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Theme 2: Water and Environment

Estimation of environmental flows in the Great Ruaha River Catchment, Tanzania: use of the desktop reserve model

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Abstract

For the past eleven years, the Great Ruaha River which flows through the Ruaha National Park, has ceased flowing during the dry season, with extended periods of zero flow. The drying up has resulted in social conflicts between upstream and downstream users. It has also caused adverse impacts on the ecosystem of the Ruaha National Park, disrupting the lives of many animals and causing changes in their behavior. In this paper we present the findings of a hydrological study conducted to estimate environmental flow requirements. The desktop reserve model was used to determine maintenance high and low flows, and drought low flow requirements within the Ruaha National Park. The results indicate that to maintain the basic ecological functioning of the river requires an average annual allocation of 635.3 Mm^3 (equivalent to 21.6% of mean annual runoff). This is the average annual maintenance flow; comprising of maintenance low flows (i.e. 15.9 % MAR; 465.4 Mm^3) and maintenance high flows (i.e. 5.8% of MAR; 169.9 Mm^3). The absolute minimum water requirement was estimated to be 0.6 m^3s^{-1} with the probability of exceedance of 0.99. The study confirms that in the absence of ecological information hydrological indices can be used to provide a first estimate of environmental water requirements. However, before being applied, greater understanding of the relationships between flow and the ecological condition of the riverine ecosystem is required.

Keyword: Great Ruaha River, Ruaha National Park, Environmental flows, desktop reserve model

Introduction

Water is essential to all kinds of human development and livelihood support systems including ecosystems management. However water resource is now under pressure due to increased competing demands and this has led to complex water management challenges.

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One of the major challenges for sustainable water resource management is to assess how much water can be taken from a river before its ability to meet social, ecological and economic needs is hampered. Another challenge is on how to estimate the ecological reserves and the mechanisms for allocation of water for highly regulated river as is the case for the Great Ruaha River (GRR), while ensuring the water dependant livelihoods of the poor are not affected.

The Great Ruaha River is one of the most important waterways in the Rufiji Basin, Tanzania. It is a major tributary of the Rufiji River. Water from the river and its tributaries is used for hydropower production (with more than 50% of the countries installed hydropower capacity) and irrigation and makes a vital contribution to the livelihoods of many rural households (Kadigi *et al*., 2004). It also supports the ecology of the Usangu wetlands, a valuable freshwater ecosystem, and the Ruaha National Park, one of Tanzania's major wildlife reserves (Kashaigili *et al*., 2005). Since early 1990s, the Great Ruaha River, which in the past was perennial, has consistently ceased flowing in the dry season, largely as a consequence of human diversions of water upstream of the Usangu wetlands (SMUWC, 2001; Lankford *et al*., 2004). This has had severe social, economic and environmental consequences. The Government of Tanzania is committed to ensuring that "year-round flow" is re-established by 2010, however, exactly how this is to be achieved is not clear. The exact hydrological requirements for ensuring flows are maintained need to be evaluated and the water resource implications need to be carefully assessed.

This paper describes a study to determine the environmental flow requirements of the Great Ruaha River within the Ruaha National Park. The estimates are evaluated through a hydrological model to determine the optimum environmental flows followed assessment of implications on water dependent livelihoods, considering the available water resources and the present water withdrawals for other anthropogenic activities.

Area descriptions, methods and material studied

Area descriptions

The Great Ruaha River catchment covers an area of about 68,000 km^2 and is located within the Rufiji basin (178 000 km^2), in the southwestern part of Tanzania. It encompasses the Usangu area, which has a total area of 20,811 km^2 (**Error! Reference source not found.**). The Usangu area is located at approximately latitudes 7^{0}41' and 9^{0}25' South, and longitudes 33^{0}40' and 35^{0}40' East. It encompasses the Usangu Plains in which the Usangu Wetland (which has an area of about 1,800 km^2) and the Usangu Game Reserve (4 148 km^2) can be found.

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

The Great Ruaha River is a major tributary of the Rufiji River. The headwaters rise in the Kipengere mountains, in south-west Tanzania, and drain through the broad alluvial plains of Usangu. The Plains are characterized by seasonally-inundated grassland and permanent swamps. From a conservation standpoint, the wetlands are amongst the most valuable ecosystems in Tanzania, providing habitat for over 400 bird species and numerous other flora and fauna (Kamukala and Crafter, 1993). Furthermore, the wetlands support numerous livelihood activities, many of which depend on water from the river, including agriculture, cattle grazing and traditional fisheries, as well as small-scale industries such as brick-making. In some villages, it is estimated that up to 95% of households benefit from the wetlands which make a vital contribution to coping strategies during times of food scarcity (Kashaigili and Mahoo, 2005). In recognition of its ecological importance, the Usangu area has been designated an Important Bird Area by Birdlife International (Mathiko, *et al*., 2006) and, in 2000, the largest, and most downstream, wetland, locally called *Ihefu* or the Eastern wetland, was gazetted into the Usangu Game Reserve. The consequence of this is that some activities, such as fishing and grazing, are no longer permitted.

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

Upstream diversions and consequent reduced inflows to the Plains have resulted in conflicts between upstream and downstream communities. In the dry season, some women and children have to walk up to 20km to find water (Kashaigili and Rajabu, 2003). Furthermore, since 1993, outflow from the *Ihefu* has ceased for prolonged periods during every dry season. This has also caused the death of many wild animals (i.e., hippopotami, fish and freshwater invertebrates) in the Ruaha National Park and disrupted the lives of many others that depend on the river for drinking water (Kashaigili *et al.,* 2005). There is concern that the loss of animals and reduction in the aesthetic appeal of the river will reduce the number of tourists visiting the Park (Mtahiko *et al*., 2006).

Method and material studied

An environmental flow (EF) is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits (Dyson *et al.,* 2003; King *et al*., 2002; Tharme and King, 1998). In recent years, there has been a rapid proliferation of methods for estimating environmental flows, ranging from relatively simple, low-confidence, desktop approaches, to resource-intensive, high-confidence approaches (Tharme, 2003). The comprehensive methods are based on detailed multi-disciplinary studies, which often involve expert discussions and collection of large amounts of geomorphological and ecological data (e.g., King and Louw, 1998). Typically they take many months, sometimes years, to complete.

A key constraint to the application of comprehensive methods, particularly in developing countries, is lack of data linking ecological conditions to specific flows. To compensate for this, several methods of estimating environmental flows have been developed that are based solely on hydrological indices derived from historical flow data (Tharme, 2003). One such method is the "desktop reserve model" (DRM), which is intended to quantify environmental flow requirements in situations when a rapid appraisal is required and data availability is limited (Hughes and Hannart, 2003). The model is built on the concepts of the building block method, which was developed by South African scientists over several years (King and Louw, 1998; Tharme and King, 1998; King *et al.*, 2000), and is widely recognised as a scientifically legitimate approach to setting environmental flow requirements (Hughes and Hannart, 2003).

The Building Block Method is underpinned by the premise that, under natural conditions, different flows play different roles in the ecological functioning of a river. Consequently, to ensure sustainability, it is necessary to retain key elements of natural flow variation. Hence, so called Building Blocks (BBs) are different components of flow which, when combined, comprise a flow regime that facilitates the maintenance of the river in a pre-specified condition. The flow blocks comprise low flows, as well as high flows, required for channel maintenance and differ between "normal years" and "drought years." The flow needs in normal years are referred to as "maintenance requirements" and divided between high and low flow components. The flow needs in drought years are referred to as "drought requirements" (Hughes, 2001). The desktop reserve model provides estimates of these BBs for each month of the year.

In the current study, the desktop reserve model was applied to the Great Ruaha River at Msembe Ferry (catchment area 24,620 km^2). To estimate the environmental flows the model requires a naturalized flow series as input. A completely naturalized flow series was unavailable, so monthly flows for years 1958 to 1973 (i.e., the least modified period) were used as input. In South Africa, rivers are classified in relation to a desired ecological condition, and flow requirements set accordingly. Six management classes are defined, ranging from A to F. Class A rivers are largely unmodified and natural, and class F rivers are extremely modified and highly degraded (DWAF, 1999). Classes E and F are deemed ecologically unsustainable so class D (i.e. largely modified) is the lowest allowed "target" for future status. This classification system is used in conjunction with the building block method and flow requirements are computed accordingly; the higher the class, the more water is allocated for ecosystem maintenance and the greater the range of flow variability preserved. In the current study, to reflect the importance of water abstractions for local communities, the desired ecological condition of the Great Ruaha River was set as C/D (i.e., moderately to largely modified).

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. The average coefficient of variation (CV) of flow for the three main months of both the wet and the dry season is calculated and the sum is the CV-Index (Hughes and Hannart, 2003). The second index is the proportion of total flow that can be considered to occur as baseflow (i.e. baseflow index, BFI). BFI varies between 0 and 1. Rivers with BFI close to 1 are less variable than those with lower BFI values (Gustard *et al.*, 1992). The model computes BFI from the monthly time series. However, in this study it was possible to calculate BFI from daily flows. This gave a BFI of 0.92, which is high, reflecting both the relatively large size of the catchment and the flow regulation effect of the *Ihefu* wetland. The two model parameters that determine BFI using the monthly data were modified, by trial and error, until the model-computed BFI closely matched that obtained from the daily data.

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 desktop reserve model also combines maintenance and drought requirements into continuous assurance or frequency curves. This enables return periods to be attached to specified environmental flows. 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 quaternary catchments in South Africa. In the current study, model parameters were initially selected to be those derived for dolomite regions of South Africa because the monthly flow regimes are 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 visual comparison, simulated and observed flow duration curves matched as closely as possible.

Results and analyses

The summary of the output results from the DRM are presented in Table 1. The results indicate that to maintain the river at class C/D requires an average annual environmental flow allocation of 635 Mm^3 (i.e., equivalent to 21.6 % of mean annual flow). This is the average annual “maintenance flow” calculated from the mean of both the maintenance low flows (i.e. 465.4 Mm^3) and maintenance high flows (i.e., 169.9 Mm^3). The drought flows correspond to 10% MAF (i.e. 293.3 Mm^3). Figure 2, presents a comparison of the observed time series and the desktop reserve model derived environmental flow series for the Great Ruaha River at Msembe Ferry for the 1958-1973 period.

>>>> Table 1: Summary output from the desktop reserve model applied to the Great Ruaha River at Msembe Ferry, based on 1958-1973 monthly flow series <<<<

>>>> Figure 2: Time series of monthly observed flow and estimated environmental flow (1958-1973) for the Great Ruaha at Msembe Ferry (note log scale on the y-axis) <<<<<<

For the period 1986-2003, average annual flows at Msembe Ferry (i.e., 2,537 Mm^3) exceeded the annual total maintenance flow requirements predicted by the model (i.e., 635 Mm^3). However, average flows in months September to November were 21% to 73% less than the simulated average monthly environmental flow requirements (Table 2; Figure 3). This substantiates the assertions of ecologists that, in recent years, dry season flows have been insufficient to maintain even basic ecological functioning of the Great Ruaha River.

>>>> Table 2: Comparison of environmental flow requirements computed by the desktop reserve model and observed mean monthly flows at Msembe Ferry between 1986 and 2003 <<<<

The monthly environmental flow requirements associated with different levels of assurance are presented in Table 3. These results indicate that absolute minimum flows attained every year should be approximately 0.8 m^3s^{-1} and 0.6 m^3s^{-1} in October and November respectively. Furthermore, on average, minimum flows should exceed 1m^3s^{-1} every other year.

>>>> Table 3: Environmental flow requirements (m^3s^{-1}) at Msembe Ferry for 4 return periods, for management category C/D<<<<

Discussion

The desktop reserve model has been used extensively in South Africa. Its use in other countries is limited, but it has been applied in Swaziland, Zimbabwe and Mozambique (Hughes and Hannart, 2003). For the current study, the accuracy of the model results cannot be substantiated without further study. However, given that it is underpinned by empirical equations developed specifically for South Africa, and is only intended to be a "low-confidence" approach, the results must be treated with caution. Nonetheless, despite the limitations, in the absence of quantitative information on the relationships between flow and the ecological functioning of the river ecosystem, it is a valuable first estimate of environmental flow requirements. Furthermore, for the dry season, the model results are consistent with the expert opinion that absolute minimum flows through the Ruaha National Park should not be less than 0.5 m^3s^{-1} (Ruaha National Park ecologist, pers comm.).

A global assessment of environmental water requirements found that typically they range from 20% to 50% of mean annual flow (Smakhtin *et al*., 2004). However, because it was a global survey, it made no allowance for setting different ecological standards for rivers. An environmental flow requirement of more than 20%, as has been found in the current study, seems like a high proportion of flow to maintain the river in a largely modified condition (i.e., C/D in the South African classification system). However, it arises because day-to-day variation in flows is relatively low and there is a high baseflow index at Msembe Ferry. Hence, although it can be assumed that river biota are adapted to high inter-seasonal variation it is probable that they are not adapted to rapid changes in flow nor to the extended periods of zero flow, that occur at present (Table 4).

>>>> Table 4: Periods of zero flow in the Great Ruaha River (1994 to 2004)< <<<

There is much scope for improving water use efficiency in the catchment particularly in the dry season. However, Kashaigili *et al.,* (2006) estimated that approximately 80% of flow in the perennial rivers flowing into the wetland needs to discharge into the *Ihefu* wetland to maintain downstream flows. This would require current abstractions to be reduced by approximately 60%. Given the socio-economic importance of the diversions it may not be possible to achieve this in the near future. Consequently consideration needs to be given to alternative options, including trade-offs between different environmental needs.

Conclusions

Although preliminary, and requiring verification through further research, the results provide a credible scientific basis for decision-making on water resource allocation in the Great Ruaha River catchment. Currently absolute minimum environmental flow requirements are not being attained. Between 1986 and 2003, there were extended periods of zero flow and average monthly flows from September to November were 21% to 73% less than estimated environmental flow requirements. The general scarcity of water in the dry season means that different environmental requirements are effectively competing with each other.

There is scope for improved water-use efficiency, particularly in the large-scale irrigation sector, which would free water for environmental flows. However, given the importance of water withdrawals for livelihood support there is also need to consider trade-offs between competing environmental water needs. Careful consideration needs to be given to active water management within the upstream wetlands, to reduce evapotranspiration and hence liberate water for downstream environmental flows.

Environmental flows are increasingly recognized as a critical component of sustainable water resources management. However, in developing countries their estimation and implementation is often impeded by lack of data. This study illustrated the viability of using the desktop reserve model to provide first estimates, based solely on hydrological data. It also highlighted, in situations where water withdrawals are essential for livelihoods, the need to consider trade-offs in water provision to different ecosystems. Population increase, in conjunction with efforts to reduce poverty, make such situations increasingly common in many African countries. Difficult choices need to be made, but informed decisions are only possible with at least a basic understanding of the requirements of all, including the environmental, components of the water system.

Acknowledgements

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Tables

Table 1: Summary output from the desktop reserve model applied to the Great Ruaha River at Msembe Ferry, based on 1958-1973 monthly flow series

Annual Flows (Mm^3 or index values)			
MAR	= 2936.3	**Total Environmental flow**	= 635.3 (21.6%MAF)
S.D.	=2932.2	**Maintenance Low flow**	= 465.4 (15.9%MAF)
CV	= 0.996	**Drought Low flow**	= 293.3 (10.0% MAF)
BFI	= 0.89	**Maintenance High flow**	= 169.9 (5.8%MAF)

	Observed flow (Mm^3)		**Environmental flow requirement (Mm^3)**			
			Maintenance flows			Drought flows
Month	Mean	CV	Low	High	Total	
Jan	279.452	1.919	35.57	37.15	72.72	13.33
Feb	451.068	1.12	67.55	18.58	86.12	22.43
Mar	682.947	1.033	106.02	86.05	192.1	72.57
Apr	803.089	0.968	131.22	18.58	149.80	91.15
May	405.689	0.784	71.75	2.30	74.05	50.69
Jun	123.363	0.587	22.05	0	22.05	15.69
Jul	56.774	0.452	10.12	0	10.12	7.22
Aug	35.002	0.548	6.22	0	6.22	4.45
Sep	21.618	0.502	3.82	0	3.82	2.75
Oct	14.729	0.519	2.58	0	2.58	1.87
Nov	10.808	0.553	1.87	0	1.87	1.37
Dec	51.762	2.118	6.67	7.21	13.88	4.77

Table 2: Comparison of environmental flow requirements computed by the desktop reserve model and observed mean monthly flows at Msembe Ferry between 1986 and 2003

Month	Total maintenance requirements Mm^3/month	Observed flows Mm^3/month	Ratio of observed to environmental flow requirement
Jan	72.7	229.2	3.15
Feb	86.1	513.0	5.96
Mar	192.1	625.2	3.26
Apr	149.8	577.6	3.86
May	74.1	358.3	4.84
Jun	22.1	148.6	6.74
Jul	10.1	44.9	4.44
Aug	6.2	8.7	1.40
Sep	3.8	2.1	0.55
Oct	2.6	0.7	0.27
Nov	1.9	1.5	0.79
Dec	13.9	26.60	1.92
Annual	635.3	2,536.5	5.76

Table 3: Environmental flow requirements (m^3s^{-1}) at Msembe Ferry for 4 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

Table 4: 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	17 November	15 December	28
1995	19 October	23 December	65
1996	17 October	16 December	60
1997	20 September	22 November	63
1998	18 November	9 March 1999*	87
1999	21 September	20 December	90
2000	17 September	22 November	66
2001	12 November	23 December	41
2002	2 November	24 December	52
2003	21 September	16 January 2004*	104
2004	3 November	4 December	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

Figures

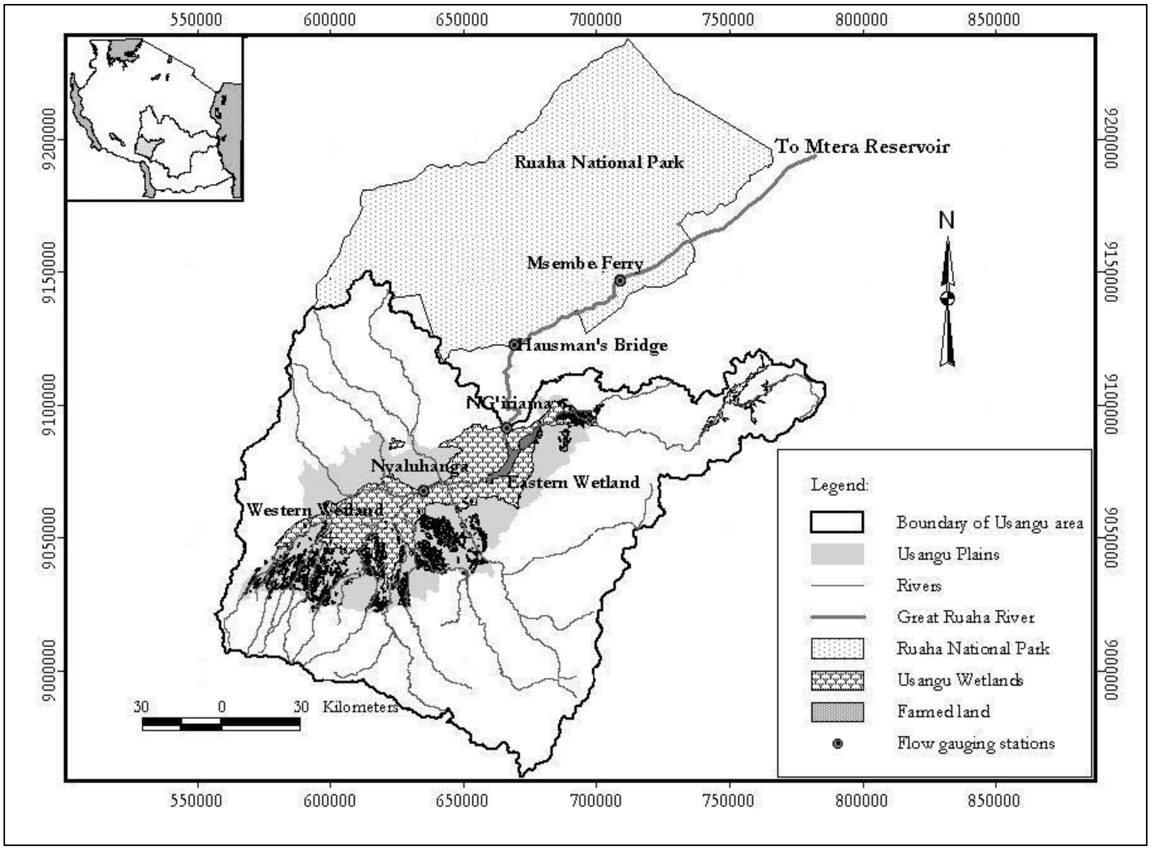

Figure 1: Map of study area including Ruaha National Park and Msembe Ferry Gauging station

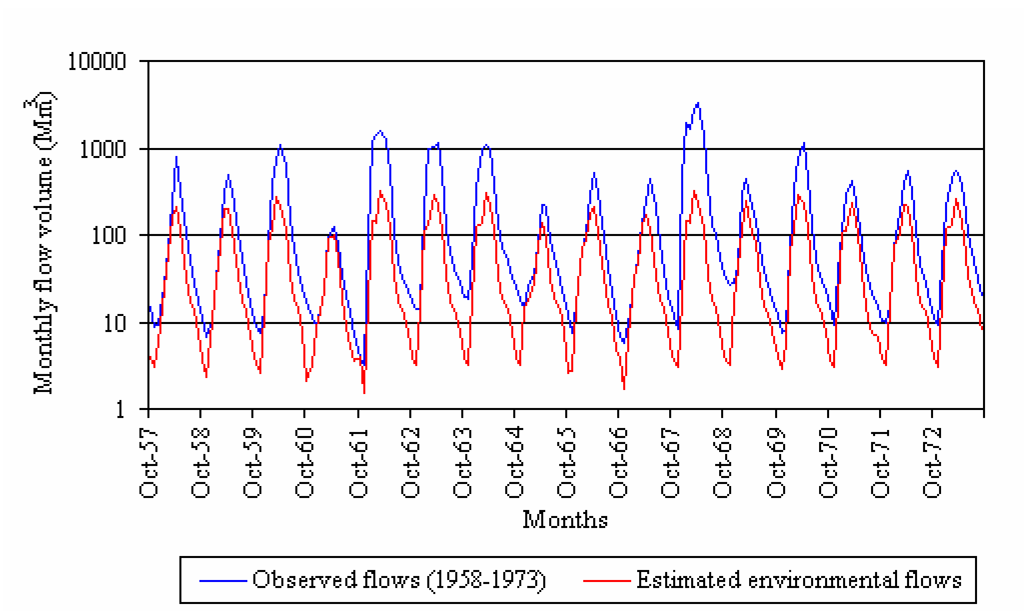

Figure 2: Time series of monthly observed flow and estimated environmental flow (1958-1973) for the Great Ruaha at Msembe Ferry (note log scale on the y-axis).

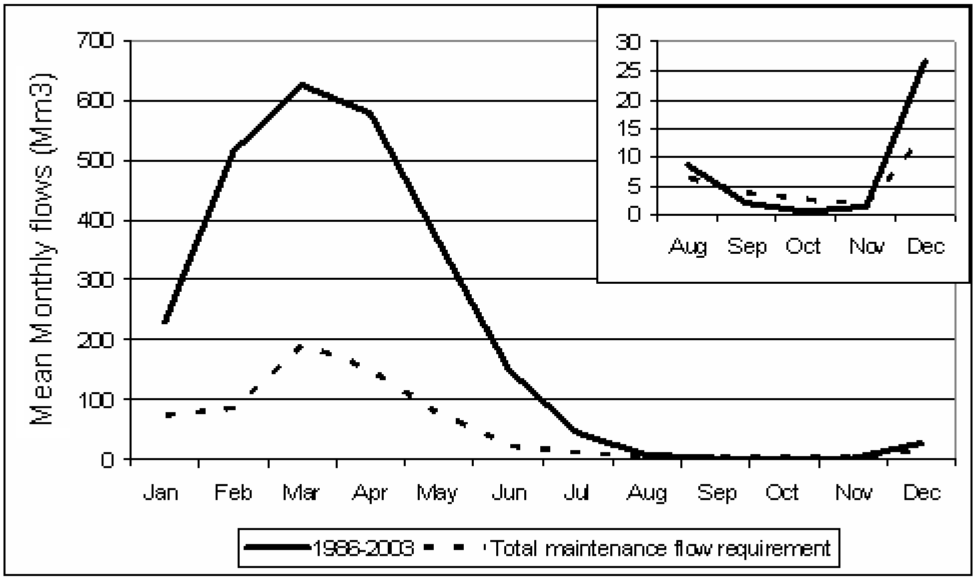

Figure 3: Comparison between observed monthly flow volumes and monthly total maintenance flow volumes for the 1986-2003 period, with months August-December magnified