# THE IMPORTANCE OF WATER QUALITY AND QUANTITY IN THE TROPICAL ECOSYSTEMS, TANZANIA

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# PREFACE

The work in this thesis has been possible through the support of various institutions and people. Tanzania National Parks (TANAPA), my employer, through Mr. Gerard Bigurube, the Acting Director General, has given me a lot of moral, financial and logistics support in carrying out the various things in the study. Being an employee of the Institution, it was my obligation to carry out such studies as an ecologist of the park and later in charge of the whole Ecology Department of TANAPA. Frankfurt Zoological Society of Germany (FZS) in Serengeti National Park and especially Dr Markus Borner, a representative of FZS for Africa Region who saw the importance of this work. He fully supported it logistically and financially without which much of the work could not be accomplished. The FZS staffs also supported the work and keep on supporting it to present. Dr Eric Wolanski of Australian Institute of Marine Science is my chief collaborator in this work since the start of the study. Through this work, we have been able to extend the water quality work to other national parks. These are Rubondo Island National Park in Lake Victoria, Tarangire National Park and now Proposed Saadani National Park located in the northern part of Dar-es-Salaam. The proposed Saadani National Park will be the only park in Tanzania with both terrestrial and marine components of the ecosystem. The water quality work is one of its kind in the area of wildlife conservation in the country. Because of the importance of water quality to wildlife the work is developing a lot of interest to conservationists. Water is a major problem in most protected areas and water quality is a major concern to a lot of people, both to the public and protected areas due to pollution brought about by modern ways of living. This kind of living is making people become a throw away society. Plastics are thrown away indiscriminately all over the areas without caring for their consequences to human health, animals and environment. Dr Wolanski has been very supportive together with his Institute in the study of water quality through material support and its science.

In Tarangire National Park, Worldwide Fund for Nature (WWF) through its Country Representative, Dr Herman Mwageni funded the initiation of this study. TANAPA and the park management continue to support the study. The Ecology Departments in these parks still play a role of continuing the work by collecting the data on monthly basis. The teams in both parks include Mr Ephraim Mwangomo, Park Ecologist, Serengeti National Park and his assistants Ernest Sitta, Christina Kibwe and Nelson ole Kwai. In Tarangire National Park, Ole Meing'ataki, Park Ecologist and his assistants, Geofrey Mkongwe, Philemon Fernandes and Mussa Mandia together with the management of those parks for their support. I thank them all and I encourage them to keep on supporting the efforts. The long term data being collected might lead us to new areas of water quality work. Who knows!

I would like to pay a special tribute to Professor Eivin Roskaft, my supervisor and his best half, Mama Roskaft. Without them I would not have the courage of pursuing this programme of higher learning. I know the demand the work creates but still I have been able to brave it. I believe the future of any nation depends on how much knowledge the citizens of that nation have for the development of that nation. Education is therefore, an indispensable attribute worth investing in. With that kind of thinking at the back of my mind, I got more encouraged to brave the turbulent weather. The support given is worth the investment.

This work cannot be complete, without thanking the Director General of Tanzania Wildlife Research Institute (TAWIRI), Dr Charles Mlingwa, for both moral and material support and encouragement he gave me in order to take this opportunity of accepting this challenge of pursuing this study of higher learning. I would also like to thank Mr Samuel Bakari, Assistant Director, Serengeti Wildlife Research Centre, for providing me with accommodation and logistical support while doing this work.

I want to thank all those who have worked with me in these studies both in the field and behind the scenes. Without them I would not go that far. I cannot mention them one by one; space would not allow, nonetheless, there are few whom I am obliged to mention. I would like to recognize Dr Simon Mduma. Mr Edward Chiombola, Mr Asukile Kajuni and Mr David Mattaka for their support and review of the manuscripts.

I would like to recognize my family for being very patient with me and being understanding during all this time of my absence to them. They would have complained and this would have made me uncomfortable to carry on with the work. I thank them very much.

Finally, I would like to thank Francisca who has been providing me with support whenever I ran out of working gear such as printer cartridges and other services and encouraging me to keep on working. I thank her very much.

# ABSTRACT

This thesis looks at the importance of water quality and quantity in the tropical ecosystems in relation to movement of animals who depend on that water for their daily lives and existence. Seasonal fluctuations of rainfall were pronounced, with marked wet and dry seasons. Surveys of water quality in the surface waters in the Serengeti and Tarangire National Parks in Tanzania, East Africa were undertaken throughout the year, in both the wet and dry seasons, from 1996 to 2003. Surveys of water quality in the surface waters of Tarangire National Park were carried out from 1999 to 2001. In the Serengeti most of the rivers were ponded, with ponds having a flushing time of 1 month in the wet season and zero flushing in the dry season. The parameters used in the water quality included temperature, pH values, dissolved oxygen (DO), salinity (S) and visibility. pH values varied spatially from extremely alkaline conditions (pH>10) in the southern plains of the Serengeti to acidic conditions in the northern region (pH=5.9). In the southern plains at the end of the dry season the salinity of the surface waters was high (5-10$^0$/00) while there was still abundant fodder, the zebras and wildebeest had started to migrate away, suggesting that excessive salinity may be the trigger initiating the annual migration. Most surface waters were heavily eutrophicated as a result of animal dung. Because of this animal dung, the dissolved oxygen concentration near the surface fluctuated widely between 1 and 200% of saturation, the smaller values occurring deeper in the water column. Stirring and mechanical aeration by various animals in the water prevented the formation of anoxic conditions. The oxygen stress was less in wetland-fringed water bodies, because of the filtering effect of wetlands. Light penetration was high (>10 cm) in saline waters because of settling of suspended matter was accelerated by flocculation caused by bacteria and vegetation detritus. Elsewhere, the euphotic zone was less than 1 cm thick and the waters generally inhospitable to aquatic life.

Tarangire National Park, on the other hand, showed similar situation as in the Serengeti.. In the dry season, the only drinking water available for wildlife was the Tarangire River and a number of small, scattered wetland-fringed water holes. The salinity was often high (>8 ppt) and was higher in the dry years than in wet years, as well as at the start of the wet season. Water quantity and quality also appeared to control the annual migration of wildebeest, zebras, elephants and buffaloes. These animals aggregated in the dry season in areas with the least salty water. The timing of seasonal variations in rainfall was largely predictable and controlled annual migration. All wildebeest and most zebras migrated out of Tarangire National Park and into the wider Tarangire ecosystem at the start of the wet season, and they returned into the park in the dry season. Some elephants and buffaloes also migrated in and out of the park and a larger resident population remained, whose size may vary interannually depending on surface water quantity and quality. The extent of the migration zone may also vary interannually.

The study also focused at the vertical distribution of temperature and dissolved oxygen over 24 hours in a pond of the Seronera River inhabited by hippos in the Serengeti. Findings showed that the waters were very turbid (visibility <2 cm). The high turbidity was from animals trampling sediment and a permanent surface algal bloom sustained by faecal matter. Direct solar heating was restricted to the top few centimetres. This resulted

in a strong thermal and density stratification inhibiting aeration of the water column. Waters at the mid-depth were aerated only when hippos stirred the water. Anoxic conditions were common in bottom water; these were occasionally ventilated in day time by mixing due to bottom heating from decaying organic matter and at night by convective cooling. Poor water quality in hippo pools may affect wildlife.

In the Serengeti ecosystem, the Mara River is the only source of permanent water supply throughout the year. Other rivers such as the Grumeti and Mbalageti dry out in the dry season with only pools of water scattered in a series. The Mara River catchment is the dry weather refuge for more than 1 million wildebeest and zebras of the Serengeti ecosystem. The Mara River flow is affected by developments in Kenya, including deforestation, water diversion for irrigation, and the proposed Ewaso Ng'iro (South) Hydropower project. An ecohydrology model was developed to predict the inter-annual fluctuations of the wildebeest and lion populations as a function of the hydrology. The model was calibrated against observations of rainfall and wildebeest and lions numbers in the period 1960-2000. This model used to predict the likely impacts of these developments on the Serengeti ecosystem. The model was forced by observed monthly rainfall in the period 1900-2000 and calibrated against observations of the number wildebeest and lions also in the period 1960-1999. The projects are predicted to have little effect on the number of migrating wildebeest in the Serengeti until a drought occurs; historically a drought occurs about every 7 years, and a severe drought occurs every 15 years. At that time 20-80% of the migrating wildebeest may die, according to the severity and duration of the drought. With a 50% die-off, it may take twenty years for the population to recover; with an 80% die-off there may be no population recovery. In practice the economic benefits would go to Kenya while Tanzania would suffer most of the economic costs, i.e. the negative impact on the tourist industry and socio-economic benefits to communities living along the Mara River. To ensure sustainable developments for both Kenya and Tanzania, a transboundary Mara River Management Plan needs to be implemented and be compatible with ecohydrology principles for the sustainable use of aquatic resources.

# LIST OF PAPERS

The thesis consists of the following papers.

I. Gereta, E. and Wolanski, E. (1998) Wildlife-water quality interactions in the Serengeti National Park, Tanzania. *African Journal of Ecology* **36**: 1-14.

II. Wolanski, E. and Gereta, E. (1999) Oxygen cycle in a hippo pool, Serengeti National Park, Tanzania. *African Journal of Ecology* **37**: 419-423.

III. Wolanski, E., Gereta, E., Borner, M., and Mduma, S. (1999) Water, Migration and the Serengeti Ecosystem: Understanding the mechanisms that control the timing of wildlife migrations may prove vital to successful management. *American Scientist* **87**: 526-533.

IV. Wolanski, E. and Gereta, E. (2001) Water quantity and quality as the factors driving the Serengeti ecosystem, Tanzania. *Hydrobiologia* **458**: 169-180.

V. Gereta, E., Wolanski, E., Borner, M., and Serneels, S. (2002). Use of an ecohydrological model to predict the impact on the Serengeti ecosystem of deforestation, irrigation and the proposed Amala weir water diversion project in Kenya. *Ecohydrology and Hydrobiology* **2**: 135-142.

VI. Gereta, E., Wolanski, E, and Chiombola, E.A.T. (2003) Assessment of the Environmental, Social and Economic Impacts on the Serengeti Ecosystem of the Developments in the Mara River Catchment in Kenya. (Frankfurt Zoological Society website).

VII. Gereta, E., Ole Meing'ataki, G.E., Mduma, S., and Wolanski, E. (2003). The role of wetlands in wildlife migration in the Tarangire ecosystem, Tanzania. Wetlands *Ecology and Management* (in the press).

VIII. Gereta, E., Røskaft, E., Stokke, S., Wolanski, E., Mwakalebe, G. and du Toit, J. The key role of water in controlling the migration of large ungulates in the Serengeti National Park, Tanzania. (manuscript)

# INTRODUCTION

Gereta and co-workers have collated in the mid to late 1990's a number of data sets concerning the hydrology (rainfall), the surface runoff (river discharge), the water quality and the animal counts and movement in the Serengeti National Park. These data extend from 1960 to 1999. Field data collection is continuing.

Gereta & Wolanski (1998) have suggested that the timing of the northward migration of wildebeest (*Connochaetes taurinus*) and zebra (*Equus burchelli*) at the end of the wet season is correlated with excessive salinity in surface waters - there is still fodder and water but the water is too saline for mammals to drink. The timing of the migration was predicted accurately within a few days, 6 weeks in advance. The data set was limited to 2 years. However more recently Wolanski & Gereta have shown that the model is most likely robust because it predicts accurately the migration in four years including an extremely dry year (1997) and an extremely wet year (1998).

Wolanski & Gereta (1999) and Gereta & Wolanski (1998) have also shown that water quality in the stagnant water holes in the dry season, the only source of water for wildlife, is extremely poor, with anoxic conditions being common. They suggested that this would affect wildlife health in the same manner that poor water quality in pasture dugouts affects cattle production and health.

More recently Gereta et al (2002) have implemented a rainfall-driven computer model of the Serengeti ecosystem. The model has three trophic levels (grass, ungulates and carnivores). The model is forced by the observed monthly rainfall data from January 1960 to June 1999. The model was calibrated against observation of total number of wildebeest and lions (*Panthera leo*). It is clear from the model that inter-annual fluctuations of rainfall play a dominant role in regulating the Serengeti biomass at all trophic levels.

The dynamics of the migration, in Serengeti National Park, and the links with the vegetation and minerals, have been reported by a number of authors including Sinclair & Arcese (1995), McNaughton (1979, 1985, 1988, 1990), McNaughton, Ruess & Seagle (1988), Ruess (1988), Ruess & Seagle (1994), Ruess and Halter (1990), Ruess & McNaughton (1987, 1988). The clue that triggers the start of the annual migration of zebras (Equus burchelli) and wildebeest away from the southern plains near the end of the wet season is still unclear. Minerals have been shown to have a large effect on plant growth and aggregation patterns of zebras and wildebeest during their annual migration (Jager 1982; McNaughton 1988, 1990; Tracy & McNaughton 1995). In these studies little attempt was made to consider also the influence of water, either quantity or quality. However, water quantity is important to wildlife, e.g. southern plains are arid in the dry season, when they cannot support the large herds of herbivores that migrate there in the wet season. No information has been gathered on water quality and its influence on the park’s ecology. Water is essential and it is life to all living organisms. Without water life will be short-lived. The value of water is in both quality and quantity. Quality is important for maintaining good health. Poor quality water is subject to bring all types of health and disease problems. Quantity is equally important because if enough water is not available a lot of functions of living organisms will cease to operate or function and that will result to death or loss of life. The studies presented in this thesis focus on the importance of water quality and quantity as they influence the sustenance of the annual migration of the wildebeest together with other animal species. Likewise, the vegetation cover which supports the wildlife is also a function of water quality and quantity. The quality affects the type of vegetation that can grow in certain habitats and quantity supplies sufficient water for such plant communities to be able to maintain themselves.

In this thesis water plays an important role in influencing the movement of different species of animals as water supply shifts from wet season to dry season to wet season. An example of this scenario is the annual migration of wildebeest in the Serengeti ecosystem as reported by Gereta & Wolanski (1998; 2002), Wolanski et al (1999); Wolanski & Gereta (2001). The water quality and quantity give the impetus to starting the long trek in the ecosystem. The value of water can, therefore, never be over-emphasized.

The first part of this thesis (Paper I), which is the basis of all the studies that followed after, focuses on the water quality from the end of the wet season (April-May 1996) and near the end of the dry season, before the onset of the rains (November 1996) covering most of the park rivers and water bodies.

The surface waters in the Serengeti National Park are commonly ponded in holes in riverbeds. They are heavily eutrophicated as a result of input of animal dung from hippos and other wildlife and the lack of rapid flushing. The resulting algae bloom and the suspension of the sediment, decaying vegetation and animal dung make the waters very turbid, commonly reducing the photic zone to the top 1-2 cm of the water column. At the surface the dissolved oxygen concentration fluctuates widely from nearly anoxic to hyper-saturation in daytime as a result of photosynthesis in daytime and respiration at night (Gereta & Wolanski 1998). This section of the thesis (Paper II) looks at the vertical stratification in a hippo pool where such stratification is the case and a description of the limnological and biological processes take place governing its oxygen balance.

Every year towards the end of the wet season (rainy season) in Serengeti National Park, an annual event takes place. This is the famous wildebeest migration. Approximately, over 1 million wildebeests and nearly a quarter of a million zebras set off on a journey that lead them to the south-west and finally back to the south. Over the course of the year, the animals travel an average of 10 Km per day. This migration of the wildebeest to the wet season southern range coincides with the calving period. Clearly, environmental factors must play an important role in forcing this migration.

Many mechanisms have been proposed as explained in the first part of this thesis (Paper I) but have all failed to predict the timing of the migration. Papers III-IV of this thesis tries to look deeper into the driving forces of the Serengeti ecosystem. Water quality data were merged with the available hydrological data. These data were analyzed to see any correlations between water quantity and quality and both the timing of migration and vegetation types and availability. Based on the information gathered out of the data analysis, the study led to a proposal that water quality and quantity make up the dominant force driving the Serengeti ecosystem. These factors also explain the timing of the wildebeest migration as well as to why vegetation occurs in the pattern that it does.

Serengeti ecosystem includes a national park, game reserves, game controlled areas and conservation areas in Tanzania and Kenya. At the centre of the ecosystem in Tanzania is Serengeti National Park whose area is 14,763 $Km^2$ . The Mara, Grumeti and Mbalageti Rivers, all of which flow westward to Lake Victoria, drain the park. Over 1 million wildebeest and a quarter of a million zebras migrate the ecosystem annually. At the end of the wet season, these animals migrate towards the lower Grumeti River and thence to the northern region of the Serengeti National Park and the Maasai-Mara Reserve in Kenya; there they take refuge during the dry season (July-October) as indicated in other papers (Paper III-IV). Papers V-VI of this thesis express concerns given that the ecosystem is impacted by deforestation in the Mau escarpment in Kenya, irrigation for mechanical wheat farming in Kenya’s Loita Plains and the proposed Ewaso Ng’iro (South) Hydropower Project, also in Kenya. The scheme would divert water from the Amala River in the Mara River catchment and divert this water to another catchment, the Ewaso Ng’iro River. The water would be used to generate hydro-electricity for use in Kenya.

A synthesis study was undertaken whereby rainfall, water quality and animal density data were combined to understand the migration patterns of large ungulates in the Serengeti National Park in 2001-2002. The data suggest that wildebeest, topi and zebra migrated clockwise in a general north-south direction, at seasonal time scale, across much of the ecosystem controlled by water quantity (i.e. rainfall) and poor water quality (salinity > 10 ppt). The migrating area of topi appeared to be smaller than that of zebra and wildebeest. The data also suggest that Grant and Thomson gazelles also dispersed in a pattern controlled by rainfall and that their dispersal range and their time scale was annual instead of seasonal. Impala migrated in a different way, preferentially east west, the animals being aggregated in the central area in the dry season, and in the Lobo area and the Western Corridor in the wet season. This migration pattern had not been studied earlier. The data clearly suggest that water quality and quantity control the migration dynamics of large ungulates in the Serengeti ecosystem.

An ecohydrology model is used to assess the likely impact of deforestation, irrigation and proposed Amala weir on the Serengeti ecosystem to Tanzania. This includes the socio-economic impacts on tourism, agriculture, livestock production, fisheries, wildlife, water supply and health status of the people along the Mara River.

Apart from working in the Serengeti ecosystem, another ecosystem in northern Tanzania was included in the study for comparison purposes and understand what goes on there as regards to both water quality, quantity and the animal movements. This is Tarangire National Park.

Tarangire National Park covers an area of about 2600 $Km^2$ of grasslands, flood plains and gently rolling hills of wooded savannah (Lamprey, 1963 and 1964; Kahurananga, 1976 and 1979). The mean elevation is about 1200 meters. Tarangire National Park and its

Tarangire ecosystem is generally found in the Maasai steppes of northern Tanzania. The rainfall pattern is bimodal, with a pronounced wet and dry season annual cycle. Just like Serengeti National Park, Tarangire rainfall also varies inter-annually; there are dry years and wet years. The area is generally arid in the dry season when wildlife aggregates at sites where drinking water is available. These sites are the Tarangire River, the Silale wetland and a few scattered water holes and wetlands. Tarangire River flows north-westward towards Lake Burunge that is located outside the park. Unlike Serengeti National Park, Tarangire National Park is used as a dry season refuge for wildlife. During the wet season most of the wildlife leaves the park and comes back at the beginning of the dry season.

This section of the thesis (Paper VII) aims at understanding the role of water and wetlands in the Tarangire ecosystem. Water quality parameters are taken into consideration and are compared with Serengeti ecosystem.

In both scenarios i.e. Serengeti and Tarangire ecosystems the hypothesis being tested is that both water quality and quantity are driving forces that trigger the movement of the animal migration.

## THE STUDY SITES

The 25,000 km$^2$ Serengeti ecosystem includes a national park, game reserves, game controlled areas, Ngorongoro Conservation area and the Masai-Mara Game Reserve in Kenya (Fig. 1). At the centre of the ecosystem is Tanzania's 14,763 km$^2$ Serengeti National Park. The Mara, Grumeti and Mbalageti rivers, all of which flow westward to Lake Victoria, drain the park. The park is listed as a UNESCO World Heritage site and is made spectacular by the annual migration of more than 1 million wildebeest and 200,000 zebras. As described by Sinclair & Arcese (1995), these animals disperse into the treeless southern grasslands (dotted lines in Fig. 1) of the park and the western region of the Ngorongoro conservation area during the rainy season (December through April). This area is the driest region of the park and is arid in the dry season. At the end of the wet season, these animals migrate towards the lower Grumeti River and thence to the northern region of the Serengeti National Park and the Masai Mara Reserve in Kenya; there they take refuge during the dry season (July to October).

The Tarangire National Park (Paper VII), Tanzania, covers an area of about 2600 km$^2$ of grasslands, floodplains and gently rolling hills of wooded savannah (Lamprey, 1963 and 1964; Kahurananga, 1976 and 1979). The mean elevation is about 1200 m. Peterson (1973) reported a mean rainfall of 0.53 m year$^{-1}$ and a potential mean annual evaporation of about 2.5 m year$^{-1}$. The rainfall is bimodal, with a pronounced wet and dry season annual cycle. The rainfall also varies inter-annually, there are ‘dry years’ and ‘wet years’. The area is generally arid in the dry season when wildlife aggregates at sites where drinking water is available. These sites are the Tarangire River, the Silale wetland and a few scattered waterholes and wetlands (these are shown in Paper VII), nearly all of them in TNP. The Tarangire River flows north-westward toward Lake Burunge that is located outside TNP. The discharge in the Tarangire River is minimal in the dry season;

during the 1999 dry season this discharge was measured to be about 0.005 $m^3s^{-1}$ (Wolanski, unp. data). The Silale wetland is an overflow flood plain that can reduce to a set of small pools in the dry season in a dry year.

The Tarangire National Park (TNP) is surrounded by a number of game controlled areas (GCA) such as the Lolkisale GCA (Paper VII). However, as shown in Paper VII, many of the GCAs are heavily encroached by cattle, sheep and goats, as well as cultivations. This leads to a further reduction of grazing land for wildlife as well as the wildlife being increasingly harassed and harmed in most GCAs.

## THE STUDY SPECIES

In both sites the study species are all animals that are involved in the movement using the ecosystem hydrology. In the Serengeti, it is the wildebeest migration with associated animals such as zebras. Also the Thomson gazelles (*Gazella thomsoni*), Grant gazelles (*Gazella granti*), Impala (*Aepyceros melampus*), Topi (*Damaliscus korrigum*) and Coke's Hartebeest (*Alcelaphus buselaphus cokii*). In Tarangire, all animals that move out of the Park in the wet season and come back in the dry season. These include wildebeests, zebras, elephants (*Loxodanta africana Blumenbach*) and buffaloes (*Syncerus caffer*).

## SUMMARY OF RESULTS

### Wildlife-water quality interactions in the Serengeti National Park, Tanzania (Paper I)

The park was surveyed both in the dry and wet seasons in 1996 in search of water quality of the surface water. Various parameters were looked at. These included the water pH, Dissolved Oxygen (DO), water salinity, temperature and visibility. Most of the rivers and water bodies were sampled at the end of dry season and near the end of the dry season before the start of rains. The main rivers included the Mara in Kenya, Grumeti and Mbalageti in Tanzania. Some stations (sampling sites) were sampled both in the wet and dry seasons. In addition, the Seronera River, a tributary of Mbalageti River, was sampled continuously at two sites for 24 hours to measure diel fluctuations. Various probes were used to take the measuments. Visibility was measured using a small secchi disc or a pen. Still or undisturbed water was collected for suspended matter using a microscope slide to measure particle size and distribution.

The three rivers, Mara, Grumeti and Mbalageti, showed different hydrological cycles but their monthly flows were significantly correlated. Maximum recorded flood discharges were about 40 $m^3$ $s^{-1}$ for the Mbalageti River, 200 $m^3$ $s^{-1}$ for the Grumeti River and 1000 $m^3$ $s^{-1}$ for the Mara River. The discharge decreased after the rains exponentially to low values maintained by seepage from the ground water table. The three rivers had different decrease rate. The Mara had the longest flow rate followed by Grumeti and lastly, the

Mbalageti. The Mara had a smooth flow whereas the Grumeti and Mbalageti had intermittent flows. This happened this way because the active ground water thickness was estimated to be 47 cm for the Mara catchment, 27 cm for the Grumeti and 32 cm for the Mbalageti. Nonetheless, the Grumeti and Mbalageti catchments the ground water reservoirs were rarely completely filled during the wet season because the infiltration rate was only a third of that of the Mara catchment. The active ground water reservoir was depleted in the dry season at a rate of 2.3% per day for the Mara basin whereas the depletion rate for the Grumeti and Mbalageti is about 4% per day. This explains why the Grumeti and Mbalageti Rivers were quickly exhausted after the rainfall ended. Because of this situation, The Grumeti and Mbalageti Rivers together with their tributaries were ponded most of the year as a result of blockage either naturally or otherwise e.g. rock bars or roads. Much of the year ponding of the water in the dry season is a normal phenomenon in the park, thus, flushing is an event that does not exist. Some of these ponds collect enough water to form hippo pools that attract other wildlife.

The hippo pools formed, tended to be compacted by trampling and filled with animal dung or waste. This situation facilitated the water in the pool to get algal growth which carpeted the water surface and sometimes rooted macrophytes were established. Under this condition the water was always turbid. On the other hand, where wetland-fringed ponds existed the water was clear and algal growth never occurred.

On the mineral side of the water, the Seronera River sediments suspension was extremely deficient in Mg and Ag and extremely rich in P (because of eutrophication by faecal matter), Zn, Cu, Pb, S and Sr. The volcanic nature of the soils may explain the richness in some minerals. Also the Seronera River suspended sediments were enriched in Ni, Mn and V but poorer in Fe, Mg and Al. The sediment was clay, being extremely fine, with 68% of the particles less than 4 micro-meter in diameter. Silt accounted for the remaining 31% of the sediment.

The salinity levels in the Serengeti National Park tended to be higher ($S>10$) in the southern part of the park compared to the northern part of the park ($S<1$). Both in the wet and dry season, salinity is still high in the southern range of the park. The difference comes when the rainfall is above normal and it rains for a much longer period, then, there is dilution of the salt in the water and this allows animals to spend longer time in the south because the water at that time becomes sweet for a considerable period of time. In the study, the Seronera River was sampled intensively and spatial salinity gradient showed that downstream in the wooded savannah in the northern part of the river (sites 1-10) to the grasslands in the south (sites 13-18) the salinity changed from low to high. This difference could be contributed by the dilution from ground water seepage into the river. The vegetation growth followed the salinity trend i.e. with wooded savannah where salinity was low and grassland where salinity was high but not high above 4 parts per thousand (ppt) It has been noted elsewhere that a salinity of about 2 ppt freshwater vegetation such as rice can grow but not above then nothing grows.

The study has also shown spatial distribution of pH (Acidity/alkalinity) in surface waters. This could be a reflection of underlying soils. The waters in the south up to the upper waters of the upper Seronera and Mbalageti Rivers are more alkaline (pH = 9-10) while the waters in lower Mbalageti were slightly alkaline up to the Mara River (pH = 7.8) in the wet and dry seasons. The Grumeti River waters were always neutral (pH = 7.1-7.3 in the Western Corridor, pH = 7.0-7.2 in the head waters). Naironya Springs at Lobo Lodge the waters were acidic (pH = 5.9).

The temperature of the water varied from pond to pond depending on the vegetation cover, openness of the area, shadowing and depth. However, the diurnal change of temperature in the Seronera River was $6^0$ C.

The spatial visibility of the waters showed no correlation from pond to pond. Visibility was generally less than 1 cm. this made aquatic life to be limited. Visibility is important because it controls light penetration and this leads to euphotic layer thickness that supports aquatic life. In ponds where wildlife used the water intensively, visibility was highly affected and the water was turbid.

Dissolved Oxygen levels showed high spatial variations both in the dry and wet seasons. These variations were brought by eutrophication in both man-made and natural river ponds. Bottom waters had less or no DO than surface waters. Daytime DO varied from pond to pond suggesting that each pond had its own DO balance independently of neighbouring ponds. The filtering effect of fringing wetlands reduced DO stress.

### Oxygen cycle in a hippo pool, Serengeti National Park, Tanzania (Paper II)

The ponded surface waters in the Serengeti National Park were studied. These water pools are the only source of water to wildlife, especially, in the dry season. These ponds are, therefore, highly dependent by the wildlife despite being eutrophicated.

These ponded waters were sampled at 18 stations (sites), in addition, at three intervals during 24 hours the water at three depths (0.3, 0.9 and 1.7m) at a river pond with maximum depth of 1.8m. In each water depth temperature, salinity, pH, DO and visibility were measured.

The ponded water had no flow and the water was turbid with fine sediment from animal trampling and with algal bloom in the surface layer sustained by continued supply of faecal matter. The salinity of the water stayed at 4 ppt throughout the water column and the pH at the surface was 8.1.

The temperature and DO content of the water varied throughout the 24 hours of recording readings. The water temperature was stratified. The stratification was caused by solar heating in the day and cooling at night, stirring by the hippos, and heating by decomposition of organic matter at the bottom. Because of the high turbidity, direct solar heating was restricted to near the surface; this generated strong temperature differences with depth (up to $2^0$ C per 0.9m). The waters below were only heated by downward turbulent heat flux. In the top half of the water column downward heat flux occurred only when the hippos stirred the water. In the bottom half of the water column, mixing occurred when the bottom waters became warmer from heating by decomposition of organic matter at the bottom. At the surface, the algae generated a strong diurnal cycle of DO. Near the bottom, decaying organic matter removed DO and made the water anaerobic. Mixing by hippos or other wild animals aerated the mid- and bottom waters. At night aeration occurred when the water column overturned from convective cooling. This is a typical position of the ponded water in the park. The water is generally polluted and since no study has been carried out on its health to animals, it is not known whether it is suitable health wise or not. Nonetheless, that is the only source of water supply to the park's wildlife.

### Water, Migration and the Serengeti ecosystem: Understanding the mechanisms that control the timing of wildlife migrations may prove vital to successful management (Paper III)

In this study, monthly rainfall data were analysed from January 1960 to 1989 from 232 stations and it was found that rainfall is greatest in the north-western and least in the south-eastern corner of the park, exceeding 110 cm per year in the northwest, and least in the east, at about 50 cm per year. A rain shadow downwind of the Ngorongoro Mountains makes the southern grasslands the driest area of the park. It is, therefore, clear that rainfall generally comes into the park as fronts from the north and the southeast. On the interannual basis, the south-eastern rainfall dominates in very wet years (top 10%), whereas the northern rains dominate in the dry years. Once in a while extreme years occur, in terms of having dry years. These patterns are reflected in vegetation, with the boundary between wooded savannah and grassland moving southward during the wetter decades.

The study showed that rainfall and river flow influence the movement of the migrating animal species of herbivores in the Serengeti ecosystem, but the mere timing or quantity of water cannot exactly explain when animals will begin to move. It has been observed that the migrating animals are in the south during the wet season and back in the northwest by the dry season, but as noted by the study, the move out of the south may vary by as much as three months from year to year. So water quality was brought to the equation.

The water quality study looked at water pH, salinity, DO and temperature. Among the data collected on water quality, salinity proved to be the most interesting. Generally, water salinity is highest in the grasslands in the southern portions of the park. Most water was very saline in the southern grasslands whereas sweet water prevailed at the same time in the north. During the dry season, evaporation dries out the water holes of the southern grasslands, leaving salt behind. This study argues that excessive salinity may be the trigger that starts the migration of wildebeest and zebras from their wet season range in the southern grasslands to the northwest. During 1996 and 1997 the animals were observed starting their migration when there was still plenty of forage and the surface water in the area to sustain the herds. The salinity of the water was very high. No data are available on the length of time that wildebeests and zebras can survive on such high salinity water. Studies in South Africa have shown that sheep have an upper limit of 10 ppt over the course of few months. In the arid Kalahari – Gemsbok National Park, ground water was pumped to ponds for wildlife. Where the water was hard and saline, the wildebeests left; where it was sweet, they stayed. The study, therefore, looks at salinity levels to predict the movement of migrating wildebeests and zebras in the Serengeti ecosystem and this goes along with helping the management to devise plan on how best to conserve natural resources.

### Water quantity and quality as factors driving the Serengeti ecosystem, Tanzania (Paper IV)

The study looked at the role water quantity and quality play in the Serengeti ecosystem. Thirty years data on rainfall from 232 stations, 5 years of river discharge data from 3 rivers (Mara, Grumeti and Mbalageti), 4 years of animal migration data and 4 years of water quality data at 60 sites were used to quantify the role of water in the Serengeti ecosystem. These data were analysed and showed that rainfall had large but predictable seasonal variation with unpredictable inter-annual variability. This rainfall variation explains for the changes in vegetation at decadal time scales.

Salinity, on the other hand, varies also inter-annually as a function of rainfall. As an example, in 1998 "wet year", salinity was about half that in other, normal year, suggesting that the mass of salt was diluted by about twice as much water in 1998 (an exceptionally wet year) than in 1996-1997 (normal years). An intermediate salinity occurred in 1999. This means there is an inverse relationship between wet season salinity and rainfall.

It appears, therefore, that excessive salinity may be the trigger that starts the annual mass migration of wildebeests and zebras near the end of the wet season away from the southern grasslands. The timing of these migrations varies annually by as much as four months; the onset of the migration is thus not driven by a biological clock. The study has observed that in 1996 and 1997 the migrations started when there was still plenty of edible forage and surface water in the grasslands enough to sustain the herds for a longer period. Nonetheless, the water at the time was highly saline ($S>10$ ppt). The model is based on the assumption that animals could not survive drinking it indefinitely, based on the Australian experience of grazing sheep in saline country.

The study developed the model to predict for the timing of the onset of the migration based on the hypothesis that the migration is triggered by excessive salinity. Lake Magadi was used as an overall indicator of salinity in the grassland, because it is located at the vegetation discontinuity between open grasslands to the south and wooded savannah to the north.

The model was tested for 1997, 1998 and 1999. In all cases the model was able to predict the movement of the migration based on the salinity levels at Lake Magadi with a variation of a few days. The water quality, therefore, has shown that plays a role in triggering the migration from the southern grasslands to the north at the end of wet season.

### Use of an ecohydrology model to predict the impact on the Serengeti ecosystem of deforestation, irrigation and proposed Amala Weir Water Diversion Project in Kenya (Paper V)

This study uses an ecohydrology model to predict the impacts that might be brought to the Serengeti ecosystem if the activities in Kenya of deforesting Mau Forest to give room for more agriculture, irrigation of wheat farms in the Loita Plains and proposed Ewaso Ngiro (South) Hydropower project, Amala Weir, all in Kenya. The Amala weir is to divert water from the Amala River in the Mara River catchment and divert this water to another catchment, the Ewaso Ngiro River. The water would be used to generate about 180 MW of hydro-electricity for Kenya using a three dam cascade. The water diversion rate would vary with the river discharge, peaking at 6 $m^3 s^{-2}$ during high flows, and being smaller when the river discharge is smaller ensuring a remaining discharge of at least 0.25 $m^3 s^{-2}$ at full scale operation of the project.

Serengeti ecosystem depends on the Mara River as dry season source of drinking water for the migrating wildebeest and especially during the drought. The Mara River passes through the Maasai-Mara National Reserve in Kenya and far north in the Serengeti national Park and drains most it in Kenya. The other main rivers in the Serengeti ecosystem are the Grumeti and Mbalageti Rivers. The Grumeti drains the wooded savannah of the central and northern hills much inside the park. The Mbalageti drains the southern grasslands and hills within the park. Of all the three rivers, the Mara River is the only river that flows throughout the year. It is so because it is fed by the Nyangores and the Amala Rivers that drain the forested Mau escarpment where their catchment areas constitute 60% and 40% respectively.

The main forested area is located in the Amala and Nyangores catchments in the Mau escarpment. This forested area was 752 $Km^2$ in 1973, 650 $Km^2$ in 1985 and 493 $Km^2$ in 2000. the actual forested area at present might be even smaller because of a large number of small artisanal clearings in the forest that cannot be detected by Landsat but they were seen from aerial observations. If the dry condition took place and without irrigation, the flow rate of the Mara River entering the Maasai-Mara National Reserve would probably be reduced from 2.1 to 1.3 $m^3 s^{-2}$ .

At present water permits have been issued in Kenya to pump water from the Mara River up at a maximum rate of 0.1-45 $m^3 s^{-2}$ to irrigate 520 Hectares of mechanized farms in Loita Plains. This represents up to 25% of dry weather flows in the Mara River. In addition, there are several illegal water abstractors who are not registered in Kenya.

These farms need 600 mm of water for a crop but the amounts pumped vary depending upon rainfall. Most pumping is done when it is dry and the river flow is small. Irrigation pumping might increase in the future because the Water Act allows abstractions up to 70% of the total flow, with only 30% of the water remaining in the river. As a result of deforestation and irrigation in Kenya, much smaller Mara River flow has been observed in recent years.

With deforestation, irrigation and water diversion at Amala weir, the discharge of the Mara River may cease along its 100 Km long course in the Serengeti ecosystem during a severe drought. The Amala weir water diversion project would worsen the situation by ensuring that, as the drought begins, the river will already be reduced to a series of small pools connected by a sluggish flow. The combined effects of deforestation, irrigation and the Amala water diversion will result in times of drought, in a flow rate less than $0.5\ m^3\ s^{-2}$ for 60 days at the entrance of the Maasai-Mara National Reserve. The flow rate of the Mara River will thus be smaller than the water consumption in the Serengeti ecosystem by animals drinking and evaporation. The pools of water in the Mara River bed will then dry out. Once the pools dry out, which would take two weeks after cessation of run-off, the wildlife will start dying at the rate estimated in the model to 30% per week starting from the end of the first week.

The model in the study is used to predict the consequences that might result from Kenya degazetting Mau Forest to get land for agriculture, irrigation for mechanized wheat farms in Loita Plains and generation of electricity for use in the country. However, the model predicts that if drought will not take place, the Mara River will not stop flowing. On the other hand, if severe drought takes place, the model predicts a loss of 50% to 80% of the wildebeest migration. At 50% loss there will be a recovery of the migration but it will take 20 years. At 80% loss the wildebeest will never recover to their original population. Furthermore, to help the model predict the likely effects of deforestation and water diversion in Kenya, 100 years of rainfall data will be required. In this study only 30 years of rainfall data have been used a difference of 60 more years will be needed.

### Assessment of the Environmental, Social and Economic Impacts on the Serengeti ecosystem of the Developments in the Mara River Catchment in Kenya: Socio-economic Impacts associated with the Proposed Developments (Paper VI)

This study is more focused on the socio-economic aspect to communities living along the Mara River, mostly on the Tanzanian side. The communities living along the Mara River depend on agriculture, livestock production and fishing for their survival. The production system they use is still primitive. Those with more cattle sometimes use their cattle to cultivate crops, otherwise the majority of them use hand-held hoes for cultivation. The livestock production does not follow modern animal husbandry as a result animal production per unit of animals owned is very low. In general, both agricultural and livestock productions are of subsistence level. The kind of production that is only enough to feed the family to most of the producers. Likewise, fishing methods are equally primitive. Traditional ways of fishing are still on use and this does not take them very far, in terms of good harvest of fish. Despite these primitive ways of food production, these communities are still able to sustain themselves and the lucky ones are able to sell surplus to others. The money accrued from such activities is used to meet family obligations such as sending children to school, pay needed taxes and buy family needs. The existence of the Mara River is of paramount importance to the communities and very crucial for their survival.

In this study, an overall picture of the economic status is given on both tourism, a major source of revenue generation to the nation and the agricultural policy of the country are highlighted. The study then narrows down to the effects the communities living along the Mara River will be able to face given that the developments intended to take place in Kenya will affect the flow of water on the Mara River. With the deforestation of the Mau Forest in the Kenya side has already shown some water flow problems on the Mara River based on the observations made by Park Wardens living along the river in the Serengeti National Park. This means that there is a real danger to the survival of such communities whose life entirely depends on the water flow of the river.

The Mara River is the only river in the Serengeti ecosystem that does not stop to flow throughout the year. This is so because of the Amala and Nyangores Rivers whose catchments are in the Mau escarpment. The deforestation of such forest, compounded by the irrigation farming plus generation of electric power using those rivers will definitely affect the mere flow of the Mara River, hence, the users and dependants of such water.

The study is, therefore, showing the effects the communities will suffer in their activities for survival once the Kenya development proposals will take effect.

### The Role of wetlands in wildlife migration in the Tarangire ecosystem, Tanzania (Paper VII)

Tarangire ecosystem is one of the ecosystems located in the northern tourist circuit. It is found in the Maasai steppe. Tarangire National Park is one of the parks that generate more revenue after Kilimanjaro and Serengeti National Parks. It is, therefore, one of the most important parks for tourism development in Tanzania.

Tarangire National Park, like Serengeti National Park, has migration of wildebeest and zebras but not at a scale of Serengeti ecosystem. Apart from wildebeest and zebra migration, the park has also elephants and buffaloes migrating. The movement of animals in this park is different from Serengeti. Here the animals leave the park in the wet season and come back in the dry season. The park, therefore, serves as a dry season refuge for the animals. However, not all animals leave the park, some remain in the park to be joined by those who migrate later in the season. Considering this scenario, the role of water quality was also studied to see if there was any similarity with Serengeti ecosystem.

Twenty two years of rainfall data from 6 sites, 5 years of animal migration data and 2 years of water quality at 13 sites were analyzed to quantify the role of water in the ecosystem. The parameters used for water quality were the same as in other studies. The animal migration data were based on the animal census figures produced by Tanzania Wildlife Conservation Monitoring (TWCM) and Tarangire Conservation Project (TCP). Data on the migration paths of 12 wildebeests and 13 zebras were radio-tracked by TCP.

The study found that the monthly rainfall in Tarangire varied spatially and there was inter-annual variability, just like Serengeti National Park. The rainfall was also more in the north-west of the park (10-20%) than the in the south-east. In the wet season, surface water was available throughout Tarangire ecosystem whereas in the dry season the area became arid and most remaining surface water was confined to the Tarangire National Park. Tarangire River had more DO (<75% saturation) whereas Silale wetland had less DO (>1% saturation) which increased to 20% in the wet season. In stagnant wetlands the DO was less than 30%. In all sites the waters had salinity but the level of salinity varied with the rainfall that fell in different years. There was also relationship between pH and salinity at most sites but varied from site to site. The timing of the migration of wildebeest, zebra, elephants and buffaloes suggest that these animals migrate out of the high salinity area as soon as non-saline water becomes available outside the park in the wet season. Thus, this ecosystem is somewhat similar to the Serengeti ecosystem.

### The Key Role of Water in Controlling the Migration of Large Ungulates in the Serengeti National Park, Tanzania (Paper VIII)

Rainfall, water quality and animal density data were combined to understand the migration patterns of large ungulates in the Serengeti National Park in 2001-2002. Wildebeest, topi and zebra migrated clockwise in a general north-south direction, at seasonal time scale, across much of the ecosystem controlled by water quantity (i.e. rainfall) and water quality (excess salinity). The migrating area of topi may be smaller than that of zebra and wildebeest. Grant and Thomson gazelles also dispersed in a pattern controlled by rainfall, but their dispersal range and their time scale was annual instead of seasonal. Their relative resident (i.e. non-migrating) populations varied, suggesting that one species may be more tolerant of saline, arid areas than the other one. Impala migrated east west, the animals being aggregated in the central area in the dry season, and in the Lobo area and the Western Corridor in the wet season. This migration pattern had not been studied earlier. Water quantity and qualities appear to control the migration dynamics of large ungulates in the Serengeti ecosystem.

# DISCUSSION

## Serengeti ecosystem

The data collected suggest that excessive salinity may be the clue triggering the onset of annual migration of zebras and wildebeest away from the southern plains at the end of the dry season. This movement is, however, being guided by the level of salinity in the existing water. The study has shown that since the rainfall pattern is predictable but the inter-annual rainfall is unpredictable in time and space, the amount of rainfall, which differs from year to year, is a contributing factor to the onset of animal movement. In years where rainfall is higher than normal and rains longer, the animals tend to spend more time in the southern plains. This is because the rain water dilutes the salt and the rain continues to fall the level of salt keeps on getting less making water be more palatable, hence, encouraging animals to use the forage for a much longer time. The reverse is true when rain is less and falls for a shorter period. The water becomes salty to the intolerable levels forcing the animals leave earlier even if the forage is available to sustain them for a longer time. The study, certainly, suggests that rainfall determines the salinity of the Mbalageti and Seronera Rivers, the two rivers that drain the grasslands; this in turns controls the discontinuity between open grasslands and wooded savannah. Also rainfall variations at decadal time scales are large (50% of the mean); they may shift southward or northward (i.e. downstream or upstream) the location of salinity threshold determining this discontinuity. In turn this introduces changes at decadal time scales in vegetation. The migration is not driven by a biological clock because it can vary by up to 4 months from year to year. The timing of migration is modeled on the basis of a threshold value or salinity, itself determined by rainfall and evaporation. The model was successful in predicting the timing of onset of the northward migration for 1996-2000.

In the dry season, most of the rivers in the Serengeti, with an exception of the Mara River, are ponded. The only source of water at that time is this ponded water. The quality of this water is generally poor. Most of these ponds are eutrophicated by animal dung and as a result their dissolved oxygen concentration fluctuates widely from 1% to 200% of saturation, with smaller values at depth. Stirring by hippos, crocodiles and other wildlife crossing the rivers aerate the waters and prevent anoxic conditions. In the absence of the heavy use by wildlife, most river ponds are fringed by wetlands and these act as filters removing fecal matter and stabilizing the dissolved oxygen. Wildlife can also affect the pH of the water at sites where it erodes the limestone to reach the water.

An ecohydrological model suggests that the combined effects of deforestation, irrigation and proposed Amala weir water diversion scheme in Kenya, may significantly impact the Serengeti ecosystem. In a severe drought, the wildebeest population would drop 80% from about 1,000,000 to about 200,000 animals, from which the population would remain depressed for ever. On socio-economic grounds, it is possible that in the drought , Kenya, which already suffers power shortage, may not necessarily stop irrigating and shut down the proposed hydro-electric scheme, at great economic costs to Kenya, in order to minimize possible environmental and economic costs in Tanzania. These schemes may be kept operational, and the Amala River flow may even altogether cease, and Kenya could choose to install a monitoring programme in the Serengeti ecosystem. Nonetheless, no remedial measures would be available in case of a water shortage in the Serengeti ecosystem, because there are no other water sources. Thus the key question of for the survival of the Serengeti ecosystem will be a decision by Kenya in a drought year whether to keep irrigate and generate hydro-electricity, or shut down these schemes for typically 60 days and possibly up to 110 days. Kenya economic needs would be satisfied in the first case, while environmental and economical costs would be borne by Tanzania. The communities living along the Mara River on the Tanzanian side will also be affected socially and economically based on their dependence of the Mara River for survival.

A transboundary Mara River management plan is thus needed, compatible with ecohydrology principles. The plan must take into account the cost-benefit analysis for Kenya and Tanzania on the projects proposed in Kenya using the Mara River. Presently, the economic benefits go to Kenya while the environmental and socio-economic costs such as negative impacts on tourism and community economic activities including Tanzania tourism industry, would be borne by Tanzania.

### Tarangire ecosystem

This ecosystem compares with Serengeti ecosystem. In the Serengeti national Park at the end of the wet season, the occurrence of high salinity of surface waters in the wet season dispersal areas coincide with the onset of the wildebeest migration out of the southern grasslands. In the Tarangire National Park, water is available all year round, yet all the wildebeest migrate out of the park in the wet season. This is the time when salinity also increases in at least some wetlands at least during the dry years. Visual observations suggest that the elephants aggregate preferentially around, and drunk more frequently from the Tarangire River water from low salinity areas (Salinity <2 ppt) than higher salinity areas (Salinity >2 ppt). This suggests that elephants may avoid high salinity areas when there is an alternative, less saline water for drinking. The study has also shown that wildebeest and elephants may avoid the saltiest water bodies in Tarangire National Park in the dry season. Thus water quality and water quantity may play a key role in regulating animal migration in the Tarangire ecosystem. Research is needed on whether salinity of surface waters outside the Tarangire National Park during the wet season is smaller than that inside the park, thereby triggering the migration. At the moment there are no data to support that. Similarly, there are no data to support the tolerance levels of salinity to various species of wildlife. This could be another area of research interest.

### Implications for Management and Conservation of the Ecosystems

The ability to predict the movements of these animals in both ecosystems is an important exercise to the management and conservation of these ecosystems. With a model to predict the migrations and impacts associated with some proposed developments, wildlife managers will be able to separate uncontrollable effects on wildlife, such as rainfall variations which cannot be controlled by the management, to those that can be managed. Examples would be the use of fire as a management tool to manipulate vegetation for visibility to tourists game viewing, prescribed burning as a means of controlling hot wild fires in the dry seasons from coming to the park and create fire hazards. The study also can help the wardens to plan properly the anti-poaching activities when you know the movement of animals and their timing. The study also provokes thinking on other areas of research that will be able to address important management issues of importance for managers to know for effective conservation of the resources.

### Conclusion

Although the salinity model may be the most important outcome of the study, it is proposed that further work should be done on the effects of water quality on wildlife. Water as poor as was sampled in the park has had documented negative effects on cattle, yet essentially nothing is known about how such water may affect wildlife population dynamics. Indeed 70% of the annual mortality of wildebeest occurs in the dry season as a result of unknown factors, definitely, not poaching or predation but perhaps poor water quality. The current practice or proposals to impound water to encourage concentration of wildlife populations to please tourists may negatively impact those very animals. Furthermore, drinking water for wildlife in the dry season is increasingly threatened by waste from tourist lodges in the park, cattle in the buffer zones around the park and siltation from erosion along tourist roads. It is not known how significant these influences are, but it may be vitally important that it is found out.

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# Use of an ecohydrology model to predict the impact on the Serengeti ecosystem of deforestation, irrigation and the proposed Amala Weir Water Diversion Project in Kenya

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**Abstract**

The Mara River catchment is the dry weather refuge for more than one million migrating wildebeest and zebras of the Serengeti ecosystem. The Mara River flow is affected by developments in Kenya, including deforestation, water diversion for irrigation, and the proposed Ewaso Ng'iro (South) Hydropower Project. An ecohydrology model was used to predict the likely impact of these developments on the Serengeti ecosystem. The model was forced by observed monthly rainfall in the period 1900–2000 and calibrated against observations of the number of wildebeest and lions also in the period 1960–1999. The projects are predicted to have little effect on the number of migrating wildebeest in the Serengeti until a drought occurs; historically a drought occurs about every seven years. At that time 20 to 80% of the migrating wildebeest may die, according to the severity and duration of the drought. With a 50% die-off, it may take twenty years for the population to recover; with an 80% die-off there may be no population recovery. In practice the economic benefits would go to Kenya while Tanzania would suffer most of the economic costs, i.e. the negative impact on the tourist industry. To ensure sustainable development for both Kenya and Tanzania, a transboundary Mara River management plan needs to be implemented and be compatible with ecohydrology principles for the sustainable use of aquatic resources.

**Key words:** hydrology, wildlife, savannah, drought, sustainable development, Tanzania

## 1. Site description

The 25 000 km$^2$ Serengeti ecosystem includes a national park, game reserves, game-controlled reserves and conservation areas in Tanzania and Kenya (Fig. 1). At the centre of the ecosystem is Tanzania's 14 763 km$^2$ Serengeti National Park. The Mara, Grumeti and Mbalageti Rivers, all of which flow westward to Lake Victoria, drain the park. The park is listed as a UNESCO World Heritage site and is made spectacular by the annual migration of more than 1 million wildebeest and

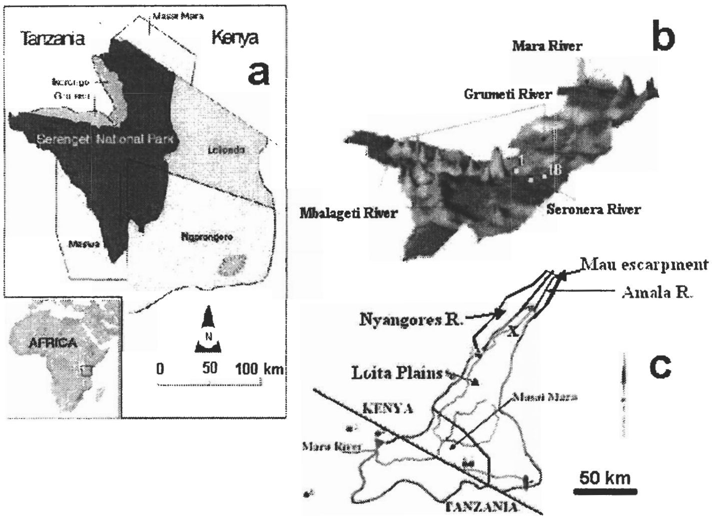

Fig. 1. (a) Map of the Serengeti National Park and surrounding game reserves, game-controlled reserves and conservation areas in Tanzania, and the Masai Mara game reserve in Kenya. (b) Three-dimensional rendering of the topography of the Serengeti National Park showing the major rivers. Stations 1–18 are key water quality sampling sites along the Seronera River, a tributary of the Grumeti River. (c) Map of the Mara River catchment showing the river gauging station and the meteorological stations (Brown *et al.* 1981). The river flows through the Masai Mara reserve in Kenya, see location map in (a). The catchment of the Nyangores and Amala rivers extend into the forested Mau escarpment. Mechanised agriculture is prevalent in Loita Plains. X and indicate the sites of, respectively, the proposed Amala water diversion weir and the Mara River gaging station at Mara Mine

200,000 zebras. As described by Sinclair and Arcese (1995), these animals disperse into the treeless southern grasslands (dotted lines in Fig. 1) of the park and the western region of the Ngorongoro conservation area during the rainy season (December through April). This area is the driest region of the park and is arid in the dry season. At the end of the wet season, these animals migrate towards the lower Grumeti River and thence to the northern region of the Serengeti National Park and the Masai Mara Reserve in Kenya; there they take refuge during the dry season (July to October).

This ecosystem may be impacted by (1) deforestation in the Mau escarpment in Kenya, (2) irrigation for mechanised wheat farming in Kenya's Loita Plains, and (3) the proposed Ewaso Ng'iro (South) Hydropower Project, also in Kenya. This scheme would divert water from the Amala River in the Mara River catchment at a site shown in Fig. 1, and divert this water to another catchment, the Ewaso Ng'iro River (Fig. 2a). This water would be used to generate about 180 MW of hydroelectricity for Kenya using a three dam cascade (Oletukat, Leshota and Oldorko). The water diversion rate would vary with the river discharge, peaking at 6 $m^3 s^{-1}$ during high flows, and being smaller when the river discharge is smaller ensuring a remaining discharge of at least 0.25 $m^3 s^{-1}$ at full-scale operation of the project (EAC 2000). Compared to the mean annual flow, the maximum water diversion rate (6 $m^3 s^{-1}$) is 33% during a dry year and only 9% during a wet year. This may have formed the basis of the reasoning that the effect of the proposed water diversion on the Serengeti ecosystem is too small to be included in the cost-benefit analysis (Knight Piesold 1992).

In this paper, an ecohydrology model is used to assess the likely impact of deforestation, irrigation and the proposed Amala weir on the Serengeti ecosystem. The model suggests that the Serengeti ecosystem will be severely affected. It is suggested that a cost-benefit analysis should be undertaken to address transboundary issues and that a Mara River transboundary management plan be set up that is compatible with ecohydrology principles for the sustainable use of aquatic resources.

## 2. Hydrology of the Serengeti ecosystem

The main dry-season source of drinking water for migrating wildlife in the Serengeti ecosystem is the Mara River, especially in a drought. This river passes through the Masai Mara reserve in Kenya (Fig. 1) and the far north of the Serengeti National Park, at 1300 to 1500 m elevation,

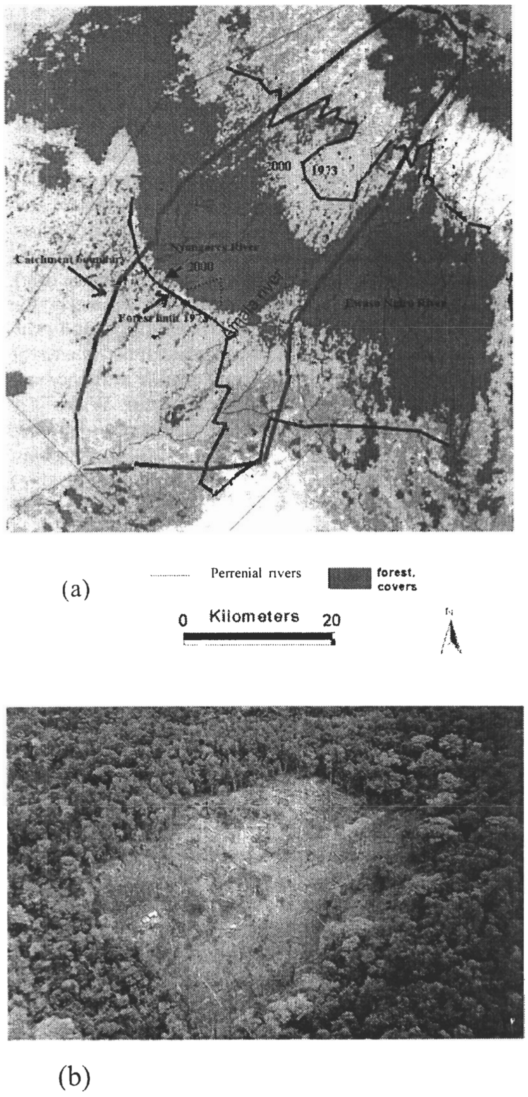

**Fig. 2.** (a) February 12, 2000, Landsat photograph showing the catchment boundary of the Amala and Nyangores rivers and, in grey, the forested area. This includes natural and regrowth forest. This catchment area is surrounded to the east by the Ewaso Ngiro River that flows south-eastward to Lake Natron, and to the west by the Gucha Migori River (not shown) that flows westward towards Lake Victoria. The forest boundaries in 1973 are also shown. The dots indicate areas proposed by the Kenya government for forest excision in 2001. This Landsat photograph does not reveal the small lots deforested within the main body of the forest. (b) is an aerial photograph of a small lot in the process of being deforested in the middle of the Amala forest catchment in the Mau escarpment during an aerial survey in April 2002. Such lots were found to be numerous throughout the Amala forest

and drains a total of 10 300 km$^2$, most of which is in Kenya. The other main rivers in the Serengeti ecosystem are the Grumeti and Mbalageti Rivers. The Grumeti River has a total catchment area of 11 600 km$^2$ and drains the wooded savannah of the central and northern hills, much inside the park's boundaries. Further south, the Mbalageti drains an area of 2,680 km$^2$ of treeless grasslands and hills lying between 1,600 and 1,660 m elevation, nearly all within the park (Wolanski, Gereta 2001).

Reliable rainfall data are available from 1960 onwards. Rainfall is generally greatest in the north-western corner of the park and in the Masai Mara, exceeding 110 cm year$^{-1}$; it is smallest in the southeast at about 50 cm year$^{-1}$. Rainfall varies inter-annually by a factor of about four between extreme wet and dry years. This rainfall variability generates wide seasonal and interannual fluctuations in river runoff (Brown *et al.* 1981).

Potential evaporation is about 173 cm year$^{-1}$, the maximum monthly evaporation is 16.9 cm in October in the dry season (Woodhead 1968). From a water balance study, Brown *et al.* (1981) estimated that potential evapotranspiration was equal to about 71% of free water evaporation on an annual basis.

The Mara, Grumeti and Mbalageti Rivers were gauged daily from 1970 to 1974 (Brown *et al.* 1981), all near the point where they leave the Serengeti National Park. Mara Mine, the location of the hydrographic station in the Mara River, is shown in Fig. 1. In peak flows, these rivers all carried a large amount of water; the peak observed flood of the Mara, Grumeti and Mbalageti rivers was, respectively, about 1,000 m$^3$ s$^{-1}$, 200 m$^3$ s$^{-1}$ and 40 m$^3$ s$^{-1}$. After the rains, discharges decreased exponentially to base flows. The Mara River always kept flowing even in the dry season, whereas the Grumeti and Mbalageti Rivers declined to zero flow in a dry year (1973). In the dry season the Grumeti and Mbalageti Rivers consist of a series of stagnant, shallow, muddy pools tens of meters long in the dry season. The Mara River and these stagnant pools along the Grumeti and Mbalageti Rivers are the only source of drinking water for wildlife during the dry season. However most of these pools dry out during a drought year, defined as a year when the yearly rainfall is at least 25% below average. In the period 1960–2000, this occurred 6 times, i.e. once every 7 years or so. However drought years can follow each other. At such times the Mara River, because so far it always has had water, is the last refuge for migrating wildlife of the Serengeti ecosystem (Gereta, Wolanski 1998).

The reason the Mara River always keeps flowing is that it is fed by the Nyangores and the Amala rivers that drain the forested Mau escarpment where their catchment area constitute respectively 60 and 40%.

For the period 1970–1974, the mean annual flow rate of the Mara River at Mara Mine was about 36 $m^3 s^{-1}$, and this varied markedly from year to year. Reliable river gauging data (Brown *et al.* 1981) during 1970–1974 showed a minimum mean annual flow rate of 18 $m^3 s^{-1}$ in 1973 and a maximum mean annual flow rate of 67 $m^3 s^{-1}$ in 1974. A mean monthly discharge less than 5 $m^3 s^{-1}$ was observed during four months in the period 1970–1974. The observed daily river discharge was calculated from daily measurements of the water level and a rating curve comprising 73 points. This rating curve has a maximum observed discharge of 216 $m^3 s^{-1}$ and a minimum discharge of 1.9 $m^3 s^{-1}$. There was a high incidence (12%) of missing records. In the period 1970–1974, a mean daily flow less than 6 $m^3 s^{-1}$ occurred during 350 days, a mean daily flow less than 2 $m^3 s^{-1}$ occurred 115 days in total or about 23 days per year.

In 1973, a relatively dry year, the mean monthly Mara River discharge at Mara Mine was about 0.9 $m^3 s^{-1}$ for two consecutive months. There are no data on the Mara River discharge during a severe drought. Drought years on record in the rainfall data period 1960–1999 included 1966, 1969, 1993, 1994, 1995; in those years rainfall was below the long–term mean by, respectively, 28, 33, 41, 35 and 32%.

## 3. Impact of deforestation, irrigation and the Amala weir on the water budget: hydrologic predictions

For the period 1970–1974, a comparison of the flow rates upstream, at the entrance of the Masai Mara reserve (Knight Piesold 1992), with those downstream, at Mara Mine (Brown *et al.* 1981) reveals that water was lost at rate of 1.2 $m^3 s^{-1}$ in the dry season. This loss is due to evaporation over the 100 km length of the river between those two points, and wildlife drinking. When forage is dry, wildebeest and zebra drink about 20 litres $day^{-1}$ $animal^{-1}$ (Church, Pond 1988).

The main forested area is located in the Amala and Nyangores catchments in the Mau escarpment. As revealed by Landsat images (Fig. 2a), this forested area was 752 $km^2$ in 1973, 650 $km^2$ in 1985, and 493 $km^2$ in 2000. The actual forested area at present is even smaller because of a large number of small artisanal clearings in the forest (Fig. 2b) that Landsat cannot detect. If the 1973 meteorological conditions were repeated, and without irrigation, the flow rate of the Mara River entering the Masai Mara reserve would probably be reduced from 2.1 to 1.3 $m^3 s^{-1}$ (Dwasi 2002).

At present water permits have been issued to pump water for the Mara up at a maximum rate of 0.1–45 $m^3 s^{-1}$ to irrigate 520 hectares of mechanised farms in Loita Plains (see location map in Fig. 1). This represents up to 25% of dry weather flows in the Mara River. In addition there are several illegal water abstractors who are not registered in Kenya due to lack of monitoring of activities on this river (J. Anakeya, pers. com.). These farms need 600 mm of water for a crop but the amounts pumped vary depending upon rainfall. Most pumping is done when it is dry and the river flow small. Irrigation pumping may increase markedly in the future because the Water Act (Chapter 372) of Kenya allow abstractions of up to 70% of the total flow, with only 30% of the water remaining in the river. Possibly as a result of deforestation and irrigation in Kenya, much smaller Mara River flows in the dry season have been observed in recent years by park wardens in the Serengeti National Park (J. Nyamhanga, pers. com.).

Thus, with deforestation, irrigation and water diversion at Amala weir, the discharge of the Mara River may cease along its 100 km long course in the Serengeti ecosystem during a severe drought. The Amala weir water diversion project would worsen the situation by ensuring that, as the drought begins, the river will already be reduced to a series of small pools connected by a sluggish flow. By contrast, during the 1993 drought, when there was negligible abstraction of water for irrigation and no Amala weir water diversion, this situation occurred only at the end of the drought. The combined effect of deforestation, irrigation and the Amala water diversion will result, in times of drought, in a flow rate less than 0.5 $m^3 s^{-1}$ for 60 days at the entrance of the Masai Mara Reserve. The flow rate would be about 0.25 $m^3 s^{-1}$ if the Amala weir blocks all the flow. The flow rate of the Mara River will thus be smaller than the water consumption in the Serengeti ecosystem by (1) the animals drinking and (2) evaporation. The pools of water in the Mara River bed will then dry out. Once the pools dry out, which would take about two weeks after cessation of runoff, the wildlife will start dying at a rate estimated in the model (see below) to be 30% per week starting from the end of the first week.

## 4. Impact of the Amala weir on the Serengeti ecosystem: ecohydrology model predictions

The effect of the deforestation, irrigation and the Amala weir water diversion scheme on the Serengeti ecosystem was quantified using two models run in parallel. The food availability was calculated by an improved version of the ecohydrology model of Gereta and Wolanski (2002 in press). The water availability was controlled by the hydrologic model of Brown *et al.* (1981), and only kicks in during a drought to estimate if the animals have insufficient water for drinking, this did not happen in historical conditions 1960–2000 for which data are available.

The ecohydrology model has three trophic layers. The bottom trophic layer is the grass, which grows when watered and withers in the absence of rainfall. The grass is grazed by herbivores. The herbivores calve once a year. The herbivores can die from poaching (for which data are available from the game warden), starvation (in the dry seasons) and disease (mainly in the dry season; Mduma *et al.* 1999). The carnivores prey upon the herbivores. The model ecosystem is divided in two areas. Area A (the southern grasslands) is used by the herbivores in the wet season. Area B (the northern region along the Mara River in the park and in the Masai Mara Reserve) is the dry season refuge for the herbivores. The herbivores migrate from area A to area B, many transiting through the lower Grumeti River, when salinity is excessive in area A (Wolanski, Gereta 2001); they return to area A at the start of the wet season. The migration results in an additional mortality of the herbivores.

The model equations are of the Lotka-Volterra type for biomass at each trophic level, they express mass conservation. The model considers separately zones A and B and the migration pathways. The equations are:

1. ZONE A

GRASS:

$dG/dt = \{g\,G\,R/20,\ \text{if}\ R > 20 \quad \} - h\,G_o\,H/H_o$

$\qquad \{-2\,g\,G\,(5-R)/20,\ \text{if}\ R<5\}$

ADULT HERBIVORES:

$dH/dt = \{s_A\,H(G-G_o)/G_o, (\text{if}\ G<G_o)\} - d_1\,H - p\,H\,C/C_o$

$\qquad \{0 \qquad , (\text{if}\ G>G_o)\}$

YOUNG HERBIVORES

Before calving $Y = 0$

In the calving month $Y = 0.5\,r\,H$

Thereafter

$dY/dt = \{s_A\,Y(G-G_o)/G_o, (\text{if}\ G<G_o)\} - 3d\,Y - p\,Y\,C/C_o$

$\qquad \{0 \qquad , (\text{if}\ G>G_o)\}$

PREDATORS

$dC/dt = \{0 \qquad , (\text{if}\ H > H_o)\} + (b - d_3)\,C$

$\qquad \{-\,d_4\,C\,(H_o - H)/H_o, (\text{if}\ H<H_o)\}$

2. MIGRATION

When migrating $A \Rightarrow B$ $\quad H(\text{new}) = q\,(H(\text{old}) + Y/r)$

$\qquad Y(\text{new}) = 0$

When migration $B \Rightarrow A$ $\quad H(\text{new}) = q\,H(\text{old})$

$\qquad Y(\text{new}) = 0$

3. ZONE B

GRASS:

$dG/dt = \{g\,G\,R/20,\ \text{if}\ R>20 \quad \} - h\,G_o\,H/H_o$

$\qquad \{-2\,g\,G\,(5-R)/20,\ \text{if}\ R<5\}$

ADULT HERBIVORES:

$dH/dt = \{s_B\,H(G-G_o)/G_o, (\text{if}\ G<G_o)\} - d_2\,H - p\,H\,C/C_o$

$\qquad \{0 \qquad ,(\text{if}\ G>Go)\}$

YOUNG HERBIVORES

$\qquad Y = 0$

PREDATORS

$dC/dt = \{0 \qquad , (\text{if}\ H>H_{o1})\} + (b - d_3)\,C$

$\qquad \{-d_4(H_{o1} - H)C/H_{o1}, (\text{if}\ H<H_{o1})\}$

where R – rainfall (mm/month), G – biomass of grass, H – biomass of adult herbivores, Y– biomass of young herbivores, r – calf to adult herbivore weight ratio in April, C – biomass of carnivores, $G_o$ – equilibrium G preventing starvation of herbivores when $H = H_o$, $s_A$ – starvation rate of herbivores in zone A if $G<G_o$, $s_B = s_A(1+H/H_o)$ – starvation rate of herbivores in zone B if $G<G_o$, h – rate of removal of grass by herbivores at equilibrium, g – growth rate of G, p – predation rate of the herbivores at equilibrium, q – fraction of herbivores that survive the migration, $d_1$ – death rate of herbivores in region A, $d_2$ – death rate of herbivores in region B, b – birth rate of carnivores, $d_3$ – death rate of carnivores (excluding starvation), $C_o$ – equilibrium carnivore biomass, $H_o$ – equilibrium herbivore biomass to prevent carnivores to starve when $C = C_o$, $d_4$ – death rate of carnivores at equilibrium, t = time (starting from January 1960 when monthly rainfall data are available), dt – model time step (1 month), $H_{o1}$ – $0.3H_o$. All rates are expressed as $\text{month}^{-1}$.

Observed monthly rainfall data from 1960 to 1999 were used to drive the model. Data are available on the number of wildebeest and lions between 1960 and 1999 (C. Packer, E. Gereta, unpubl.; Serneels, Lambin 2001). The model was successful (Fig. 3) in reproducing these observations. The model was also successful in reproducing the 20% die-off of wildebeest during the 1993 drought (Mduma *et al.* 1999). Predation by lions is predicted to be of secondary importance for the herbivore population dynamics in the Serengeti ecosystem. The model reproduces Mduma *et al.* (1999) observations that the population of herbivores is limited by the availability of water and forage, and thus fluctuates inter-annually as a result of rainfall. It is apparent that the population of wildebeest did not reach a quasi-steady state (i.e. a population $\geq 1$ million animals) until 1976.

To help predict the likely effects of deforestation and water diversion in Kenya, the model requires 100 years of rainfall data. The rainfall data from 1960 to 1999 were used. To fulfil the data set length, a further 60 years of data is required. These were simulated using the rainfall conditions from 1900 to 1959, for which data are available for Lake Victoria catchment (Mnaya,

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# ASSESSMENT OF THE ENVIRONMENTAL, SOCIAL AND ECONOMIC IMPACTS ON THE SERENGETI ECOSYSTEM OF THE DEVELOPMENTS IN THE MARA RIVER CATCHMENT IN KENYA:

## Socio-economic impacts associated with the proposed developments

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## ABSTRACT

The implementation of Mau forest degazettement, irrigation of mechanized farming in the Loita Plains of Kenya together with the development of the Amala Weir hydropower project in Kenya will obviously affect the ecosystems of the surrounding region, and with it, the socio-economic dynamics of the people of the region. Tourism industry will also be seriously affected, as it is the main source of revenue for Serengeti National Park. The major type of tourism in Tanzania is nature-based and national parks are the only providers of such experience.

Tanzania could lose up to 125,000 (about 40%) tourists or visitors currently visiting Serengeti. Given the average annual rate of increase of 12.3%, the figure would have grown to 397,330 by the year 2011. Furthermore, the other parks of Northern Tourist Zone would get very few visitors, if any, since most of them, if not all, do come because of the famous Serengeti. In effect, therefore, Tanzania may lose about 75% of all the tourists coming to the country. This works out to be about 238,814 visitors by 2001 statistics and the figure would grow to about 510,828 by the year 2011.

In terms of revenue generation Serengeti National Park will outright lose more than USD 6,040,290 and this is projected to increase to USD 40,636,057 by the year 2011 at an average annual rate of 21%. Considering the Northern zone aspect, the loss would be USD 13,932,938 by 2001 statistics and would grow to USD 70,488,117 by the year 2011, the average annual rate being 17.6%.

Serengeti's existing workforce of about 385 people will lose their jobs as well as their income amounting to about USD 836,000. This will mean suffering not only to themselves, but also to their dependants, particularly spouses and children.

Communities living around the national park will no longer benefit from the support they have been getting in terms of community based development projects. Communities around Serengeti National Park will be losing an average of about USD 40,000 per year. The Government will lose tax revenues it has been getting from the operations of the park. Serengeti District, for example, will be losing an annual tax income of more than USD 1.0 million from the operations of the Serengeti National Park.

Serengeti National Park has been getting significant amounts of donations and assistance from various countries and institutions. If the park collapses the donations and assistance will cease. As an example, the donation to Serengeti National Park from Frankfurt Zoological Society during the first half of 2000 was close to USD 1,440,000. This amount would have been lost.

The majority of people living in this region engage in agriculture and livestock keeping as their economic activities. The Mara River supports these activities. In the event of serious and prolonged drought, this region will lose about USD 17 million worth of crops, USD 25 million worth of livestock and annual milk production worth USD 960,000. Apart from these monetary values, livestock in this part of the country is associated with other intrinsic cultural and social values, which will also be lost. The fisheries sub-sector will also be affected with an expected loss of foreign earnings

amounting to the equivalent of USD 65 million. Other development projects impacting on health, water supply etc. based on Mara River will also be adversely affected.

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## INTRODUCTION

The government of Kenya is proposing to develop a hydroelectric power scheme, Amala Project and Degazettement of the Mau Forest to provide land for agriculture. Based on that decision by the Kenya Government, some concerns and fears have been expressed by both conservationists and Tanzania Government, in general, on the present and future position of the Serengeti ecosystem if implemented. These developments will, therefore, affect the ecosystem and the surrounding areas in a way, which will have consequences environmentally, socially and economically. More specifically, Serengeti National Park, with the only intact big mammal migration in their thousands is likely to collapse.

The proposed Amala Project in the Ewaso Ngiro (South) River based in Kajiado and Narok Districts in Kenya consists of a cascade development of three hydroelectric schemes at Oletukat (36 MW), Leshota (54 MW) and Oldorko (96 MW). Altogether, this project along the Ewaso Ngiro River will have the capacity to produce 186 MW of electric power with the support scheme to transfer water from the Amala River to the headwaters of Ewaso Ngiro River. The Amala River flows southwards into Mara River, which originates from the southern slopes of the Mau escarpment in Kenya and flows through the Masai-Mara Game Reserve, the Serengeti National Park in Tanzania and eventually drains into Lake Victoria. Diversion of water from the Amala River will lead to the possible decline of water flow in the Mara River.

The Mau Forest, also in Kenya, forms very crucial water catchments for some of the largest rivers in Kenya that feed such lakes as Nakuru, Bogoria, Victoria and Natron. Again the Mara River, the only permanent water source in the Masai-Mara Game Reserve and Serengeti National Park, originates in the Mau Forest. The forest also supports the flamingos not only directly through Lake Nakuru in Kenya, which is a very important feeding site; but also indirectly through Lake Natron in Tanzania, the only known breeding habitat for the flamingos. The degazettement of the Mau Forest in Kenya, will, therefore, pose a threat to these affected areas and their environments.

It is obvious that the 25,000 Km$^2$, which forms the Serengeti Ecosystem covering Serengeti National Park, Maswa, Grumeti and Ikorongo Game Reserves, Ngorongoro Conservation Area and Loliondo Game Controlled Area in Tanzania and the Masai-Mara Game Reserve in Kenya will be impacted by the proposed developments in Kenya (Fig. 1).

It is noted that the engineering feasibility study of the hydroelectric project (Knight Piesold 1992) argued that for a typical year, the project would not modify the mean discharge of the Mara River and therefore the project would not impact the Serengeti ecosystem. However, this prediction is flawed. Firstly, no prediction of the availability of water in the Mara River during a drought was carried out by Knight Piesold (1992) because the data used in the study spanned over the years when no severe drought occurred. Secondly, the study by Knight Piesold (1992) did not adequately calculate the availability of water in the Mara River as it flows through the Serengeti ecosystem because the study neglected the impact of deforestation and irrigation in Kenya. Thirdly, the study did not include the additional impact on the availability of water resulting from the likely climate changes from the enhanced greenhouse effect.

The hypothesis being tested is the Mau Forest degazettement, irrigation of the mechanized farming in the Loita Plains and the development of the Amala weir hydropower project, all in Kenya, will affect the socio-economic existence of the communities living along the Mara River. What are the impacts to the community activities as a result of such developments.

## METHODS

Literature search and reviews of notable Tanzania government relevant legislation and institutional framework on tourism and agriculture have been studied. Field surveys, interviews and field visits to district authorities and rural communities of Serengeti, Musoma Rural, and Tarime Districts where the Mara River is being shared by communities were conducted and observations were made on the existing position of the river.

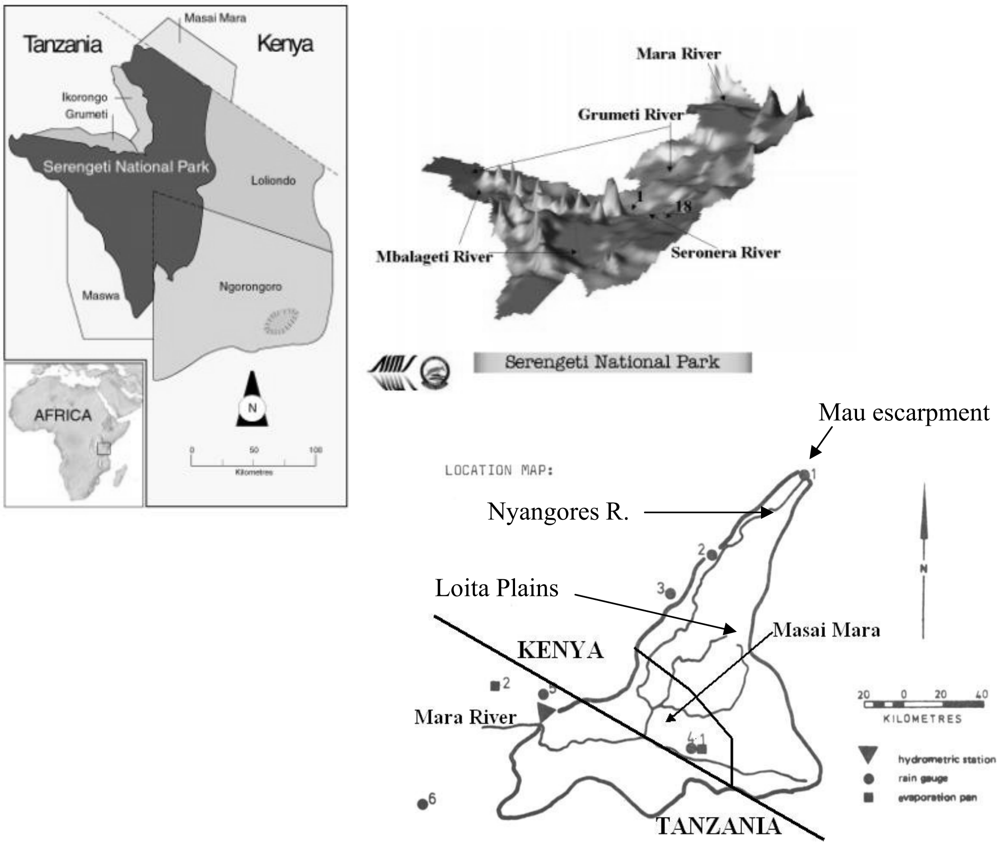

**Fig. 1.** (a) Map of the Serengeti National Park and surrounding game reserves, game controlled areas and the Ngorongoro Conservation Area in Tanzania, and the Masai Mara Reserve in Kenya. (b) Three-dimensional rendering of the topography of the Serengeti National Park showing the major rivers. Stations 1-18 are key water quality sampling sites along the Seronera River, a tributary of the Grumeti River. (c) Map of the Mara River catchment showing the river gauging station and the meteorological stations (Brown *et al.* 1981). The river flows through the Masai Mara Reserve in Kenya, see location map in (a). The catchment of the Nyangores and Amala rivers extend into the forested Mau escarpment. Mechanised agriculture is prevalent in Loita Plains. X and ∇ indicate the sites of, respectively, the proposed Amala water diversion weir and the Mara River gauging station at Mara Mine.

## RESULTS

### International Tourism

International tourism and business travelling are among the world's largest and most rapidly expanding economic activities. As an earner of foreign exchange, tourism and travelling have become increasingly important when compared to other exports in developing countries. In 1998, for example, international tourism arrivals attained a growth rate of 2.4 percent to reach a level of 625 million tourists. The corresponding tourism receipts amounted to US $ 436 billion. In the ten years (1989 – 1998) period, arrivals worldwide grew by an average annual rate of 4.3 percent. International tourism receipts (excluding transport) increased by a corresponding 8.1 percent per annum over a 10 year period as shown in Table 1.

**Table 1: International Tourist Arrivals and Receipts World-wide during the years 1989 – 1998**

| Year | Arrivals (million) | % Arrival Change | Receipts US $ billion | % Annual change |
|---|---|---|---|---|
| 1989 | 426 | 8.02 | 221 | 8.31 |
| 1990 | 458 | 7.47 | 269 | 21.54 |
| 1991 | 464 | 1.25 | 278 | 3.21 |
| 1992 | 503 | 8.49 | 315 | 13.52 |
| 1993 | 519 | 3.12 | 324 | 2.85 |
| 1994 | 550 | 6.05 | 354 | 9.23 |
| 1995 | 565 | 2.73 | 405 | 14.44 |
| 1996 | 597 | 5.49 | 436 | 7.52 |
| 1997 | 611 | 2.39 | 436 | 0.09 |
| 1998 | 625 | 2.37 | 436 | 2.01 |

*Source: World Tourism Organization (WTO) A Report on "Tourism Market Trends in Africa."*

### The Performance of the Tourism Industry in Tanzania

The performance of the tourism industry in Tanzania, particularly in the light of the above mentioned key industry characteristics, has generally been impressive over the past ten years. The total number of tourist visitors grew four fold in ten years, from 153,000 in 1990 to 627,325 in 1999 before decreasing to 502,000 in the year 2000. This implies an annual growth rate in the number of tourists of 13.56%. Total tourist bed nights in hotels rose from 1.03 millions in 1991 to 3.38 million in 1999.

During the period under consideration the foreign exchange earnings went up more than ten times, from USD 65 million (1990) to USD 739.1 million (2000); giving an average rate of increase, in foreign exchange earnings, of 28.12%. During this period the average daily expenditure per tourist increased from USD 72.42 (1991) to USD 152.00 (1999). In the year 2000, the foreign exchange earnings increased to USD 739.1 million, from USD 733.3 million in 1999, despite the decrease in the number of tourists as indicated above.

Tourism activities in the country contributed 13.15% to the Gross Domestic Product in 2000, and 12.25% in 2001. In terms of foreign exchange generation, tourism accounts for over 50% of the total foreign exchange earnings in the country. On the other hand, employment in the industry, through its chain of actors, rose from 45,000 people in 1991 to 148,000 in 1999. Table 2 presents a detailed scenario of the performance of the tourism industry in Tanzania.

The contribution of tourism to the Gross Domestic Product is by no means mean. It stands at an annual average of about 15%, being second only to the mining industry in terms of its rapid growth rate as documented in the National Economic Survey for the year 2000. There is no doubt therefore that the industry is one of the key drivers of the country's economy.

**Table 2: Tourism Industry Performance**

| Item | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 153.0 | 186.8 | 201.7 | 230.2 | 261.6 | 295.3 | 326.2 | 360.0 | 482.3 | 627.3 | 502.0 |
| 2 |  | 171.8 | 187.6 | 216.3 | 238.5 | 268.2 | 296.2 | 345.0 | 457.3 | 564.6 |  |
| 3 | 65.0 | 94.73 | 120.04 | 146.84 | 192.10 | 259.44 | 322.37 | 392.41 | 570.00 | 733.3 | 739.1 |
| 4 |  | 507.0 | 595.0 | 637.9 | 734.3 | 878.5 | 1090.0 | 1181.8 | 1169.0 |  |  |
| 5 |  | 7.0 | 7.0 | 7.1 | 7.1 | 7.2 | 7.3 | 7.5 | 7.6 | 7.7 |  |
| 6 |  | 72.42 | 85.00 | 89.80 | 103.40 | 122.00 | 135.00 | 145.00 | 155.50 | 152.00 |  |
| 7 |  | 205 | 207 | 198 | 208 | 210 | 212 | 213 | 215 | 321 |  |
| 8 |  | 5484 | 6150 | 6100 | 6335 | 6935 | 6970 | 7470 | 7500 | 9575 |  |
| 9 |  | 1.03 | 1.13 | 1.32 | 1.45 | 1.67 | 1.87 | 2.25 | 2.94 | 3.38 |  |
| 10 |  | 9878 | 10963 | 10860 | 11335 | 12145 | 12348 | 13248 | 13400 | 17235 |  |
| 11 |  | 56 | 56 | 56 | 56 | 57 | 56 | 56 | 60 | 64 |  |
| 12 |  | 45.0 | 50.0 | 66.0 | 86.0 | 96.0 | 100.0 | 110.0 | 132.0 | 148.0 |  |

*Source: The Economic Survey 2000. The Planning Commission.*
*Key: 1 = Total number of tourists (thousands)*
*2 = Number of tourists in hotels (thousands)*
*3 = Total earnings (in USD millions)*
*4 = Average earnings per tourist (in USD)*
*5 = Average number of bed nights per visit (in days)*
*6 = Average daily expenditure per tourist (in USD)*
*7 = Number of hotels (number)*
*8 = Number of hotel rooms (number)*
*9 = Tourist bednights in hotels (millions)*
*10 =Number of hotel beds (Number)*
*11 = Average hotel occupancy rate per year*
*12 = Number of employees in the tourist industry (thousands)*

According to industry estimates, over 75% of tourists visiting Tanzania are Northern Tourist Circuit bound, where Serengeti, Ngorongoro Conservation Area, Tarangire, Arusha and Lake Manyara national parks are the major tourist attractions. It is worth noting at this juncture that Tanzania offers a very limited tourist product, based on a limited resource, that is, wildlife, which is concentrated in the Northern circuit. This implies that Tanzania's tourist industry is dominated by the safari element as neither the beach nor the sight seeing tourist products are yet to be well developed. The country's tourist industry is thus highly dependent on wildlife.

In view of the strategic importance of the tourist industry in the national economy, the Government gives it the attention and focus it deserves. The recently revised tourism policy (1999) and The Integrated Tourism Master plan (1996) is a clear testimony to this effect.

### Tourist Visitors

About 75% of the tourist visitors in the country go to the Northern Tourist Circuit, which comprises of Serengeti, Lake Manyara, Tarangire, Ngorongoro, Kilimanjaro and Arusha national parks. Available documentation reveals that Serengeti is the dominant player in the Northern circuit accounting for about 40% of the tourist activities in the country. This is largely explained by its international fame, as it is one of the best known in the world.

Going by the available statistics as shown in table 3 below, the total visits to the national parks in 1995 were 431506. Serengeti's share by then was 104672 visits, which is 24% of the total visits. In the year 2000 the total figure for all parks was 777533, with Serengeti's share rising to 309517 visits, which is about 40%. On the average the number of the visits were increasing at an annual rate of 26.7%. In terms of the visitors to Serengeti, the average annual rate of increase for the period 1987/88 to 2000/01 was 12.3%. Details are given in Table 4.

### Revenue Generation

The Serengeti National Park generated a total of USD 3,547,778 in the year 1995/96 and this figure increased to USD 6,040,291 in the year 2000/01. These figures when compared to the TANAPA totals of USD 10,270,002 for 1995/96 and USD 18,577,250 for 2000/01 show that the average performance of Serengeti Park, over the years, was over 30% of the totals. Additionally, it will be noted that revenues for Serengeti National Park and TANAPA were increasing at an annual rate of 21.0% and 17.6% respectively. Table 7 shows the visitor and revenue Statistics for TANAPA and Serengeti National Park for the period 1987/88 to 2000/01.

It is worth noting, at this stage that in terms of revenue generation Serengeti National Park is second to only Kilimanjaro National Park, and the two parks account for about 77% of the TANAPA's total revenue. Actually the two parks do support the operations of the other parks financially. Table 5 gives a comparison of the revenues generated by the various parks during the year 2000/2001.

**Table 3: Visits to the National Parks**

| Park/ Years | N / % | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Serengeti | N | 104,672 | 110,334 | 116,993 | 123,652 | 202,858 | 309,317 |
| | % | 24.3 | 24.4 | 24.5 | 24.7 | 32.3 | 39.8 |
| Manyara | N | 56,825 | 58,780 | 60,735 | 62,690 | 73,820 | 85,775 |
| | % | 13.2 | 13.0 | 12.7 | 12.5 | 11.8 | 11.0 |
| Ngorongoro | N | 172,091 | 178,020 | 185,468 | 192,917 | 200,800 | 208,249 |
| | % | 39.9 | 39.3 | 38.9 | 38.5 | 32.0 | 26.8 |
| Arusha | N | 22,153 | 24,276 | 26,821 | 29,366 | 45,880 | 48,425 |
| | % | 5.13 | 5.36 | 5.62 | 5.86 | 7.31 | 6.23 |
| Mikumi | N | 11,843 | 10,431 | 7,031 | 3,630 | 12,784 | 10,609 |
| | % | 2.74 | 2.3 | 1.47 | 0.75 | 2.04 | 1.36 |
| Ruaha | N | 4,269 | 5,098 | 5,683 | 6,268 | 10,936 | 11,523 |
| | % | 0.99 | 1.13 | 1.19 | 1.25 | 1.74 | 1.48 |
| Tarangire | N | 44,755 | 49,880 | 57,097 | 64,315 | 56,724 | 67,720 |
| | % | 10.4 | 11.0 | 12.0 | 12.8 | 9.04 | 8.71 |
| Kilimanjaro | N | 14,468 | 15,423 | 16,378 | 17,333 | 22,560 | 33,515 |
| | % | 3.35 | 3.41 | 3.43 | 3.46 | 3.60 | 4.31 |
| Gombe | N | 430 | 670 | 910 | 1,150 | 961 | 2,201 |
| | % | 0.1 | 0.15 | 0.19 | 0.23 | 0.15 | 0.28 |
| **TOTAL** | **N** | **431,506** | **452,912** | **477,116** | **501,321** | **627,325** | **777,534** |

*Source: The Economic Survey, 2000. The Planning Commission.*

**Table 4: Visitor and Revenue Statistics for Serengeti National Park and TANAPA**

| Years | SENAPA | | TANAPA | |
|---|---|---|---|---|
| | Visitors | Revenue (USD) | Visitors | Revenue (USD) |
| 1987/88 | 47,625 | 647,984 | 132,876 | 2,534,481 |
| 1988/89 | 55,176 | 598,887 | 152,867 | 2,157,795 |
| 1989/90 | 59,069 | 1,194,472 | 177,941 | 2,898,975 |
| 1990/91 | 66,380 | 1,241,982 | 182,868 | 4,383,555 |
| 1991/92 | 79,713 | 1,620,477 | 209,447 | 4,872,814 |
| 1992/93 | 80,804 | 1,848,421 | 212,479 | 5,545,418 |
| 1993/94 | 105,751 | 2,129,450 | 263,527 | 6,624,330 |
| 1994/95 | 91,234 | 3,097,655 | 237,326 | 8,903,140 |
| 1995/96 | 98,501 | 3,547,778 | 259,905 | 10,270,002 |
| 1996/97 | 96,886 | 3,831,727 | 284,656 | 12,215,304 |
| 1997/98 | 90,793 | 4,631,247 | 268,902 | 14,218,208 |
| 1998/99 | 198,934 | 4,521,690 | 367,022 | 14,465,553 |
| 1999/00 | 113,867 | 5,119,417 | 293,036 | 16,787,204 |
| 2000/01 | 124,553 | 6,040,291 | 318,419 | 18,577,250 |

*Source: TANAPA – Planning Unit. (1987/88 figures were only for Arusha and Gombe Parks)*

**Table 5: Park-wise Revenue Records for 2000/2001**

| Park | Revenue in USD |
|---|---|
| Arusha | 648,889 |
| Gombe | 85,478 |
| Katavi | 21,703 |
| Kilimanjaro | 8,164,945 |
| Manyara | 1,460,782 |
| Mahale | 57,862 |
| Mikumi | 154,924 |
| Ruaha | 209,922 |
| Rubondo | 13,784 |
| Serengeti | 6,040,291 |
| Tarangire | 1,486,040 |
| Udzungwa | 20,614 |
| **TOTAL** | **18,365,234** |

*Source: TANAPA Planning Unit Data Survey, 2001*

### Employment

In terms of direct employment Serengeti National Park has the largest permanent work force of all the parks. The Park's work force, by 2000/01 statistics, consists of 351 males and 34 females, a total of 385 staff. The Park's work force constitutes 29.3% of TANAPA's total workforce, which is 1313 employees. The Park's annual wage bill including related allowances is about TAS 820.8 million for permanent employees and TAS 15.0 million for casual labourers. It is obvious from these statistics that Serengeti is the biggest employer of all the parks. Table 6 provides statistics on employment on a park-by-park basis.

**Table 6: TANAPA'S Manpower Record**

| Park | Male Staff | Female Staff | Total Staff | % of total Staff |
|---|---|---|---|---|
| Arusha | 98 | 12 | 110 | 8.4 |
| Gombe | 33 | 5 | 38 | 2.9 |
| Katavi | 60 | 1 | 61 | 4.6 |
| Kilimanjaro | 132 | 24 | 156 | 11.8 |
| Manyara | 93 | 15 | 108 | 8.1 |
| Mahale | 50 | 4 | 54 | 4.2 |
| Mikumi | 103 | 18 | 121 | 9.2 |
| Ruaha | 106 | 13 | 119 | 9.1 |
| Rubondo | 49 | 5 | 54 | 4.2 |
| Serengeti | 351 | 34 | 385 | 29.3 |
| Tarangire | 95 | 15 | 110 | 8.4 |
| Udzungwa | 52 | 6 | 58 | 4.4 |
| **TOTAL** | **1,162** | **151** | **1,313** | **100** |

*Source: TANAPA Planning Unit Data Survey, 2001*

Apart from the actual Park employees, the Park also supports employees and casual labourers of other establishments/visitor facilities within the park. Currently there are a total of eleven permanent visitor facilities with a total bed of capacity of 836. In addition to the permanent facilities, there are twenty- seven special campsites and ten public campsites, making a total of 720 non-permanent beds in the park (Table 7).

**Table 7: Establishments/Facilities within Serengeti National Park**

| Category | Units | No. of Beds |
|---|---|---|
| Hotels/ Lodges | 5 | 650 |
| Permanent Tented Camps | 6 | 186 |
| Non-Permanent Tented Camps | 37 | 720 |

*Source: Management Zone Plan. Planning Unit. Tanzania National Parks.*

### The Impact of the Industry to Communities along River Mara

The tourist activities as outlined above have direct as well as indirect benefits, some of which are described here below:

### Employment

- Subordinate staff and labourers are usually employed from the communities neighbouring the hotels and the parks
- Artisanal activities such as handcraft local to the communities find ready market from the tourists.
- Development infrastructures such as roads, electricity intended for the tourist industry do also traverse through these communities.
- Some of the tax revenue normally finds its way back to the local communities

### Assistance to Communities

Inline with the existing TANAPA policy, communities living around the National parks are generously supported through the main community based development projects such as construction of school facilities, health facilities, water facilities and village feeder roads, 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 to create awareness on the importance of conservation of wildlife and the benefits accrued from it.

During the past 10 years, Serengeti National park was able to contribute a total of TAS 370.95 million to surrounding communities for implementation of various community based projects as shown in Table 8.

**Table 8: Assistance to Local Communities (TAS Millions)**

| District | Education | Health | Roads | Water | Total |
|---|---|---|---|---|---|
| Tarime | 40.39 | 13.17 | | 18.49 | 72.05 |
| Ngorongoro | 63.04 | 10.66 | | | 73.7 |
| Meatu | 1.83 | | | | 1.83 |
| Bariadi | 19.28 | | | | 19.28 |
| Magu | 15.77 | | | | 15.77 |
| Serengeti | 118.03 | 17.37 | 27.02 | 6.67 | 169.09 |
| Bunda | 19.23 | | | | 19.23 |
| **Total** | **277.57** | **41.2** | **27.02** | **25.16** | **370.95** |

*Source: SENAPA/TANAPA*

### Economic and Social Impacts of Amala Project on Agriculture

Agriculture in this context refers to crop and livestock production as well as related agribusiness activities. Fisheries and hunting/wildlife that are normally included in the formal definition of agriculture will be considered separately. The importance of agriculture to Tanzania's economic and social development is clearly manifested by the following points:

Studies by the World Bank and others indicate that over 50% of Tanzanians can be defined as poor, that is, they have a per capita income of less than USD 1.00 per day. The studies have also shown that well over 80% of the poor are in rural areas and depend on agriculture for their livelihood. Additionally, about 82% of the Tanzanian population live and earn their living in rural areas where agriculture is the mainstay of their living. This implies, therefore, that improvement of farm incomes of the majority of the rural population is a precondition for reduction of rural poverty in Tanzania.

Recent estimates show that about 42% of households regularly have inadequate food. Food insecurity is often a manifestation of poverty. Localized food insecurity and hunger are common and reflect inadequate resource endowments at the household level. This implies that any effort to address food security must involve actions to improve agriculture so as to ensure availability and access to food.

Over the years, agriculture has been the single dominant contributor to GDP and foreign exchange earnings. During the year 2000, for instance, agricultural sector contributed

48% to the GDP, and 65% of foreign exchange earnings (FEE). 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. As such, agriculture remains the engine of economic growth in the country.

**Table 9: Agriculture's contribution to real GDP and FEE.**

| Particulars | 1987-1990 | 1990-1993 | 1994-1998 |
|---|---|---|---|
| Contribution to GDP (%) | 48.2 | 48.4 | 50.0 |
| Contribution to FEE (%) | 55.0 | 56.0 | 56.2 |

*Source: Agricultural Sector Development Strategy*

*Key: GDP = Gross Domestic Product*
*FEE = Foreign Exchange Earnings*

## Features of Agricultural Sector

### Land Area

Tanzania is endowed with a total land area of 94.5 million hactres, out of which 44.0 million hectares are classified as arable. Again, only 10.1 million hacters or 23% of the arable land is under cultivation. It is also estimated that about 50 million hactres of land is suitable for livestock production, but out of this only 26 million hactres or 50% of the rangeland is currently being used. Some of the reasons that render part of the available land area unutilized for crop or livestock production include soil leaching, drought proneness, tsetse infestation and lack of appropriate physical infrastructures (Table 10).

**Table 10: Selected Main Features of the Agricultural Sector**

| **Feature**<br>**Land Resource (in million ha.)** | **Quantity** |
|---|---|
| Total Land | 95.5 |
| Arable Land | 44.0 |
| Rangeland | 50.0 |
| Land under Livestock | 24.0 |
| Tsetse infested area | 26.0 |
| Cultivated Land | 10.1 |
| Area suitable for Irrigation | 1.0 |
| Area under Irrigation | 0.2 |
| Land under medium & large scale farming | 1.5 |
| Per capita holding | 0.1 |
| Livestock population (millions) | |
| Cattle | 15.6 |
| Goats | 10.7 |
| Sheep | 3.5 |
| **Poultry** | **27.0** |

*Source: Agricultural Sector Development Strategy. Ministry of Agriculture and Food Security, 2001.*

## Mara Region

The agricultural policies and infrastructures as described above also affects the agricultural activities of the Mara Region, including communities along River Mara. The main characteristics of these economic activities are described below.

## Land Area

The Mara region has a total surface area of about 30,150 km2 of which Lake Victoria occupies 7,750 km2 and 7,000 km2 is part of the famous Serengeti National Park. Hence the area available for agricultural activities is only about 14,799 km2, out of which only about 3,000 km2 are utilized for agriculture. With the limited availability of suitable land for agriculture, it appears there is struggle for land in the region taking into account the current population standing at about one million people. Thus any intervention in the land utilization efforts would mean disaster to the people.

People in the three vulnerable districts together with their livestock depend on the waters of the River Mara for their daily living. Table 11 shows the population by district in the region.

**Table 11: Human Population**

| **District** | **Population Census (1978 to 1988)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1967** | **1978** | **1988** | **Estimate 1995** | **Estimate 1998** | **estimate 2000** | **Growth %** |
| Tarime | 188,596 | 252,513 | 333,888 | 402,616 | 436,116 | 459,984 | 2.7 |
| Musoma-Rural | 340,177 | 219,127 | 248,268 | 295,114 | 317,805 | 333,894 | 2.5 |
| Musoma-Urban | 15,412 | 43,980 | 68,364 | 93,034 | 106,167 | 115,936 | 4.5 |
| Serengeti | | 207,675 | 111,710 | 195,206 | 247,958 | 290,827 | 8.3 |
| Bunda | | | 190,386 | 198,527 | 202,121 | 204,554 | 0.6 |
| **Total** | **544,185** | **723,295** | **952,295** | **1,184,497** | **1,310,167** | **1,405,195** | **2.6** |

*Source: Population Census Report of 1967& 1988, Planning Commission.*

The majority of the people in these districts live in rural villages where agriculture and livestock keeping are the major economic activities on which they depend for their living. Table 12 shows the population distribution between rural and urban areas in the districts and that the major economic activity employing a large number of people is agriculture, which absorbs over 80% of the population in the region and utilizing between 30% and 50% of the total arable land available.

**Table 12: Population Distribution**

| District | Formal Jobs | Agriculture | Industry & Trade | Unemployed | Total |
|---|---|---|---|---|---|
| **Males** | | | | | |
| Tarime | 3,996 | 57,246 | 2,332 | 32,063 | 97,293 |
| Serengeti | 1,223 | 19,057 | 897 | 11,470 | 32,768 |
| Musoma Rural | 2,659 | 41,528 | 1,132 | 24,040 | 69,587 |
| Musoma Urban | 4,843 | 4,395 | 4,022 | 7,468 | 20,967 |
| Bunda | 2,625 | 38,324 | 1,574 | 18,298 | 61,324 |
| **Total** | **15346** | **160,550** | **9,957** | **93,339** | **279,192** |
| **Females** | | | | | |
| Tarime | 1,667 | 84,302 | 1,010 | 30,637 | 118,632 |
| Serengeti | 504 | 27,280 | 312 | 11,417 | 39,618 |
| Musoma Rural | 965 | 56,950 | 316 | 24,154 | 82,659 |
| Musoma Urban | 3,395 | 8,069 | 2,674 | 10,928 | 25,234 |
| Bunda | 957 | 49,729 | 665 | 19138 | 70,956 |
| **Total** | **7,488** | **226,330** | **4,977** | **96,278** | **335,099** |

*Source: Planning Commission; Compiled Data on Mara Regional Statistical Abstract, 1993.*

## Crop Production

Most of the people engage in subsistence agriculture producing only enough food crops for home use and selling the marginal surplus to meet financial requirements for the home. The areas bordering the River Mara have relatively fertile soils where production of food and cash crops is at optimum levels. The plains bordering the Serengeti National Park are largely used for livestock. Agriculture production is practised on small acreage ranging between 4 and 5 acres. Both food and cash crops are produced. Food crops include maize, sorghum, millets, cassava, groundnuts etc. Cash crops include Cotton, Coffee (in Tarime), Paddy and Beans. Some Sugarcane is also produced along the banks of The River Mara. It is worth emphasising here that one of the major constraints facing agricultural sector is inadequate and unreliable rainfall. Hence, the importance of the Mara River. Tables 14 & 15 give the estimates of crop production in the districts of Musoma rural, Tarime and Serengeti (areas influenced by the river).

**Table 13: Crop Production in Metric Tons, and Values (in TAS million)**

| Crop | 1996/97 | | 1997/98 | | 1998/99 | | 1999/2000 | |
|---|---|---|---|---|---|---|---|---|
| | Ton | Value | Ton | Value | Ton | Value | Ton | Value |
| Maize | 45,300 | 3,624.0 | 48,200 | 3,856.0 | 48,200.0 | 3,856.0 | 43,600 | 3,488.0 |
| Sorghum | 61,460 | 3,687.6 | 44,110 | 2,646.6 | 51,000.0 | 3,060.0 | 39,380 | 2,362.8 |
| Paddy | 2,480 | 372.0 | 2,270 | 340.5 | 5,310.0 | 796.5 | 2,000 | 300.0 |
| Millets | 22,000 | 2,640.0 | 180,000 | 2,160.0 | 10,510.0 | 1,261.2 | 18,900 | 2,268.0 |
| Beans | 2,700 | 675.0 | 3,000 | 750.0 | 2,150.0 | 537.5 | 3,150 | 787.5 |
| Cassava | 57,740 | 1,732.2 | 77,000 | 2,310.0 | 51570.0 | 1,547.1 | 62,000 | 1,860.0 |
| Sweet Potatoes | 47,630 | 1,428.9 | 650,050 | 1,951.5 | 51570.0 | 1,547.1 | 50,000 | 1,500.0 |
| **Total** | **239,310** | **14,159.7** | **257,630** | **14,014.6** | **220,310** | **12,605.4** | **219,030** | **12,566.3** |

*Source: Extract from Mara Region Economic Profile and from Regional Agriculture Statistical Reports; 2000.*

**Table 14: Cash Crop Production in Metric Tons, and Values (in TAS million)**

| Crop | 1996/97 | | 1997/98 | | 1998/99 | | 1999/2000 | |
|---|---|---|---|---|---|---|---|---|
| | Ton | Value | Ton | Value | Ton | Value | Ton | Value |
| Cotton | 29140 | 5828.0 | 26860 | 5372.0 | 22480 | 4496.0 | 18100 | 3620.0 |
| Coffee | 1370 | 822.0 | 1300 | 780.0 | 1110 | 666.0 | 1410 | 846.0 |
| Sunflower | 10 | 32.7 | - | - | - | - | 4 | 0.64 |
| Groundnuts | 2310 | 369.6 | 90 | 14.4 | 110 | 17.6 | 230 | 36.8 |
| Sesame | 240 | 28.8 | 20 | 2.4 | 15 | 1.8 | 30 | 3.6 |
| Yellow gram | 1110 | 33.3 | 830 | 24.9 | 150 | 4.5 | 267 | 8.0 |
| Total | 33940 | 7114.4 | 28920 | 6133.7 | 23865 | 5185.9 | 20041 | 4515.0 |

*Source: Extract from Mara Region Economic Profile and from Regional Agriculture Statistical Reports; 2000.*

### The Mara River Basin Health Status

According to the survey that covered the three districts through which the Mara River traverses, the most common water related diseases and their average levels of incidence are as follows:

| | |
|---|---|
| • Malaria | 40% |
| • Schistomiasis | 17% |
| • Diarrhoea | 16% |
| • Dysentery | 8% |
| • Typhoid | 5% |
| • Skin infections | 2% |

Malaria (water-related), Schistomiasis (water-based) and diarrhoea (water-borne) are thus the most threatening diseases in this area. Mortality rates of malaria and diarrhoea, as given in the Serengeti District Health Profile Report of 2001, are as follows:

- Disease 5 years (Mortality; Malaria 19 %, Diarrhoea 5 %); 5 years (Infection; Malaria 23 %, Diarrhoea 10 %).

## DISCUSSION

### Government Plans and Priorities

The major thrust of the macro-economic and sectoral policies so far have been to debottleneck structural impediments and to establish a self-sustaining economy in the long-term development perspective. Along with improvement of the physical infrastructure in support of directly productive sectors and restoration of the internal and external imbalances in the economy by pursuing prudent and appropriate fiscal, monetary and trade adjustments, increasing foreign exchange earnings by export trade have been key issues addressed by the Government. It is worth noting, again, that Tourism is among the top foreign exchange earners in the country. Currently, Government plans are focused on consolidation of the economic gains so far achieved, poverty alleviation, good governance as well as institutional and administrative structure improvements.

According to available documentation by the World Tourism Organization (WTO), international tourism and business travelling are among the world's largest and most rapidly expanding industries. In Tanzania, and indeed else-where in the developing countries, tourism sector has become one of the main drivers of economic growth, particularly because of its strategic significance and capacity to earn foreign exchange.

The strategic significance of the tourism sector in the country's economy is based on the following facts:

- It generates hard currency (foreign exchange) for the economy
- It creates employment opportunities.
- It generates tax revenue for the Government.
- It has an important impact on regional economic activity.
- It enhances enterprise economy because it attracts establishment of small and medium scale enterprises.
- It brings about significant economic and social benefits to local communities.
- It has considerable potential for expansion and increased value added.
- It has extensive forward and backward linkages.

In terms of the general policy objectives, Tanzania's National Tourism Policy seeks to assist in efforts to promote the economy and livelihood of the people, essentially poverty alleviation, through encouraging the development of sustainable and quality tourism that is culturally and socially acceptable, ecologically friendly, environmentally sustainable, and economically viable. It also seeks to market Tanzania as a favoured tourist destination for touring and adventure (wildlife safari) in a country renowned for its cultural diversity and numerous beaches.

Under the ongoing prudent economic and financial management strategies as well as the existing political and social tranquillity, most of the economic activities have been recording significant growth. It is worth noting that Tourism, among others, has benefited tremendously from this favourable social economic environment. Under the circumstances, Tanzania's economic future outlook can be described as highly promising and bright.

### Agricultural and Livestock Policy Objectives

The Agricultural and livestock policy (1997) aims at ensuring that the direction and pattern of development in the agricultural sector meets social objectives and outputs. The policy emphasizes the importance of competitive markets, with the Government providing priority public goods and services and the conservation of the environment as a rational basis for agricultural development. The Policy has the following major objectives.

- Assure food security for the nation, including improvement of national standards of nutrition.

- Improve standards of living in rural areas
- Increase foreign exchange earnings
- Production and supply of raw materials and expansion of the role of the sector as a market for industrial output.
- Develop and introduce new technologies for land and labour productivity
- Promote integrated and sustainable use and management of natural resources (environmental sustainability).
- Develop human resources
- Provide support services
- Promote access of women and youth to land, credit, education and information

**Agricultural Sector Development Strategy**

According to the Tanzania Development Vision 2005, the Government and agricultural stakeholders envisage an agricultural sector that is modernized and commercial as well as highly productive and profitable. In addition, they expect the sector to utilize natural resources in an overall sustainable manner and to act as an effective basis for inter-sectoral linkages.

The primary objectives of the Agricultural Sector Development Strategy are to create an enabling and conducive environment for improving the productivity and profitability of the sector. This will, in turn, serve as a basis for improving farm incomes and reduction of rural poverty in the long term. The strategy, therefore, focuses on the following main issues.

Strengthening of the institutional framework for managing agricultural development in the country. Of particular importance is defining the roles of the Government versus those of the private sector.

Creation of a favourable climate for commercial activities so as to increase private sector participation and agricultural development in general. This includes a stable macroeconomic environment and appropriate changes to the administrative and legal framework.

Clarifying, public and private roles in improving support services including agricultural research extension, training regulation, information and technical services as well as finance. Improved delivery of these services is critical to increasing agricultural production and productivity.
Pay attention to marketing of inputs and outputs in order to improve net farm returns and to commercialize agriculture.

Working out mechanisms for mainstreaming planning for agricultural development in other sectors so that due attention is paid to issues such as rural infrastructure development, the impact of HIV/AIDS and malaria, gender issues, youth migration, environmental management, etc.

### A Review of the Mara Region

Mara Region is the habitat of the direct beneficiaries of the Mara River. The region comprises five administrative districts, namely, Tarime, Musoma rural, Musoma urban, Serengeti and Bunda. Out of the five districts the River traverses through Tarime, Musoma Rural and Serengeti districts. As such, the effect of any interference with the Mara River waters will be most felt in these areas, and hence this review.

### The Role of the Serengeti to the Tourism Sector

The Serengeti is one of the greatest wildlife wonders in the world and indeed a key endowment to Tanzania and the tourism industry. Covering an area of 14,763 km2 Serengeti is the home of a variety of animals and birds. The annual animal migration is yet another spectacular aspect of this renowned game park, thus offering a unique wildlife viewing experience. The Serengeti National Park is among the 12 parks managed by the Tanzania National Park.

### What Will Happen If Serengeti National Park Disappeared From The Tanzanian Map Following Drying Of The Mara River? What If This Catastrophe Happened In Ten Years To Come?

The answer to this question is simple and straightforward! It will entail a disaster to the tourism industry, a disaster to the national economy, and disaster in many other dimensions. In short all the benefits to the national economy and society in general as presented above will simply perish, resulting into detrimental social, economic as well as political implications.

Tanzania will outright lose close to 125,000 (about 40%) tourist visitors currently visiting Serengeti. Given the average annual rate of increase of 12.3%, the figure will have grown to 397,330 by the year 2011. Furthermore, the other parks of Northern Tourist Zone would get very few visitors, if any, since most of them, if not all, do come because of the famous Serengeti. In effect, therefore, Tanzania may lose about 75% of all the tourists coming to the country. This works out to be about 238,814 visitors by 2001 statistics and the figure would grow to about 510,828 by the year 2011.

In terms of revenue generation Serengeti National Park will outright lose more than USD 6,040,290 and this is projected to increase to USD 40,636,057 by the year 2011 at an average annual rate of 21%. Considering the Northern zone aspect, the loss would be USD 13,932,938 by 2001 statistics and would grow to USD 70,488,117 by the year 2011, the average annual rate being 17.6%.

Serengeti's existing workforce of about 385 people will lose their jobs as well as their income amounts to about TAS 836 million. This will mean suffering not only to themselves, but also to their dependants, particularly spouses and children. In addition, the employment of the staff in the other parks of the Northern zone, as well as that of the staff in the various visitor facilities, will be at stake, as there would be no visitors and therefore no revenue to support them.

Communities living around the national parks will no longer benefit from the support they have been getting in terms of community based development projects. Communities around Serengeti National Park will be losing an average of about TAS 40 million per year. The Government will lose tax revenues it has been getting from the operations of the parks. Serengeti district for example, will be loosing an annual tax income of more than TAS 1.0 billion from the operations of the Serengeti National Park.

Serengeti National Park has been getting significant amounts of donations and assistance from various countries and institutions. If the park collapses the donations and assistance will cease. As an example, the donation to Serengeti National Park by the Frankfurt Zoological Society during the first half of 2000 was close to Euros 1440 thousand. This amount would have been lost.

Serengeti National Park, along with Kilimanjaro National Park, is the major financial supporter of the operations of the other parks. Collapse of Serengeti will therefore seriously weaken the other parks.

### What Will Happen to Agriculture In The Mara Basin Areas If Drought Occurs And The Mara Dries Off?

In an event that drought occurs and the Mara River dries off, there would be insignificant crop production, if any, in the three districts endowed with the river. As a result, the three districts would loose about TAS 17 billion worth of crops and there would be hunger and starvation. Declined production of food and cash crops as well as the resulting hunger and starvation are known to be closely associated with increased poverty and illiteracy levels among the rural communities.

### Irrigation and Hydro-electric Power Generation

The Tanzanian Government realized, long ago, the great potential of the Mara River and its basin in terms of irrigated agriculture and hydroelectric power generation. In this context the Government with some foreign assistance commissioned a study on the possible development of the Mara river basin. The study came up with the following findings:

About 65% of the Mara river basin surface is in Kenya and 35% of the basin surface is in Tanzania. Specifically the basin covers 8,030 Km2 in Tanzania and 16,320 Km2 in Kenya, a total of 24,350 Km2.

About 75-85% of the Mara River waters and their regime comes from the larger upper reaches of the Mara River.

An estimated 70 – 90,000 ha of land are good soils in the Mara River valley, especially the riparian zone of the Lake Victoria.

The study also established that the river basin area had the following investment potentials:

- Production of sugar cane on an irrigated area of about 10,000 ha at Ikongo valley, along with a sugar factory capable of producing about 75,000 tonnes of sugar per annum valued at about TAS 22 billion.
- Generation of hydroelectric power at the Mara mine taking advantage of the 304.8 m head between the Kenyan border and the Mara mines. This could produce an estimated 380 million kWh of electric power. Valued at current prices this is worth.
- Production of paddy by irrigation on 20,000 ha using 2 sequences harvested during a year, the valued of which would about TAS 12 billion.
- Possibility to employ about 1,600 people at the sugar estate/factory.

If the Mara River dries, all these investment opportunities, worth more than TAS 34 billion along with the employment opportunity, would be forfeited. However, these investment potentials would not be exploited without assessing their possible impact on the environment.

### Livestock Production

The Mara River basin currently supports the life of about 167,670 cattle, 46,265 goats and 23,042 sheep, valued at TAS 25.15 billion, 416.4 million and 172.8 million respectively. The livestock depend on the Mara River for drinking water and pasture production. The cattle population in this area has the capacity to produce about 9,557,190 litres of milk per annum, valued at TAS 955.7 million. If the Mara River dries off, most of these livestock if not all will die and all the associated benefits will be foregone.

Apart from the monetary values, livestock in this part of the country 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, and marriages are respected and valued if cattle are used as dowry.

### Fisheries in Mara River

The current level of fish stock in the Mara River is not established, but research work by TAFIRI shows that most of the fish species that have disappeared from Lake Victoria are now found in Mara River. Such species include *Oreochromis* and *Esculenta*. Some rare species like C*tenopoma murici* are also found in this river. Apart from being a good habitat for rare species, the river is an important breeding ground for fish.

Despite the fact that the Mara River has a wide range of fish species, the fishing activities in the three districts of Serengeti, Musoma and Tarime are only at subsistence level. People use local fishing gear to catch fish for food and to earn some money. Average income from fishing is about TAS 10,000 per head per day. If the Mara River dries the fishing community will be denied of this income. Additionally, the inhabitants of this area will be denied of the food that is very rich in nutrients. And above all, the potential for improved fish production is immense.

If the Mara River dries off, most of the migrating ungulates in the Serengeti and Masai Mara ecosystem will simply perish. Following this most of the tourist visiting Serengeti

National Park will disappear, since the Park supports the largest herds of migrating ungulates in the World.

## General Health Status in the Country

The Tanzania government has been implementing reforms in the delivery of primary health care to all Tanzanians particularly the vulnerable and risky groups. Various guidelines are being prepared and the existing ones are being reviewed in order to provide better services. The policy guidelines are intended to meet the current demands and challenges such as control of HIV/AIDS as well as monitoring of activities such as traditional medicine, family health care, food and nutrition. The Government has continued to emphasize on establishment of a better health system that will ensure increased capacity and better services. Private institutions and individuals are encouraged to participate in this move. According to the Economic Survey, 2000 there has been a little change in the number of patients reporting and admitted in hospitals between 1996 and 1999. The rate of increase was higher in 2000 compared to previous five years.

Malaria, Diarrhoea and acute respiratory diseases remained major causes and leading diseases for admission to hospitals and for death of people. Preventable diseases by vaccines, malnutrition and reproduction complications which are preventable as well as HIV/AIDS continued to be problematic.

Severe drought or formation of water pockets in the Mara River is likely to increase the incidence and mortality rates of some diseases and thereby necessitating the utilization of the TAS 50,000 per household. This is the amount that is estimated to be required for control/treatment of these various diseases. Diseases such as diarrhoea, dysentery and skin infections would increase because they are associated with personal and general hygiene. The formation/creation water pockets, instead of water flowing in the river, would provide a favourable environment for the spread of diseases like malaria and *Schistosomiasis.*

## General

The Government's water policy is intended to ensure proper protection and equitable use of water sources for both social and economic development for the benefit of all communities. The Government has been involving various communities in the processes of planning, selection of appropriate technology, construction, contribution and management of water projects. In addition, the Government has been encouraging the participation of institutions, non-governmental organizations, private institutions, religious organizations and the public in improving the provision of water services in the country.

Once the Mara River Basin initiative will take roots, the establishment of transboundary plan on how best to share the resources for the benefit of all users will save the Mara River from drying. This action will facilitate the maintenance of the of the Serengeti ecosystem from perishing.

## Conclusion

The Government of Kenya envisages the undertaking of two developments , that is, the generation of hydro-electric power along the Ewaso Ngiro River ( the Amala Project) and the Degazettement of the Mau Forest to open up more land for agriculture. This study has shown that the two development concepts, along with the irrigation of mechanized wheat farming in the Loita Plains are going to have serious detrimental impacts on the Serengeti and Masai-Mara ecosystem, both, in terms of environmental sustainability and social-economic stability.

The study has revealed that the proposed diversion of the Amala River waters into the Ewaso Ngiro River, deforestation of the Mau Forest as well as the irrigation of the mechanized farming will have negative effects on quantity and quality of the waters of the Mara and Ewaso Ngiro Rivers that form a major stabilizing factor of the ecosystem in this region. One obvious effect of the combined developments in Kenya will be the reduced quantities of water in the Mara River. In fact, it is predicted that during severe drought the River may dry off completely. If this happens, the entire wildebeest population of about 1.3 million will be wiped out in matter of four weeks. This scenario will equally affect the communities living along the Mara River economically including the lives of the other flora and fauna in the ecosystem.

The study also shows another impact that may be associated with the proposed developments in Kenya on the life of the yet another unique feature of the ecosystem, the lesser flamingos. The Lakes Natron, Nakuru and Bogoria support about 98% of the World's population of the flamingos. If the proposed developments especially the irrigation project, the excess water from irrigation will dilute the normal alkalinity of the lakes leading to non-production of blue-green algae (Spiriluna platensis), the main diet of the flamingoes. Lake Natron, which is the only known breeding site for the flamingoes in the world, will lose its value. It is feared, therefore, that if the alkalinity of the lakes is disturbed significantly, the entire population of the lesser flamingos will disappear.

Above all, there would be tremendous far-reaching social-economic effects, over and above the collapse of the Serengeti-Mara ecosystem that is a unique natural feature and one of the wonders of the World. The industries and sectors that will be impacted directly include Tourism, Agriculture, Fisheries, Wildlife as well as Health and Water supply.

### Tourism

Tanzania could lose close to 125,000 (about 40%) tourist visitors currently visiting Serengeti National Park, and given an annual average rate of increase of 12.3%, the figure would grow to 397,330 visitors by the year 2011. In addition to this, the other parks of the Northern Zone would get very few visitors, if any, since most of them, if not all, do come because of the famous Serengeti. As a net effect, therefore, Tanzania could lose about 75% of all the tourists coming to the country. This works out to be 238,814 and 510,828 by statistics of years 2001 and 2011 respectively.

Likewise, Serengeti National Park could lose more than USD 6,040,290, and this would increase to USD 40,646,057 by the year 2011, given the an annual rate of increase of

21%. Considering the Northern Zone aspect, the loss would be USD 13,932,938 by 2001 statistics and this would grow to USD 70,488,117 by the year 2011, the average rate of increase being 17.6%.

About 385 employees currently working at Serengeti National Park would be rendered redundant and thus lose their income totaling USD 836,000. This will imply suffering not only to themselves, but also to their dependants, particularly spouses and children. In addition, the employment of the staff in other parks of the Northern Zone, as well as those other staff from various visitor facilities, would be at stake, as there would be no visitors and thus no revenue to support them.

Communities living around the national parks would no longer enjoy the support they have been getting in terms of community based development projects. Communities around Serengeti would lose about USD 40,000 per year. The Serengeti district authorities would lose an annual income of USD 1,000,000 in the form of taxes.

Serengeti National Park would lose the donations and assistance it has been getting from various countries and institutions. FZS, for example, donated close to 1,440,000 Euros during the first half of the year 2000.

### Agriculture

In the event of a prolonged drought, this region, around the River Mara, will lose USD 17 million worth of food and cash crops per annum, USD 25 million worth of livestock and an annual milk production worth USD 960,000. Monetary values apart, people in this region will lose other intrinsic social and cultural values that are associated with livestock. Nutrition and lives of the people of this area would be at stake for lack of food and money.

### Fisheries

Fish earnings amounting to USD 10 per day per fisherman will be lost if drought occurs. This and the impacts above will lead to starvation, malnutrition and eventual death of the vulnerable groups of the population in this region.

### Wildlife

Activities such as tourist hunting, as well as marketing of live animals and trophies would be reduced significantly, and so will the revenues accruable from the activities.

### Health

It is predicted that the incidence and mortality rates of the water related diseases such as diarrheoa, dysentery, malaria, *schistosomisis* and skin-diseases would increase. The cost of controlling these diseases is estimated to be USD 50 per household.

### Water Supply

It is predicted that there would be acute shortage of water, both, for domestic purposes and for agricultural and livestock production. Additional funds would be required for the provision of alternative sources of water.

The Mau Forest degazettement, irrigation of the mechanized farming in Loita Plains and the proposed Amala weir hydro-electric power project will definitely affect the socio-economic existence the communities living along the Mara River and equally impact their activities as a result of such proposals. This scenario has been explained in the study.

### Recommendations

The damage that can result following the implementation of the development proposals in Kenya is likely to be much more immense than this study suggests. And this is because there are some cost elements that have not been analysed, and yet other costs are not easy to determine. Possible loss of a unique national heritage like the Serengeti National Park, along with the wonderful migration, for example, can hardly be valued, leave alone its recovery. However, no historical data are available that suggest that human ingenuity can create such wonderful creatures of God like elephants, wildebeests, giraffes and such like. It is imperative, therefore, that there should be agreeable efforts to conserve and protect wildlife the world over. It is, therefore, proposed that a trans-boundary Mara River Management Plan/Authority be established. This should comply with ecological principles and cost/benefit analysis be conducted so that both sides can benefit from the proposals.

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# THE KEY ROLE OF WATER IN CONTROLLING THE MIGRATION OF LARGE UNGULATES IN THE SERENGETI NATIONAL PARK, TANZANIA

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## Abstract

Rainfall, water quality and animal density data were combined to understand the migration patterns of large ungulates in the Serengeti National Park in 2001-2002. Wildebeest (*Connochaetes taurinus)*, topi (*Damaliscus korrigum*), and zebra (*Equus burchelli*), migrated clockwise in a general north-south direction, at seasonal time scale, across much of the ecosystem controlled by water quantity (i.e. rainfall) and water quality (excess salinity). The migrating area of topi may be smaller than that of zebra and wildebeest. Grant's (*Gazella granti*) and Thomson's gazelle (*G. thomsoni*), also dispersed in a pattern controlled by rainfall, but their dispersal range and their time scale was annual instead of seasonal. Their relative resident (i.e. non-migrating) populations varied, suggesting that one species may be more tolerant of saline, arid areas than the other one. Impala migrated east west, the animals being aggregated in the central area in the dry season, and in the Lobo area and the Western Corridor in the wet season. This migration pattern had not been studied earlier. Water quality and quantity appear to control the migration dynamics of large ungulates in the Serengeti ecosystem.

## Introduction

The world famous Serengeti National Park (SNP; Figure 1a) has the largest concentration of wildlife on earth. The system constitutes more than 50 larger mammal species as well as the great migratory ungulates in Africa (Prins 1992), wildebeest (*Connochaetes taurinus*) being most important (McNaughton 1985; Serneels & Lambin 2001; Sinclair & Arcese 1995). The migratory population represent a large proportion of the biomass of the Serengeti ecosystem by migrating to the plains which provide only seasonal grazing, thereby avoiding competition with other ungulates for a large part of the year (Maddock 1979). Food quality and availability (Bergman et al. 2001) limit ungulate intake during the dry season.

Although the ecology of several mammal species in the SNP has been studied extensively over the last 40 years, the importance of water quantity and quality has been largely overlooked until recently. Three major rivers drain the park and control the ecosystem, namely the Mbalageti, Grumeti and Mara rivers (Figure 1b; Gereta & Wolanski 1998), while other permanent water also play an important role for the survival of mammals during the dry season. Water is the base for all life in the Serengeti ecosystem because the ecosystem is semi-arid, rainfall is commonly less than 600 mm/year (Gereta & Wolanski 1998; Wolanski & Gereta 2001; Wolanski et al. 1999). Rainfall varies seasonally with distinct dry and wet seasons. Rainfall also varies spatially. In the dry season water remains available in the northern part of the ecosystem while the southern area is arid. As a result, the wildebeest and zebras (*Equus burchelli*), migrate seasonally between their wet season range in the south and their dry season range in the north. The migration proceeds clockwise as the animals transit through the western corridor during their northward migration during the onset of the dry season. The driving force towards this movement is the availability of both water quality and quantity. As the wet season ends and the dry season sets in, the water becomes highly saline and less palatable to the animals; this increasing salinity appears to trigger the onset of the animal migration towards the north and north-west where water is less saline and remains available (Wolanski et al. 1999).

There are significant inter-annual differences in the pattern of migration, and these appear to be linked with patterns of rainfall (Frank et al. 1998; Maddock 1979; Mduma et al. 1999; Pennycuick 1975; Sinclair 1979; Sinclair & Arcese 1995; Sinclair & Norton-Griffiths 1979). Rainfall does not just determine the availability of drinking water and fodder, it also determines water quality, principally salinity. One of the underlying factors controlling the timing of the wildlife migration appears to be water quality (Wolanski & Gereta 1999; 2001; Wolanski et al. 1999). This adaptive seasonal migration and aggregation of ungulates, has contributed to spatial heterogeneity (Fryxell 1995; Sinclair & Arcese 1995); an instrumental factor in the relative stability of herbivore-plant and herbivore-carnivore interaction.

Only a fraction of the Serengeti ecosystem is protected. The availability of water for wildlife is threatened by human activities both inside and outside the protected areas. These activities include deforestation, shifting cultivations, human settlements, irrigation, farming, and indiscriminate setting of wild fires. Gereta et al. (2002) have demonstrated likely severe impacts that might result from developments in Kenya on the Mara River, a transboundary river, shared by Kenya and Tanzania and that is a vital source of water for Serengeti wildlife. These developments include deforestation of Mau Forest, irrigation mechanised wheat farming, and construction of the proposed Ewaso Ng'iro (South) hydropower project, all in Kenya. Gereta et al. (2002) concluded that there is a need for a transboundary Mara Management Plan that would be compatible with ecohydrology principles.

The aim of this study is to demonstrate to what level the large ungulate community structure and diversity vary seasonally and spatially in relation to water quality and quantity access. The following species were evaluated: wildebeest, zebra, Grant's gazelle (*Gazella granti*), Thomson's gazelle (*Gazella thomsoni*), impala (*Aepyceros melampus*), topi (*Damaliscus korrigum*) and Coke's hartebeest (*Alcelaphus buselaphus*).

## Materials and methods

### *Animal distribution*

We recorded the location of every solitary mammal and clusters of mammals seen along a grid of systematically spaced lines or transects that were randomly superimposed on the existing road-system in the study area. Each transect had a total length of 1 km. and they were spaced with intervals of 2 km. Transects were repeatedly driven on a monthly bases to detect changes in species density due to seasonal changes. In total transects were driven 11 times, during the period April 2001 – March 2002. By using this approach it is possible to obtain unbiased estimates of animal densities if certain assumptions are met, namely: 1) animals on the line are always detected, 2) all animals are detected in their initial locations and 3) all measurements are correctly recorded. All sampling of data was conducted by the use of a pickup that travelled at 20 km/h or less along transects with two observers standing at the back. The observer standing on the right hand side at the back of the pickup covered a sector of 180 degrees to the right side whereas the other observer covered the left-hand side in the same manner. When animals were spotted, the vehicle immediately halted and the observers recorded the UTM-position of the car and the distance to the animal/s with a rangefinder. If the object was a cluster of animals, the distance was defined to represent the line from the observers to the estimated middle of the animal group. Then the angle of the road and the angle of the straight line between the observers and the object were measured, relative to true north, with the rangefinder's internal compass. These measurements allow the computation of the perpendicular distance from the object to the line. This basic information was used with the Distance software (Buckland et al. 2001) to fit detection functions that determined the density of animal species per habitat type. One great advantage of this approach is that we need draw no distinction, within reasonable limits, between habitats with good or poor visibility. The fitted detection function reflects both the decrease in detectability with distance and the lover proportion of animals that are potentially detectable (Buckland et al. 2001). It is sufficient to assume that all objects close to the line are seen.

Altogether 992 km were driven monthly with 130 transects. The data were used to calculate average animal density data in four areas:

- *Central area* – covering the woodlands around Seronera (24 transects).
- *Lobo* – From northern parts of the central area passing Lobo Lodge in the north, covering woodland as well as small stretches with plains (16 transects).
- *Southern Plains (grasslands)* – From Seronera River in north to Olduvai Gorge in south, in addition two stretches one east and one west from the main road were added (32 transects).
- *Western corridor* – From Serena and up to Grumeti camp site (37 transects).

Most habitats inside the park were covered by these transects.

### *Rainfall and water quality*

Monthly rainfall data were measured at 55 stations and these data were provided by TANAPA. Water quality data were measured at monthly to three-monthly intervals at 57 stations spread throughout SNP (Gereta & Wolanski, 1998). These data were provided by TANAPA.

*Data analysis*

The year was divided into three periods to enable tracking of animal movements: November up to and including March, April up to and including July and August up to and including October. Data storage and manipulation was performed in Visual FoxPro 5.0. We used this software to calculate perpendicular distances and to exchange files with Distance 3.5 (Buckland et al., 2001) so that density estimates could be calculated for certain habitat types at different times of year. To avoid unnecessarily increase of the sampling variance and to minimise the number of parameters necessary to model the data with series expansions we removed obvious outliers. A reasonable preliminary model was fitted to the data and the distance corresponding to a value of 0.15 of the probability distribution was calculated and used as the truncation point for further analyses. We fitted all data to the following key functions: uniform, half-normal, negative exponential and hazard-rate. The uniform and cosine series expansions were used as they are considered to be excellent omnibus models (Burnham et al. 1980; Crain et al. 1979). The relative fit of alternative models was evaluated using the Akaike's Information Criterion (AIC) (Hurvich & Tsai 1995; Sakamoto et al. 1986).

## Results

The rainfall fluctuated seasonally with a marked dry season in June-September and a wet season peaking in April, in all the four areas. Further there was a large interannual variability that is shown as error bars in this figure. The rainfall also varied spatially, with the Southern Plains area being the driest. Annual rainfall was largest in Western Corridor followed by Lobo and the central area.

Salinity was less than 1 psu in all regions except the Southern Plains. In the Southern Plains the salinity of surface waters at these sites varied from site to site. The Mbalageti and Seronera rivers drain this area. Salinity increased up-river along these two rivers. Salinity varied seasonally, it was the smallest in the wet season and the highest in the dry season. Salinity of the headwaters of the Seronera River in the southern plains exceeded 10 psu in the dry season. This occurred after the wildebeest had migrated out of the area. Such high salinity water is presumed to be stressful and harmful to most mammals; maximum allowable salinity for sheep is known to be about 8 psu (Gereta & Wolanski, 1998). Most water bodies in the Southern Plains dried out near the end of the dry season.

The highest density of animals was observed from November to March on the southern plains when wildebeest, zebra and Thomson's gazelles reached densities of 183, 70 and 56 animals km$^{-2}$ respectively (Table 1). The second highest densities were seen between August and October when Thomson's gazelle density on the Southern Plains was 53 animals km$^{-2}$, zebra density in the central area was 49 animals km$^{-2}$, and wildebeest density in the western corridor was 48 animals km$^{-2}$. The smallest density was observed for Coke's hartebeest, topi and Grant's gazelle.

The spatial/temporal fluctuations of the density of the dominant seven ungulate species in the various areas at various times of the year (Table 1) show that some species nearly completely migrated out of specific areas at some times of the year (e.g. wildebeest and zebra) while other species (e.g. Grant's and Thomson's gazelles) migrated much less. Most species had at least a few resident animals residing in each area. However some species were totally absent in specific areas at some times of the year. For instance, impala was never seen on the plains and wildebeest was never observed in the eastern part of the western corridor between November and March although this area is known to have a resident population of wildebeest (Maddock 1979; Georgiadis 1995). Coke's hartebeest was not observed in the eastern part of the western corridor between April and July. Some species were observed too infrequently in some areas to enable any density analysis, namely zebra, Grant's and Thomson's gazelles between November and March in the central area; Grant's gazelle between August and October in the central area; wildebeest between November and March in Lobo and Thomson's gazelle and Coke's hartebeest between November and March in the eastern part of western corridor (Table 1).

The ratios of the density of species (Table 2) enable an estimate of the consistency of migration patterns between different species. As seen in Table 2 across a diagonal, the density-ratio for wildebeest/zebra remained about constant during their migration, a finding suggesting that they migrated together at the same time. Looking at Table 2 in a similar diagonal following the wildebeest migration, the density-ratio for wildebeest/Grant's gazelle varied from 14.1 in the southern plains to 1.81 (a change of 1.81/12.8 = 0.13) in the central area; similarly the density-ratio of wildebeest/Thomson's gazelle varied from 3.25 to 0.41 (a change of 0.13). This suggests that about 13% of both the Grant's and Thomson's gazelles follow the northward migration from the southern plains to the central area.

Of these migrating gazelles, there were dispersion patterns at longer time scales (Table 2). The ratio wildebeest/Grant's gazelle density in the southern plains was 14.1 in November-March (when the migrating wildebeest were present – see Table 1), 1.86 in April-July (when the wildebeest were migrating out) and 0.13 in August-October (when the migrating wildebeest had left the area, only a few remaining animals being present – see Table 1), for a total change of 0.13/14.07 = 0.009. The similar values for wildebeest/Thomson's gazelle densities were 3.25, 0.44 and 0.05, respectively, for a total change of 0.05/3.25 = 0.015. These suggests that more of the Thomson's than the Grant's gazelles remained throughout the year in the southern plains – the most arid of the area. Thus these animals were more tolerant of high salinity surface water or, alternatively, they relied less on surface waters than on other sources of water (e.g. possibly using the mildew from grass in the early morning).

The Pearson's correlation coefficient, σ, describing the relationship between animal densities for all species and average rainfall per study site was 0.20 (n = 72, p = 0.11). The spatially averaged density of topi was significantly correlated with rainfall (Table 3). There was also a strong, though slightly weaker synergy but still significant, between rainfall and spatially averaged wildebeest and impala densities (Table 3).

The area-specific Pearson's correlation coefficient for relating animal density to rainfall (Table 4) reveals that there was a very strong, significant positive relationship between rainfall and density of topi and rainfall variation in the central area and for Grant's gazelle in Lobo. There were also strong relationships between animal densities and rainfall variations for wildebeest (>0), zebra (>0) and topi (>0) on the southern plains; zebra (>0) and topi (>0) in the Lobo area, and finally for zebra (<0) and Grant's gazelle (<0) in the western corridor. Table 4 suggests that topi migrated with the zebras and wildebeest but possibly not as far out in the Western Corridor. Table 4 also suggests that the impala migrated east-west, the animals being aggregated in the central area in the dry season, and in the Lobo area and the Western Corridor in the wet season.

## Discussion and Conclusion

Our data indicate that wildebeest, topi and zebra migrated clockwise in a general north-south direction, at seasonal time scale, across much of the ecosystem controlled by water quantity (i.e. rainfall) and water quality (excess salinity). Although the migrating area of topi was smaller than that of zebra and wildebeest, all these species show a clear seasonal migratory pattern. The migratory pattern of these species shown in the present paper is not surprising because it has been suggested for a long time that the migration of wildebeest is one of the key tools of the ecosystem. Wolanski & Gereta (2001) suggested water quantity and quality as a major driving force of the Serengeti migratory system, and the present paper supports their hypothesis. It is however surprising that so few previous studies has highlighted the role of water quality and quantity as driving forces in animal movements. Although it has been known for a long time that Grant's and Thomson gazelles also migrate these two species dispersed in a pattern controlled by rainfall, but their dispersal range and their time scale was annual instead of seasonal. Their relative resident populations varied, suggesting that one species may be more tolerant of saline, arid areas than the other one.

A species that has not previously been studied with regard to annual movements is the impala. The species was aggregated in the central area not far from the permanent water in Seronera river during the dry season. However, several individuals migrated to the Lobo area and the Western Corridor and aggregated here in the wet season. This east-west migration pattern of impalas has not been studied earlier and therefore need more attention in future research of migratory ungulates in the Serenget9i ecosystem.

This study has highlighted the key role of water in controlling migration dynamics of large mammals in the Serengeti ecosystem. Much more attention should therefore be put on water as a driving force in the Serengeti ecosystem in future research.

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**Table 1**

Density estimates (individuals per km$^2$) and standard errors for the seven species calculated per time period and study area. Cells containing X means that no reliable estimate of animal density could be calculated due to an insufficient number of observations. Cells containing – means that no animal observations were made.

| **Area and species** | **November to March** | | **April to July** | | **August to October** | |
|---|---|---|---|---|---|---|
| **Plains** | **Ind./km$^2$** | **SE** | **Ind./km$^2$** | **SE** | **Ind./km$^2$** | **SE** |
| Wildebeest | 182.9 | 60.0 | 8.0 | 5.2 | 2.7 | 2.0 |
| Zebra | 70.1 | 26.0 | 3.4 | 1.8 | 5.8 | 2.4 |
| Grant’s gazelle | 13.0 | 4.2 | 4.3 | 1.1 | 20.8 | 6.0 |
| Thomson’s gazelle | 56.2 | 16.0 | 18.0 | 3.4 | 52.6 | 14.0 |
| Impala | - | - | - | - | - | - |
| Topi | 0.7 | 0.3 | 0.2 | 0.1 | 0.3 | 0.1 |
| Coke’s hartebeest | 0.3 | 0.1 | 0.2 | 0.1 | 0.4 | 0.4 |
| **Central area** | | | | | | |
| Wildebeest | 3.9 | 1.3 | 2.9 | 2.7 | 8.7 | 4.8 |
| Zebra | X | X | 1.3 | 0.9 | 48.9 | 16.0 |
| Grant’s gazelle | X | X | 1.6 | 1.3 | X | X |
| Thomson’s gazelle | X | X | 7.1 | 2.3 | 5.0 | 1.9 |
| Impala | 18.5 | 8.3 | 24.5 | 5.6 | 31.4 | 7.0 |
| Topi | 4.6 | 3.8 | 1.6 | 0.7 | 1.6 | 0.8 |
| Coke’s hartebeest | 0.7 | 0.1 | 1.3 | 0.8 | 0.4 | 0.2 |
| **Lobo** | | | | | | |
| Wildebeest | X | X | 3.4 | 3.2 | 17.6 | 14.8 |
| Zebra | 19.1 | 10.3 | 15.8 | 11.5 | 14.9 | 8.8 |
| Grant’s gazelle | 6.9 | 4.4 | 0.5 | 0.4 | 0.9 | 0.4 |
| Thomson’s gazelle | 13.4 | 8.2 | 14.5 | 7.5 | 17.8 | 6.7 |
| Impala | 42.1 | 15.0 | 20.5 | 7.6 | 11.5 | 6.6 |
| Topi | 8.8 | 4.9 | 2.1 | 1.3 | 0.8 | 0.5 |
| Coke’s hartebeest | 1.1 | 0.9 | 0.8 | 0.4 | 1.8 | 1.5 |
| **Western Corridor** | | | | | | |
| Wildebeest | - | - | 3.2 | 2.3 | 48.0 | 17.0 |
| Zebra | 5.9 | 3.2 | 14.5 | 4.9 | 20.8 | 5.9 |
| Grant’s gazelle | 0.3 | 0.1 | 1.3 | 0.8 | 2.0 | 1.0 |
| Thomson’s gazelle | X | X | 14.7 | 3.3 | 17.9 | 6.5 |
| Impala | 36.6 | 10.0 | 19.5 | 6.9 | 21.7 | 7.0 |
| Topi | 3.2 | 1.1 | 1.4 | 0.6 | 1.4 | 0.4 |
| Coke’s hartebeest | X | X | - | - | X | X |

**Table 2**

Ratio of animal density for different species in different regions. W = wildebeest; Z = zebra; G = Grant's gazelle; Th = Thomson's gazelle

| Area and species | November to March | April to July | August to October |
|---|---|---|---|
| **Southern plains** | | | |
| W/Z | 2.61 | 2.35 | 0.47 |
| W/G | 14.10 | 1.86 | 0.13 |
| W/Th | 3.25 | 0.44 | 0.05 |
| **Central area** | | | |
| W/Z | No data | 2.23 | 0.18 |
| W/G | No data | 1.81 | |
| W/Th | No data | 0.41 | 1.74 |
| **Western Corridor** | | | |
| W/Z | No data | 0.22 | 2.31 |

**Table 3**

Spatially-averaged Pearson's correlation coefficient (σ) per species between rainfall and animal density for different species. The two-tailed level of significance is shown in the column named p and sample size is in the N column.

| **Species** | **Pearson's σ** | **p** | **N** |
|---|---|---|---|
| Wildebeest | 0.60 | 0.07 | 10 |
| Zebra | 0.25 | 0.45 | 11 |
| Grant's gazelle | -0.14 | 0.69 | 10 |
| Thomson's gazelle | 0.15 | 0.67 | 10 |
| Impala | 0.49 | 0.18 | 9 |
| Topi | 0.65 | 0.02 | 12 |
| Coke's hartebeest | -0.06 | 0.85 | 10 |

**Table 4**

Pearson's correlation coefficient (σ) per species, study area and season. – indicates that no coefficient could be calculated due to lack of animal density data. The two-tailed level of significance is exhibited in the p column. Particularly significant correlations are highlighted.

| **Species** | **Plains** | | **Central area** | | **Lobo** | | **Western corridor** | |
|---|---|---|---|---|---|---|---|---|
| | **σ** | **p** | **σ** | **p** | **σ** | **p** | **σ** | **p** |
| Wildebeest | 0.97 | 0.10 | -0.40 | 0.73 | - | - | - | - |
| Zebra | 0.96 | 0.10 | - | - | 0.96 | 0.10 | -0.99 | 0.06 |
| Grant's gazell | -.20 | 0.87 | - | - | 1.00 | 0.00 | -0.99 | 0.07 |
| Thomson's gazelle | 0.36 | 0.76 | - | - | -0.65 | 0.54 | - | - |
| Impala | - | - | -0.87 | 0.32 | 0.94 | 0.20 | 0.90 | 0.28 |
| Topi | 0.97 | 0.10 | 0.99 | 0.02 | 0.98 | 0.10 | 0.95 | 0.20 |
| Coke's hartebeest | -.36 | 0.75 | -0.06 | 0.96 | 0.09 | 0.94 | - | - |