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Research Paper

# Informing regional water-energy-food nexus with system analysis and interactive visualization – A case study in the Great Ruaha River of Tanzania

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ABSTRACT

In sub-Saharan Africa, water resources are scarce and subject to competing uses – especially for agricultural production, energy generation, and ecosystem services. These water intensive activities in the Usangu plains and the Ruaha National Park in southern Tanzania, present a typical case for such water competition at the water-energy-food nexus. To decipher the coupled human-nature interactions in the Great Ruaha River basin and effectively communicate the results to non-technical practitioners, the water-energy-food nexus competition in the system is simulated using an advanced water system modeling approach and findings are visualized via interactive web-based tools (Data-Driven Document, D3) that foster fuller understanding of the findings for both practitioners and stakeholders. Our results indicate that a combination of infrastructural and procedural measures, each acceptable from a social and economic perspective, and understanding that zero flows cannot be totally eliminated during dry years in the Ruaha National Park, are likely to be the best way forward. This study also reveals that the combination of improvements in irrigation efficiency, cutbacks on proposed expansion of irrigated lands, and a low head weir at the wetland outlet, significantly reduces the number of zero flow days (i.e., increasing ecosystem function), resulting in positive effects on agricultural sector from limited (if any) reduction in rice crop yields. These upstream measures are all relatively cost efficient and can combine to free-up resources for other economic activity downstream (i.e. more stable hydropower production).



## 1. Introduction

Water competition among different sectors in Sub-Saharan Africa is both common and inevitable since water is the key resource for food production, power generation, navigation, and wildlife. Activities performed by a variety of stakeholders along the Great Ruaha River, one major tributary of the Rufiji River instigate such competition at the local water-energy-food (WEF) nexus. The Ruaha National Park (RNP, Fig. 1), the largest national park in Tanzania, is one of the key tourism spots in the country and the Great Ruaha River is the only water source for wildlife in the dry season (usually between June and September). The Mtera and Kidatu reservoir (Fig. 1, downstream of the RNP), which supply a majority of electricity for Tanzania, need stable streamflow to maintain their hydropower generation. Large scale rice irrigations located inside the Usangu plain (upstream of the RNP) started in the early 1980s and require water for their crop production. A clear water competition between irrigation (upstream), ecological purpose (midstream) and hydropower generation (downstream) make the water resources management difficult in that the major irrigation water use is located upstream of the hydropower facility (a unique setting similar to the Volta Basin).

Decreasing volumes of streamflow and a growing number of "zero-flow" days inside the RNP during the dry season became observable two decades ago, thus intensifying water competition and threatening biodiversity values and related tourism income in the RNP. The Government of Tanzania and several international agencies like World Bank, International Water Management Institute, and African Development Bank conducted a number of studies to examine the hydro-climatic condition for this region. Studies by SMUWC, (2001), Lankford et al. (2009), Kangalawe et al. (2011) and Shu and Villholth (2012) showed no significant long-term trend in precipitation, a slight downward trend in total streamflow, and a

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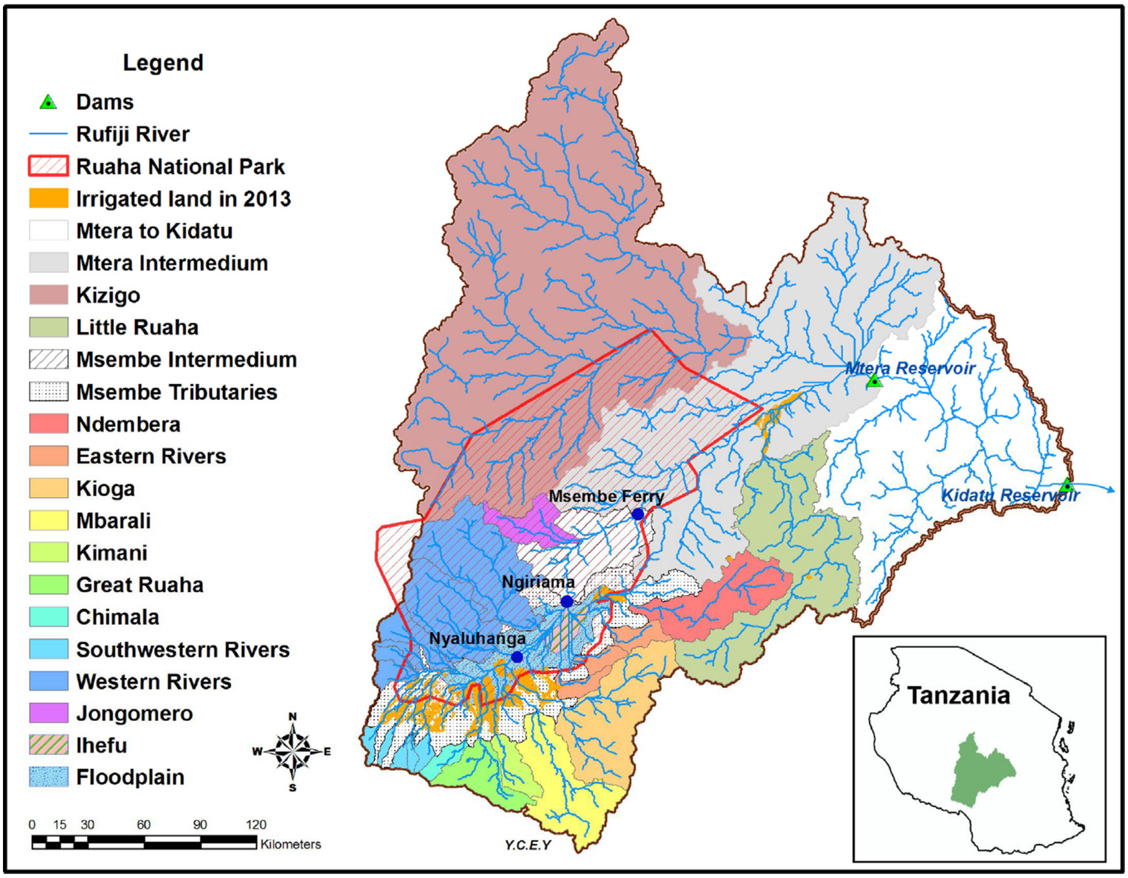


**Fig. 1.** The Great Ruaha River upstream of the Kidatu reservoir. Color codes represent different subbasins, major irrigation schemes and Ihefu wetland.

relatively clear downward trend for the dry season streamflow from 1958 to 2004, especially at Msembe Ferry station (Fig. 1).

Previous ecological studies emphasized the importance of the Ihefu wetland (Fig. 1). Low flow condition in sections of the Great Ruaha River, upstream of the Ihefu wetland in the RNP is of particular interest for ecosystem preservation. Drying of the Great Ruaha River not only threatens wildlife but also promotes unusual migration of local wildlife towards the nearby farms (Mtahiko et al., 2006). To maintain a healthy ecosystem for the entire Usangu Plains, different environmental flow requirements were proposed. Mtahiko et al. (2006) estimated the drinking water demand by large mammals in the national park as 17.09 million cubic meters (mcm) per year. Kihwele et al. (2012) suggested that the reduced peak flow into the Ihefu wetland could result in a growth of vegetated (silted) islands in the river channel and affect fish migration. WWF, (2010) estimated the long term average annual environmental flow requirement of 303.2 mcm at Msembe Ferry.

Several studies estimated the total irrigated land and water uses (mostly for the rice irrigation) in the Usangu plains, however, their results vary considerably due to critical detailed data such as crop cycle in each plot are not available. The first estimation of the total maximal irrigated area ranges are from 42,000 to 55,000 ha and the annual gross irrigation requirement ranges from 557 mcm to 815 mcm according to SMUWC, (2001). Some follow-up studies applied the same range of crop area but estimated different irrigation requirements: 576 mcm per year (Kadigi et al., 2013); 810 mcm per year (Mdemu et al., 2004); 350 mcm per year (Mwakalila, 2005) and 979 mcm per year (Kadigi et al., 2008). More recently, Critchley (2015) used the remote sensing data from the Landsat TM/SPOT high-resolution satellite image to identify the irrigation area developed during the period 1985–2013 in the Great Ruaha River basin (the upstream of the Mtera reservoir). Based on the Landsat TM/SPOT for the year 2013, Critchley (2015) identified an expansion of irrigation area to about 115,400 ha.

Some previous modeling studies that applied a modeling framework integrating hydrologic and human-induced water cycles include the SMUWC (2001), Kashaigili et al. (2006, 2007), WWF (2010), WREM (2013) and MoW (2015). Suggestions from these studies are summarized: improving local irrigation efficiency is still important; irrigation infrastructures need to be carefully designed; economic efficiency is necessary but insufficient to determine water allocation; water use trade-off between human livelihood and ecosystem preservation need to be carefully reviewed and water management plan should build on the traditional (informal) arrangements.

Despite the invaluable insights on the fundamental understanding of the WEF nexus in the Great Ruaha River, some research gaps still exist. Specifically, limitations found in the previous studies are: 1) used a single model (either process-based hydrologic model or empirical-based water balance model) to quantify the water available in the entire system, 2) diagnose their models with a single target only; i.e., streamflow and 3) put little emphasis on using novel and more effective tools to communicate their results to non-technical practitioners. The objective of this paper is to address these gaps by developing a coupled modeling framework capable of explicitly quantifying natural and human components that affect the WEF nexus in the Great Ruaha River system, calibrating the model based on the pooled calibration with multiple targets of streamflow, water depth, and hydropower generation, and providing an interactive web-based visualization tool (via a JavaScript library: Data-Driven Documents) designed to facilitate the communication with decision makers about our findings. Our modeling