APPLICATION OF THE SOIL WATER ASSESSMENT TOOL (SWAT) USING REMOTE SENSED DATA ON THE KABOMPO RIVER BASIN, ZAMBIA

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ABSTRACT

A river basin-scale hydrological model of the Kabompo river basin located in the north-west of Zambia was developed using remote sensed data to address key water resources management problems of water allocation to agriculture and ecosystems, effects of land-cover change on the flow regime and potential impacts from mine tailing dams. Because of paucity of observed data in the Kabompo basin, the model primarily depended on remote sensing datasets for calibration and validation. Methodology included the use of a semi-distributed; ArcGIS based Soil Water Assessment Tool (SWAT) software for hydrological modeling. The Kabompo basin was discretized into 177 sub-basins with a total of 1004 hydrological response units. Remote sensing data sets that included weather data, drainage network and slopes, landuse/ land cover and soils were used to create a database for the sub basins using ArcGIS. The simulated flow from the SWAT model was calibrated with ESA ERS-2 and ENVISAT radar altimetry river stage data. The model's results showed good correlation with observed data giving a Nash Sutcliffe coefficient of 0.87 and an R^2 value of 0.93, after calibration. The simulation results obtained from the model can be used in a number of water resources management activities like water rights, water allocation, and flood warning. It's also able to simulate long term data of a wider area including inaccessible locations which makes it to be more convenient than conventional hydrological techniques. Hence it is concluded that remote sensing is a useful tool for hydrological modeling in the generation of hydrological data where it is lacking or in ungauged and inaccessible areas. Its wide use in a country like Zambia would greatly improve water resources management.

***Keywords**: SWAT, Remote sensing, Kabompo basin, ArcGIS*

INTRODUCTION

The use of traditional hydrological methods in acquiring land, hydrogical and meteorological data have proved to be expensive and time consuming in water resources and land management in Zambia. There are a number of gaps in hydrological data records on stream flow (discharge) and water levels due to poor and inconsistent submissions of data from monitoring stations in various parts of the country including the Kabompo basin. Remote Sensing (RS) and Geographic Information System (GIS) based data acquisition methods have been shown to provide faster, cheaper and much wider coverage of data acquisition and has made it a major contributor to a number of hydrological models worldwide. Nayak and Jaiswal (2003) showed that remote sensing data can be used to derive thematic information on land use, soil, vegetation and drainage in combination with climate parameters (precipitation, temperature), and topographic parameters (height, contour, slope) to provide necessary input to hydrological models.

In this study Remote Sensing data alongside a semi-distributed, ArcGIS based Soil Water Assessment Tool (SWAT) software were used to develop a hydrological model for the Kabompo River a tributary of the Zambezi River. The 72,200 km^2 watershed occupies most parts of the North-Western province and part of Western provinces. The basin has experienced an influx of large scale mining and a number of small scale mineral processing industries resulting in a rapid economic and population growth (Sichela, 2009). This suden development has led to an urgent need for a reliable water resources management system to help monitor and manage the water resource which is currently under pressure from domestic, industrial and commercial use. The developed model therefore, will help address these water resource problems and will be useful to other studies such as those on water quality and soil erosion in the basin.

THEORETICAL BASIS

The soil Water Assessment tool (SWAT) was developed by Dr. Jeff Arnold of the United States Department of Agriculture (USDA)–Agriculture Research Service (ARS) to predict the impact of land management practices on Water, Sediment and Agriculture Chemical yields in large complex watersheds that have varying soils and landuse (Neitsech et al. 2005). SWAT is physically based and does incorporate regression equations to describe the relationship between input and output. SWAT requires specific information about weather, soil properties, topography, vegetation and land management practices to operate (Neitsech et al. 2005). However, SWAT allows users to choose different theories with different data input requirements. For example to calculate the rate of evapotranspiration in the Kabompo river basin, the Hargreaves method that only required minimum and maximum temperature was chosen instead of the Penman-Monteith that required wind speed, relative humidity , solar radiation and air temperature.

Unlike other modeling tools which are either too expensive or have numerous data input requirements, SWAT is a freeware, and has been used by a number of researchers all over the world in a number of applications. For example; Vassilos et al (2009) developed a hydrological model for the Kosynthos River Watershed located in Northeastern Greece; Schuol et al. (2008) used SWAT to estimate the fresh water availability in Africa; Sanjiv Kumar (2008) used SWAT to study the effect of spatial scaling on hydrologic model calibration, and Stéphane et al. (2009) used SWAT to study the effect of land use changes on the Chaudière River watershed in Québec.

Due to insufficient hydrological data for the Kabompo river basin, SWAT was chosen because all the necessary variables needed to operate it could be obtained from remote sensing derived data. The SWAT model did not only have minimal data input requirement, but was also user friendly as you could assemble the model graphically stage by stage.

Background of remote sensing method in hydrology

Imagery acquired by airborne or satellite sensors provide an important source of information for mapping and monitoring natural and manmade features on the land surface (Randall, 2006). Remote sensing (RS) is defined as the acquisition of information about an object without being in physical contact with it. In remote sensing, information is acquired by detecting and measuring changes that the object imposes on the surrounding field, be it an electromagnetic, acoustic, or potential field (Elachi et al, 2006). Remote sensors measure electromagnetic (EM) radiation that has interacted with the

Earth's surface. Interactions with matter can change the direction, intensity, wavelength content, and polarization of EM radiation (Randall, 2006). Two types of sensors can be distinguished depending on the energy source. **Passive sensor:** Sensor detects the reflected or emitted electro-magnetic radiation from natural sources while **Active sensor:** Sensor detects reflected responses from objects that are irradiated from artificially-generated energy sources, such as radar. Remote sensing can be split in three section of the electromagnetic spectrum; Visible and Reflective, Infrared, emissive infrared and, microwave Remote sensing (Elachi et al, 2006). The visible wavelengths cover a range from approximately 0.4µm to 0.7 µm. The longest visible wavelength is red and the shortest is violet. **Blue** (0.45—0.52µm) which is highly absorbed by water, it provides the best data for mapping depth-detail of water-covered areas. It is also used for soil-vegetation discrimination, forest mapping, and distinguishing cultural features. **Green** (0.50—0.60 µm) corresponds to the chlorophyll absorption of healthy vegetation and is useful for mapping detail such as depth or sediment in water bodies. Cultural features such as roads and buildings also show up well in this band. Finally, **Red** (0.60—0.70 µm) in healthy vegetation is highly absorbed by Chlorophyll hence; this band is useful for distinguishing plant species, as well as soil and geologic boundaries (Lillesand, 2004) .Thermal Radiation is between 3 µm and 35 µm, this is the black body radiation emitted from earth's surface. It is useful for crop stress detection, heat intensity, insecticide applications, thermal pollution, and geothermal mapping. This channel is commonly used for water surface temperature measurements. The microwave region is the longest wavelength used in remote sensing. The shortest wavelengths in this range have properties similar to thermal infrared region. The main advantage of this spectrum is its ability to penetrate through clouds, fog, and rain and images can be acquired in the active or passive mode (Shefali, 2000), (Lillesand, 2004).

There are various archives of global datasets both remote sensed and non remote sensed data available online that could be used for hydrological modeling, they range from topographic data Shuttle Radar Topographic Mission (SRTM) to soil data (FAO soils maps) and Land use (Global land use maps) and Climate Data (Haguma, 2007). Other technology available today are the Gravity Recovery and Climate Experiment (GRACE), a joint mission of NASA and the German Space Agency, this technology , uses gravity to show how mass is distributed around the planet and how it varies over time. GRACE data are important tools for studying Earth's hydrology, geology, and climate (Davis, 2002).

Major driving processes and equations in SWAT

Swat divides simulation of hydrology in a watershed in two main components namely, Land and routing phase of the hydrological cycle.

Landphase

Neitsch et al. (2005) describes the land phase of the hydrological cycle for the SWAT to be based on the equation

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad (1.0)$$

Where SW_t is the final soil Water Content (mm H_2O), SW_0 is the Initial soil Water Content , t is the time (days), R_{day} is the amount of Precipitation in day i (mm H_2O), Q_{surf} is the Surface runoff in day i (mm H_2O), E_a is the evapotranspiration in i (mm H_2O), w_{seep} is the water entering vadose zone soil profile in day i (mm H_2O) and Q_{gw} is the return flow on day i (mm H_2O).

Surface runoff

Is computed using a modified Soil Conservation Service (SCS) curve number method. The curve number drops none linearly as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. The SCS curve number is given by the equation (SCS, 1972).

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad (1.2)$$

Where; I_a is the initial abstraction which includes surface storage (mm H_2O) and S is the retention parameter (mm H_2O). The Retention parameter varies due to change in soils, landuse management, slopes and temporal change in soil water content. The retention parameter is given by the equation:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (1.3)$$

Where CN is the curve number for the day. The initial abstraction is approximated by 0.2S (SCS, 1972), hence equation 1.2 becomes:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} - 0.8S)} \quad (1.4)$$

Runoff only occurs when $R_{day} > I_a$. The subbasin time of concentration is estimated using Manning's formula considering both overland and channel flow.

Evapotranspiration

The potential evaporation method used in this study is the Hargreaves Method (Hargreaves and Samani, 1985) which only requires air temperature. It is given by the equation:

$$\lambda E_o = 0.0023 \cdot H_o \cdot (T_{mx} - T_{mn})^{0.5} \cdot (\overline{T}_{av} + 17.8) \quad (1.5)$$

Where λ is the latent heat of vaporization (MJ Kg^{-1}), E_o is the evapotranspiration (mmd^{-1}), H_o is the extraterrestrial radiation (MJ $m^{-2}d^{-1}$), T_{mx} is the maximum air temperature for a given day($^{\circ}C$), T_{mn} is the minimum air temperature for a given day ($^{\circ}C$), and $\overline{T}_{av}$ is the mean air temperature for a given day ($^{\circ}C$).

Recharge

Recharge is the water that moves past the lowest depth of the soil profile by percolating through the vadose zone and contributing to both the shallow and deep aquifer. Recharge to both aquifers in mm H_2O, is given by the equation:

$$w_{rchrg,i} = (1 - \exp\lfloor -1/\delta_{gw} \rfloor) \cdot w_{seep} + \exp\lfloor -1/\delta_{gw} \rfloor \cdot w_{rchrg,i-1} \quad (1.6)$$

Where δ_{gw} is the delay time or drainage time of the overlaying geological formations (days), w_{seep} is the total amount of water entering the aquifers on day I(mm H_2O), and $w_{rchrg,i-1}$ is amount of recharge entering the aquifers on day i-1(mm H_2O) Sangrey et al. (1984). Furthermore, the total amount of water exiting the bottom of the soil profile on day I is given by;

$$w_{seep} = w_{perc,ly=n} + w_{crk,btm} \quad (1.7)$$

Where $w_{perc,ly=n}$ is the amount of water percolating out of the lowest layer, n, in the soil profile on day i (mm H_2O), and $w_{crk,btm}$ is the amount of water flow past lowest boundary of the soil profile (mm H_2O). Neitsch et al. (2005) shows that the swat calculates the amount of water diverted from shallow aquifer to deep aquifer as:

$$w_{deep} = \beta_{deep} \cdot w_{rchrg} \quad (1.8)$$

Where w_{deep} is the amount of water moving into the deep aquifer on day I (mm H_2O), β_{deep} is the aquifer percolation coefficient, and w_{rchrg} is the amount of recharge entering both aquifers on day I (mm H_2O). Hence the recharge to the shallow aquifer is given by

$$w_{rchrg,sh} = \cdot w_{rchrg} - w_{deep} \qquad (1.9)$$

Where $w_{rchrg,sh}$ is the amount of water entering the shallow aquifer on day I (mm H_2O).

Return flow or base flow

Return flow or base flow is the volume of stream flow originating from ground water. Base flow is allowed to enter the reach only if the amount of water stored in the shallow aquifer exceeds a threshold value specified by the user, $aq_{shth,q}$ Neitsch et al.(2005). Based on the steady state response of ground water to recharge used by Hooghoudt (1940) and the water table fluctuation due to non steady state response to ground, the ground water for a given day is given by:

$$Q_{gw,i} = Q_{gw,i-1} \cdot \exp\left\lfloor -\alpha_{gw} \cdot \Delta t \right\rfloor + w_{rchrg,sh} \cdot (1 - \exp\left\lfloor -\alpha_{gw} \cdot \Delta t \right\rfloor)$$
(2.0)

Where $Q_{gw,i}$ is the groundwater flow into the main channel on day I(mm H_2O), $Q_{gw,i-1}$ is the groundwater flow into the main channel on day i-1(mm H_2O), and α_{gw} is the base flow recession constant, Δt is the time step (1day). Neitsch et al. (2005) further shows that given the threshold value for $aq_{shth,q}$ .I then:

$$Q_{gw,i} = 0 \qquad \text{if}$$

$$aq_{sh} > aq_{shth,q}$$
$$aq_{sh} \le aq_{shth,q} \qquad (2.1)$$

Where aq_{sh} is the amount of water stored in the shallow aquifer at the beginning of the day i(mm H_2O).The base flow recession constant is given by:

$$\alpha_{gw} = \frac{1}{N}\left[\frac{Q_{gw,N}}{Q_{gw,0}}\right] = \frac{1}{BFD} \cdot in[10] = \frac{2.3}{BFD} \qquad (2.2)$$

Where $Q_{gw,N}$ is the ground water flow on day N (mm H_2O), $Q_{gw,0}$ is the ground water flow at the start of the recession ,and BFD is the number of base flow days for a watershed.

Routing phase of the hydrological cycle

SWAT assumes the main channels or reach have a trapezoidal shape (Neitsch et al., 2005) .

When using SWAT the user is required to define the depth and width of the channel when filled to the top of the bank, as long as the channel length and slope along the channel length and manning's n value. Swat assumes side slopes of 2:1 or $z_{ch} = 2$. Neitsch et al., (2005) indicates that once the volume exceeds the maximum amount that can be held by the channel, excess water spreads across the flood plain shown below. The flood plain side slopes are approximated to be 4:1.

The manning's equation for uniform channel flow is used to calculate the rate and velocity in a reach segment

$$v_c = \frac{R_{ch}^{2/3} \cdot slp^{1/2}}{n} \qquad (2.3)$$

Where v_c is the flow velocity (m/sec), R_{ch} is the hydraulic radius for a given depth (m), slp is the slope along the channel length (m/m), and n is the manning's coefficient for the channel (Neitsch et al., 2005).

Routing method

To route water to the main channel, the variable storage coefficient method based on the variations of the Kinematic wave model (chow et al, 1988) and initially developed by Williams (1969) has been chosen in this study. The variable storage coefficient is:

$$V_{out2} = SC \cdot (V_{in} + V_{stored}) \qquad (2.4)$$

Where SC is the storage coefficient , V_{out2} is the volume of out flow at end of time step (m^3 H_2O), V_{in} is the volume of in flow during the time step (m^3 H_2O), and V_{stored} is the stored volume during time step (m^3 H_2O)

Channel water balance

Water storage in the reach at the end of the time step is calculated as:

$$V_{stored,2} = V_{stored,1} + V_{in} - V_{out} - t_{loss} - E_{ch} + div + V_{bank} \qquad (2.5)$$

Where $V_{stored,2}$ is the volume of water in the reach at the end of the time step (m^3 H_2O), $V_{stored,1}$ is the volume of water in the reach at the beginning of the time step (m^3 H_2O) , V_{in} is the volume of the reach during the time step (m^3 H_2O), V_{out} is the volume of water flowing out of the reach during the time step, t_{loss} is the volume of water lost trough Transmission via the river bed (m^3 H_2O), E_{ch} is the evaporation from the reach for the day(m^3 H_2O), div is the volume of water added or removed for the day trough diversion ,and V_{bank} is the volume of water added to the reach via return flow from the bank storage (m^3 H_2O) (Neitsch et al., 2005).

A number of parameters presented in the SWAT equations above, can be derived from remote sensing data when ground measurement data is not available. There are various archives of global datasets available online that could be used to access hydrological modeling data. Types of data that is mostly used in hydrological modeling includes; topographic data (SRTM) , soil data (FAO soils maps) , Land use (Global land use maps) and Climate Data (Haguma, 2007). Other databases useful databases for hydrological modeling includes the Gravity Recovery and Climate Experiment (GRACE), a joint mission of NASA and the German Space Agency, this technology , uses gravity to show how mass is distributed around the planet and how it varies over time. GRACE data are important tools for studying Earth's hydrology, geology, and climate (Davis, 2002).

A summary of some of the key inputs needed to run SWAT model on the Kabompo river basin have been listed in table 1. The table also shows how variables were derived from remote sensing data in the Kabompo basin model.

STUDY AREA

The Kabompo river basin lies between Latitudes 11^0S and 15^0S, Longitudes 23^0E and 26^0E in Northwestern and Western Provinces of Zambia. The mean annual rainfall for the Kabompo basin varies between 900mm in the south most to 1400mm in the north (IWRM, 2006). JICA (1995) indicates that distribution of temperature in most parts of Zambia that includes the basin depends on altitude rather than latitude. The average temperature for the Month of July varies from 14°C to 16°C while November temperatures vary between 20 °C to 22 °C.

Kabompo River is one of the main tributaries of the Zambezi River. Some of the tributaries of the Kabompo River are the Lumwana East, Mutanda, West Lunga, Maheba, Mumbeji and the Dongwe. Based on Department of Water affairs discharge data measured at Watopa Pontoon, the Kabompo has an average annual discharge of 210m^3/sec with lowest and highest discharge records of 37 and 1039 m^3/sec respectively, recorded between the periods of the year 1958 and 2007.

Table 1: How variables in SWAT were derived from remote sensing

Parameter (Symbol)	**Parameter Description**	**Remote Sensing / Global database data sets**
R_{day}	Preciptation	TRMM (3B42)datasets data (Tropical Rainfall Measuring Mission) data
E_a	Evapotransipration (Calculated using Hargreaves Method requiring Maximum and Minimum temperature only)	Daily Maximum / Minimum temperature data from European Centre for Medium-Range Weather Forecast (ECMWF)data
CN	Curve Number (Soil Service Conservation Method applied-for infiltration and surface runoff)	CN derived from landuse/ landcover maps of the. Global Land Cover Characterization database (GLCC) from the U.S. Geological Survey and has a 1km resolution (USGS, 2008)
		FAO soil map of Zambia with a scale of 1: 2,500,000
slp	Slope	The Digital Elevation Model used in the SWAT interface was derived from the SRTM image downloaded from the CGIAR-CSI GeoPortal
W	Channel Widith	Approximated using Landsat and Google earth images.
-	Calibration data	ESA radar altimetry data and Department of Water Affairs Records were used to Calibrate and Validate the model

METHODOLOGY

Data

Two types of data sets were needed to successfully apply SWAT model on the Kabompo basin namely, secondary and primary type of data. Primary data collected included locations of all gauging stations, major reservoirs, and commercial abstraction river cross sections of radar altimetry targets. Other data sets were remotely sensed weather data. Primary data collected were mostly used as input and calibration data. Secondary data such as meteorological and hydrological reports were mostly collected from government departments and were used for validation purposes and have not been fully discussed in this paper.

Primary datasets

The main data used as an input to SWAT were, Weather (climate) data, soil, Topography and Landuse data. Among these data sets were; The European Centre for Medium-Range Weather Forecasts (ECMWF) Daily maximum and minimum temperature data. A sub-daily data set with a spatial resolution of 0.25 degrees (27km) from 2000 to 2008 (Berrisford et. al, 2009). Tropical Rainfall measuring Mission (TRMM) 3B42 precipitation data. TRMM is a satellite based program used to measure tropical rainfall and to quantify the associated distribution and transport of latent heat, which drives the global atmospheric system (Wolf et al, 2004). TRMM (3B 42) representing most parts of the Kabompo basin and covering the period between 1998 to 2006 were used in the Model. Soil data used was extracted from a FAO soil map of Zambia with a scale of 1: 2,500,000. The map is based on the soil survey done in 1983 by Mt. Makulu Research Station in Zambia and compiled by the National Council for Scientific Research. Topography data was extracted from a Digital Elevation Model derived from the SRTM image. The

SRTM 90m Digital Elevation Model 's have a resolution of 90m at the equator, and are provided in mosaiced 5 deg x 5 deg tiles for easy download and use. They can be downloaded from the CGIAR-CSI GeoPortal website (http://srtm.csi.cgiar.org/). Finally, land cover/ landuse maps used are for the Global Land Cover Characterization database (GLCC) from the U.S. Geological Survey and has a 1km resolution (USGS, 2008).

Analysis

Two main software ArcGIS and ArcSWAT were used for analysis of data. ArcGIS being the main software was used to compile all the data into computable SWAT input data sets mostly in dbf. File format. The interface between the model SWAT and ArcGIS is called ArcSWAT. ArcGIS allowed the integration of the main model input data sets (precipitation, temperature, topography, soil data and landuse data) which had varying spatial resolutions. In the model, the coordinate system (projection) for the input data sets were set to UTM WGS84 before being load in SWAT.

ArcGIS calculates basic hydrologic information for the model (i.e. surface slope, water flow paths), it also calculates the position and the size of the hydrologic response units, and provides the necessary files which are used by the SWAT model (Winchell et al., 2007).

SWAT partitions a watershed into a number of sub watersheds or subbasins. The use of subbasins is considered beneficial when different areas of a watershed have different landuses or soil types hence, the application of unique data sets spatially to a sub basin is very possible and the model can also reflect differences in evapotranspiration for various crops and soils.

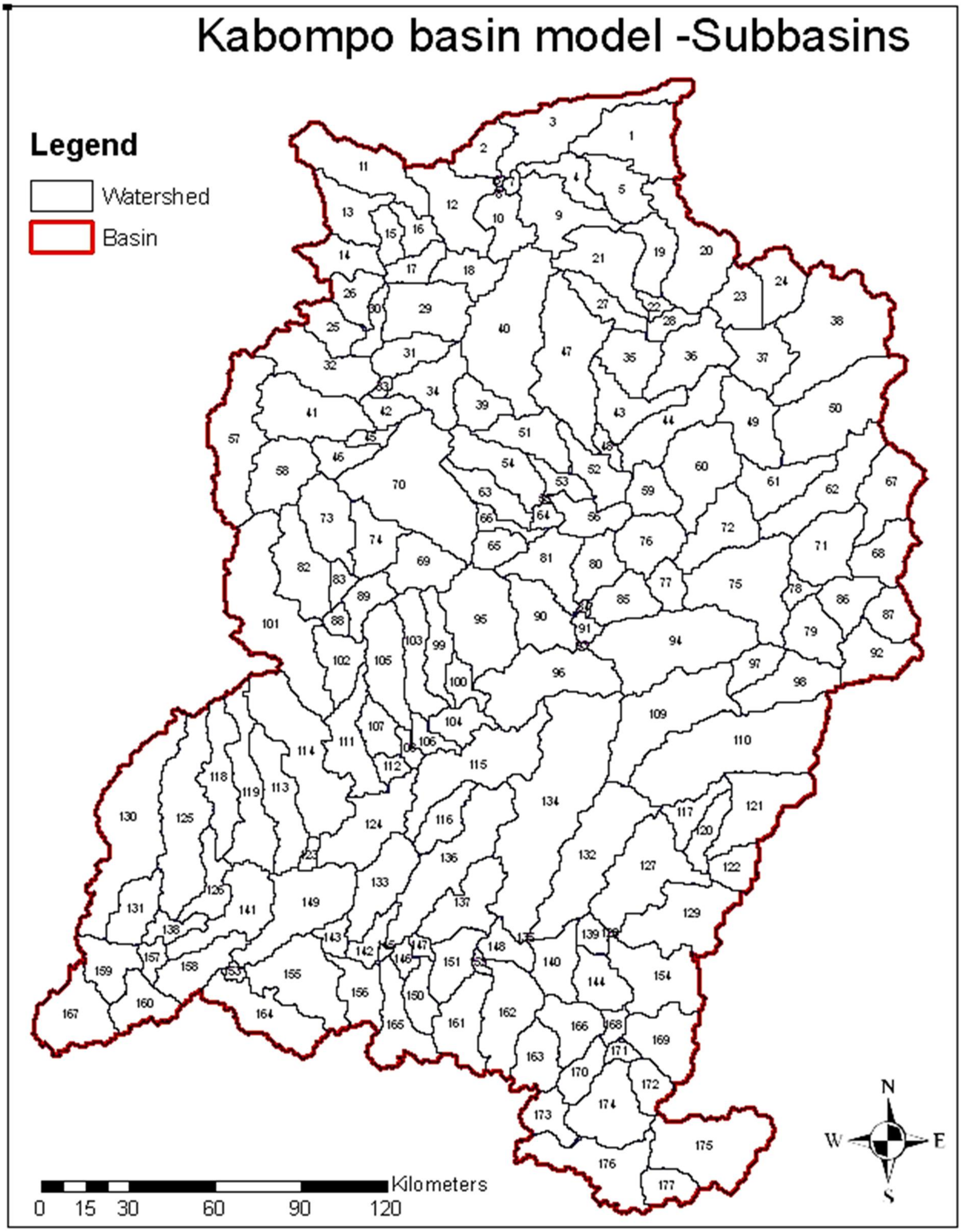
The Kabompo River basin was divided into 177 sub basin (as shown in Figure 1) which were further subdivided into smaller units called Hydrological Response Units (HRU). These are lumped land areas within the subbasin that are comprised of unique landcover, soil and Management (Neitsch et al., 2005). HRU allows for more accurate runoff to be predicted separately for each unit and routed obtaining a total runoff.

The simulated flow from the model was calibrated with radar altimetry values convert to discharge using Manning’s channel flow method. Location of radar altimetry targests, Weather and gauging stations used in the model are shown in Figure 2.

RESULTS

The model was run several times during the calibration process before obtaining satisfactory results. The period between1995 to 2000 was used as a warm up period so that the model could initialize unknown conditions such as ground water properties. Results for five stations mostly radar altimetry targets and two DWA hydrological stations were analyzed. Figure 3 shows results for Radar altimetry Virtue station, Target ERS2-31 and Department of Water Affairs hydrological Station called Watopa pontoon located on the Kabompo River. The temporal resolution for radar altimetry target is about 35days, meaning radar altimetry data is represented by one measurement every month. Simulation results for ERS2-31 against Watopa Pontoon (Subbasin 160 of Hydrological Model) which are only 1.8Km apart showed acceptable correlation of r^2= 0.56 and Ns = 0.46. The daily simulated discharge for this station was also compared with a few DWA observation readings measured between the period September 2000 and April 2006 which gave good results of r^2= 0.934 and Ns = 0.87.

Kabompo basin Watershed



Figuer 1:Subbasins generated by SWAT

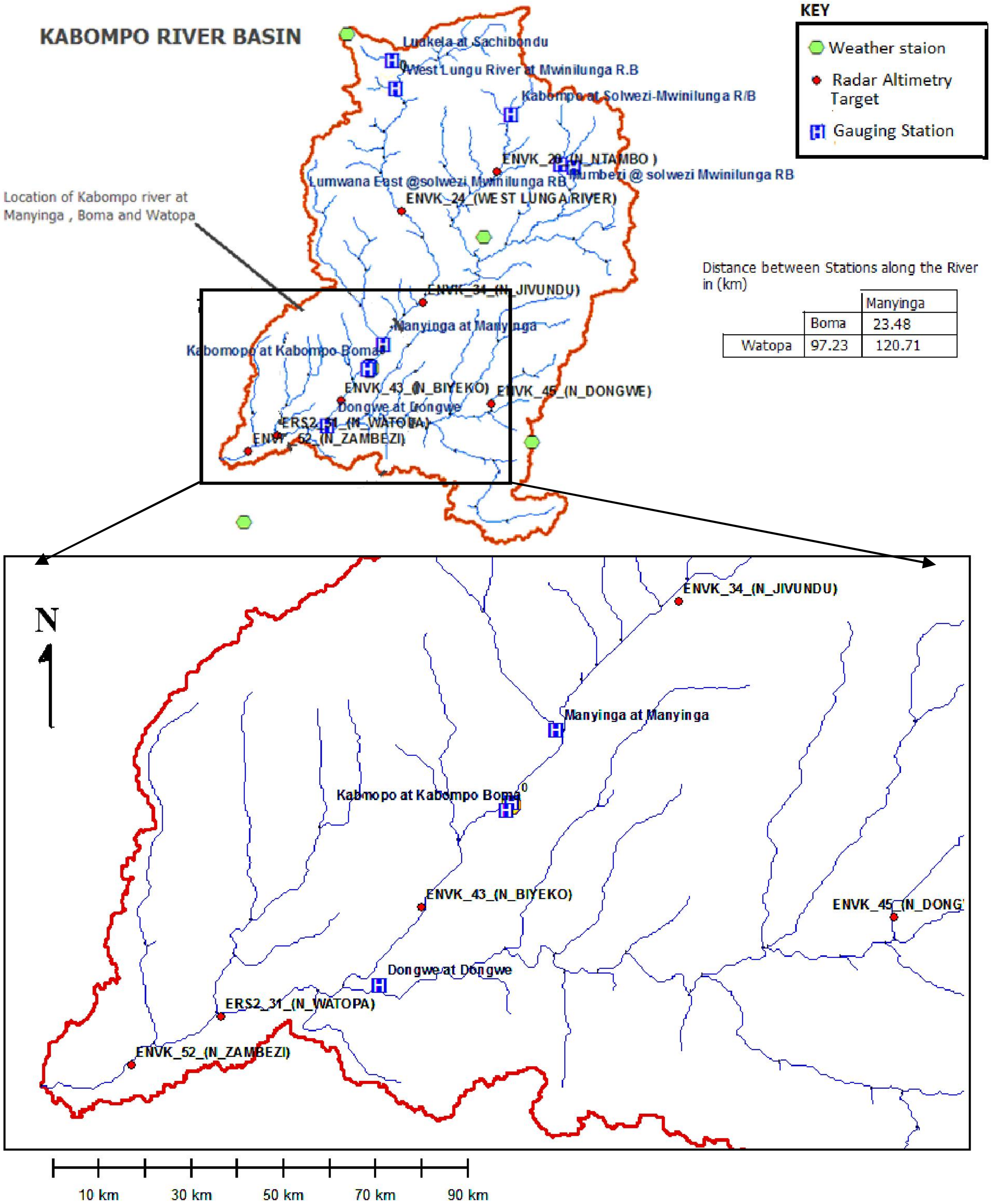


Figure 2: Location of Watopa, Boma and Manyinga with close radar Altimetry targets ENVK-34, ENVK-43, ERS2-31, ENVK-45 and ENVK-52

ERS2-31 and Watopa (Sub-Basin 160)

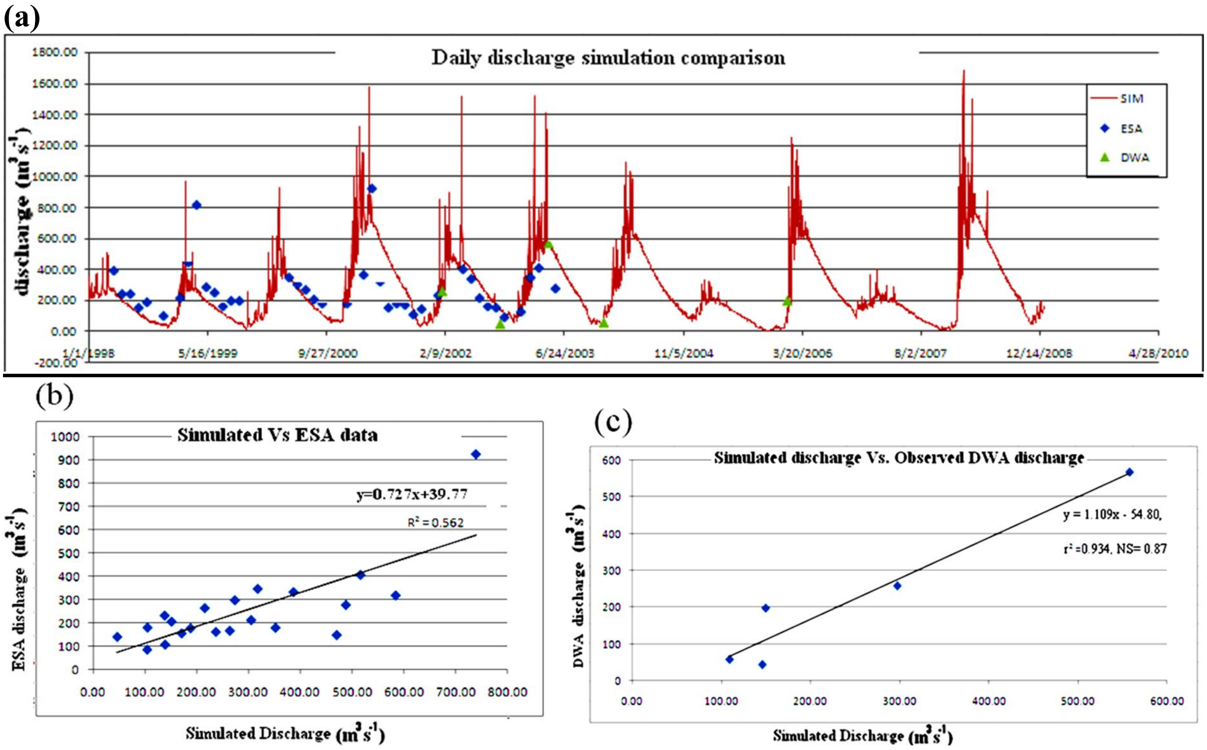


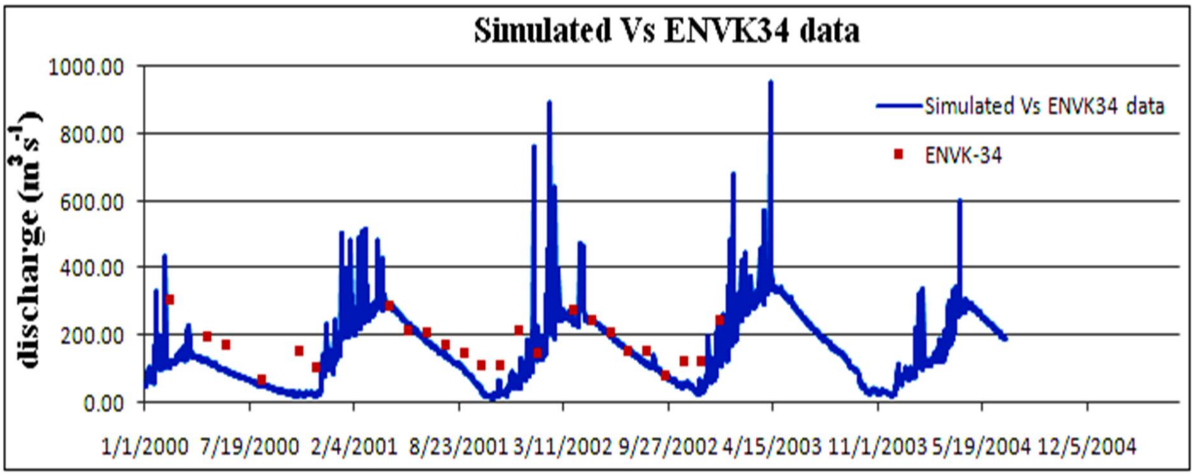
Figure 3: Daily simulation results graphs (a) Daily Simulated flow against ERS2-31 data and DWA data. (b) Scatter plot for Simulated vs. ERS2-31 flow data (c) Scatter plot for Simulated vs. DWA observed data.

Simulation results were also compared with Target ENVK-34 located in subbasin 100 of the hydrological model, 20km downstream the West Lunga National park in the Northwestern Province. Daily simulated results for this subbasin showed reasonable correlation with radar altimetry derived flows with r^2=0.482 and Ns=0.41 (Figure 4).

A plot was also done on Target ENVK-43, located in subbasin 149 of the Kabompo river basin model, 5km upstream Kabulamema Mission located in the south of Kabompo district (Figure 5). Radar altimetry data for target ENVK43 exhibit unrealistic fluctuations which made poor correlation between Simulated and Radar altimetry derived discharge of r^2 = 0.09 and Ns = 0.47. In this case low correlation may be attributed to changing radar position on the target which was observed when locating targets on the ground.

Comparisons were also done between monthly simulated data against average monthly discharge data from the Department of Water Affairs Database. Depending on the availability of flow records for a particular station, average monthly values for a period of 2 to more than 20 years were used. The average values create a basis for comparison because there is insufficent or no observed data for most stations in the Kabompo basin . Average values from DWA records help to determine the practical discharge range of a river or stream. For example, DWA records for Lumwana East river located in subbasin 50 of the model, had average flow values for the month of April of about 21 m^3 s^{-1} from 1976 to 1978. Simulated data for the same sation in the month of April , show a value of 12 m^3 s^{-1} . Table 2 summaraises results for three other sations Figures namely;Kabompo river at Manyinga, West Lunga River at Solwezi Mwinilunga Road Bridge and Luakela River at Sachibondo.

ENVK-34 (sub-basin 100)



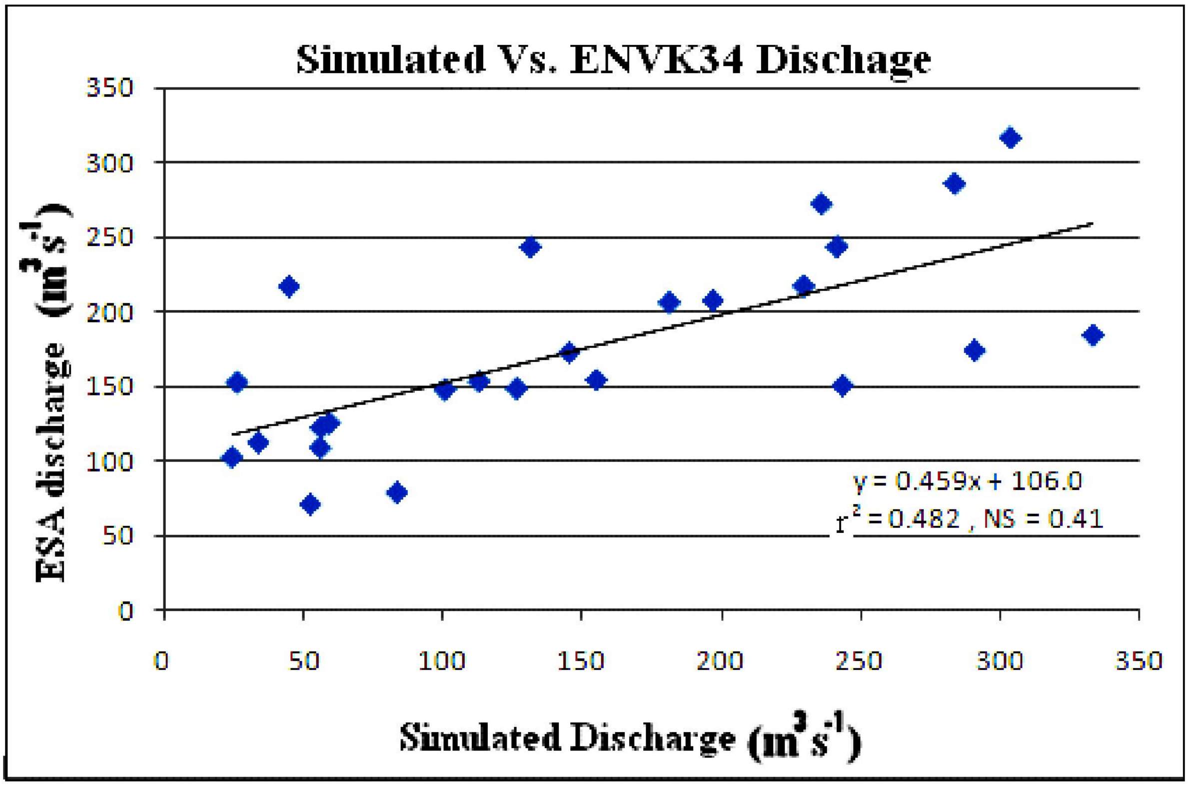
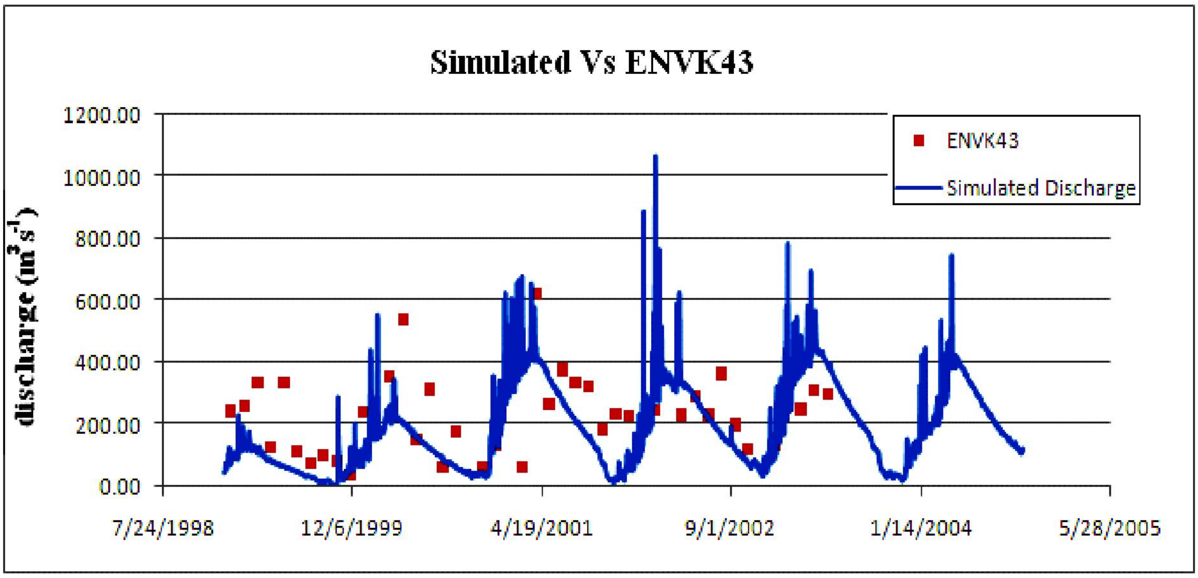


Figure 4: Simulation results graphs for ENVK-34 near Jivundu **(a)** Simulated flow against ENVK-34 **(b)** Scatter plot of daily simulated flow vs. ENVK-34 data

ENVK-43 (Sub-Basin 149)



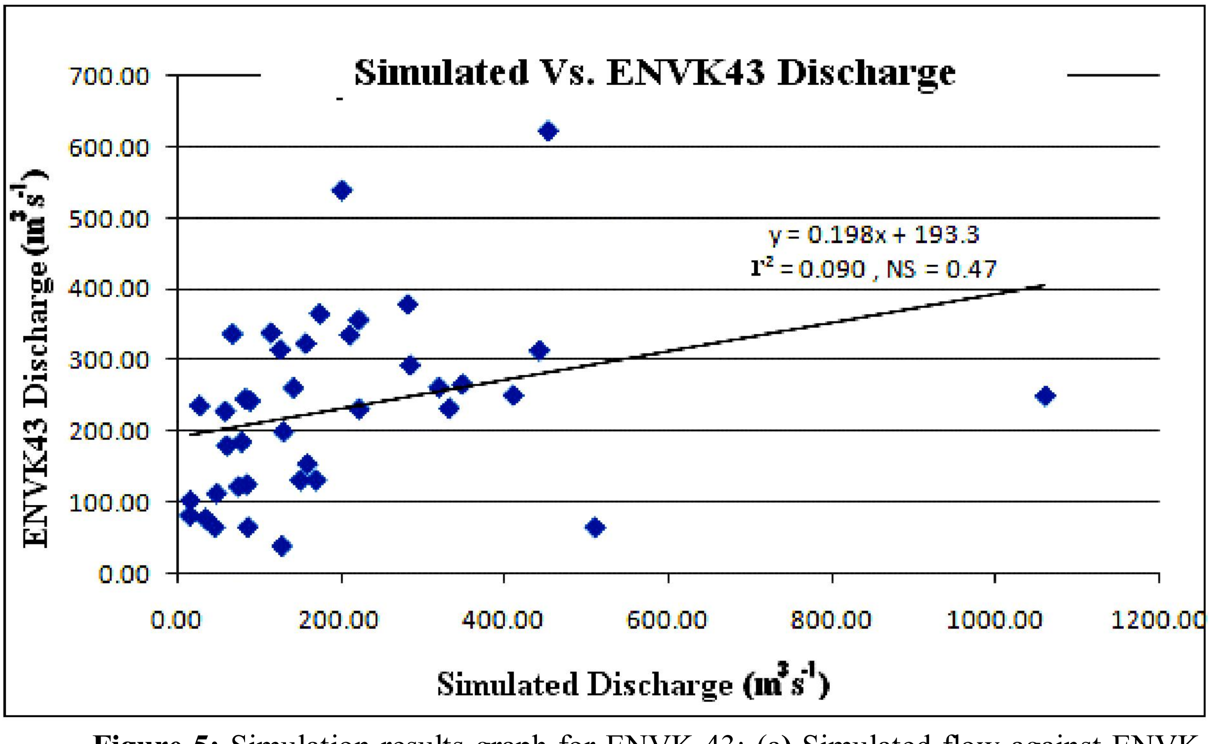


Figure 5: Simulation results graph for ENVK-43: (a) Simulated flow against ENVK-43 near Biyeko Village **(b)** Scatter plot of daily simulated flow vs. ENVK-43 data

Table 2: Comparison of simulated discharge against observed monthly average DWA data

S/N	River / Station	Sub-basin	Simulated discharge ($m^3 s^{-1}$)		DWA Discharge ($m^3 s^{-1}$)	
			Maximum	**Minimum**	**Maximum**	**Minimum**
01	Lumwana East at Solwezi-Mwinilunga Rd. bridge	50	18.3	0.12	21	0.35
02	Manyinga River at Manyinga	111	28.7	1.2	25	0.9
03	West Lunga River at Solwezi-Mwinilunga Rd. bridge	16	88.6	0.14	110	32
04	Luakela River at Sachibondo	11	12.9	0.3	25	2.1

Possible applications for the model

The generated stream flow values from the model are available for almost any important river or stream in the Kabompo basin including those located in active economic and industrial zones such as the mines or commercial farms. This therefore is an assurance that the generated stream flow values can be safely used in various water resource management applications including water allocations (under water rights), approximation of trace elements and sediment movements in the basin by using the flows alongside soil and sediment sampling results. Effects of landuse changes on the river flow regime can also be studied by relating the rate of landuse change to stream flow.

Discussion

ArcSWAT with remote sensed data were successfully applied on the Kabompo basin to derive river flow data. Based on the input data from the database, the model was able to simulate stream flow parameters successfully. The model operates on a daily time step using input data to account for some spatial differences in channel morphology, soils, landuse, climate and topography. The developed model is availed in a soft-copy and can be run from any computer without ArcGIS by using SWAT editor.

A validation exercise conducted on remote sensed weather data (precipitation and temperature) for six Zambian towns yielded results with RMSE values ranging from 0.090 to 0.934. One noticeable anomaly that could have affected the simulation results was the TRMM data set's failure to quantify the amount of precipitation correctly even though the timing was perfect. This anomaly was probably caused by the difference in actual location of the correcting rain gauge and the TRMM co-ordinates. The validation results do not imply TRMM data is of poor quality because Wolf et al, (2004) conducted a ground validation of space-based rain estimates from the TRMM satellites for 10 sites located around four continents and got correlation coefficients (r^2) as good as 0.96. Their technique included a broad distribution of rain gauges spread across a site covering a radius of up to 100km. For this study, the spatial distribution of precipitation could not be verified because metrological stations used in the verification only have single rain gauges set at the station rather than having a distributed network at a specific grid.

CONCLUSION

Remote sensing is a useful tool for hydrological modeling and generation of hydrological data where it is lacking more especially in ungauged and in accessible areas. This study has applied the soil water assessment tool SWAT together with remote sensing data and successfully developed a hydrological model for the Kabompo basin with various applications. The wide use of remote sensing in Zambia would definitely help improve water resources management.

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