Journal of the Geographical Association of Tanzania, Vol. 40, No. 1: 1–20

Assessment of Water Management and Development Scenarios in the Great Ruaha Catchment, Rufiji Basin

Joel Nobert*

Abstract

Water supplies have been declining sharply in the Great Ruaha catchment due to socio-economic development, over-abstraction, illegal use, and seasonal and inter-annual variations in climate. Despite the current pressure on water supplies, there are plans for significant agricultural expansion as a part of the Southern Agricultural Growth Corridor in Tanzania (SAGCOT), though significant uncertainty still revolves around the availability of water in the catchment. This paper aims to assess the water management and development scenarios in the catchment within the context of the current agricultural transformations. The baseline model was set up and calibrated for the Great Ruaha River (GRR) basin to simulate the existing conditions. The purpose of the baseline model was to describe the existing situation and provide a platform upon which future development intervention scenarios can be built and their impacts compared with. The model was calibrated using the observed records at Msembe gauging station and Mtera reservoir water level. The NedborAfstromnings Model (NAM) rainfall-runoff model was used to estimate the flows for sub-catchments with poor data. Five irrigation schemes were evaluated using social, environmental, and economic criteria using multi-criteria analysis techniques to assess how interventions affected the direction of change in environmental, social, and economic performance; and measure the magnitude of that change. The results indicated that the construction of the Lugoda dam, diversion canal from Ihefu wetlands, and improvement of irrigation schemes in the sub-basin are the best development and management scenarios. These will improve water availability for the expansion of the Madibira irrigation scheme; as well as ensure water availability for the Ruaha National Park (RNP), which experiences water shortage during the dry season.

Keywords: *water resources modelling, scenarios, multi-criteria analysis*

1. Introduction

Water is necessary for all forms of human, animal, and plant life. It is essential for overall human well-being, and supports all aspects of human livelihoods. Furthermore, water plays an important role in supporting productive human activities such as agricultural, energy and industrial production, sanitation, transportation services, fishing, and tourism (UNEP, 2009). The global water demand will primarily grow due to population and economic growth, rapid urbanization, and the increasing demand for food and energy (GWP, 2009).

*Department of Water Resources Engineering and Institute of Resource Assessment, University of Dar es Salaam, Tanzania: njoelk@yahoo.com

This in turn impacts the spatial and temporal distributions of water availability by altering the quantity and quality of freshwater resources on which we depend to survive both physically and economically (Cosgrove & Loucks, 2015). The interdependency between social or human ambitions on one hand, and availability and quality of natural resources and the environment on the other, is obvious: it determines the kind of development that is realistic and stable (Cosgrove & Loucks, 2015). This calls for sustainable management of water resources since the demand and competition for finite and vulnerable water will continue to expand. Mays (2006) defined sustainable water management as meeting current water demand for all water users without impairing future supply. More specifically, sustainable water management should contribute to the objectives of society, while maintaining ecological, environmental, and hydrologic integrity (Loucks & Gladwell, 1999). Sustainable water management involves allocating water between competing purposes and users. This allocation can be represented as a hierarchy, similar to Maslow's hierarchy of human needs (Table 1).

Table 1: Comparison of Maslow's Hierarchy of Human Needs and the Hierarchy of Water Management Needs

Level	Maslow's Hierarchy of Human Needs	Hierarchy of Water Management Needs
5	Self-fulfilment	Water resources sustainability
4	Esteem (status, recognition)	National water projects (supply, remediation, public awareness)
3	Social (family, community)	Regional water projects (supply and treatment plants)
2	Safety (security, stability, law, order)	Local development (agriculture, domestic water, water quality standards)
1	Physiological for survival (Air, water, food, shelter, procreation)	Biophysical individual needs, water for survival

Note: Adapted from Melloul and Collin (2003)

The two hierarchies share commonalities from levels 1 to 4. Maslow's inward-looking—or self-fulfilment—contrasts with resource sustainability, which emphasizes an outward-looking perspective, including the fulfilment of other users both now and in the future (Russo et al., 2014).

Decisions regarding water allocations are increasingly important as river basins are further developed and managed to meet social, economic, and environmental needs (Grabow & McCornick, 2007). The allocation of water to sustain natural ecosystems, restore rivers degraded by over-abstraction, and to protect biodiversity for future generations, has become a key issue (Petts, 1996). At the heart of the problem is the conflict between competing users, such as irrigation, hydropower, and domestic water needs. So far, a centralized system by a central planner has been the standard water management approach, by which the whole water basin is modelled as a centralized system, and then water is distributed for maximizing the total benefit of users (Ding et al., 2016). Water resource decisions generally involve large numbers of alternatives and criteria that are often characterized by uncertain consequences, complex interactions, and participation of multiple stakeholders with conflicting interests (Hyde et al., 2004).

Sustainable management of water resources requires clear understanding of water resources in water basins to meet the growing demand of the world's population for water, and to achieve secure and sustainable water in the future (Malual, 2015). Any assessment of the availability of water resources requires detailed insights into hydrological processes. Generally, hydrology models focus on understanding how water flows through a watershed in response to hydrologic events, while water resource planning models primarily focus on describing the allocation of water within a water management context (e.g., supply and demand decisions) (Yates et al., 2009). Therefore, an integrated use of hydrological and water resource planning models is recommended for sustainable water resources management and planning.

The Great Ruaha sub-basin is facing a lot of challenges related to water resource management. Water levels in the Mtera dam have been declining to the extent of stopping the production of hydropower. Since the early 1990s, the dam has experienced shortage of water in one of its major power plant reservoirs. This has even resulted to power rationing in the country, particularly during the period from 1992 to 1994 (Kadigi et al., 2004). The problem of water shortage is linked to the over-use of water resources upstream for other competing activities. Upcoming large agricultural developments under the SACGOT initiative have added another complexity of water resource management in the basin. Water shortage also affects other downstream users, including fragile ecosystems in the Usangu wetlands and the Ruaha National Park (RNP). The RNP is one of the key tourism spots in the country, and the Great Ruaha River (GRR) is the only water source for wildlife in the dry season (usually between June and September) (Yang & Wi, 2018). This paper aims to assess water management and development scenarios to support decision-making processes.

2. Context and Methods

2.1 Study Area

The GRR sub-basin is situated within a semi-arid belt, which runs from north to south of the basin through the central portion of Tanzania (Figure 1). It is in the southwest of Tanzania, approximately latitudes 6°4' and 9°41' South, and longitudes 33°40' and 37°41' East (Kashaigili et al. 2005).

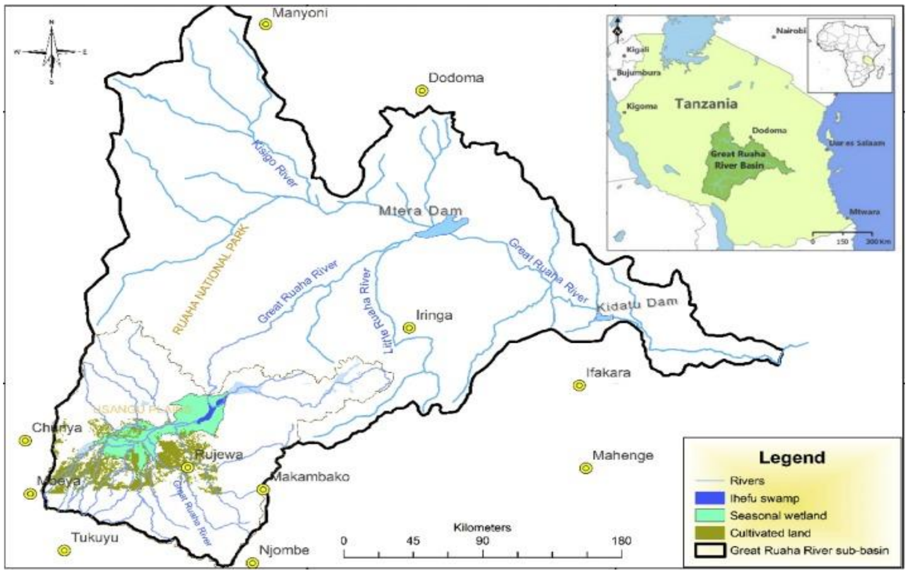

Figure 1: Great Ruaha River Sub-basin
Source: England, 2019

The GRR catchment—which is one of Tanzania's major rivers and an important tributary of the Rufiji River—drains an area of about 68,000km². It originates from several large and small streams on the slopes of the Poroto Mountains and Kipengere range southeast of Mbeya, which is one of the areas with the heaviest rainfall in Tanzania, and from where the bulk of the flow is generated. As the river reaches Usangu plains, the gradient decreases abruptly and the southern part of the plains consists of alluvial fans formed by sedimentation from the rivers. Within the plains, several other rivers—the major ones being Mbarali, Kimani, and Chimala—flow from the highlands to join the GRR.

From the Usangu wetlands, the GRR flows through the RNP, serving as the main source of water for the park. Further downstream the river is joined by the Little Ruaha and Kizigo River just upstream of the Mtera reservoir and hydropower plant, with an installed capacity of 80MW. Downstream of the Mtera reservoir, the river flows to Kidatu reservoir, with an installed hydropower capacity of 204MW.

The mean annual rainfall around Mtera is about 500mm per annum. Rainfall increases southwards and on the slopes of the Udzungwa and Kipengere range. The mean annual rainfall in Great Ruaha ranges from 400mm to 1,200mm. There is only one rainy season from mid-November to May. The dry season occurs earlier in the Great Ruaha than in Kilombero. The rainfall variability is high, and precipitation is often in the form of heavy showers causing rapid surface runoff and sudden spates in seasonal streams and rivers. The climate is characterized by low humidity. Potential evaporation is highly variable, estimated to range from 1,200mm in the South to 2,000mm in the North per year; particularly in the months of December and January.

2.2 Context and Methods

The major irrigation schemes in the GRR basin involved in this research included Mbarali, Madibira, and Kapunga. The main reservoirs used in the GRR basin modelling framework are the Mtera and Kidatu reservoirs, and the Lugoda dam for future plans. The Lugoda dam in Ndembera catchment is currently at a feasibility study stage, and is meant for hydropower production and irrigation scheme. To assess water management and development scenarios in the sub-basin, primary hydrological and water resources input data were captured and used for the analysis. These included streamflow time series data; reservoir and wetlands data (including stage-area-volume curves); and water demand data, which included domestic and industrial water demand and irrigation water abstractions. sets of data are used as presented in the sub-sections that follow.

2.2.1 Streamflow Data

The flow data were obtained from the Rufiji Basin Water Board (RBWB). Table 2 shows the summary of the available data for the major tributaries in the GRR sub-basin, and Figure 2 shows the spatial distribution of the gauging stations. Some of the stations have data up to the 1980s, and therefore rainfall-runoff modelling was applied to extend the records to 2009. The study used global dataset from the Climate Research Unit (CRU) for stations that were missing rainfall and potential evaporation data.

Table 2: A Summary of Available Data for the Major Tributaries in the Great Ruaha (GRR) Sub-basin

Reg. No.	River	Location	Coordinates		Years of Record		Years	% of gaps in the data
			Lat.	Long.	Start	End		
1KA2	Little Ruaha	Iringa	-7.78	35.72	1954	2009	56	38
1KA7A	Chimala	Chitekelo	-8.92	33.97	1963	1992	30	29
1KA8A	Great Ruaha	Salimwani	-8.90	34.13	1955	2009	55	46
1KA11	Mbarali	Great N. Road	-8.78	34.37	1955	1983	29	8.4
1KA15A	Ndembera	Ilonga	-8.28	35.21	1957	2010	54	11.1
1KA31	Little Ruaha	Mawande	-7.50	35.48	1957	2009	53	25
1KA33a	Ndembera	Madibira	-8.20	34.80	1957	1989	33	27.7
1KA42	Kizigo	Kinuguru	-6.90	35.42	1957	1982	26	43.6
1KA51	Umrobo	Great N. Road	-8.82	33.67	1961	1993	33	4.8
1KA56	Ruaha	Malangali	-8.56	34.85	1961	1980	20	9.7
1KA59	Great Ruaha	Msembe	-7.75	34.90	1964	2010	37	6.5

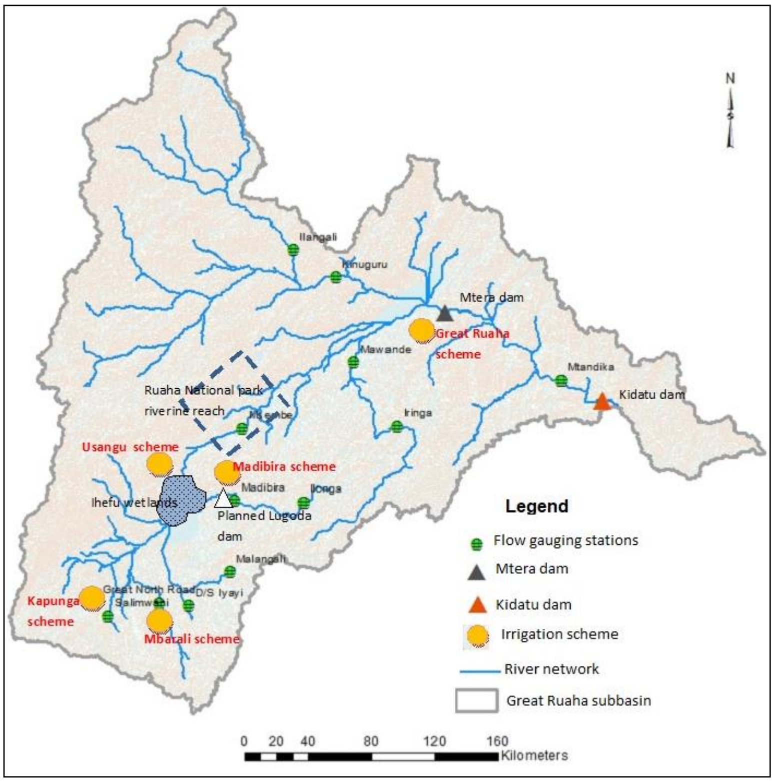

Figure 2: Location of Flow Gauging Stations, Water Users, and Infrastructures in the GRR Sub-basin

2.2.2 Irrigation Schemes

The main irrigation schemes identified include Mbarali, Madibira, Great Ruaha Irrigation scheme, and Kapunga (Table 3).

Table 3: Main Irrigation Schemes in Great Ruaha Basin

Name of Irrigation Scheme	Area (ha)	Source of Water	Type of Crop
Mbarali state farm	2,460	Mbarali river	Paddy
Madibira Irrigation scheme	3,000	Ndembera river	Paddy
Kapunga Rice farm	3,000	Great Ruaha river	Paddy

2.2.3 Wetlands Data

Information on area-volume-elevation relationship of the wetlands/swamp was derived from the hydraulic survey of the wetlands conducted by the WWF in 2010. This was based on bathymetry survey at some selected points using the digital elevation model. Figure 3 shows the elevation-area-volume relationship for the wetlands.

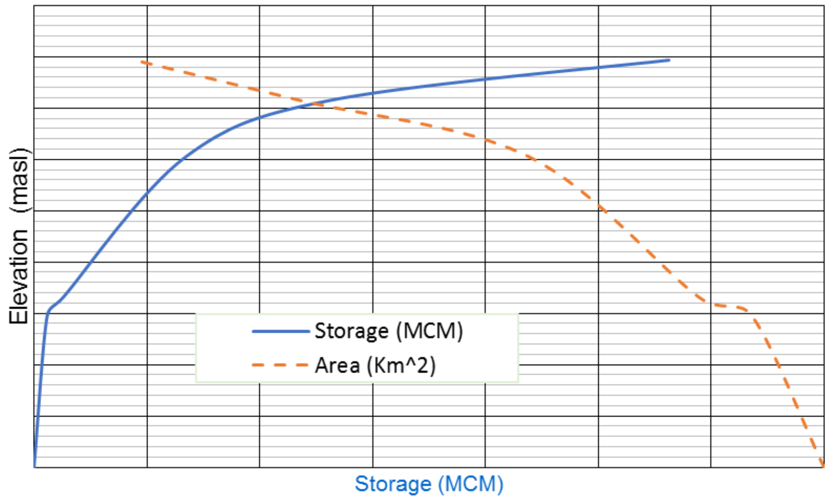

Figure 3: Elevation-Area-Storage Relationship for Wetlands
Source: WWF, 2010

2.3 Data Infilling and Record Extension

To fill gaps, linear interpolation techniques in MIKE-Hydro were applied for all stations, except for Ndembera catchment where the area-ratio method (scaling factor) was used to fill gaps because it had an upstream gauging station with better data than the station of interest. For the ungauged Kioga catchment, flow data was generated through rainfall-runoff modelling using the NAM model by transferring the parameters of the calibrated adjacent Mbarali catchment to the Kioga catchment. The NAM model was also used to extend the flow records for Mbarali, Kioga, and Kimbi catchments to 2009.

The NAM model consists of four interrelated storages to describe a hydrological cycle of a land phase (Figure 4). Surface storage represents the fraction of precipitation intercepted by plant canopy and depression on the land surface. The water in this storage may be lost by evaporation and leakage to streams in the form of interflow (Wakigari, 2017).

On the other hand, if a storage is filled fully, excess water may join a stream as an overland flow, whereas the remaining one is diverted in the form of infiltration and recharge to lower zones and ground water storage, respectively. Lower zone storage represents the moisture stored within the root zone of the soil. Transpiration is responsible for the loss of water in this storage. The moisture content of the lower zone storage governs the amount of water that goes into overland flow, interflow, and groundwater flow (Wakigari, 2017).

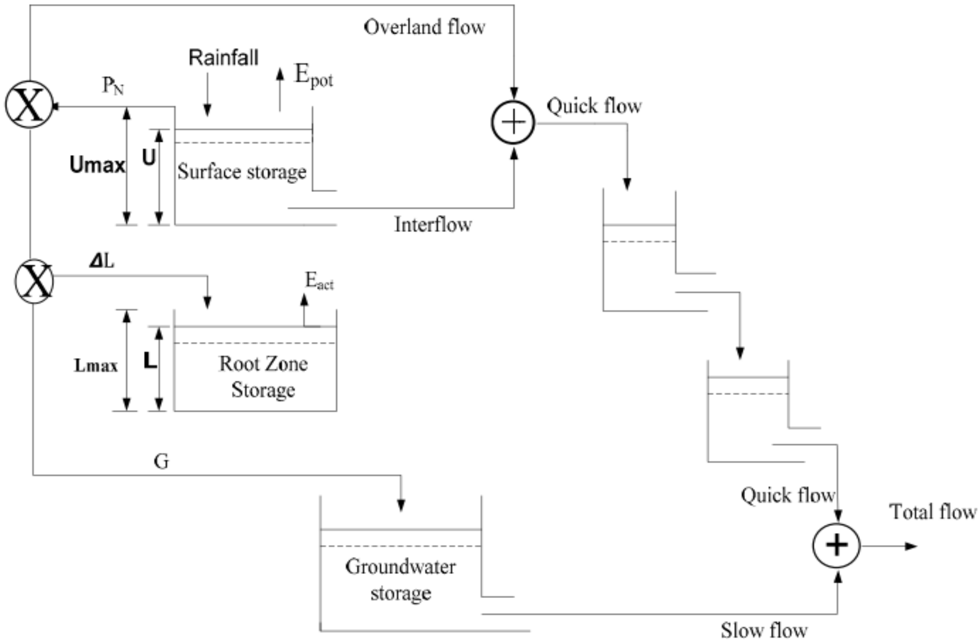

Figure 4: Structure of the NAM Model

2.4 Development of the MIKE-HYDRO Model

A Mike Hydro model was developed using the Mike Hydro building blocks connected by traced river reaches, channels, as well as delineated catchments. The building blocks are basically used to represent the natural systems of the basin—i.e. wetlands, swamps, and natural lakes—and the development interventions introduced in the basin like irrigation use, abstractions for water supply, hydropower, and reservoirs.

Water resources management and development options for the existing and planned hydrological infrastructure in the basin were reviewed. The process started with the identification of the existing hydrological infrastructure, including all abstractions, to develop the baseline model for the basin. After the baseline calibration, the planned hydrological infrastructure and development were incorporated under different scenarios.

All water demand points—mainly irrigation and domestic and livestock water supplies—were considered. The Ihefu wetland was included in the model as a prominent sensitive ecosystem. Wetlands/swamps act as regulators of river flows as they store water and lose some through evaporation and infiltration. The modelling of wetlands was achieved using the Mike Hydro Reservoir building block (node) by treating the wetlands as a natural lake.

Hydropower was modelled using the hydropower building block/node which, in MIKE-Hydro, has to be connected to a reservoir. The reservoirs included in the GRR basin modelling framework are Mtera, Kidatu, and Lugoda. As mentioned earlier, the Lugoda dam in Ndembera catchment is currently at a feasibility study stage; and is meant for hydropower production and irrigation scheme. Basic data required to model hydropower are installed capacity (80MW), tail water level time series, and power demand (target power, 80(MW). This was the modelling approach followed in modelling hydropower generation in the GRR basin.

2.5 Building Baseline Model

The baseline model was set up and calibrated for the GRR basin to simulate the existing conditions (Figure 5).

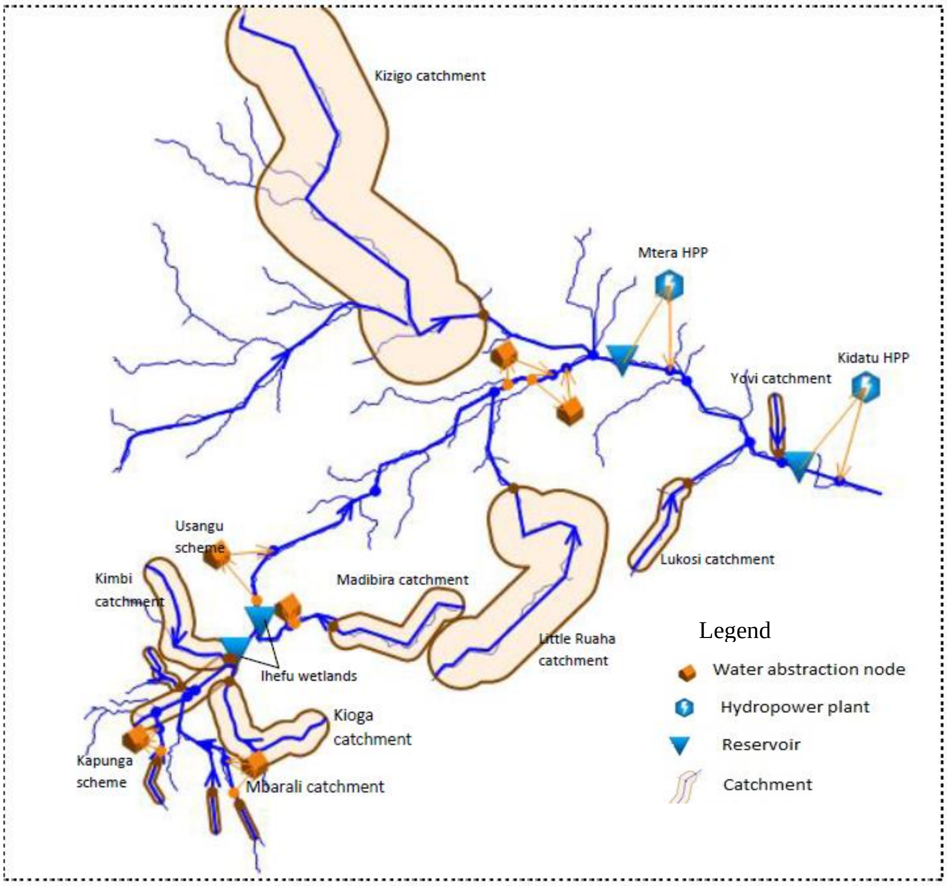

Figure 5: Baseline Schematic Layout

The purpose of the baseline model was to describe the existing situation and provide a platform upon which future development intervention scenarios can be built and their impacts assessed. After the model set-up, simulations were run and the results compared to observed records at the Msembe gauging station and Mtera reservoir water levels.

The model was calibrated using the Msembe gauging station (1KA59) and Mtera reservoir water levels. Model calibration and validation was based on a generic approach of hydrological/water resources models. After setting-up the model, simulations were run and the results compared to observed records at desired points.

2.6 Scenarios Definition and Implementation

Scenario analysis is a process of analysing possible future water resource development and management options by considering alternative possible outcomes. The main objective for scenario analysis is to develop the potential of water resources in such a way that the expected value of the (net) benefits are maximized, while minimizing negative impacts on public health, welfare, and environment. The scenarios evaluated in this paper are as presented in Table 4. These scenarios were necessary for understanding water availability for agricultural expansion and the RNP during the dry season, as well as for the downstream Mtera and Kidatu hydropower plants.

Table 4: Proposed Scenarios for the Great Ruaha Basin

Scenario Name	Description
Baseline Scenario (SC0)	Current situation (covering existing irrigation schemes - Madibira, Kapunga, Mbarali and Pawaga), domestic/livestock water demand and Ruaha National Park
Scenario1 (SC1)	Baseline plus construction of Ndembera/Lugoda dam and hydropower production
Scenario 2 (SC2)	Scenario 1 plus expansion of Madibira irrigation scheme
Scenario 3 (SC3)	Scenario 2 plus Construction of diversion canal from the Ihefu wetland to Great Ruaha River
Scenario 4 (SC4)	Scenario 3 plus improvement of management and irrigation efficiency

2.6.1 Scenario 1: Establishment of Lugoda dam for Irrigation and Hydropower Production

Construction of a storage dam at Lugoda would address the problem of water storage, which remains a key constraint in the current Madibira irrigation scheme. The dam would regulate and ensure constant water flows. The proposed Lugoda dam would have a maximum storage capacity of 210m^3 with 4,800ha water surface area. Water for irrigating the entire 6,600ha area will be obtained by gravity from the dam and the Ndembera river. The discharge would be adequate for irrigating an existing area of 3,000ha for paddy, and 3,600ha of the proposed expansion of paddy. This dam would also provide the regulation of flow downstream to the RNP during the dry season. The target power for the plant is 3MW, with annual electrical energy production of 18.4GWh.

2.6.2 SCENARIO 2: Expansion of Irrigation Scheme at Ndembera

Scenario two involves the expansion of the irrigation scheme at Madibira (Ndembera River) to 6,600ha due to the construction of Lugoda dam (Figure 6).

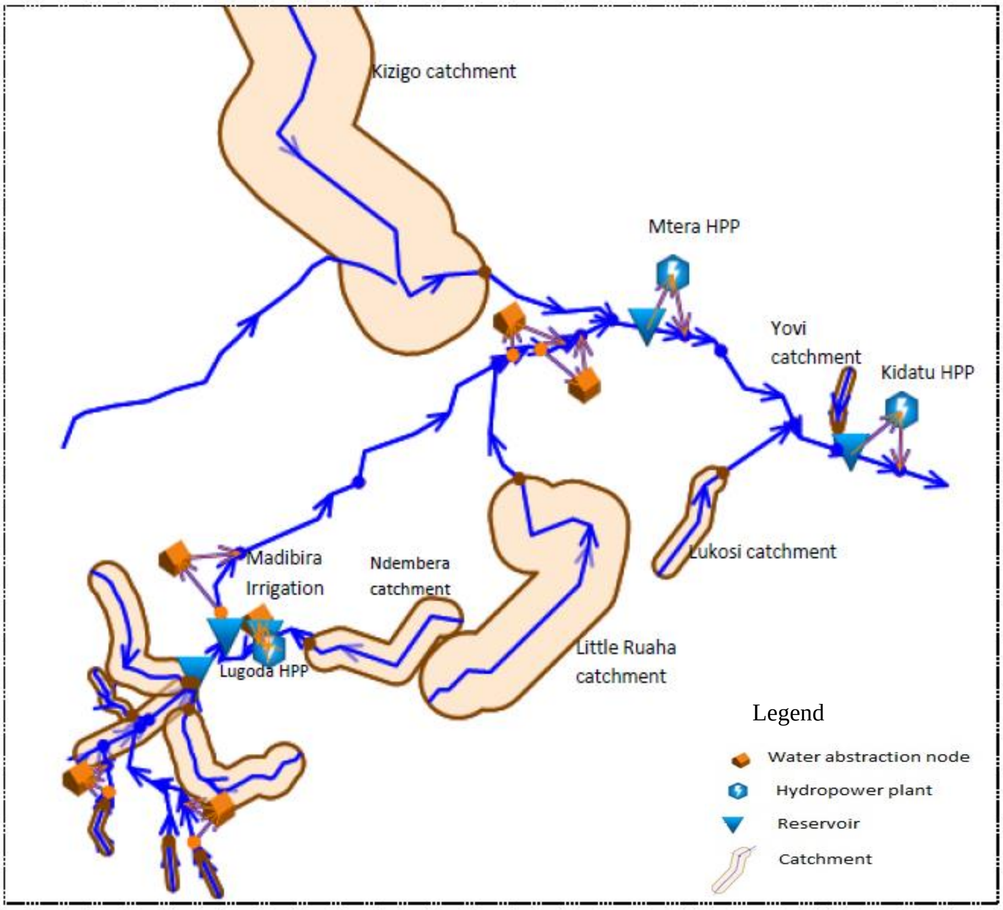

Figure 6: Scenarios 1 and 2 - Construction of Lugoda Dam and Expansion of Irrigation

2.6.3 *SCENARIO 3: Construction of a Diversion Canal*
This scenario involves the construction of a diversion canal from Ndembera River to the Great Ruaha River (Figure 7) to bypass the Ihefu wetlands and reduce losses due to evaporation.

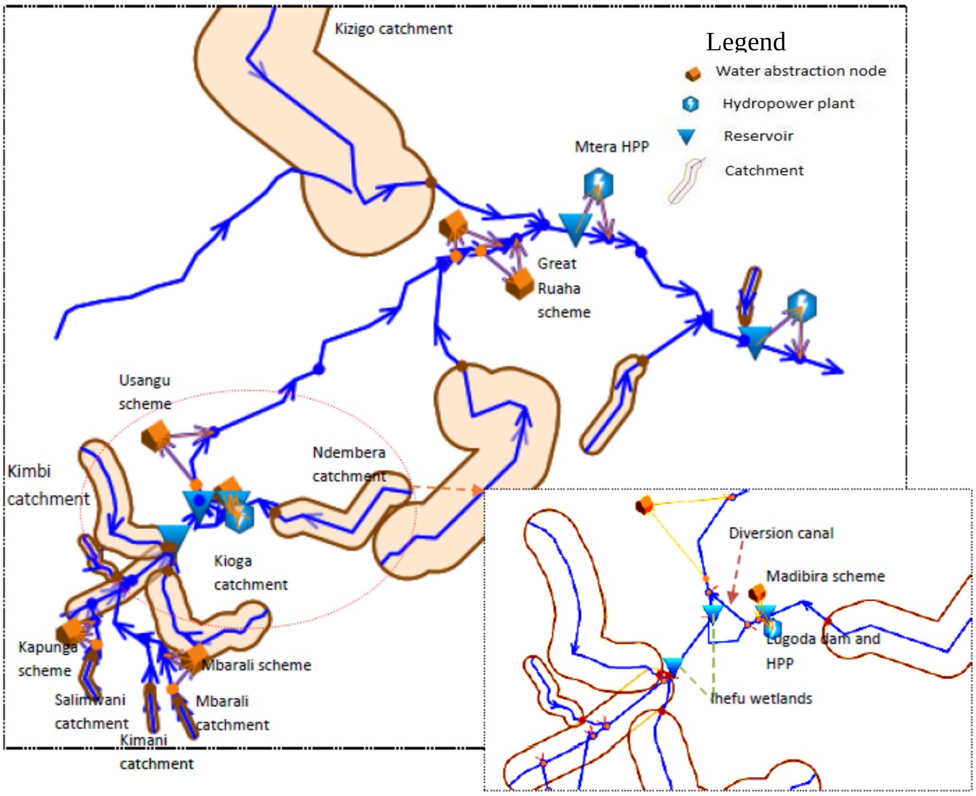

Figure 7: Schematic Layout for Scenario 3 - Construction of Lugoda Dam and Expansion of Irrigation Plus Diversion Canal *(Inset shows the zoom to Ihefu wetlands and diversion from Ndembera river)*

2.6.4 *SCENARIO 4: Improvement of Irrigation Efficiency*
This scenario builds up on scenario 3 by improving the irrigation efficiency from 30% to 50%.

2.6.5 *Scenarios Evaluation Criteria*
Evaluation criteria are a key component associated with the evaluation of water management scenarios. These criteria assess how interventions affect the direction of change in environmental, social, and economic performance, and measure the magnitude of that change.

The indicators used for the evaluation of the scenarios are as follows:

1. *Social indicators:* water availability - Mtera inflow; water availability - middle GRR irrigation scheme
2. *Environmental indicators:* Carbon emissions (Lugoda and Mtera dams), floodplain area inundated, and wetland area inundated (Lugoda dam and Ihefu wetlands), and flow variability for the RNP and Ihefu wetlands.
3. *Economic indicators:* evaporation from dams (Lugoda, Mtera, and Kidatu); food production (Great Ruaha, Madibira scheme, Kapunga and Highlands estate schemes); and energy production (Lugoda, Mtera, and Kidatu HP schemes).

The selection of these indicators was guided by the main issues of concern in the basin, which are water availability for irrigation schemes, environmental issues (RNP and Ihefu wetlands), and power deficit; which have resulted into power rationing in recent years.

Weights were then assigned to the criteria by prioritizing, first, economy; followed by environment and social indicators. The weights assigned to the criteria are as presented in Table 6. The assignment of the weights was based on the priority of the criteria. Highest priority was assigned number 1, and the lowest number 7. The rank order was then used to derive the weights using equation (1).

$$w_j = \frac{\left(m - r_j + 1\right)}{\sum_{j=1}^{m}(m - r_j 1} \qquad (1)$$

Where:

w_j is the weight of *j-th* attribute;
m is the number of attributes; and
r_j is the rank of *j-th* attribute.

2.6.5.1 Normalization of the Attribute Values (Indicators)

Normalization is a process of converting attribute values which are on different scales to an equal scale, usually between 0 and 1. Score-range normalization techniques were used for the normalization of the attribute values as shown in equations (2) and (3).

$$y_{ij}^{*} = \frac{y_{ij} - y_j^{min}}{y_j^{max} - y_j^{min}} \text{ for max;} \quad (2)$$

$$y_{ij}^{*} = \frac{y_j^{max} - y_{ij}}{y_j^{max} - y_j^{min}} \text{ for min;} \quad (3)$$

Where:

y_{ij}^{*} is the normalized value for *i-th* alternative and *j-th* attribute;
y_{ij} is the original value for *i-th* alternative and *j-th* attribute;
y_j^{max} is the maximum value for *j-th* attribute; and
y_j^{min} is the minimum value for *j-th* attribute.

The total outcome of each scenario was then calculated as weighted sum of its respective normalized attribute values.

2.6.5.2 Multi-criteria Analysis

The Multi-Criteria Analysis (MCA) tool of the Nile Basin Decision Support System (NBDSS) compares criteria for various solutions (scenarios), weighted by preferences in a matrix form. It also allows a comparison of multiple decision matrices ('sessions') that were created by different stakeholders.[1]

Six criteria were used in the analysis:

(a) Water availability at Middle Great Ruaha, which considered all indicators on availability of water for the irrigation schemes;
(b) Water availability at Mtera;
(c) Food security, covering indicators on food production from the irrigation schemes;
(d) Flow variability at downstream nodes (Ihefu wetlands);
(e) Energy production covering indicators on power generation for Mtera, Kidatu and Lugoda dams; and
(f) Evaporation from the dams.

The selection of the criteria was based on key socio-economic and environmental issues in the sub-basin.

3. Results and Discussions

3.1 Model Calibration

The comparison between the simulated and observed discharge at Msembe gauging station is as shown in Figure 8. Simulated and observed water levels for Mtera reservoir are shown in Figure 9. The discrepancies between the observed and simulated Mtera water levels can be attributed to the input data. As stated before, rainfall-runoff modelling (NAM model) was used to extend the flow records from the 1980s to 2009 for some stations such as Mbarali river at 1KA11. However, the model did not reproduce well the peaks, and there was some discrepancy in the catchment water balance. It is also worth noting that the climatic data for Kimbi and Kioga catchments were not available, and hence global dataset from the Climate Research Unit (CRU) was used.

[1] Details for the MCA process in the NBDSS can be obtained from: http://nbdss.nilebasin.org/support/solutions/articles/4000041698-mca-definition -and-process.

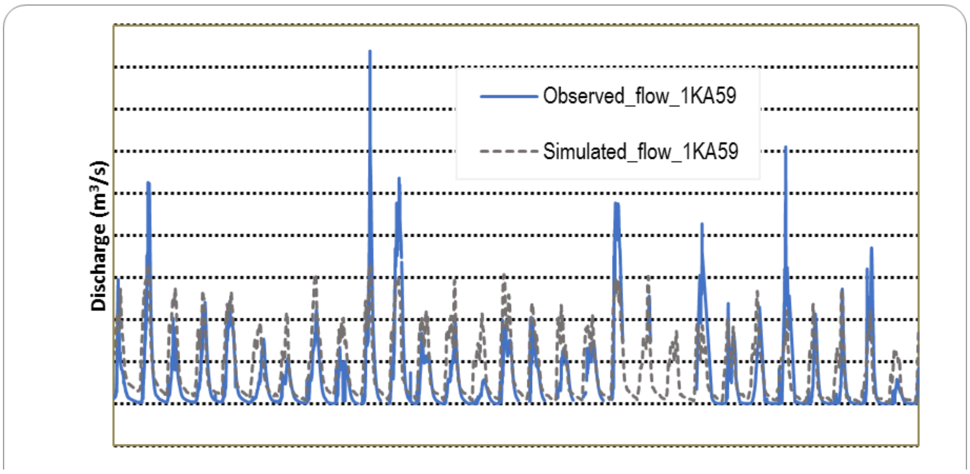

Figure 8: Observed and Simulated Flows at Msembe Gauging Station (1KA59)

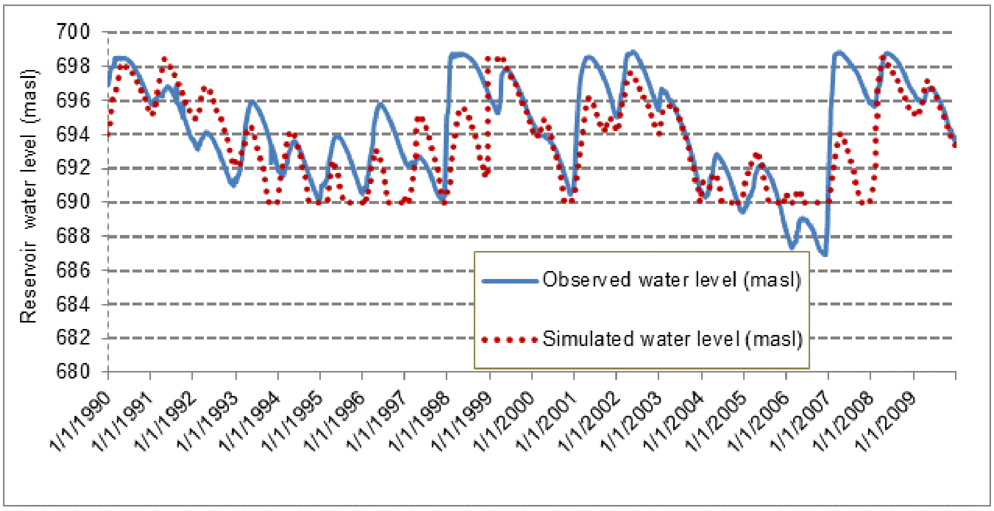

Figure 9: Simulated and Observed Water Levels for Mtera Reservoir

3.2 Evaluation of Scenarios

Having defined the relevant environmental, social, and economic indicators, the indicators were quantified in the NB-DSS by using the scripts. Scripts are created using the python programming language, and were used to calculate the indicator values for each scenario, e.g., energy generated, evaporation from the reservoirs, food production, etc. Tables 5, 6 and 7 show the indicator values for economic, environmental, and social criteria, respectively. The weights assigned to the criteria are as presented in Table 8.

Table 5: Economic Indicators
(*Evaporation loss, food, and energy production*)

Category		Name	Units	SC1	SC2	SC3	SC4
Water conservation	Evap.	Mtera reservoir	MCM /yr	13.84	12.64	12.64	22.47
		Lugoda Reservoir		0.006	0.006	0.006	0.006
		Kidatu reservoir		16.02	16.03	16.03	16.03
	Total	**System-wide**		**29.87**	**28.68**	**28.68**	**38.78**
Food production	Middle GRR irrigation scheme		'000 tons /yr	4.9	4.8	4.8	5.7
	Madibira irrigation scheme			17.1	17.7	17.7	20.1
	Highlands irrigation scheme			5.1	5.1	5.1	5.9
	Kapunga irrigation scheme			4.3	4.3	4.3	5.0
	Total food production			**31.4**	**31.9**	**31.9**	**36.7**
Energy production	Lugoda energy production		GWh /yr	15.84	15.03	15.03	19.63
	Mtera energy production			609.46	610.26	610.30	648.78
	Kidatu energy production			945.66	946.20	946.29	973.20
	Total energy generated			**1570.96**	**1571.49**	**1571.63**	**1641.61**

Table 6: Environmental Indicators
(Change in flow and inundated wetland area)

Category	Location name	Indicator	Units	SC1	SC2	SC3	SC4
Down-stream areas	Lugoda dam	Floodplain and wetland area inundated	% change compared to baseline	-47.9	-44.3	-44.3	-49.8
	Ihefu wetlands			124.4	128.8	79.9	73.5
	Ruaha National Park	Flow variability	% change compared to baseline	-26	-23.7	-23.7	-23.7
	Ihefu wetlands			-22.6	-22.3	-23.5	-23.2

Table 7: Social Indicators
(water availability)

Category	Location name	Units	SC1	SC2	SC3	SC4
Water availability	Water availability highlands irrigation scheme	% change compared to baseline	0	0	0	0
	Water availability middle GRR irrigation scheme		43.4	31.8	31.6	23.9
	Water availability Kapunga irrigation scheme		0	0	0	0
	Water availability Mtera		156.3	141.2	134.8	264.4

Table 8: Weights Used for Each Stakeholder Group

CRITERIA	RANK		
	ECON	*ENV*	*SOC*
Water availability-Middle Great Ruaha	4	6	1
Water availability – Mtera	3	5	2
Food security – system-wise	5	4	3
Flow variability - Ihefu wetlands	7	2	4
Energy production – system	1	3	5
Flow variability Ruaha National Park	6	1	6
Evaporation – System	2	7	7

Figure 10 shows the results of the scenario evaluation. It indicates the performance of each scenario for the economic, social, and environmental criteria.

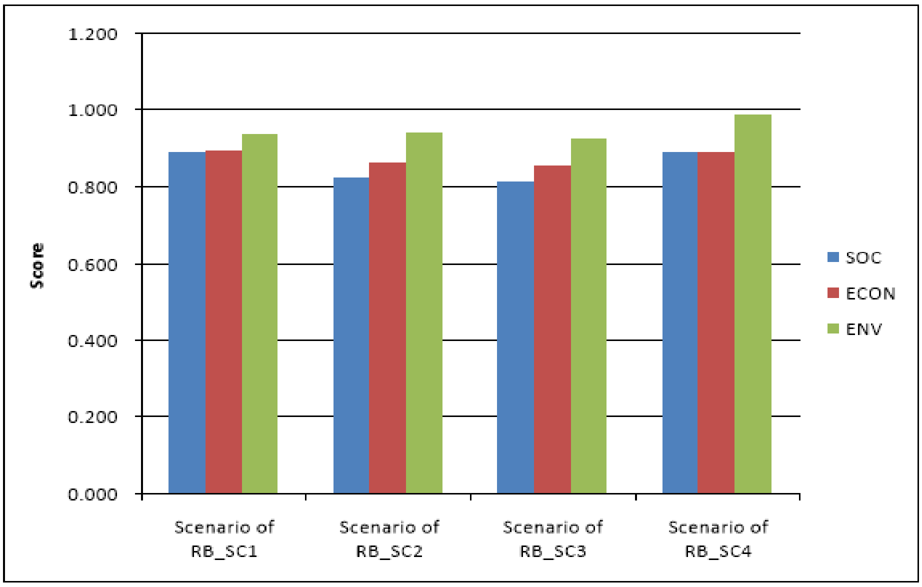

Figure 10: Scores for Different Scenarios

Scenario 4 has the highest score when environment and social attributes are prioritized, while scenario 1 has the highest score when the economic attributes are prioritized. The highest economic score for scenario 1 is due to increase in energy production because of the Lugoda HPP (emphasis on energy production). The highest environmental score for scenario 4 is due to increase of flow to the RNP. Similar results were obtained by Yanga and Wi (2018), who suggested a combination of measures, each acceptable from social and economic perspective, and accepting that zero flows cannot be totally eliminated during dry years in the GRR basin are likely to be the best way forward. In their study, Yanga and Wi (ibid.) suggested a combination of measures such as irrigation efficiency improvements, modest reduction of irrigation areas, and improved productivity through agriculture management. From the results of this paper, the overall plausible scenario is a combination of measures, which include the development of infrastructures (Lugoda dam and diversion canal), as well as management measures in terms of improving irrigation efficiency.

4. Conclusions

This paper has assessed development and management scenarios for improving water availability for different socio-economic activities and the environment. Based on the findings of the DSS application, the potential environmental, social, and economic impacts and/or benefits associated with developments in the Great Ruaha sub-basin under the various scenarios that were considered may be summarized as follows:

(a) Scenario 4 is seen to be the best as it has the highest scores in social and environmental perspectives. However, this will depend on whether irrigation efficiency of 50% will be achieved.

(b) From the economic perspective, scenario 1 is the best because of the increased production of energy, and also given the highest weight by stakeholders (emphasis on energy production).

(c) From the environmental perspective, scenario 4 is also scoring high because of increased flow to the RNP, which surpasses the negative impacts of by-passing the flows to Ihefu wetlands from Ndembera catchment. It also implies that the impact on Ihefu wetlands is not significant as much of the flows to the wetlands is contributed from other catchments apart Ndembera catchment.

Acknowledgment

The author would like to acknowledge the financial support from Nile Basin Secretariat and the Ministry of Water, Tanzania for conducting the study.

References

Cosgrove, W.J. and Loucks, D. P. (2015). Water management: Current and future challenges and research directions. *Water Resources Res.,* 51(6), 4823–4839, doi:10.1002/2014WR016869.

Ding, N., Erfani, R., Mokhtar, H. and Erfani, T. (2016). Agent based modelling for water resource allocation in the transboundary Nile River. *Water*, 8 (4), 139; doi: 10.3390/w8040139.

England, M. I. (2019). Contested waterscapes: Irrigation and hydropower in the Great Ruaha River Basin, Tanzania. *Journal of Agricultural Water Management*. 213 (1), 1084–1095.

Grabow, G. L. and McCornick, P.G. (2007). Planning for water allocation and water quality using a spreadsheet-based model. *Journal of Water Resources Planning and Management, ASCE*, 133(6): 560–564.

Global Water Partnership (GWP). (2009). A handbook for integrated water resources management in basins.

Hyde, K. M., Maier, H. R. and Colby, C. B. (2004). Reliability-based approach to multi-criteria decision analysis for water resources. *Journal of Water Resources Planning and Management,* 130(6): 429–438.

Kashaigili, J. J., Kadigi, R. J., Lankford, B. A., Mahoo, H. F. and Mashauri, D. A. (2005). Environmental flows allocation in river basins: Exploring allocation challenges and options in the GRR catchment in Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C*, 30(11–16): 689–697.

Loucks, D. and Gladwell, J. (1999). *Sustainability criteria for water resource systems*. Cambridge, UK: Cambridge University Press.

Malual, D. M. (2015). Assessment of surface water resources and its allocation: Case study of Bahr el-Jebel river sub-basin, South Sudan. Institute of Climate and Society, Makelle University.

Mays, L. (2006). *Water Resources sustainability.* New York, NY, USA: McGraw-Hill Professional.

Melloul, A.J., Collin, M.L. (2003). Harmonizing water management and social needs: A necessary condition for sustainable development. The case of Israel's coastal aquifer. *J. Environ. Management*, 67(4) 385–394.

Petts, G.E, (1996). Water allocation to protect river ecosystems. Regulated Rivers: *Research and Management*, John Wiley & Sons Ltd, 12 (4–5), 353–365.

Kadigi, R., Kashaigili, J. and Mdoe, N. (2004). The economics of irrigated paddy in Usangu Basin in Tanzania: water utilization, productivity, income and livelihood implications. *Physics and Chemistry of the Earth,* 29 (15), 1091–1100.

Kadigi, R., Mdoe, N., Ashimogo, G. and Morardet, S. (2008): Water for irrigation or hydropower generation? – Complex questions regarding water allocation in Tanzania. *Elsevier - Agricultural Water Management,* 95 (8), 984–992.

Russo, T., Alfredo, K. and Fisher, J. (2014). Sustainable water management in urban, agricultural, and natural systems. *Water* 6(12), 3934–3956; doi:10.3390/w6123934.

United Nations Environment Programme (UNEP). (2009). Water security and ecosystem services. The critical connection. A contribution to the United Nations World Water Assessment Programme (WWAP).

Wakigari, S. A. (2017). Evaluation of conceptual hydrological models in data scarce region of the Upper Blue Nile basin: Case of upper Guder catchment. *Hydrology* 4(4), 59; doi:10.3390/hydrology/4040059.

WWF Tanzania Country Office (WWF-TCO). (2010). Assessing environmental flows for the Great Ruaha River, and Usangu wetland, Tanzania.

Yang, Y.C, and Wi, S. (2018): Informing regional water-energy-food nexus with system analysis and interactive visualization – A case study in the Great Ruaha River of Tanzania. *Elsevier - Agricultural Water Management,* 196 (C),75–85.

Yates, D., Purkey, D., Sieber., J, Huber-Lee, A., Galbraith, H., West, J., …, and Rayej, M. (2009). Climate Driven water resources model of the Sacramento basin, California. *Journal of Water Resources Planning and Management, ASCE,* 135(5): 303–313.