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104

Use of a Hydrological Model for Environmental Management of the Usangu Wetlands, Tanzania

Japhet J. Kashaigili, Matthew P. McCartney, Henry F. Mahoo,
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Cover photograph by Bruce Lankford shows the Eastern (Ihefu) Wetland on the Usangu Plains.

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Acronyms

amsl	above mean sea level
CV	coefficient of variation
BB	building block
BFI	baseflow index
FORS	Friends of Ruaha Society
GIS	Geographical Information System
GPS	Global Positioning System
MAR	Mean Annual Runoff
MMF	Mean Monthly Flow
RBWO	Rufiji Basin Water Office
RIPARWIN	Raising Irrigation Productivity and Releasing Water for Intersectoral Needs
SMUWC	Sustainable Management of Usangu Wetlands and its Catchment

Summary

This report presents the findings of a study to assess changes to flows into, and downstream of, the Usangu Wetlands, located in the headwaters of the Great Ruaha River, Tanzania. Hydrological data, in conjunction with remote sensing techniques, were used to provide insights into changes that have occurred to the Eastern Wetland. Results indicate that, between 1958 and 2004, inflows to the wetland declined by about 70 percent in the dry season months (July to November) as a consequence of increased human withdrawals, primarily for irrigation. This resulted in a decrease in the dry season area of the wetland of approximately 40 percent (i.e., from 160 km^2 to 93 km^2). In the last decade, outflows from the wetland have ceased for extended periods. An environmental flow model indicates that a minimum dry season outflow of approximately 0.6 m^{3}s^{-1} is essential to sustain the basic ecological condition of the river. To maintain this outflow from the wetland, a minimum average dry season inflow of approximately 7 m^{3}s^{-1} (i.e., approximately double current dry season flows) is required. To achieve this, dry season flows in the perennial rivers discharging into the wetland would have to be apportioned so that 20 percent is used for anthropogenic purposes and the remaining 80 percent discharges into the wetland. There is significant potential for improving water use efficiency. However, to ensure minimum downstream flow requirements, consideration should also be given to active water management within the wetland itself.

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Introduction

Wetlands are valuable ecosystems. In addition to supporting immense biodiversity, they play an important role in maintaining environmental quality and sustaining livelihoods. In Africa many millions of people depend on them for livelihood benefits derived from the ecological functions they perform (Denny 1991).

Wetland ecosystems are adapted to the prevailing hydrological regime. The spatial and temporal variation in water depth, flow patterns and water quality, as well as the frequency and duration of inundation, are often the most important factors determining the ecological character of a wetland. Hence, these factors also determine the functions of a wetland (Ramsar Convention Secretariat 2004). Human activities that alter natural flow regimes can have major consequences for wetland ecosystems. Impacts on wetlands can be caused by human activities that take place within them, and by activities that take place within the wider catchment. In this regard, agriculture, both through modification of land cover and irrigation abstractions, is the foremost cause of wetland loss and degradation (Millennium Ecosystem Assessment 2005). Conversely, changes to wetlands can have significant impacts on ecosystems and people living downstream.

The importance of ecological and hydrological functioning of wetlands is recognized (Mitsch and Gosselink 1993; Barbier et al. 1996; Acreman 2000). However, increases in human population, coupled with river regulation and changes in land-use, continue to add to the pressure on wetlands throughout Africa. The International Convention on Wetlands (Ramsar, Iran, 1971) promotes the sustainable utilization of wetlands within a local context and mandates that adequate water is provided to them to maintain those ecological functions, which in turn benefit people. However, how to determine a wetland's water requirements, particularly in the context of multiple competing needs, is not always clear. Furthermore, there have been relatively few attempts to quantify water allocation for wetlands, globally. This is particularly the case in data sparse regions of the world, such as many places in Africa.

Against this background, this report describes a study undertaken to estimate water allocation for the wetlands of the Usangu Plains in Tanzania. These wetlands are located in the floodplain, close to the headwaters of the Great Ruaha River. 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 percent of the country's installed hydropower capacity and significant agricultural production (Kadigi et al. 2004). Furthermore, it is the main source of water during the dry season, and as such, is vital for the ecology of the Ruaha National Park. Since 1992/1993, the previously perennial Great Ruaha River has ceased flowing downstream of the wetlands, during the dry season and in the early part of the wet season (i.e., September to January). The drying up of the river has been widely attributed to irrigation abstractions from the rivers flowing into the wetlands (SMUWC 2001a; Lankford et al. 2004).

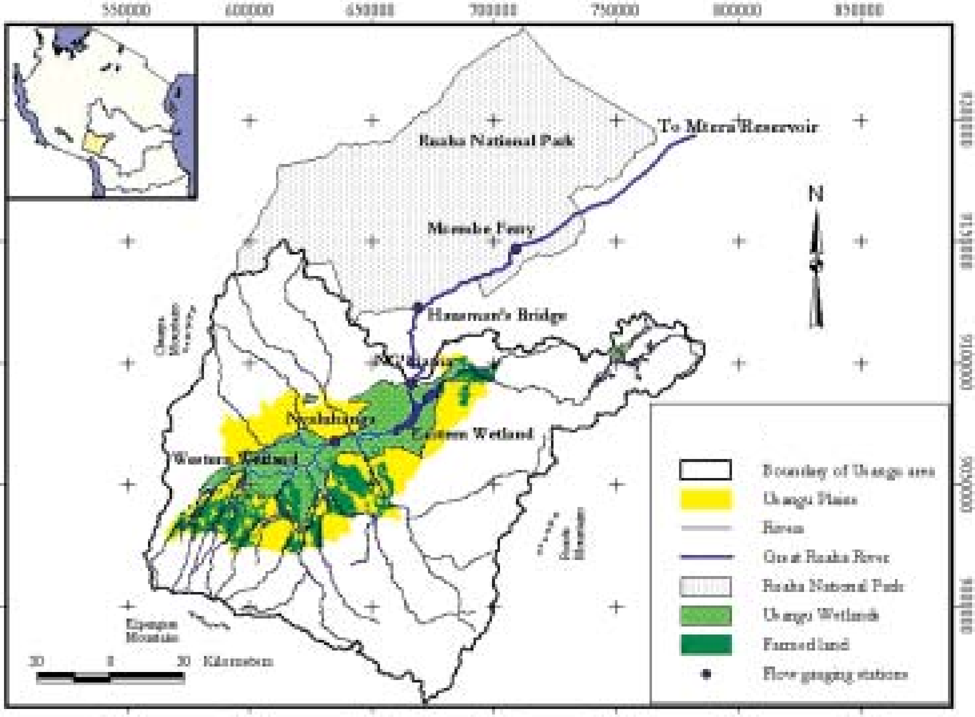
Although previous studies have been carried out in the Usangu Plains (Kikula et al. 1996; SMUWC 2001a), none of these explicitly investigated the water requirements of the wetlands and the maintenance of downstream flows. The current study sought to improve understanding of the hydrology of the Usangu Wetlands and the hydrological implications of increased irrigation abstractions and land-cover changes in the catchment. In addition, an attempt was made to assess the amount of water required to discharge into the wetlands to maintain downstream flows during the dry season.

Description of the Study Area

The Usangu Plains are located in the south-west of Tanzania (figure 1). They lie between longitudes 33°00'E and 35°00'E, and latitudes 8°00'S and 9°30'S, covering an area of approximately 4,480 km^2. The Usangu Plains, which lie at an average elevation of 1,100 m above mean sea level (amsl), are surrounded by the Poroto, Kipengere and the Chunya mountains, with elevations up to 3,000 m amsl.

The climate is largely controlled by the movement of air-masses associated with the Inter-Tropical Convergence Zone. The rainfall regime is unimodal with a single rainy season from December to June. However, rainfall is irregular, highly localized and spatially varied, and is strongly correlated with altitude. The mean annual rainfall is up to about 1,600 mm in the mountains and between 500 and 700 mm on the

FIGURE 1.
Map showing the location of the study area.



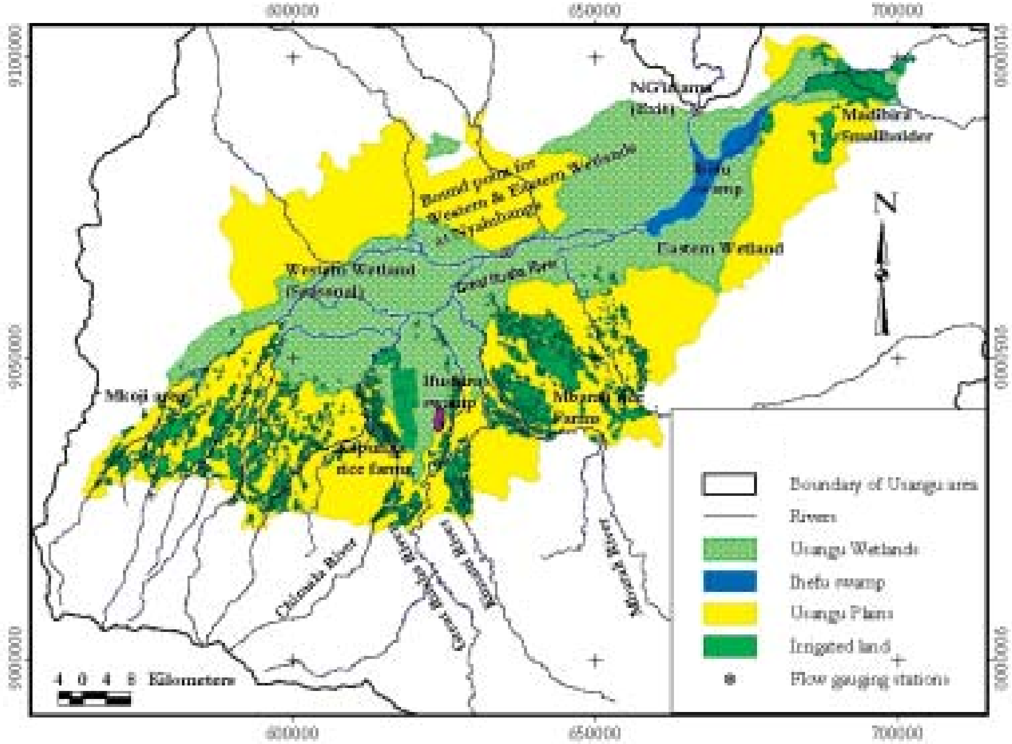
Source: SMUWC (2001) Database shapefiles

Usangu Plains. The mean annual temperature varies from about 18^{0}C at higher altitudes to about 28^{0}C in the lower and drier parts of the Usangu Plains. The mean annual potential evapotranspiration is 1,900 mm (SMUWC 2001a).

There is a distinct change in vegetation from the highlands to the lowlands. Above 2,000 m amsl, remnant montane humid forest gives way to afro-alpine vegetation and, between 2,000 m amsl and 1,100 m amsl, Miombo woodland dominates (SMUWC 2001a). Below 1,100 m amsl, two broad areas are delineated by different vegetation composition and characteristics: i) the fans; and ii) the Usangu Wetlands. The fans are alluvial deposits spreading from the base of the mountains onto the Usangu Plains. Natural vegetation comprises thorny woodland and wooded grassland. However, the fans are fertile and consequently many agricultural activities are concentrated in this area. As a result, significant areas have been cleared and replaced by cultivation or secondary thorn bush. The vegetation of the lower fans naturally grades into natural bush, which is mixed with open grassland. The Usangu Wetlands, located below the fans, comprise of the Western and Eastern Wetlands, which are divided by higher ground in the centre of the Usangu Plains and joined only by a narrow band of land along the Great Ruaha River at Nyaluhanga (figure 2). The Western Wetland comprises seasonally flooded areas, which are not contiguous but broken into a number of independent wetlands. The Eastern Wetland comprises seasonally flooded grassland and a perennial swamp, known locally as *mbuga* and *ihefu,* respectively.

The Usangu Plains are drained by the Great Ruaha River, which exits at a point called NG'iriama. At this location, a rock outcrop acts as a natural dam controlling the flow from the Eastern Wetland. Major tributaries to the Great Ruaha River, with confluences on the Usangu Plains, are the Mbarali, Kimani, Chimala and Ndembera (figure 2). These rivers have their sources at high elevations, in the high rainfall areas, and account for 85 percent of the total

FIGURE 2.
Map of drainage patterns and land use in the Usangu Plains.



Source: SMUWC (2001) Database shapefiles discharge from the Usangu Plains (SMUWC 2001a). Other smaller rivers include the Umrobo, Mkoji, Lunwa, Mlomboji, Ipatagwa, Mambi, Kioga, Mjenje, Kimbi, Itambo and Mswiswi. Most of these smaller rivers have their sources in lower rainfall areas and are ephemeral. The major water supplier to the Eastern Wetland is the Great Ruaha River, which flows from the Western Wetland through the constriction at Nyaluhanga. The only other significant inflow into the Eastern Wetland is the Ndembera River, which discharges into it from the north-east. Downstream of the Eastern Wetland, the Great Ruaha River flows through the Ruaha National Park, serving as the main source of water for the Park and, ultimately, into the Mtera hydropower reservoir. The long-term (i.e., 1958–2004) mean annual runoff (MAR) for the catchment up to the Msembe Ferry Gauging Station, located 80 km downstream of NG'iriama (figure 1), is 2,442 Mm^3 (i.e., 77.4 m^3s^{-1}).

For conservation, the Usangu Wetlands are one of the most valuable freshwater ecosystems in Tanzania. They are home to over 400 different types of bird species and numerous other flora and fauna. Most of the Eastern Wetland lies within the recently gazetted Usangu Game Reserve. Before it was officially declared a game reserve, the Eastern Wetland supported various socioeconomic activities (e.g., fishing, collection of medicinal plants and cattle grazing). It also had a certain degree of cultural importance and, as such, was used as a site for ritual prayers (Kashaigili 2003). In recent decades, in part because of the various benefits derived from the wetlands, many ethnic groups have immigrated to the Usangu Plains from other parts of Tanzania. The groups include pastoralists from Mwanza, Shinyanga and Tabora, as well as farmers and business people from other neighboring regions. Some people have also moved in to the region from outside the country (i.e., from Europe and Asia) (SMUWC 2001a).

The higher population and increased human activities in and around the wetlands have resulted in increased water demand. Demand for irrigation water exists in both wet and dry seasons and, with the exception of hydropower generation that takes place a long way downstream, is by far the largest water user (table 1).

Over the past 30 years, there has been a rapid expansion in the irrigated area. From 1970 to 2002, the irrigated area increased from approximately 10,000 ha to about 44,000 ha (SMUWC 2001b)—(figure 3; table 2). However, the area varies from year to year depending on the rainfall. Currently in low rainfall years, it may still be as little as 20,000—24,000 ha (SMUWC 2001b).

Irrigated agriculture is located on the middle and lower parts of the alluvial fans, primarily on the southern margins of the Usangu Wetlands (figure 2). The irrigation comprises large state-owned (but soon to be privatized) rice farms (covering approximately 6,200 ha), as well as smallholder irrigation, comprising both formal schemes and informal systems (covering approximately 37,000 ha). It is estimated that approximately 30,000 households are involved in irrigation. Water is diverted from both the perennial and seasonal rivers. For some villages, irrigation canals are also the primary source of domestic water. Rain-fed cultivation, some using water harvesting techniques, exists on the upper parts of the fans where rainfall is slightly higher. Dry season irrigation is also concentrated on the upper parts of the fans and largely comprises

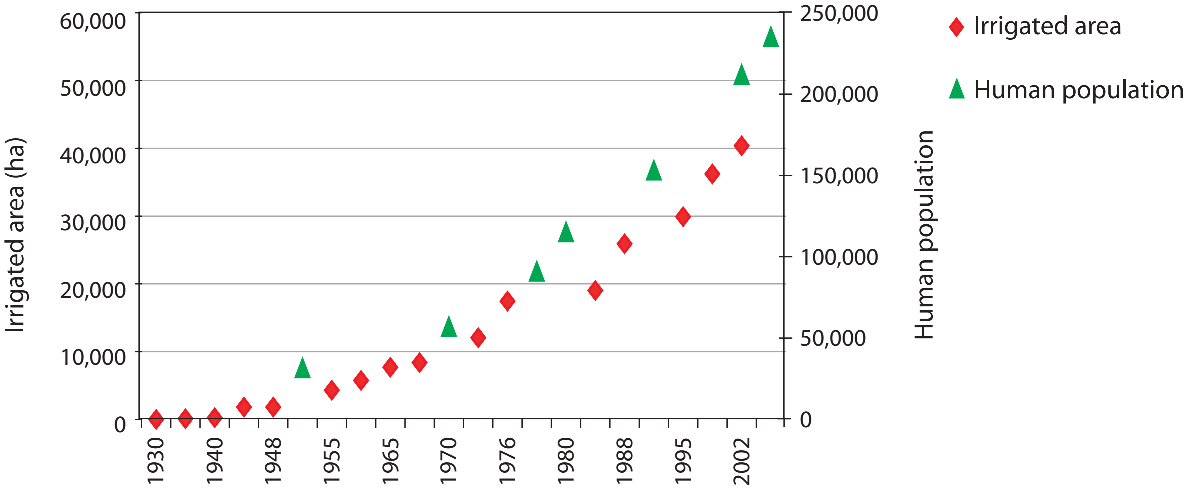
TABLE 1.
Water use in different sectors.

	Water use	
Sector	Wet season (December to June) ($x10^6$ m^3)	Dry season (July to November) ($x10^6$ m^3)
Irrigation	775.6	24.3
Livestock	8.2	19.6
Brick-making	-	0.2
Domestic	2.6	3.5
Total	786.4	47.6
Hydropower	Annual value = 4,096.3*	

Source: RIPARWIN (2005) Water productivity studies

Note: * Hydropower is a long way downstream of the Usangu Plains. Incorporates turbine discharge plus evaporation loss from reservoirs

FIGURE 3.
Changes in population and the area under irrigation in Usangu (1930-2005).



Source: SMUWC (2001b), Hazelwood and Livingstone (1978), Franks et al., 2004, Tanzania National Bureau of statistics – population census

TABLE 2.
Growth of irrigated rice area and water abstraction in selected periods.

Time period	Number of years	Total rice area at end of period (ha)	Estimated total abstraction at end of period (m^3s^{-1})
1935–1967	33	8,500	11
1968–1973	6	15,000	17
1974–1985	12	36,000	29
1986–1991	6	31,000	34
1992–1999	8	40,400	45

Source: SMUWC (2001b)

irrigation of high-valued crops such as green vegetables, onions, tomatoes and beans.

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 downstream of irrigated areas, divert water for various uses including domestic supply, irrigation and brick-making. Dry season irrigation is much less than wet season irrigation. It is estimated that it covers only about 2,500 ha (SMUWC 2001b). However, increasingly, rice farmers are planting before the start of the wet season in an attempt to meet early season demand, when rice prices are highest. Furthermore, within irrigated areas, large volumes of water continue to be diverted throughout the dry season, even though they are not used for irrigation. Some of this water is used for domestic supply and livestock watering (table 1), but large quantities are simply discharged into non-productive fields and plots. A lot of this water is evaporated or infiltrates to groundwater. As a result, with the exception of four perennial rivers (Mbarali, Kimani, Ndembera and the Great Ruaha) the rivers cease to flow, and even the perennial rivers have very low flows in most dry seasons.

Historically, the Great Ruaha River was perennial with the flow lasting throughout the dry season, in all, but in the exceptionally dry years, such as 1947 and 1954. Flows at the Msembe Ferry at the end of the dry season were typically between $1m^3s^{-1}$ and $3m^3s^{-1}$ (SMUWC 2001b). Since 1993, flows downstream of NG'iriama have ceased in the dry season every year because water levels in the Eastern Wetland have dropped below the crest of the rock outcrop. Table 3 shows the periods of zero flows observed at the Jongomero Camp in the Ruaha National Park. The river even dried up in the dry season of 1997, following high rainfall in the wet season, associated with the *El Niño* phenomenon.

TABLE 3.
Periods of zero flow in the Great Ruaha River (1994 to 2004).

Year	Date flow stopped	Date flow started	Period of no-flow (days)
1994	November 17	December 15	28
1995	October 19	December 23	65
1996	October 17	December 16	60
1997	September 20	November 22	63
1998	November 18	March 9 1999*	87
1999	September 21	December 20	90
2000	September 17	November 22	66
2001	November 12	December 23	41
2002	November 2	December 24	52
2003	September 21	January 16 2004*	104
2004	November 3	December 4	31

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

The drying up of the Great Ruaha River has resulted in social conflicts between upstream and downstream users. In the dry season, women and children have to spend much of their time searching for water, with some having to walk up to 20 km to locate sources (Kashaigili and Rajabu 2003). The cessation of flow is also having adverse impacts on the fragile ecosystem of the Ruaha National Park. It has caused significant mortality of fish and hippopotami. For example, in the dry season of 2003, 5,000 fishes and 49 hippopotamuses died following the drying up of the river (Ecologist for the Ruaha National Park, personal communication.). It also disrupts the lives of many animals that depend on the river for drinking water, causing changes in their behavior and leading to outbreaks of disease such as Anthrax.

In 2002, Tanzania launched a new National Water Policy, which established the environment as the second priority in allocating water, behind basic human needs. As a result of the increased water competition and concerns about the environment of the Usangu Wetlands and the Ruaha National Park, the Government of Tanzania is committed to ensuring that the Great Ruaha River has "year-round flow by 2010" (Prime Minister, Mr. Frederick Sumaye, speaking at the Rio+10 preparatory meeting in London). Furthermore, the government is committed to "integrated comprehensive approaches towards resources planning, development and management so that human activity does not endanger the sustenance of the Great Ruaha ecosystems" (Guardian newspaper (Tanzanian daily), 8 Nov 2001). This means ensuring enough water to sustain both the wetlands and the river downstream. In addition, the Tanzanian Government has recently become a signatory to the Ramsar Convention on Wetlands (August 13, 2000) and so is bound to the "conservation and wise use" of all wetlands. Although the Usangu Wetlands are not designated a Ramsar site, signing the convention commits the country to a general stewardship of wetlands (Franks et al. 2004).

Increasing competition for water resources is adding to the pressure on the wetlands of many developing countries. New approaches are required to determine how available water can be shared between the environment, which is essential if environmental services are to be maintained, and other water users.

Study Approach and Rationale

The Usangu area is subject to a complex set of environmental pressures and associated management problems. There are important gaps in the understanding of the hydrology of the wetland and the consequences of changes in land use that have taken place over time, particularly in relation to the impact of these changes on river flows. Understanding these is vital for improving water resource management in the catchment. This study had two key objectives:

- to ascertain the changes in the hydrologic response caused by increased irrigation and changed land use;
- to evaluate the discharge into the Eastern Wetland required to maintain specified dry season flows downstream of the NG'iriama outlet.

There were four components to the study:

- use of satellite images to investigate changes in land cover and the area of the Eastern Wetland over time;
- analysis of flow data to quantify changes in the flow regime downstream of the Eastern Wetland;
- development of a hydrological model to determine water fluxes and the water budget of the Eastern Wetland;
- estimation of desired environmental flows downstream of the wetland.

The current study focused primarily on the Eastern Wetland and flows downstream of it in the dry season when, as discussed above, impacts are greatest and the most significant environmental problems occur. The analyses considered three time frames or 'windows': 1958–1973, 1974–1985 and 1986–2004. These windows correspond approximately to different levels of human intervention in the catchment (Yawson 2003).

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 and the construction of the 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, the irrigated area was about 26,000 ha and the population was estimated at 150,000. This represents a 67 percent increase in population and a 117 percent increase in the area under irrigation within a period of 12 years.

The post-1985 (i.e.,1986-2004) window is characterized by increasing water abstraction as a result of continued population growth, increased irrigation and increased pastoral activities. It is also characterized by increased catchment degradation, expanded markets and an increase in the incidence of conflicts over limited water resources (SMUWC 2001a). During this period, the Kapunga rice farm (3,000 ha) was developed. It was irrigated 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).

Changes in Land Cover

Analysis of land cover was undertaken using satellite images. Images obtained in different years were used to determine the extent to which the wetlands and neighboring areas have changed over time. Change detection entails finding the type, amount and location of land use changes that have taken place. Various algorithms are available for change detection analysis (e.g., ERDAS 1999). In this study, a post-classification approach was used (Coppin et al. 2004). To ensure accurate detection of land cover change, and reduce effects of seasonal phenological differences (Jensen 1996), analyses were conducted on images from the wet and dry seasons independently (table 4). A hand-held GPS was used to obtain the geographical location of different types of land cover. These were used in conjunction with a base map and color composite image derived from an image obtained on September 7, 2000. Seven distinct land-cover classes were identified: closed woodland (CW); open woodland (OW); vegetated swamp (VS); closed bushland (CB); open bushland (OB); bushed grassland (BG); and cultivated land and bareland (CLB). Cultivated land and bareland were grouped together because they are a sign of direct human modification of land cover. Standard techniques of analysis (i.e., pixel to pixel comparison of multi-temporal images) were conducted to determine changes in land cover between different images (ERDAS 1999). Further details of the change detection methodology undertaken in this study are presented in Kashaigili et al. (2006).

Analyses of the images show changes in land cover between the different dates. To illustrate the changes, the percentage area cover of four classes (i.e., VS, CW, OW and CLB) for the dry season in the years 1973, 1984, 1991, 1994 and 2000 are presented in figure 4 and summarized in table 5. It is important to note that VS, CW and OW represent a major portion of the wetlands in the Usangu Plains. Figures 5 and 6 are maps showing the changes in land cover between 1984 and 2000.

These results indicate:

- there was a steady increase in cultivated area, from 121.2 km^2 to 874.3 km^2, between 1973 and 2000;
- the other land covers do not show such clear trends but fluctuate from year to year (these changes reflect, at least in part, the differences in rainfall between the years);
- there is a significant difference in the area of the vegetated swamp between the wet and dry season. Although findings are

TABLE 4.
Landsat images used in the analysis of land-cover change.

Image	Date of acquisition	Season	Cloud cover (%)
Landsat MSS$^+$	September 4, 1973	Dry	0
Landsat TM*	June 15, 1984	Wet	11
Landsat TM	September 3, 1984	Dry	0
Landsat TM	August 22, 1991	Dry	0
Landsat TM	August 14, 1994	Dry	1
Landsat ETM+$^\bullet$	May 26, 2000	Wet	8
Landsat ETM+	September 7, 2000	Dry	10

Source: SMUWC (2001) Database, EURIMAGE Image supplier

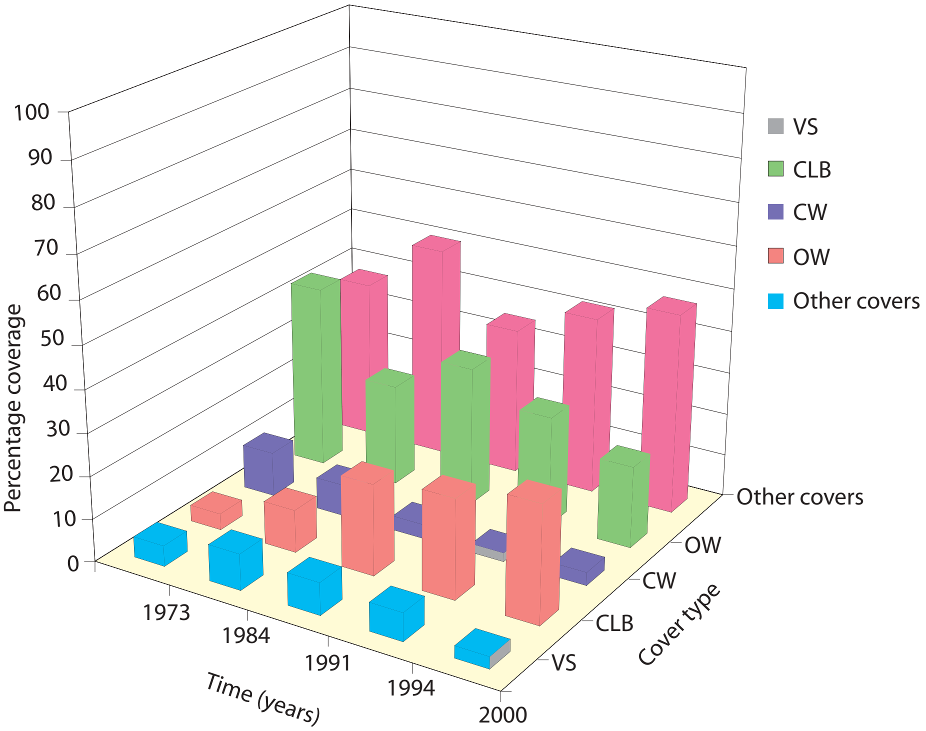
Notes: $^+$ MSS = Multi spectral scanner

* TM = thematic mapper

$^\bullet$ ETM + = enhanced thematic mapper plus

FIGURE 4

Percentage coverage for different land-cover (VS = vegetated swamp, CLB = cultivated land and bareland, CW = closed woodland, OW = open woodland and), other covers comprise of closed bushland (CB), open bushland (OB) and bushed grassland (BG).



Source: Image analysis from Kashaigili et al. (2006)

based on only 2 years of observations i.e., 1984 and 2000 (when wet season images are available), the dry season vegetated swamp area appears to be between 25 percent and 60 percent of the wet season area with absolute decreases in area of up to 230 km^2 from the wet to the dry season; and,

- the dry season area of the vegetated swamp appears to be correlated with the annual rainfall.

TABLE 5.

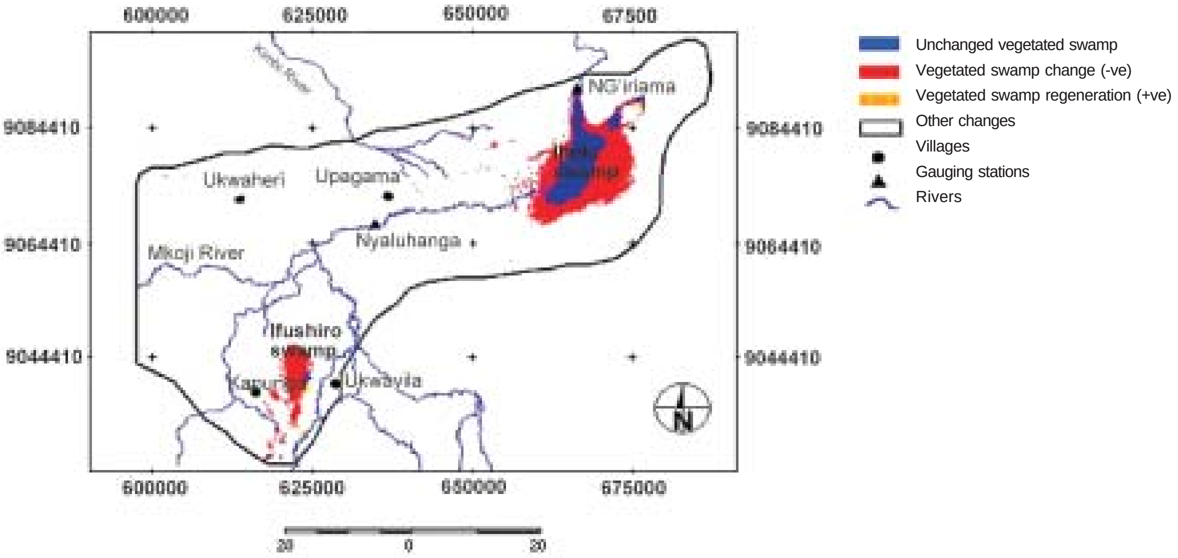
Comparison of wet and dry season areas of selected land covers.

		Wet season	Dry season			
Year	Annual rainfall on the plains (mm)	Vegetated swamp (*Ihefu* area) (km^2)	Vegetated swamp (*Ihefu* area) (km^2)	Bareland + cultivated area (km^2)	Closed woodland area (km^2)	Open woodland area (km^2)
1973	696.4	na	119.6	121.2	331.6	1,368.9
1984	641.3	436.4	223.4	318.6	236.2	756.2
1991	519.2	na	204.1	679.3	105.7	1,038.9
1994	791.8	na	187.9	743.4	64.9	821.5
2000	403.0	318.1	82.9	874.3	97.1	609.3

Source: Image and rainfall analysis from Kashaigili et al. 2006

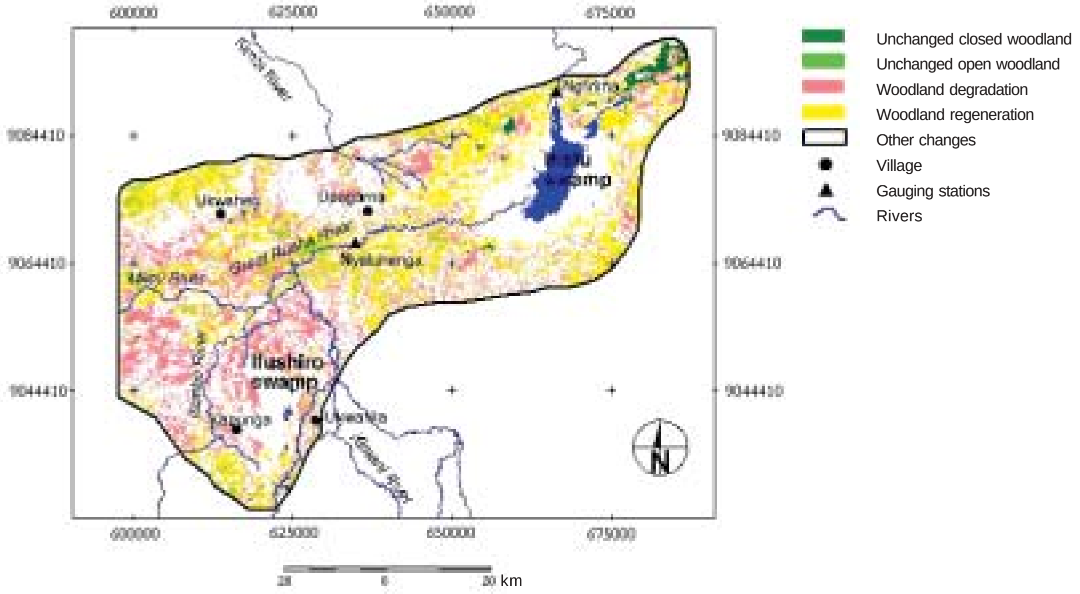
Note: na = not available

FIGURE 5.
Dry season land cover change for vegetated swamp from 1984 to 2000.



So

FIGURE 6.
Dry season land cover change for woodland from 1984 to 2000.



Source: Image analysis from Kashaigili et al., 2006

Changes in the Flow Regime Downstream of the Eastern Wetland

A time series of flow data from the Msembe Ferry Gauging Station was used to investigate temporal changes in the flow regime, downstream of the wetland. This station has operated from 1963 to date. The record was extended back to 1958 using data measured at Haussman's Bridge, a flow gauging station, located approximately 50 km upstream of the Msembe Ferry. This station operated between 1958 and 1988. The intervening catchment (ca. 4,200 km^2) is predominantly forest. There are no major abstractions between the two sites, but tributaries contribute to the flow at the Msembe Ferry, particularly in the wet season. Using the period when both stations were operating (i.e., 1963 to 1988), a simple regression relationship was developed between the flows measured at the two stations (SMUWC 2001b):

$$Q_{Msembe}(t) = A.Q_{Haussman}(t-b) \quad (1)$$

Where:

Q_{Msembe} = daily flow at the Msembe Ferry
$Q_{Haussman}$ = daily flow at Haussman's Bridge
A = constant derived by linear regression
t = time interval (days)
b = lag time in days

The regression was done separately for the low-flow season and for the high-flow season. In both cases, the constant 'b' was found to be zero. The constant 'A' was determined to be 0.9217 and 1.0046 in the low-flow and high-flow season, respectively (SMUWC 2001b). By interpolating to in-fill short periods of missing data, a complete daily flow record was derived for the Msembe Ferry from January 1, 1958 to December 31, 2004.

Visual inspection of time series of annual and dry season flows in the Great Ruaha River at the Msembe Ferry suggests that there is no significant trend in the annual flows. However, dry season flows have declined (figure 7). To be more rigorous, long-term trends in river flows and rainfall over the Usangu Plains were analyzed using conventional techniques of linear regression. 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 was derived by combining data from a number of rain gauges located in the Usangu Plains (table 6). Daily rainfall was calculated as the numeric mean of the rainfall recorded at each gauge. The results indicate that, between 1958 and 2004, there was no statistically significant trend in total annual flows, but there were statistically significant (at the 95% level) declines in both rainfall over the Usangu Plains and the dry season flows at the Msembe Ferry (table 7).

Specific data on changes in dry-season irrigation over time are not available. However, there is a clear correlation between the decrease in the average of the dry-season flow at the Msembe Ferry and the increase in total irrigated area within the Usangu Catchment (figure 8). This is to be expected, because though not extensively used for irrigation, it is the continued

TABLE 6.
Rainfall stations used for the estimation of rainfall on the plains.

Station name	Easting	Northing	Date of start of record	Status
NG'iriama	667,427	909,130	Dec. 1, 1998	Stopped 2002
Upagama Primary School	638,232	907,173	Dec.1, 1998	Stopped 2002
Ikoga Primary School	677,933	907,010	Dec. 1, 1998	Stopped 2002
Madibira	701,500	909,190	Restarted Sept. 1, 1999	Indeterminate
Mbarali	642,200	904,280	Jan. 1, 1958	Continuous

Source: SMUWC 2001b

TABLE 7.

Summary of statistical trends in annual and dry season river flow at the Msembe Ferry and annual rainfall over the Usangu Plains.

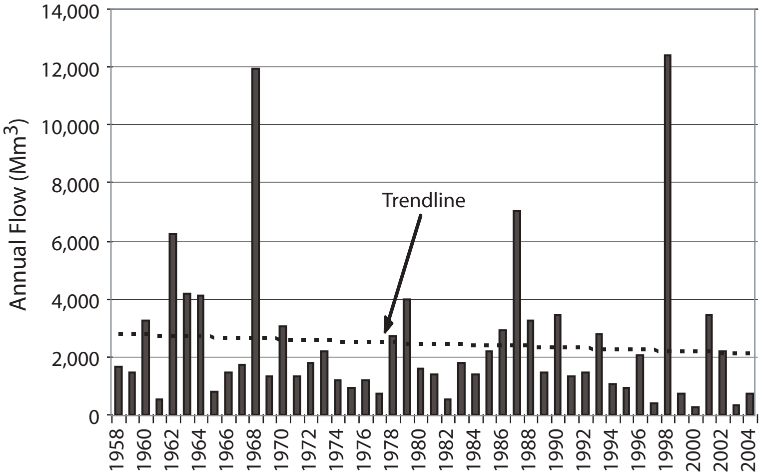
Description of parameter	Start year	End year	No. of years	Slope of trend line	t-statistics	t-critical	Remarks
Annual river flow at Msembe	1958	2004	47	-18.89	-0.546	2.016	Not a significant trend
Dry season river flow at Msembe	1958	2004	47	-2.73	-4.48	2.016	Significant decreasing trend
Annual rainfall over the Usangu Plains	1958	2004	47	-4.456	-3.020	2.016	Significant decreasing trend

Source: Rainfall and river flow analysis (own analysis)

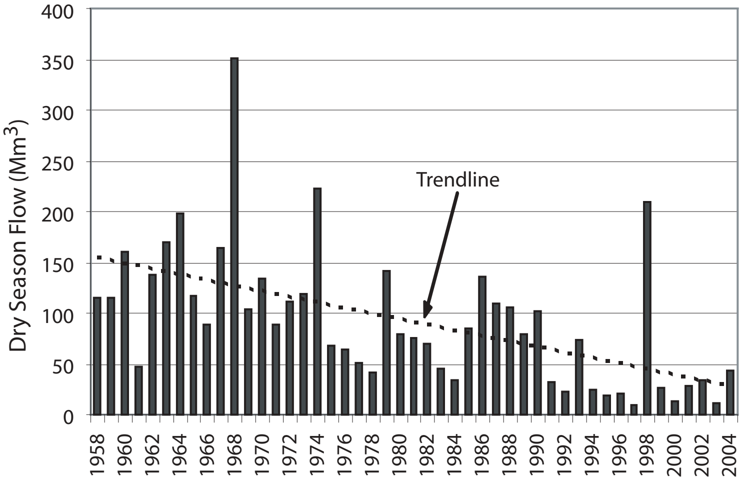
FIGURE 7.

a) Annual flows and b) Dry season flows (July to November) in the Great Ruaha River at the Msembe Ferry.

a) Annual flows

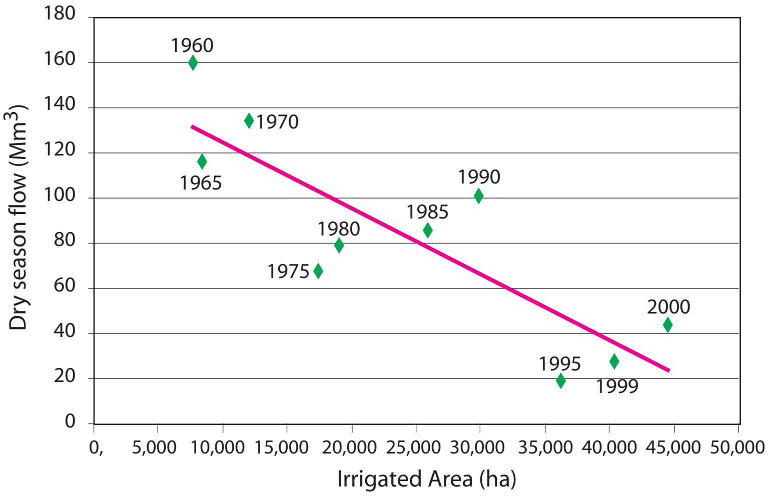


b) Dry season flows



Source: Daily river flow data for the Msembe Gauging Station from Rufiji Basin Water Office (RBWO)

FIGURE 8.
Comparison of dry season flow at the Msembe Ferry and irrigated area in the Usangu Catchment.



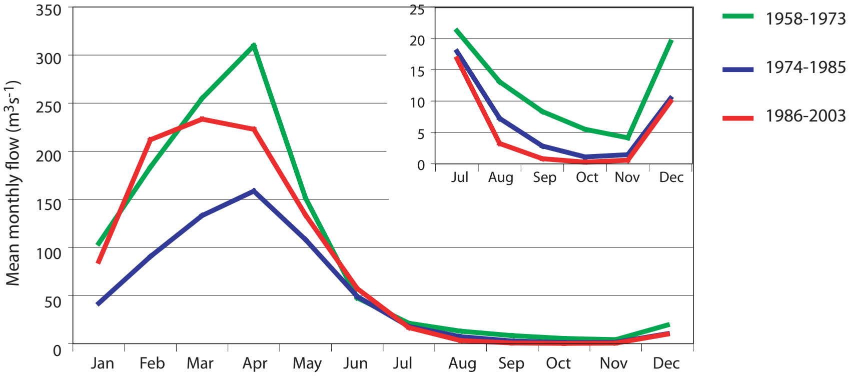
Source: Irrigated area from SMUWC, 2001b

Note: $y = -0.0029x + 153.75$
$R^2 = 0.7136$

diversion of water to irrigation areas during the dry season, which is the major factor in reduced inflows to the wetland.

Figure 9 shows the mean monthly flow at the Msembe Ferry for each of the three windows. 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.

FIGURE 9.
Mean monthly flow at the Msembe Ferry (m^3s^{-1}) derived for each of the three time windows with the dry season flows magnified (inset).



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

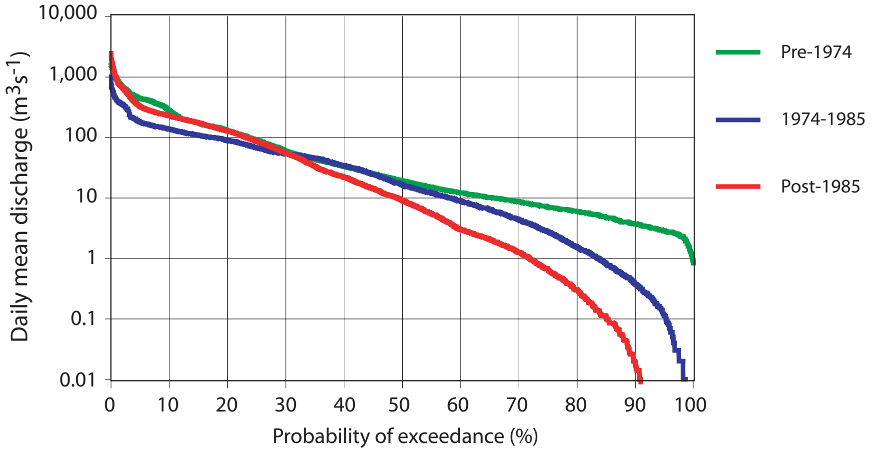
Source: Own analysis

Note: MAR = mean annual runoff

Flow duration curves are cumulative frequency distributions, which show the percent of time that a specified discharge is equaled or exceeded during a period of interest. Hence, for example, Q_{95} is the mean daily flow that is exceeded 95 percent of the time. Annual flow duration curves were developed for the three windows using the Galway Flow Forecasting software (NUI 2002). The curves confirm the progressive and significant decline in flows lower than Q_{50} (figure 10). 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 large inter-annual variability, which tends to mask trends, and the fact that wet season flows, which dominate the annual series, have not changed significantly, despite the fact that absolute volumes diverted in the wet season are much greater than in the dry season.

Using the ARIDA software (Fry et al. 2001) the frequency of occurrence of low-flow events was investigated. For each time window, the minimum flow over different durations (i.e., 1-day, 10-days, 30-days and 60-days) was determined. The results verify the increasing frequency and extension of low-flow periods between the pre-1974 and post-1985 windows (table 8). 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. Between 1986 and 2004, zero-flows of one-

FIGURE 10
Flow duration curves for the Great Ruaha River at the 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

Source: Own analysis

Note: The flows are shown on a log scale to illustrate clearly the differences between low flows in the three different time periods

TABLE 8.
Comparison of minimum flows (m^3s^{-1}) for different durations for each of the time windows.

	Duration			
	1-day	10-days	30-days	60-days
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

Source: Own analysis

day duration occurred in all years and zero flow for durations of 60 days and greater were common.

The results of the analyses of flow at the 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.

Simulation of Wetland Hydrology

Since downstream flows are dependent on the hydrological balance of the Eastern Wetland, one of the primary objectives of this study was to estimate the inflows required to generate desired downstream flows. One of the challenges in doing this is the fact that inflows, in the perennial rivers, have only been monitored over a few years. Therefore, a simple spreadsheet model was developed to simulate the water budget of the wetland and compute the inflows during the period 1958 to 2004.

Model Description

The model represents the wetland as a reservoir (figure 11) and computes the water budget using the following equation:

$$Q_{in} = E + Q_{out} - P + \Delta S \qquad (2)$$

where: ΔS is change in water stored within the wetland

Q_{in} is the total inflow to the wetland, including contributions from groundwater

Q_{out} is the total outflow from the wetland at the NG'iriama 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)

The model was run on a daily time step, but data were aggregated to months for analysis. A key assumption of the model is that wetland storage, area and outflow are all a function of water level at the outlet (i.e., at the rock sill at NG'iriama). Water elevation-area and water elevation-storage relationships derived during the SMUWC study (SMUWC 2001b) were fitted with power functions to enable the wetland area and the storage to be calculated from water levels at NG'iriama (figure 12).

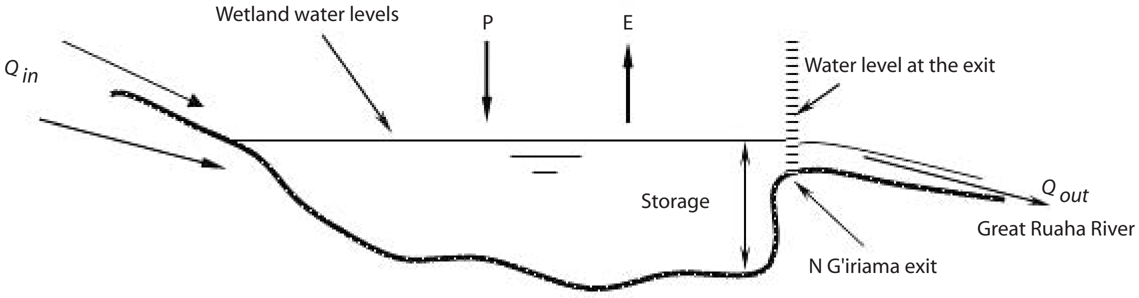
The outflow from the wetland is dependent solely on the water elevation at the NG'iriama outlet. From measured water levels and discharge measurements, a rating equation was developed to convert levels measured at the outlet to discharge (SMUWC 2001b), when water level $h \geq 4.30$ m:

$$Q = 5.449\,(h - 4.3)^{3.375} \qquad (3)$$

where: h is the water level measured to a local datum at the outlet. On this scale, the rock sill is at 4.30 m (= 1,009.525 m amsl). For water levels lower than this, there is no flow from the wetland.

Measured water levels are available at NG'iriama only for the period October 20, 1998 to October 30, 2002. To extend the water level series, it was assumed that flow at NG'iriama was the same as that at Haussman's Bridge, which is located 30 km downstream of the outlet, as there are no major abstractions or tributary inflows between the two locations. The flow-record at Haussman's Bridge was extended from 1988 to 2004 using the Ksembe Ferry flow-record and equation 1. The flow at Haussman's Bridge was assumed to equal the flow from the wetland and the NG'iriama rating (equation 3) was applied in reverse to compute the time series of the

FIGURE 11.
Conceptualization of the Eastern Wetland as a simple reservoir.

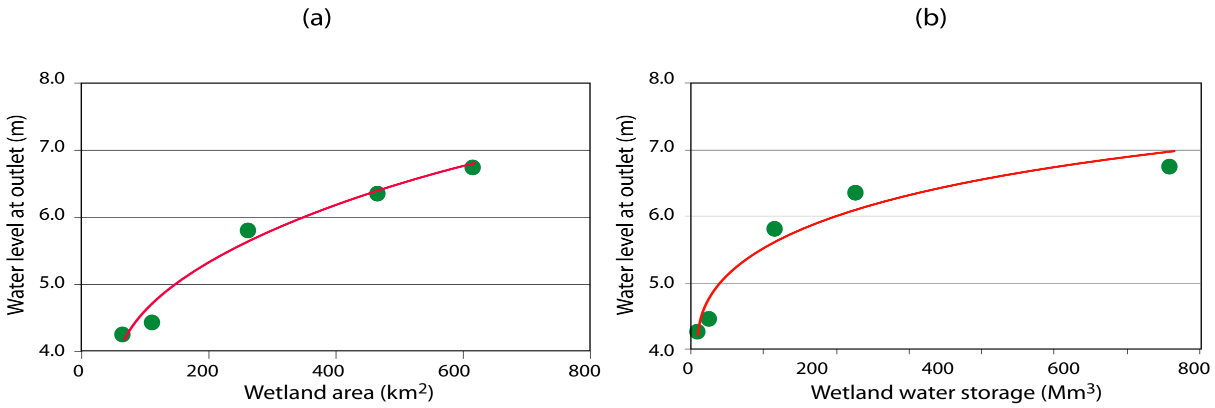


Source: Own analysis

water level at the outlet. Thus, a complete daily water level record was derived for NG'iriama for the period 1958 to 2004. This provided the basis for calculating the wetland storage and area.

Rainfall over the wetland was assumed to be the same as the rainfall over the Usangu Plains, derived using data from the rain gauges in table 6. Potential evapotranspiration data derived at the Dodoma meteorological station were used, as the data measured at this station have been found to be representative of evaporation from the Usangu Plains (SMUWC 2001b; Yawson 2003). Evapotranspiration from the wetland surface was assumed to be at potential rates in all months. This is a simplification that makes no allowance for restrictions in evapotranspiration caused by water

FIGURE 12.
a) Water elevation-wetland area curve and b) Water elevation-wetland storage curve (developed from data in SMUWC 2001 b).



Source: SMUWC (2001) database

Notes: $y = 1.6734\ x^{0.2177}$ (a)
$R^2 = 0.9757$

$Y = 3.1954\ x^{0.1196}$ (b)
$R^2 = 0.9593$

stress. For each simulation time step, the rainfall into, and the evapotranspiration from, the wetland were derived by multiplying by the wetland area.

Having used the water level information to compute outflows and evaporation, and taking rainfall over the wetland and the storage within it into account, the inflows were calculated as the unknown term in the water budget (i.e., equation 2).

Comparison of Simulated and Observed Wetland Area

The wetland model was used to simulate hydrological fluxes for the period 1958 to 2004. Wetland areas simulated by the model were compared to "observed" estimates derived from Landsat images and from aerial surveys combined with GPS ground measurements of the wetland perimeter (SMUWC 2001b). It is recognized that there may be a considerable amount of error in the "observed" areas determined by different methods. Nonetheless, they are at least indicative of the wetland area and so provide a useful check on the model's performance. The results suggest that the model tends to underestimate the wetland area, especially in the wet season, and simulates a lower variability than what occurs in reality (table 9; figure 13). It is possible that the tendency to underestimate the wetland area is a consequence of the assumption that evapotranspiration is always at potential rates, or it may be that the model is overestimating wet season outflow. However, overall, there is reasonable correspondence between observed and simulated values, particularly in the dry season, which was of most concern to the current study. This factor provides a degree of confidence in the model's performance.

TABLE 9.
Comparison of "observed" and simulated wetland area.

Source	"Observed" wetland area Date	(km^2)	Model simulated area $^+$ (km^2)	Difference (km^2)	Percentage error (%)
L	September 4, 1973	120	202	+82	+68
L	June 15, 1984	436	217	-219	-50
L	September 3, 1984	211	137	-74	-35
L	August 22, 1991	204	136	-68	-33
L	August 14, 1994	188	154	-34	-18
S	November 21, 1998	111	90	-21	-19
S	January 21, 1999	64	79	-15	-23
S	May 2, 1999	611	436	-175	-29
S	May 12, 1999	465	365	-100	-22
S	May 11, 2000	217	267	+50	+23
S	May 26, 2000	318	243	-75	-24
L	September 7, 2000	79	108	+29	+37
S	November 7, 2000	27	75	+48	+178

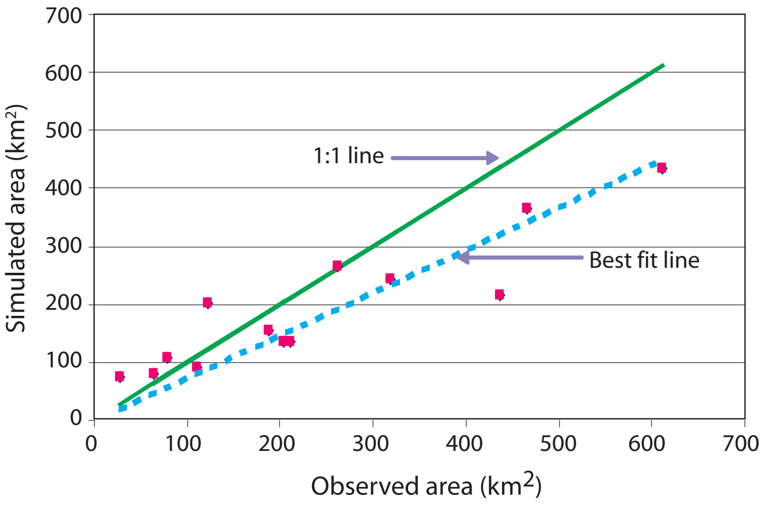
Source: SMUWC (2001b) database and own image analysis

Note: $^+$ data from daily model for exact date of the "observed" area

S = SMUWC (2001b) – areal estimates derived from satellite observations, aerial photgraphs and GPS fixing of wetland perimeter

L = Landsat images

FIGURE 13.
Comparison of observed and simulated wetland area.



Source: SMUWC (2001b) and image analysis

Notes: $y = 0.7333x$

$R^2 = 0.7525$

Wetland Water Budget

Figure 14 shows simulated water levels at the NG'iriama outlet, illustrating the decline in levels and increase in periods below the level of the rock sill from the 1990s onwards.

Figure 15 presents simulated mean monthly inflow and outflow from the wetland for the 1958-1973 window (i.e., the most natural period). This illustrates the effect of wetland attenuation on flows and indicates that there is approximately a 4- to 6-week lag between inflows to, and outflows from, the wetland.

For the 1958 to 1973 window, the average annual influx to the wetland (i.e., rainfall + inflow) was 3,881 Mm^3. However, there was considerable inter-annual variability. The minimum influx was 1,320 Mm^3 in 1961 and the maximum was 14,424 Mm^3 in 1968 (i.e., an *El Niño* year). Although rainfall is measured on the Usangu Plains, and a lot of inflow is generated in the highlands, rainfall and inflow are well correlated (figure 16). Rainfall equals 13 percent (i.e., 491 Mm^3) of total annual influx to the wetland, on average. Of the total inflow, 22 percent (i.e., 835 Mm^3) is evapotranspired and 78 percent (i.e. 3,045 Mm^3)[1] flows from the wetland at NG'iriama, on average.

As would be expected, there is high correlation between the simulated maximum area of the wetland each year and the total annual influx of water into the wetland (figure 17).

The scatter in points can be attributed to the fact that, in any given year, the maximum areal extent of the wetland will also be partly affected by the temporal distribution of rainfall and flow within the year.

The simulated annual water budget of the wetland varies considerably between the three time windows (table 10). These results corroborate the flow analyses, presented above, that the second window was a lot drier than either the first or the third window. During the second window, average annual outflow from the wetland was considerably less than it was in the post-1985 period. However, dry season outflows from the wetland did not cease. This confirms that it is

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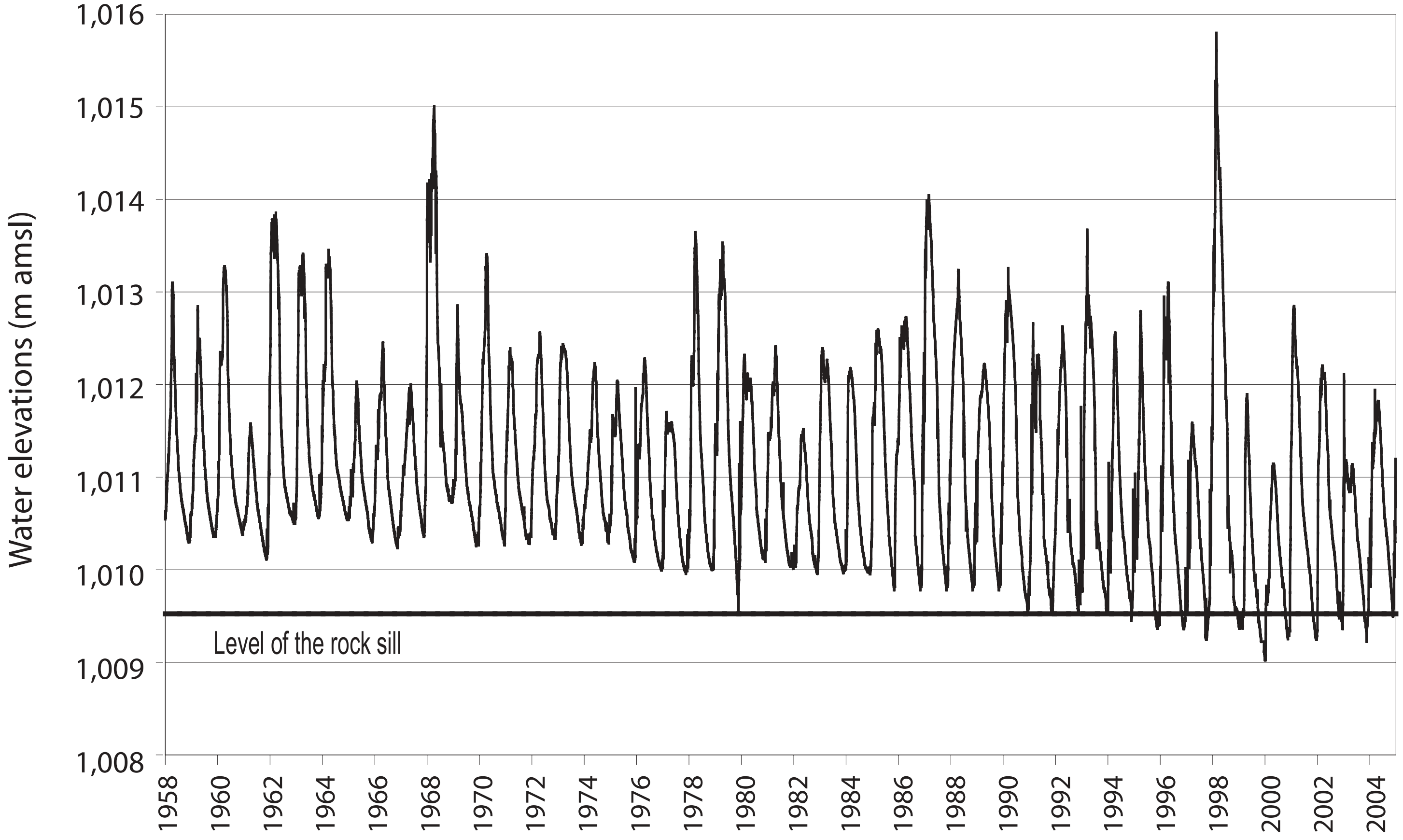
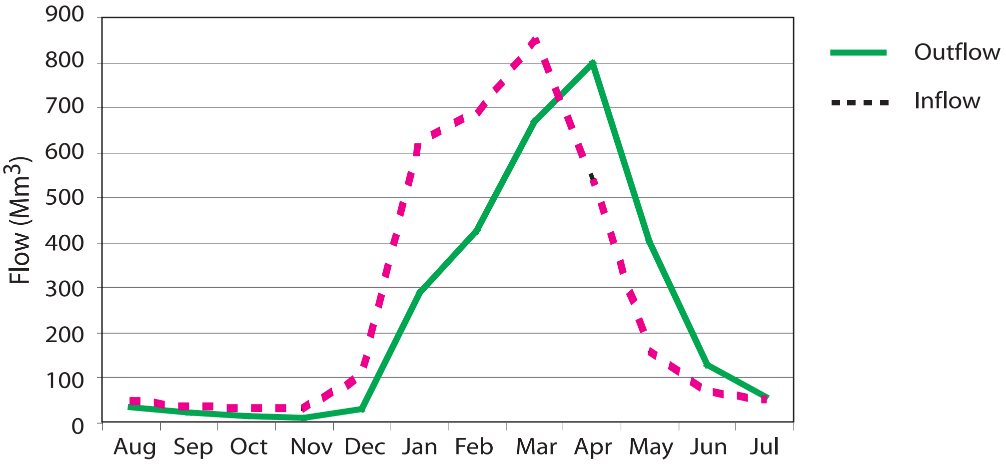
[1] This compares well with the estimated average annual flow at the Msembe Ferry over the same period, which was 2,934 Mm^3.

FIGURE 14.
Simulated water levels at NG’iriama for the period 1958 to 2004.



Source: NG’iriama exit flow analysis

FIGURE 15.
Simulated mean monthly inflow and outflow from the Eastern Wetland (1958-1973).



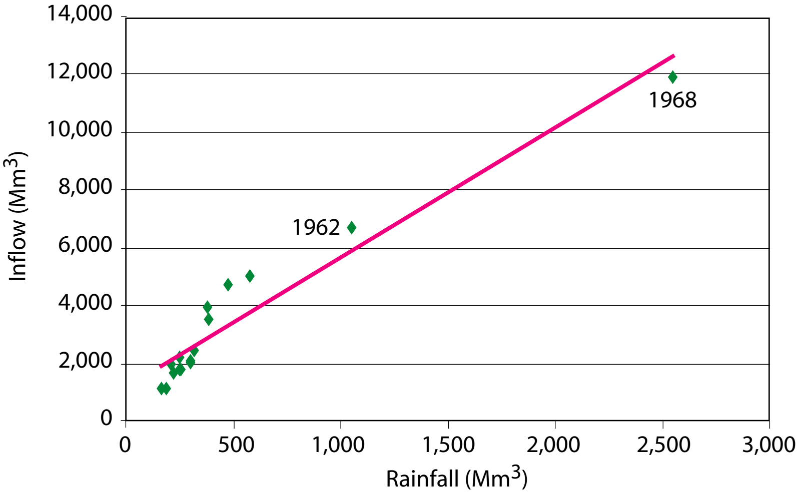
Source: Own analysis

TABLE 10.
Simulated average annual water budget for the three time windows.

Period	Rainfall onto wetland (Mm³)	Inflow to wetland (Mm³)	Outflow from wetland (Mm³)	Evaporation from wetland (Mm³)
1958–1973	491	3,390	3,045	835
1974–1985	251	2,096	1,731	608
1986–2004	319	2,920	2,531	720

Source: Own analysis

FIGURE 16.
Comparison of plains' rainfall and inflow to the Eastern Wetland (Mm³).

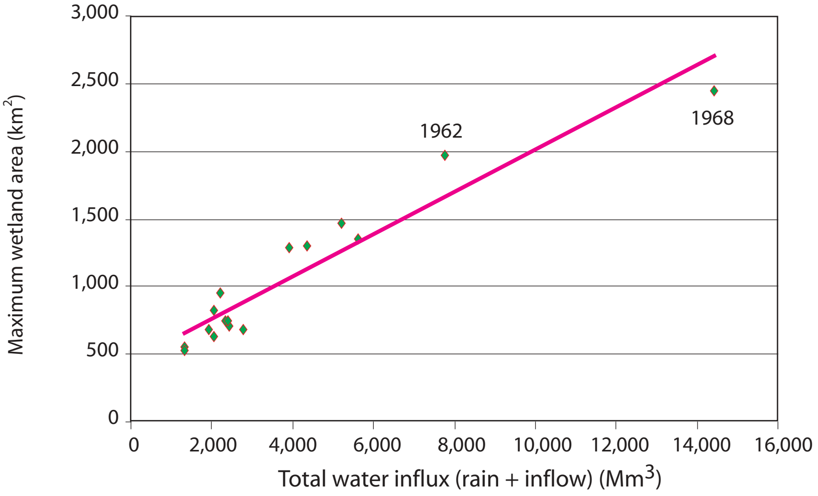


Source: Own analysis

Note: $y = 4.4867x + 1186.8$

$R^2 = 0.9213$

FIGURE 17.
Relationship between annual maximum wetland area and total annual influx of water (i.e., rainfall + inflow) (Mm^3).



Source: Own analysis

Note: $Y = 0.1565x + 446.83$

$R^2 = 0.9052$

not declines in inflow per se, but rather a decrease in inflows during critical periods, which resulted in the cessation of dry season outflows in the post-1985 window.

Simulated Water Fluxes and Changes in the Area of the Eastern Wetland

Comparison of the model results for the three windows enables evaluation of temporal changes in the wetland area and water budget. Between the pre-1974 and the post-1985 windows, the average area of the wetland in the wet season has not changed significantly. However, the dry season minimum area (occurring in October) has decreased by about 40 percent from an average of $160km^2$ to 93 km^2 (table 11; figure 18) .

From the pre-1974 window to the 1974-1985, and then to the post-1985 window, there was a progressive decrease in the average minimum dry season inflows to the Eastern Wetland. Average flow in October decreased from 32.1 Mm^3 to 18.6 Mm^3, and to 9.2 Mm^3. Similar percentage declines occurred in August and September (table 12; figure 19). Over the entire period, there was a total decrease of approximately 70 percent in the simulated dry season inflows.

The average minimum dry season wetland “storage”, occurring in October, decreased from 58 Mm^3 to 40 Mm^3 to 24 Mm^3 in the pre-1974, 1974-1985 and post-1985 windows (table 13). Overall, this represents a 60 percent decrease in the minimum dry season storage.

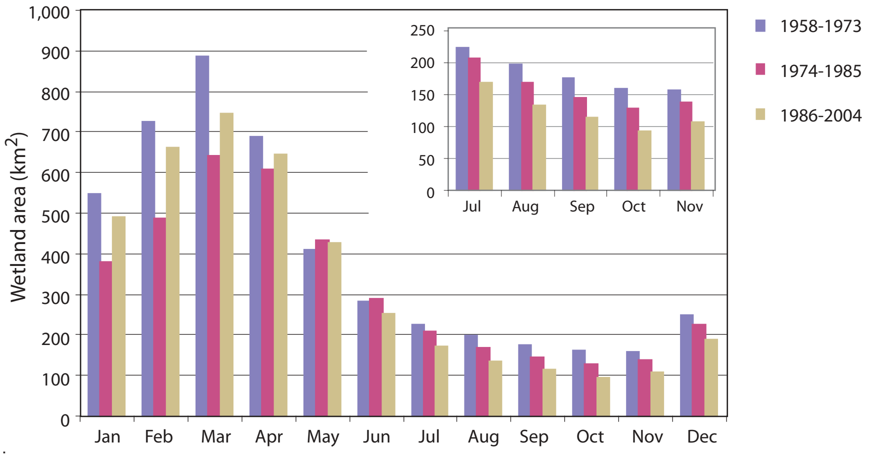
Simulated wet season outflows from the wetland vary between the time windows. There

TABLE 11.
Simulated mean monthly wetland area (km^2) for each of the time windows.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-1973	547	725	885	687	409	283	225	197	176	160	158	249
1974-1985	380	488	642	607	434	288	207	169	144	129	139	226
1986-2004	490	659	744	646	427	253	170	134	114	93	107	188

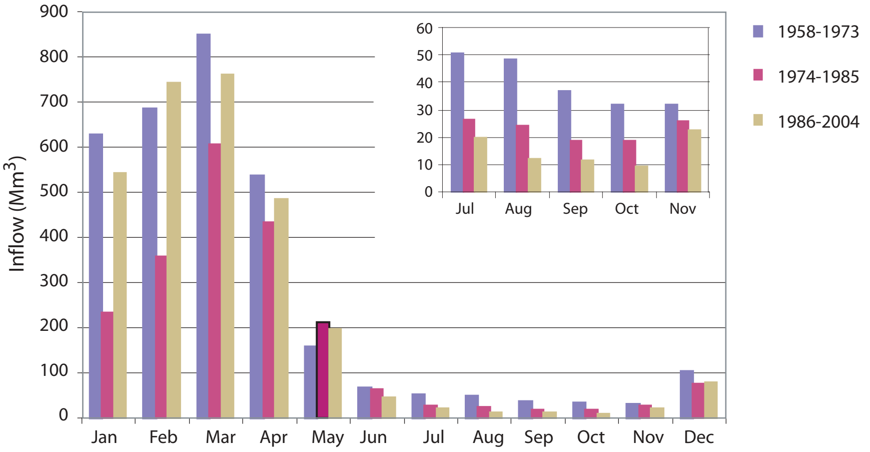
Source: Own analysis

FIGURE 18.
Simulated mean monthly area of the Eastern Wetland, with the dry season magnified (inset).



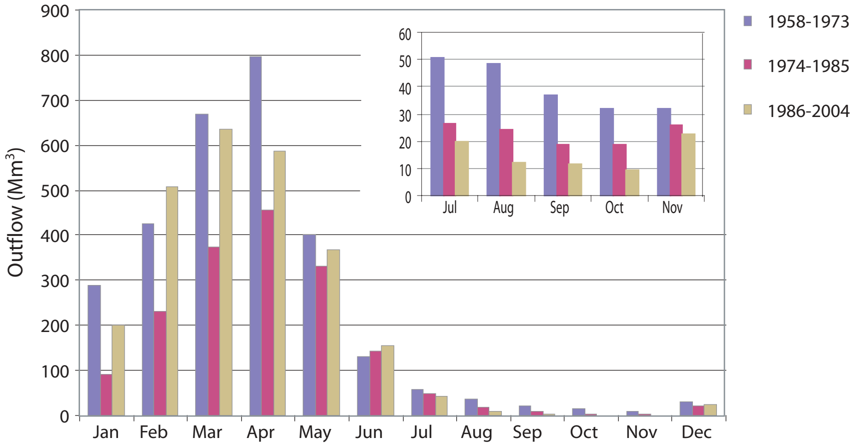
Source: Own analysis

FIGURE 19.
Simulated mean monthly inflows to the Eastern Wetland, with the dry season magnified (inset).



Source: Own analysis

FIGURE 20.
Simulated mean monthly outflow from the Eastern Wetland, with the dry season magnified (inset).



Source: Own analysis

TABLE 12.
Simulated mean monthly inflows (Mm³) for each of the time windows.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-1973	626.1	685.8	849.6	536.1	158.4	67.7	50.9	48.4	36.8	32.1	31.7	102.8
1974-1985	234.1	359.0	605.2	433.0	212.8	63.1	26.2	24.5	18.8	18.6	26.0	74.5
1986-2004	542.5	741.2	761.8	485.4	197.4	45.6	20.0	12.2	11.8	9.2	22.3	78.7

Source: Own analysis

TABLE 13.
Simulated mean monthly wetland storage (Mm³) for each of the time windows.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-1973	485	730	927	583	251	140	98	80	67	58	57	129
1974-1985	225	331	543	462	270	140	84	61	48	40	46	99
1986-2004	422	632	723	533	279	118	62	42	33	24	32	83

Source: Own analysis

TABLE 14.
Simulated mean monthly wetland outflow (Mm³) for each of the time windows.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-1973	287.8	426.3	668.9	797.8	402.7	130.5	57.1	35.1	21.7	14.3	10.2	30.3
1974-1985	92.0	231.8	374.7	456.4	331.5	142.1	48.5	18.9	7.7	3.6	3.6	20.0
1986-2004	202.0	506.7	635.3	587.8	367.8	154.7	43.5	8.3	1.9	0.3	0.6	22.8

Source: Own analysis

is no clear trend over time and, hence, no trend in annual data, because the wet season flows dominate the annual flow series. In contrast there is a steady decline in the outflows in the dry season. In the post-1985 window, the average minimum dry season outflows, which occur in October/November declined to just 0.3-0.6 Mm^3 and just 2-6 percent of the values they were in pre-1974 window (table 14; figure 20).

Between 1998 and 2003, flows were measured on the perennial rivers flowing into the wetland, upstream of the abstractions on the Usangu Plains. Dry season results are summarized and compared to the simulated dry season inflows to the Eastern Wetland in table 15. The data indicate that, between 1998 and 2003, average dry season flows in the perennial rivers totaled 112.6 Mm^3, but only 56.3 Mm^3 flowed into the Eastern Wetland. The difference suggests that, on average, a total of 56.3 Mm^3 (i.e., exactly 50%) of the dry season flow was abstracted for human use. This compares reasonably well with the total of 47.6 Mm^3 derived independently from the sectoral dry season water use estimates (table 1) and equates to an average dry season abstraction of 4.25 m^{3}s^{-1}. The most significant reduction in the flow occurs during October because the exceedingly high demand for irrigation water (which arises when the paddy fields are flooded prior to planting), coincides with the period of lowest flows.

The results obtained through the use of the model indicate a large decrease in the dry season inflows to the Eastern Wetland. This, in conjunction with the decrease in rainfall over the Usangu Plains, has resulted in a shrinking of the perennial swamp, a decrease in water stored within the wetland and a marked decline in the dry season outflow from the wetland.

TABLE 15.
Comparison of average monthly dry season flows (m^3s^{-1}) for perennial rivers and simulated inflows to the Eastern Wetland (1998-2003).

	Average monthly flows (m^3s^{-1})					
Sub-catchment	July	August	September	October	November	Average
Great Ruaha	3.64	2.86	2.41	2.31	2.29	2.70
Mbarali	5.00	3.93	3.09	2.39	2.68	3.42
Kimani	1.46	1.11	0.90	0.76	0.74	0.99
Ndembera	2.50	1.50	1.00	1.00	0.90	1.38
Current water available at gauging stations before abstractions in the plains	12.59 (33.7)	9.40 (25.2)	7.40 (19.2)	6.47 (17.3)	6.62 (17.2)	8.50 (112.6)
Simulated total inflow to the Eastern Wetland (1998-2003)	4.58 (12.3)	4.51 (12.1)	4.81 (12.5)	2.80 (7.5)	4.58 (11.9)	4.26 (56.3)

Source: Own analysis

Note: Nos. in brackets are the flow converted to Mm^3

Maintaining Flows Downstream of the Eastern Wetland

Currently, although most were developed for temperate climates, there are more than 200 methods for estimating environmental flows (Tharme 2003). A number of these approaches were considered in an attempt to determine “desired” dry season flows downstream of the Eastern Wetland. In the Usangu Catchment, where water is already over-allocated without any consideration of the environmental requirements, it is not reasonable to plan only environmentally favorable allocations. For this reason, the analyses conducted included consideration of current human abstractions as well as routing requirements. A number of alternative allocation scenarios were evaluated. For each of these alternative allocations, the wetland model was used to compute the inflows required to guarantee minimum dry season outflows.

The lack of data is often a constraint to the estimating of environmental flows. This is true for the Great Ruaha River, where lack of requisite data and understanding of the linkages between different flow regimes and ecological impacts make estimating flow requirements difficult. The South African Building Block Methodology (King and Tharme 1994; King et al. 2000) and the Downstream Response to Imposed Flow Transformations Method (King et al. 2003), are approaches that have been developed and used in southern Africa. However, full application of these methods requires significantly more data on aquatic habitat than were available for the current study. In this study, the ecologist of the Ruaha National Park and the Friends of Ruaha Society (FORS) were consulted to provide estimates, based on expert judgment, of the minimum flow needs in the Ruaha National Park.

To compensate for the lack of ecological information, several methods of estimating environmental flows have been developed that are based solely on hydrological indices derived from historical flow data (Tharme 2003).

Although it is recognized that a myriad of environmental attributes influence the ecology of aquatic ecosystems (e.g., temperature, water quality and turbidity), the common assumption of these approaches is that flow regime is the primary driving force (Richter et al. 1997). The hydrological index methods include: a) the Tennant (or Montana) method (Tennant 1976);
b) the Texas method (King et al. 1999); c) flow duration curve analysis (Pyrce 2004);
and d) Range of variability approach (Richter et al. 1996, 1997). Most of these methods have been developed in Europe and the USA. However, as noted above, considerable work on environmental flows has also been undertaken in South Africa. This includes the development of what is known as the "desktop reserve model," which is intended to quantify ecological flow requirements in situations when a rapid appraisal is required and data availability is limited (Hughes and Hannart 2003). To date, the model has not been used extensively outside of South Africa. However, because it was developed specifically for conditions experienced in the rivers of South Africa, it was felt to be the most appropriate tool to use in the current study. Results derived from the model were compared with flow duration curve analysis, the method used most commonly elsewhere in the world (Tharme, 2003; Pyrce 2004).

Flow Duration Curve Analysis

Generally, the "design" low-flow range of a flow duration curve is in the Q_{70} to Q_{99} range (Smakhtin 2001). Q_{95} and Q_{90} are frequently used as indicators of low flow and have been widely used to set minimum environmental flows (Pyrce 2004; Tharme 2003; Smakhtin 2001). From the flow duration curve for the pre-1974 period (i.e., least modified), low-flow percentiles were extracted (figure 10). The Q_{95} derived from the flow duration curve is 2.84 m^3s^{-1}. However, the low-flow analysis (page 14) indicates that, even in the pre-1974 period, flows lower than this occurred every year. Consequently, there is no doubt that the ecology of the river and its surrounds will have adapted to dry season flows lower than 2.84 m^3s^{-1}. Nonetheless, for purposes of comparison, this value was used in one scenario developed to estimate inflow requirements to the wetland (page 30).

Application of the Desktop Reserve Model

The desktop reserve model was developed to provide a method for generating initial, low confidence estimates of ecological flow requirements for rivers in South Africa (Hughes and Münster 2000). The model incorporates the concepts of the building block method (King et al. 2000), which is widely recognized as a scientifically legitimate approach to setting environmental flow requirements (Hughes and Hannart 2003). The approach is based on the fact that, under natural conditions, different parts of the flow regime play different roles in the ecological functioning of a river and, as such, it is necessary to retain fundamental differences between wet season and dry season flows. Hence, the Building Blocks (BBs) are different components of flow, which combined comprise an ecologically acceptable, modified flow regime. The major BBs are low flows (baseflows), small increases in flow (freshes) and larger high flows, required for river channel maintenance (Hughes 2001).

BBs differ between "normal years" and "drought years." The former are referred to as "maintenance requirements" and the latter as "drought requirements" (Hughes 2001; Hughes and Hannart 2003). The frequency with which maintenance and drought years occur is defined on the basis of the variability of the natural hydrological regime, which is largely a function of climatic conditions. Hence, maintenance years occur quite frequently (typically 60–70%) in wetter, more reliably flowing rivers, while they occur much less frequently in semi-arid and arid rivers (typically 20% or lower) (Hughes and Hannart 2003). The set of BBs, therefore, includes maintenance low flows, maintenance high flows and drought flows, reflecting the natural variability of the flow. The desktop reserve model provides estimates of these BBs for each month of the year.

The major assumption of the desktop reserve model, which emerged from an analysis of comprehensive environmental flow studies conducted in South Africa, is that rivers with more stable flow regimes (i.e., a higher proportion of their flow occurring as baseflow) have relatively higher low-flow requirements in normal years (i.e., “maintenance low-flow requirements”) than rivers with more variable flow regimes. This assumption is founded on the premise that, in highly variable flow regimes, the biota will have adjusted to a relative scarcity of water, while in more reliably flowing rivers, the biota are more sensitive to reductions in the flow (Hughes and Hannart 2003). The consequence is that, generally, the long-term mean environmental requirement is lower for rivers with more variable flow regimes.

In South Africa, rivers are classified in relation to a desired ecological condition, and flow requirements set accordingly. The classification system recognizes that while some rivers are environmentally important, the requirements for socioeconomic development mean that not all rivers can be retained in a near natural state. Thus four possible target “environmental management classes” (A-D) are defined. Class A rivers are largely unmodified and natural. Class D rivers are largely modified, with large loss of natural habitat, biota and basic ecosystem functioning (DWAF 1999). Class B and C rivers lie between these extremes. However, it is acknowledged that all resource development must be environmentally sustainable and, as such, even category D rivers should retain some basic ecological functioning. Transitional categories (e.g., A/B and B/C) are also used to increase the range of possible environmental flows. This classification system is used within the desktop reserve model, and flow requirements computed accordingly; the higher the class, the more water is allocated for ecosystem maintenance and greater the flow variability preserved.

In the current study, the desktop reserve model was applied to the Great Ruaha River downstream of the Eastern Wetland. The model is based on monthly time step data and, to estimate environmental flow requirements, a naturalized flow series must be entered.[2] In this case, monthly flows from the Msembe Ferry for years 1958 to 1973 (i.e., the least modified period) were used as input. To reflect the reality of the importance of water abstractions for local communities, the desired ecological condition of the river was set as C/D.

Flow variability plays a major role in determining environmental flow requirements. Within the model, two measures of hydrological variability are used. The first is a representation of long-term variability of wet and dry season flows and, is based on calculating the coefficient of variation (CV) for all monthly flows for each calendar month. The average CVs for the three main months of both the wet and the dry season are then calculated and, the final CV-Index is the sum of these two season’s averages (Hughes and Hannart 2003). A limitation of the model is that, in computing CV-Index, the model assumes that the primary dry season months are June to August and wet season months are January to March, as occurs over much of South Africa. Within the model this cannot be altered. However, for the Great Ruaha the key months are February to April and September to November for the wet and dry seasons, respectively. To ensure that the model computed a flow variability index much closer to reality, and since it is dominated by the wet season months, the input time series of flows was shifted by one month (i.e., January became February and so forth). The model output was then corrected to ensure that the results were applied to the appropriate months.

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[2] In South Africa, a 70-year naturalized flow series has been developed for each quaternary catchment (i.e., the principal water management unit) as part of a comprehensive national water resource assessment (Midgley et al. 1994). It was these flow series that the model was developed to use.

The second index is the proportion of the total flow that can be considered to occur as baseflow (i.e., baseflow index [BFI]). Rivers with high BFI are less variable than those with low BFI values. The model computes the BFI from the monthly time series. However, in this study it was possible to calculate the BFI from the daily flows. This gave a BFI of 0.92, which is a high value reflecting both the relatively large size of the catchment to the Msembe Ferry (24,620 km^2) and the flow regulation effect of the Eastern Wetland. The two model parameters that determine the BFI using the monthly data were modified (by trial and error) until the model computed BFI closely matched that obtained from the daily data.

The model results are presented in table 16. These indicate that, to maintain the river at class C/D, requires an average annual environmental flow allocation of 635.3 Mm^3 (equivalent to 21.6% of MAR). This is the average annual "maintenance flow"; the sum of the maintenance low flows (i.e., 15.9 % MAR; 465.4 Mm^3) and the maintenance high flows (i.e., 5.8% of MAR; 169.9 Mm^3). The drought-low-flows correspond to 10 percent MAR (i.e., 293.3 Mm^3).

For the period 1986-2004, average annual flows at Msembe were significantly greater than the annual total maintenance flow requirements predicted by the model (i.e., 2,538 Mm^3 and 635.3 Mm^{3,} respectively). However, average flows in months September to November were

TABLE 16.
Summary output from the desktop reserve model applied to the Great Ruaha at the Msembe Ferry, based on 1958-1973 monthly flow series.

Annual flows (Mm^3 or index values)

MAR	=	2,936.30	Total environmental flow	=	635.30	(21.6% MAR)
S.D.	=	2,932.16	Maintenance low flow	=	465.44	(15.9% MAR)
CV	=	0.996	Drought low flow	=	293.26	(10.0% MAR)
BFI	=	0.89	Maintenance high flow	=	169.86	(5.8% MAR)
CV (SON + FMA) Index	=	1.541				

Month	Observed flow (Mm^3)			Environmental flow requirement (Mm^3)			
				Low-flows		High-flows	Total-flows
	Mean	SD	CV	Maintenance	Drought	Maintenance	Maintenance
Jan	279.452	536.153	1.919	35.57	13.33	37.15	72.72
Feb	451.068	505.184	1.12	67.55	22.43	18.58	86.12
Mar	682.947	705.617	1.033	106.02	72.57	86.05	192.1
Apr	803.089	777.042	0.968	131.22	93.15	18.58	149.80
May	405.689	318.063	0.784	71.75	50.69	2.30	74.05
Jun	123.363	72.367	0.587	22.05	15.69	0	22.05
Jul	56.774	25.68	0.452	10.12	7.22	0	10.12
Aug	35.002	19.179	0.548	6.22	4.45	0	6.22
Sep	21.618	10.842	0.502	3.82	2.75	0	3.82
Oct	14.729	7.644	0.519	2.58	1.87	0	2.58
Nov	10.808	5.974	0.553	1.87	1.37	0	1.87
Dec	51.762	109.609	2.118	6.67	4.77	7.21	13.88

Source: Own analysis using desktop reserve model significantly less than suggested by the model (table 17; figure 21). This simply confirms the assertions of ecologists that, in recent years, dry season flows have been insufficient to maintain even the basic ecological functioning of the river.

In addition to using the hydrological characteristics of the naturalized flow series to compute annual totals and the seasonal distribution of environmental flow requirements, the model also combines maintenance and drought requirements into continuous assurance or frequency curves. This enables a time series of "historic" environmental flow requirements to be derived, and also means that assurance levels, or return periods, can be attached to specified environmental flow requirements. Details of the process are provided in Hughes and Munster (2000) and Hughes and Hannart (2003). To do these analyses, the desktop reserve model includes parameters for 21 regionalized assurance curves. The regionalization was based upon the natural flow duration curve characteristics of 1946 quaternary catchments in South Africa.[3]

In the current study, the 1958-1973 observed series was used. Initially, the model parameters chosen were those derived for dolomite regions of South Africa as thier monthly flow regimes were most similar to that of the Great Ruaha River at Msembe Ferry. However, these parameters were then modified, through a process of trial and error, until, based on a visual comparison, simulated and observed monthly flow duration curves matched as closely as possible.

Figure 22 presents a comparison of the observed time series and the model derived environmental flow series for the Great Ruaha River at the Msembe Ferry for the pre-1974 period. Over this period, which was relatively wet (table 10), the average annual environmental flow requirement was 780 Mm^3.

The monthly flows associated with different levels of assurance are presented in table 18. These results indicate that absolute minimum flows attained every year should be approximately 0.80 m^3s^{-1} and 0.60 m^3s^{-1} in October and November, respectively, but with, on average, minimum flows exceeding 1 m^3s^{-1} every other year.

TABLE 17.
Comparison of environmental flow requirements computed by the desktop reserve model and actual mean monthly flows at the Msembe Ferry between 1986 and 2004.

	Total maintenance flow requirement		Observed flows		Ratio of observed to environmental flow requirement
Month	(Mm^3)	(m^3s^{-1})	(Mm^3)	(m^3s^{-1})	
Jan	72.7	27.2	229.2	85.6	3.15
Feb	86.1	35.6	513.0	212.1	5.96
Mar	192.1	71.7	625.2	233.5	3.26
Apr	149.8	57.8	577.6	222.8	3.86
May	74.1	27.7	358.3	133.8	4.84
Jun	22.1	8.5	148.6	57.3	6.74
Jul	10.1	3.8	44.9	16.8	4.44
Aug	6.2	2.3	8.7	3.3	1.40
Sep	3.8	1.5	2.1	0.8	0.55
Oct	2.6	1.0	0.7	0.3	0.27
Nov	1.9	0.7	1.5	0.6	0.79
Dec	13.9	5.2	26.60	9.9	1.92

Source: Own analysis

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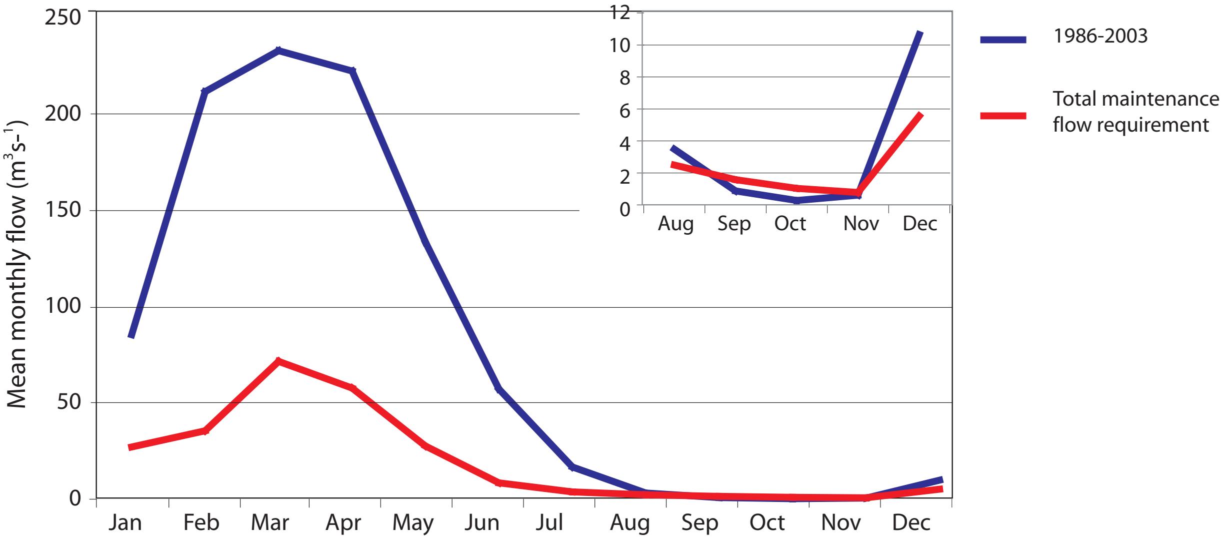
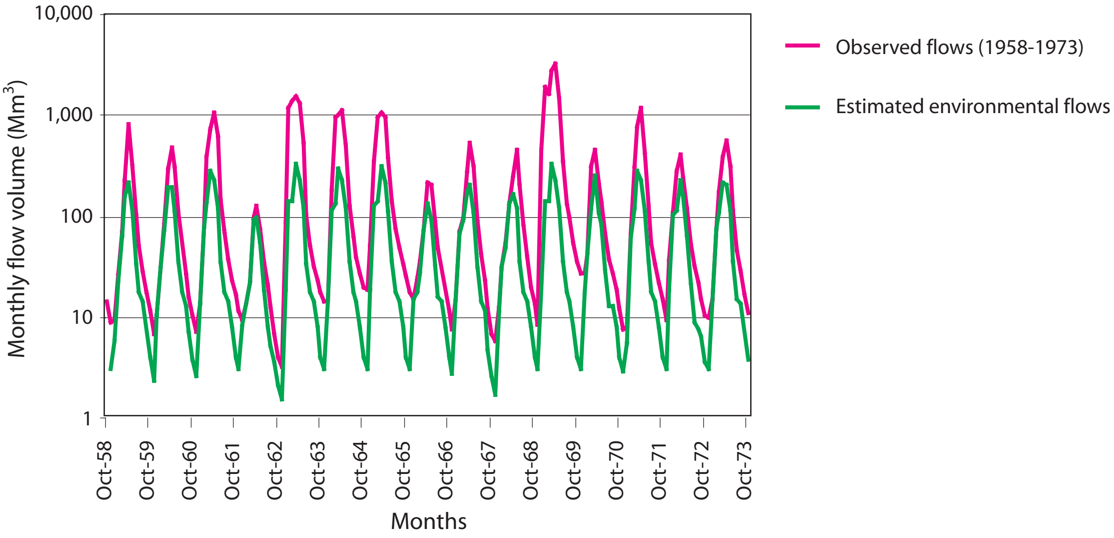
[3] The regionalized assurance curves were derived from the 70-year naturalized flow series developed for each quaternary catchment.

FIGURE 21.
Comparison between observed mean monthly flows and total maintenance flow requirements (m^{3}s^{-1}) for the 1986-2004 period, with months August-December magnified (inset).



Source: Own analysis

FIGURE 22.
Monthly observed flow and estimated environmental flow time series for the Great Ruaha at Msembe Station (1958-1973).



Source: Own analysis

Note: Log scale on the y-axis

TABLE 18.
Low flow maintenance requirements (m^3s^{-1}) at the Msembe Ferry for four return periods, for management category C/D.

Chance of exceedance	Return Period (years)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.99	1	5.0	8.4	31.1	36.1	21.3	7.0	3.4	1.9	1.4	0.8	0.6	1.9
0.50	2	18.8	36.2	64.7	70.7	43.3	13.0	6.8	5.3	2.9	1.6	1.2	3.4
0.30	3	21.5	37.9	66.1	72.9	44.3	13.2	6.9	5.4	3.0	1.6	1.2	3.5
0.20	5	22.0	37.9	66.4	73.2	44.4	13.2	6.9	5.4	3.0	1.6	1.2	3.6

Source: Own analysis

Although used extensively in South Africa, application of the desktop reserve model in other countries is relatively limited. It has, however, been used successfully in Swaziland, Zimbabwe and Mozambique (Hughes and Hannart, 2003). The accuracy of the model results cannot be substantiated without further study. Given that it is underpinned by empirical equations developed specifically for South Africa, and is, furthermore, only supposed to be a “low-confidence” approach, the results must be treated with caution. Nonetheless, in the absence of any specialist knowledge on the relationships between hydrology and the ecological functioning of the river, it was felt to be the most appropriate method for use in the current study. Furthermore, for the dry season, the model results are consistent with the expert opinion that absolute minimum environmental flows should be not less than 0.5 m^3s^{-1}.

Scenario Analysis

Realizing the need to balance environmental water requirements and livelihoods issues under the prevailing water resource conditions, four possible flow scenarios were formulated. In each case the wetland model was used to compute the inflows to the Eastern Wetland that is required to maintain the specified minimum downstream flows for the period 1999 to 2004.

Ensuring a Dry Season Outflow of 2.84 m^3s^{-1} (i.e., corresponding to the “natural” Q_{95})

The Q_{95} as derived from the flow duration curve is 2.84 m^3s^{-1}. The corresponding average dry season inflow required to maintain this outflow was estimated to be 11.6 m^3s^{-1}. This is significantly greater than the perennial river flows measured upstream of the off-takes on the Usangu Plains between 1998 and 2003 (table 15). Hence, it is greater than the currently available water resource, and it is completely unrealistic to contemplate achieving this flow.

Ensuring the Estimated 2-year Return Period Environmental Flows

The average dry season inflow needed to maintain downstream environmental flow requirements with a return period of 2 years (table 18) was estimated to be 9.98 m^3s^{-1}. This is slightly more than the average dry season flow in the perennial rivers, upstream of the abstractions on the Usangu Plains (table 15), but is slightly lower than the pre-1974 dry season inflows. However, under current conditions it is also unrealistic to contemplate achieving this flow.

Ensuring the Estimated One-year Return Period Environmental Flows

The average dry season inflow required to maintain downstream environmental flow requirements with a return period of one-year (table 18) was estimated to be 7.68 m^3s^{-1}. This is close to the current average dry season inflow in the perennial rivers upstream of the Usangu Plains (table 15). However, allocating this amount of water for environmental needs would leave very little for irrigation and other livelihood support activities.

Ensuring an Absolute Minimum Flow of Between 0.5 and 0.6 m^3s^{-1}

The absolute minimum dry season flow required to maintain conditions (i.e., temperature and dilution requirements) suitable for wildlife in the pools and the river in the Ruaha National Park during the dry season was judged to be 0.5 m^3s^{-1} (Ecologist for the Ruaha National Park, personal communication). This is similar to the absolute minimum flow of 0.6 m^3s^{-1} derived from the desktop reserve model for October. Average dry season inflows required to maintain outflows of 0.6 m^3s^{-1} and 0.5 m^3s^{-1}, without consideration of minimum flow requirements in other months, were 7.22 m^3s^{-1} and 6.98 m^3s^{-1}, respectively. This suggests an absolute minimum dry season inflow of about 7.0 m^3s^{-1}. This is approximately 3.25 m^3s^{-1} greater than current average dry season inflows (table 15). To maintain this average inflow would require the available dry season surface water resource to be divided in the ratio of 80 percent for the environment (i.e., 7.0 m^3s^{-1}) and 20 percent for anthropogenic water needs (i.e., 1.50 m^3s^{-1}). In absolute terms this would require current dry season abstractions to be reduced from approximately 4.25 m^3s^{-1} to about 1.50 m^3s^{-1} (i.e., a 65% reduction).

Discussion

The analyses conducted in this study indicate that, to maintain absolute minimum desired flows downstream of the Eastern Wetland (i.e., 0.5 m^3s^{-1}), would require a 65 percent reduction in the current dry season abstractions from the perennial rivers. Some reduction in abstraction may be possible through improved water use efficiency. Currently demand management is being implemented through a program of gate closure on the large irrigation schemes. By reducing water diversions at the start of the dry season (i.e., June) it was hoped to “top-up” the wetland storage sufficiently to ensure the maintenance of dry season flows. However, to date, although it may have improved the situation, it has not prevented zero flow occurring in the Great Ruaha River in the dry season. The current study has shown that with only a 4- to 6-week lag between inflows and outflows, it is the maintenance of flows throughout the dry season, not storage within the wetland per se, which is critical to sustaining the downstream river flows.

Increased use of groundwater is another possible approach to reducing surface water abstractions. No detailed survey of groundwater sources has been conducted, but it has been estimated that annual groundwater inflow, combined with inflow from the ephemeral rivers, may be in the range of 29-36 Mm^3 (SMUWC 2001b). It is recommended that careful consideration be given to installing boreholes and wells to provide the required domestic supply in villages. Currently many of the villages rely on water supplied by the irrigation canals and this means that diversions have to be maintained throughout the dry season, even at locations where irrigation is minimal or non-existent. Since much of the water diverted is “lost” through seepage and evaporation, significant water saving might be possible if alternative options for domestic supply could be found. Replacing the existing domestic supply with groundwater sources would enable some off-takes to be closed completely in the dry season. However, groundwater distribution, which is likely to be closely associated with permeable deposits and paleo-river channels (SMUWC 2001b), may be very variable and not located close to where the water is needed. Furthermore, since groundwater flows, combined with the surface inflow, may contribute to the maintenance of the wetland during the dry season, the impact of significant dry season groundwater abstraction (e.g., if groundwater was used for irrigation) on low flows is not clear.

To ensure an outflow of 0.5 m^3s^{-1}, an average dry season inflow to the wetland of 7 m^3s^{-1} must be guaranteed. Clearly, there is significant potential for dry season water savings in the Usangu Catchment. However, given the current importance of the river abstractions for dry season livelihood needs (i.e., irrigation, water supply and others), it is very difficult to see how, under existing circumstances, the reductions required to attain these inflows could be achieved. Consequently, it is necessary to consider alternative management scenarios.

Management of the Wetland

The difference between the relatively large inflows and small outflows from the wetland is attributable to evapotranspiration from within the Ihefu swamp and the surrounding grassland. Clearly, although many benefits are derived from the wetland, the wetland depletes the water resources of the catchment and, in relation to downstream water requirements, can be considered a “scarcity enhancer.” Given the currently limited possibility of significantly reducing dry season abstractions, the only possible trade-off that might be considered is that between the wetland itself and the Ruaha National Park. This trade-off can be expressed in terms of evaporation in the wetland versus uses in the Ruaha National Park and the downstream hydropower dams. Alternatively it could be considered in terms of benefits for fisheries, livestock and biodiversity in the wetland versus wildlife conservation and energy generation. Either way, the trade-off can be expressed as a decision over the size of the permanent wetland as presented in the following statement:

Either a larger wetland evaporating all the incoming water or alternatively a smaller permanent wetland evaporating most of the inflow but allowing an exit flow of about 0.5 m^3s^{-1} *to the Ruaha National Park.*

In the first instance all ecological benefits of the inflow are attained by the wetland and there is no exit flow. In the second, the ecological benefits of the inflow are shared between the wetland and the Ruaha National Park.

Figure 23 is a schematic representation of these two possible management options. If the second option is favored, the objective becomes to manage the wetland in a way that, despite the limited inflows, retains as far as possible the benefits provided by the wetland but simultaneously ensures a flow from the wetland to the Ruaha National Park. Such a strategy can only be achieved if evapotranspiration from the wetland is reduced. This in turn requires “active management” of water within the wetland; specifically a better control of flows within it.

If flows through the wetland were increased so that inflowing water reached the outlet more rapidly, evapotranspiration would be reduced and downstream flows could be maintained. Currently, there is no defined channel extending all the way from Nyaluhanga to NG’iriama and, within the wetland, water moves as a sheet through reed beds, at all but the lowest flows. More rapid flows could be achieved by ensuring that major pools within the wetland are linked by channels and the major channels are kept clear of reeds and other aquatic vegetation.[4]

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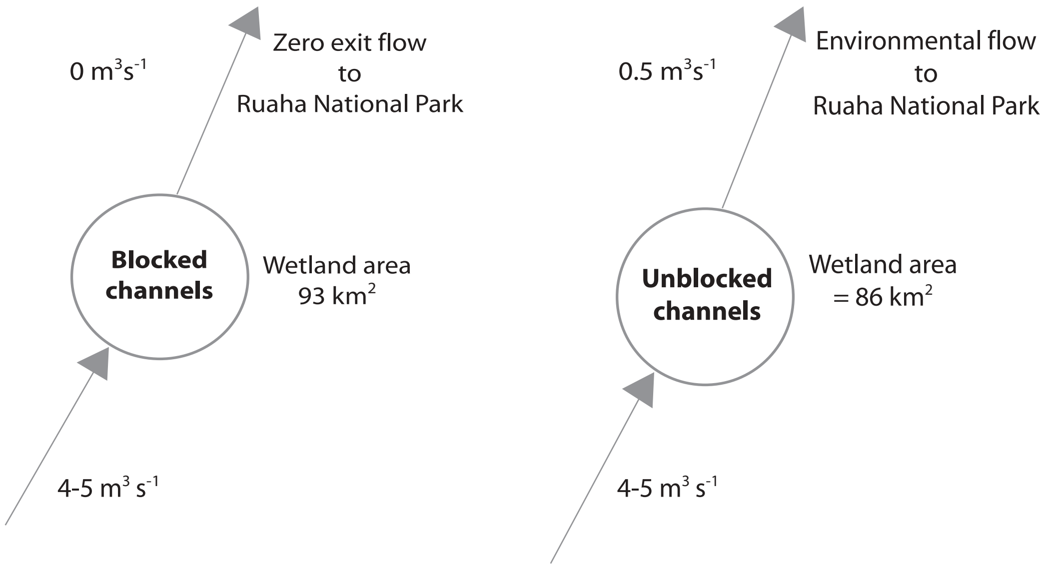
[4] Despite the increased irrigation, fertilizer use within the catchment is low and there is no evidence of enhanced reed growth arising as a consequence of greater nutrient inputs (SMUWC 2001c).

FIGURE 23.
Schematic outlining possible management scenarios.



Un-managed tradeoff, zero-flow to Ruaha National Park

Managed tradeoff, small environmental-flow to Ruaha National Park

Today, the Ihefu wetland is in an "unmanaged" scenario because livestock keepers and fisher folk have been excluded. Although supposedly natural, the channels have been blocked in the past by livestock keeping and fishing activities.

Inflow to the wetland spreads and this generates greater evapotranspiration loss. Although the inflow in now greater than before 2001, because of canal regulation by RBWO, the average dry season flow of about 4-5 m^{3}s^{-1} is insufficient to generate 'spill' at the outlet. Consequently the Ruaha National Park is left without water for several months.

The situation may not improve because:

- No one is allowed in the area (although there is some discussion of fisher folk being allowed return)
- No use of wetland resources is allowed
- No human action is occurring on the wetland

In an alternative 'managed scenario', the wetland is more carefully managed. All stakeholders (RBWO, Ruaha National Park, Mbarali, Usangu Safaris Ltd., livestock keepers and fisher folk) agree to a community management plan, where livestock keepers are not excluded, but numbers are decreased. Fisher folk are not excluded but their number and use of resources are "controlled" or self-regulated. Active management of water flows results in reduced evapotranspiration.

The situation may improve because:

- Negotiated uses of wetland is promoted
- "Controlled" use of wetland resources is allowed
- The wetland is managed in order to ensure minimum flows of 0.5 m^{3}s-^{1} at the outlet.

Source: Own analysis

Before they were expelled from the wetland, at the time it was gazetted, the local fisher folk were very effective at blocking and unblocking channels. If they endorsed the plan and were allowed to return to the reserve, they could be encouraged to keep the channels open, especially if the practice resulted in improved fisheries. Otherwise, mechanical and perhaps even chemical removal of reeds, and dredging of channels, might have to be considered.

Alternative Options

To maintain flows downstream of NG'iriama a number of engineering alternatives could also be considered. These include:

- Raising the sill level at the outlet, by constructing a low (i.e., 0.5 to 1.0 m) weir across the rock lip at NG'iriama (i.e., crest level between 1010.0 m amsl and 1010.5 m amsl). Such a structure would increase the size of the perennial swamp and effectively transform the wetland into an inter-seasonal reservoir by increasing the volume of water "stored" in the swamp at the end of the wet season. Although evapotranspiration losses would be significantly increased, if flow through the weir was regulated via an adjustable sluice gate, downstream flows could be controlled to ensure that minimum flow requirements were met. To minimize changes to wet season flows from the wetland, the weir would have to be designed to be overtopped during periods of high flow.
- Construction of a pipe to transfer a portion of the inflow at Nyaluhanga directly to NG'iriama. This would reduce both the permanent size of the wetland and evapotranspiration from it. It would also ensure that minimum flow requirements downstream of the outlet were secured, provided current inflows to the wetland were maintained in the future.
- Construction of a dam on the Ndembera River to store water for the purpose of ensuring controlled inflows to the north-eastern end of the wetland. Preliminary studies for the construction of such a dam have been conducted as part of the feasibility investigations of the Madibira Rice Project (Halcrow and Partners 1985). However, the dam was not built, largely because the cost involved made it uneconomic. Certainly building a dam is an expensive option, and it could be difficult to justify construction solely for the purpose of maintaining dry season flows. If, however, the dam was built for multiple purposes and careful management practices were put in place to ensure that environmental flows did not lose out to other demands, it could be considered a viable option.

The ecological impacts of these measures would need to be carefully assessed through detailed environmental impact assessments. Detailed surveys of the wetland geometry as well as hydraulic analyses would be required to determine likely changes to the areal extent of the permanent swamp, and the resulting consequences for the seasonal wetland. The implications for fisheries and grazing, as well as other livelihood activities in the area would also have to be carefully evaluated. Participation of local people in the decision-making process would be essential for any intervention to be successful and sustainable.

Conclusion

The determination of environmental water requirements, especially in developing countries, faces many challenges. This study has highlighted the value, particularly for relatively data-sparse regions, of integrating findings and results from a number of different research approaches and utilizing scenarios to assess the feasibility of different allocation decisions. The development of a simple computer model has improved the understanding of the hydrological functioning of the Usangu Wetlands. It also has enabled a quantitative assessment of the changes that have occurred over time. Reduction in dry season inflows has resulted in the shrinking of the dry season area of the wetland, and a consequent decline in downstream flows. Since 1958, increasing diversions of water has caused average dry season inflows to the Eastern Wetland to decrease from approximately 15.0 m^3s^{-1} to 4.3 m^3s^{-1} (i.e., a 70% decrease). This has led to a reduction in the average minimum dry season area of the wetland from approximately 160 km^2 to 93 km^2 (i.e., a 40% decrease). Since the early 1990s, the decrease in dry season water levels within the wetland has resulted in prolonged periods of zero flow in the Great Ruaha River, with severe consequences for the ecology of the Ruaha National Park.

A number of management options exist for maintaining dry season river flows downstream of the Eastern Wetland. The wetland model enabled calculation of the inflows required to maintain specified discharges. To maintain a flow of 0.5 m^3s^{-1}, required for the most critical dry season period for the Great Ruaha River through the Ruaha National Park, an average inflow of approximately 7.0 m^3s^{-1} (i.e., almost double current values) is required. Although significant opportunities exist to increase local water use efficiency, and thereby enhance the inflows to the wetland, given the current levels of diversion it will be very difficult to “release” sufficient water to ensure the desired downstream flow of 0.5 m^3s^{-1}. Consequently, a pragmatic approach is to consider alternative options that manage water within the wetland to either reduce evaporation or increase water storage. A number of alternative options have been discussed, including increasing the speed of flow through the wetland by removing reeds and dredging channels, piping water from Nyaluhanga directly to NG’iriama, and construction of either a low weir at the outlet or a dam on the Ndembera River. All these alternatives would have ecological, as well as socioeconomic consequences, which need to be carefully assessed through environmental and social impact assessments, in conjunction with discussions with all the stakeholders.

Maintenance of aquatic ecosystems is a pre-requisite for sustainable development. In an environment of increasing water scarcity, the allocation of water must consider the environmental implications. However, estimating water requirements for wetlands in water-stressed catchments, in which peoples’ livelihoods are highly dependent on water abstraction, is a far from trivial task. It is essential that consideration is given not only to environmental requirements, but also to the economic and social implications of maintaining environmental flows. In such situations, an understanding of flow regimes and hydrological functioning is necessary for informed decision-making. There is a need to develop approaches to assist decision-makers in the allocation of water for the environment. This study has demonstrated the value of relatively simple models to provide a credible scientific basis to underpin decisions relating to environmental water allocations.

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