valley (Chitengo, Urema), and 2 on the Cheringoma plateau (Muanza, Chinizuia). He noted also interrupted daily rainfall records available for Chitengo, Gorongosa, Dondo, Maringue and Metuchira spanning the period from 1997 to 2002. Owen used the static rainfall data from the meteorological stations, cumulative rainfall graphs, and from the FAO climate estimator model to build a suite of rainfall distribution contour maps for selected periods during the wet and dry seasons.

The *Pungwe River Basin Joint Integrated Water Resources Management Strategy* (SWECO & Associates 2004) provides recommendations to ARA-Centro for the rehabilitation of the existing rainfall gauging network. Chitengo, Piro, Morombodzi, Muanza, and Nhamatanda (Figure 6) have been rehabilitated at historic locations with long-term data with gaps. Gorongosa NP currently maintains 21 rain gauges associated with remote guard posts around the Park, and a total weather station at Chitengo with tipping-bucket rain gauge (Figure 6).

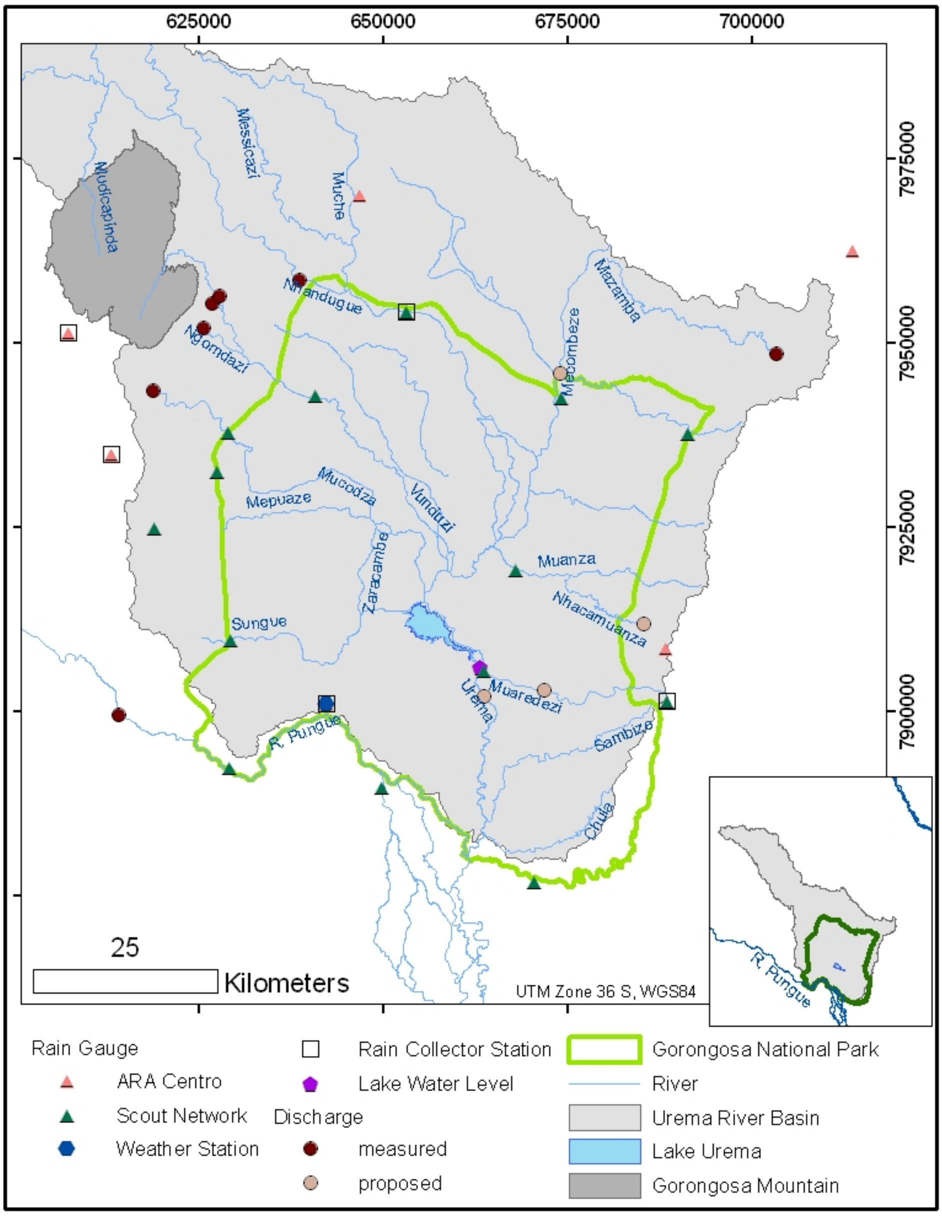

Figure 6. Current and proposed hydrometric monitoring stations around Gorongosa NP.

Recommended actions:

- Compile and analyze rainfall data from the regional and local stations as available
- Reduce the number of rainfall gauging stations in Gorongosa National Park from 21 to 8, corresponding to the new plan for law enforcement outposts around the Park. These stations are more than sufficient to characterize rainfall around the Park and provide a cross-check for quality control.
- Collect rainwater samples for isotope analysis from Chitengo, Kaganthole, Villa Gorongosa, and Muanza stations.
- Install a new rainfall collection site for isotope sampling on Gorongosa Mountain (Figure 6).

Evaporation and evapotranspiration

There is no system in place at present to measure evaporation or evapotranspiration from the Gorongosa region. Goncalves and Soares 1972 (cited in Tinley 1977) provide regional data on potential and actual evapotranspiration from Vila Gorongosa, Vila Machado, Inhaminga, and Beira. The Beira station remains in operation but does not reflect local conditions on the Rift Valley floor. Owen (2004) used the potential evapotranspiration (PET) and precipitation data from the FAO climate estimator programme (in conjunction with the static rainfall data (P)) to produce contour plots of the [P-PET] relationship for different time periods during the year. These contour maps help to provide an image of the water availability during both the wet and dry seasons.

Recommended actions:

- Install a Class A Evaporation Pan with the total weather station at Chitengo (Figure 6), to enable Penman calculations of potential evaporation.
- Install a lysimeter near Lake Urema (Miradouro dos Hipopotamos) as soon as all-season road access is extended to this site. The lysimeter will measure evapotranspiration losses from a cross-section of soil with Echinochloa-Setaria grassland cover.
- Direct measurements of lake evaporation are also possible through advanced instrumentation, but will depend entirely on external specialists and funding (lower priority).

Surface water inflows

Owen (2004) reviewed the historical data available from river gauging stations in the Greater Gorongosa region. Monthly river flow time series data, ranging from 9 to 23 years, are available for 5 recording stations; two from the Barue plateau -- Pungwe at Bue Maria (20 years) and Vanduzi (20 years); one from Gorongosa Mountain -- Nhandare (14 years); one from the Rift floor -- Urema (23 years); and one from Cheringoma escarpment -- Chinizuia (9 years). The time series data provided raw data for the rainfall–runoff models that have been developed for each of the available river flow records.

Surface water gauging is underway in collaboration with ARA-Centro for the Vunduzi, Mucodza, and Nhandugue Rivers, and a new staff gauge was recently installed on the Nhandugue River (Figure 6). ARA-Centro is installing automatic instruments on existing gauging sites on the Pungwe River at Bue-Maria and establishing new gauging locations on the Vunduzi and Nhandare Rivers to replace old (inactive) stations.

Recommended actions:

- Establish new river gauging station on Muaredzi River, monitored by the scout outpost there (Figure 6).
- Measure x-section profiles and discharges associated with elevation data for each river gauging station to establish rating curves—especially important are peak discharge Q vs. H measurements.
- Map physical location of major springs on Gorongosa Mountain, Barue plateau, and the Cheringoma escarpment, and measure discharges.
- Measure discharge at Mazamba spring (Figure 6).

- Measure discharge in the Mecombeze River along the Casa Banana-Inhaminga Road during large flooding events (only intermittent measurements possible at this site) (Figure 6).
- Collect surface water quality samples from selected points by ARA-Centro, including conductivity, temp; turbidity sensors with automatic dataloggers could be planned for future.

Surface water outflows

Surface water outflow from Lake Urema was historically measured at the Urema station (Figure 6). ARA-Centro is installing automatic instruments to rehabilitate the Urema station.

Recommended actions:

- Measure x-section profiles and discharges associated with elevation data from the Urema gauging station to establish rating curves—especially important are peak discharge Q vs. H measurements.

Groundwater fluxes

There have been limited studies of the hydrogeology of the Rift Valley system. Owen (2004) reviewed records from about 300 shallow community wells (<4 m) in Gorongosa District and several deeper wells in Cheringoma District. He assessed groundwater recharge based on percentage of mean annual rainfall. Merkel and Steinbruch (2007) assessed the hydrogeologic pathways and water chemistry associated with hotsprings on the southwestern border of Gorongosa NP. An analysis of aeromagnetic data is in progress (O. Gwavava, University of Zimbabwe).

Recommended actions:

- Geophysics -- resistivity transect along Chitengo-Muanza Road (using groundbased multi-electrode resistivity surveying); with differential GPS profiling (ideally) down to <1 cm. Additional transects may be planned based on results (Figure 7).
- Drill 3 to 5 deep geological cores to 100m (150m for one hole) depth along transect.
- Install deep piezometer nests in association with deep cores to assess gradients between escarpment-valley floor sediments-Lake Urema and between Lake Urema-Pungwe. Accurately survey (differential GPS) the borehole collar positions (especially elevation) for these boreholes / piezometer nests.
- Monitor groundwater levels weekly / monthly at different depths from the piezometer nests to determine groundwater flow patterns.
- Sample groundwater isotopes / chemistry from piezometers to determine age, origins and flow direction of the groundwater.
- Access seismic/drilling data from hydrocarbon prospecting north of Gorongosa NP.
- Investigate groundwater information from thermal bands of Aster, Landsat; and MODIS over Lake Urema.
- Geophysics – possible helicopter borne TEM (SkyTem) for selected areas of the Urema Rift (lower priority)

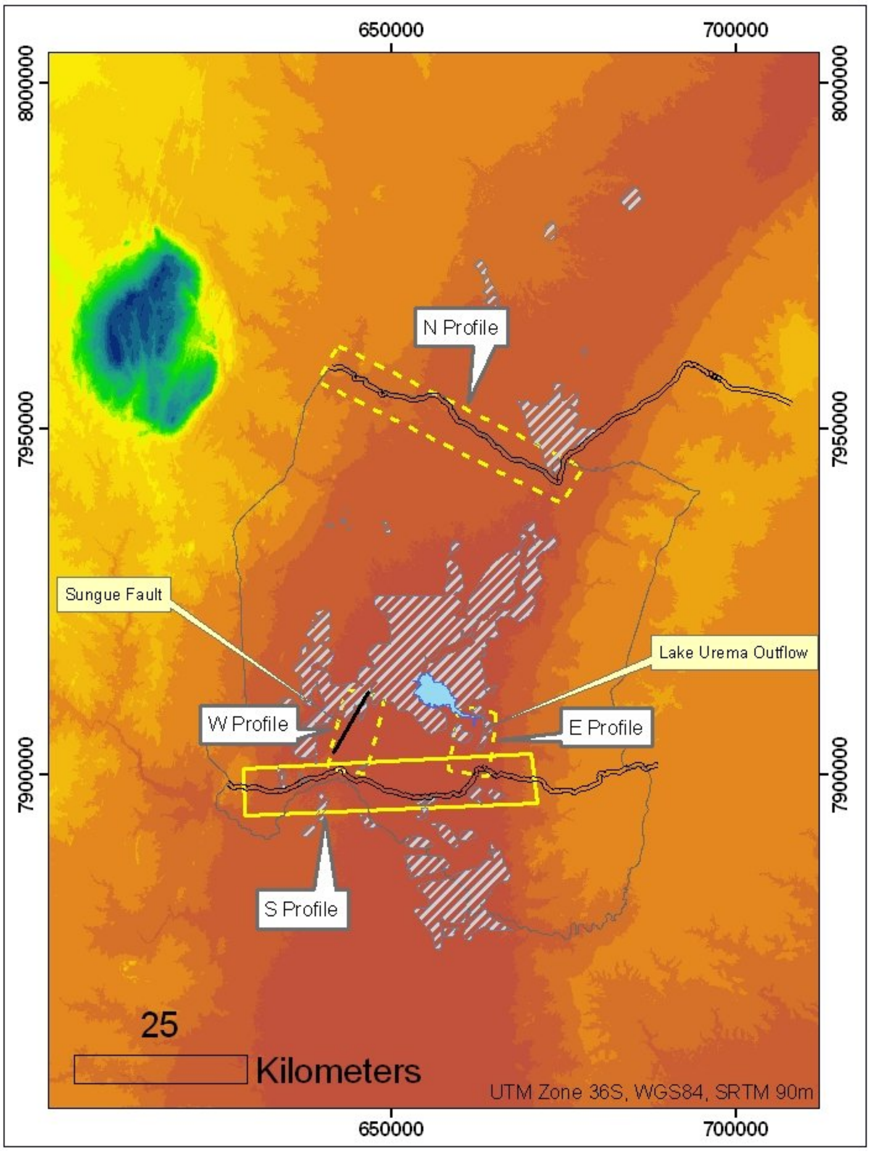

Figure 7. Proposed resistivity transect along the Chitengo-Muanza Road, using groundbased multi-electrode resistivity surveying (solid yellow box). Based on results, additional north-south and east-west transects may be planned (dashed yellow boxes).

Lake/floodplain volume

Bohme (1995) studied the hydrology of Lake Urema using field measurements and remote sensing imagery, including remote sensing time series of lake flooding extent, but no monitoring system is currently in place. ARA-Centro is rehabilitating a station to measure lake elevation above the Muaredzi River confluence (data collected by scouts).

Recommended actions:

- Determine Lake Urema bathymetry (echo sounding) using equipment available at Museum of Natural History.
- Correlate lake elevation data from Muaredzi station with lake volumes from Bathymetry and assess time series data for lake stage and volume.

- Create L-SAR moisture profile with monthly time step for February 2008-2009; using topography reflectance markers.
- Create floodplain DEM using L-SAR or high resolution satellite imagery.
- Install and monitor shallow piezometer/well network on floodplain corresponding to game drive network (using truck mounted direct push or augering).
- Determine neo-tectonic movements using L-SAR and differential GPS with fixed points for Gorongosa Mountain, Cheringoma escarpment, and Rift floor.
- Annually survey the benchmark at the Muaredzi lake elevation station using digital GPS or other accurate methods.

Pungwe River interactions

A Pungwe River flow model was developed by SWECO. The Pungwe River is gauged by ARA-Centro at EN1 bridge just upstream of Gorongosa NP, EN6 bridge downstream of Gorongosa NP, and at the Beira pump station.

Recommended actions:
- Assess hydraulic and land surface gradients between Lake Urema-Dingedinge-Pungwe River using DEM (see above).
- Analyze Pungwe River streamflow data including time series of flow difference between EN1 and EN6 gauging stations.
- Assess seasonal two-way surface water flux through Nhacapanda channel between Pungwe River and Gorongosa wildlife sanctuary.
- Initiate stream gauging for Vanduzi River (with ARA-Centro).

4.2 Water quality network

The water quality network should build on the hydrometric network described in detail in the previous section. Rainwater, surface water, groundwater, and lake elevation gauging sites will also serve as water quality sampling sites to enable quantification of fluxes in water quality indicators.

Recommended actions:
- Set up a regular monitoring scheme to collect and analyze water and sediment samples from gauging sites.
- Identify key water quality indicators to be monitored, including but not limited to nitrite/nitrate, iron, phosphate, sulphate, bacteria and other water-borne pathogens, as well as temperature, turbidity, alkalinity, dissolved oxygen, pH, and conductivity.
- Identify target pesticides for water quality analysis based on an assessment of commercial chemical product use in the catchment.
- Develop a water quality analysis laboratory at Gorongosa NP for basic analyses.
- Establish an Agreement for Scientific Cooperation with a professional water quality laboratory to enable pesticide analysis and other more advanced chemical analyses.
- Determine sediment transport rates based on surface water fluxes and sediment concentrations in grab samples.
- Develop and implement a more concentrated sampling framework to detect mercury bio-availability associated with artesanal mining, including bioassay of susceptible aquatic species in river, lake, and wetland systems.
- Identify additional gauging sites, as necessary, to better characterized water quality conditions

4.3. Synergistic studies

In addition to direct measurements of water balance components and water quality fluxes, other synergistic studies are recommended to provide an integrated assessment of the underlying hydrological components and process at Gorongosa NP. These approaches will complement and expand upon data generated by the hydrometric and water quality network described in previous sections. Project priorities are briefly described below, and will be fully elaborated in research proposals to be developed:

1. Isotope differentiation of rainfall, surface water, and groundwater inputs to Lake Urema. Discern relative magnitudes of water budget components, on a seasonal or annual basis, and provide an independent check on water balance calculations based on the measured or estimated magnitude of each component.

2. Comprehensive analysis of Lake Urema hydrodynamics. Bathymetry, sediment thickness, stratigraphy, geochemistry, surface chemistry, isotope hydrology, and palaeontology / palynology measured through boat sampling and coring.

3. Status assessment of the Muaredzi plug as a constriction to Lake Urema. The annual rate of erosion (incision) of the Muaredzi plug monitored using differential GPS or radar imagery, supplemented by historic air photos and satellite imagery to detect changes in geomorphology of the Muaredzi alluvial fan.

4. Long-term changes in sediment aggradation on the Rift floor. Assessed through comparison of historical aerial photos with current imagery, coupled with ground truthing, especially at the Vunduzi River breakslope and near the Urema lakeshore.

5. Finite Element or Finite Difference model of the Rift Valley hydrogeologic system. A comprehensive model of the Rift Valley system has never been developed, and would enable sensitivity testing of input parameters and data, and scenario testing for changes in groundwater and surface components.

6. Environmental Flow Requirements for Pungwe River system. The “Environmental Reserve” requirements must be determined for Gorongosa NP, as recommended by the Mozambique National Water Resources Management Strategy, and integrated with Integrated Water Resources Management planning for Pungwe Basin development. Research components include hydraulic modeling and hydrologic and water quality data analysis, in addition to ecological components and downstream user groups.

5. DATA MANAGEMENT AND QUALITY CONTROL

It is the mission of the Gorongosa Research Center to maintain a central database and information management system for generating, compiling, integrating, analyzing, and disseminating hydrological data, and ensuring data quality. Information is directly available to senior management for the adaptive management of Gorongosa NP, as well as to researchers and to general public with permission. Updated background and archived data relevant to the implementation of this strategy will be obtained by the Gorongosa Research Center.

As most of the water resources of Gorongosa originate outside the park boundaries, strong collaboration with Government of Mozambique authorities and agencies are required to ensure highest possible legal protection of water fluxes and quality. Ongoing collaboration provides for data sharing, the rehabilitation of the historical gauging network, identification of new gauging locations, maintenance of existing stations, replacement of manual stations with automated stations, and application and improvement of protocols for data acquisition and management. The information management system will feed hydrometric and selected water quality data into existing national and global databases, such as ARA-Centro, the National Institute of Meteorology (INAM), Global Network of Isotopes in Precipitation under the International Atomic Energy Association (IAEA-GNIP), and the Global River Runoff Database.

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