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Modeling Surface Water Availability for Irrigation Development in Mbarali River Sub-Catchment Mbeya, Tanzania

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Abstract

Although Tanzania has a large land suitable for irrigation development, only 4.2% of the arable land which is potential for irrigation has been developed. Mbarali District is characterized by commercial and small-scale irrigation activities for paddy production. Currently, surface water availability for irrigation in Mbarali District is dwindling due to high water demands. Inadequate studies that estimate water availability for irrigation is one of the underlying factors to the lack of irrigation development in many parts of Tanzania including in Mbarali District. This study, therefore, aimed to model surface water availability for irrigation development in Mbarali River sub-catchment Mbeya, Tanzania. The Soil and Water Analysis Tool (SWAT) model and field observations were used to accomplish the study. The model estimates that Mbarali River sub-catchment receives about 631 mm of total mean precipitation annually. About 53% of received precipitation is lost through evapotranspiration, 12% recharged to deep aquifer and the remaining 35% discharged to the stream flow through surface runoff, lateral flow and return flow from unconfined aquifer. Discharge to the steam flow contributes to the total annual means of river discharge ranging from 0 - 10 cubic meters per second at upper catchment to 120 - 140 cubic meters per second at lower catchment. The study recommends that the lower reach of the Mbarali River sub-catchment is potential for irrigation than the upper reach as it has potential river flow that can support irrigation activities. The study also notes the urgent need for water reallocation plan to meet competing water needs in the lower reach of Mbarali River sub-catchment. Moreover, the study addresses the potentiality of irrigation in upper catchment under sustainable water management practices including excavation of small ponds to capture and store surface runoff for dry season use or to supplement irrigation as the rainfall declines.

Keywords

Irrigation, Mbarali River Sub-Catchment, Surface Water Availability, SWAT

1. Introduction

Surface water is an essential natural resource that plays a vital role in human life and has an important role in irrigation, drinking and economic development. According to FAO statistics, 20% of the land is irrigated but produces 40% of the global food production (Tiri et al., 2018). Irrigation is an effective way to improve productivity significantly. However, there are environmental risks associated with irrigation, especially water stagnation and increased salinity (Tiri et al., 2018). Consequently, many countries in sub-Saharan Africa are planning to increase irrigated agriculture as a contribution to attaining the Millennium Development Goals (McCartney et al., 2007). In Sub-Saharan Africa (SSA), by contrast, only 4% of agricultural land is irrigated. Although an estimated 40 million ha are suitable for irrigation, only 7.3 million ha are actually irrigated (FAO, 2012).

Tanzania has a territorial area of 948,000 km^2, of which on average about 80 percent receives less than 1000 mm of seasonal rainfall which sometimes is unreliable. According to the (URT, 2005), out of the territorial area, about 2.1 million hectares have high potential, 4.8 million hectares have medium potential, and 22.3 million hectares are of low potential for irrigation development. Currently cultivated area is estimated to be 10 million hectares, of which only about 292,895 ha are currently under irrigation which is only 3 percent of the current cultivated area. This shows that land and water resources are not effectively utilized (URT, 2005). Agricultural production in Tanzania is dominated by smallholder farms (peasants), cultivating on average farm sizes of between 0.9 hectares and 3.0 hectares. About 70% of Tanzania's crop area is cultivated by hand, 20% by ox plough, and 10% by tractor. It is mainly rain-fed agriculture. Food crop production dominates the agriculture economy, where 5.1 million ha is cultivated annually, of which 85% is under food crops (NBI, 2011).

Mbarali River sub-catchment is among of potential areas for paddy production in the Southern Highland of Tanzania which counts for about 70% of the average annual paddy production for Mbeya region (Ngailo, 2016). As a strategy to cope with the uncertainty and poor distribution of rainfall during the crop growing season, the local farming systems in the Mbarali River sub-catchment have constructed diversions to abstract water from Mbarali river for supplementary irrigation in order to minimize the risks of crop failure (Lankford et al., 2009). Many studies revealed the decrease in river flow in the Mbarali River sub-catchment due to several factors including climate and land-use change, water abstraction for irrigation and other overlapping uses (Mutayoba et al., 2018). Nevertheless, there is a limited understanding of the current quantity of water available to meet these competing demands. Therefore, this study was conducted to assess the surface water availability for irrigation development in Mbarali River sub-catchment.

2. Materials and Method

2.1. Description of Study Area

The Mbarali River sub-catchment (**Figure 1**) is located between latitude 7˚S and 9˚S and between longitude 33.8˚E and 35˚E in the upper Great Ruaha sub-basin of the Rufiji basin in the southern highlands of Tanzania. The population of Mbarali depends mainly on subsistence agriculture and livestock keeping for livelihood. The river catchment has a total area of 1530 km^2, of which 321,500 ha are arable land that has potential for agriculture production and currently 187,600 ha have been developed (TNBS, 2012). Paddy production becomes the main food/cash crop which makes Mbarali become one of the main paddy producers and exporters in Tanzania and neighboring countries. Other crops which are also grown include maize, sweet potatoes, sorghum, sunflower, onions, cassava,

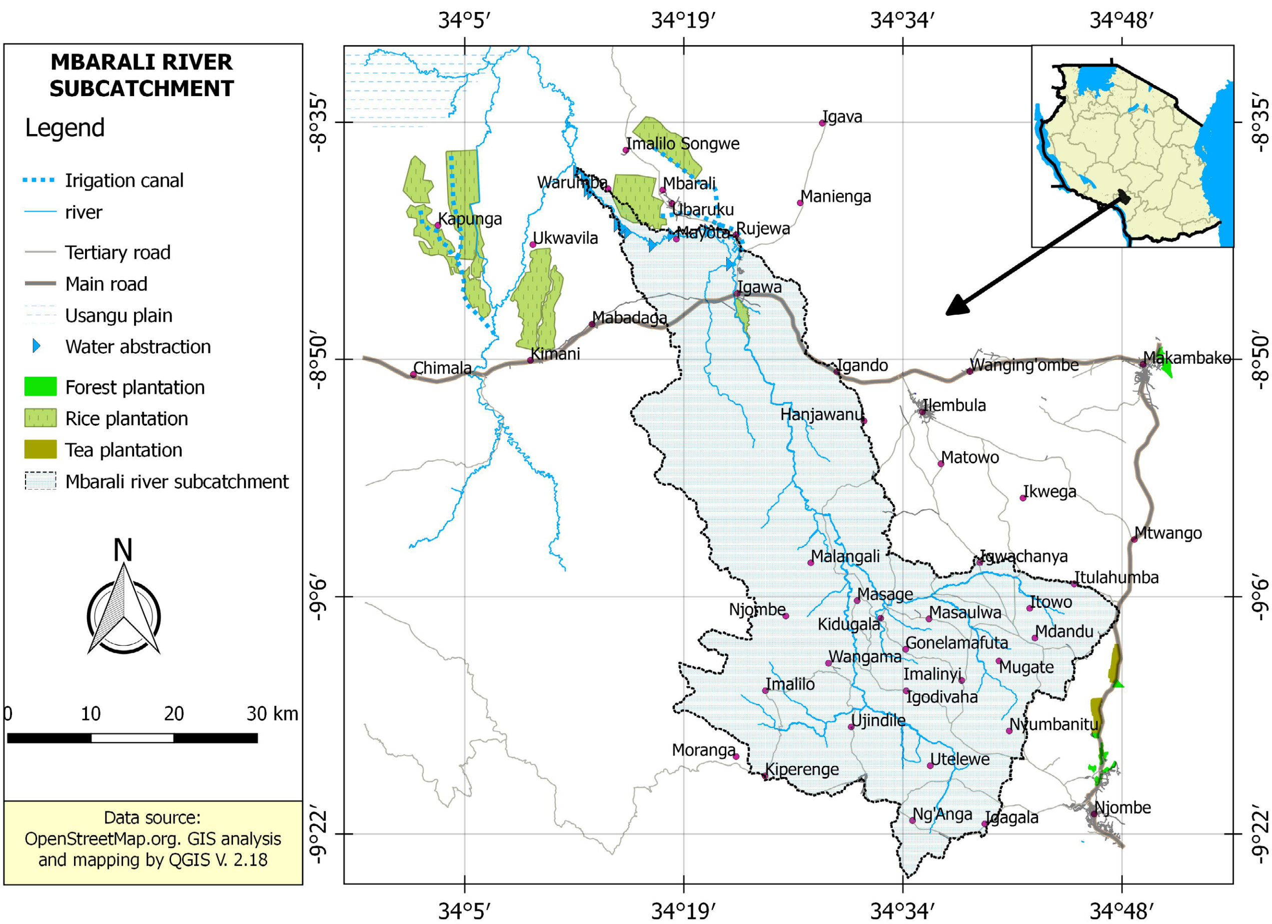

Figure 1. Map of study area.

beans, groundnuts and vegetables (Mutayoba et al., 2018). Apart from rain-fed agriculture the river catchment also undertakes agriculture irrigation farming and paddy is the main crop cultivated at large scale under irrigation. The district has a total of 44,000 (Ha) cultivated under irrigation which is equivalent to 13.7% of the total arable land potential for agriculture. The sub-catchment is at an altitude ranging from 1000 to 1800 meters above sea level, and its average temperature ranges between 25˚C and 30˚C, while its mean annual rainfall is about 450 to 650 mm that starts from October through to April or May (Mutayoba et al., 2018).

2.2. Model Selection and Setup

2.2.1. Model Selection

The study employed Soil and Water Analysis Tool (SWAT). The model is capable of integrating different remote sensed spatial data and ground observation data sets (soil, land cover, weather data) describing the land surface to calculate the basin hydrologic water cycle (Arnold et al., 2012) thus making it versatile in the area of watershed management and water resource planning (Gyamfi et al., 2016). SWAT model used in this study was built on QGIS 2.6.1 interface. The inputs data collected to develop the model were included spatial data, hydrological data and meteorological data. Spatial data includes satellite images and 30 m resolution digital elevation model (**Figure 2**) downloaded from USGS-GLOVIS and NASA reverb respectively.

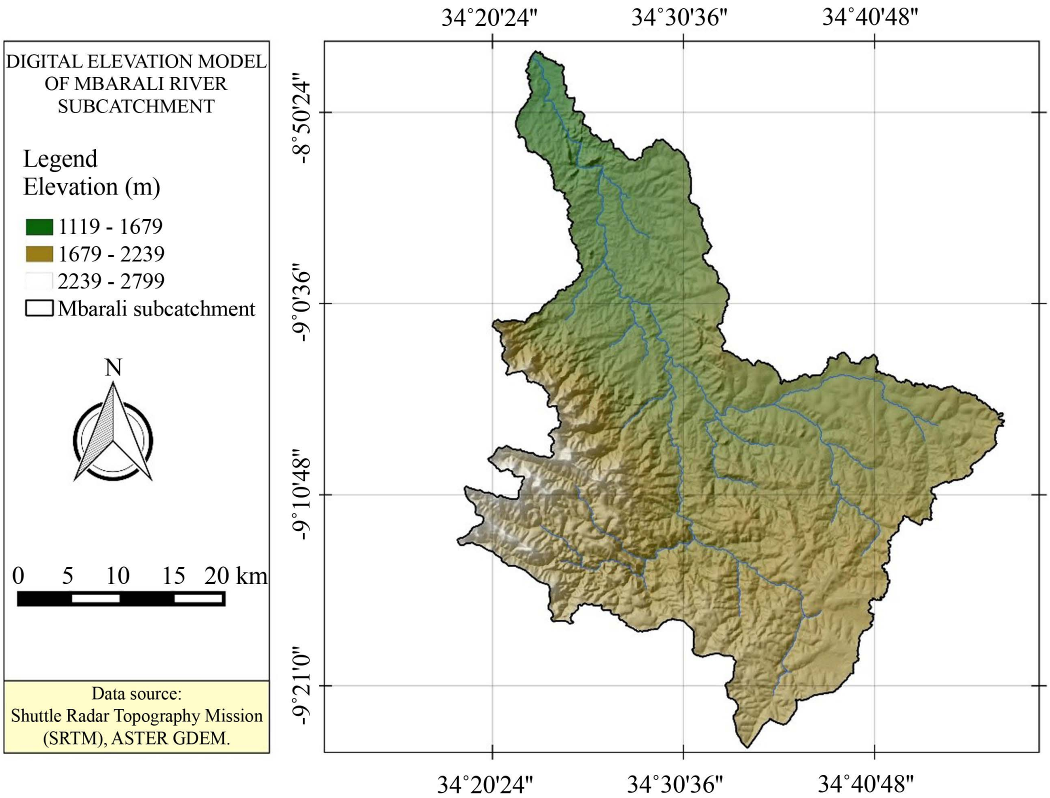

Figure 2. Digital elevation model of Mbarali River sub-catchment.

Soil data (**Figure 3**) and information on related soil properties were obtained from the Food and Agriculture Organization (FAO) soil map (FAO, 2005) and Land use data (**Figure 4**) developed by digital image classification of Landsat 8 imagery of 2020. Land use coverage in the Mbarali River sub-catchment is represented in **Table 1**.

Meteorological data comprised rainfall, relative humidity, solar radiation, wind speed and minimum and maximum temperature data, which were obtained from Tanzania Meteorological Agency and SWAT Global Weather Data. Hydrological data included water discharge, recorded from Mbarali Maji Gauge Station (IKA11A). Location of metrological and hydrological stations is represented in **Figure 5** below.

Model development involved two major steps which are Model setup, Model run, Model Calibration and Validation.

2.2.2. Model Set up and Run

The first step was watershed delineation which split the catchment into sub-basins according to the terrain model and river channels. The DEM was used to delineate the topographic characterisation of the watershed and to determine the hydrological parameters of the watershed. Hydrological Response Units (HRUs) were then generated based on user-defined threshold percentages (Arnold et al., 1998). Before defining the HRUs, the Land use data were reclassified to match the SWAT land use classification and inserted into the model together with Soil data. Climatic data which includes precipitation (pcp), temperature (tmp), relative humidity (rh), solar radiation and wind speed were loaded in the model and written under the Write SWAT Input Tables interface of the SWAT Model. Tables for observed weather data were created and after completing creating table, the model parameters were updated and the SWAT model was run.

Model Calibration and Validation

Model Calibration is to adjust a set of parameters so that the model agreement is maximized with respect to a set of experimental data. It is the process of turning

Table 1. Land use/cover coverage in Mbarali River sub-catchment.

Land use/cover	Area [Ha]	Percentage [%]
Forest	14,656	9.76
Woodland	42,600	28.36
Bushland	64,200	42.73
Grassland	10,560	7.03
Water	122	0.08
Wetland	379	0.25
Agriculture	17,628	11.73
Settlement	92	0.06
TOTAL	150,236	100

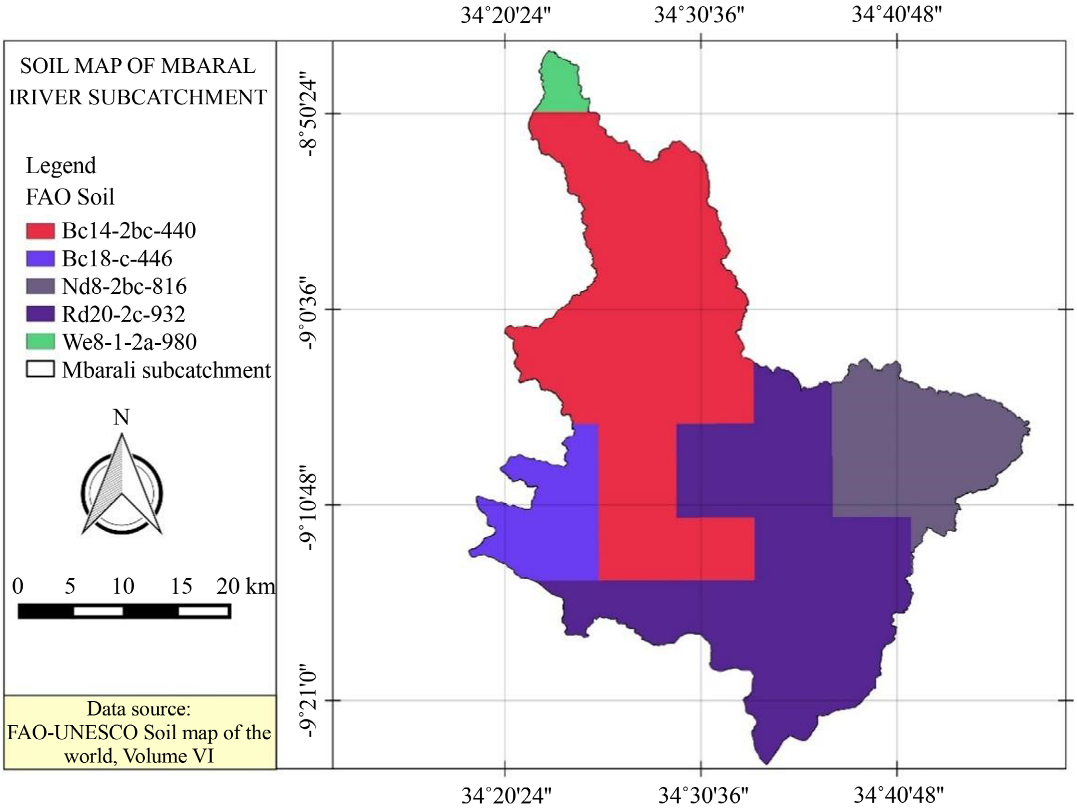

Figure 3. Soil map of Mbarali River sub-catchment.

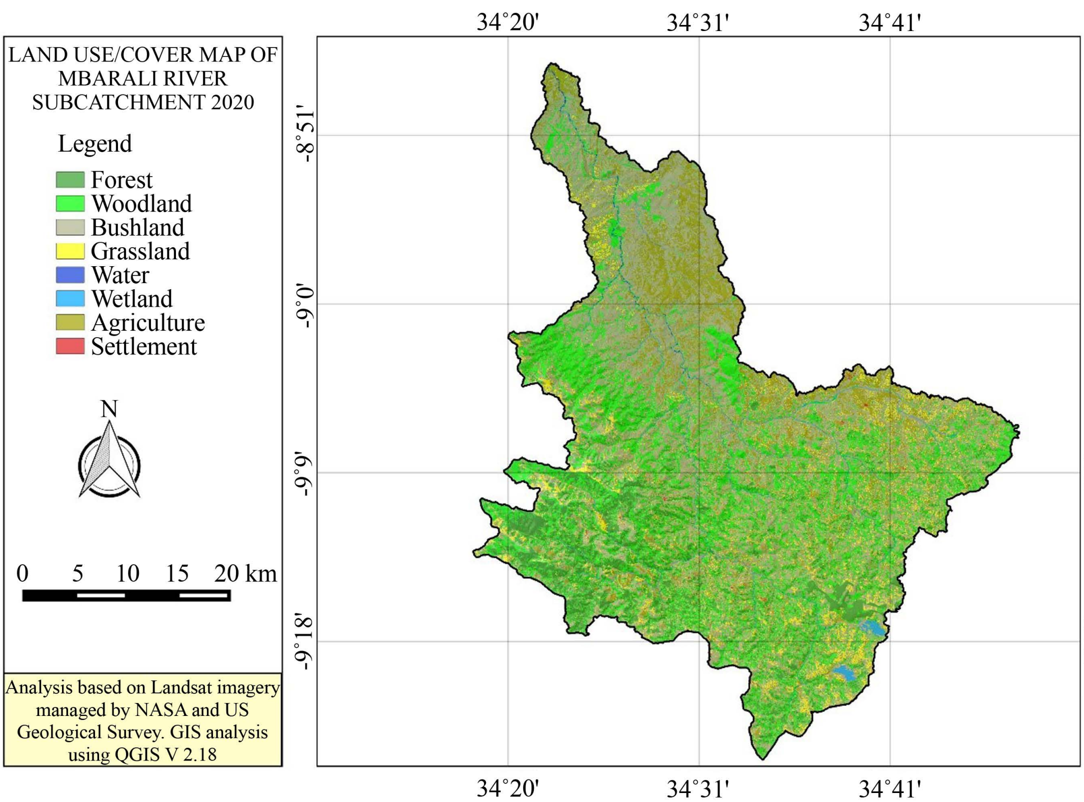

Figure 4. Land use/cover map of Mbarali River sub-catchment.

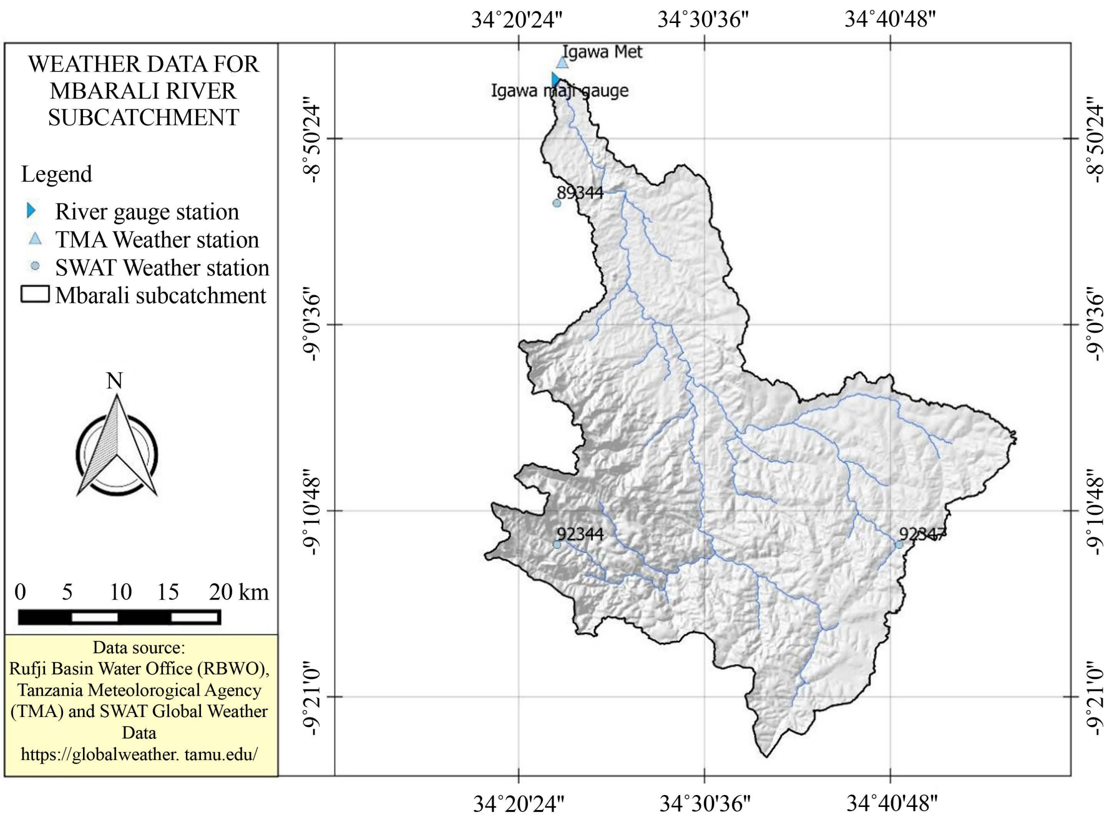

Figure 5. Weather data station in Mbarali River sub-catchment.

model parameters based on checking results against observations to ensure the same response over time (Zeray et al., 2007). Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (Trucano et al., 2006). Calibration and Validation process in SWAT model involves three steps which are Sensitivity and Uncertainty Analysis, Model Calibration and Model Validation. The calibration and validation processes were carried out using the Sequential Uncertainty Fitting (SUFI-2). The model performance was assessed based on three objective functions namely, Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2) and Probability bias (PBIAS). The general performance rating statistics for NSE, R^2 and PBIAS (**Table 2**) as proposed by Morias et al. (2007) and Gyamfi et al. (2016) were used to determine the performance of the model. The model performance objective function was explained by Chilagane et al. (2021); The Nash-Sutcliffe efficiency determines the relative magnitude of the residual variance compared to the measured data variance (Nash & Sutcliffe, 1970). It is used in the model to indicate how well the plot of observed versus simulated data fits the 1:1 line (Morias et al., 2007). Nash-Sutcliffe efficiency range from $-\infty$ to 1 where efficiency of one (E = 1) corresponds to a perfect match of modeled discharge to the observed data. Coefficient of determination (R^2) is a measure of the strength of the linear correlation between the predicted and observed variables. It ranges from 0 to 1, with higher values indicating

Table 2. Recommended objective function statistics.

Objective function	Performance rating for acceptable model
Nash-Sutcliffe Efficiency (NSE)	>0.5
Coefficient of determination (R^2)	>0.5
Probability bias (PBIAS)	≤±25%

less error variance, and typically values greater than 0.5 are considered acceptable (Van Liew et al., 2003). Probability bias (PBIAS) is the measure of how much (in percentage) the simulated variable is to be larger or smaller than its observed counterparts (Gupta et al., 1999). The optimum value of PBIAS is zero, where low magnitude values indicate better simulations, positive value indicated model underestimation and negative values indicated model overestimation (Gupta et al., 1999). After calibration and validation, the model was then used to assess the hydrology of Mbarali River sub-catchment evaluating surface water potential for irrigation.

3. Results and Discussion

3.1. Sensitive Parameter

Sensitive parameters are presented in **Table 3** below. The curve number (CN2) which indicates the runoff response of a catchment was found to be the most sensitive parameter followed by base flow alpha, groundwater delay, threshold depth of water in the shallow aquifer required for return flow.

3.2. Model Accuracy

Comparison of the results between the measured and calibrated stream flows show a good agreement with Nash-Sutcliffe efficiency (NSE), Coefficient of Determination (R^2) and Percentage Base (PBIAS) statistical values falling within the range of a satisfactory to good model. For calibration and validation period are represented in **Figure 6** and **Figure 7** respectively. Nash-Sutcliffe efficiency (NSE) was 0.70, Percentage Base (PBIAS) of 4.6 and coefficient of determination (R^2) of 0.72. During validation period, Nash-Sutcliffe efficiency was (NSE) of 0.74, Percentage Base (PBIA) 1.5 and Coefficient of Determination (R^2) of 0.76. The observed mean monthly streamflow for the calibration period (1998-2007) in the Little Mbarali river at Igawa Maji Gauge Station was 10.50 m^3/s while the simulated was 11.01 m^3/s. Results for the validation period (2008-2012) show that the observed mean monthly streamflow was 11.56 m^3/s and simulated mean monthly flow was 11.74 m^3/s for Igawa Maji Gauge Station.

3.3. Basin Water Balance

The water balance in SWAT considers precipitation as inflow to the watershed unit, evapotranspiration and deep percolation as loss and surface runoff, return flow and lateral flow as the outflow. Result from the model showed that on

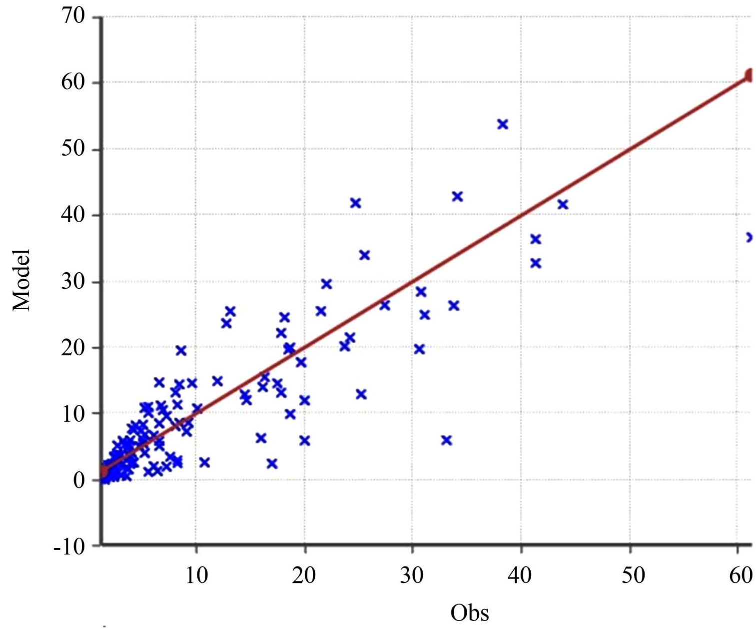

Figure 6. Comparison of measured and simulated streamflow during model calibration.

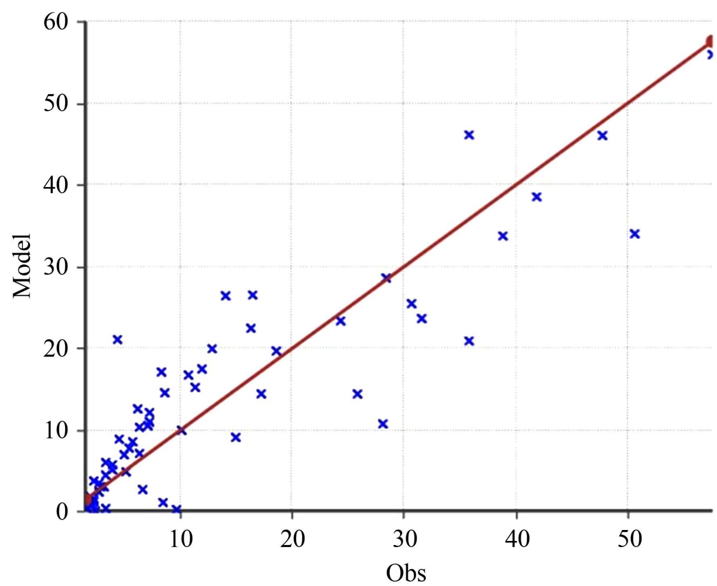

Figure 7. Comparison of measured and simulated streamflow during model validation.

Table 3. List of model-sensitive parameter.

Rank	Parameter	Parameter definition	Fitted value
1	CN2.mgt	SCS runoff curve number	−0.295000
2	ALPHA_BF.gw	Base flow alpha factor	0.268333
3	GW_DELAY.gw	Groundwater delay	93.699997
4	GWQWN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	1,436,666,626

average, the catchment receives about 631 mm of annual precipitation. The annual precipitation distributed into evapotranspiration, surface runoff, lateral flow, shallow aquifer storage and deep aquifer recharge. Results revealed that 339 mm of rainfall lost from the catchment through evapotranspiration. This is the largest water balance component, representing 53% of received rainfall. The study also indicate that evapotranspiration is the water balance component that consumes a large amount of received rainfall in the catchment.

The contribution to the shallow aquifer recharge is the second leading component which consumes about 242 mm representing 38% of received rainfall. The portion of shallow aquifer storage amounting 197 mm represents 82% of shallow aquifer storage loss to streamflow as return flow and 32.54 representing 13% revap from shallow aquifer storage to root zone where it contributes to lateral flow. The remaining portions of shallow aquifer recharge about 12.14 mm representing 5% of shallow aquifer storage recharge to the deep aquifer. Another portion of annual precipitation was distributed to surface runoff which receives 32.23 mm representing 5% and lateral flow which received 14.62 mm representing 2.32% of the total annual average precipitation. Figure 8 below illustrates the distribution of total annual average precipitation into different hydrologic components in the Mbarali River sub-catchment.

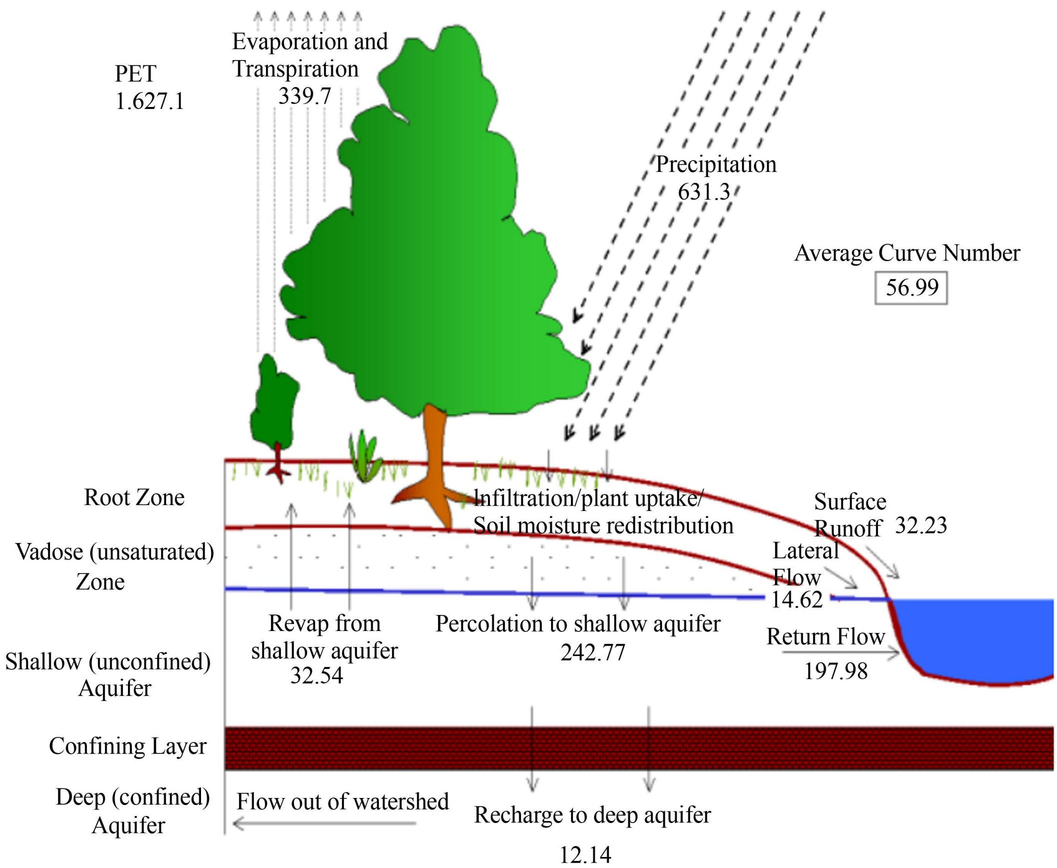

Figure 8. Modeled water balance of Mbarali River sub-catchment.

3.4. Water Available in Mbarali River Sub-Catchment

The results showed that about 53.84% of the catchment water is lost through evapotranspiration. The remaining water is distributed to discharge (surface runoff, lateral flow and return flow) and the ground percolation (Vadose zone, unconfined aquifer and confined aquifer). From the model, total annual means river discharge ranges from 0 - 10 cubic meters per second at upper catchment to 120 - 140 cubic meters per second at lower catchment (Figure 9). From these results, it shows that the lower reach of the Mbarali River sub-catchment is more potential for irrigation than the upper reach as it has potential river flow that can support irrigation activities. It is important to note that, at the lower reach of Mbarali River sub-catchment there are other water demands for domestic uses for the growing population at Igawa, Rujewa and Ubaruku towns. Moreover, water demand for livestock and wildness of Ruaha National Park and for environmental flow. There is an urgent need for water reallocation model to estimate and distribute sustainably the available limited river discharge into competing different water users.

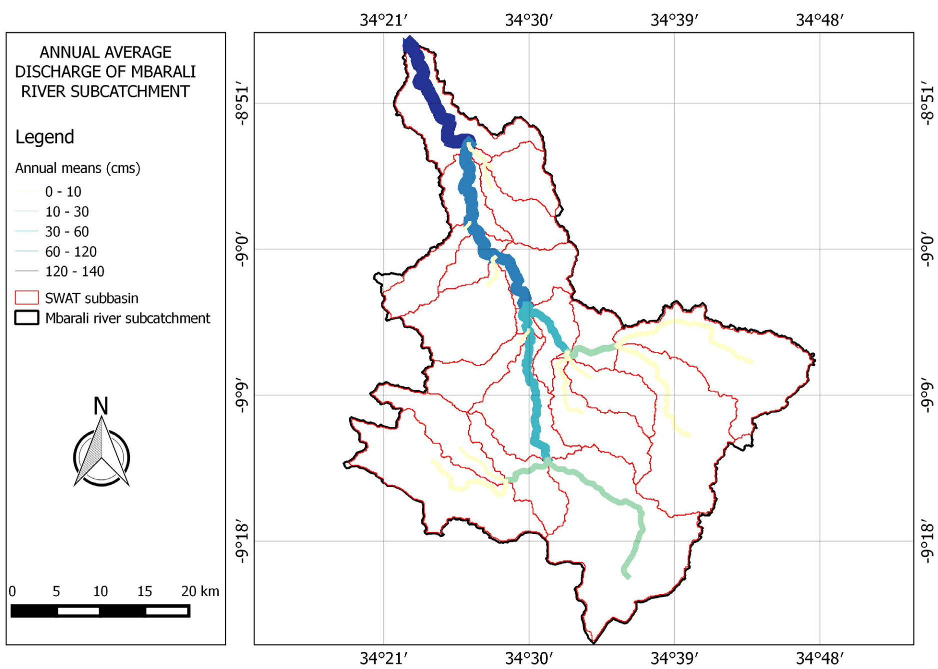

Figure 9. Modeled annual mean river discharge of Mbarali River sub-catchment.

Apart from irrigation that needs to abstract water from the river, the upper reach of Mbarali River sub-catchment is also potential for non-abstraction irrigation agriculture. The model as illustrated in Figure 10 and Figure 11 showed that there is enough surface runoff and water percolation in upper reaches of the catchment. Hence, there is great possibility of relying on the runoff captures and store in ponds for dry season use or to supplement for irrigation as the rainfall declines. Percolation is the movement of water through the soil itself. Finally, as the water percolates into the deeper layers of the soil, it reaches groundwater, which is water below the surface. The upper surface of this underground water is called the water table. Showing high percolation is an indicator of good water availability for dry season through return flow and revap flow depending on the soil water holding capacity of the given. It also means that the catchment water table is high and can hold water at a shallow depth for use during the dry season. This was confirmed in some parts of the sub-catchment whereby farmers do extract groundwater from shallow wells for domestic use and dry season farming. It is also to note that, irrigation development in the upper reach of the catchment must be planned very sustainably without interfering with the functioning of hydrologic components of the upper catchment, as the downstream flows depend on the upper functioning of hydrological processes.

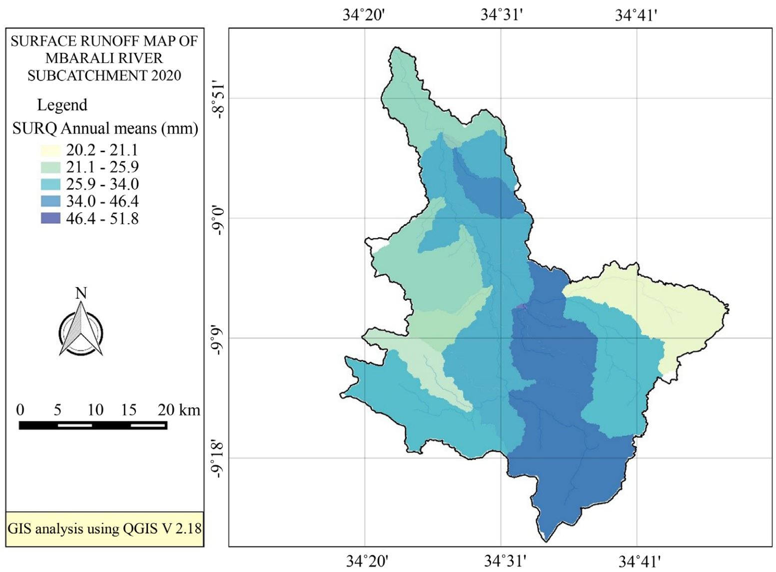

Figure 10. Sub-basin contribution to annual surface runoff in Mbarali River sub-catchment.

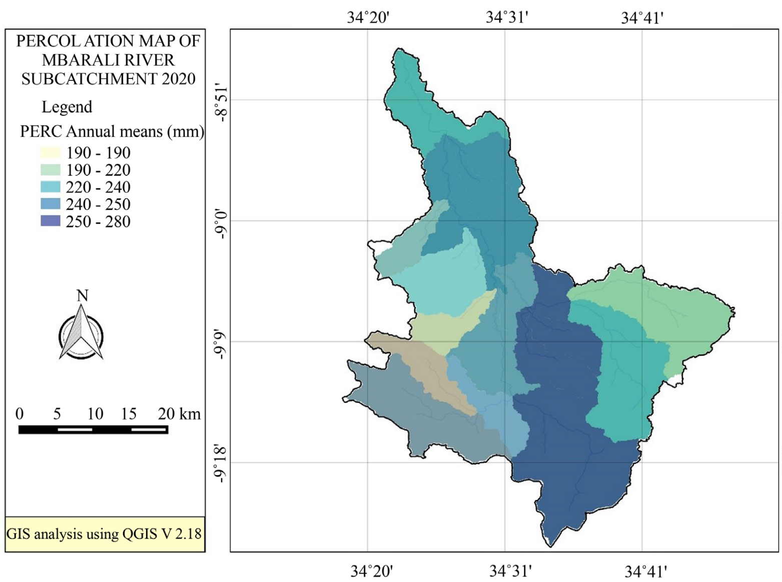

Figure 11. Sub-basin contribution to annual percolation in Mbarali River sub-catchment.

4. Conclusion

The study assessed the availability of surface water for irrigation development in the Mbarali River sub-catchment. The results from the SWAT Model disclose the availability of surface water and its distribution into different hydrologic components. The findings from the model have revealed the availability of surface water for irrigation development. Surface water was found to be more available in the lower catchment compared to the upper catchment by the consideration of river discharge. At the sub-basin level, the upper catchment is also found to be potential for irrigation as it has available surface water that is discharged to the river. The study recommends the proper irrigation strategies including excavation of ponds to capture and store runoff in the upper catchment in order to be used during the dry season or supplement irrigation as the rainfall declines. Moreover, the study recommends the need for the installation of another gauge station down from Igawa Maji gauge station, the place where the Mbarali River nearly meets the Kimani River. This gauge will help to monitor the amount of water that will remain in the Mbarali River after allocation to different uses.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., van Griensven, A., Van Liew, M. W., & Kannan, M. K. (2012). Model Use, Calibration, and Validation. *Transactions of the ASABE, 55,* 1491-1508. https://doi.org/10.13031/2013.42256

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large Area Hydrologic Modeling and Assessment Part 1: Model Development. *Journal of American Water Resource Association, 34,* 73-89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Chilagane, N. A., Kashaigili, J. J., Mutayoba, E., Lyimo, P., Munishi, P., Tam, C., & Burgess, N. (2021). Impact of Land Use and Land Cover Changes on Surface Runoff and Sediment Yield in the Little Ruaha River Catchment. *Open Journal of Modern Hydrology, 11,* 54-74. https://doi.org/10.4236/ojmh.2021.113004

FAO (Food and Agriculture Organization of the United Nations) (2005). *United Nations Educational, Scientific and Cultural Organization Soil Map of the World* (Volume VI).

FAO (Food and Agriculture Organization of the United Nations) (2012). *AQUASTAT—FAO's Information System on Water and Agriculture.* http://www.fao.org/NR/WATER/AQUASTAT/main/index.stm

Gupta, H. V., Sorooshian, S., & Yapo, P. O. (1999). Status of Automatic Calibration for Hydrologic Models: Comparison with Multilevel Expert Calibration. *Journal of Hydrologic Engineering, 4,* 135-143. https://doi.org/10.1061/(ASCE)1084-0699(1999)4:2(135)

Gyamfi, C., Ndambuki, J. M., & Salim, R. W. (2016). Hydrological Responses to Land Use/Cover Changes in the Olifants Basin, South Africa. *Water, 8,* Article No. 588. https://doi.org/10.3390/w8120588

Lankford, B. A., Tumbo, S., & Rajabu, K. (2009). 8 Water Competitions, Variability and River Basin Governance: A Critical Analysis of the Great Ruaha River, Tanzania. In F. Molle, & P. Wester (Eds.), *River Basin Trajectories: Societies, Environments and Development* (pp. 171-195). CAB International. https://doi.org/10.1079/9781845935382.0171

McCartney et al. (2007). *Agricultural Water Management in a Water Stressed Catchment: Lessons from the RIPARWIN Project.*

Morias, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE, 50,* 885-900. https://doi.org/10.13031/2013.23153

Mutayoba, E., Kashaigili, J. J., Kahimba, F. C., Mbungu, W., & Chilagane, N. A. (2018). Assessing the Impacts of Land Use and Land Cover Changes on Hydrology of the Mbarali River Sub-Catchment. The Case of Upper Great Ruaha Sub-Basin, Tanzania. *Engineering, 10,* 616-635. https://doi.org/10.4236/eng.2018.109045

Nash, J. E., & Sutcliffe, J. V. (1970). River Flow Forecasting through Conceptual Models Part I—A Discussion of Principles. *Journal of Hydrology, 10,* 282-290. https://doi.org/10.1016/0022-1694(70)90255-6

NBI (2011). *Assessment of the Irrigation Potential in Burundi, Eastern DRC, Kenya, Rwanda, Southern Sudan, Tanzania and Uganda.*

Ngailo, J. (2016). *Rice Farming in the Southern Highlands of Tanzania: Management Practices, Socio-Economic Roles and Production Constraints.*

Tanzania National Bureau of Statistics (TBNS) (2012). *Statistics for Development.*

Tiri, A., Belkhiri, L., & Mouni, L. (2018). Evaluation of Surface Water Quality for Drinking Purposes Using Fuzzy Inference System. *Groundwater for Sustainable Development, 6,* 235-244. https://doi.org/10.1016/j.gsd.2018.01.006

Trucano, T. G., Swiler, L. P., Igusa, T., Oberkampf, W. L., & Pilch, M. (2006). Calibration Validation and Sensitivity Analysis. *Reliability Engineering &System Safety, 91,* 1331-1357. https://doi.org/10.1016/j.ress.2005.11.031

URT (United Republic of Tanzania) (2005). *Bankable Investment Profile "Phase II of Madibira Rural Development".*

Van Liew, M. W., Arnold, J. G., & Garbrecht, J. D. (2003). Hydrologic Simulation on Agricultural Watersheds: Choosing between Two Models. *Transactions of the ASAE, 46,* 1539-1551. https://doi.org/10.13031/2013.15643

Zeray, L. (2007). Calibration and Validation of SWAT Hydrologic Model for Meki Watershed. In *Ethiopia, Conference of International Agricultural Research for Development* (5 p). University of Kassel Witzenhausen and University of Göttingen.