Integrated Hydrological Modelling of Wetlands for Environmental Management: The Case of the Usangu Wetlands in the Great Ruaha Catchment

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Abstract

Knowledge of wetland hydrology and quantification of water inputs and outputs are prerequisites to understanding wetland environments and determining their vulnerability to change. To get a better understanding of the dynamics of wetland change in the Usangu Plains, a study was conducted to: a) investigate the effects of human interventions on the wetlands, and b) determine the amount of dry season inflow required to maintain environmental flows downstream of the wetlands. The study integrated hydrologic data, remote sensing and GIS techniques to study the dynamics and spatial response of the wetlands. A monthly water balance model was developed for the wetlands to determine the major components of the water budget. The results of the analyses indicate that the wetlands have changed appreciably in size over recent years and the inflow volumes have decreased with time as a result of increased human interventions. The dry season vegetated swamp cover, a major component of the swamp, decreased by 67% over the 16 years from 1984 to 2000. If this trend continues, it is possible that the wetlands will undergo a change which will be extremely difficult to reverse. Downstream of the wetlands an environmental flow of 0.5 m^3/s *was estimated. To maintain this outflow, the corresponding inflow volume into the wetlands was estimated to be* $7m^3/s$*. To achieve this, the available dry season water resource will have to be divided 20% for anthropogenic needs and 80% for the environment to feed the wetland. The study has demonstrated the need for integrated water resources management to balance the demands between different sectors and enable appropriate catchment interventions to ensure the sustainability of wetland resources.*

Key words*:* Wetlands, Environmental flows, Modelling, Water balance, GIS, Remote sensing, Integrated water resources management

Introduction

Wetlands exist in the landscape where the water balance ensures an adequate water supply at or near the surface (Price *et al.,* 2005). Therefore sustained wetland functioning requires proper land use and water management. To achieve this, an integrated understanding of the spatial dynamics and hydrological balance of the wetland ecosystem, among other factors, is required. An important note is that wetlands are linked through the hydrological system to upstream and downstream areas. What happens upstream will affect a wetland, while what happens in a wetland will affect the environment and people living downstream. As Abbot and Hailu (2001) argue, wetlands may be influenced by broad environmental changes, such as deforestation and climate change driven by socio-economic factors, including national economic policies and local market conditions. Worldwide it has become evident that many aquatic ecosystems have changed as a result of modification of the flow regime caused by river regulation (Poff *et al.,* 1997; McCully, 2001; Tharme, 2003; Postel and Richter, 2003; Bunn and Arthington, 2002; and Brown and King, 2003). The modification of the hydrologic regime can indirectly alter the composition, structure, or function of aquatic, riparian and wetland ecosystems through their effects on physical habitat characteristics, including temperature, oxygen content, water chemistry and substrate particle sizes (Dynesius and Nilsson, 1994; Richer *et al.*, 1996).

The importance of hydrology for the maintenance of wetlands is widely recognised. However, knowledge of the interlinkages between upstream land use and water diversions and the resulting impacts on wetland hydrology and spatial dynamics as well as the implications for downstream flows is still limited. Such information is required for informed decision-making and for influencing policy changes towards sustainable and “wise use” of wetlands. Hayashi and Rosenberry (2001) note the need for understanding the linkages between adjacent uplands and wetlands because of their importance in maintaining the hydrological and ecological integrity of wetlands. Also, Hill (2000) and Bedford (1999) both stress the need for a catchment /landscape approach to understand upland-wetland linkages and the potential impact of individual and cumulative catchment disturbance on the receiving wetland. Therefore, an integrated understanding both upstream and downstream of the wetland is required.

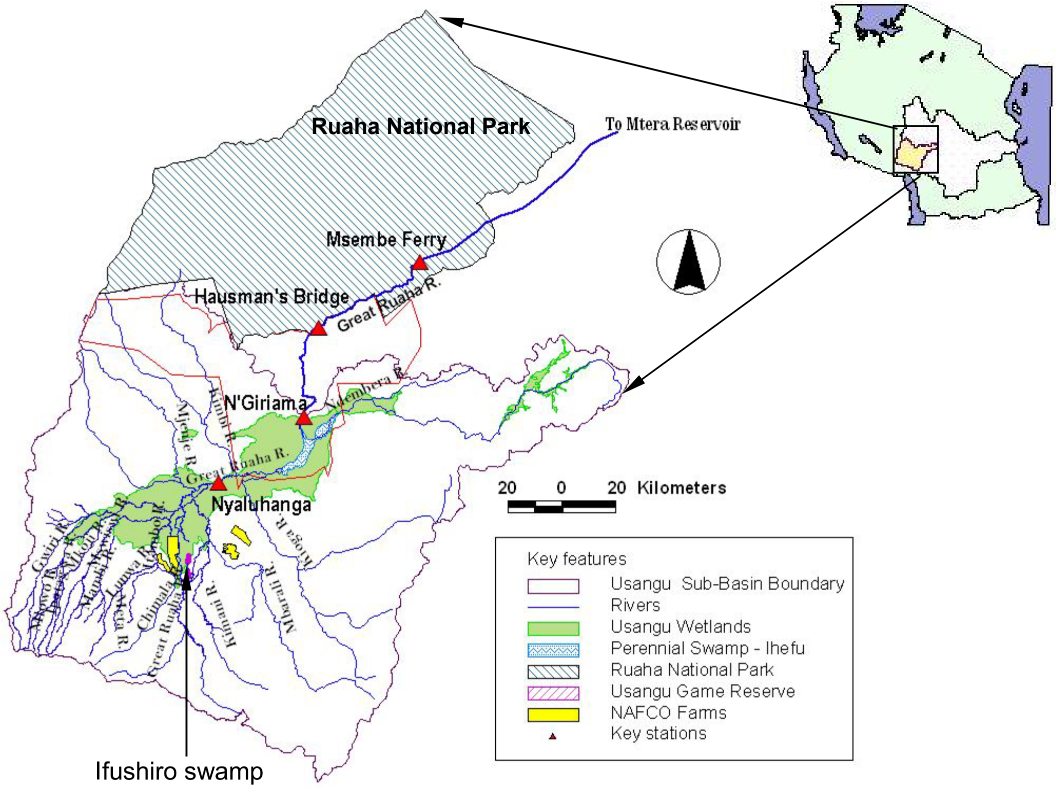
This paper is based on the research undertaken to improve understanding of the spatial dynamics and the hydrology of the Usangu Plains wetlands within the Great Ruaha Catchment in Tanzania and the impact of increased upstream water diversions for anthropogenic activities on wetlands and the downstream. The work was divided into three parts: a) an analysis of land cover change between 1973 and 2000 using satellite imagery, b) an evaluation of changes in flow downstream of the wetland over the same time period, and c) an estimate of the dry season inflows required to maintain predetermined flows downstream of the wetlands.

Description of the study area

Location and topographical features

The Usangu Plains are located in the southern western part of Tanzania between longitudes 33^{o}E and 35^{o}E and latitudes 8^{o}S and 9^{o}30’S (Figure 1). They form the upper catchment of the Great Ruaha River. This river, in turn, is a main tributary to the Rufiji River, the largest drainage basin in Tanzania, covering some 174 800 km^{2}, or about 18% of the area of mainland Tanzania. The plains cover an approximate area of 15,560 km^{2}. The plains are flat and surrounded by the Poroto and Kipengere mountains in the Southern Highlands between Mbeya and Iringa, and the Chunya mountains. They lie at an average elevation of 1100 m above mean sea level (amsl) while the surrounding hills are at average elevation of 3000 m amsl. The Usangu wetlands are located at the centre of the Usangu Plains. They comprise the western and eastern wetlands joined by a narrow band of land along the river at Nyaluhanga and intermediate wetlands (i.e., the Ifushiro swamp).

Figure 1: Map of Tanzania showing location of the study area



Drainage pattern

The major rivers (perennial) draining the Usangu Plains are the Great Ruaha, Mbarali, Kimani, Chimala and Ndembera. The first four account for 70% of measured average annual flow, while the Ndembera accounts for an additional 15% (SMUWC, 2001 a). The small rivers include Umrobo, Mkoji, Lunwa, Mlomboji, Ipatagwa, Mambi, Kioga, Mjenje, Kimbi, Itambo and Mswiswi. Most of these rivers, especially in the southwest, are perennial but make zero contribution to inflows to Usangu wetlands in the dry season. The major water supplier to the Usangu wetlands is the Great Ruaha River (GRR), which flows as a single river after being joined by other rivers in the western wetland to supply the eastern wetland. A natural rock outcrop at N'Giriama controls the outflow from the eastern wetland. Downstream of the Usangu wetlands the GRR flows first through the Ruaha National Park (RNP) serving as the main source of water for the Park in the dry season. Thereafter, together with the Little Ruaha River and Kisigo River, the river supplies water to the Mtera and Kidatu hydropower reservoirs.

Climate

The rainfall regime in the area is unimodal with a single rainy season from November to May. Rainfall is brought by monsoon winds associated with the biannual passage of the Inter-tropical Convergence Zone (ITCZ), although the spatial distribution of rainfall is also strongly influenced by topography. The rainfall distribution varies greatly across the catchment and rainfall amounts are strongly correlated to the elevation of the terrain with the higher areas receiving average annual rainfall ranging between 1 000 mm to over 1 600 mm. In contrast, rainfall on the Usangu Plains is low, ranging between 500 and 700 mm annually.

Land cover and land use

There is distinct variability in land cover, use and vegetation patterns from the highlands to the lowlands. Miombo woodland dominates naturally throughout the highlands except at the higher altitudes. At higher altitudes (>2 000 m amsl), there is remnant montane humid forest, giving way to afro-alpine vegetation (Hagenia forest, Erica, and Alpine grassland) (SMUWC, 2001 a). Cultivation is extensive in the lower rolling hills northeast, in Iringa Region, the Mbarali sub-catchment and the south-western part of the Mkoji sub-catchment. The lowland areas (below 1100 m amsl) may be divided into two broad areas: (i) the wetland, and (ii) the fans with their different vegetation composition and characteristics. The fans are alluvial deposits spreading from the base of the escarpments onto the plains. The southern fans are naturally occupied by thorny woodland and/or wooded grassland, with *Acacia tortilis, Commiphora spp.,* and *Lannea humilis.* However, this has been largely cleared and replaced by cultivation or secondary thorn bush. The fans are fertile and most agricultural activities are concentrated in this area. The large rice irrigation schemes (Kapunga and Mbarali rice farms) are found in the fans. In the lower fans vegetation grades into *Acacia kirkii* bush mixed with open grassland. The grass emerges with the rains but is rapidly removed by livestock, and for much of the year these 'open grasslands' appear as bare soil. The *Acacia tortilis* - *Commiphora* thorny bush is therefore less extensive and soon gives way to miombo-transitional vegetation types. The Usangu wetlands contain a mix of seasonally flooded open grassland (*mbuga*), seasonally flooded woodland, and a smaller perennially flooded swamp (*Ihefu*). The perennial swamp is dominated by water lilies and/or water chestnut (floating) including herbaceous vegetation. Also *Vossia*, which is indicative of unstable hydrological regime, has been found (Denny, 1985).

Water uses and users in the Great Ruaha River catchment

The Great Ruaha River Basin is a complex basin with diverse multi-sectoral water uses and users. A great proportion of the population (about 80%) of the basin is sustained by irrigation and water-related livelihoods such as fishing and livestock keeping. Irrigation in the basin is the major activity and the largest water user, mainly during the dry season. The dry season irrigation is concentrated in the upper courses of the rivers, irrigating high-value crops such as green vegetables, onions, tomatoes, beans and maize.

In contrast to the wet season, the dry season is a water-scarce period associated with conflicts and disputes over access to water. During the dry season, villagers along the rivers in the mid-catchments divert water to both fallow and cropped irrigated fields in plot-to-plot distribution and to the villages for consumptive domestic uses as well as for brick-making. Downstream of the irrigation schemes, with the exception of the major perennial rivers, most rivers dry up. However, even the perennial rivers retain minimal flows in the dry season. Since 1993, dry season flow in the GRR has been so low that water levels in the eastern wetland (Ihefu) have dropped below the top of the rock outcrop at the outlet, with the result that flows downstream of the wetland have ceased completely. Failure in outflows from the Eastern wetland has resulted in extended periods of zero flow through the RNP (Table 1).

Table 1: Drying up of the Great Ruaha River for the period from 1994 to 2004.

Year	Date flow stopped	Date flow started	Period of no flow (days)	Annual rainfall (mm)
1994	17 November	15 December	28	na
1995	19 October	23 December	65	388**
1996	17 October	16 December	60	401
1997	20 September	22 November	63	815
1998	18 November	9 March 1999*	87	392
1999	21 September	20 December	90	527
2000	17 September	22 November	66	960
2001	12 November	23 December	41	706
2002	2 November	24 December	52	619
2003	21 September	16 January 2004*	104	532
2004	3 November	4 December	31	na

Source: Sue Stolberger's records at Jongomero Camp in the Ruaha National Park (UTM: 679147E 9127828N)

NOTE: * with some intermediate start and stop to flow
** incomplete records
na - not available

The drying-up of the GRR in the RNP has caused a lot of environmental concern and led to the Government of Tanzania committing its support for a program to ensure that year-round flow is restored to the GRR by 2010. It is a challenge that has brought a number of studies (i.e., SMUWC, 2001; RIPARWIN[1] - ongoing) to investigate the causes of the drying up and to suggest mitigation measures to balance various sectoral demands. Also, the Tanzania Government has recently signed up to the Ramsar convention on wetlands (13 August 2000), so it is bound to the "conservation and wise use" of wetlands. Although the Usangu wetlands have not yet been designated as a Ramsar site, signing the convention commits the country to a general stewardship of wetlands (Frank *et al.,* 2004). Managing of wetlands is a comparatively new phenomenon in many developing countries; therefore new thinking is required on how the water for the wetland can be considered equally with other water users within a catchment. In this context, the dynamics, hydrology of the wetlands and the routing requirements need to be studied well so that the amount of water required to sustain the wetlands and the linked downstream water needs can be ensured. There is also a need to increase understanding amongst the range of stakeholders in the basin of the problems of not managing the wetlands.

Materials and methods

To gain an understanding of the dynamics of wetlands and the changes that have taken place over time, the impact of changes to the downstream end of the eastern wetlands and an estimate for the environmental flows onto the wetlands and the Great Ruaha River through the Ruaha National Park, three basic lines of research were formulated: a) use of satellite images to investigate changes in land cover and wetland extent over time; b) analyses of flow data to determine changes in flow regime downstream of the wetlands and to assist in identifying desired dry season environmental flows; and c) development of a simple model of wetland hydrology to determine the inflows to the wetland required to sustain specified dry season flows downstream of the wetlands. The analysis considered three

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[1] RIPARWIN stands for Raising Irrigation Productivity and Releasing Water for Intersectoral Needs. It is a River Basin Research project.

periods of time or “windows”: pre-1974, between 1974 and 1985 and post-1985. These windows depict the different levels of expansion of human activities and developmental interventions in the area. The pre-1974 period is regarded as a natural state period with limited human interventions. The 1974-1985 period represents an intermediate period characterised by the start of various human developmental interventions. The post-1985 period is characterised by greater water abstraction as a result of increased population growth, increased irrigable areas, increased pastoral activities, increased catchment degradation, expanded market and increased conflict over the available resources.

Methods

Image analysis and change detection

To ensure the accurate detection of land cover change and reduce effects of seasonal phenological differences (Jensen, 1996), images acquired during the same anniversary period were collected (Table 2). A base map and colour composite image from the 7th September 2000 image were used for ground-truthing. Standard techniques of image analysis were conducted to determine land-cover changes over time. Details are presented in Kashaigili *et al.* (2004).

Table 2: The input data - Landsat TM and MSS

Image	Date of acquisition	Season	Cloud cover %
Landsat MSS	4th September 1973	Dry	0
Landsat TM	15th June 1984	Wet	11
Landsat TM	3rd September 1984	Dry	0
Landsat TM	22nd August 1991	Dry	0
Landsat TM	14th August 1994	Dry	1
Landsat TM	26th May 2000	Wet	8
Landsat TM +	7th September 2000	Dry	10

Hydrological analyses to determine historic change and estimate for environmental flows

Historical river flow changes

Comparative analysis of hydrological year (August-July) flows recorded at Msembe gauging station, located downstream of the wetlands within the Ruaha National Park for different windows, was done. Changes in flow characteristics relative to the pre-1974 window were determined.

Environmental flows assessment

Due to the paucity of available data on habitats, substrata and quality, the hydrological approach (method relying on historical flow records) was used to evaluate the environmental flows (EF) for the GRR downstream of the Usangu wetlands. This entailed analysis of flow duration curves and low flows, utilizing data from Msembe. Flow duration curves were derived using the Galway Flow Forecasting System (GFFS) software and flows at 95, 75 and 50 exceedence percentiles were extracted.

The flows at 95% exceedence percentile (i.e. Q_{95}) for the post-1985 (present situation) and the pre-1974 (natural condition) periods provided the range for environmental flow values. From the range, Target Environmental Flow (TEF) values at intervals of 0.1 m^3/s were derived. The derived flows were added to the discharge records at Msembe for the period of low flows (July to November) one at a time. By using the regression equation between Msembe station and N'Giriama exit, the flows at N'Giriama were reconstructed. These were then used as input in the wetland simulation model to estimate the amount of inflow required onto the wetland to maintain the specified outflow at the exit. Before recommending environmental flows, the available water resources had to be assessed considering perennial rivers, including anthropogenic demands. The first estimate for an environmental flow was arrived at through trade-off analysis between environment and anthropogenic water needs.

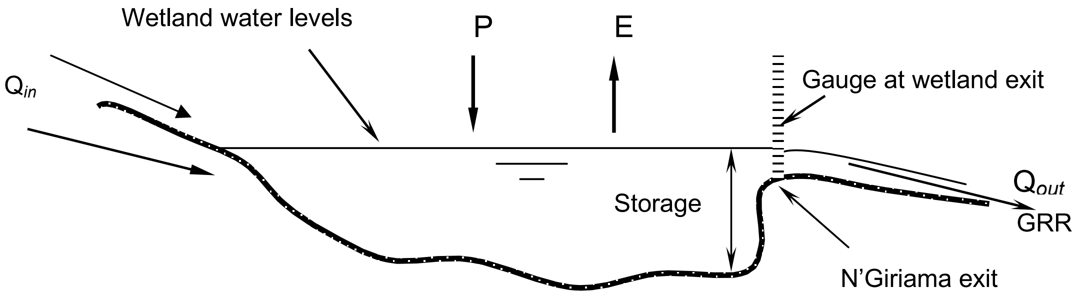
Development of wetland hydrology model

One of the primary objectives of this study was to evaluate the inflows required to generate specified dry season outflows from the Eastern wetland. It is important to note that the outflow for downstream needs depends on the hydrological balance of the Eastern wetland. However one of the challenges is the fact that inflows to the wetlands are not monitored. Therefore, in order to address this challenge, an EXCEL based water balance model was developed to simulate the inflows over the period 1958 to 2004. The simplified wetland water balance model (Mitsch and Gasselink, 1993) is presented in Equation 1.

$$\Delta S = P + Q_{in} - E - Q_{out} \tag{1}$$

where: ΔS is change in water stored within the wetland
Q_{in} is total inflow to the wetland including contributions from groundwater
Q_{out} is total outflow from the wetland at N'Giriama exit
P is rainfall falling directly onto the wetland (a function of wetland surface area)
E is evaporation from the wetland (a function of wetland surface area)

Figure 2: Conceptualisation of the eastern wetland as a simple reservoir



The model treated the wetland as a simple reservoir (Figure 2), with dependent variables of storage and area, as well as outflow controlled by the water level at the outlet (i.e. the rock sill at N'Giriama). Storage-area and storage-elevation relationships derived during the SMWUC study (SMWUC, 2001b) were modified and fitted with the power function to calculate the wetland area and the volumes of water stored from water-levels at N'Giriama. Rainfall data were obtained from nearby meteorological stations while evaporation data from the Dodoma meteorological station was used. The Dodoma station was found to represent evaporation from the Usangu Plains (SMUWC, 2001b; Yawson, 2003). Evaporation from the wetland surface was assumed to be at potential rates in all months. Outflow was calculated using data from Msembe station. It is important to note that discharge from the Eastern wetland is not monitored because of difficulties in accessibility coupled with financial constraints for maintaining the N'Giriama station. The first water levels were measured at N'Giriama during the SMUWC project, and measurements ceased shortly after the SMUWC project ended in 2002. Hence measured levels are available only for the period 20/10/1998 to 30/10/2002. To extend the water-level data series at N'Giriama, the developed relationship (SMUWC, 2001c) between two gauging stations located on the Great Ruaha River, namely Hausman's Bridge (1KA27) and Msembe Ferry (1KA59) (Figure 1) was used. Hausman's

Bridge, which is located 30 km downstream of the N'Giriama outlet, was assumed to have the same flow as at N'Giriama, since there are no major abstractions or tributary inflows between the two locations. The inflows were calculated as the unknown term in the water budget (Equation 1).

Results and discussion

The detected landuse/cover change

The comparative analysis of the land uses and covers between 1973-1984, 1984-1991, 1991-1994, and 1994-2000 identified the changes that took place in the different time horizons. Eight covers (closed woodland, open woodland, vegetated swamp, closed bushland, open bushland, bushed grassland, cultivated land and bareland) were identified. To represent the changes, four covers (vegetated swamp – VS, closed woodland – CW, open woodland – OW and cultivation+bareland – CB) were selected from the eight classes and their percentage area coverages are presented in Figure 3 for the years 1973, 1984, 1991, 1994 and 2000. Other land covers were grouped together as "Others". It is important to note that the three covers (VS, CW, and OW) were selected because they represent a major portion of the wetlands in the Usangu Plains and CB gives a direct indication of human modification.

Figures 4 and 5 present the land use/cover change maps for the 1984 to 2000 period. Table 3 presents the area coverages of different land covers and annual rainfall for the plains. The total area of vegetated swamp in the dry season, which occupied 15,455 ha (i.e. 5% of the total geographical subset study area of 316,979 ha) in 1973 increased to 26,928 ha (8%) in 1984, indicating an increase in vegetated swamp area of about 3%. Between 1991 and 1994 it decreased to 26,861 and 19,746 ha respectively. In 2000, the swamp area coverage decreased to 8,777 ha (i.e., 3% of the subset study area) signifying a 67% reduction in vegetated swamp area from 1984 to 2000.

The increase in vegetated swamp area between 1973 and 1984 was further investigated to identify its causes. A linear trend analysis on rainfall for the period 1973 to 1984 (Table 4) revealed that there was no statistical significant increase in rainfall amount between 1973 and 1984 at the 95% confidence level. Likewise, the analysis for inter-annual variability did not reveal a significant change in rainfall patterns. It is possible that the apparent increase in vegetated swamp cover is an artefact of the different resolutions of the two images (i.e., Landsat MSS of 1973 - 79m x 79m while Landsat TM of 2000 was 30m x 30m). Some studies (Zhou *et al.,* 2004 b; Benson and MacKenzie, 1995; Frohn *et al.,* 1998) have indicated the effects of differences in spatial resolutions on change detectability. For example, a study by Zhou *et al*. (2004 a) on detecting and modelling land use change using multi-temporal and multi-sensor imagery concluded that poor classification results were associated with lower spatial resolution.

Table 3: Comparison of annual rainfall and dry season area of selected land covers

	Wet season			Dry season			
Year	Annual Rainfall For Plains mm	Vegetated Eastern wetland (km^2)	Vegetated Ifushiro swamp (km^2)	Vegetated Eastern wetland (km^2)	Vegetated Ifushiro swamp (km^2)	Bareland + cultivation area (km^2)	Closed+open woodland area (km^2)
1973	696.4			119.62	34.63	121.16	1700.57
1984	641.3	436.36	116.45	269.28	46.33	318.55	992.43
1991	519.2			204.09	36.60	613.02	1144.60
1994	791.8			187.94	21.01	677.14	886.37

2000	403.0	318.06	83.20	87.77	4.84	807.65	706.44

Table 4: The statistical trend analysis results on rainfall over the plains for the period 1973-1984

Description of parameter	Starting year	Ending year	No. of years	Slope of trend line	t-statistics	t-critical	Remarks
Annual rainfall over the Usangu Plains	1958	1973	11	-0.733	-0.094	2.262	No significant trend
Rainfall for April over the Plains	1958	1973	11	-1.710	-0.728	2.262	No significant trend
Rainfall for February to April over the Plains	1958	1973	11	-8.675	-1.824	2.262	No significant trend

Figure 3: Percentage coverage for different land-cover

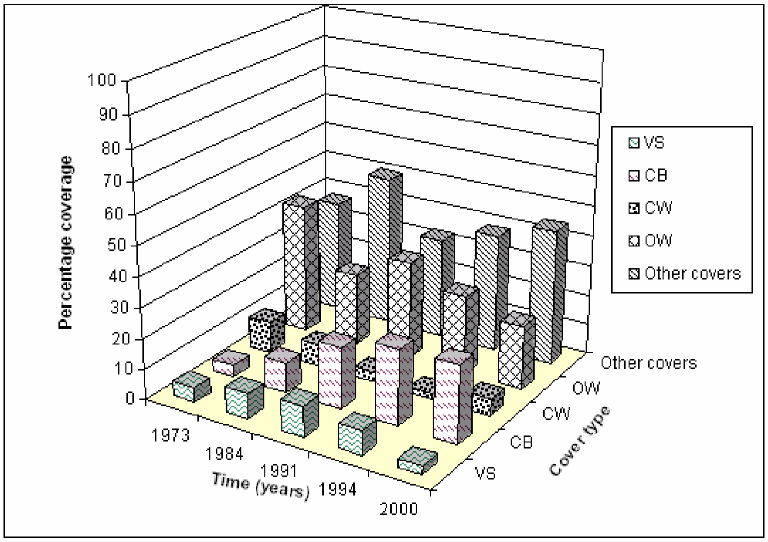


Figure 4: Land use/cover change map for selected covers from 1984 to 2000 in the dry season for vegetated swamp

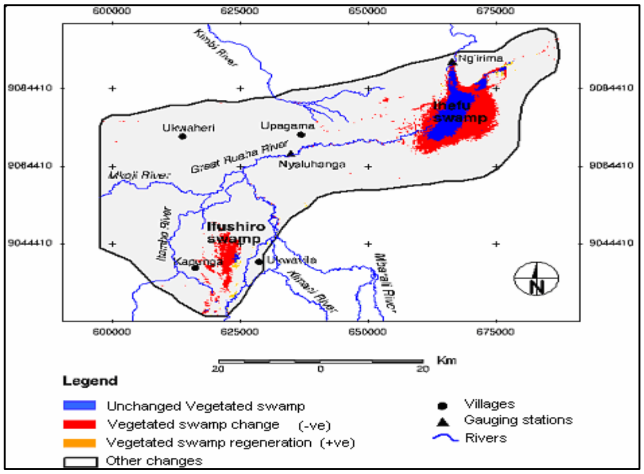
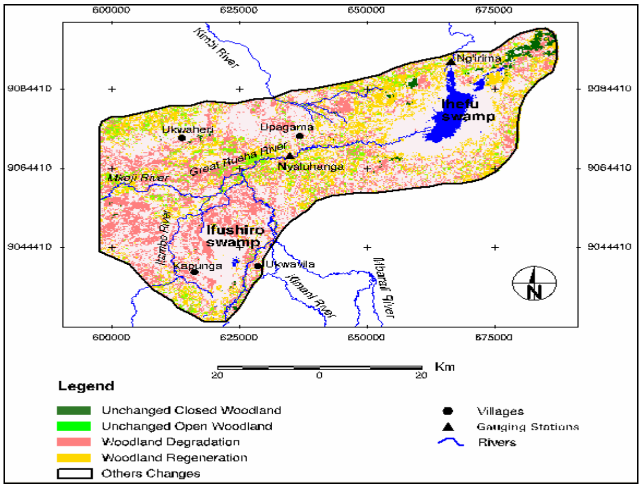
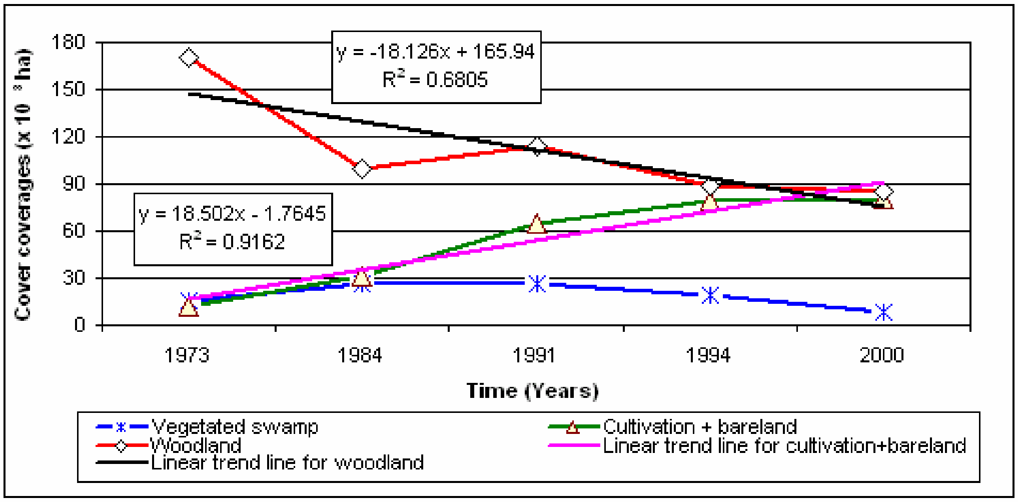


Figure 5: Land use/cover change map for selected covers from 1984 to 2000 in the dry season for woodland



The analysis for the rate of change in the dry season for the different covers revealed that between 1973 and 1984 86% of vegetated swamp remained unchanged while 14% of its cover in 1973 changed, and for closed woodland, 23% remained unchanged and 77% changed. Likewise for open woodland, 30% remained unchanged while 70% changed. The 14% change in vegetated swamp indicates an expansion of the vegetated swamp area coverage in 1984, while the 77% and 70% changes in closed woodland and open woodland respectively between 1973 and 1984 indicate the respective decline in coverage areas due to various conversions. The remaining unchanged cover between 1973 and 1984 for closed woodland and open woodland were 23% and 30% respectively. Between 1984 and 2000, 30% of vegetated swamp remained unchanged while 70% of its cover in 1984 changed, while for closed woodland, 17% remained unchanged and 83% changed. Likewise for open woodland, 23% remained unchanged while 77% changed. This implies that overall, almost all the selected covers experienced a significant decline between 1984 and 2000 (Figure 6). The period coincided with various human interventions and the introduction of large irrigation schemes (i.e., Kapunga rice farm), smallholder cultivation and expansion of paddy cultivation within and around the wetlands. It was also a period associated with high in-migration of people from different regions in the country. The growth in population reflects on the water consumption and diversification of human socio-economic activities that require more water use. Since the available surface water resource is almost constant (not increasing – i.e. SMUWC, 2001 b) the abstraction for socio-economic activities results in denial of water to other downstream users (i.e., wetlands, Ruaha National Park).

Figure 6: Dynamics of land covers for different years as detected from images



Historic river flow change and environmental flows

Historic river flow changes

The flow duration curves derived at Msembe for the three windows are presented in Figure 7. The extracted exceedence percentiles, namely Q_{95}, Q_{75} and Q_{50}, are presented in Table 5. These data confirm a decline in flows downstream of the Usangu wetlands for the GRR through the Ruaha National Park. The flow reduction was most pronounced during the periods of low flows between August and November. During that period, the only major dependent water supply into the Park is the GRR. Therefore, any flow alteration occurring upstream impacts on the amount of water reaching the Park. A considerable reduction in high flows has also been noted. For the pre-1974 period, the average monthly flow for April (the highest flow month) was about 311.6 m^3/s, which decreased to as low as 158.5 m^3/s for 1974-1985 and 220.8 m^3/s for the post-1985 period. However, it is important to note that the *El Nino* years are inclusive and have a bearing on the averages. When excluding *El Nino* hydrological years, the average monthly flow in April for the pre-1974 period was about 200.4 m^3/s, 158.5 m^3/s for 1974-1985 and 182.65 m^3/s for the post-1985 period.

Figure 7: One Day Flow Duration Curves (FDCs) at Msembe gauging station on a semilog scale

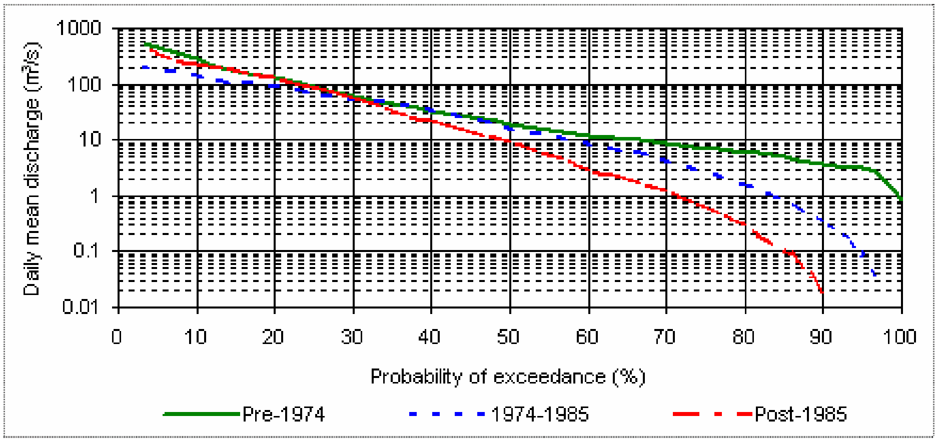


Table 5: The flow statistics and derived indices at Msembe Gauging station for the different time window frames

Time window	Maximum Flow m^3/s	Minimum flow m^3/s	Average daily flow m^3/s	Q_{50} m^3/s	Q_{75} m^3/s	Q_{95} m^3/s
Pre -1974	1582.00**	0.84	93.05**	19.23	7.09	2.84
1974 - 1985	1012.90	0	51.59	16.51	2.77	0.11
Post - 1985	2468.10**	0	80.42**	9.04	0.65	0

** With *El Nino* years

The linkage between flow indices and environmental flows assessment

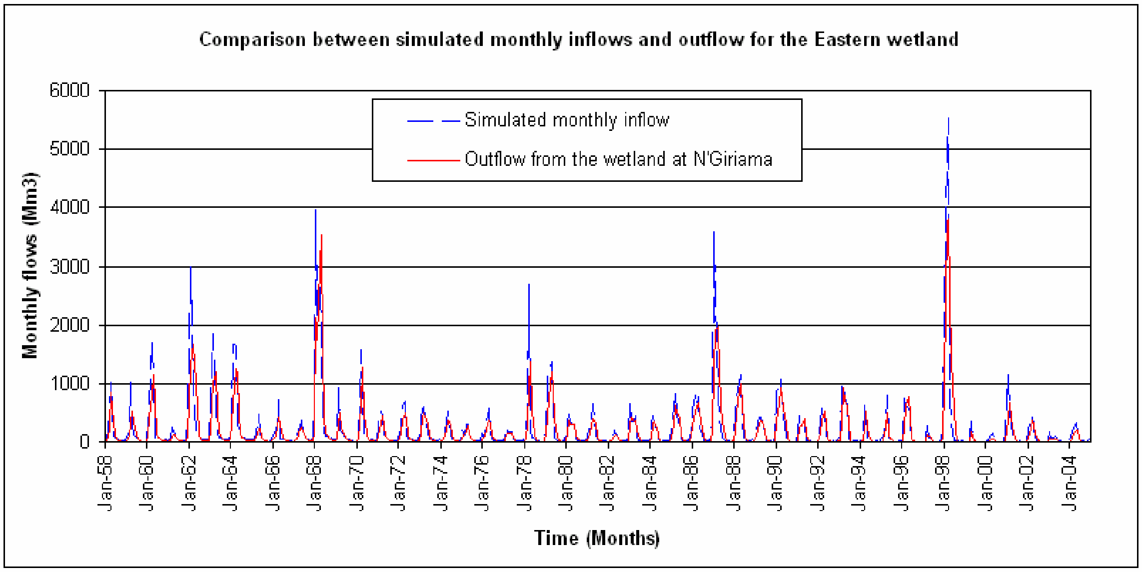
The flow indices Q_{50} indicate the middle value (median) of the flow time series. The Q_{95} is an absolute minimum flow beyond which no abstraction could be allowed (Smakhtin, 2001). In some countries, the Q_{95} has been used for licensing surface water abstractions and it has been widely used for the assessment of effluent discharge limits to the receiving streams (Smakhtin *et al.,* 1998). Hughes (1999) provided for the importance of defining frequency of exceedence in ecological flow requirements of South African rivers. The Q_{95} is associated with dry season flows and is aimed at ensuring channel maintenance. For the GRR, the maintenance of Q_{95} through the RNP would depend on the inflows entering the wetland that emerge as outflows at the N'Giriama exit of the Eastern wetland.

The comparative analysis for the flow indices revealed that the Q_{95}, Q_{75} and Q_{50} have all declined over time. This is attributable to increased water utilization in the upstream in different forms. The Q_{95} at Msembe gauging station was found to be 2.84, 0.11 and 0 m^3/s for the pre-1974, 1974-1985 and post-1985 windows respectively.

Wetland water balance and inflows simulations

The results of the estimated inflows are presented in Figure 8. The pattern compared well with the observed outflows at N'Giriama.

Figure 8: Estimated outflows and simulated total inflows to the Eastern wetlands for the period 1958 to 2004



It should be noted that the estimated inflows represent a lumped sum which aggregates different components, namely surface and groundwater inflows. However, the model could not estimate well the total inflows for the transition period, from months with high flows to months with low flows for some years. This might have been caused by either under-estimation or over-estimation of some components of the water balance. It could be argued that the under-estimation of the inflows might be due to uncertainties of the upper part of the stage-area and stage-volume curves. Also, some error could be attributable to using data from Msembe station. Despite few observed deviations, the model has managed to estimate well the inflows to a greater extent. Therefore, it can be used to simulate the inflows into the wetland under different management objectives/scenarios.

Simulation of inflows with target environmental flows (TEF) and trade-offs

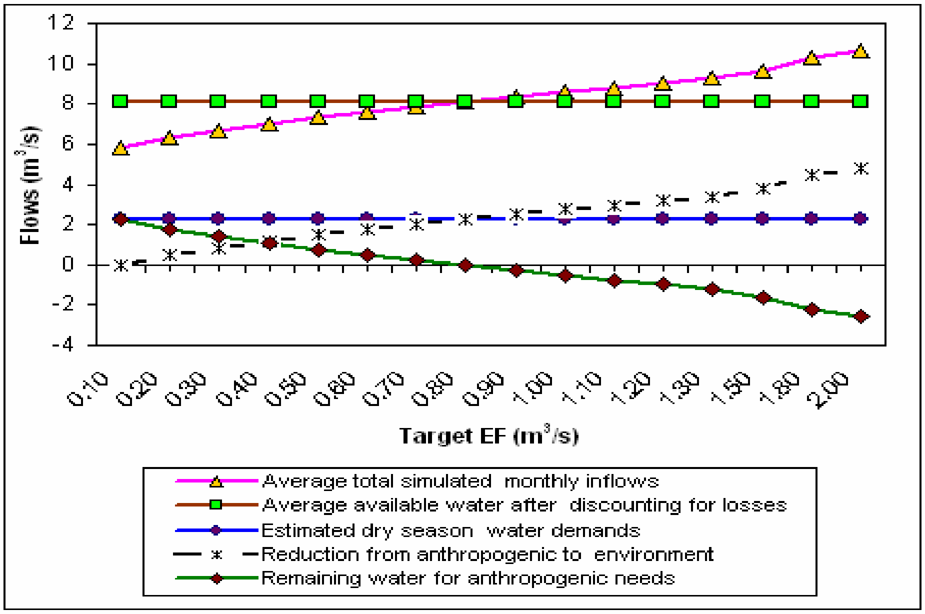
Trade-off analysis

A trade-off analysis was conducted between the environment and anthropogenic water demands. This involved the analysis of the monthly average available surface water resources, simulated average monthly inflows and anthropogenic water demands. The available water resource for the four (perennial) rivers for the period 1999 to 2004 was found to be 8.495 m^3/s (Table 6) and anthropogenic demands estimated at 2.227m^3/s. The results for the analysis are presented in Figure 9.

Table 6: Average monthly dry season flows (m^3/s) for perennial rivers (1999-2004)

Sub- catchment name/ description	**Average monthly flows (m^3/s)**					
	July	August	September	October	November	**Average**
Great Ruaha	3.640	2.861	2.407	2.314	2.293	2.703
Mbarali	4.996	3.926	3.094	2.394	2.683	3.419
Kimani	1.455	1.109	0.902	0.762	0.740	0.994
Ndembera	2.500	1.500	1.000	1.000	0.900	1.380
Total available water at gauging stations before abstractions	**12.591**	**9.395**	**7.403**	**6.469**	**6.617**	**8.495**

Figure 9: Trade-off analysis for environmental water allocation (a rule-based decision framework approach)



As presented in Figure 9, for each targeted environmental flow (x-axis) there is a corresponding estimate for inflows to the eastern wetlands. The environmental flow value corresponds to the TEF value on the x-axis at the point of intersection between the curve for the remaining water for anthropogenic needs and the foregone or reduction for the environment, and in that case it corresponds to TEF value of 0.5m^3/s.

The analysis indicates that for the low flow period (July-November), 2.85 m^3/s on average will be required to meet dry season water demands and losses. However, the available water resource at the gauging station was estimated at 8.5 m^3/s for the same period. This translates to 5.65 m^3/s being available for the wetlands and downstream environmental needs. From Figure 9, this corresponds to about 0.2 m^3/s at a point where the foregone reduction curve intercepts the x-axis. If the objective is to maintain 0.5 m^3/s through the Ruaha National Park, inflows will have to be maintained at at least 7 m^3/s and the anthropogenic water needs will have to be reduced to about 20%. This implies that by aiming at high environmental flow values through the RNP, more water will have to be taken from the anthropogenic side and allocated to the environment. However, by increasing the environmental flows, it reaches a point whereby no more water could be available from anthropogenic needs to be allocated for the environment (a point when the remaining water for anthropogenic needs touches the x-axis). An alternative to raising the available water resources could be seeking an alternative supply source or reducing demand during the dry season. However, with the present hydrological understanding of the basin, the possibility of an external source is unlikely as there is no alternative water supply at the moment.

Key issues arising from trade-off analysis and their implications

- The analysis reveals that an environmental flow between 0.1 – 0.2 m^3/s could be met under current anthropogenic demands provided that good mechanisms for monitoring and control are put in place.
- A decrease in available water resource will have a great impact on the allocative decision between environment and the livelihoods.
- An environmental flow corresponding to 0.5 m^3/s will be required through the Ruaha National Park after considering other factors like evaporation losses, dilution requirement and temperature regulation for the remaining ponds in the Park. To achieve this, the inflows into the eastern wetland will have to be maintained above 7 m^3/s and the available water resource will have to be divided to allow 20% for anthropogenic needs and 80% for the environment.

Conclusions

An improved understanding of the ecosystem response under varying hydrological conditions is crucial to the design and implementation of effective water management strategies that ensure environmental sustainability.

This research has examined the dynamics of the wetlands associated with climate and increased human developmental interventions via the water balance. The research has shown that the Usangu wetlands have changed over time. The decline in wetland area is closely linked to increased human activities, particularly increases in irrigation. Modelling has revealed that to maintain a flow of 0.5 m^3/s required for maintenance of fish habitat and ecology in the Ruaha National Park during the dry season, inflows to the wetland must be maintained at 7 m^3/s. Inflows of this magnitude can only be maintained by reducing current abstractions for irrigation and other human uses. Proper monitoring and control will be necessary to ensure the water reaches the wetlands.

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