Water Practice & Technology

 Water Practice & Technology Vol 17 No 2, 598 doi: 10.2166/wpt.2022.010

Effects of community-based water management decisions at catchment scale, an interdisciplinary approach: the case of the Great Ruaha River Catchment, Tanzania

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ABSTRACT

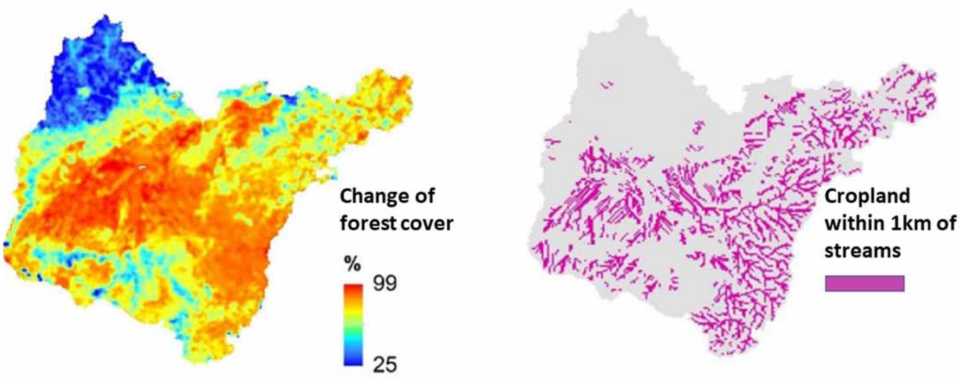
Water User Associations are community-based institutions that cover segments of rivers and are responsible for water management decisions. These are the result of institutional blueprints designed by the international community, widely adopted around the world. However, the implementation gaps between these generic institutional designs and the working on the ground are vast and require site-specific information to support water management decisions at the local scale. We used a hydrological modelling approach to assess how community-based decisions can maximize their outcomes and improve overall availability of water resources in the Great Ruaha River Catchment in Tanzania, a catchment that is under severe drought pressures and is of the utmost ecological, social, and political relevance at the national scale. We provide information to support decisions on when and where to focus conservation and management strategies by identifying the seasonal and spatial variability of water availability in the catchment. Our methods have the potential to be used in other catchments around the world. This study shows the importance of assessing the hydrological processes affecting the geographies of community-based institutions to identify priority areas of action.

Key words: integrated water resources management, interdisciplinary geographical methodology, participatory natural resources management institutions, water insecurity, waterworld

HIGHLIGHTS

- Uniform implementation of institutional blueprints requires additional information to succeed in an African context.
- Interdisciplinary methodology is key to determining scope and outcomes for WUAs.
- Multi-scale approaches are necessary to improve the outcomes of community-based water management institutions.
- WUAs in the Great Ruaha River Catchment can optimize outcomes by focusing on site-specific actions.

GRAPHICAL ABSTRACT



INTRODUCTION

Blueprints for crafting Community Based Natural Resources Management (CBNRM) institutions such as Water Users Associations (WUAs) are designed by global epistemic communities, often influenced by Euro-centric models of thinking. These sets of principles for institutional crafting are applied to complex realities across different regions of the Global North and Global South. Ostrom's (1990) institutional design principles have majorly influenced the setting-up of CBNRM institutions in contexts such as the Great Ruaha River Catchment (GRRC) in Tanzania. This catchment is one example amongst 80% of countries worldwide which have adopted the Integrated Water Resources Management (IWRM) framework (Allouche 2016). These countries have translated the blueprint into national water policies and by-laws down to the lowest formal institutional level, including the intent to set-up WUAs for active participation of communities in water resources management. When applied to various formal and informal institutional landscapes, this uniform IWRM blueprint produces place-dependent outcomes.

Implementation gaps between IWRM blueprints and institutional workings on the ground have been discussed before (see Anderson *et al.* 2008; Biswas 2008; Mdee & Harrison 2019). Building on these reflections which highlight the discrepancies between policies and practice, we aim to assess how the decisions made at the community level by CBNRM institutions, such as WUAs, can impact water availability at the catchment level. We used the case of the GRRC to exemplify the relevance of considering a multi-scale approach to inform community-based management decisions.

We first provide an overview of the current institutional landscape for water management in Tanzania and the debate around the causes for the drying up of the GRRC affecting the outcomes of the WUAs. Secondly, using a hydrological modelling tool, we apply two scenarios of land use and cover change in the catchment to identify the potential impacts that management decisions at the community-based level can have on the overall water balance of the catchment. Our results highlight the need for institutional structures to govern at the scale at which the biophysical boundaries operate, for water resources management interventions to achieve the desired impact.

Institutional landscape for water management in Tanzania

Integrated Water Resources Management (IWRM) is the coordinated planning, development, protection, and management of water, land, and related resources in a manner that fosters sustainable economic activity, improves or sustains environmental quality, ensures public health and safety, and provides for the sustainability of communities and ecosystems (de Oliveira Vieira 2020). The World Summit on Sustainable Development set the target for all countries to adopt IWRM by 2025. The adoption of IWRM has started a wave of reforms in sub-Saharan Africa to revise statutory laws and institutional frameworks for the regulation of water resources (Jones & Van der Walt 2004; Kabudi 2005; Sokile *et al.* 2005).

The adoption of IWRM vests the ownership of water resources into the state, and the administration of resources by semi-autonomous regulators (basin boards), required to involve stakeholders as participants in decision-making. This framework also adopts a permitting system to regulate water abstractions. The success of IWRM in Europe has led Western donors to push the adoption of this framework in sub-Saharan Africa (see Balassanian & Wignaraja 2006). It is the Global Water Partnership which stands today as the leading global action network for the promotion of the adoption of IWRM (Mehta & Movik 2014). In this context, particular attention is paid to the 'integration' aspect of water resources management, due to past issues faced by unintegrated sectors such as government ministries and economic sectors not collaborating over the use of the same resource (Molle 2008). Unintegrated water resources management leads to upstream-downstream conflicts, contradictory policies and practices increasing the chance for land-use changes to negatively affect water resources, and trade-offs between ecosystems, social equity and economic profitability being overlooked.

The institutionalisation of IWRM within countries takes place in nested scales, with Water Users Associations (WUAs) at the lowest level (Figure 1). WUAs are community-based institutions, which cover segments of rivers, and are broadly responsible for water conservation activities, conflict management over water issues, and water allocation to irrigators through a permitting system (Richards & Syallow 2018; Richards 2019).

In Tanzania, fulfilling the policy objectives of securing environmental flows and providing adequate water supply for domestic and agricultural purposes is challenging. The Great Ruaha River in the Southern part of Tanzania supplies water to the breadbasket of Tanzania, as much as it provides to the safekeeping of the biodiversity

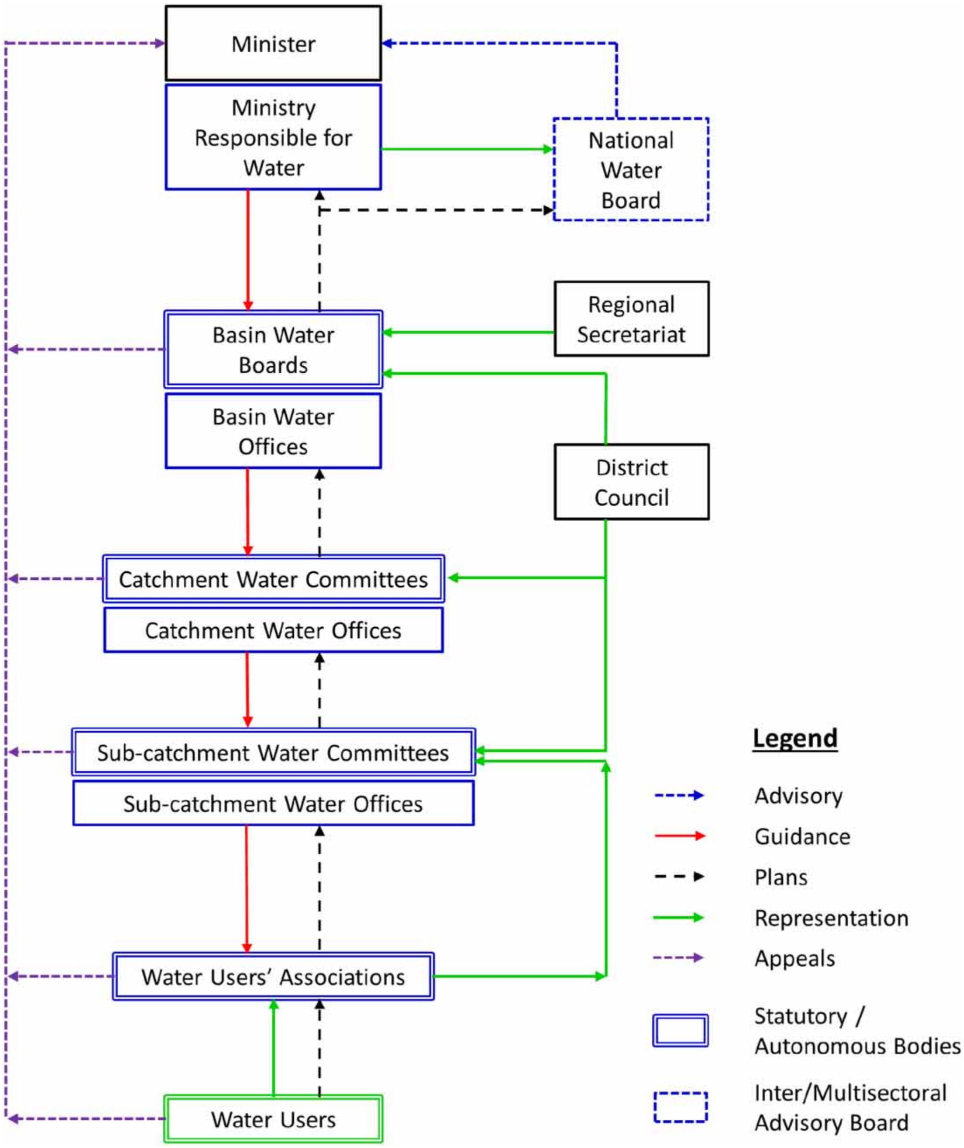


Figure 1 | Institutional set-up for water management in Tanzania (Richards 2020). Water Users Associations sit at the lowest institutional level. They are meant to represent water user interests and are accountable upwards to basin water offices, as most sub-catchment and catchment water committees are still waiting to be created in Tanzania.

of the Ruaha National Park resources. The GRRC has been drying up since 1993, and has suffered from pollution, deforestation, upstream/downstream and cross-sector water conflicts, and destruction of aquatic ecosystems (Kashaigili *et al.* 2007). Current reports explain that the situation is due to poor coordination and cooperation, low understanding of water resources leading to poor accountability, and low technical and financial capacity of the different stakeholders, particularly users and responsible authorities for water resources management, including community-based water users associations (Mlozi 2009; WREM 2016).

The Tanzanian Water Act of 2009 (URT 2009) lays the ground for the set-up and following support of WUAs. The institutional framework for water management in Tanzania is illustrated in Figure 1. Organizations such as GIZ, DFID (now FCDO), USAID, WWF, and more, have committed several years of funding and efforts to support newly established basin authorities in various tasks (e.g., data gathering), with substantial support towards the setting-up and follow-up on WUAs (e.g., WWF since 2002). WUA Operational Guidelines developed by these donors, implementation agencies and international non-governmental organizations are currently being endorsed by the Ministry of Water. In summary, the roadmap for WUAs in Tanzania is still being tested: the application of the institutional blueprint to local realities faces many implementation challenges (see Richards & Syallow 2018; Richards 2019).

The debate about the causes for the drying up of the Great Ruaha River

Previously perennial, the river dried only once on record before 1993, in 1952 (Mtahiko *et al.* 2006). Since 1993 the river has seen significant periods of inflow cessations, some years extending beyond three months (Mtahiko *et al.* 2006; Kashaigili 2008). The causes leading to the deterioration of the river are contested by the various water users. The GRRC is facing closure; that is, the water commitments for domestic, industrial, agricultural or environmental uses cannot be met during all or part of a year (Falkenmark & Molden 2008).

The data gaps in the records of the flow of the Great Ruaha river have led stakeholders to question the existing scientific evidence and allocation of water resources. Stakeholders have thus been disputing what the real explanatory factor behind the deterioration of the river flows is. Throughout the dispute, powerful stakeholders have been able to maintain a hegemonic narrative about the cause(s) of the drying up of the river. This hegemonic narrative promotes certain water users over others, and the lack of consensus about the explanatory factors behind hydrological changes are therefore a representation of social relations of power and knowledge (England 2019). Water is indeed allocated hierarchically according to principles such as economic, social or environmental value creation. It is key to understand how these narratives shape water allocation between actors.

England's (2019) study reveals that today's sanctioned discourse is a reinforced version of last decade's, whereby irrigation area and inefficiency are the key causal explanations for low river flows. This stance is unsurprising for two reasons: 1. Water science professionalism tends towards simplifying hydrological narratives in policy-type messages and producing simplified actions (Chambers 1998). The political agenda for agricultural modernisation has been constant over the past decade, revolving around production and irrigation efficiency –to maintain that irrigation efficiency is needed, one must first prove that irrigation methods are inefficient and causing harm.

Because of the highly politicised nature of this catchment, it is crucial to investigate some of the basis on which this narrative rests. This is of importance and timely as since 2010, when the Kilimo Kwanza (Agriculture First) Growth Corridors based on public-private partnership were launched at the World Economic Forum on Africa, Tanzania has been multiplying initiatives to deliver rapid and sustainable agricultural growth. One of the key initiatives is the Southern Agricultural Growth Corridor of Tanzania, involving further irrigation development in a time where the GRRC seems to have already reached closure. Finally, to understand the effects of water governance structures, it is key to allow room for questioning and changing perspective on the narratives that are currently justifying specific water policy and allocation choices. The following materials and methods section demonstrates how, and the extent to which, hydrological processes can affect the outcomes of WUAs in the GRRC.

MATERIALS AND METHODS

Study area

The Great Ruaha River Catchment (GRRC, Figure 2) is situated in the South-West of Tanzania, within the Eastern arm of the Rift Valley, and is an important tributary of the largest drainage basin of the country, the Rufiji Basin. The catchment covers about 21,500 km^2. With its five large perennial rivers (Chimala, Ruaha, Kimani, Mbarali, Ndembera), the GRRC feeds the Usangu wetlands, including the Ihefu swamp (30–65 km^2) and the seasonally wetted areas (260–1,800 km^2, Mwakalila 2011).

The Great Ruaha River (hereafter 'the river') is considered the most important river system of the country economy and its 'ecological backbone' (Kashaigili *et al.* 2007). There is an acute national interest in it, as it provides an important supply of rice nationally, sustains the ecological requirements of the Ruaha National Park, and provides water resources for hydropower generation at the Mtera and Kidatu dams– together providing for 40% of Tanzania's hydropower capacity in 2015 (URT 2015).

The GRRC is surrounded by high mountains to the east and south, and low hills to the west (Figure 3(a)). These upper areas receive an annual rainfall of approximately 2,500 mm and feed the plain, which receives 690 mm annually (Figure 3(b)). The plain has an area of 4,480 km^2 and encloses the Usangu wetlands. The rainfall regime is unimodal, with a rainy season starting in mid-November and ending around April, it is spatially varied and irregular inter-annually. Mean annual temperature varies from 18 °C in the mountains to 28 °C in the drier areas of the plains.

In the upper catchments, water use goes from rain-fed to irrigated agriculture (horticulture products), whereas on the foot slopes of the escarpment and plains, rice paddy is the most common water-consuming livelihood

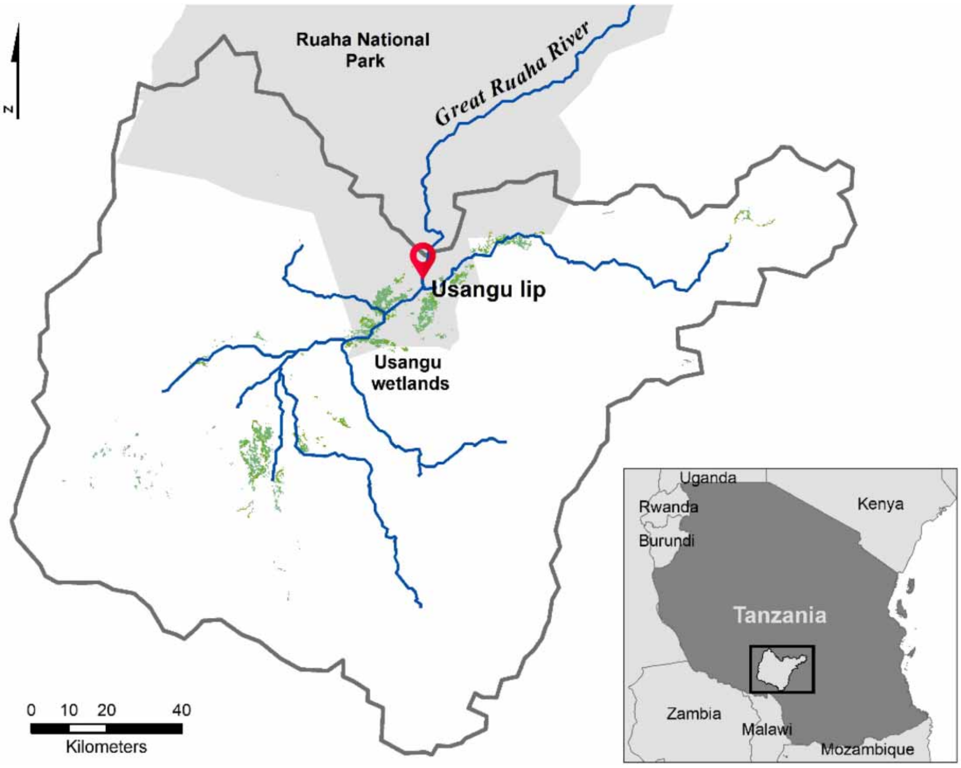


Figure 2 | Great Ruaha River Catchment, Tanzania. The study area is delimited by the Ruaha River Catchment, this includes the Usangu wetlands (green) and the southern part of the Ruaha National Park. The catchment outflow is denominated Usangu lip.

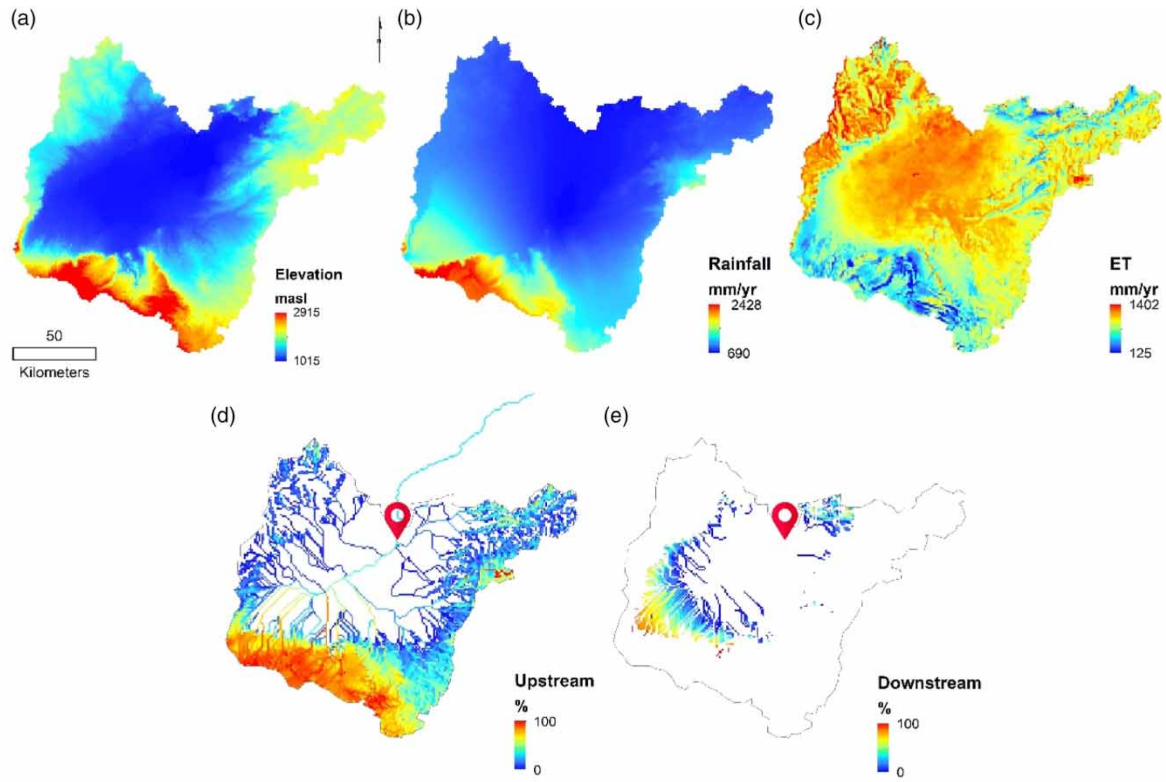


Figure 3 | Physical geography of the Great Ruaha River Catchment. (a) Elevation, (b) total annual rainfall, (c) total annual potential evapotranspiration (ET), (d) annual downstream influence in areas above 1,300 meters and (e) below 1,300 meters of the catchment. Location pin indicates the Usangu Lip (produced by authors using datasets available in WaterWorld).

activity. Livestock rearing is also found in the plains. Dry season irrigation is concentrated in the upstream areas and is used to produce high-value crops such as vegetables, potatoes, beans, and maize. In the mid-catchment, water is diverted for furrow irrigation in plot-to-plot distribution. Finally, most of the rivers dry up before they reach the plains, and for those which are perennial, they feed small gardens mostly through schemes and pumps (Richards 2020).

The Usangu plains contribute 15% of rice production in Tanzania and are the livelihood basis of a growing population (Mdemu *et al.* 2003). It is estimated that 44,500 ha are under irrigation, although this approximation is disputed due to an unknown area of unpermitted expansion of irrigation. Most of the area under irrigation is for rice cultivation in the wet season, and about 2,500 ha are cultivated for mixed crops such as maize, beans, vegetables and fruits (McCartney *et al.* 2007). The various types of irrigation systems practised in the area can be categorised as traditional smallholder systems; improved traditional smallholder systems – which have received government or donor assistance– and modern large-scale schemes such as Kapunga, Mbarali Estates, and Madibira cooperative (Richards 2020). The profitability of rice in the Usangu plains has drawn attention to the area since colonisation. It currently still brings international investments to the area, where a certain number of powerful stakeholders have staked their claim (e.g. agribusinesses such as Mbarali Estates and Kapunga; Richards 2020).

Regarding the upper areas of the catchment, even less information is available on the extent and growth of irrigated areas both in the dry and wet seasons. This lack of information is likely due to the potential of the Usangu plains for rice growing, contrary to the upper areas of the GRRC.

Although the plains have been the central focus of past and recent studies (Kadigi *et al.* 2005; McCartney *et al.* 2007; England 2019), there is still a lack of comprehensive and detailed research on the GRRC.

Hydrological modelling

Baseline runoff and seasonality

Due to the lack of hydrological data at the basin scale, we used the policy support tool WaterWorld to assess the status of water resources in the GRRC. WaterWorld (http://www.policysupport.org/waterworld) is a web-based tool for modelling hydrological services associated with specific activities under current conditions and under scenarios for land use, land management and climate change. It provides quantitative biophysical results or relative indices that can be used to understand hydrological ecosystem services, water resources and water risk factors (Mulligan 2012). The tool uses global spatial information and the analyses we performed for the GRRC are potentially applicable to other catchments in the world.

We first defined the watershed of interest by delineating the point that represents the outflow of interest; that is, the junction of the river and wetland. We then used the HydroSHEDS flow network (Lehner *et al.* 2008) available within WaterWorld to define the upstream catchment of this point as our area of study. We defined the lip of the Usangu wetland as the catchment outflow (Figure 2); this is the exit point of the wetland from where it feeds the river, which crosses the Ruaha National Park and two important hydropower stations for Tanzania – the Mtera and Kidatu dams.

We performed a baseline analysis to estimate the annual and monthly water balance, using the global land cover and use (Friedl *et al.* 2010) and climatology for 1950–2010 (Hijmans *et al.* 2005) datasets. This is calculated as the sum of rainfall and fog minus actual evapotranspiration (i.e., water evaporation from the soil and other surfaces and by transpiration from plants), which is cumulated down the flow network as so-called runoff (i.e., the downstream flow of water on the land surface). In WaterWorld there is no explicit subsurface flow model, water balance is assumed to flow downstream in the subsurface as well as on the surface.

To understand precipitation seasonality, we use the Walsh and Lawler index (Walsh & Lawler 1981). The index compares monthly precipitation totals against the annual mean and provides an assessment of seasonality, where the lowest values indicate low seasonality (i.e., precipitation throughout the year) and the highest values indicate extreme seasonality (i.e., almost all precipitation occurs in 1–2 months).

Water balance

Water balance, and thus runoff, is effectively the difference between rainfall and evapotranspiration. The evapotranspiration in the Usangu plains (surrounding the wetlands; Figure 2(c)) have a higher evapotranspiration rate than the higher elevation upper reaches of the catchment. This is because the climate is warmer and less cloudy at lower altitudes. The water balance is thus low in the lowlands as it has both higher evapotranspiration and receives less rain. The opposite applies to the highlands, where the water balance is high due to lower evapotranspiration and higher rainfall.

To determine whether the majority of the river flow to the wetland originates from the highlands or the Usangu plains, we chose 1,300 meters (Kashaigili 2008) as the limit separating lowlands and uplands (Figure 3(d) and 3(e)). We used the WaterWorld hydrological influence metric to map the percentage of runoff present at Usangu lip originating from areas at 1,300 meters and above. This was done for both annual total runoff and monthly runoff identifying the maximum influence of uplands for each river pixel (1 km resolution).

Modelling potential impacts of deforestation and irrigation

To put the scale of WUA activities and permitting into perspective, we use modelling to assess what changes in river flows would result from the maximum possible changes in irrigation. This helped us to identify the potential impact of WUAs at the catchment scale, as well as the purpose of water permits, at seasonal intervals. The variables that have affected the river flow the most are an increase in population, an increase in irrigated areas and a decrease in woodland cover (Kashaigili 2008; see Box 1). We developed two possible scenarios of land-use change based on these events:

Box 1 | Timeline of the main events that have changed the hydrology of the Great Ruaha River Catchment
Kashaigili (2008) identifies three main periods since 1958:

1. 1958–1973, which is the near-natural land use period.
2. 1974–1985 is marked by an increase of population of 67% and a 117% increase in irrigated areas (mostly rice). This period experienced an increase in the seasonality of flows, with lower flows than the previous period and the following period.
3. 1985–2004 showed a continuous increase in population and irrigated areas. This period shows an increase in overall runoff (due to a decrease of 22.3% of woodland cover) despite the decreased rainfall amount. Seasonality was at its highest, leading to the first drying up of the river.

Kashaigili (2008) identified a correlation between the reduction in average dry season flows and the increase in total irrigated area. It is dry season flows specifically that have reduced, as no significant change of annual flows were detected. Flows generated from the high catchment have not significantly changed over time, meaning that the change in the Usangu plains is what has contributed to a decrease in dry season flows.

The increase in population signifies important land-use changes. Most of the population's livelihoods are based on smallholder agriculture, and most households' energy consumption is based on wood burning, conversion of land from woodland to agriculture (whether irrigated or not) is to be expected.

Kashaigili 2008) refers to changes taking place in the Usangu plains and not the high catchment. However, from the authors' observations and conversations with the Wanging'ombe district (Richards 2020), changes seem to also be taking place in the higher catchment recently (keeping in mind that Kashaigili's study is dated from 2008).

1. Converting cropped areas into forested areas

Currently, the GRRC is highly deforested, with most of the area showing up to 99% loss of their original forest cover (Figure 4(a), see Box 1). We assessed the impact that the increasing deforestation for conversion to irrigated and non-irrigated cropland has had on river flows by replacing current agriculture with forest.

2. Converting land into irrigated cropland

We defined the maximum possible irrigated areas by selecting all areas within 1 km^2 of a river and are classified by MODIS (Friedl *et al.* 2010) satellite images as cropland areas (Figure 4(b)). We assessed the potential impact of increasing irrigated cropland in both the upper and lower parts of the GRRC, on the dry and wet season flows. Since upstream areas (>1,300 m) are largely irrigated in the dry season, and downstream areas (<1,300 m) abstract more water during the wet season (particularly for paddy irrigation), we expected the impacts to be

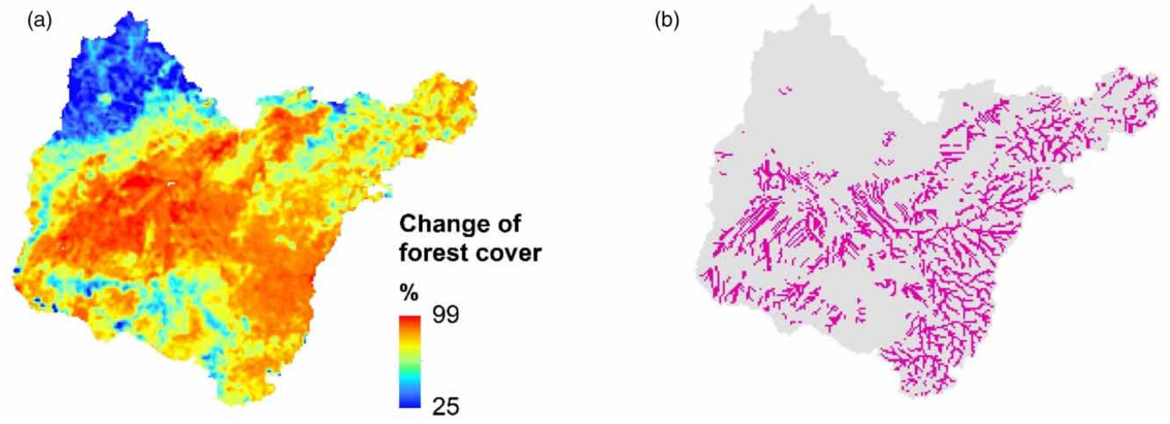


Figure 4 | Scenarios of change in the Great Ruaha River Catchment. In scenario 1, we used a land-use change model to reforest all areas where there has been a change in percentage of forest cover (a); In scenario 2, we identified all the areas that are within a 1 km distance of a river and are currently classified as cropland and converted them to irrigated cropland (b).

different between upstream and downstream. By separating the upstream and downstream irrigated areas, we disaggregated the impact of irrigation on downstream flows stemming from one area or the other. We did so by calculating the hydrological footprint of each area.

The hydrological footprint estimates the contribution to downstream flows of water originating from each of these irrigation zones (upland and lowland) for each month. Should all these flows be consumed by irrigation the resulting contribution would be missing from the downstream flows. A hydrological footprint is only possible for areas that generate runoff; if there is no runoff, no footprint can be calculated.

RESULTS

Baseline runoff and seasonality

The rainfall in the upland areas (Figure 3(b)) differs in magnitude and seasonality, significantly impacting the source of runoff from uplands and lowlands. The pattern of mean annual rainfall follows closely that of elevation (Figure 3(a)), with upland showing the highest precipitation values. The uplands of the Southwestern part of the catchment are considered marked seasonal with a long dry season (SI 0.850–0.99) whereas the lowlands in the North-eastern are considered close to extreme seasonality ($SI \geq 1$,), with all precipitation occurring in 1–2 months.

The seasonality of runoff is crucial to identify water use activities and their relationship to drier and wetter months. The estimated runoff (Figure 5) shows wetter months from November to April and drier months from

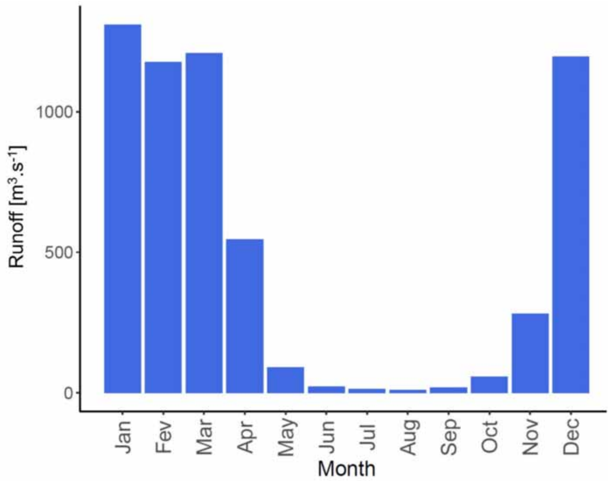


Figure 5 | Monthly runoff at Usangu lip. This chart shows the estimated monthly runoff (m^3/s) at the Great Ruaha River Catchment outflow point, the Usangu lip, calculated from the monthly average rainfall data of 1950–2010 by the WaterWorld policy support system tool (Mulligan 2012).

May to October (average monthly and annual between 1950 and 2010). The month with minimum runoff is August, whereas the month with maximum runoff is January. Flows are visibly highly seasonal in response to the highly seasonal rainfall.

Water balance

The annual hydrological footprint indicates that 28.3% of the water at Usangu Lip comes from areas above 1,300 meters. The same process was applied with a benchmark at 2,000 meters and showed that 13% of the water present at the Usangu lip originates in areas above 2,000 meters. This is important to understand the maximum possible influence of land use/management in different parts of the catchment as determined by the total water originating in those areas.

The minimum monthly contribution of areas above 1,300 m is 0.2%, whereas the maximum monthly influence reaches 64.8%**.** These minima and maxima reflect the spatial distribution of rainfall in different seasons between upland and lowland areas and indicate the contributions of these areas to flow into the wetland under the current climate and land use/cover conditions. The flows of the month of April are most strongly impacted by water production above 1,300 meters, followed by the months of March and May. The uplands contribute the most to flows of different tributaries in different months and for the mainstem, the month of greatest contribution of the uplands is July when evapotranspiration in the lowland is high and most rain is falling only in the highest parts of the uplands.

In contrast, the minimum contribution of the uplands to flow is in February. This is in the midst of the rainy season in which much of the catchment, including the lowlands, is receiving rainfall and hence the contribution of the uplands is minimal.

In dry season months, little flow is produced in the lowlands due to higher evapotranspiration than rainfall. Thus, higher elevations (with more rainfall) contribute significantly to flow in downstream areas. Conversely, in the wet seasons, when rain occurs throughout the catchment, the contribution to downstream flows from mountainous areas is less. This is due to their proportionately smaller surface area compared with the plains, which are also heavily contributing to flows from their rainfall.

Potential impacts of deforestation and irrigation

1. Converting cropland areas into forested areas

When calculating the change in runoff under this scenario, we observed a diminution of runoff of -108 m^3/s per year, indicating the deforestation of the entire surface that is now cropland has increased the runoff by 1.8% compared to the baseline (Table 1). This suggests that the reduction of evapotranspiration in the conversion

Table 1 | Change in runoff under scenario 1*, at the Usangu Lip

Period	Baseline [m^3/s]	Change in runoff [m^3/s]	% in runoff change when deforesting
Year	**5,932.9**	**−108.0**	**1.8%**
Jan	1,310.7	−31.5	2.4%
Feb	1,176.8	−30.3	2.5%
Mar	1,209.2	−30.7	2.5%
Apr	545.9	−5.1	0.9%
May	90.7	3.4	−3.7%
June	21.9	2.1	−9.7%
July	14.0	2.3	−16.0%
August	9.7	2.2	−22.9%
Sept	18.4	2.6	−13.8%
Oct	58.0	1.8	−3.1%
Nov	281.0	0.2	−0.5%
Dec	1,196.4	−24.9	2.0%

*Current cropland was converted to forest in the Great Ruaha River Catchment and the difference in runoff was calculated to identify the effect of previous deforestation in the area on the river flow. Dry season months in grey, wet season months in white. Source: Produced by authors using WaterWorld data (Mulligan 2012).

from forest to rainfed cropland would have led to a significant increase in runoff. Irrigated cropland may have higher evaporative loss than rainfed cropland, but this loss must be seen relative to the forest cover preceding the agriculture, not in isolation.

The percentage of change in runoff is calculated by dividing the yearly change of runoff by the baseline runoff at the exit of the wetland. Results summarised in Table 1 are inverted to reverse the process (deforestation rather than afforestation). The results indicate that runoff at the exit of the wetland has increased by 1.82%, indicating a small overall annual impact at the catchment scale.

While the annual estimation showed a small change, when this is calculated monthly, the changes are considerable for some months (Table 1), particularly during the dry season when much more evapotranspiration would have occurred in forested areas than occurs now. This largely reflects the change in forest cover in the lowlands that receive little rain in the dry season. Thus, the seasonal effect of deforestation is evident under this scenario.

Here deforestation has two impacts. First, croplands tend to transpire less and have lower interception losses than tree cover, increasing water balance and thus runoff (Mulligan 2012). Second, croplands tend to capture less of the ground level cloud (fog) that is present in tropical mountainous areas, particularly in the dry season, decreasing water balance (Mulligan 2012). The net effect of these contrasting effects determines the extent to which water balance increases or decreases on deforestation. As the fog effect is greater in the dry season, it explains why dry season flows decrease with deforestation. The decrease in evaporation on deforestation is thus less than the decrease in fog input on deforestation, leading to reductions in water balance. In contrast, as most of the water in the wet season stems from rain, the impact of deforestation in the wet season is much greater on reducing evapotranspiration than reducing fog inputs, hence we observe a significant increase in water balance.

2. Converting land into irrigated cropland

The converted areas (Figure 4(b)) reached an extension of 3,509.58 km^2, 16.69% of the catchment area (21,024.9 km^2). The estimated potential area of upstream irrigation was 1,787 km^2, 15% of the upper catchment and 8% of the entire catchment. The estimated potential area of downstream irrigation was 1,567 km^2, 17% of the lower catchment areas and 7% of the entire catchment.

The annual footprint of upstream potentially irrigable areas was 2.18% compared with 0.62% for lowland areas (Table 2). This is the result of the different proportions of the irrigable areas and because lowland areas are closed in the dry season and thus irrigation at this scale would not be possible. For the upland, potentially irrigable areas

Table 2 | Hydrological footprint of upstream (≥1,300 m) and downstream (<1,300 m) potentially irrigable areas

	Hydrological footprint	
Period	**Upstream**	**Downstream**
Annual	2.18%	0.62%
Annual maximum	2.86%	1.61%
Annual minimum	0.08%	0%
January	2.58%	1.05%
February	2.70%	0.95%
March	3.19%	1.11%
April	3.62%	1.61%
May	1.70%	0.42%
June	0.41%	0%
July	0.21%	0%
August	0.08%	0%
September	0.10%	0%
October	0.18%	0%
November	2.52%	0.34%
December	2.86%	1.17%

Wet season months in grey and dry season months in white. Source: Produced by authors using WaterWorld data (Mulligan 2012).

runoff occurs throughout the year and thus there are positive footprints throughout the year, though these are greater in the wet season when uplands contribute more to the flow into the wetlands because the lowlands are drier. A 0% in Table 2 indicate months when there is no excess of rainfall over evapotranspiration to use for irrigation over large parts of the lowland basin.

DISCUSSION

Hydrological modelling to support WUAs decision-making

The analyses using the hydrological model support the statement that an ecological crisis has been taking place since 1993, particularly in the dry season, when the catchment reaches closure. In line with most rivers in sub-Saharan Africa, seasonality is a key feature: in the GRRC, river runoffs are at their highest from November to April, and at their driest between May and October. In the dry season, the lowlands entirely depend on the highlands for the river to flow, whereas in the wet season, lowlands provide their own rainfall to fill their rivers.

Identifying spatial and seasonal patterns of water provision at the catchment level allows to assess to what extent agriculture-related activities (such as irrigation) can impact water availability in a given time (e.g., wet or dry season) and space (e.g., highlands or lowlands) within the catchment. For instance, the model suggests that when the contribution of an area to flow to the mainstem in a given month is low, the addition of irrigation in this area at this time could not have a significant impact on the mainstream flow.

The combination of hydrological models with land-use and cover models enables us to suggest that, in the wet season, irrigation in the uplands or the lowlands can occur extensively without basin closure and having considerable hydrological footprints on flow at the wetland. In contrast, in the dry season, irrigation in the uplands could be extensive whilst still maintaining flows downstream, whereas irrigation in the lowlands leads to closure of the basin well upstream of the wetland, and thus, no flow from which to calculate a hydrological footprint.

Using a model to assess the various effects of land-use changes has been useful as local data is both scarce and inaccessible. Although currently remote sensing datasets do not differentiate rainfed versus irrigated cropland, it was possible to develop scenarios for the potential areas that could be irrigated. This has helped us establish what a hydrologically worst-case scenario would look like. The identified potential areas of irrigation (Figure 4(b)) showed the extent of the area WUAs would have to monitor for water abstraction under such a scenario.

The WaterWorld model indicates that the GRRC is a closed basin during the dry season. During the dry season, any water in the rivers of the Usangu plains stems from the upper reaches of the catchment, as there is more evaporation than rainfall in the lowlands. This means that there is an extreme influence of irrigation in the dry season in the Usangu plains (<1,300 meters), and that any water abstracted during that period and at that altitude would impact flows to the wetland. Dry season irrigated areas in the Usangu plains are thus 100% dependent on water from upstream areas.

The results under the afforestation scenario suggest that deforestation during the period of agriculturalisation was a significant factor in the drying up of the river, especially for deforestation that has occurred in the mountain cloud forests, which has reduced capture of fog (Mulligan 2012). This loss of water reduced the positive impacts on flows that deforestation (and thus reduced ET) in the lowlands has led to. Reforesting the lower catchment would not help, as trees would evaporate more water than most croplands. Trees bring additional infiltration at the expense of runoff in the wet season, which would positively impact downstream areas (perhaps past the wetlands) through increased baseflows in the dry season, but if there is less effective rainfall (rainfall− evapotranspiration) to start with then both quick flows and baseflows will be lower. Exposed previously high forested mountains are where afforestation could take place most usefully, leading to increases in flow downstream (Richards 2020).

The following causalities lead to reduced dry season flows: (a) upstream deforestation leads to lower infiltration and more quick flow in the wet season, resulting in lower baseflows in the dry season; (b) upstream deforestation leads to lower fog capture in the dry season when there is little rainfall and flow depends heavily on this capture; (c) potential borehole irrigation would reduce the water table depth, thus negatively affecting the baseflow; and (d) greater evapotranspiration through irrigation evaporative losses in the dry season pumped from the rivers leads to reduced flows, although much would depend on the irrigation type (e.g. flood irrigation allows water to infiltrate back into the soil and water table). In conclusion, a comprehensive understanding of environmental relationships is necessary, particularly those associated with deforestation, rather than assuming that the declines in flow are a direct result of water abstraction by irrigators.

Policy implementation at a relevant scale

Our hydrological modelling approach has helped us answer how the scale of hydrological processes can affect the ouctomes of WUAs in the GRRC. Currently, WUAs are formed out of institutional blueprints, far removed from the landscapes within which they operate. The prerogatives and setting-up of WUAs across Tanzania are uniform, and there is no clear area of focus for them to start putting efforts into. In contrast to the institutional blueprints of WUAs, the waterscapes within which they operate are seasonal and diverse, though often misunderstood.

Until now, narratives shaped by political and economic interests have been confusing a clear overview of what water security actions need to be undertaken where, and with what capacity. This study has contributed to clarifying water scarcity risks in the catchment, thus reducing the weight of political narrations and increasing scientific evidence and identifying where WUAs of the GRRC can have the most impact.

Based on the identification of scale and location of water scarcity risks, CBNRM institutions such as WUAs present an opportunity to monitor and intervene in localized actions, which have large-scale impacts on the catchment. The capacitation and follow-up of WUAs should thus consider place-dependent hydrological processes in order to improve their impacts. Our study has shown specifically that WUAs have a high potential for impact if they actively monitor downstream irrigation in the dry season. While the model suggests that reforestation at a large scale would have a significant positive impact, the scope and scale of reforesting the upper catchment seems to go beyond what a single of multiple WUAs can achieve without wider stakeholder involvement.

The case of the GRRC serves as an example for seasonal catchments where most of the population's livelihoods depend on the availability of water resources, but it also makes a case against uniform policy implementation. Despite ready-made policies and blueprints for sustainable natural resource use, the haphazard implementation of these in the Global South have forced policymakers and practitioners to question their efficacy.

There is no shortcut to sustainably managing water resources, and time needs to be made for contextually relevant solutions to emerge through integrated approaches. Sustainability goes together with context, and policies and their implementation should allow some margin for practitioners to consider this when implementing frameworks such as IWRM.

Investigating the hydrological processes affecting the geographies of WUAs through an inter-disciplinary lens opened the exploration of context-relevant priority areas of action for these community-based institutions. We thus argue that institutional structures should be capacitated to govern at the scale at which the biophysical boundaries operate, for water resources management interventions to achieve the desired impact.

CONCLUSIONS

The use of interdisciplinary methods, involving modelling and ground-based institutional analysis, allowed us to demonstrate that the grounding of decision-making in site-specific analysis at an adequate geographical scale enables CBNRM institutions to concentrate their scope of work on activities with high impact potential.

The results from the hydrological modelling suggest that impacts on flow in a catchment such as the GRRC are multiple and vary spatially, seasonally, and with land use. Changes to flow cannot be considered a function of abstraction losses for irrigation only since deforestation for agriculture also showed a degree of contribution for these changes.

The scale of current and potential irrigation has important local impacts on flow but the scale of these is diminished as we travel downstream, given inputs of water from additional areas. Since irrigation still covers a relatively small proportion of the landscape, other much more widely dispersed factors, such as rainfall patterns and deforestation, may be as or more important.

Small water users are particularly unlikely to have significant impacts downstream at the catchment scale individually. Even if these were to expand significantly to all areas within 1 km of a channel, their impact would depend on altitude and season. In the wet season, they may still have little impact and even in the dry season those in the uplands may have little impact on the wetland. Dry season irrigation in the lowlands will, however, have a significant impact and it is these that must be carefully monitored.

WUAs could have a real impact on securing water resources for the GRRC by targeting action based on season and catchment area. WUAs in the upstream areas could focus their efforts on reforestation, whereas downstream WUAs could focus on monitoring and managing dry season irrigation abstractions. Institutional blueprints applied uniformly in the catchment lead to inefficient outcomes. Instead, deploying and capacitating WUAs for specific interventions could lead to significant improvements to the Great Ruaha's river flows, and potentially, benefit other catchments by applying this approach in other areas in the world.

ACKNOWLEDGEMENTS

NR thanks the Economic and Social Research Council of the United Kingdom for the sponsorship granted for doctoral studies, in a CASE partnership with WWF-UK under grant number ES/J500057/1, from which this manuscript was produced. NR thanks Prof. Frances Cleaver, Prof. Mark Mulligan and Dr Emma Tebbs for supervising this research. She also recognises the improvements made to the arguments presented thanks to the feedback of Dr Julia Brown and Prof. Philip Woodhouse. The authors thank Dr Alois Tilloy for his technical help.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 27 October 2021; accepted in revised form 14 January 2022. Available online 1 February 2022