INTEGRATED WATER RESOURCES MANAGEMENT UNDER SOCIO-ECONOMIC AND CLIMATE CHANGE OF GREAT RUAHA CATCHMENT IN TANZANIA USING THE WEAP MODEL

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Abstract: **Water resources management under socio-economic and future climate change is very crucial, particularly while striving to achieve the Sustainable Development Goals (SDGs) related to water. A water Evaluation and Planning System (WEAP) model was used to explore the quantity of surface water, demand, allocate the resources and apply different integration measures to meet unmet demand in the Great Ruaha River Catchment. The WEAP model was calibrated using river gauge stations, 1KA31. For 1KA31 (2006-2010) calibration, NSE, R^2, and RSR was 0.88, 0.88 and 0.35, respectively and validation (2011-2015), NSE, R^2, and RSR was 0.83, 0.87 and 0.42, respectively. Three scenarios were developed and evaluated. First was the reference scenario, evaluated the situation as it is without imposing any changes. The results show that in the current account, (2010) average annual runoff was 109.88 m^3/s, the minimum runoff was 37.77 m^3/s, and the maximum was 262.93 m^3/s. In future, (2050) result shows that average annual runoff will be 126.78 m^3/s, minimum runoff 47 m^3/s and maximum 308.06 m^3/s, whereas, demand 2010 was 100% covered (980.52 Mm^3) and in future demand of 168.14 Mm^3 (2030), 381.45 Mm^3 (2040) and 844.26 Mm^3 (2050) will not be met, which is 13% of uncovered percent. The second was the demand management scenario, assessed reuse of the supply (40%) and adaptation of modern irrigation methods (50% of all users) to meet unmet demand. The results show that 87% of unmet demand in the second scenario will be covered. Third, storage reservoirs scenario, three reservoirs evaluated to store water to supplement unmet demand in the second scenario. The results show that the remaining unmet demand 13% from the third scenario will be covered. Therefore, the study recommends the measures in the second and third scenarios should be implemented to meet the demand driven by the high growth of socio-economic and climate change impacts.**

Keywords: **Great Ruaha Catchment, WEAP model, Water availability, Water demand, water reuse, Storage reservoirs**

1. Introduction

The vast of the water sources globally are drying up, causing a water shortage for different sectors. Globally, the use of water has more increased by a factor of six (6) over the past hundred (100) years. This tendency steadily continues to rise at a rate of 1% per year resulted by growing of population, economic development and fluctuating consumption patterns, which cause water stress even in regions where today water resources are plenty (UNESCO 2020). Water resources are potentially useful natural resources; it is needed for people, crops, animals, wildlife, fishing, maintaining environment and power generation. The high increasing of population in the global, along with economic growth putting pressure on the water resources and hydrological cycle results in the decrease in the per capita water availability (Amin et al. 2018). Apart from the above factor, climate change (CC) on the hydrological system and natural water resources processes, as shown in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2014). Those factors give rise to growing water demand beyond the available water supply because of inadequate water resources management initiatives and insufficient water management structures (Hoekstra et al. 2012).

In the circumstance of rapid human development makes water demand increase and diversify, and its management becomes more complex (Momblanch et al. 2019). Catchment or basin water officers try to integrate the series number of complex and challenging issues to allocate the limited resource equally and used efficiency (Li et al. 2015). The environmentally sustainable use of water is a fundamental requirement for protection of future generations to access the reliable and safe water while striving to achieve goal 6 of the Sustainable Development Goal (SDGs) (UNs 2015). Ensuring that water is spatially and temporally available for competing uses a holistic approach that is accounting both human needs and environmental protection together is required. Many models have been used to support the management of water resources that considers the interlinkages between all sectors in a system (Momblanch et al. 2019). Integrated Water Resources Management (IWRM), a platform that pursues multi-purpose management to optimise the socio-economic welfare by jointly managing the land and water (GWP 2000).

Water resource planning is a complex process because it involves multi-disciplinary stakeholders with different interests. A successful plan requires effective Integrated Water Resources Management (IWRM) models that can set out all multi-disciplinary issues that may arise (Loucks 1995). The IWRM recognises the presence of competing water uses that are highly interrelated and strive to facilitate the sustainable management of water resources by fostering information exchange and helping to match needs with the given resources (Maliehe and Mulungu 2017). IWRM was put forward by the Global Water Partnership purposely to meet present and future generation needs (Zhang et al. 2008). Effective IWRM models must address the two distinct systems that shape the water management landscape, namely biophysical and socio-economic (Yates et al. 2005).

Addressing the different components involved in IWRM requires capable tools that represent the natural and social habitual systems (Karabulut et al. 2016). WEAP has been used to simulate the hydrological system and assess multi-sectorial water demand allocation challenges, including the environment in various applications over the world (Yates et al. 2005). It is an easy to use tool for matching available water resources and competing demands and optimisation options in terms of their resulting water sufficiency or unmet demands. It uses the basic principle of water balance accounting (SEI 2016a); total inflow at the node equals to the total outflows net of any change in storage (Hoff et al. 2007). It allows users to give operation rules by assigning priorities and supply preferences for each node. WEAP then applies the priority-based optimisation algorithm a condition in which the concepts pf equity groups to allocate water in times of scarcity (Hoff et al. 2007).

The objectives of this study are (i) to assess the baseline water supply and demand of the catchment (ii) to assess the future water supply and demand gap under socio-economic and climate change (iii) to apply integrated water resources management approaches for adapting and mitigating the gap. The modelling system approach used to simulate the impacts of future Climate and Socio-economic on the water availability in spatial and temporal. A set of different scenarios are proposed to assess the supply-demand gap and integrated measures to provide the basis for improved decision making. The model employed in a Great Ruaha Catchment, which combines large irrigation farms, hydropower plants, national parks and other economic activities which are very beneficial to the nation at large.

2. Materials and Methods

2.1 Study area

Great Ruaha River Catchment is one among four catchments in Rufiji basin in Tanzania covers an area of 85,554 km^2. The source of the Great Ruaha River is the Poroto Mountains and the Kipengere Range in the southwestern part of Rufiji Basin at 5°35’ and 9°30’ South latitude and between 33°55’ and 38°1’ East longitude. Elevations range from 120 m above sea level (masl) to almost 2,869 masl. The mean annual rainfall ranges from 400 mm to 1,200 mm with only one rainy season from mid-November to May. The population within the catchment estimated to be 2.7 million (NBS 2012). Great Ruaha river is a very important river because it is the most used for agriculture, domestic water use, fishing, and hydropower generation in Rufiji Basin. This river is central to ecology and tourism in the Ruaha National Park. It provides over half the water at Mtera (80MW) and Kidatu (204 MW) hydropower plants which are over 70% of the total hydropower production. Downstream these plants, the Great Ruaha river used for watering large Sugar cane farms, feeding Selous Game Reserve and offers additional hydropower potential after joining the Rufiji River at Stiegler’s Gorge which is under construction (2100 MW).

In the catchment, there is an extensive expansion of agricultural activities both rain-fed and irrigated with low efficiency, mainly local farmers use surface irrigation (flooding), of which their efficiency is 15 to 20 per cent (MoW 2012). In two decades, these have resulted in a shortage of water availability for Ruaha National Park and less inflow for Mtera reservoir. Many rivers upper part of the basin especially Usangu which usually were perennial are no longer flowing throughout the year, now drying up in dry season months of September and January (MoW 2012).

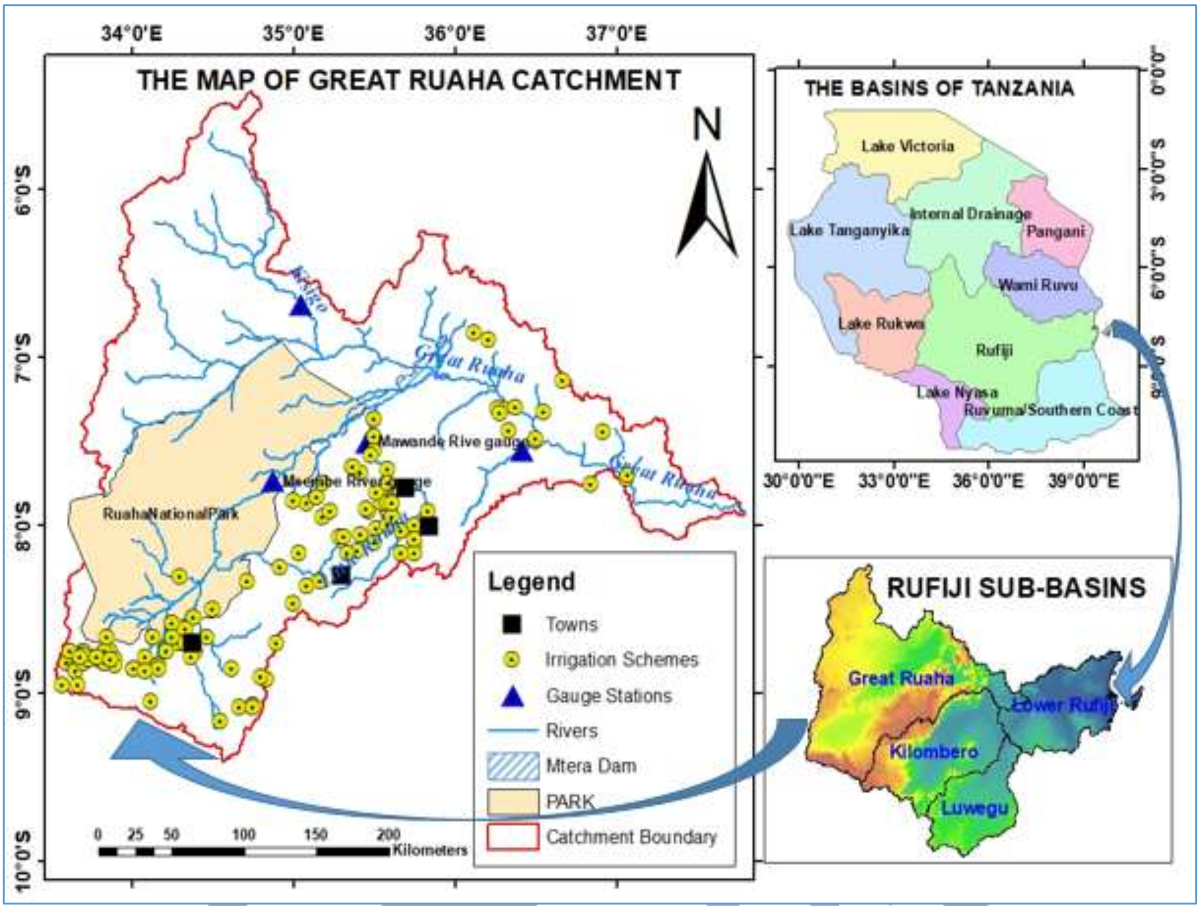

Figure 1: Great Ruaha River Catchment Map

2.2 WEAP model.

Water Evaluation and Planning System (WEAP) is a generalised simulation model for the analysis of water resources systems (Yates et al. 2005); it has two main functions, firstly, simulation of the natural hydrological process such as evapotranspiration, runoff, and infiltration to assess water availability and secondly, simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (SEI 2016b). The tool matches water supply and competing demands and assesses the upstream and downstream links for different management options. WEAP employs a priority and preference-based optimisation algorithm and the concept of equity groups to allocate water in times of shortage. The schematic diagram of the WEAP model established, figure 2 and the time frame was set from 2010 to 2050, whereas, the year 2010 set as current account and model simulation from 2011 to 2050 accounted as business as usual or reference scenario.

Precipitation and temperature data were collected from the Rufiji Basin Water Board (RBWB) and Tanzania metrological Agency (TMA) in Tanzania. Also, historical and projected climate data were collected from the Intergovernmental Panel for Climate Change from 1980 to 2050 with RCP 4.5 and 8.5. The socio-economic data, urban and rural population were obtained from the National Bureau of Statistic (NBS). Water design use rate for Urban and Rural was obtained from Water Supply Design Manual from the Ministry of Water. The data on Livestock population and their use rate derived from the Ministry of Livestock and Fisheries. Data on irrigated area obtained from the Rufiji Basin Water Board (MoW 2012) and Crop water use requirement calculated by using CROPWAT based on the cropping pattern in the study area. And data on Industry were picked from the Ministry of Industry and Investment.

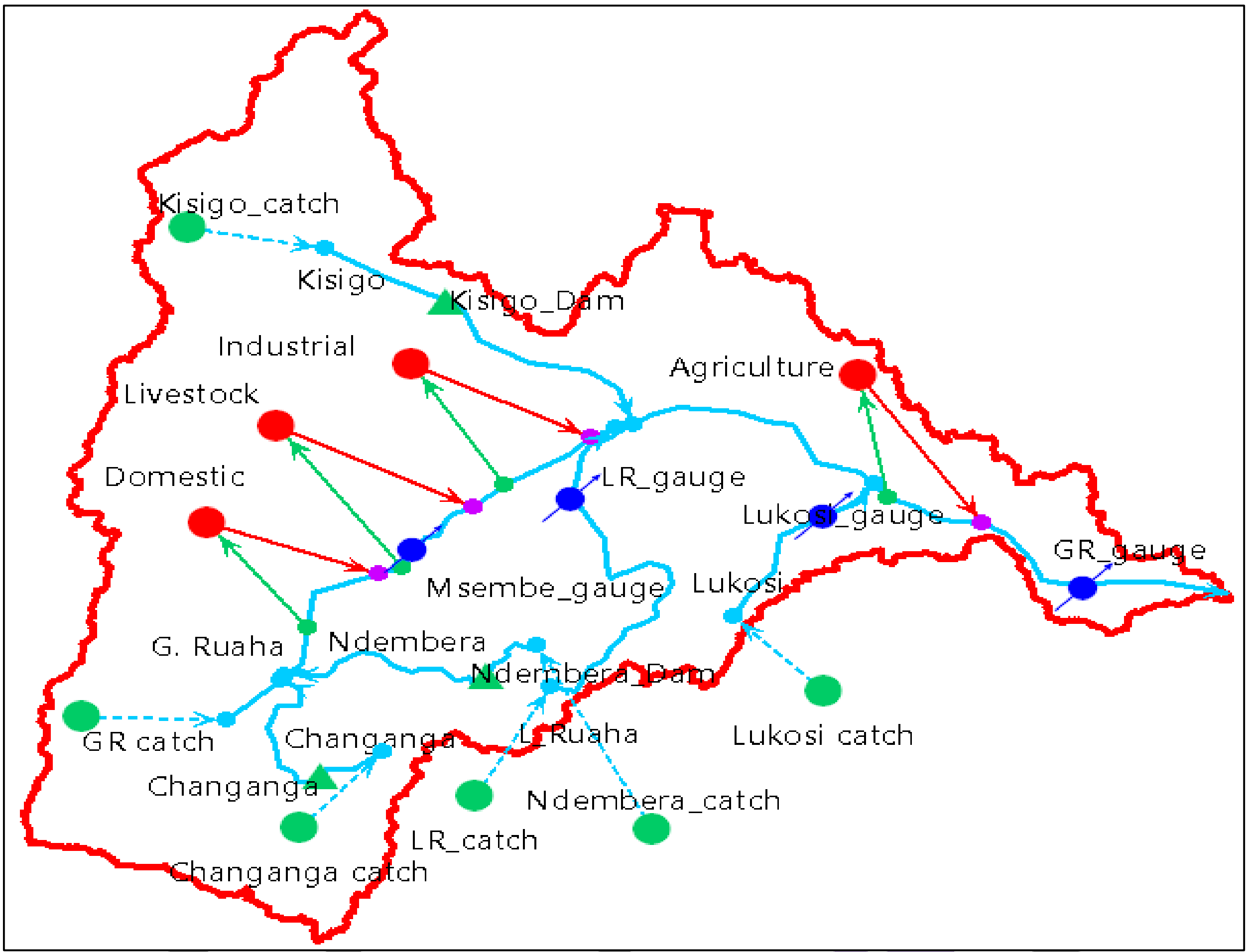

Figure 2: Schematic diagram of the WEAP model for the Great Ruaha River Catchment

The model was calibrated and validated against observed streamflow data from river gauge station, calibration from 2006 to 2011 and validation from 2012 to 2016. The calibration done manually by adjusting different parameters such as soil water capacity (SWC), deep water capacity (DWC), root zone conductivity (RZC), runoff resistance factor (RRF), Preferred flow direction (PFD), Crop Coefficient (kc), initial topsoil storage layer (Z1) and initial bottom soil storage layer (Z2). Model simulations are most sensitive to SWC, RZC, RRF, and PFD (Worldbank 2017). The quality of the model evaluated based on the study carried by Moriasi et al. (Moriasi et al. 2007). The quantitative approaches used are: Nash-Sutcliffe efficiency (NSE), the root mean square error (RMSE)-observations standard deviation ratio (RSR) and the coefficient of determination (R^2).

2.3 Climate change Scenarios

The climate change assessments for the catchments are based on the most recent Intergovernmental Panel for Climate Change (IPCC) emission scenarios and climate projections. Specifically, the scenarios and climate projections used are part of the World Climate Research Program (WCRP) Coupled Model Intercomparison Project Phase Five (CMIP5). Climate projections are generated from circulation models (GCMs) that are driven by greenhouse gas (GHG) concentrations scenarios. GCM sequences thus processed through downscaling procedures to become relevant for application at finer spatial scales based on the Bias Corrected Spatial Downscaling (BCSD) statistical downscaling approach (WREM 2015). Precipitation and temperature (1x1 degree) spatial resolutions are obtained and then bias corrected and downscaled to a finer resolution (0.5x0.5 degrees). Finally, mean aerial averages of the bias corrected and downscaled variables are computed over the catchment of interest (WREM, 2015). The RCP4.5 and RCP8.5 greenhouse gas concentration scenarios used in this study.

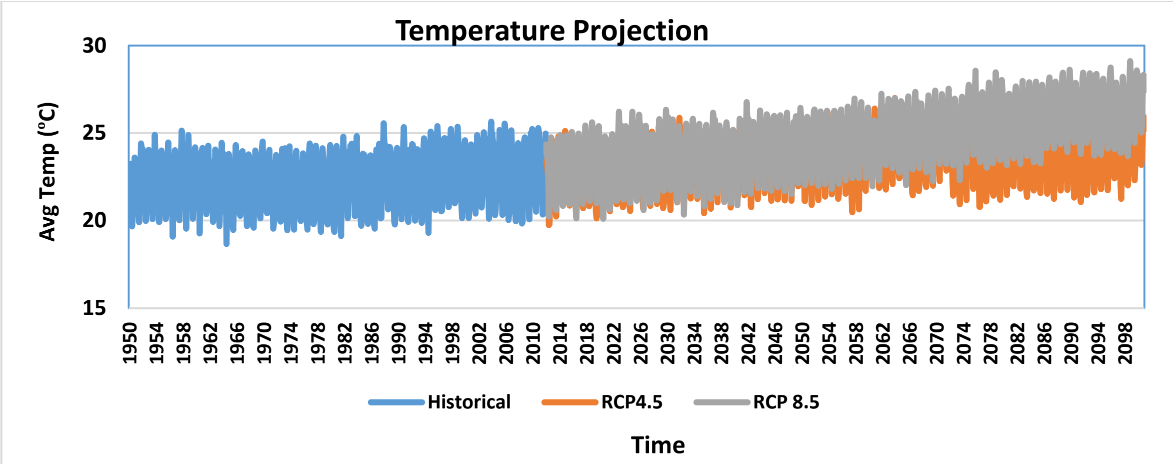

Figure 3: Mean Temperature (of the Great Ruaha Catchment): RCP4.5 and RCP8.5 GHG Concentration Scenario.

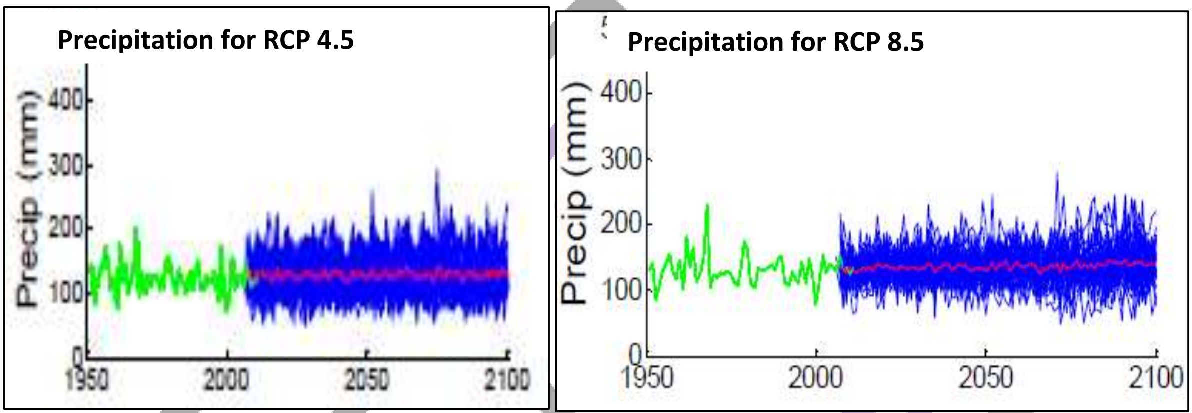

Figure 4: Precipitation (of the Great Ruaha Catchment) RCP4.5 and RCP8.5 GHG Concentration Scenario

2.4 Water use.

Water uses in this study, considered four main components, domestic, agricultural, industrial, and Livestock use. The data on population and water use rate were derived from the Ministry of water, Rufiji Basin Water Board (RBWB), Ministry of Agriculture, National Bureau of Statistics (NBS), and Ministry of Livestock and Fisheries.

2.4.1 Domestic.

The population that falls within the catchment estimated to be 2,031,889 for Rural settlements and 523,741 for Urban settlements (NBS 2012). The rural water use rate is 70 l/ca/day, and Urban is 100 l/ca/day (MoW 2012). The current account annual growth rate was 2.7% and in this study will be assumed to remain the same.

2.4.2 Livestock

The Livestock population in 2010 estimated be 1,545,857, including indigenous, dairy and beef cattle, goats, sheep and donkeys (MoW 2012). The average water use rate for Livestock estimated to be 20 l/ind/day. The annual growth rate in the current account was 9.2% and assumed to remain the same in the projection horizon (MoW 2012).

2.4.3 Industrial

The quantity of water demand for industrial purpose is around 20% to 25% of the total demand of the city, that gives 2500 L/day per industry. The total of 14 manufacturing industries was collected from Rufiji Basin Water Board (MoW 2012), falling within Great Ruaha catchment, with the annual growth rate of 10%.

2.4.4 Irrigation

The irrigated land is estimated to be 97000 ha in the study area. The CROPWAT found that paddy rice requires 1300 mm, equivalent to 13,000 m^3/ha, while other crops, including maize, potatoes, beans crops, require 400 mm, equivalent to 4000 m^3/ha for total gross water supply. The irrigated area annual growth rate was 3.1% in the current account and assumed to remain the same in the projection horizon. Then, these irrigated land, water-use rates, and growth rate used to determine the agriculture water demand in the WEAP model.

3. RESULTS AND DISCUSSIONS

3.1 Model calibration and validation

The calibrated and validated model presented the simulated streamflow from the Little Ruaha River and Great Ruaha River with observation flow data from Mawande gauge station 1KA31, figure 5. The five years of historical discharge data from 2006 to 2010 and from 2011 to 2015 were used for calibration and validation, respectively. The results both rivers match well in almost years as good ability of the model to simulate river flows as recommended (Moriasi et al. 2007).

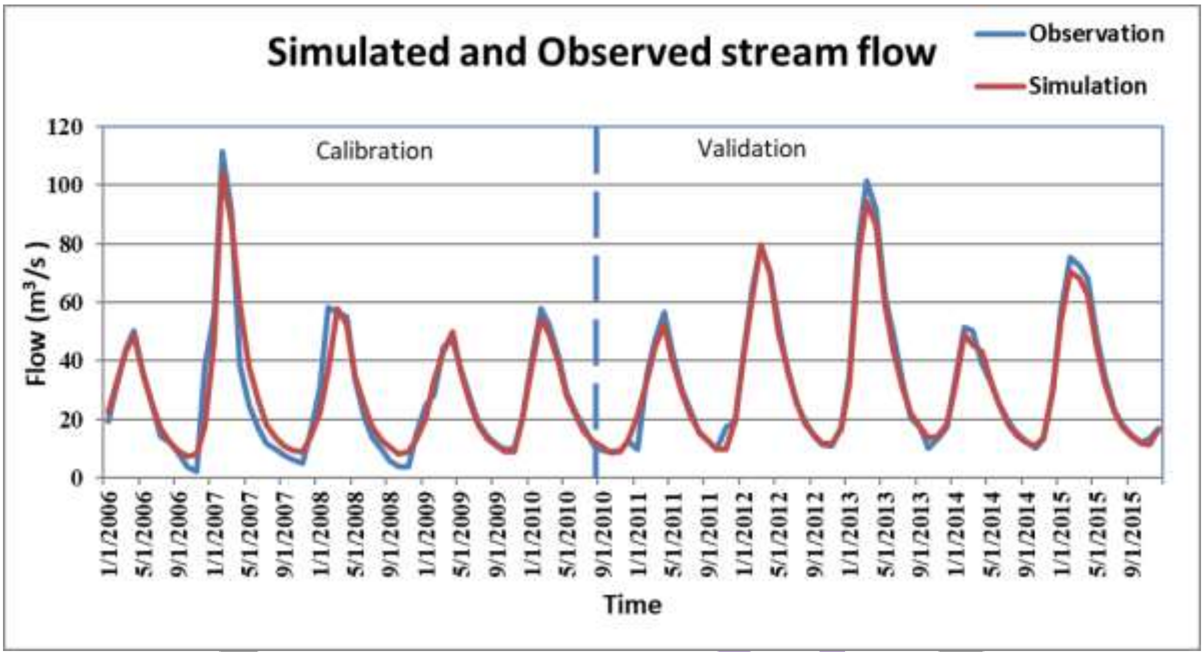

Figure 5: Observed and simulated flow at Little Ruaha river (Mawande gauge station 1KA31).

3.2 Comparison of Scenarios.

The main objective of modelling is to compare scenarios (Hoff et al. 2007). In “Reference scenario” the climate variables used to simulate rivers flow and water demand. The analysis of water availability in this study considered only surface water due to the limitation of groundwater data availability. The annual average discharge of the entire Great Ruaha catchment is 109.88 m^3/s, with a minimum and maximum of 37.77 m^3/s and 262.93 m^3/s, respectively. The high flows observed in the rainy season (Dec-may) than a dry season (June-Nov) because of high contribution from rainfall. The basin water demand in 2010, estimated to be 980.52 MCM from four components considered in this study (agriculture, domestic, Livestock and Industrial). In 2019, the demand was estimated to rise to 1,311 MCM, which is an increment of 330.48 MCM. The agriculture found to be a leading sector in water use over 90% of the total water supply, then followed by the domestic sector (6%). The demand said to be satisfied in the first five years, and after that, it shows the shortage starts to occur, figure 8. In 2030, 2040 and 2050 unmet demand estimated to be 168.14, 381.45, and 844.26 Mm^3, respectively.However, “Socio-economic issues” in which different changes posed (annual population and irrigated area growth rate) imbedded in reference scenario, causing the rise of water demand for the projection period (2011-2050). The result shows that the demand will rise from 980.52 Mm^3 in 2010 to 1,842.81 Mm^3 in 2030, 2,565.06 Mm^3 in 2040 and 3,641.43 Mm^3 in 2050, figure7. In this scenario, none satisfied demand estimated to rise to 218.16, 570.73 and 1916.55 Mm^3 in 2030, 2040 and 2050 years, respectively, figure 8. The supply coverage shows to depend on the availability of water in a particular year (very wet, wet, normal, dry or very dry). The domestic and Livestock are said to be covered almost 100% because of its given highest priority supply to them for projection horizon except for few months in very drought years 2043 and 2044, figure 9. The Industrial was given second priority, and the mean coverage is 99%, figure 10, whereas agriculture which given third priority said to be covered by 81% on average, figure 11.

3.3 Water Management measures.

To solve unmet demand an integrated approach in water resources management employed by adding two scenarios. The first one was “water demand management scenario” that involved recycling water or reuse of the total supplied water for 40% by the end of 2050. But also demand-side management (DSM) by the end of 2050, 50% of all water users should adopt modern technology with high efficiency. Over 83% of unmet demand found in socio-economic change scenario would be covered, figure 12. The second one was the storage reservoirs scenario assesses three reservoirs Ndembera, Chang’anga, and Kisigo with storage capacity 500, 550, and 400 Mm^3, respectively. The daily reservoirs release estimated to range between 154,396 to 1,680201 m^3/d depending on the type of the year. This amount will cover the remaining 17% of unmet demand in water demand management scenario, figure 13.

4. Conclusion

Water is a crucial resource for all living beings, including humans who use water for domestic and development activities. Socio-economic factor has always been a cause of the increase in water demand. In dissimilarity, water availability trends decrease in the system because of climate change and anthropogenic activities. However, human development activities, in conjunction with climate change, trigger more severe either frequent floods or drought, which lead to degradation of water quantitatively and qualitatively.

A study carried out to assess existing water availability and demand using the WEAP tool. Apart from that, also simulated the future water demand concerning population growth, Livestock growth, industrial development, and agricultural expansion, and future water availability based on climate change conditions projection. The average mean temperature anticipated to increase by 2.19 ºC (2050) more than the present average temperature. The owing rising temperature in the catchment, more water will be evaporated, which would eventually affect the water availability. Likewise, the projected precipitation trend showing that there will be a variation of rainfall, which, therefore, will highly reduce the amount of runoff in the river system in some years. Hence, under anticipated climate change scenarios, future water availability in the catchment said to be variable.

The leading sector for high water demand is agriculture over 90% of the total demand and will be more affected because of less priority given in the allocation. Results show that the domestic and Livestock sectors, even though they are given high priority, still, in some months in 2043,2044, and 2050 years, the supply will not be fully covered because of severe drought that will affect the water availability.

Thus, water demand management and water infrastructure measures are strongly recommended to be implemented to ensure water is available, efficiently utilised and distributed equally for the benefit of all competing uses. Study found that if users will recycle water to reach to 40% and irrigation sector by 2050 adopt modern technology just 50% of users, then 83% of unmet demand will be covered. Besides, the remaining 17% found to be covered by establishing storage reservoirs. Therefore, as the water demand keeps increasing, there is needs to focus on more effective water management and water allocation planning (IWRM), to protect the sustainability of water resources over the long-term and allocate water equitably for all users, which will ensure availability and sustainability of water and sanitation for all in the present generation and future.

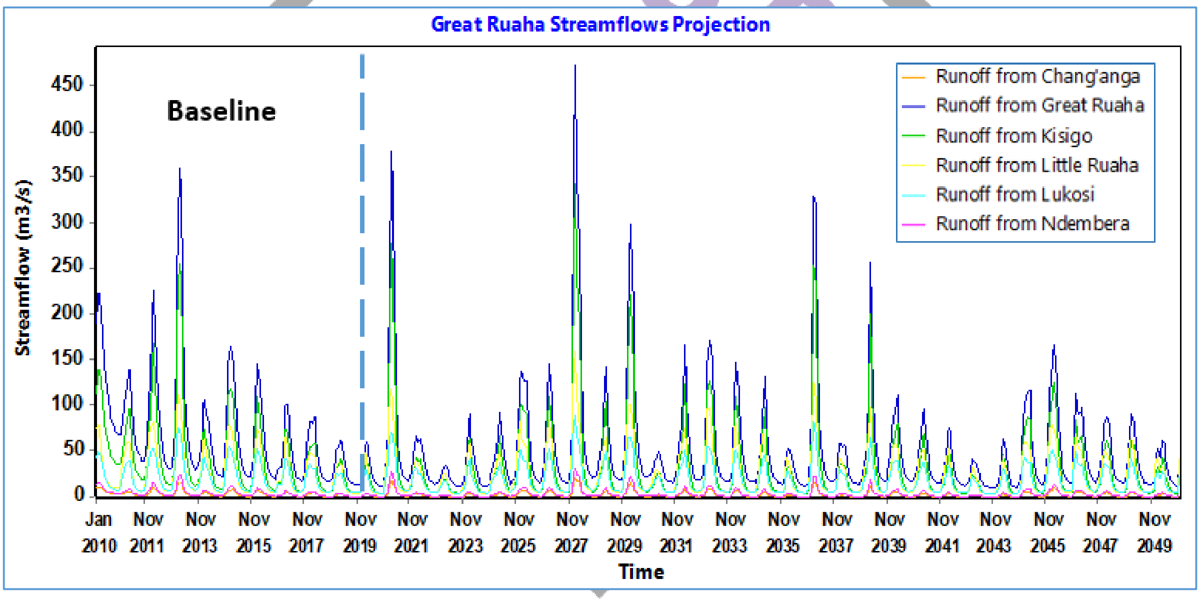

Figure 6: Great Ruaha river flows projection

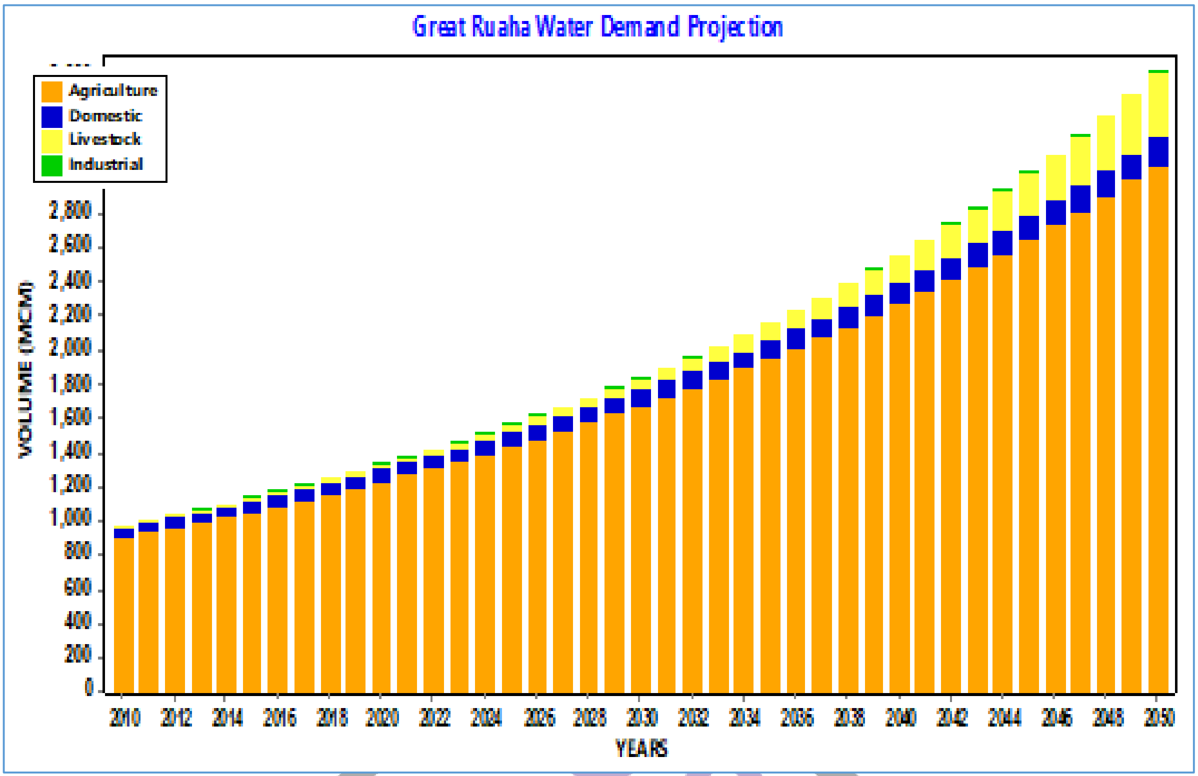

Figure 7: Future water demand projection.

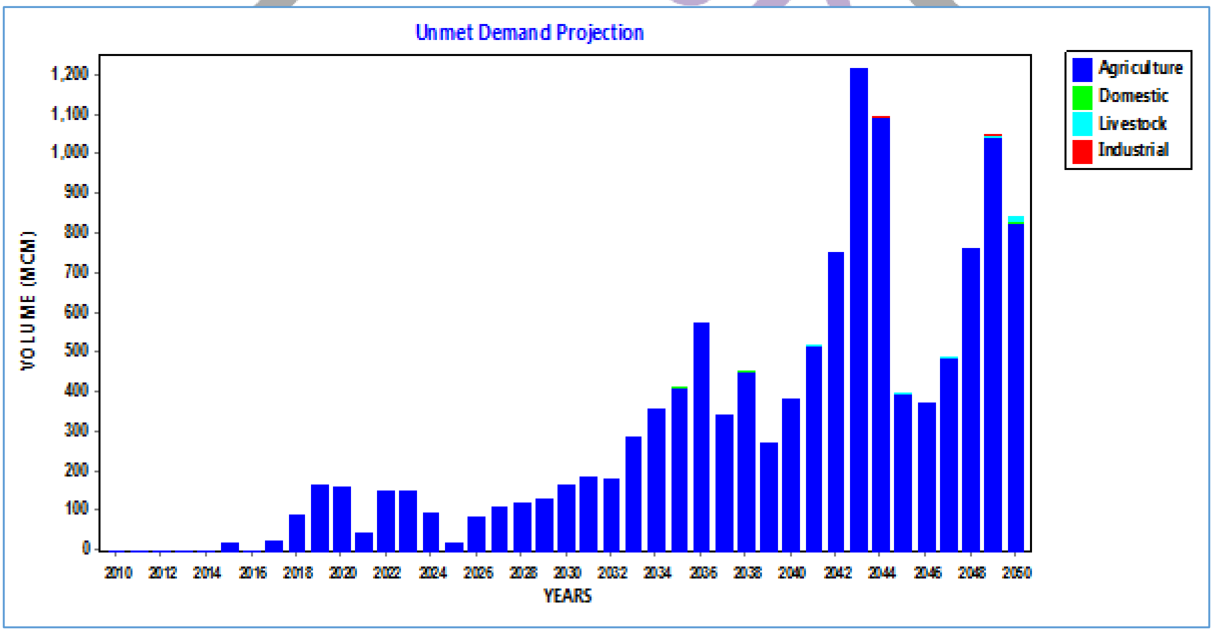

Figure 8: Future unmet demand projection

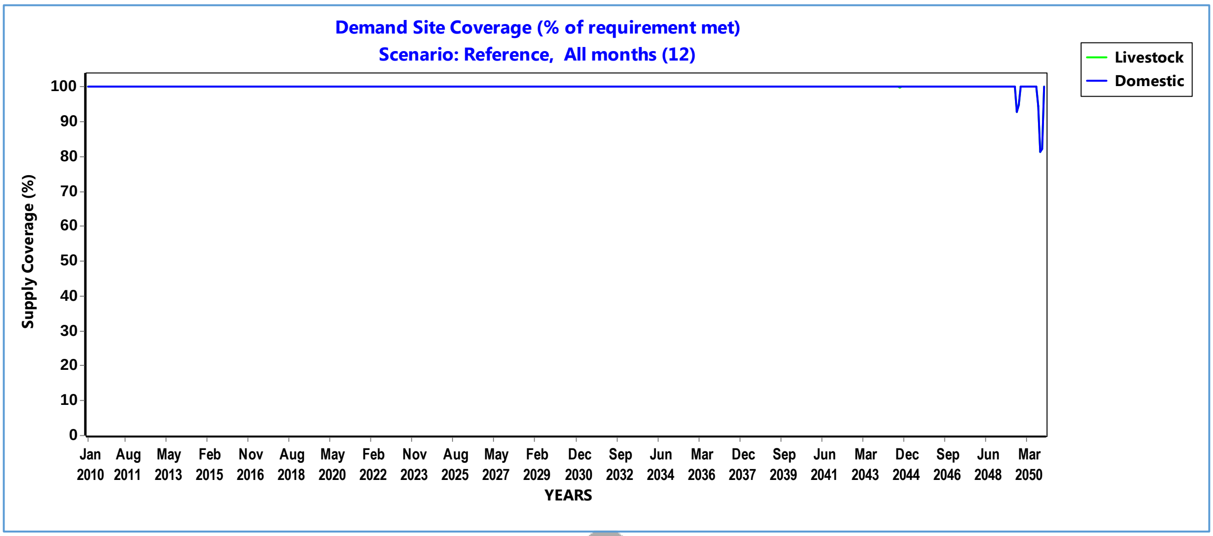

Figure 9: Supply coverage for Domestic and Livestock.

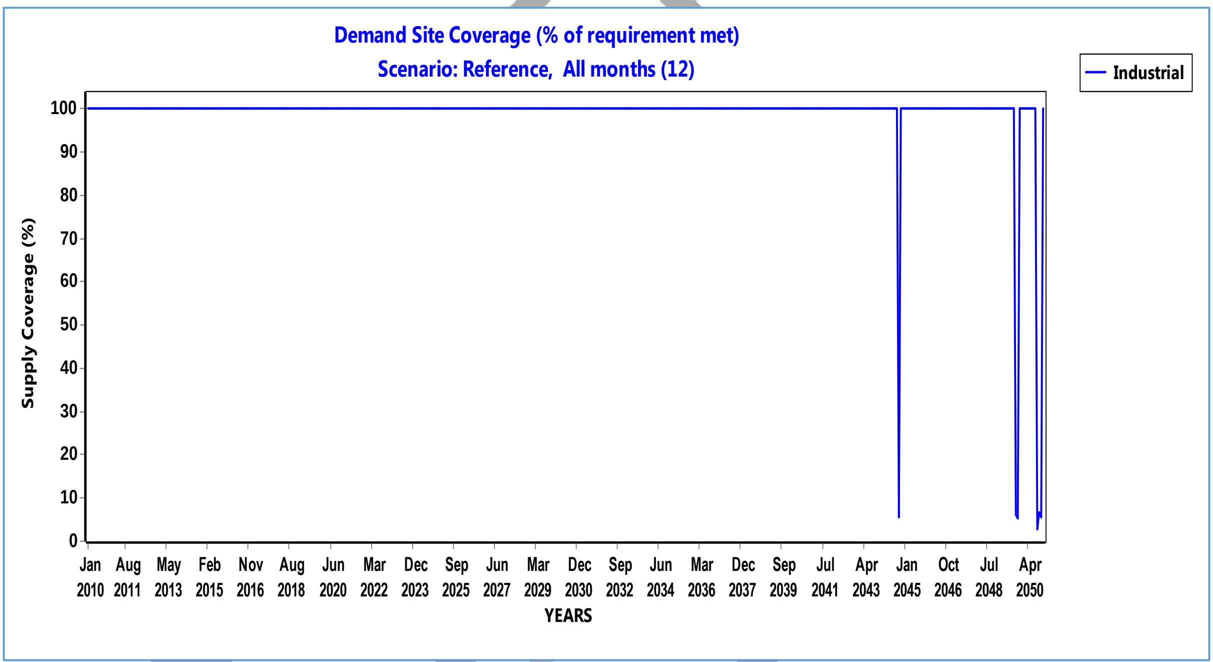

Figure 10: Supply Coverage for Industrial.

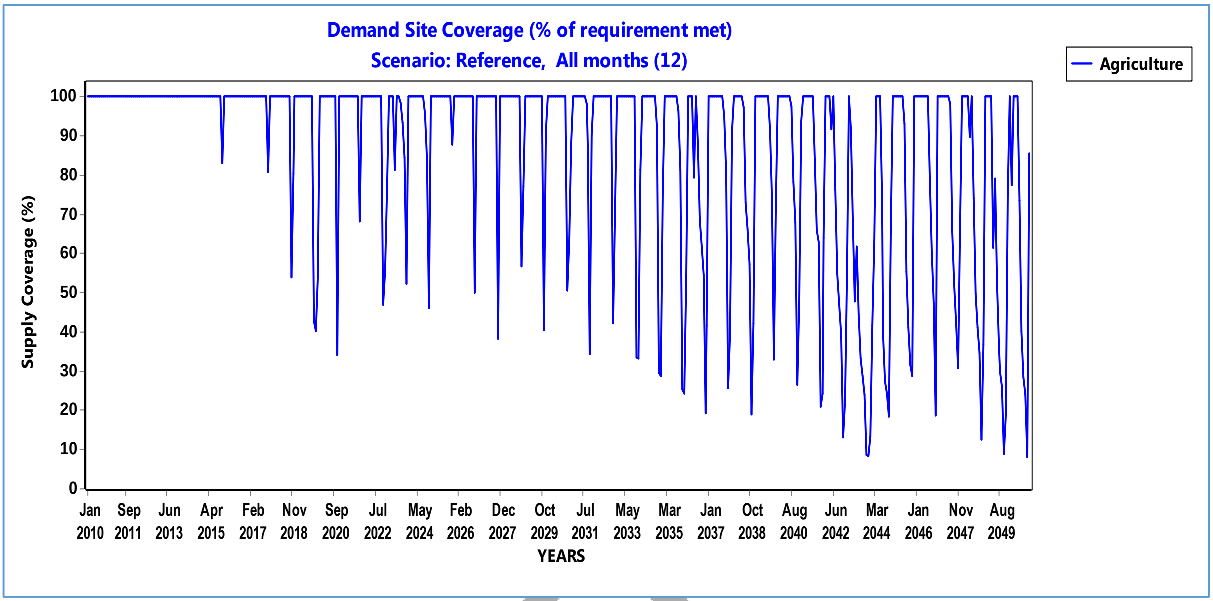

Figure11: Supply coverage for Agriculture.

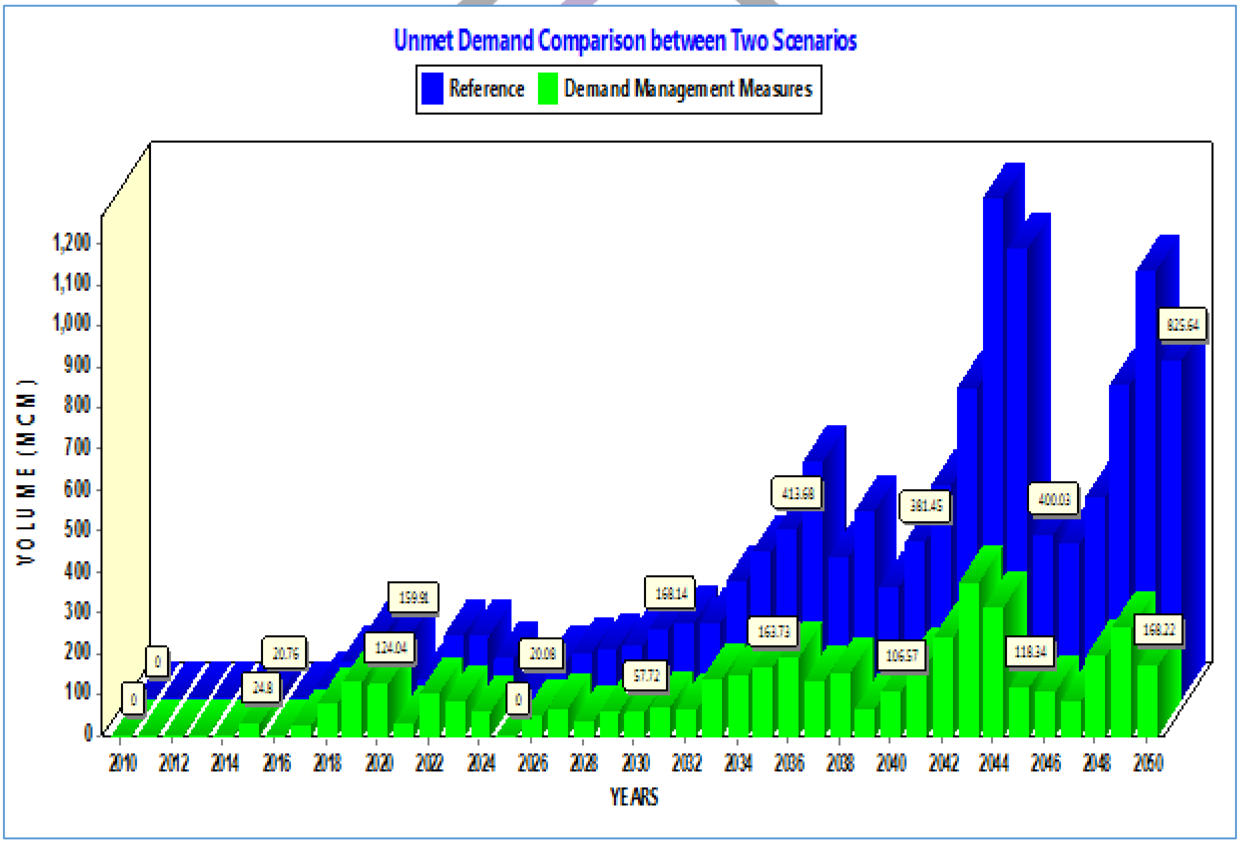

Figure 12: Comparison between Reference and demand management measures scenarios.

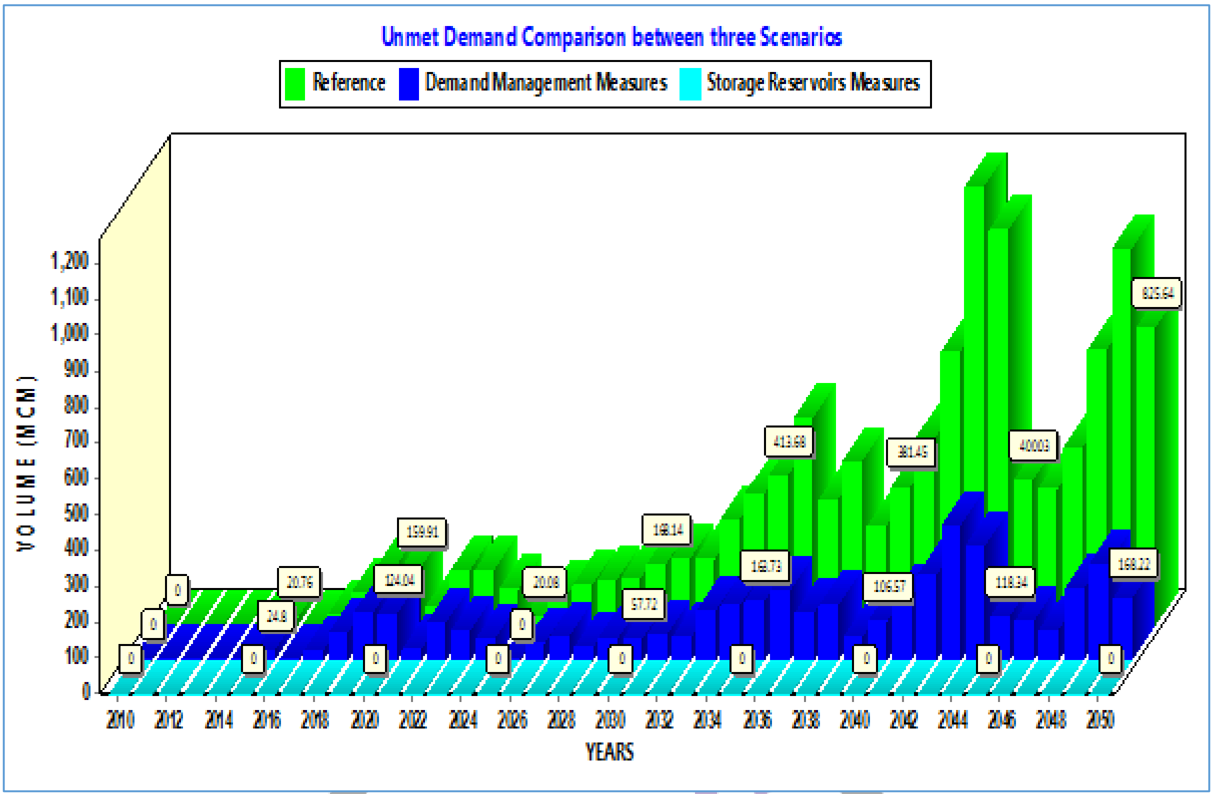

Figure 13: Comparison between Reference, demand management measures and storage reservoirs scenarios.

References

Amin, A., Iqbal, J., Asghar, A., and Ribbe, L. (2018). "Analysis of current and future water demands in the Upper Indus Basin under IPCC climate and socio-economic scenarios using a hydro-economic WEAP Model." *Water (Switzerland)*, 10(5).

GWP. (2000). *Integrated Water Resources Management*. Global Water Partnership, Stockholm, Sweden.

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., and Richter, B. D. (2012). "Global monthly water scarcity: Blue water footprints versus blue water availability." *PLoS ONE*, 7(2).

Hoff, H., Noel, S., and Droogers, P. (2007). "Water use and demand in the Tana Basin: analysis using the Water Evaluation and Planning tool (WEAP)." *Green Water Credits Report*, 4.

IPCC. (2014). *Climate Change 2014 Impacts, Adaptation, and VulnerabilityPart A: Global and Sectoral Aspects*. *Cambridge*, (C. B. Field and V. R. Barros, eds.), Cambridge University Press, New York.

Karabulut, A., Egoh, B. N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Maes, J., Vandecasteele, I., and Mubareka, S. (2016). "Mapping water provisioning services to support the ecosystem-water-food-energy nexus in the Danube river basin." *Ecosystem Services*, 17(2016), 278–292.

Li, X., Zhao, Y., Shi, C., Sha, J., Wang, Z. L., and Wang, Y. (2015). "Application of Water Evaluation and Planning (WEAP) model for water resources management strategy estimation in coastal Binhai New Area, China." *Ocean and Coastal Management*, Elsevier Ltd, 106, 97–109.

Loucks, D. P. (1995). "Developing and Implementing Decision Support Systems: A Critique and a Challenge." 31(4), 571–582.

Maliehe, M., and Mulungu, D. M. M. (2017). "Assessment of water availability for competing uses using SWAT and WEAP in South Phuthiatsana catchment, Lesotho." *Physics and Chemistry of the Earth*, Elsevier Ltd, 100(May 2012), 305–316.

Momblanch, A., Papadimitriou, L., Jain, S. K., Kulkarni, A., Ojha, C. S. P., Adeloye, A. J., and Holman, I. P. (2019). "Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system." *Science of the Total Environment*, Elsevier, 655, 35–47.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., D., H. R., and Veith, T. L. (2007). "Model evaluation guidelines for Syatematic Quantification of Accuracy in Water Simulations." *American Society of Agricultural and Biological Engineers*, Soil & Water Division of ASABE, 50(3), 885–900.

MoW. (2012). "Rufiji IWRMD Plan : Interim Report Volume III, Current Water Use and Infrastructure Assessment." *WREM International Inc*, 3, 227.

NBS. (2012). “Census-Tanzania Country Profile.” *NBS website*, 1–2.

SEI. (2016a). “Water Evaluation And Planning System Tutorial.” *SEI website*, (August).

SEI. (2016b). “Water Evaluation And Planning System.” *Weap*, (August), 1–202.

UNESCO. (2020). *United Nations World Water Development Report 2020: Water and Climate Change*. United Nations Educational, Scientific and Cultural Organization, Paris.

UNs. (2015). “Sustainable development goals.” *UNDP website*, 24.

Worldbank. (2017). “Lesotho WEAP Manual.” *Lesotho WEAP Manual*, Volume 1, 23.

WREM. (2015). “Rufiji IWRMD Plan Interim Report II, Volume I: Climate and Hydrologic Modeling and Assessments. Technical Report prepared for the United Republic of Tanzania, Ministry of Water, by WREM International Inc.” *WREM International*, 1.

Yates, D., Sieber, J., Purkey, D., and Huber-Lee, A. (2005). “WEAP21 – A Demand- , Priority- , and Preference-Driven Water Planning Model Part 1 : Model Characteristics.” *Water International*, 30(4), 487–500.