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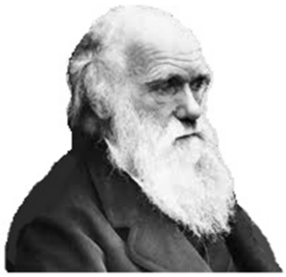

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Modelling of Rainfall-Runoff Relationship in Big-Akaki Watershed, Upper Awash Basin, Ethiopia

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ABSTRACT

Accurate estimation of surface runoff is a challenging task, but it is an important research topic because surface runoff plays a vital role in the study of the hydrological cycle, climate change, water resources, flood management, etc. Surface runoff reflects the amount of water that moves from the watershed into the river system and the amount that is drawn from it. The Big-Akaki watershed has suffered severe flooding due to increasing urbanization, deforestation, as well as reckless use of land and water resources that has led to the appearance of soil erosion. In our work, the SCS curve number was used to estimate runoff from the basin surface, and SWAT was used to delineate the basin and analyze the slope of the watershed, the soil and land uses. In addition, ground control points, interviews and field observation were carried out to collect data on the LULC classification. Moreover, model calibration (1991-1998) and validation (1999-2004) were performed for the monthly flow at the Akaki measuring station. The Big-Akaki watershed has a drainage area of 971,849 km^2. The simulation was carried out by dividing the watershed into 33 sub-basins and assigning a hydrological response unit based on the definition of multiple HRU. The results indicate that SWAT generally works well by simulating runoff according to the result of three objectives (NSE, R^2 and RSR). For surface runoff, the NSE, R^2 and RSR values were 0.81, 0.82 and 0.44 during the calibration and 0.77, 0.77, and 0.48 during the validation period, respectively. Finally, the annual average precipitation and surface runoff of the Big-Akaki basin is 1,183.56 mm and 227.634 mm, respectively. In addition, the results showed a direct relationship between rainfall and surface runoff.

Keywords: Stream flow, Big-Akaki watershed, LULC, SWAT

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1. INTRODUCTION

Currently, there has been a growing interest in understanding hydrological connectivity processes [1], such as surface runoff (SURQ) ([2, 3, 4]. Surface runoff is an important component in the circle of water balance and is linked to numerous environmental issues, for example, excessive runoff causes soil erosion and water pollution [4] and [5], degradation of the land [6], floods [7] and habitat destruction [8]. Surface runoff is defined as the part of the rain that is not observed by the infiltration of the soil, and that flows by land into river systems and is carried to the sea. All of this depends on the amount of rain, the intensity of the rain and infiltration capacity [9].

Nowadays, hydrological models are good for representing hydrological characteristics [10]. Although many studies have been carried out using these basin scale models to estimate Q [11, 12], using the SWAT, HBV and VIC models. Little attention has been given to tropical regions with the exception of applying the SWAT model as in [13] and for Ethiopia in [14, 15]. According to [16], the increase in urbanization has affected both the runoff behavior and the balance that exists between evaporation, recharge of groundwater and discharge of currents in specific areas and in complete watersheds, with consequences considerable for all water users.

The highland areas of Ethiopia, which range from approximately 1000 to 4533 m a.m., hold the majority of the country's population [17]. It is also known that half of the country is covered by this elevation range. More than 90% of the highlands were once forested. Today, the percentage of forest cover is decreasing dramatically due to human activity. The result of the extensive deforestation is increased surface runoff throughout the country in general and in the highlands in particular [17]. The Big-Akaki watershed is the main part of the Upper Awash basin, which includes most of the city of Addis Ababa and some cities around the city. The city has grown since its founding and the rapid transformation of land from rural to urban uses has occurred more than anywhere else in the country. Indeed, during the last 100 years, there has been a serious transformation of rural land to urban development such as buildings, transport networks, shopping centers, various types of industries, parks and recreational areas.

Therefore, the intention of this study was to identify the rainfall-runoff relationship of the Big-Akaki watershed by using a SWAT (Soil and Water Assessment Tool) model with physical basis and spatial distribution.

Description of the study area

Big-Akaki Watershed (**Figure 1**) is located in central Ethiopia along the western margin of the main Ethiopian rift valley. The watershed is located at the north-western Awash River between 8°46’–9°14’ N Latitude and 38°34’–39°04’ E Longitude. The Big Akaki watershed has a coverage of about 971.849 km^2. The topography is undulating and form plateau in the northern, western and southwestern parts of the city, while gentle morphology and flat land areas characterize the southern and southeastern parts of the city [18].

The range of mean annual rainfall for the stations in the period 1985-2016 is 1183.56 mm. The mean monthly rainfall between June to September is above 100 mm, with monthly maximum rainfall record 298.88 mm in August, while November to January shows the lowest mean monthly rainfall record 9.6 mm. The maximum temperature of Addis Ababa ranges between 21 ºC (in wet season) to 26 ºC (in dry season), while the minimum falls between 8 ºC to 12.5 ºC in the year.

The major soils types in this watershed are Chromic Luvisols, Verti Cambisols, Water, Eutric Vertisols, and Humic Nitisols having coverage of 21.06%, 1.99%, 0.72%, 60.42% and 15.81%, respectively (**Tables, 1**, **2**).

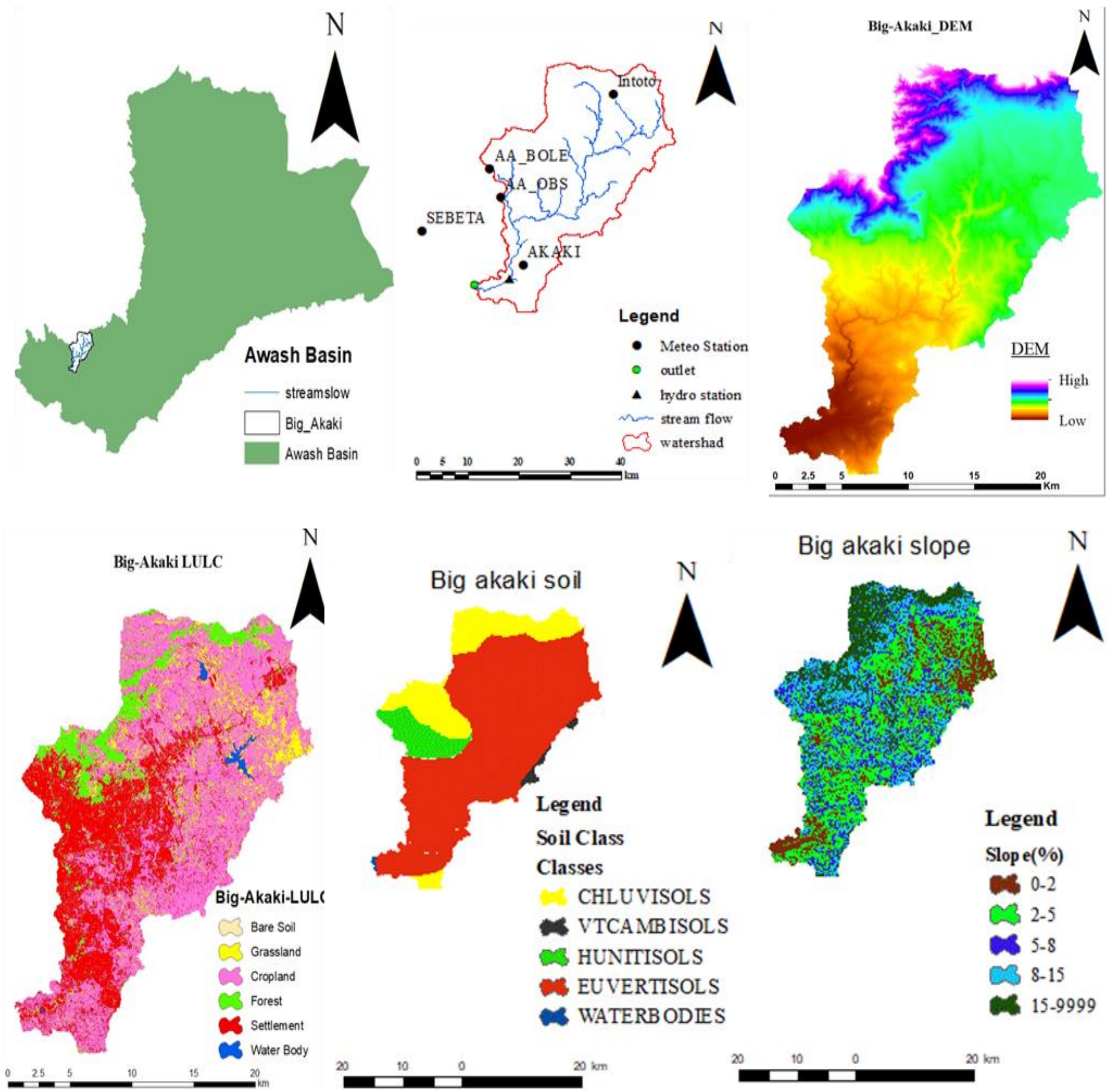

Figure 1. The study area and Awash basin

Table 1. Soil Big-Akaki Watershed

Major Soil	Area Coverage (km^2)	Area (%)	Texture
CHLUVISOLS	192.30	19.79	Loma
EUVERTISOLS	701.48	72.18	Clay
HUNITISOLS	66.96	6.89	Loma
VTCAMBISOLS	10.00	1.03	Clay
WATERBODIES	1.11	0.11	Water

Table 2. Slope of Big-Akaki Watershed

Slope Class	Area Coverage (km^2)	Area Coverage (%)
0-2	143.17	14.73
2-5	342.39	35.23
5-8	162.8	16.75
8-15	170.26	17.52
15-999	153.22	15.77

2. RESULTS AND DISCUSSION

Methodology

SWAT is a physically based, continuous model and is computationally efficient, enabling users to study long-term impacts and is a long-term yield model [19]. The model simulates surface runoff volumes and peak runoff rates for each hydrologic response unit (HRU) using a modification of the SCS curve number method [20] or the Green & Ampt. infiltration method [21]. The evaporation from soils and plants are computed separately by the method described in [22]. Wherein, the potential evapotranspiration (PET) is the ET rate of a large area completely and uniformly covered with growing vegetation and an unlimited supply of soil water.

In addition, the micro-climatic processes such as advection or heat-storage should not have effects on PET. The model uses Hargreaves [23], PriestleyTaylor [24] and Penman-Monteith [25] approaches for the estimation of PET.

SWAT simulates the hydrological cycle based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where: SW_t is the final soil water content at the end of i days (mm), SW_o is the initial soil water content (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

When the rate of precipitation exceeds the rate of infiltration, surface runoff will be generated.

The SCS curve number equation is:

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

where: Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), S is the retention parameter (mm).

The retention parameter is defined by equation:

$$S = 25.4\left(\frac{100}{CN} - 10\right) \quad (3)$$

where: CN is the curve number for the day and it is a function of land use, soil permeability and antecedent soil water condition.

Input Data for SWAT

SWAT requires four groups of input data including topography, LULC, soils and climatic data.

- The topographic dataset commonly used is a Digital Elevation Model (DEM), which is employed to generate drainage network, flow directions, flow accumulation, etc. for the topographical model's parameterization.
- The Land use/land cover (LULC) map (Figure 1) of six classes (excluding cloud) was produced from Landsat scenes acquired in 2018 with 30×30 m spatial resolution, seven bands of reflections. The map was classified using the supervised method in ERDAS IMAGINE software. The ground truth data was collected. The accuracy of the classification was examined by calculating the user, producer accuracy and Kappa statistics for categorized classes (**Table 4**). The data shown within the table indicates the precision of the classification is at a good level with an overall accuracy of 93.96% and the Kappa coefficient of 0.922.
- Various physical and hydrological properties of soils are required by the model such as texture, hydraulic conductivity, bank density etc.
- Climatic data required by the model includes daily rainfall, minimum and maximum temperature, wind speed, relative humidity, solar radiation and dew point temperature. This data can be read from measured data set or generated by a weather generator algorithm. We collected this data from the gauges (Figure 1) recorded from 1st January 1985 to 31st December 2016.

Model Calibration, Validation and Simulation

Stream flow sensitivity analysis was carried out to get the best sensitive parameters for Big-Akaki watershed in SWAT-CUP. Manual calibration for 8 years' period from 1991–1998 was performed at monthly time step using SUFI-2. The aim of calibration process is to create agreement between the simulated and observed value by adjusting the sensitive flow parameters in the recommended range and finally, after calibrating and getting acceptable results the model was validated for the simulated stream flow for 6 years' period from 1999–2004 was performed.

For this study, model simulation was evaluated using efficiency criteria such as Nash and Sutcliffe simulation efficiency (NSE), coefficient of determination (R^2) and Root mean square error observation standard deviation ratio (RSR). In general, NSE and R^2 are used to evaluate the model ability to reproduce the pattern of the observed hydrograph.

Land use/land cover analysis

Spatial analysis was carried out to describe the LULC change for 2018. The land cover map showed dominantly covered with Cropland with 51.37% coverage followed by settlement, forest and grassland with 29.79%, 8.3% & 8.54%, respectively (**Table 3**). Bare soil and water body covers small percentage i.e. 1.39 % and 0.61%, respectively. Likewise, [26] showed that the Settlement area was 31.51% and Forest land was 11.90% for Akaki watershed during 2015.

Table 3. LULC of Big-Akaki Watershed

SWAT LULC	SWAT code	Area (km^2)	Coverage (%)
Barren	BARR	13.51	1.39
Range-Brush	RNGB	82.97	8.54
Agricultural Land	AGRC	499.27	51.37
Forest-Mixed	FRST	80.67	8.3
Residential-High Density	URHD	289.52	29.79
Water	WATR	5.91	0.61

Accuracy assessment of land cover classification

Accuracy assessment is an important step in the process of analyzing remote sensing data. It determines the value of the resulting data to a particular user, i.e. the information value. The accuracy assessment is used to determine the degree of 'correctness' of a map or classified image. The confusion matrix/error matrix has numbers as the quantity of sample. Any particular quantity arranged in rows and columns i.e. square matrix, where columns represent the referencing data while row represents the classification data [28].

The overall accuracy for the LULC image are defined as the total correct pixels (major diagonal's sum) divided by the total number of pixels in the provided matrix which is 93.96%. In addition, the overall kappa coefficient for the image was 0.922, i.e. 92.2% better agreement than by chance alone respectively.

Table 4. Error matrix accuracy for the classified image

Classifications	Reference Data							Percent	
	BS	GL	CL	F	S	WB	Total	CE(%)	UA(%)
BS	3	0	0	0	1	0	4	25	75
GL	0	19	2	2	0	0	23	17.39	82.61
CL	1	1	43	0	0	0	45	4.44	95.56
F	0	0	0	30	2	0	32	6.25	93.75
S	0	0	0	0	37	0	37	0	100
WB	0	0	0	0	0	8	8	0	100
Total	4	20	45	32	40	8	149	OA=93.96%	
OE	25	5	4.44	6.25	7.5	0	0		
PA	75	95	95.56	93.75	92.5	100	100	Kappa=0.922	

Bare Soil (BS), Grassland (GL) Cropland (CL), Forest (F), Settlement (S), Water Bodies (WB), Omission error (OE), Commission error (CE), Producer accuracy (PA) and User accuracy (UA) and Overall accuracy (OA).

$$OA = \frac{((3+19+43+30+37+8)}{(4+23+45+32+37+8))} * 100 = 93.9$$

$$Kappa = \frac{(149*(3+19+43+30+37+8)) - ((4*4)\ +(20*23)\ +(45*45)\ +(32*32)\ +(40*37)\ +(8*8))}{((149\hat{}2)\ -((4*4)\ +(20*23)\ +(45*45)\ +(32*32)\ +(40*37)\ +(8*8)))}$$

$$Kappa = \frac{15791}{17132} = 0.922 = 92.2\%$$

Kappa values are characterized as <0 as indicative of no agreements and 0 to 0.2 as slight, 0.2 to 0.41 as fair, 0.41 to 0.60 as moderate, 0.60 to 0.80 as substantial and 0.81–1.0 as almost perfect agreement. Therefore, the overall classification accuracy of the image yielded a Kappa statistic of 92.2% for the 2018 image. This implies that the image classification accuracy was almost perfect agreement.

Stream Flow Modeling

Stream flow sensitivity analysis was carried out and the ranks of the parameters assigned depending on p-value and t-stat (**Table 5**). P-value indicates significance of sensitivity and t-stat provides the measure of parameter sensitivity [27].

Table 5. List of Parameters and their ranking based on t-stat and p-values

Parameter	Description	Range	t-stat	p-value	Rank	Significance
GW_DELAY	Groundwater delay (days)	0-500	–3.4	0	1	very high
SOL_Z	Total Soil depth (mm)	0-1	–2.3	0.04	2	high
ALPHA_BF	Base flow alpha factor (days)	0-1	2.02	0.07	3	high
SOL_BD	Moist bulk density	0-1	1.87	0.09	4	high
CN2	Runoff curve number (%)	± 0.25	1.47	0.17	5	medium
SOL_AWC	Available water capacity of the soil layer	0-1	–1.1	0.31	6	medium
HRUSLP	Average Steep Sloppiness	0-1	0.86	0.4	7	low
OV_N	Manning's n value for overland flow	0-1	–0.4	0.73	8	low
CANMX	Maximum Canopy Storage	0-100	0.15	0.88	9	low

Manual calibration for 8 years' period from 1991–1998 was performed for the simulated results based on the sensitive parameters ranked in Table 1 at monthly time step using Sequential Uncertainty Fitting program (SUFI). The eleven influential flow parameters from high to low sensitive and which were used for further iterations in the calibration periods is listed in Table 6 below.

Table 6. Summary of calibrated value of flow parameters

Parameter	Description	Range	Calibrated value	Rank
GW_DELAY	Groundwater delay (days)	0-500	63.25	1
SOL_Z	Total Soil depth (mm)	0-1	0.048	2
ALPHA_BF	Base flow alpha factor (days)	0-1	0.19	3
SOL_BD	Moist bulk density	0-1	0.17	4
CN2	Runoff curve number (%)	±0.25	-0.075	5
SOL_AWC	Available water capacity of the soil layer	0-1	0.068	6
HRUSLP	Average Steep Sloppiness	0-1	0.13	7

OV_N	Manning's n value for overland flow	0-1	-0.06	8
CANMX	Maximum Canopy Storage	0-100	51	9

After calibrating manually and getting acceptable values of NSE, R^2 and RSR, Validation of simulated stream flow for 6 years' period from 1999–2004 was performed without changing the calibrated parameter values.

Table 7. Performance evaluation of calibrated and validated sediment yield

Performance criteria	Calibration	Validation
NSE	0.77	0.81
R^2	0.77	0.82
RSR	0.48	0.44

The monthly calibrated and validated results of stream flow for 2018 LULC are presented below (**Figure 2**).

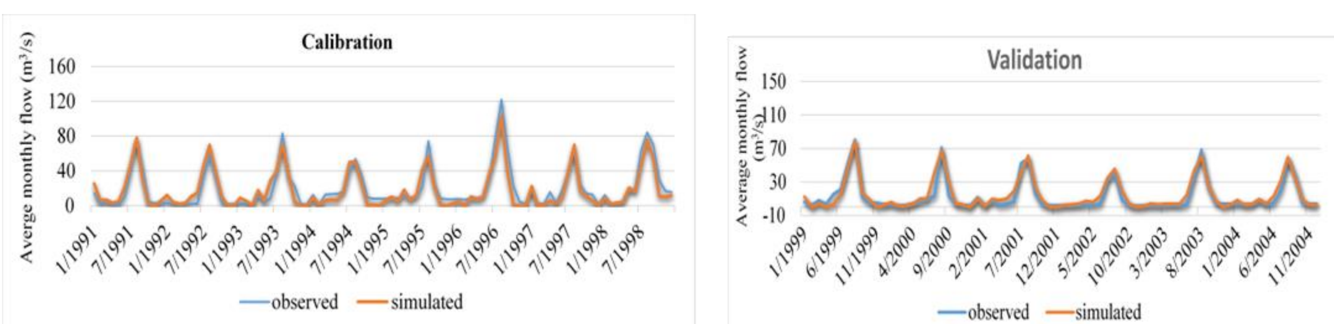

Figure 2. Monthly calibrated and validated stream flow results for 2018 land use

Hydrologic Water Balance

Water balance is the driving force behind everything that happens in the watershed. In SWAT simulation of hydrology of the watershed can be separated in to two major divisions. The first division is the land phase of hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings in to the main channel in each sub basin. The second division is the routing phase of hydrological cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet. As far as this thesis work is concerned the hydrologic cycle mainly focused on only on the movement of water, which is the runoff generation. **Figure 3** shows the total hydrological cycle used in SWAT Model.

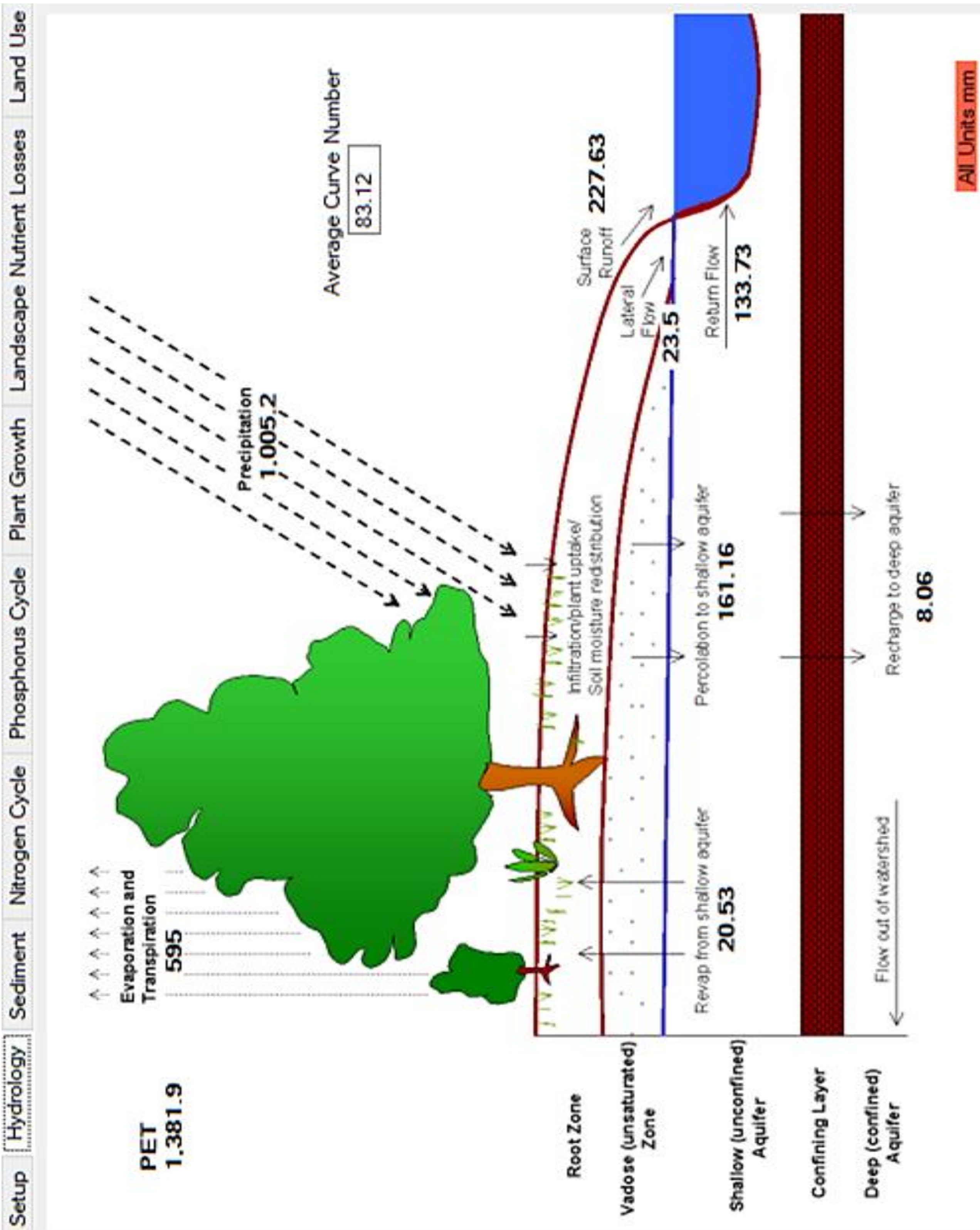

Figure 3. Schematic representation of hydrological cycle used in SWAT model

Rainfall-runoff relationship

After calibration and validation of the SWAT model for Big_Akaki watershed, model simulation was performed from 1991-2016 on monthly bases to observe the relationship between rainfall and runoff in the watershed. The result of this process is shown in the **Figure 4**, the surface runoff has the same pattern with rainfall of the watershed. For instance, if high rainfall was recorded in the watershed, the peak runoff was inevitable.

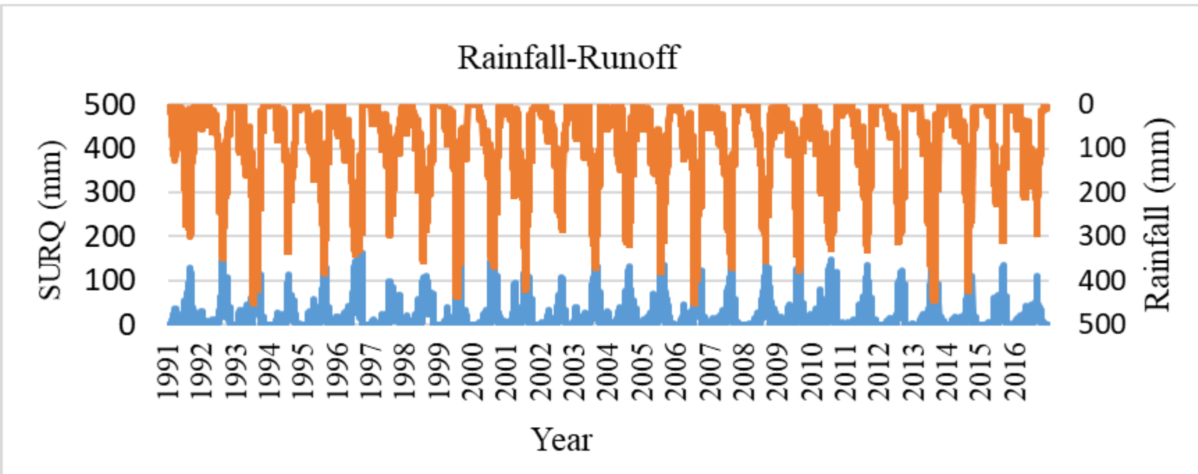

Figure 4. Rainfall-Runoff relation in Big-Akaki watershed

3. CONCLUSIONS

The general objective of this study was to identify the rainfall-runoff relationship of the Big-Akaki watershed through the use of a physical and spatial distribution SWAT. The objective of the project was not to produce highly accurate results for immediate decision-making, but to evaluate SWAT's ability to perform at higher spatio-temporal resolutions. The classification of the LULC images was made in ERDAS IMAGINE 2015 integrated with other GIS data, as a result of runoff and sediment simulations were performed using the SWAT model. The performance of the model for watershed calibration and validation turned out to be a very good agreement with values of Nash-Sutcliffe coefficients (ENS) of 0.77 and 0.81, values of coefficient of determination (R2) of 0.77 and 0.82, and observation of mean squared error standard deviation ratio (RSR) 0.48 and 0.44 for calibration and validation respectively.

To conclude, the annual average rainfall and surface runoff of the Big-Akaki basin is 1,183.56 mm and 227.634 mm, respectively. In addition, the results showed a direct relationship between rainfall and surface runoff.

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