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Assessment of rainwater harvesting potential of Rachuonyo North Sub-Catchment in Kenya using the Australian water balance model

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ABSTRACT

Rainwater harvesting (RWH) is emerging as a promising alternative source of water in sub-Saharan Africa. It can be an alternative source of good-quality water to substitute other freshwater sources, to enable crop production beyond the growing season through supplemental irrigation as well as to improve the environment by minimizing the effect of drought and floods. The Rachuonyo North Sub-County of Kenya experiences low rainfall coupled with high population with limited access to reliable water sources. The study assessed the RWH potential of the Rachuonyo North Sub-Catchment with the aim of providing information on alternative water resources to meet the water demands for agriculture as well as domestic use in the region. The Australian water balance model (AWBM) was used to simulate the RWH potential of the Rachuonyo North Sub-Catchment using the area rainfall, evapotranspiration and river flow data. The calibration and validation of the model were performed with calibration and validation results yielding Nash–Sutcliffe efficiency (NSE) values of 0.503 and 1.00, respectively. Research findings indicated that the area has a potential for RWH with runoff harvest of between 104,496 and 43,646,142 m^3/month, which can significantly support the residential and irrigation water demands for the area. Policymakers and development agencies in the region should pro-actively put in place measures to promote RWH interventions as a tool for increasing access to water. The methodology in the study is suitable for adaption for rainfall–runoff simulation in other sub-Saharan African regions where data are limiting.

Key words: evapotranspiration, irrigation, rainfall, runoff, small-scale farmers

HIGHLIGHTS

- Resilience to climate change.
- Increased access to clean water.
- Increased access to irrigation water.
- Flood management.
- Integrated water resources management.

LIST OF ABBREVIATIONS AND ACRONYMS

AWBM	Australian water balance Model
CIDP	County Integrated Development Plan
CRCCH	Corporative Research Center for Catchment Hydrology
FAO	Food and Agriculture Organization
GoK	Government of Kenya
LVSC	Lake Victoria South Catchment
NSE	Nash–Sutcliffe efficiency
PC	Personal computer
RRL	Rainfall–Runoff Library
RWH	Rainwater harvesting
SWAT	Soil and Water Assessment Tool
UN	United Nations

1. INTRODUCTION

Kenya is a water-scarce country; its per capita water availability was estimated to be 647 m^3 in 2000 which dropped to 502 m^3 in 2012 (Bancy 2015). The value is estimated to further drop to 235 m^3 by the year 2025 (FAO 2013). Water allocation is thus a critical issue that requires careful consideration. A number of competing water demands exist that include irrigation, domestic and industrial use. Agricultural water demand in Kenya is estimated at 59%, whereas domestic and industrial water demand are estimated at 37 and 4%, respectively (FAO 2015). Water is therefore an essential commodity required by every Kenyan in adequate quantity and quality. The Rachuonyo North Sub-Catchment in Homa Bay County experiences low rainfall ranging between 700 and 800 mm/year which is erratic and unreliable (Opere *et al.* 2016). Crop failure is common with many parts of the area constantly being food-insecure. The prices of common foods are normally high during dry periods and sometimes not affordable by poor households. Drinking water supply is also a major problem with a number of towns without access to treated water supply (Okinyi *et al.* 2018).

Small-scale farmers in the region have adopted various strategies' such as irrigation, planting of drought-resistant and drought-tolerant crops among others as a way of building resilience. A number of small-scale farmers in the region have diversified to grow horticulture crops mainly kales, tomatoes, onions, capsicum and watermelon under irrigation to increase their household income (Jeckonia 2019). However, unreliable rainfall has rendered these strategies ineffective (Clifford 2018).

Rainwater harvesting (RWH) has a number of potential social and economic benefits as outlined by Mati *et al.* (2005). First, it can be a better tool to alleviate poverty and achieve sustainable development. Second, it is essential in reducing the risk of crop failure as well as reducing the gap in domestic water supply. Finally, RWH improves the environment by minimizing the effect of droughts and floods. Past studies on the potential of RWH on improving food production have shown that by applying conservation agriculture, the production of maize can be tripled (Baron & Rockstrom 2003). Rainwater harvested from rooftops can also be an alternative source of good-quality water to substitute other freshwater sources. It is economical in areas where surface and groundwater sources are prone to contamination either by harmful chemicals, pathogenic bacteria or with saline water (UN habitat 2015).

However, the adoption of RWH systems is low. A study by Kerich (2020) on household drinking water sources and treatment methods indicated that only 2.8% of the area population used rainwater as a source of drinking water despite the other surface water sources' vulnerability to agricultural pollution and requiring treatment.

RWH is gaining popularity over time among many industry players in Kenya. Government agencies, non-governmental organizations and private firms have embarked on initiatives to promote RWH technologies in Kenya. In April 2017, the Kenyan government launched a robust program dubbed 'Billion dollar alliance for Rainwater harvesting'. The program is a partnership between the Kenyan government, development agencies as well as business communities. The project aims at scaling up farm pond technology for agribusiness and livelihood in arid and semi-arid areas (Onyango 2017).

There are two main factors that influence the generation of runoff from a watershed, namely precipitation and abstraction. Precipitation can be in the form of rainfall, snow melt or hail storm. Rainfall rates and distribution within the watershed vary both temporally and spatially (Tarboton 2003). A number of techniques can be used in the estimation of runoff rates and volumes. These include the rational method, runoff coefficient method and National Resources Conservation Services (NRCS) runoff curve number methods, among others. Krisnayanti *et al.* (2021) showed that the NRCS runoff curve number method can be used for runoff estimation in small ungauged watersheds with frequent climate variability.

Hydrological models are planning tools used to assess the existing water quantity and quality as well as predict the water situation in the future due to changes in land use or climate (Devia *et al.* 2015). Models can be categorized based on the simulation approach as conceptual, empirical or stochastic. They can also be classified based on spatial representation as lumped or distributed models (Kanda *et al.* 2018). There are a number of models used in rainfall–runoff simulation. The choice depends on many factors including ease of running and interpretation of the results, availability of data, model availability and applicability as well as the accuracy of its prediction (Singh & Frevert 2002). Models are therefore essential decision support tools enabling efficient management of water resources as well as water allocation in a water stress environment at river basin level (Tsanov *et al.* 2020).

The Australian water balance model (AWBM) is a catchment water balance model currently developed under the Rainfall–Runoff Library (RRL) Tool KIT and is supported by vast knowledge and experience of catchment researchers and hydrologists. The model relates daily rainfall and evapotranspiration to runoff and calculates losses from rainfall for flood hydrograph modeling (Boughton 2004). The model was originally developed by Dr Boughton in 1993 in Australia. It has two main versions: one for daily water yield and low flow studies and another for continuous simulation of flood flows (Boughton 1993).

The AWBM is a conceptual model developed from the concept saturation of overland flow and generation of runoff. The model has a unique calibration procedure that is specific to the model and is based on its structure. It is operated on either daily or hourly time steps. Finally, it has been adopted for use in the ungauged catchment (Boughton & Chiew 2003).

Comparative analyses of the AWBM with other rainfall–runoff models have indicated that it yields better results in a number of catchment areas (Yu & Zhu 2014). The model has a unique calibration procedure that is specific to the model and is based on the model structure (Boughton 2004). The model is also part of the Corporative Research Center for Catchment Hydrology (CRCCH) tool kit: a collection of highly recommended rainfall–runoff models hence making it more reliable. In addition, the model software and manual is distributed for free and is available for downloading at the CRCCH website. The AWBM is reportedly easy to use with user-friendly graphical presentation on personal computer (PC) screens.

It is also less demanding in terms of input data with rainfall, evapotranspiration and streamflow data as the only required data to run the model (Boughton & Chiew 2003).

The influence of climate on crop water needs is given by the reference crop evapotranspiration usually denoted by ET_0 and is expressed as millimeters per given time. There are a number of methods for calculating the reference evapotranspiration. FAO recommends the use of the FAO Penman–Monteith formula that was developed in 1990 through a collaboration of the International Commission on Irrigation and Drainage and the World Meteorological Organization.

The equation is expressed as follows (FAO 1990):

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_\mathrm{n} - G) + (\gamma 900/(T + 273))U_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_\mathrm{s} - e_\mathrm{a}$ is the saturation vapor pressure deficit (kPa), Δ is the slope vapor pressure curve (kPa $°\mathrm{C}^{-1}$) and γ is the psychometric constant (kPa $°\mathrm{C}^{-1}$).

The FAO Penman–Monteith equation has been widely accepted for use in the estimation of crop water requirement by the International Commission on Irrigation and Drainage as well as the World Meteorological Organization since it has a broad theoretical base that accommodates small time periods (FAO 1990). However, climatological data required for accurate prediction of ET_0 are often lacking in many countries especially in Africa (Hargreaves & Samani 1985). Important parameters in estimating ET_0 are temperature and solar radiation. About 80% of the ET_0 can be explained by temperature and solar radiation alone. A simple formula to estimate ET_0 using minimum climatological data can be indicated by the following equation (Hargreaves & Samani 1985):

$$\mathrm{ET}_0 = (T_\mathrm{max} - T_\mathrm{min})^{1/2} \times 0.0135 \times \mathrm{KT} \times R_a \times (\mathrm{TC} + 17.81) \tag{2}$$

where T_max is the maximum temperature (°C); T_min is the minimum temperature (°C); TC is the average daily temperature (°C); R_a is the extraterrestrial radiation (mm/day) and KT is the empirical coefficient of 0.162 for interior regions or 0.19 for coastal regions.

2. RESEARCH METHODOLOGY

2.1. Study area

The study was carried out in the Rachuonyo North Sub-County of Homa Bay located at 3.795°S and 34.6567°E (Figure 1). The region is made up of seven administrative units, namely West Rachuonyo, North Rachuonyo, Central Rachuonyo, Kendu Bay Town, Wang'chieng, Kanyaluo and Kibiri. The area covers approximately 435.4 km^2 with an average population of 178,686 (GoK 2019).

The region is classified under the Lower Midland (UM_4) agro-ecological zones. It is characterized by two rainy seasons: long rains from March to June and short rains from August to November. Rainfall ranges from 700 to 1,800 mm with an average of 949 mm. The temperature ranges from a minimum of 17.1 °C to a maximum of 34 °C. Recently, the region has experienced high rainfall variability characterized by years of increasing dry months and shorter rainfall followed by sometimes heavy rainfall resulting in floods (Opere *et al.* 2016). The average farm sizes are 0.607028 ha for small-scale farmers and 4.04686 ha for the large-scale farmers (Okinyi *et al.* 2018).

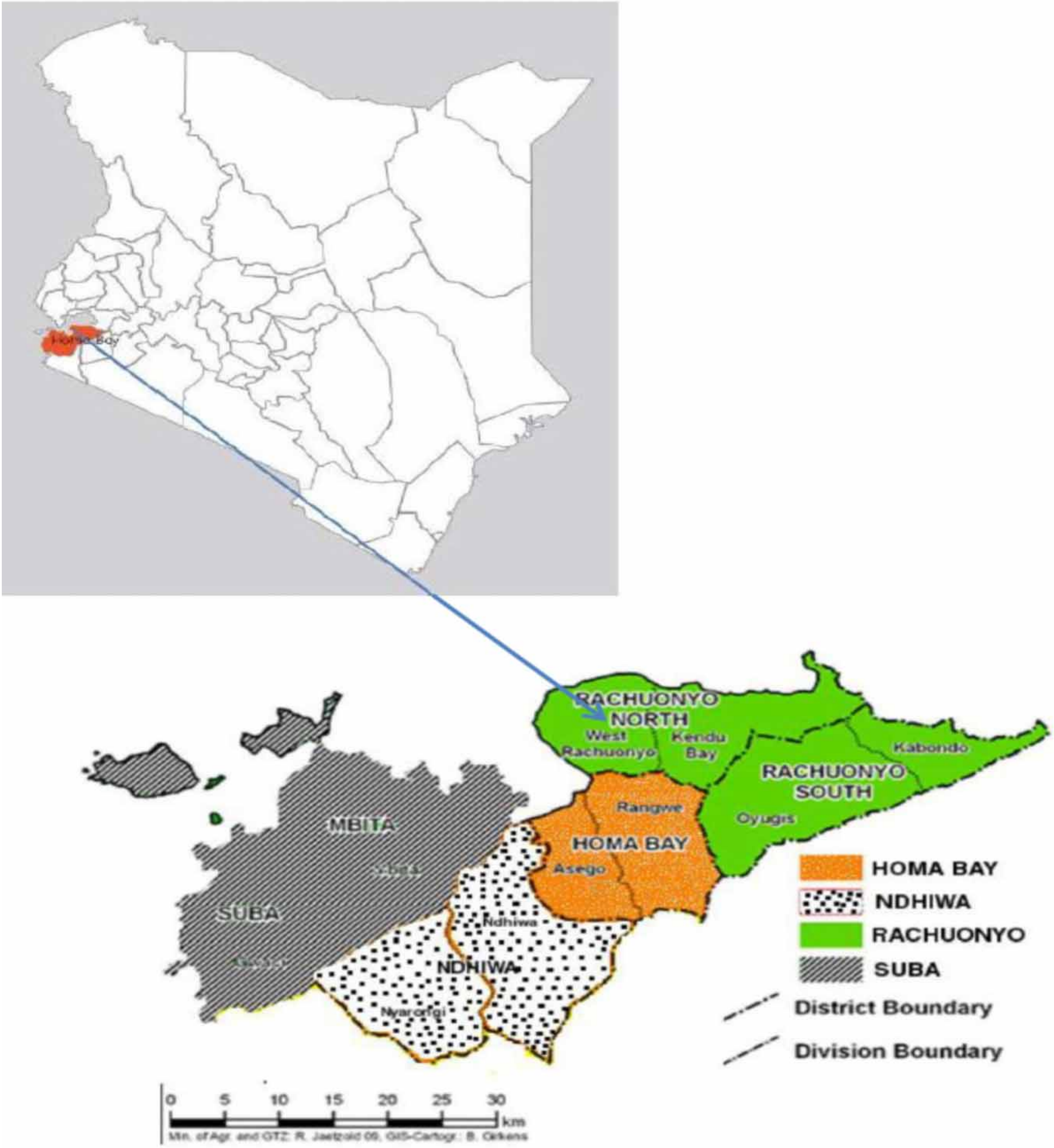

Figure 1 | Map showing location of the study area in Homa Bay County, Kenya.

2.2. Model description

The parameters in (Figure 2) the AWBM according to the RRL user guide (Podger 2004) are explained as the following: the three parameters A_1, A_2 and A_3 represent the portion of the areas of the catchment, the default values of $A_1 = 0.134$, $A_2 = 0.433$ and $A_3 = 0.433$. When runoff occurs, part of it becomes base flow. The fraction of the runoff used to recharge the base flow storage is BFI × Runoff, where BFI is the base flow index. The BFI is therefore the ratio of the base flow to the total flow in the stream. The remainder of the runoff (1.0–BFI) × runoff is the surface runoff.

The base flow storage is depleted at the rate of (1.0–K) × BS, where BS is the current moisture in the base flow store and K is the base flow recession constant of the time step that is under the application. Routing of runoff through the storage can be done to simulate the delay of runoff reaching the outlet. The surface store acts as the base flow storage and is depleted at the

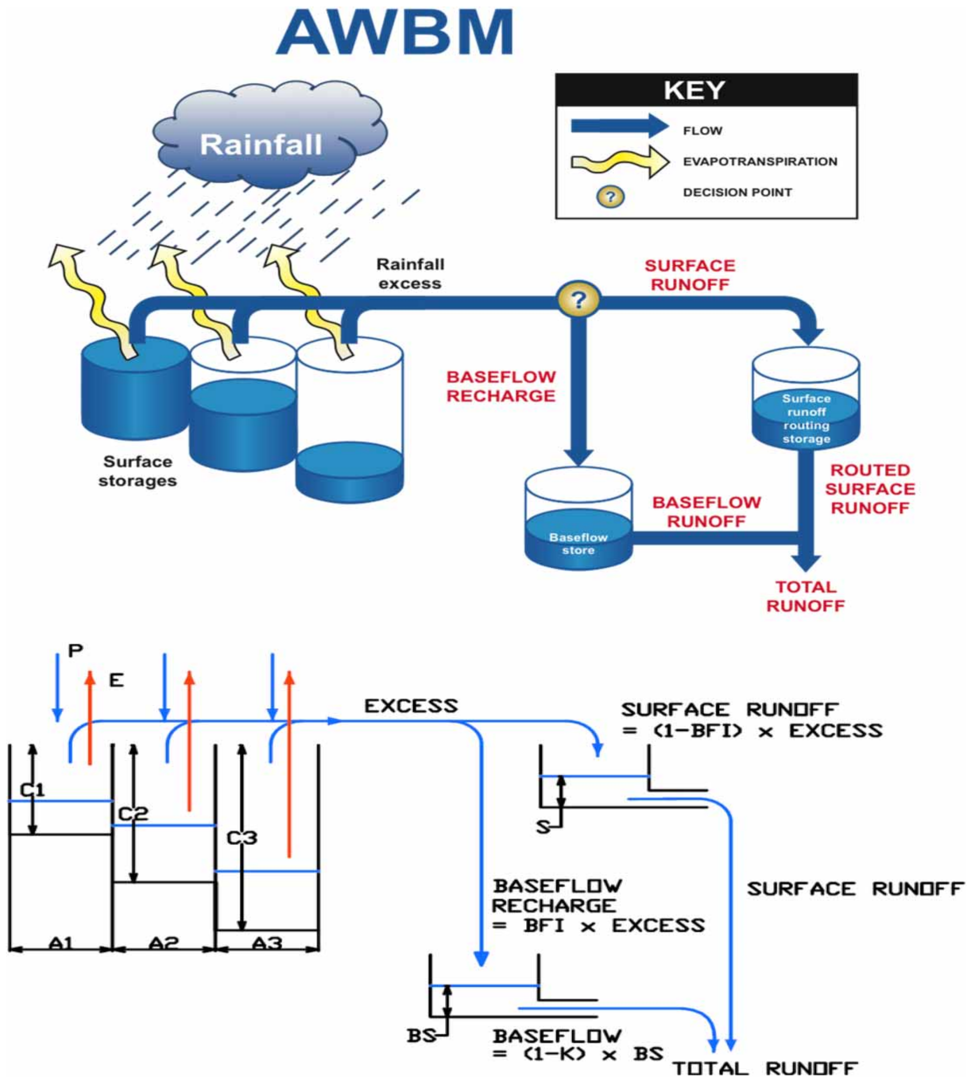

Figure 2 | Schematic view of the AWBM structure (Boughton & Chiew 2003).

rate of (1.0–KS) × SS, where SS is the current moisture in the surface runoff store and KS is the surface runoff recession constant of the time step in use.

2.3. Research design

The study employed an experimental design in the project to investigate the RWH potential of Rachuonyo North Sub-Catchment. Secondary data were used together with established rainfall–runoff models to predict the potential of RWH in the study area. Daily rainfall from the area was transformed to harvested runoff using the AWBM: a software within the RRL. The potential runoff volume from the study area was established from the predicted runoff depth and catchment area.

2.4. Data input into the model

2.4.1. Weather data/climate data

Rainfall data, temperature, wind velocity, relative humidity and solar radiation data were used to calculate the daily potential evapotranspiration. This was input into the AWBM together with daily rainfall and river flow data to simulate potential runoff depth from the study area.

Sample data were obtained from different sources at varying time frames. Rainfall, temperature, wind velocity, relative humidity and solar radiation data were obtained from SWAT GLOBAL with a time frame ranging from 1 January 1979 to

31 July 2014. Potential evapotranspiration was therefore calculated from the SWAT GLOBAL data using Equation (2). River gauging's records at station 1HE01 along Awach Tende were obtained from the Water Resources Authority (WRA), Lake Victoria South Catchment (LVSC) for the period 1979–2014. The rainfall, evapotranspiration and river flow data were sorted and arranged in a format that would be read by the AWBM. The river flow data had a lot of gaps making most of it unusable except for 1987–1992.

2.5. Data processing and analysis

Daily rainfall, runoff and evapotranspiration data were processed in the AWBM to simulate the catchment runoff. The process of runoff simulation was carried out as shown in Figure 3 where daily river flow records at station 1HE01 along Awach Tende, daily rainfall and evapotranspiration data were sorted in Excel. These data were organized into a format compatible

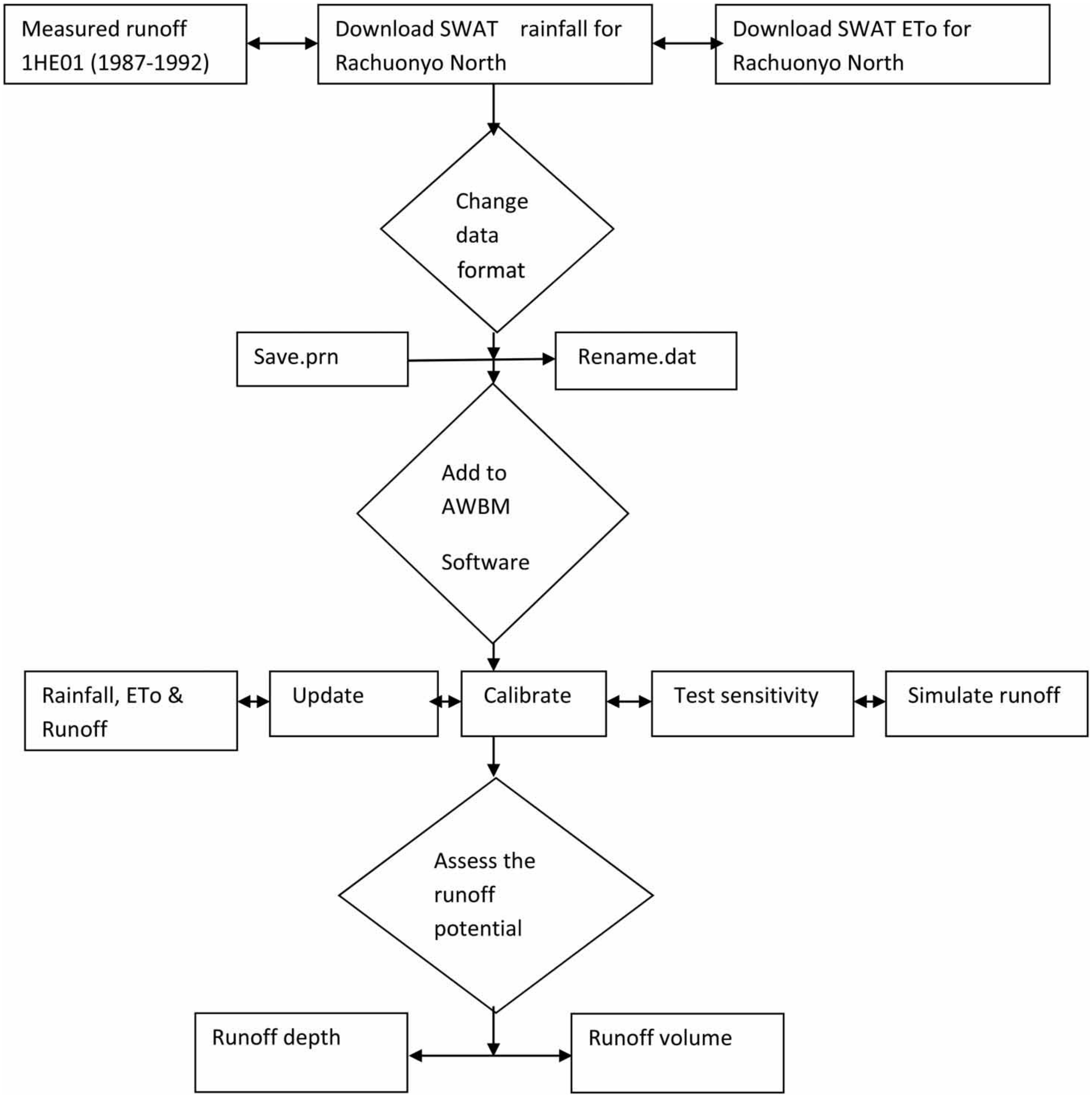

Figure 3 | Flow diagram of runoff simulation.

with the AWBM; they were then saved as formatted text (space-delimited). The data were finally renamed as .dat; a format that the AWBM uses to simulate runoff as indicated in Figure 3. The model was calibrated using rainfall, runoff and ET_0 data for the period 11 May 1987 to 31 August 1991. Model verification was performed using the input data for the period 1 September 1991 to 30 August 1992. The warmup period of 19 August 1987 to 30 August 1992 was chosen for calibration and verification, respectively.

2.6. Model calibration and verification

The model was calibrated using rainfall, runoff and ET_0 data for the period 11 May 1987 to 31 August 1991. Model verification was performed using the input data for the period 1 September 1991 to 30 August 1992. The warmup period of 19 August 1987 and 30 August 1992 was chosen for calibration and verification, respectively.

2.7. Model sensitivity analysis

Sensitivity of the model parameters were carried out by changing each of the single parameters by a range of $+10\%$ while keeping other parameters constant and observations made on how the change on each model parameter affected the output by the use of NSE values as the objective function in the graph area.

2.8. Model performance evaluation

Model evaluation was performed by comparing the simulated and observed results both visually and by the use of NSE. NSE values greater than 0.75 were preferred for good model efficiency. However, NSE values between 0.36 and 0.75 represented satisfactory model performance (Moriasi *et al.* 2007).

3. RESULTS AND DISCUSSION

Daily rain, ET_0 and runoff were input into the AWBM according to the procedure outlined in Figure 3 to simulate the runoff-generating potential of the catchment. During calibration, the default model parameters in Table 1 were kept constant and the model was run in auto-calibration mode. During validation, the set model parameters in Table 2 obtained during calibration were used and the model was run without auto-calibration to simulate runoff.

Table 1 | Model parameters and variables

C_1–C_3	Surface storage capacities
A_1–A_3	Partial areas represented by surface storage
BFI	Base Flow Index
K	Daily base flow recession constant
BS	Current volume in base flow store
KS	Daily surface flow recession constant
SS	Current volume in surface routing store

Table 2 | Boundaries and fixed parameters for AWBM calibration and validation

$A1$	0.134
$A2$	0.433
BFI	0.435
$C1$	44.320
$C2$	100.817
$C3$	77.133
K base	0.918
K surf	1

The AWBM model was calibrated with an NSE as the objective function. The model gave good performance in simulation of runoff with calibration and validation results yielding NSE values of 0.503 and 1.00, respectively, as demonstrated in Figure 4, which showed a good correlation between the observed and the calculated results. The model was therefore found to be efficient, hence, suitable for simulating runoff from the Rachuonyo North Sub-County catchment. The model was therefore adapted for simulation of runoff from the catchment; hence, it could be used for water resources planning and management for the catchment.

The graph of the calculated runoff was compared to the observed runoff as shown in Figure 5. From the graph, it was evidenced that the AWBM is actually underestimating runoff from the catchment with the observed runoff higher than the forecasted runoff. The simulation results are obtained as shown in Figure 6.

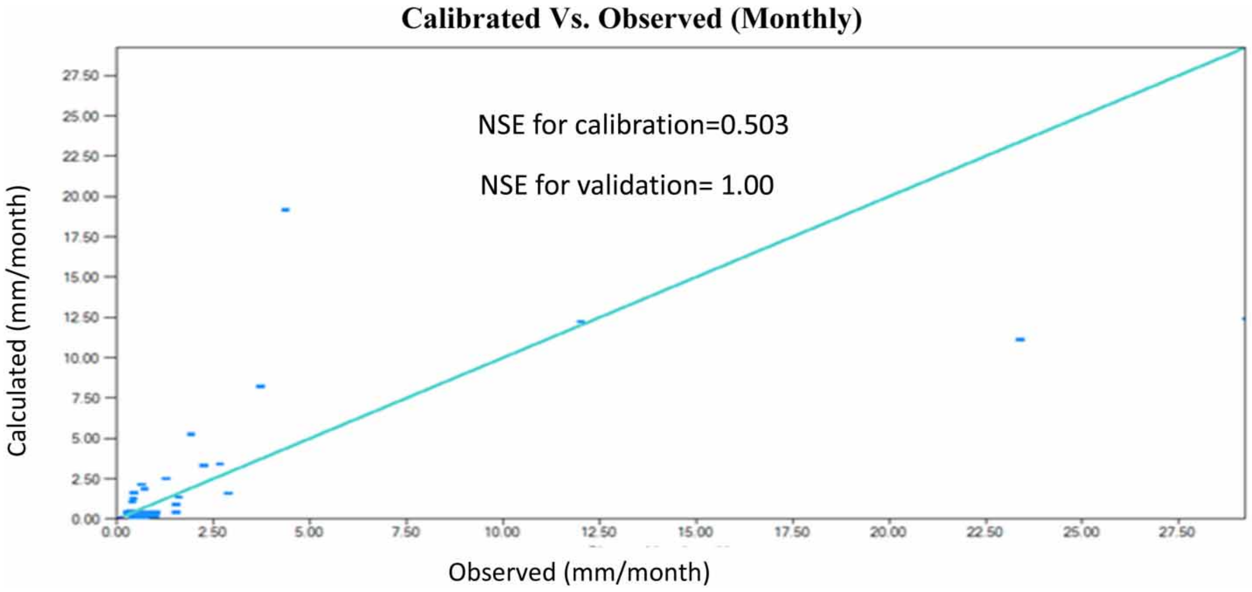

Figure 4 | Nash–Sutcliffe efficiency chart of simulated and observed data.

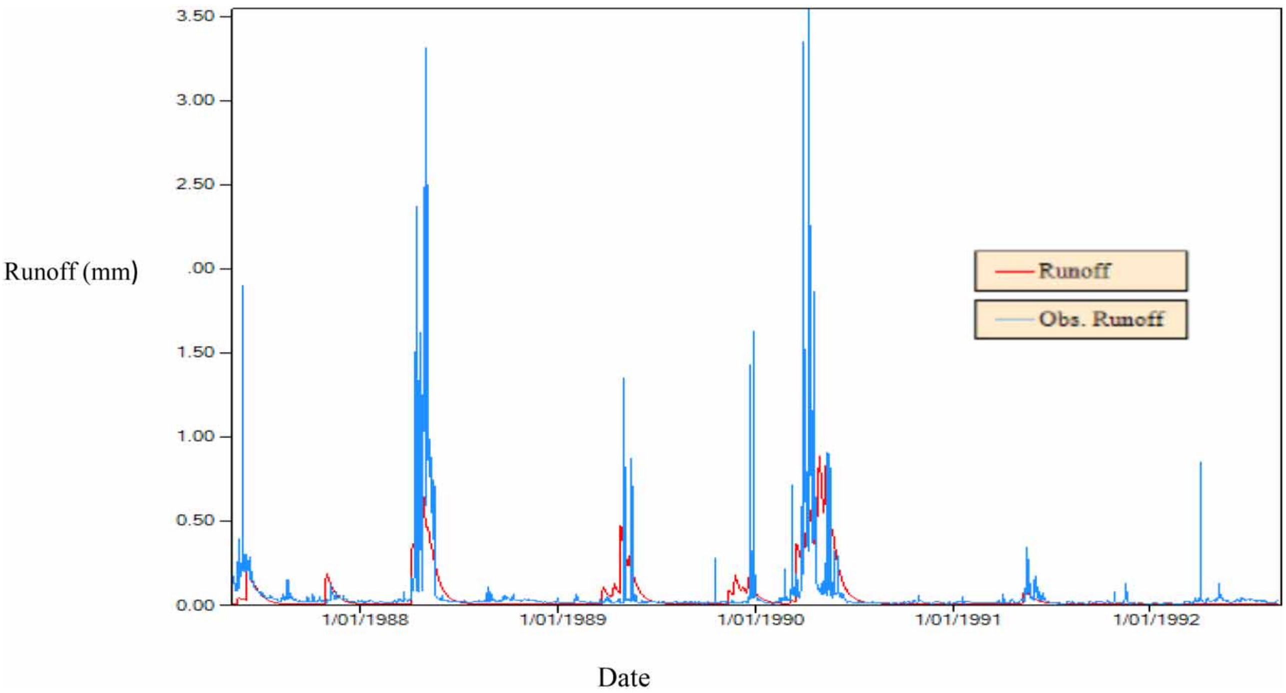

Figure 5 | Calculated versus observed runoff.

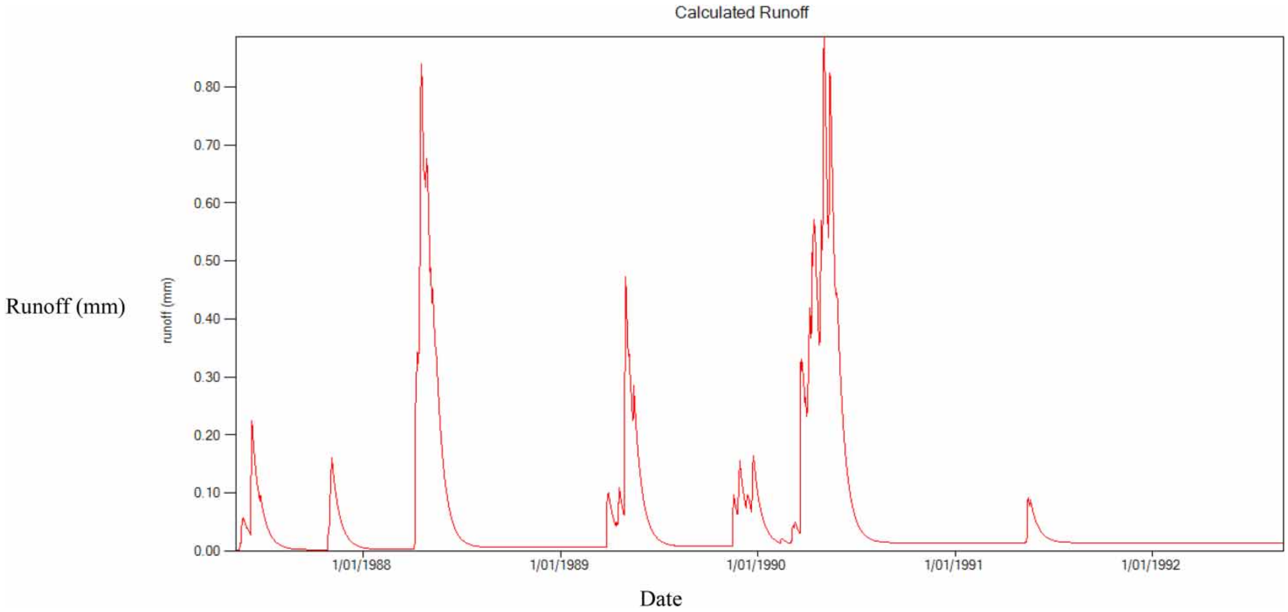

Figure 6 | Result of running daily runoff for 1987–1992 in the AWBM.

It was found that the area has a potential runoff harvest ranging from 0.00024 to 100.23 mm depth per month over the entire 435.4 km^2 area. If converted to cubic meters, this translated to arrange between 104,496 and 43,640,142 m^3/month of potential runoff harvest, indicating that RWH in the area has the potential to offset fresh residential water demand, irrigation water demand as well as potential to manage stormwater that causes floods in the area as demonstrated by Aroka (2010).

4. CONCLUSION AND RECOMMENDATION

The study revealed that the catchment has a potential for runoff harvest of between 104,496 and 43,640,142 m^3/month which could provide adequate rainwater to meet the domestic water demands as well as the irrigation water requirements of smallholder irrigation farmers in the region. It was therefore prudent for government and other development agencies working in the area to consider interventions toward promotions of RWH at individual as well as community levels. This would contribute to social and economic development through poverty alleviation and the achievement of sustainable development. Furthermore, this would enable smallholder irrigation farmers in the region who are often vulnerable to develop resilience to climate shock.

DATA AVAILABILITY STATEMENT

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

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