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Towards an ecohydrology-based restoration of the Usangu wetlands and the Great Ruaha River, Tanzania

M. G. G. Mtahiko[1], E. Gereta[2,*], A. R. Kajuni[3], E. A. T. Chiombola[4], G. Z. Ng'umbi[1], P. Coppolillo[5] and E. Wolanski[6]
*[1]Ruaha National Park, Tanzania National Parks, PO Box 369, Iringa, Tanzania; [2]Tanzania National Parks, PO Box 3134, Arusha, Tanzania; [3]USAID, PO Box 9130, Dar Es Salaam, Tanzania; [4]Lighthouse Group Limited, PO Box 72391, Dar es Salaam, Tanzania; [5]Wildlife Conservation Society, Rungwa-Ruaha Program, PO Box 1654, Iringa, Tanzania; [6]Australian Institute of Marine Science, PMB No. 3, Townsville MC, Queensland, 4810, Australia; *Author for correspondence (e-mail: emmanuel_gereta@hotmail.com)*

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Abstract

An open channel flow model, calibrated against field data, suggests that cattle intrusion in the eastern Usangu wetlands, as well as both dry and wet weather irrigation upstream, are responsible for the seasonal drying out of the Great Ruaha River (GRR) downstream. This human-induced change has severe socio-economic implications downstream, including hindering hydroelectricity production, as well as a devastating impact on the Ruaha National Park (RNP) ecosystem that is now shifting from wet tropics to dry tropics. To ensure sustainable development, governance is urgently needed for the Usangu catchment in a way that is compatible with ecohydrology principles for the sustainable use of water resources. In order to do that, perennial flow must be restored to the GRR. For this to happen this study suggests that all the livestock must be removed from the eastern Usangu wetlands and dry weather irrigators must return at least 25% ($\sim$4 m^3 s^{-1}) of the water to the river.

Introduction

Freshwater is fast becoming an international crisis, largely brought upon by mismanagement (de Villiers 2000; Postel and Richter 2003). Of all the continents, Africa, and particularly semi-arid East Africa may be evolving the fastest towards such a major water crisis (Crisman et al. 2003). The reasons are many and include poverty, lack of governance, and lack of will to manage water resources on an ecologically sustainable basis. Underpinning all this is the lack of a river basin-wide ecohydrology approach to managing water resources. Ecohydrology incorporates the use of ecosystem properties at the river basin scale as a guiding principle in implementing a program of water resource management (Zalewski 2002). More often than not the present practices by official institutions ignore ecohydrology and are based on counties or districts as an administrative unit, or on the narrowly focused approaches of managers of specific activities (e.g., farming and fisheries, irrigation, hydroelectricity, flood prevention, urban and economic developments, nature conservation). Without a change in thinking and management concept, many rivers, and the ecosystems that they support, will continue to degrade in East Africa. To prevent or reverse such ecologically unsustainable degradation, a number of authors (e.g., Gereta et al. 2002; Harper and

Mavuti 2004) have recently demonstrated the need to adopt ecohydrology as the guiding principle towards water resources management in semi-arid regions of East Africa. This paper highlights a similar freshwater crisis in the Great Ruaha River (GRR) catchment, and its Usangu wetlands, in Tanzania (Figure 1). We describe the dramatic changes that human-induced changes in river flow have on the ecosystem of the Ruaha National Park (RNP). We document the socio-economic implications of these human-induced changes in river flow. We argue that developments in the Usangu catchment are unsustainable and that governance is urgently needed for the river basin in a way that is compatible with ecohydrology principles for the sustainable use of water resources (Zalewski 2002). We conclude that perennial flow must be restored to the GRR and that for this to happen, as a minimum measure, all the livestock must be removed from the eastern Usangu wetlands and that dry weather irrigators must return at least 25% ($\sim$4 m^3 s^{-1}) of the water to the river.

The Great Ruaha River

The GRR (Figure 1) drains an area of about 68,000 km^2. It is one of the three major tributaries of the Rufiji River Basin, the largest basin in Tanzania with an area of about 177,000 km^2. The GRR originates from a number of streams in the southern highlands of Tanzania from where the bulk of the flow is generated. It flows to the Usangu plains where their gradient decreases abruptly. These streams are perennial and form the western and eastern Usangu wetlands (Figure 1). Most of the eastern Usangu wetlands are located inside the Usangu Game Reserve. From the wetland outlet at N'Giriama, the GRR flows northeast through the RNP and its buffer zones of wildlife reserves. It discharges into Lake Mtera that provides water for two hydroelectricity plants (Mtera and Kidatu) that together generate about 50% of Tanzania's electricity. Further downstream this water joins the Rufiji River.

The Usangu plain is the area north of the railway line from Mbeya (see Figure 1). The

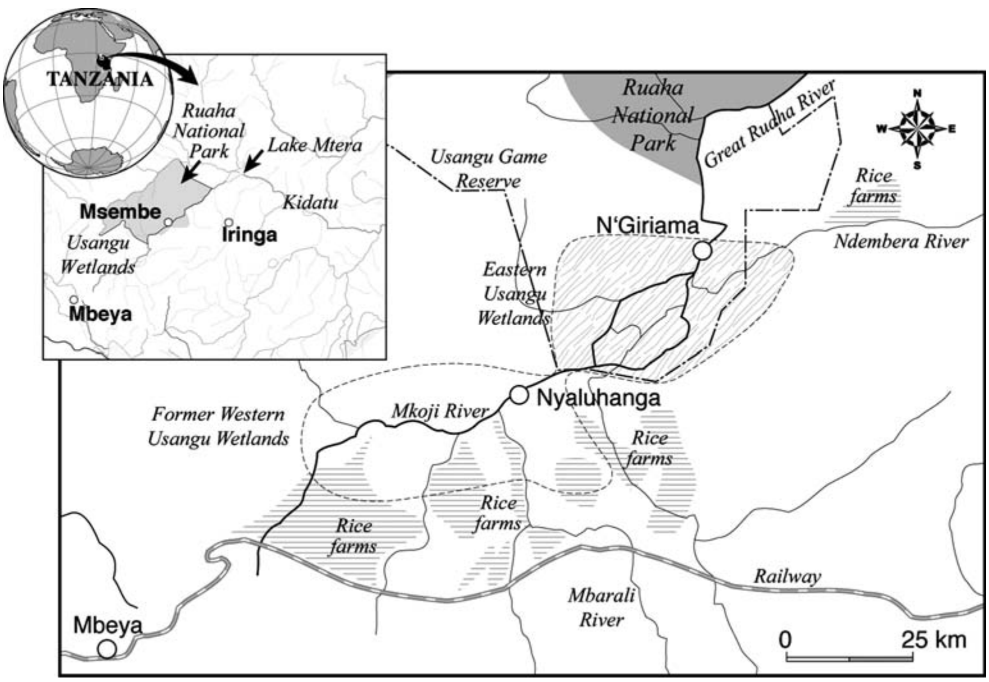

Figure 1. Map of the Usangu plains, showing the drainage pattern, key locations, and approximate location of rice farms. The inset is a general location map of the GRR. Nyaluhanga and N'Giriama are river gauging stations located at, respectively, the inlet and the outlet of the eastern Usangu wetlands. Much of the eastern Usangu wetlands are located in the Usangu Game Reserve. Msembe is the river gauging station in the RNP. The GRR flows into Lake Mtera, and this water is used to generate hydroelectricity at the Mtera and Kidatu plants.

Usangu plains drain a catchment of about 21,000 km^2, have a surface area of about 5800 km^2, and are located at an elevation between about 1000 and 1100 m. The remaining 72% of the catchment is the highlands at an altitude of over 2900 m. The plain is semi-arid, with mean rainfall of about 0.72 m year^{-1} and mean potential evaporation of about 1.7 m year^{-1}; this rainfall has considerable interannual variability as the minimum and maximum values over 45 years were 0.60 and 0.83 m year^{-1} (SMUWC 2002). About 90% of the rainfall falls between January and April. The dry season extends from May to November. By contrast the highlands are much wetter, with annual rainfall of 1.47 m, also with a large interannual variability as the minimum and maximum values were 1.3 and 1.6 m year^{-1}. As a result the seven rivers draining the highlands are perennial; all these rivers form the eastern and western Usangu wetlands in the Usangu plain. The mean inflow in the Usangu plain is about 73 m^3 s^{-1} in the wet season and 17 m^3 s^{-1} in the dry season (SMUWC 2002). These wetlands cover about 2000 km^2 and are separated by a narrow channel at Nyaluhanga; their total area was about 2000 km^2. The core of the wetland (locally called *ihefu*) is perennial. These wetlands are important for biodiversity as they support an exceptional bird population, with species diversity of more than twice that of the whole of Europe.

Human impacts

The Usangu plain retains water throughout the year due to the perennial rivers draining the Usangu highlands. As a result there has been a huge growth of human activities in the last 50 years, and increasingly so in the last 10 years. The total population in the Usangu catchment was 1,177,854 in 2002. Their major occupation is agriculture in the form of farming and livestock. In the Usangu plain, the population has grown from 31,000 in 1948 to around 210,000 in 2002. Associated with this have been major land use changes. The natural vegetation of the alluvial fans has been largely cleared and replaced with both rain-fed and irrigation cultivation as well as pastoral settlements (locally called bomas) and grazing areas. Irrigated rice, alone, has increased in area from about 3000 ha in 1958 to around 40,000 ha in 2005. The livestock population is about 550,000 head of cattle in the early 1980s and 300,000 in 2005, with about 85,000 other livestock (SMUWC 2002).

Such changes in human population and associated activities have had a marked effect on the environment. Most of the southern alluvial fans have been cleared of the original vegetation, and are now occupied by cultivation or by secondary-growth bushland. Cultivation is also pushing onto the wetland. The once-large wildlife herds on the plain have disappeared. The wetland is now occupied by cattle. Throughout the plain, there is evidence of changes in grass species, often accompanied by encroachment of woody species, which suggests a degradation of the range. The expansion of cultivation has taken traditional grazing areas, including important wet season grazing areas, and cut stock routes; this is one source of increased conflict on the plain. In the highlands, changes have perhaps been less dramatic. However, ever-increasing areas have been (and are being) converted to cultivation and settlement, erosion on steep slopes is advanced in places, and even where the woodland is relatively intact, it is exploited for important timber species and in some areas the indigenous tree species are deliberately replaced by exotic ones (pines and *eucalyptus)*.

The Usangu plain is now the rice-producing hub of Tanzania. When originally planned the irrigation farms released unused water back to the GRR through irrigation ditches. However, in recent years, in the dry season all this return water has been captured by licensed and unlicensed farmers at community and family levels (see Figure 2a, b). Some recent irrigation schemes sponsored by international development agencies, notwithstanding their alleged commitment to minimize negative environmental impacts, do not even permit any dry season environmental flows in the rivers (Figure 2c). There are considerable losses of water by leaking from irrigation channels (Figure 2d). As a result, in recent years, in the dry season all the river water is used for irrigation and there is now practically zero flow downstream of the farms into the eastern wetland. This large-scale farming has also resulted in essentially permanently drying out the western Usangu wetlands. The eastern Usangu wetland (Figure 1) is thus the only remaining wetland,

with an area varying seasonally and interannually between 150 and 650 km^2 (SMUWC 2002). Most of this remaining wetland is inside the Usangu game Reserve, i.e. in a wildlife sanctuary; however in the dry season it is invaded, overgrazed, and compacted by about 300,000 cattle (Figure 2e;

Figure 2. Photographs of (a) dry-weather, irrigated, small-scale rice farms in the Usangu plain draining water from the river on the left and returning no water to the river; (b) this unlicensed weir intercepts return flow from an irrigated, industrial rice farm on the right, redirects the water to the left towards a small unlicensed farm, and prevents any water to return to the GRR in the dry season; (c) this World Bank-sponsored irrigation weir on a perennial tributary of the GRR was built in such a way that water can only enter the irrigation channels on the left if the operator closes the gate in the middle that sends water to the river, thus completely stopping the flow in the river when the fields are irrigated. The intention to use 100% of the water for irrigation and ensure zero environmental flow explains why there is no valve to control the flow through the gate; (d) leakage of water from an irrigation channel in the Usangu plain; (e) some of the 300,000 cattle that in the dry season invade the eastern Usangu wetlands. The river shown is the GRR meandering through the wetlands; (f) the dry GRR in the RNP during the 2004 dry season; some of the small holes in the sandy river bed are dug by elephants in search for groundwater; (g) a small water hole remaining in the dry season in the bed of the GRR near Msembe in the RNP. These small, shallow water bodies are the only water available for the animals to drink in the dry season; most are overcrowded with crocodiles and/or hippos; and (h) an erosion gully along the banks of the GRR near Msembe in the RNP due to the destruction of the riparian vegetation by wildlife aggregating near a rare remaining water hole in the river bed.

SMUWC 2002), and it is now also burned annually.

Until the mid-1990s, the GRR was a perennial river in the semi-arid RNP where it sustained a rich wildlife ecosystem in RNP. Before the 1990s, the GRR only once briefly dried out in 1954. Starting in the 1990s, the flow at Msembe in the RNP in the dry season decreased yearly (see Figure 3), although there were no changes in the intensity, the distribution, or the timing of rainfall that may explain the decrease in dry season flow. In the last ten years the GRR dried out every year in the dry season for periods of up to 111 days (SMUWC 2002). The resulting impact on the RNP ecosystem is dramatic (see later). The water available for hydroelectricity production at Mtera Dam has also decreased (SMUWC 2002).

The GRR has thus established a new pattern of drying up in the dry season. The reasons for this are hotly contested by the various stakeholders. This may have been exacerbated by channel changes within the eastern wetland; previous clear through-channels have become blocked such that there is no longer a clear water passage through the swamp. Many of the rivers have changed their courses in this area as a result of siltation of river beds and digging of irrigation canals. The western wetland has largely dried out. The eastern wetland, with its permanent *ihefu* swamp, continues to flood seasonally although the length of flooding may have changed. Water shortages at Mtera have resulted in national power shortages. In the RNP, the GRR has dried up every dry season since 1993, with the dry period tending to start earlier and last longer. There has now been a succession of years in which the GRR in the RNP has dried up completely during the dry season and for increasing periods. This has had severe impacts on the wildlife, including the aquatic and terrestrial fauna.

Within Usangu itself, there has also been concern about rising conflicts over resources, again especially over water availability for irrigation and access to water for livestock.

Clearly there is serious issue of water resources governance in the GRR catchment. There is no agreement amongst the various stakeholders (industrial rice farmers; artesanal rice farmers; pastoralists; hydroelectricity producers; upland farmers) and various national and regional water resources management agencies (Lankford et al. 2004). As a result there is no integrated water resources management.

Rainfall

There are rainfall data from 100 stations with historic records of varying length, are located in and around the Usangu catchment. These stations are concentrated in the southern and eastern highlands. These include five climatic stations, for which data is also available on temperature, humidity, wind speed, and sunshine hours, from which estimates of potential evaporation were calculated by SMUWC (2002). Rainfall distribution varies greatly across the catchment whose amount strongly correlates to the elevation of the terrain. Historical rainfall patterns show no statistically significant trends over time (SMUWC 2002). Variation occurs between stations, with some showing increasing trends in rainfall and others decreasing trends. However, no overall pattern is discernible. The conclusion is that there has been no long-term decline in average or wet-season rainfall. Similarly, no long-term trends

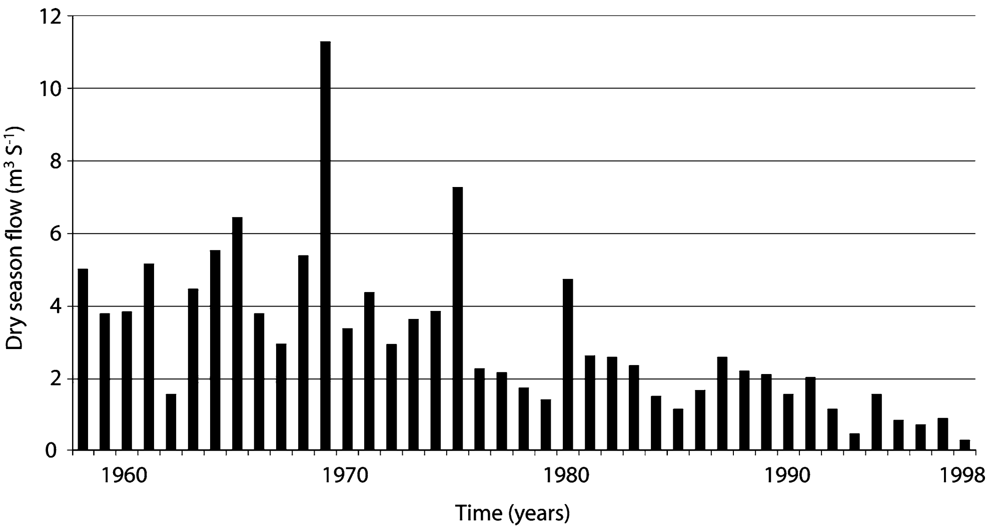

Figure 3. Annual dry-season flows in the GRR at Msembe. Adapted from SMUWC (2002).

are detectable in either the onset or the cessation of the rainy season. While anecdotal evidence consistently suggests that rainfall has declined, analysis of the data does not support this view. Thus, rainfall is not responsible for the seasonal drying out of the GRR in the RNP since 1993.

River flows

An analysis of the historic river flow data shows (SMUWC 2002) that (1) the flow from the highlands to the plain, measured at the base of the highlands, shows no decrease in net runoff, wet-season runoff, and dry-season runoff into the GRR, with some rivers showing a decreasing trend and others an increasing trend; (2) there is no measurable decline in the average annual or wet season flows in the seasonal rivers downstream of Usangu; (3) there is no significant trend in the start and peak of the hydrograph of the GRR in the RNP; (4) the decline of the GRR flow is a dry season phenomenon, starting around the mid-1970s; (5) the flows at the end of the dry season at Msembe in RNP were always very small, about 1–3 m^3 s^{-1}. The change from past low dry season flows to current zero flow is a small one but it is ecologically very significant (see later); and (6) the GRR flow at Msembe first ceased completely in 1993, and has stopped every year since then, even during the exceedingly wet 1997–1998 *El nino* year. Moreover the date that the GRR flow stops now occurs earlier in each successive year, advancing from December in 1993 to September to November in 1994 and 1995, and September in 1997 and 1999. Similarly the period of no flow has extended, from 20 to 113 days. Cessation of dry season flow was exceptionally rare prior to 1993, occurring only once in 1954. Thus the recent succession of zero flows of the GRR at Msembe in the RNP is unprecedented.

The Usangu wetlands

There is much evidence for river course changes and migration within the Usangu plains, both natural and human-induced changes. The upper GRR changed course in the 1968 *El Nino* flood, the old channel was abandoned and the river split into three courses. The tributaries are also known to have changed course. One of them, the lower Mbarali River, has naturally changed course at least three times, in the late 1800s, in the 1930s, and most recently in 1995. Another tributary, the Mkoji River, is known to have changed course, sometime before 1957; the old course is labelled as such on the 1960 topographic maps. Satellite images also show several old channels in the wetland, presumably old courses of the GRR. There have also been human-induced changes; for instance the Ndembera River was diverted to its old course some 30 years. However, all these rivers still flow into the Usangu wetlands.

With the sluggish flow and shallow, poorly defined channels in the western wetland, much of the inflow would have spread out over the western wetland. This is attested to by the vegetation – grassland and *Acacia seyal* woodlands on vertisols, which were almost certainly seasonally flooded in normal years. The western wetlands have now largely dried out due to irrigation farming preventing inundation. The only remaining wetlands are now the eastern wetlands. (1) The perennial swamp (*ihefu*) was measured as 76 km^2 in September 1998 from SPOT images, 82 km^2 in January 1998 from aerial observations, and 27 km^2 during the exceptionally dry year of 1999/2000 from aerial observations. (2) The perennial swamp is always shallow, of relatively even depth (i.e. a level bottom) and with maximum depths of only about 2.5 m. (3) The fringing seasonal wetland (locally called mbuga) is large and flat, and water spreads out evenly over the surface. Lower inflows as well as losses to evaporation result in a gradual decline in water levels during the dry season; in 1999 the difference between maximum and minimum levels was about one metre. (4) Water levels in the swamp vary not only through the year, but also spatially within the swamp. Thus, at high water, there appears to be a single water level for the swamp. However, with the advent of the dry season, the water level slopes towards the outlet at N'Giriama. At that stage the swamp consists of a series of pools in the old channel of the GRR, connected by shallower areas, forming a 'cascade' downstream. Water flow is impeded by the high vegetation density. Topographic surveys have confirmed that the seasonal wetland has virtually no slope. (5) The eastern wetland is maintained by GRR water flowing past Nyaluhanga, and to a lesser degree (< 1/4 of the inflow) through the Ndembera River. In very wet years an unknown contribution may come from local seasonal streams and overland flow. (6) As inflows increase in the wet season, the wetland fills and an outflow results over the rock bar at N'Giriama, thus generating flow in the GRR downstream, for which a rating curve is available (SMUWC 2002). As river inflows decline in the dry season, the combination of flows over the bar at N'Giriama and evapotranspiration from the swamp surface empty the swamp to a water level where overflow over the rock bar ceases, and the GRR downstream dries up. Further losses from evapotranspiration result in further declines in the swamp water level to below the rock bar level. The GRR stops flowing until the swamp refills to above the level of the rock bar. There is believed to be only minor or minimal contributions from groundwater (SMUWC 2002).

Ecosystem impact on the RNP

For every animal to survive it needs water; the resulting drinking water requirement for the large mammals in RNP is no more than 0.01 $m^3 s^{-1}$ (Table 1). This drinking water requirement is small compared to the minimum flow needed (≥0.5 $m^3 s^{-1}$) in the GRR at N'Giriama in the dry season to sustain water losses from evaporation and infiltration (see later). There has now been a succession of years since 1993 in which this minimum flow has not occurred and when the GRR in the RNP has dried up completely during the dry season and for increasing periods. This has had severe impacts on the wildlife, especially the aquatic fauna. The dry season, between months of August/September to November/December (before on-set of rains) is critical because this is when GRR is the major source, often the only source, of drinking water to wildlife. This timing coincides with the peak of tourism in the park where game viewing is the main economic-earning of the park. It also coincides with the scarcity of feed material for the animals within "reachable distances" from the water sources.

Drying of the GRR (Figure 2f) has significantly affected the biological, ecological, socio-economical and the physiological functioning of the ecosystem in the following ways. (1) It has promoted the movement, in search for water, of hippos, crocodiles, water-birds, and other animals away from RNP to other areas out of the RNP where some get killed, and yet others increasingly become a problem by raiding farms. (2) Animals do concentrate along the few water holes in the GRR during the dry season when other minor water sources dry-up (Figure 2g). They will remain at close vicinity until the water holes become algae-laden and turn the water green in colour, at which time they are forced to move to various other areas in search for water and feed materials. (3) Aquatic animals cannot move to alternative water sources,

Table 1. Water-use by the large mammals in the RNP.

Animal species	Water requirements (l day^{-1} per animal)	Estimated number of animals (in 2002)	Total water consumed (l day^{-1})
Buffalo	31	29,279	7,107,649
Bushbuck	1.5	177	265.5
Duiker	1.5	53	79.5
Eland	23	310	2,210,300
Elephant	300	5934	37,384,260
Giraffe	40	1665	66,600
Greater Kudu	10	230	2300
Lesser Kudu	9	27	243
Impala	2.5	1125	2812.5
Hartebeest	5.5	53	291.5
Roan Antelope	10	89	890
Sable Antelope	9	80	720
Warthog	3.5	89	311.5
Waterbuck	9	–	–
Zebra	12	5075	60,900
Total water consumed (l day^{-1})			46,837,623

as they are isolated in these water holes that progressively shrink and suffer from hypoxia, overheating, and algae blooms. This commonly results in massive deaths of fish and fresh water invertebrates (Mtahiko, unp. data). (4) Fresh water oysters and some fish that were common in the perennial river before 1993 have become extinct in the RNP. (5) The aggregation of animals along the GRR near the few water holes has led to the local over utilization of the vegetation in those areas, this leaves the river banks bare and subject to erosion at the onset of the rains. This weakens the river bank and promotes gully erosion (Figure 2h). This has resulted in widening the river (Figure 4), rising the river bed by an average of 0.03–0.05 m $year^{-1}$ (Ng'umbi, unp. data), and consequent siltation of water holes in the river bed. (6) Crocodiles cannot feed properly when all the fish have died; it is also difficult for them to kill mammals as these avoid when possible the filthy water. The lack of feed may affect their physiological functioning and this may take a long time to have an impact on the population. Further, many hatchlings succumb to unavailability of feed. Hatching normally occurs in September to October, when the river is dry and with no fish. It is until when the fish swim upstream from Mtera dam or downstream from the wetland around January/February when the water has started flowing again, that they can feed on fish. (7) An ill-fed animal has poor health. This, together with the stress from long daily walks in search for food and water, reduces immunity and lead to diseases. (8) Territorial antagonism has frequently been observed among hippo bulls in shrinking water holes. Territorial bulls often inflict deep wounds to each other; some may be fatal or expose the animals to serious infections. (9) The animal dung accumulating in water holes results in algae blooms and anoxic waters (e.g., Wolanski and Gereta 1999). Poor water quality is promoted by the frequent churning of the water by animals (Figure 2g). (10) As a result of increasing bank erosion, the river bed has widened with deposition of sand from the bank, further filling the water holes and exacerbating the stress on wildlife. (11) Tourism in RNP is wildlife-based and is threatened by this ecosystem degradation. (12) For species that are heavily dependent on water, i.e. those that must remain within one km of water (e.g. buffalo, waterbuck, many waterbirds), the lack of water has reduced the dry season habitat by nearly 60% (Coppolillo et al. 2004). The local distribution of African Buffalo (*Syncerus caffer*) along the GRR appears to have decreased by about 42%, with no buffalo recorded in aerial surveys along the lower 92 km of the GRR in 2004 (Coppolillo et al. 2004). It is unclear what knock-on effects the reduction in buffalo will have, but one possible result may be an increase in lion predation on giraffe (Lugano, pers. obs.).

While the effects mentioned above have focused on the RNP, the biological significance of the Usangu wetland itself must also be acknowledged. Usangu, the largest and only protected wetland in

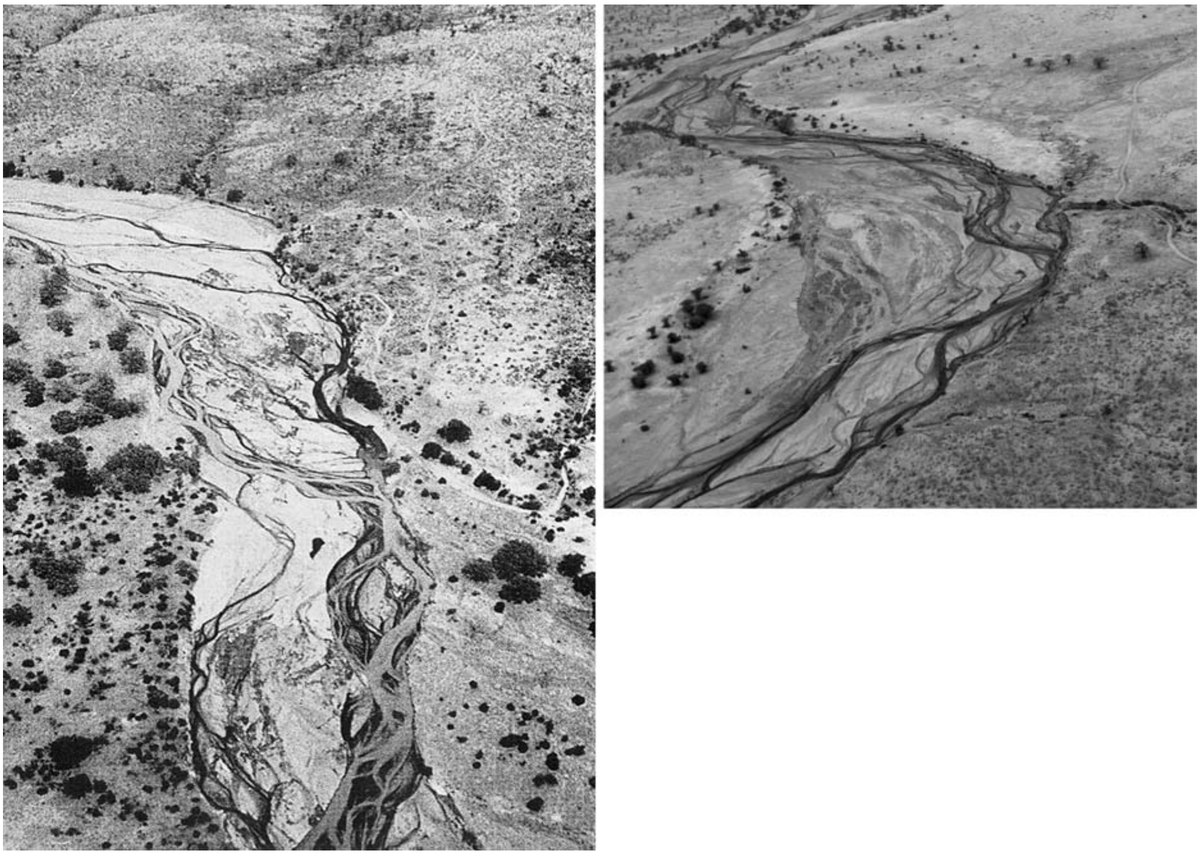

Figure 4. Aerial photographs of the GRR near Msembe on (left) November 7, 1975, and (right) October 26, 2005. Notice the decreasing vegetation, including the riparian vegetation, and the widening of the river channel.

the Rungwa–Ruaha landscape, has tremendous conservation value: it was home to hundreds of thousands, if not millions, of breeding waterbirds including the globally threatened Wattled crane (*Bugeranus carunculatus)* (Moyer 2000), as well as plains game including the only population of topi (*Damaliscus lunatus*) in central Tanzania. Wild mammals are essentially gone from nearly one third (1344 km^2) of the Usangu Game Reserve and in the aerially sampled area wildlife was outnumbered 151:1 by livestock (Coppolillo et al. 2004). Usangu has been designated an Important Bird Area by Birdlife International, but its designation as a Ramsar Wetland of International Importance is on hold due to its degraded state.

Socio-economic implications

The activities in the Usangu catchment include agriculture, livestock keeping, tourism, wildlife, mining, forestry (timber and logging), and fishing. The importance of agriculture to Tanzania's economic and social development is highlighted by the following points. (1) Over 50% of Tanzanians can be defined as poor, with a per capita income of less than US$ 1 per day. Over 80% of the poor are in rural areas and depend on agriculture for their livelihood. (2) About 42% of households regularly have inadequate food. (3) Agriculture is the single dominant contributor to Tanzania's GDP and foreign exchange earnings. During the year 2002–2004, for instance, agricultural sector contributed about 45.0% to the GDP. Furthermore, recent studies by the World Bank have shown that agriculture's growth linkages (multipliers) in Tanzania were higher than those of the other sectors and they are felt in both rural and urban areas. Both rainfed and irrigated farming is practiced in the Usangu plain. According to Sosovele and Ngwale (2002), the industrial irrigated paddy farms have a total area of 3200 ha. The dominant rice farm however is small scale irrigation (see Figure 2). Overall, irrigated farming in the Usangu Plains has increased from 10,000 ha in 1970 to 42,000–45,000 ha at present.

As a result of this irrigation, the former western wetland is no longer a wetland. The responses by pastoralists include greater reliance on the eastern wetland, and/or migration upland in search of water, exacerbating conflicts with cultivators.

Another impact of the human-induced, decreased wetting and the faster draining of the Usangu wetlands is that water is now transferred four months faster from the highlands to Mtera Dam. Because of differences in temperature and altitude, evaporation at Mtera Dam is 0.8 m $year^{-1}$ higher than in the Usangu plain. This increases the loss of water by evaporation by about 100×10^6 m^3 $year^{-1}$. This decreases by 5% the annual GRR inflow to Mtera Dam, in addition to the 5–10% decrease due direct water abstraction for irrigation (SMUWC 2002). The total water loss for Mtera Dam from land use in the Usangu catchment is thus about 10–15% of the GRR total annual runoff, i.e. about 50–100% higher than previously estimated by SMUWC (2002). This may explain why the water level in Mtera Dam is consistently lower, and hydroelectricity production is more often stopped, than was planned by earlier hydrologic studies. This has important economic implications because Tanzania's electricity is the most expensive in East Africa and this lack of reliability (from the closing of the power plants on the GRR) is a major limitation to Tanzania's industrial development (Confederation of Tanzanian Industries 2004).

Water rights in the Usangu plain are ill-defined and not enforced (Lankford et al. 2004). Current reforms in local government intend to place more and more responsibility on local people for resource management. However, it is apparent that local people and their governments, at regional, district and village levels, are poorly equipped to take on these new responsibilities. There are also on-going major changes in water policy; the move towards more regulated management of water (water users associations and water users fees) contrasts with traditional 'free goods' approaches to such resource management. The Usangu Game Reserve includes most of the eastern Usangu wetland. This reserve, if enforced, would exclude both pastoralists and their livestock, and fishermen. This will have serious negative implications for both these economic activities.

The total rice production from the Usangu plain is about 75,000 tonnes. Assuming that the end consumer price of rice is US$ 500 per tone, the rice would fetch a total of US$ 37.5 million.

Both local and migrant cattlemen use the Usangu plain. For 300,000 heads at an average price of US$ 100 per head, the value of the entire population is US$ 30 million. However, livestock in this area are not basically kept for their monetary values, and they are associated with some intrinsic cultural and social values. Cattle, for instance, are associated with prestige and respect on the part of the owners. Cattle are also used as dowry; marriages are respected and valued if cattle are used as dowry. As such if all the livestock were removed from the Usangu Plains, there would be no great loss to the total economy. The district authorities would however lose an income of US$ 150,000 from a charge of US$ 0.5 per head per year to access the grazing resource.

In Tanzania tourism has become a main driver of economic growth and in southern Tanzania the main attraction is the RNP. In 2003/04 the RNP generated a total income of US$ 316,040 that is rapidly growing. The communities living around RNP are generously supported by Tanzania National Parks through community-based development projects such as construction of school facilities, health facilities, water facilities and village feeder roads, both, in terms of materials and finance. The major objective of the support is to ensure that the communities fully enjoy and gain from the resources with which they have some entitlement. Also this support is intended to create awareness on the importance of conservation of wildlife and the benefits accrued from it. The drying of the GRR threatens all this.

GRR water flows into Mtera Dam and this water is used to generate hydroelectricity at two plants (Mtera and Kidatu). Their installed power generating capacity is 284 MW, i.e. about half the total capacity of Tanzania. Assuming an actual power generation of 80% of the time, the other 20% being used for maintenance and repairs, the power generation per year is 1990 million kWh. For an average power charge to customers of US$ 0.0739 per kWh, the value of power is US$ 147.08 million $year^{-1}$. About 52% of the electricity is used in industry and commerce (President's Office 2004);

the power utilized in the latter would be US$ 0.2 million day^{-1}. Assuming that the value of output resulting from the power utilization in industry and commerce is tenfold, the output foregone if power is shut off for a day would be US$ 2 million day^{-1}. In the 2004 dry season, the lack of water in Mtera Dam required the power station to be closed for about 60 days, resulting in an economic loss of US$120 million.

In conclusion, this study (see later) shows that irrigated farming and livestock keeping taking place in the Usangu plains is the cause of dry season drying of the GRR in the RNP and at the downstream Mtera Dam. The economic balance sheet from these activities is negative by a factor of about 3:1.

A model for an ecohydrology-based solution

In this section we used an open-channel flow model, verified against field data, to quantify the role of the eastern Usangu wetlands in maintaining flow in the GRR in the dry season, and we predict the effectiveness of various remedial measures on water and land use activities in the Usangu catchment in restoring permanent flow in the GRR.

Eastern Usangu flow model

Because the GRR flows through well-defined channels of about equal depth in the eastern Usangu wetlands, these were combined in an open channel flow model as one channel of equivalent total width and the same depth. This preserves the wetted permitter and the depth, thus friction and channel conveyance are correctly parameterized.

The model used is that of Wolanski et al. (1980, 2000) that was modified for taking into account the water loss by evaporation and evapotranspiration. The model solves fully implicitly the open channel flows equations (Chanson 2004) around a non-structured grid that follows the topography as shown in Figure 5. The upstream boundary condition is that measured at Nyaluhanga and the downstream boundary condition is the rating curve at N'Giriama (SMUWC 2002). The time step was 5 min.

Detailed studies have been undertaken on total evaporation and evapotranspiration losses in other African wetlands, namely the Okavango and Sudd swamps that are surrounded by arid areas with high free water evaporation rates, similar to the Usangu wetlands. These studies suggest that shading by vegetation reduces considerably the total water loss (McCarthy and Ellery 1995; Bauer et al. 2004; Mohamed et al. 2005). Thus within the pristine wetlands, the total daily water loss was set at 0.5 cm day^{-1}, while in open water and in wetlands were overgrazing has destroyed the vegetation, the daily total water loss was set at 0.7 cm day^{-1}.

The Manning roughness coefficient was set at 0.025 in open waters, 0.1 in the pristine swamp, and 0.05 in the overgrazed, denuded wetland (Petryk and Bosmajan 1975; Arcement and Schneider 2004; Chanson 2004).

Snapshots of the predicted flow field in the Usangu plains during flooding and flow recession periods (Figure 5) shows that only a fraction of the water that enters the swamp during flooding return to the river at flow recession, that the outer regions of the swamp take several months to dry out after the outflow has ceased, and that a core area of permanently wetted swamp remains near the centre. All these predictions are in agreement with field observations (SMUWC 2002).

The GRR model

The model was also used to predict the GRR dynamics from the Usangu wetland outlet at N'Giriama to Mtera Dam. Snapshots of the predicted flow field at the end of the flow recession period shows that the river initially dries out downstream and that this front moves slowly upstream; the last river reach to dry is the upstream one, about three weeks later (Figure 6). This prediction is in agreement with observations (Mtahiko, unp. data). The model suggests that water losses through evaporation and infiltration in the sandy river bed may reach 0.5 m^3 s^{-1}, and this requires an infiltration rate of 0.5 cm day^{-1}.

Model verification and predictions

The model appears verified by the encouraging comparison is found between observed and predicted recession flows at Msembe (Figure 7). The

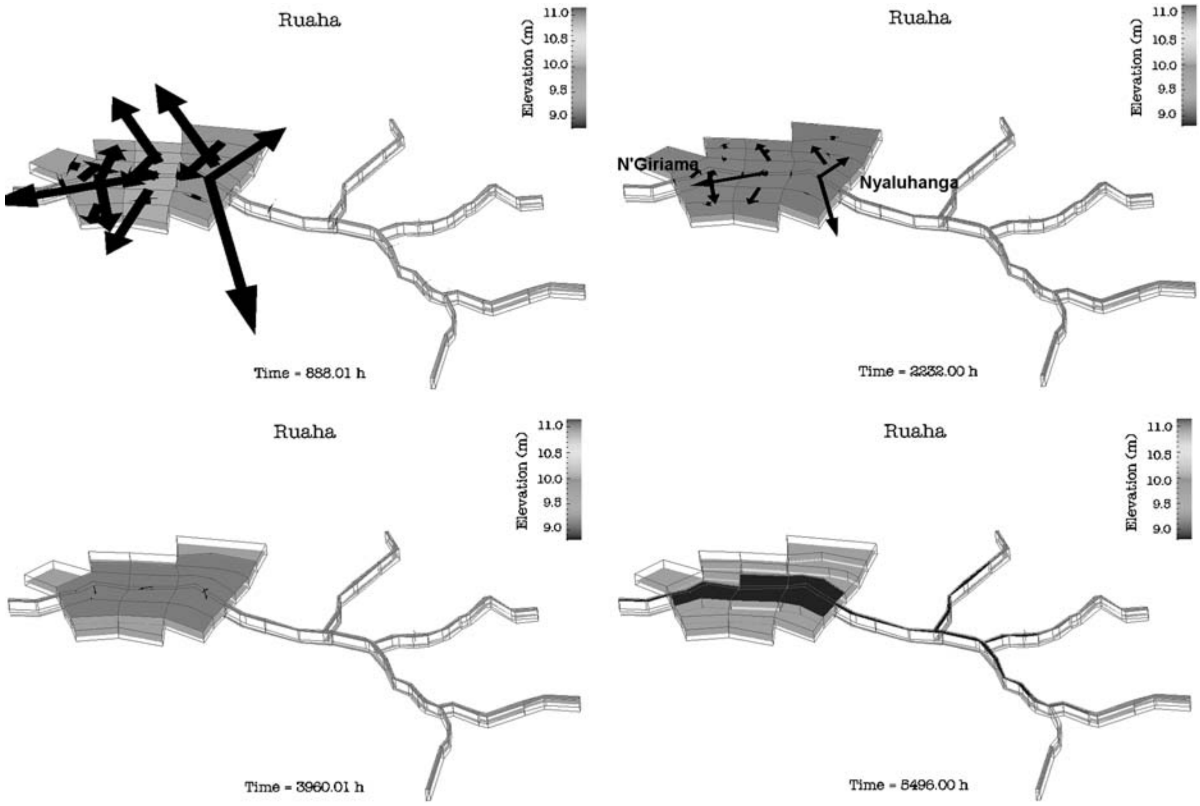

Figure 5. Snapshots of the predicted flow field in the eastern Usangu wetlands for present conditions showing processes of infilling in the wet season and drying out of the outer regions in the dry season. The longest arrow = 280 $m^3 s^{-1}$.

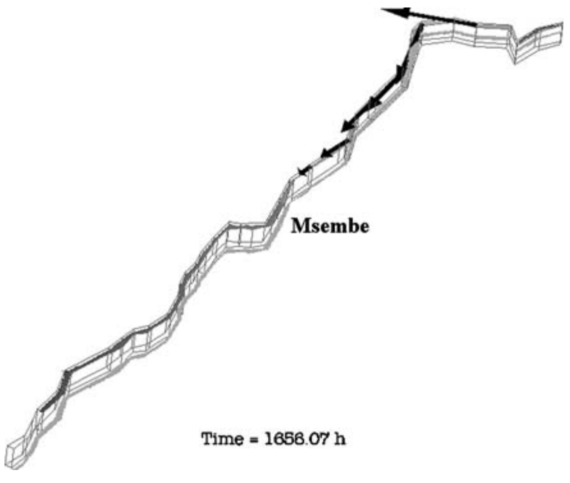

Figure 6. Snapshot of the predicted flow in the GRR downstream of N'Giriama (top right-hand side) near the end of the flow recession period. The longest arrow = 0.5 $m^3 s^{-1}$.

model was used to test the sensitivity of various remedial measures in the Usangu catchment. The results (Figure 8) suggest that dry weather irrigation reduces the recession by up to two months, wet-weather irrigation by about two weeks, and cattle and goats overgrazing the eastern Usangu wetlands by about a month, and that the river would be readily perennial, even with the loss of the western Usangu wetland, with no dry-season irrigation and no livestock in the eastern Usangu wetlands.

Discussion

The model reveals the role of the Usangu wetlands in regulating the discharge of the GRR. Floods are attenuated and recession flows are lengthened. There are considerable surface slopes within the wetlands, thus it would be incorrect to calculate a water budget under the assumption that the water level is horizontal. This incorrect assumption was made in the SMUWC (2002) swamp model and this may explain why that model was unsuccessful.

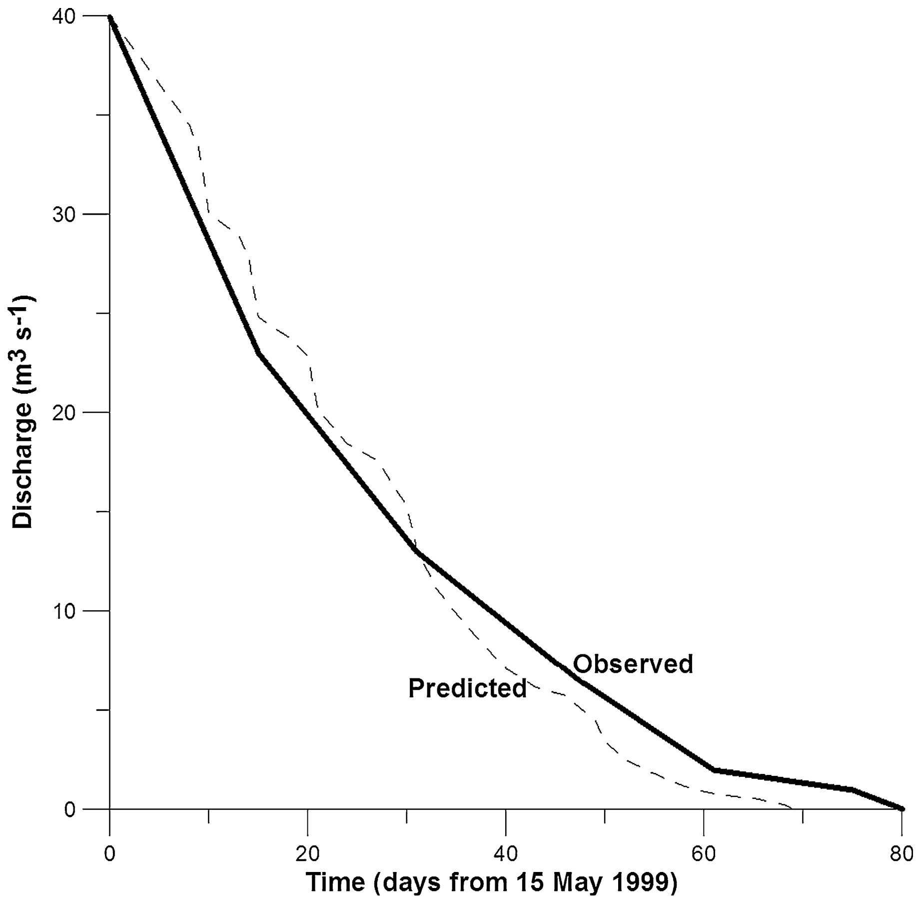

Figure 7. Time series plot of observed and predicted flow in the GRR at Msembe during the 1999 recession period.

This study demonstrates that considerable volumes of water may be stored within the eastern Usangu wetlands during the wet season. In the dry season most of this water is depleted through evaporation and evapotranspiration, as is common with most wetlands (e.g., Bullock and Acreman 2003). The remaining water in the wetlands together with a continuous river inflow of 4 $m^3 s^{-1}$ is necessary to support downstream recession flows of the GRR over the entire dry season to ensure that the river does not dry up. Dry season irrigators cut off all flow into the wetlands. The model suggests that this shortens the river flow recession by about 6–7 weeks. Overgrazing by cattle in the wetlands destroys the vegetation that retards the flow back from the wetlands into the river; and this effect, together with soil compaction and creation of small gullies dug by cattle, facilitates the draining of the wetlands; the model suggests that this shortens the dry season river recession by about another 4 weeks. Wet-weather irrigators also extract water at the start of the wet season to prepare the fields; this water does not inundate the wetlands which are therefore not fully flooded anymore. The model suggests that this reduces the dry season river recession by about two weeks. Irrigation farming has also quasi permanently dried out the western Usangu wetlands; while most of this water would have been lost through evaporation and evapotranspiration, just like for the eastern Usangu wetlands some of that water would have supported the dry-season recession flow of the river; the model suggests that the recession has been shortened by about another two weeks at least. All these impacts add up so that the recession flow has been shortened by up to four months during the eight months long dry season.

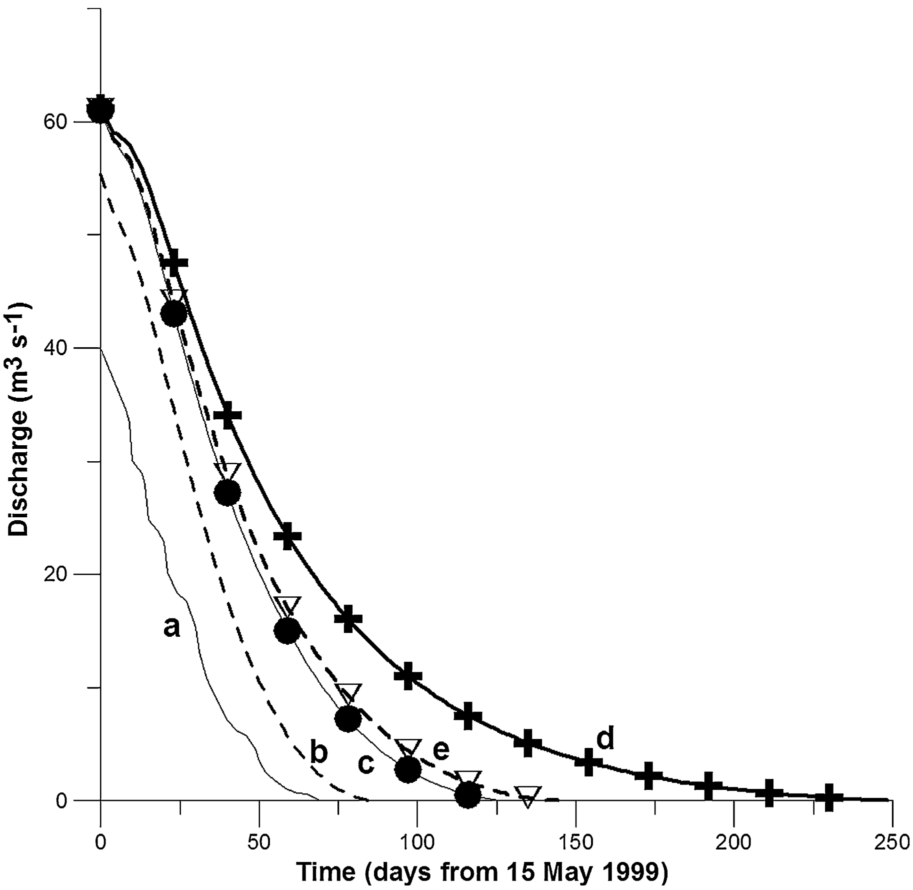

Figure 8. Time series plot of the predicted flow in the GRR at Msembe during the 1999 recession period for various scenarios. (a) present conditions; (b) present conditions minus wet season irrigation; (c) present conditions minus both wet season and dry season irrigation; (d) no irrigation and no livestock in the eastern Usangu wetlands; and (e) present conditions but the dry season irrigators return 25% of the water to the river and no livestock in the eastern Usangu wetlands.

This recent, human-induced change has severe socio-economic implications downstream, as well as a devastating impact on the RNP ecosystem which is shifting from wet tropics to dry tropics system. Perennial flow must be restored to the GRR. As there is not single stakeholder responsible for drying out the GRR, there is no expedient political solution. To ensure sustainable development, governance is urgently needed for the Usangu catchment in a way that is compatible with ecohydrology principles for the sustainable use of water resources (Gereta et al. 2002; Zalewski 2002). For this to happen, this study suggests that all livestock must be removed from the eastern Usangu wetlands, which are in the Usangu Game Reserve, and that dry weather irrigators must return at least 25% (~4 $m^3 s^{-1}$) of the water to the river.

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