Effects of land use/ cover changes on flow regime of the Usangu wetland and the Great Ruaha River in Tanzania

J.J. Kashaigili
Department of Forest Mensuration and Management, Sokoine University of Agriculture
P.O. Box 3013, Morogoro, Tanzania. Email:jkashaigili@yahoo.co.uk

Abstract
The Usangu wetland (*Ihefu*) is a wetland of great importance for its biodiversity and acts as regulator for downstream flows for the Great Ruaha River through the Ruaha National Park. While recognizing the importance of this wetland, little is known about the effects of land use and cover changes on the wetland itself and the flow regime of the Great Ruaha River in the downstream. Recognizing that, a study was conducted using remote sensing and GIS techniques to inventory land use/cover changes in the watershed over the years. Hydrological data were analyzed to reveal the alterations and trends at three periods (pre-1974, 1974-1975 and post 1985) from 1958 to 2004. It was revealed that there was a steady increase in cultivated area, from 121.2 km^2 to 874.3 km^2 between 1973 and 2000 while the woodland area decreased significantly over years. The minimum dry season area of the wetland declined significantly, with more changes occurring between 1984 and 2000 at 67% reduction. The river was found to be sensitive to land use/ cover changes and highly variable on an intra annual (seasonal) and inter-annual (year to year) basis. There was a slight shift in the peaking for the post-1985 period with high flows attained earlier in February instead of April. The Q_{50} flow progressively declined from 19.23m^3s^{-1} in the pre-1974 to 16.51 m^3s^{-1} and 9.04 m^3s^{-1} for 1974-1975 and post-1985 period respectively. The Q_{95} (low flow) declined from 2.84 m^3s^{-1} to 0.11 m^3s^{-1} and 0.0 m^3s^{-1} for pre-1974, 1974-1975 and post-1985 period respectively. The study concludes that the modification of the land use and cover has resulted into changes in time distribution of runoff within the catchment. The study highlights the effects of land use /cover changes on ecosystems and water resources for an informed decision on proper catchment planning and management.

Key words: Land use/ cover changes, Usangu wetland, Great Ruaha River, flow regime, remote sensing

Introduction
Understanding the influence of land use/ cover change on river flow regimes is important for sustainable catchment management. Worldwide it has become evident that river ecosystems have changed as a result of river regulation modifying the flow regime (Postel and Richter, 2003; Brown and King, 2003). Also, the increased competition for water and alterations in land use in the upstream of many rivers, are argued to have contributed to change in hydrological regimes of many rivers and wetlands. While that has been acknowledged, few studies have been conducted in developing countries.

Against this background, this paper presents a study undertaken to investigate the influence of land use/cover changes on the hydrological regimes of the Great Ruaha River (GRR) downstream of the Usangu Plains in Tanzania. The Great Ruaha River is a major tributary of the Rufiji River. In terms of the national economy it is one of the country's most significant waterways, with more than 50% of the countries installed hydropower capacity and significant agricultural production (Kadigi *et al.*, 2004). Furthermore, it is the main dry season source of water, and so is vital for the ecology of the Ruaha National Park. Since 1992/93, the previously perennial river has ceased flowing downstream of the Eastern (*Ihefu*) wetland, every dry season and the early part of each wet season (i.e., September to January). Various studies have been conducted in the area trying to investigate the possible causes for the changes and options for mitigation of the prevailing effect on the Great Ruaha River environment especially through the Ruaha National Park.

Although previous studies have been carried out in the Usangu Plains (Moirana and Nahonyo, 1996; SMUWC, 2001a), none of these explicitly investigated the influence of land use change on river flow regimes. The current study sought to improve understanding on the influence of land use and cover changes on hydrological regimes of the GRR. The study acknowledges the fact that formulation of appropriate strategies to manage the water resource depends on a sound understanding of the causes of problems and the impacts it has on the downstream.

Area descriptions, methods and material studied

Area descriptions

The Usangu wetlands are located at the centre of the Usangu Plains, comprising of Western and Eastern (*Ihefu*) wetlands - joined by a narrow band of land along the Great Ruaha River at Nyaluhanga. The wetlands covers about 1,800 km^2 and contains the Usangu Game Reserve (4 148 km^2). The Usangu Plains are located in the south west of Tanzania (Figure 1). They lie between longitudes 33^{o}00’E and 35^{o}00’E, and latitudes 8^{o}00’S and 9^{o}30’S. The plains are located within the Great Ruaha River catchment (GRRC) which has an area of about 68 000 km^2. The GRRC is located within the Rufiji River Basin (the largest basin in Tanzania) which covers an area of about 177 000 km^2. The Plains, which lie at an average elevation of 1100 m above mean sea level (amsl), are surrounded by the Poroto, Kipengere and the Chunya mountains, with elevations up to 3000 m amsl.

>>> *Figure 1: Map of study area including Ruaha National Park and Msembe Ferry Gauging station* <<

The Great Ruaha River is a major tributary of the Rufiji River. The headwaters rise in the Kipengere mountains, in south-west Tanzania, and drain through the broad alluvial plains of Usangu. The Plains are characterized by seasonally-inundated grassland and permanent swamps. From a conservation standpoint, the wetlands are amongst the most valuable ecosystems in Tanzania, providing habitat for over 400 bird species and numerous other flora and fauna (Kashaigili, 2006). Furthermore, the wetlands support numerous livelihood activities, many of which depend on water from the river, including agriculture, cattle grazing and traditional fisheries, as well as small-scale industries such as brick-making. In some villages, it is estimated that up to 95% of households benefit from the wetlands which make a vital contribution to coping strategies during times of food scarcity (Kashaigili and Mahoo, 2005). In recognition of its ecological importance, the Usangu area has been designated an Important Bird Area by Birdlife International (Mtahiko, *et al*., 2006) and, in 2000, the largest, and most downstream, wetland, locally called *Ihefu* or the Eastern wetland, was gazetted into the Usangu Game Reserve and presently processes are underway to transform it to Ruaha National Park. The consequence of this is that some activities, such as fishing and grazing, are no longer permitted.

The Great Ruaha River discharges from the *Ihefu*, and leaves the Plains, at NG’iriama. About 30km downstream of NG’iriama the river enters the Ruaha National Park. During the dry season, the river, which provides the southern boundary of the Park, is the major source of water for much of the wildlife. Just downstream the RNP, the GRR joins another river (the Little Ruaha) to supply water to the Mtera hydropower plant. The GRR provides about 56% of runoff to Mtera reservoir.

Materials and Methods

Land use/cover changes affect the water yield (total runoff) and flow regimes (i.e., the seasonal distribution of stream flow or runoff). To understand the effects of land use/ cover changes on hydrological flow regimes for the Eastern (*Ihefu*) wetland and the Great Ruaha River, analysis of flows and rainfall data was conducted. The rainfall over the Usangu Plains and the high catchment as well as the flow data from Msembe station located downstream of the Eastern (*Ihefu*) wetland were used. The analysis was augmented by a land use/ cover change analysis as reported in (Kashaigili *et al.,* 2006). Three time frames or "windows": 1958-1973, 1974-1985 and 1985-2004 were considered. These windows correspond approximately to different levels of human intervention in the catchment (Kashaigili, 2006; Yawson, 2003). As presented by Kashaigili *et al.* (2006) the pre-1974 (i.e., 1958-1973) window was regarded as a near-natural period with only moderate human interventions. The major interventions during this period were the introduction of irrigated agriculture by people from Baluchistan in the 1940s and the construction of Mbarali rice farm (3,200 ha) in 1972. At the end of this window, the population in Usangu was approximately 90,000 and the irrigated area was approximately 12,000 ha. The 1974-1985 window was a period characterized by rapid increase in both population and irrigation. At the end of the window, irrigated area was about 26,000 ha and the population was estimated at 150,000. This represents a 67% increase in population and a 117% increase in the area under irrigation in 12 years. The post-1985 (i.e., 1985-2004) window was characterized by increasing water abstraction as a result of continued population growth, increased irrigation and increased pastoral activities. It was also characterized by increased catchment degradation, expanded markets and increased conflict over limited water resources (SMUWC, 2001b). During this period, the Kapunga rice farm (3,000 ha) was developed and began irrigating with water from the Great Ruaha River. Other new schemes commissioned in this period include: Kimani (6,000 ha), Madibira (3,000 ha), Majengo (800 ha), Mswiswi (800 ha), Motombaya (800 ha), Ipatagwa (700 ha), Meta Lunwa (1,200 ha) and Chimala (3,000 ha).

Rainfall and flow analysis

Long-term trends in river flows at Msembe station and the most perennial rivers contributing a great amount of flows into the Usangu plains and rainfall over the plains were analyzed using conventional techniques of moving averages and linear regression. For perennial rivers, the flow at gauging points just upstream of the plains was used. The student t-test (Helsel and Hirsch, 1993) was applied to test the significance of the slope of the trend-lines. The rainfall time series over the Usangu Plains was derived by combining data from rain gauges located on the Plains. Daily rainfall was calculated as the numeric mean of the rainfall recorded at each gauge. Annual and seasonal flow duration curves were developed for the three windows using the Galway Flow Forecasting software (NUI, 2002). From flow duration curve (FDC) (i.e., a cumulative frequency distribution that show the percent of time that a specified discharge is equaled or exceeded during a period of interest), indices of flows were extracted and compared for the different time periods. To investigate the frequency of occurrence of low flow events, the ARIDA software (Fry *et al*., 2001) was used.

Results and analyses

Annual rainfall and discharge for the Great Ruaha River

Figure 2 shows the time series of annual rainfall over the Usangu Plains, while Figures 3 and 4 show the time series of annual flows and dry season flows in the Great Ruaha River as recorded at Msembe Ferry station respectively. Figure 5 presents the annual rainfall over the high catchment and the Usangu Plains for the period 1973 to 1984. Visually, the annual rainfall over the Usangu Plains and the annual flows at the Msembe station do not clearly depict any increasing or decreasing pattern unlike the dry season flows (Figure 4) which shows a declining pattern, much occurring from early 1990s.

>>>>Figure 2: Annual rainfall over the Usangu Plains (1958-2004) <<<<<

>>>> Figure 3: Annual flows in the GRR at Msembe Ferry (1958-2004) <<<<

>>>>Figure 4: Dry season flows (July to November) in the Great Ruaha River at Msembe Ferry (1958-2004) <<<<

>>>> Figure 5: Annual rainfall over the high catchment and the Usangu Plains <<<<

Statistical trend analysis results on rainfall and flows

Table 1 presents results of trend analysis on rainfall over the Usangu Plains and selected stations in the high catchment while Table 2 presents results of trend analysis on annual and dry season flows at Msembe Ferry. The results (Table 1) indicates that there was no significant decreasing or increasing trend in the annual rainfall in the high catchment but with the significant decreasing trend in annual rainfall over the Usangu Plains for the period 1958 to 2004 at the 95% level of significance. However, considering the period 1973 to 1984 there was no significant trends on the annual rainfall over the Plains.

The results (Table 2) indicates that there was no significant decreasing or increasing trend in the annual river flows for the Great Ruaha River downstream of the Usangu wetlands at the 95% level of significance. However, a significant downward trend in dry season flows has been depicted. The perennial rivers (Great Ruaha River at Salimwani and Mbarali River at Igawa) which contribute a large quantity of flow to the Usangu Plains and the most important rivers in the dry season indicated a no significant trend in annual flows.

>>>> Table 1: Summary of statistical trends in annual rainfall at some stations in the high catchment and in the Plains <<<<

>>>> Table 2: Summary of statistical trends in annual and dry season river flow at Msembe Ferry, annual flow for Great Ruaha River at Salimwani and Mbarali River at Igawa <<<<

The results concluded the fact that the amount of flows generated from high catchment has not statistically changed. Therefore if any change might have occurred in the high catchment could not have contributed to decreased dry season flows in the Usangu Plains. It was therefore the changes in land use and land cover in the plains which contributed to decreased dry season flows. A study by Kashaigili *et al.* (2006) on land use and cover changes in the Usangu area has revealed that there has been a great change in land use and cover mainly caused by increased anthropogenic activities within the catchment. For example there was a steady increase in cultivated area, from 121.2 km^2 to 874.3 km^2 between 1973 and 2000 while the woodland area decreased significantly over years. The minimum dry season area of the wetland declined significantly, with more changes occurring between 1984 and 2000 at 67% reduction.

Mean annual runoff and mean monthly flows for GRR

To discern seasonal changes within the annual cycle, changes in flow regimes were investigated. Figure 6 shows variations in flow regimes, based on mean monthly flow at Msembe Ferry for each of the three windows. As revealed in Figure 6, there is a slight change in peaking for the post-1985 period. It is possible that, this has contributed to attainment of higher flows earlier in February as compared to April for other periods.

>>>> Figure 6: Mean monthly flow at Msembe Ferry <<<<

This highlights the fact that there has not been a decrease across the full spectrum of the flow regime. In fact between 1974 and 1985 overall flows were lower (MAR was 51.6 m^3s^{-1}) than in either of the other two windows (i.e. MAR was 93 m^3s^{-1} and 80.5 m^3s^{-1} for pre-1974 and post-1985 windows respectively), but throughout this period the Great Ruaha River continued to flow in the dry season.

Flow duration curves for GRR

Figure 7 shows the flow duration curves of one day duration at Msembe Ferry drawn on a log scale to illustrate clearly the differences between low flows in the three different time periods. The flow duration curve (FDC) is cumulative frequency distribution that shows the percent of time that a specified discharge is equalled or exceeded during a period of interest. For example, Q_{95} is the mean daily flow that is exceeded 95% of the time. From Figure 7, the curves confirm the progressive and significant decline in flows lower than Q_{50}. Between the pre-1974 and post-1985 windows, Q_{95} and Q_{90} decreased from 2.84 m^3s^{-1} and 3.73 m^3s^{-1} to 0.0 m^3s^{-1} and 0.02 m^3s^{-1} respectively. The non-significant trend in annual flows can be attributed to the fact that wet season flows, which have not changed significantly, are much greater than dry season flows and hence dominate the analysis of the annual series.

>>>> Figure 7: Flow duration curves for the Great Ruaha River at Msembe Ferry <<<<

Frequency of occurrence of low flow events

The analysis for frequency of occurrence of low flow events for each time window revealed an increasing frequency and extension of low flow periods between the pre-1974 and post-1985 windows (Table 3). Between 1958 and 1973 there was not a single day with zero flow and the return period of a minimum one-day duration flow of 0.84 m^3s^{-1} was approximately 30 years. Between 1974 and 1985 short periods of zero flow occurred and a zero flow of one-day duration had a return period of approximately 4 years. Post-1985, zero flows of one-day duration occurred in all years and zero flow for durations of 60 days and greater were common.

>>>> Table 3: Comparison of minimum flows (m^3s^{-1}) for different durations for each of the time windows <<<<

The results of the analyses of flow at Msembe Ferry, confirm the progressive decrease in dry season flows in the Great Ruaha River since 1958. They indicate that changes to the hydrological balance have occurred upstream in the Usangu catchment, which is associated with the increased change in land use and covers.

Linkage between land use/cover and flow regimes changes

There is a clear linkage between land use/cover changes (Kashaigili *et al.*, 2006) and the changes in hydrological regime for the Usangu wetlands and the Great Ruaha River. According to Kiersch (2000), the impacts of land use practices on surface water can be two fold: (i) on the overall water availability or the mean annual runoff, and (ii) on the seasonal distribution of water availability. With regard to the latter, impacts on peak flows and impacts on dry season flows are of importance. A clear correlation existed between the detected changes and the change in hydrological regime of the Great Ruaha River. For example, there was a clear correlation (73%) between the decrease in average dry season flow at Msembe Ferry and the increase in total irrigated area within the Usangu area (Figure 8). This was to be expected, because though not extensively used for irrigation, it was due to the continued diversion of water to irrigation areas during the dry season, which was a major factor in reduced inflows to the wetland.

>>>> Figure 8: Comparison of dry season flow at Msembe Ferry and irrigated area in the Usangu Plains <<<<

Comparatively, the post-1985 period has experienced more changes in dry season flows, which were linked to changes in base flow within the Great Ruaha River catchment.

Discussion

Impacts of land use/cover changes on flow regime

It is important to note that the Usangu wetlands are maintained by the inflows from upstream areas and rainfall. Therefore any alteration in inflows may impact the general response of the wetland and the downstream flows for the Great Ruaha River. The expansions in agricultural activities are reflected on the increased land use transformations and the increased water abstractions for irrigation upstream of the wetland. The decrease in woodland areas (Kashaigili *et al.*, 2006) reflected on the increased timber logging activities and forest clearance for agriculture. The deforested woodland areas were mainly replaced by shifting cultivation and home gardens. This is still practised in Usangu and is one of the characteristic of the farming systems of the Usangu Plains. These land use changes, particularly the conversion of natural forests (woodland) for the post-1985 period must be responsible for the increased runoff generation process during the post-1985 as revealed by the analysis. Increase in storm runoff is mainly due to the reduced infiltration rate when forest is converted to other land uses (Kiersch, 2000; Allan, 2004). These changes in runoff generation are in agreement with the state of knowledge that reducing forest cover results into an increase in the water yield. However the sustenance of baseflow (groundwater) in the dry season becomes more questionable especially in the arid and semi-arid areas (Kiersch, 2000; Allan, 2004). In the post-1985, the woodland cover decreased to 22.3 percent of the study area (Kashaigili *et al.*, 2006); however, the changes in flow regimes were on the higher side as compared to the 1974-1985 period despite the decreased rainfall amount. The observed reduction in dry season flow after 1985 during low flow periods is accompanied by increased storm runoff during high rainfall months compared to that observed with the high percentage of forest cover. Such phenomena might be due to reduced infiltration as explained by

Bruijuzeel (1990) cited in Elkaduwa and Sakthivadivel (1998) that if infiltration opportunities after forest removal have decreased to the extent that the increase in amounts of water leaving the area as storm runoff exceeds the gain in base flow associated with decreased evapotranspiration, then the result is diminished dry season flow.

Therefore in comparison with the pre-1974 period which had substantial woodland cover, the significant deviation of flow regimes during the post-1985 (as well as during the 1974-1985) is a clear indication that the present management of agricultural land uses has failed to sustain the flow regimes closer to its initial existing conditions with substantial forest and wetland covers. Studies in other countries (e.g. Asia) have also shown the influence of land use changes on runoff generation (e.g. Madduma, 1997; Elkaduwa and Sakthivadivel, 1998). It is apparently clear that, land use and cover changes impact the flow regimes and have implications on the sustenance of dry season river flows. The major land use changes during the study period were the reduction in forested area, area of the vegetated swamp and increase in cultivated and bare land.

Implications of changed flow regimes

The modification of the land use and cover results in changes in time distribution of runoff with the reduction in low flows and an increase in high flows. The major impacts include the shrinkage of the Eastern wetland and decreased dry season flows downstream of the wetlands through the Ruaha National Park. Other impacts include decreased water availability for domestic uses. During focus group discussion and interviews it was revealed that in the dry season, women and children had to spend more time searching for water and some had to walk up to 20 km to locate sources (Kashaigili *et al.*, 2005). Therefore, the reduced low flows are reflected in reduced dependency on a reliable supply of good quality water downstream during periods of less rainfall.

The cessation of flows also adversely impacted on the fragile ecosystem of the Ruaha National Park. It also caused significant mortality of fish and hippopotami. For example, in the dry season of 2003, 5,000 fishes and 49 hippos died following the drying up of the GRR (Gladys, Ecologist for the Ruaha National Park, Pers. Comm. Cited in Kashaigili *et al*,. 2005). The lives of many animals that depend on the river for drinking water were disrupted which ultimately led to change in their behavior. Associated to that was the outbreaks of disease such as Anthrax which costed lives of many aquatic and wild animals. Kashaigili *et al.* (2005) furthermore highlighted on the impact of the drying up of the Great Ruaha River as the extinction of some bird species (i.e., the fresh oyster), extinction of the endemic fishes, and severely threat by lack of success in breeding for White Crowned Plover, whose only breeding ground in Tanzania is on the Great Ruaha River.

The change in river channel morphology experienced in the Usangu Plains is attributable to land use changes. This has resulted from the disturbance to the land forms, without appropriate soil conservation measures and seems to have aggravated the sediment supply into streams, sometimes with landslides resulting from the indiscriminate removal of the toe-support. The dominant cultivation practices involve those along the river banks and these compounds to the problem of sediment generation and destabilization of river banks. Also, poor fishing practices that involve construction of barriers across the river channel reduces sediment flushing because of reduced velocity of flow, enhancing sediment deposition and this contribute to changes in river courses.

Conclusions

The flow regime for the Great Ruaha River and the Usangu wetlands has changed significantly as a result of increased human interventions which have led to modification of land covers and change in land use. The modifications of natural vegetation cover as well as soil conditions usually lead to modified runoff production and consequently to changing flow regimes. Major changes have been observed in recent years which are related to such modifications.

The inflows that used to maintain the wetland has decreased because of intensification in agricultural activities and river flow regulations in the upstream. Since the maintenance of downstream flows depends on the inflows into the Eastern (*Ihefu*) wetland, the decreased inflows led to cessation of outflows at the exit of the wetlands which led to drying of the Great Ruaha River. In this case the inflows into the Eastern wetland were insufficient to surpass the evaporative loss in the wetland. Unlike the dry season, because of changes in land use and cover, more runoff is being generated in the wet season but not sustained during the dry season. This indicates an impact of changes on the base flows which are responsible for dry season maintenance.

The analysis for mean monthly flows separated to three time periods (i.e. pre-1974, 1974-1985 and 1986-2003) indicated variations in the peaking with the latter skewed to the left but relatively flat from February to April as compared to the former periods. In the latter period, the peak flow is attained in March while in the former years was in April. It is possible that, this has contributed to attainment of higher flow earlier in February as compared to April for other periods. The trend analysis on mean annual runoff did not reveal any significant trend at 95% level of confidence but a declining trend in low flows has been detected. The analysis for Flow Duration Curves confirmed a decline in low flows likewise the frequency analysis for low flows.

The study concludes that the modification of the land use and cover has resulted into changes in time distribution of runoff within the catchment. The study highlights the effects of land use /cover changes on ecosystems and water resources for an informed decision on proper catchment planning and management. A follow-up study is required to investigate appropriate interventions and alternative livelihood strategies in the area to ameliorate the prevailing situation.

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References

Allan, J.D. (2004). Landscapes and Riverscapes: The influence of land use on stream ecosystems. *Annual Review Ecology Evolution System*, 35:257–284

Brown, C. and King, J. 2003. Environmental Flows: Concepts and methods. *In Davis, R. and Hirji, R. (eds) Water Resources and Environment Technical Note C.1*. Washington, D.C.: The World Bank.

Bruijnzeel, L. A. (1990). *Hydrology of moist tropical forests and effects of conversion: A state of knowledge review*. UNESCO International Hydrologic Programme, Amsterdam: Humid Tropics Programme, Free University.

Elkaduwa, W. K. B. and Sakthivadivel, R. (1998). Use of historical data as a decision support tool in watershed management: A case study of the Upper Nilwala basin in Sri Lanka. Research Report 26. Colombo, Sri Lanka: International Water Management Institute.

Fry, M.J., Folwell, S.S. and Tate, E.L. 2001. *ARIDA Operation Manual*. Centre for Ecology and Hydrology, Wallingford, UK.

Helsel, D.R and Hirsch, R.M. 1993. Statistical methods in water resources. Elsevier.

Kadigi R.M.J., Kashaigili, J.J. and Mdoe, N.S., 2004. The economics of irrigated paddy in Usangu basin in Tanzania: water utilization, productivity, income and livelihood implications. Elsevier Journal, special edition of Physics and Chemistry of the Earth 29: 1091-1100.

Kashaigili, J.J. 2006. Landcover dynamics and hydrological functioning of wetlands in the Usangu Plains in Tanzania. PhD Thesis, Sokoine University of Agriculture.

Kashaigili, J.J., Mbilinyi, B.P., McCartney, M. and Mwanuzi, F.L. (2006). Dynamics of Usangu Plains wetlands: use of Remote Sensing and GIS as management decision tools. Journal of Physics and Chemistry of the Earth 31: 967–975.

Kashaigili, J.J. and Mahoo, H.F. (2005). Towards valuation of wetlands in the Usangu Plains for environmental management: Livelihoods issues and perceptions. In Proceeding of conference on Water for Sustainable Socio-Economic Development, Good Health for All and Gender Equity, 1st – 3rd November 2005, Ezulwini, Swaziland.

Kashaigili,J.J., Kadigi, R.M.J, Lankford, B.A, Mahoo, H.F. and Mashauri, D.A. (2005). Environmental flows allocation in river basins: Exploring allocation challenges and options in the Great Ruaha River catchment in Tanzania. *Journal of Physics and Chemistry of the Earth*, Volume 30, Issues 11-16: 689-697.

Kiersch, B. (2000). Land use impacts on water resources: a literature review. FAO E–workshop on Land-Water Linkages in Rural Watersheds. [www.fao.org/ag/agl/watershed/watershed/en/mainen/index.stm] site visited on 22/11/2006.

Madduma, B, C. M. (1997). Land-use changes and tropical stream hydrology: Some observations from the upper Mahaweli Basin of Sri Lanka. In Process and forms in geomorphology. (Edited by Stoddart D.R.). London and New York: Routledge.

Moirana, L. and Nahonyo, C.L. 1996. Why the Usangu Plains should be an environmentally protected area (Usangu Game Reserve).

Mtahiko, M.G.G., Gereta, E., Kajuni, A., Chiombola, E.A.T., Ng'umbi, G.Z., Coppolillo, E., Wolanski, E., (2006). Towards an ecohydroloogy-based restoration of the Usangu wetlands and the Great Ruaha River, Tanzania. Wetlands Ecology and Management

National University of Ireland (NUI) 2002. Galway Flow Forecasting System. Department of Engineering Hydrology, National University of Ireland, Galway, Ireland.

Postel, S. and Richter, B. 2003. *Rivers of life: Managing water for people and nature.* Washington: Island Press.

SMUWC (Sustainable Management of Usangu Wetlands and its Catchment). 2001a. Baseline 2001. [http://www.usangu.org/] site visited on 20/08/2003.

SMUWC. 2001b. Final Report, *Water Resources*. Supporting report 7, Volume 3. Directorate of Water Resources Dar es Salaam, Tanzania. 203 pp.

Yawson, D.K. 2003. Development of a Decision Support System for the Rufiji River Basin – Tanzania. A Ph.D. Thesis submitted to the University of Dar Es Salaam, Tanzania.

Tables

Table 1: Summary of statistical trends in annual rainfall at some stations in the high catchment and in the Plains

Description of parameter	Start year	End year	No. of years	Mean Annual Rainfall (mm)	Slope of trend line (mm/year)	t-statistics	t-critical	Remarks
High catchment								
Annual rainfall at Mbeya Maji	1961	2003	43	943.580	-3.198	-1.540	2.019	Not a significant decreasing trend
Annual Rainfall at Tanganyika Wattle	1928	2003	76	1103.470	2.079	1.893	1.993	Not a significant increasing trend
Annual rainfall at Ichenga Agriculture	1958	2001	44	1343.040	-4.456	-1.668	2.018	Not a significant decreasing trend
Annual rainfall at Mbeya Met.	1956	1999	44	973.070	2.541	0.986	2.018	Not a significant decreasing trend
Areal annual rainfall (1973-1984)	1973	1984	12	1536.3	-2.372	0.381	2.228	Not a significant decreasing trend
Usangu Plains								
Annual rainfall over the Usangu Plains	1958	2004	47	701.470	-4.456	-3.020	2.016	Significant decreasing trend
Annual Rainfall over the Plains (1973-1984)	1973	1984	12	699.200	2.592	0.676	2.228	Not a significant increasing trend

Table 2: Summary of statistical trends in annual and dry season river flow at Msembe Ferry, annual flow for Great Ruaha River at Salimwani and Mbarali River at Igawa

Description of parameter	Start year	End year	No. of years	Slope of trend line	t-statistics	t-critical	Remarks
Annual river flow at Msembe	1958	2004	47	-18.890	-0.546	2.016	Not a significant trend
Dry season flow at Msembe	1958	2004	47	-2.730	-4.480	2.016	Significant decreasing trend
Annual flow for Great Ruaha River at Salimwani	1955	2004	50	20.702	0.910	2.013	Not a significant trend
Annual flow for Mbarali river at Igawa	1955	2004	50	-9.974	-0.709	2.013	Not a significant trend

Table 3: Comparison of minimum flows (m^3s^{-1}) for different durations for each of the time windows

Window	Duration			
	1-day	10-day	30-day	60-day
1958-1973	0.84	0.89	1.04	1.34
1974-1985	0.00	0.00	0.01	0.11
1986-2004	0.00	0.00	0.00	0.00

Figures

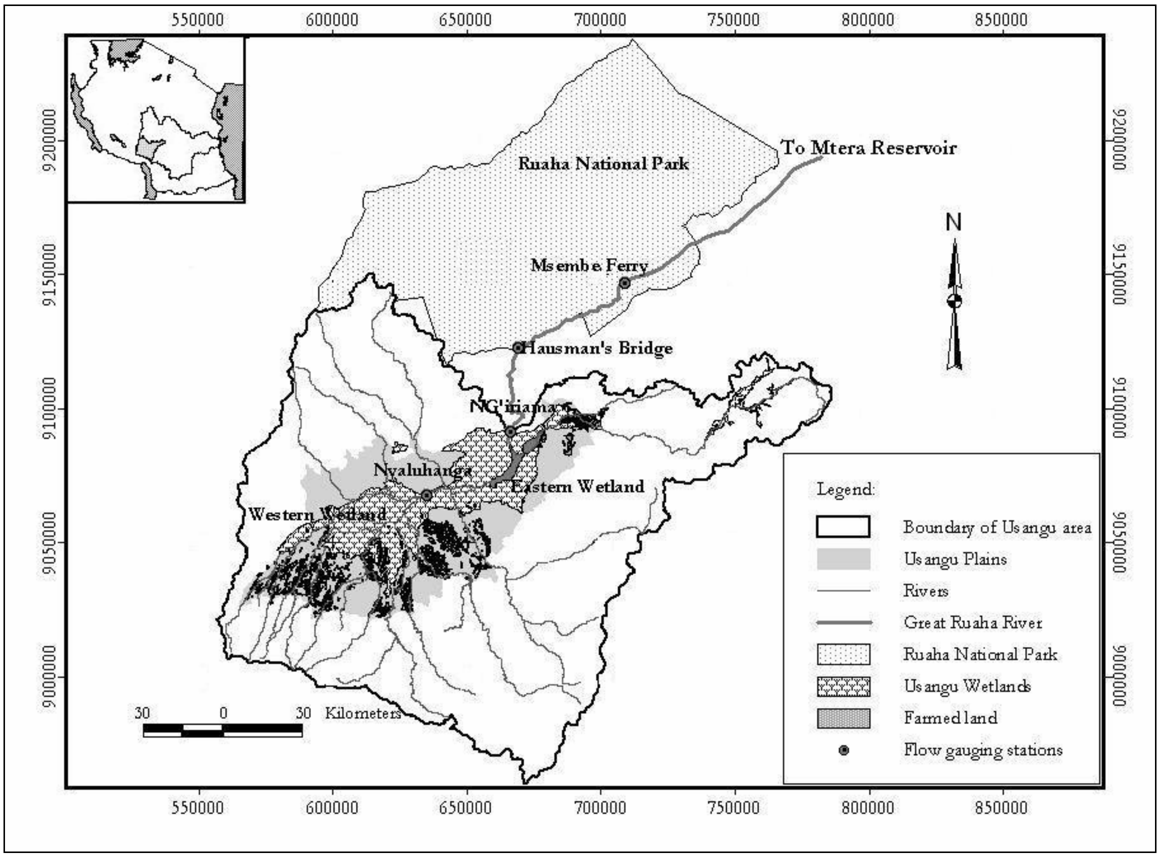


Figure 1: Map of study area including Ruaha National Park and Msembe Ferry Gauging station

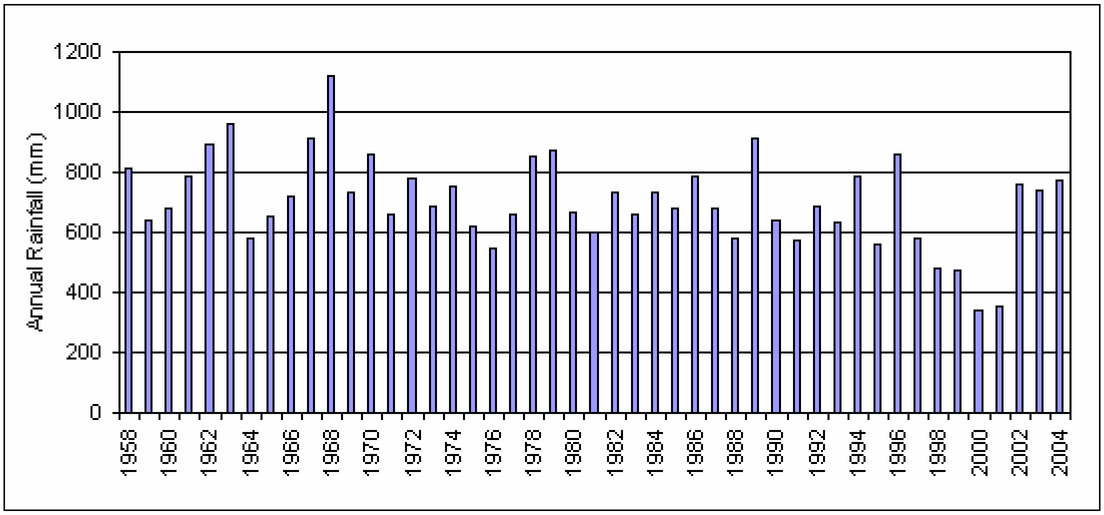


Figure 2: Annual rainfall over the Usangu Plains (1958-2004)

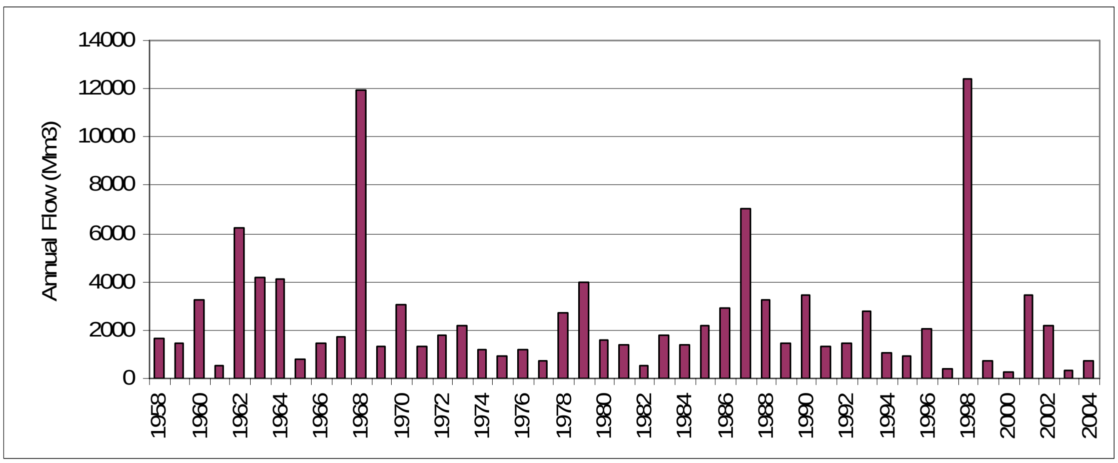


Figure 3: Annual flows in the GRR at Msembe Ferry (1958-2004)

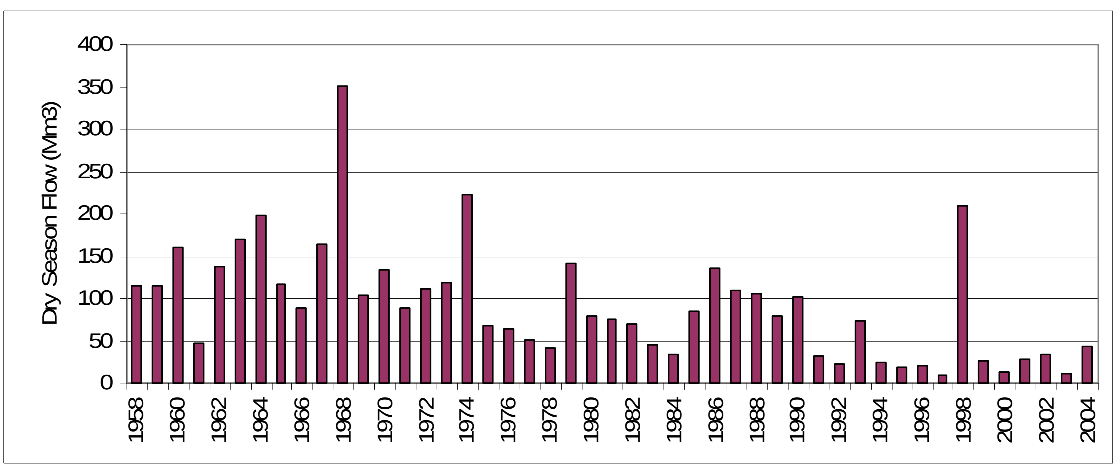


Figure 4: Dry season flows (July to November) in the Great Ruaha River at Msembe Ferry (1958-2004)

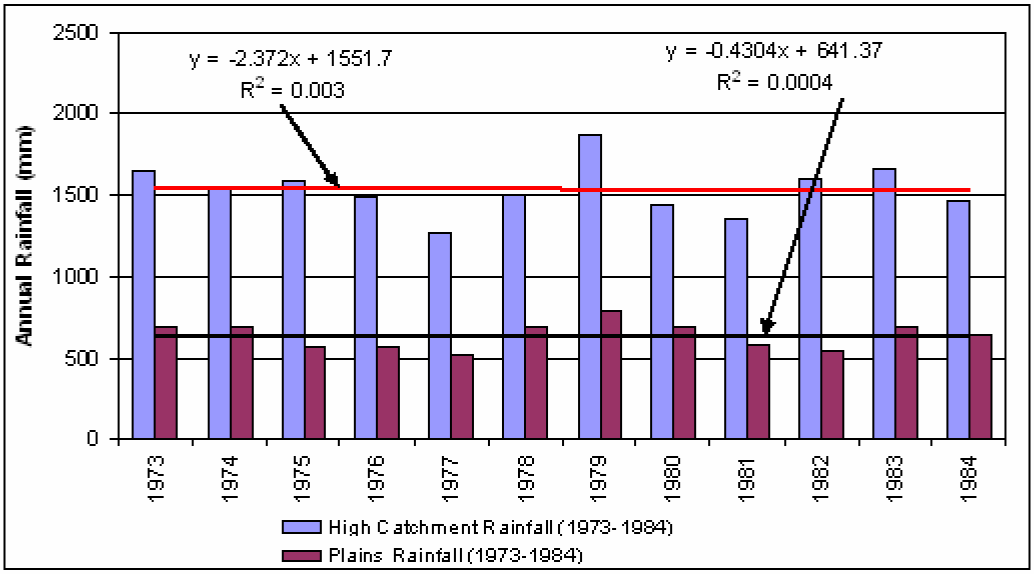
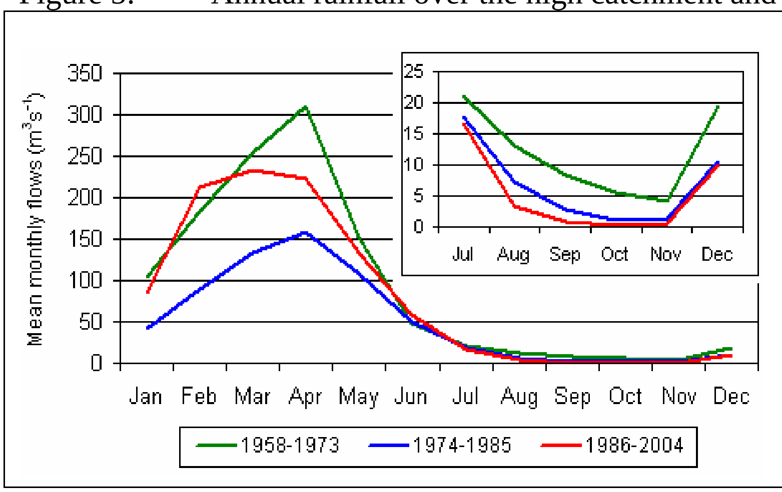
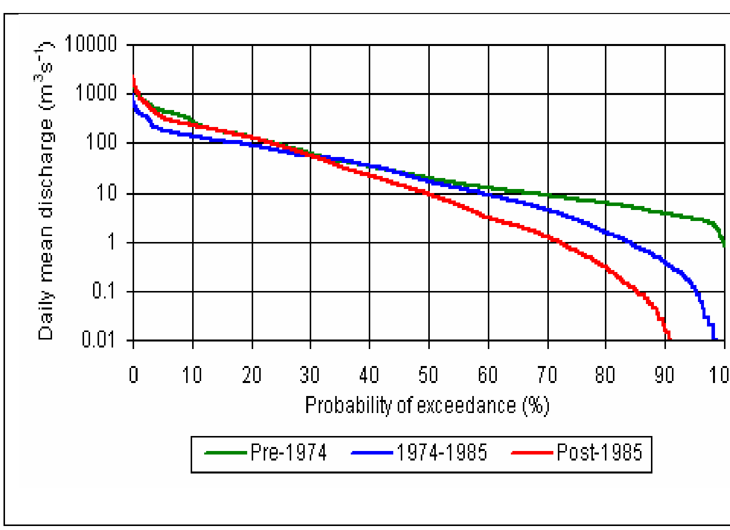


Figure 5: Annual rainfall over the high catchment and the Usangu Plains



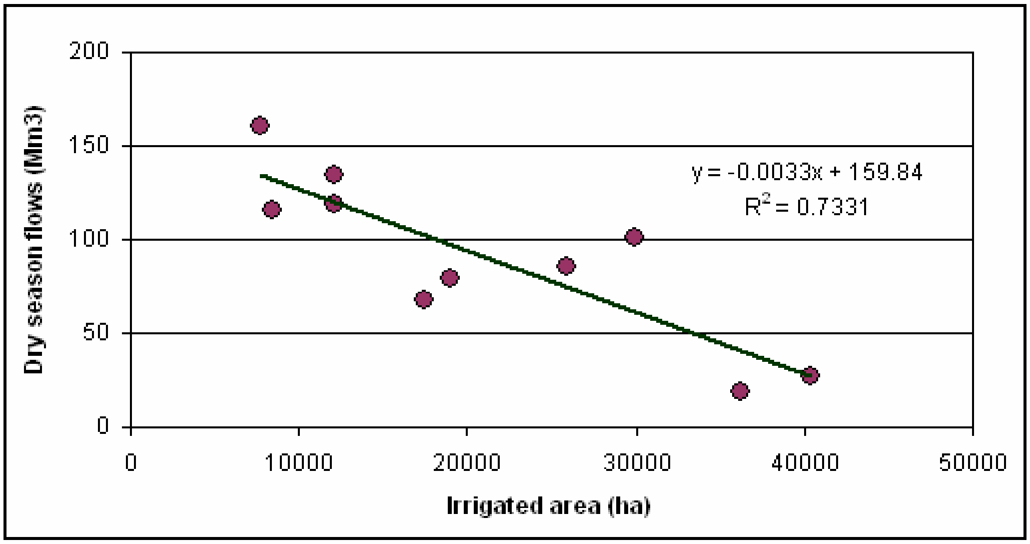
	1958-1973	1974-1985	1986-2003
Jan	104.34	42.00	85.58
Feb	183.65	90.61	212.06
Mar	254.98	133.21	233.43
Apr	309.83	158.63	222.83
May	151.47	108.13	133.79
Jun	47.59	48.97	57.34
Jul	21.20	17.91	16.76
Aug	13.07	7.25	3.25
Sep	8.34	2.84	0.81
Oct	5.50	1.09	0.26
Nov	4.14	1.46	0.57
Dec	19.42	10.42	9.93
MAR	**93.0**	**51.62**	**80.48**

Figure 6: Mean monthly flow at Msembe Ferry



	1958-1973	1974-1985	1986-2003
Q_{95}	2.84	0.11	0.0
Q_{90}	3.73	0.37	0.02
Q_{75}	7.09	2.77	0.65
Q_{50}	19.23	16.51	9.04
Q_{25}	91.28	68.09	86.68
Q_{10}	281.01	138.86	228.73
Q_{5}	445.09	181.50	325.79

Figure 7: Flow duration curves for the Great Ruaha River at Msembe Ferry



Source: Kashaigili (2006)

Figure 8: Comparison of dry season flow at Msembe Ferry and irrigated area in the Usangu Plains