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Modelling the Impacts of Land Use Change on Stream Flow in the Kimwarer Catchment Using SWAT

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Abstract: The Kimwarer River basin covers 138.2 km^2. It has experienced ecosystem degradation due to extensive farming that has impacted on water yield. This study was undertaken to assess the impacts of land use changes on river flow using SWAT, a mathematical model that has the potential to predict the impact of land management practices on water at catchment scale. Current and historic flow data were collected for model calibration and validation. The model was then used to simulate stream flow for different land use and land cover scenarios by varying the extend of forest cover and agriculture. The model was successfully calibrated and validated for stream flow, and proved capable of predicting flow with R^2 and NSE values of 0.79 and 0.31 respectively. During validation, the model predicted flows with R^2 and NSE values of 0.70 and 0.50 respectively. For scenario analysis to determine the effect of land use change on stream flow, it was observed that runoff decreased with increase in forest cover, while base-flow increased. Introduction of terraces as a management operation on agricultural land reduced runoff by 46%. It is evident from the study that the current trend of land use change affects stream flow.

Keywords: Basin, Land Use, Modelling, Stream Flow, SWAT

1. Introduction

Changes in land cover and land management practices have been regarded as the key influencing factors behind the alteration of hydrologic systems, leading to changes in both runoff volumes and water quality [1]. Land use changes can have significant impacts on water and energy balances, directly affecting climatic conditions. The impacts of these changes can become globally significant through their cumulative effects [2].

Most Kenyan farming is rain fed, and occurs where annual and seasonal rainfall patterns are reliable. About 90% of croplands are in areas with high agricultural potential and support about 75% of the country's population [3]. Only about eight per cent of the country's land area is arable, and the agriculturally productive areas in the highlands and their productivity are declining due to population pressure. The pressure on land has resulted in increased land use competition which, in turn, has impacted on natural ecosystems and water resources [3].

The runoff from a watershed indicates both the amount and intensity of precipitation, and the nature of the watershed in relation to the land use/ cover and management aspects. Increasing pressure on land, and especially water catchment zones, has a direct bearing on the quantity and quality of renewable water resources. Dense population coupled with increased agricultural activity upstream in the catchment's settlement areas may lead to reduced flows in dry weather and low water quality during rainy periods [4]. This arises mainly from increased water demand for both agricultural and domestic use, which may reduce base flow during dry weather. Similarly, during the rainy season, increased runoff from densely populated and expansive agricultural areas is normally accompanied by increased sediment loads and other non-point source pollutants which lower water quality. The situation is the same in Tumeiyo, one of the main sub basins of the Kimwarer River.

The Kimwarer River and its distributaries lie in the South Mau Complex draining to the Rift Valley. The area's cover is mainly agriculture and forest, forming part of the greater Mau forest. The forest cover change analysis done between 2003 and 2005 revealed that the Mau forests were being destroyed at an alarming rate [5]. Some 9,813 hectares (roughly 9,295 hectares of indigenous forest and 517 hectares of plantation) were cleared, compared to7, 084 hectares in total (mostly plantation) between 2000 and 2003.

The purpose of the study was to assess the effects of land use changes on the volumetric river flow in the Kimwarer Catchment, using a Soil and Water Analysis Tool (SWAT) model. SWAT was used as it is widely accepted, easy to use and appropriate for the study [6]. Land use cover change scenarios were determined and simulations run to predict their relationship to volumetric stream flow.

2. Methods

2.1. Description of Study Area

The study watershed (Figure 1) is between latitudes 0° 03` and 0° 18` N and longitudes 35° 31` and 35°38` E. It covers 138.2 km^2 at elevations between 2,422 and 2,834m above sea level. The Kimwarer River flows through the Elgeyo Escarpment to discharge into the Kerio River in Kenya's Rift Valley.

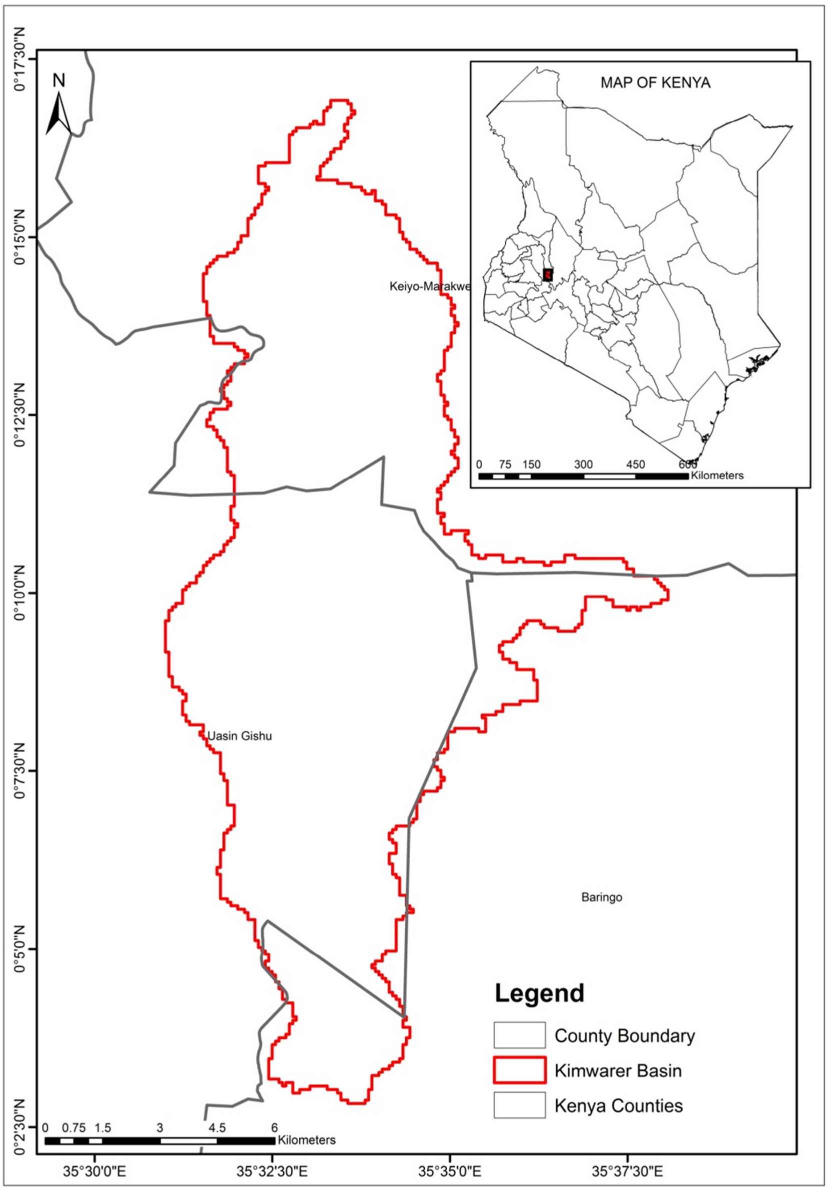

Figure 1. *Study area location.*

The catchment climate is sub-tropical, with moderate temperatures mean 17^{0}C, low evaporation, high rainfall and moderate to strong winds. Most soils in the basin are nitisols with high silt and clay content , according to the Food and Agricultural Organization (FAO) soil classification [7].

2.2. SWAT Input Data

Both surface and satellite derived data were collected for the study. The necessary input data parameters to the model were; digital elevation model (DEM), land use, soils, weather and drainage. A DEM 90 m resolution of the study area was downloaded from CIAT-CSI (http://srtm.csi.cgiar.org) [8] and clipped from the larger DEM path169/row060; UTM zone 37 and datum WGS84.

For land use/ cover data, ground truthing was the first stage in land use layer preparation. The coordinates for the locations of the different vegetation types identified were recorded using GPS. Landsat images 30 m resolution for the study area were acquired from the United States Global Land Cover Facility website [9] and loaded into ArcMap 10.2 for processing. Supervised classification and maximum likelihood method was used for clustering vegetation types. Land cover change over time was examined using available Landsat images for the years 1986, 2000, 2006 and 2010.

A Shape file soil map for the study area was obtained from the Kenya Soil and Terrain database (KENSOTER)[10] Version 2.0 KENSOTER at scale 1:1M compiled by the Kenya Soil Survey (KSS) and ISRIC using SOTER methodology.

Weather data were obtained from the United States National Centers for Environmental Prediction's (NCEP's) Climate Forecast System Reanalysis (CFSR), as the source is readily available as a global reanalysis set, open source and contains the data necessary for SWAT in suitable form [11]. NCEP CFSR data are available globally at 30 km scale for the period 1979 to 2014.

Observed stream flow data from 2000 to 2009 were used for model calibration and validation. Tallal gauging station was selected as the watershed outlet, on which the SWAT model was calibrated and validated.

2.3. Watershed Delineation

ArcSWAT links SWAT with ArcGIS 10.2, it appears in the graphic user interface (GUI) of ArcGIS. Upon project set up in ArcSWAT, a projected DEM was loaded. The catchment delineation tool under hydrology in the spatial analyst extension was directed by ArcSWAT to fill sinks, determine flow directions and identify paths (reaches) in the DEM. Visual analysis was used to determine the likely catchment boundaries based on the selected outlet, with a mask added manually to place the focus on the study area. A threshold value of 65 ha was set to generate the stream network, sub-basin and main basin from the catchment outlet.

2.4. Hydrological Response Units (HRUs) Development

Three parameters are used to define HRUs; land use, soils and slope. A projected land use layer was loaded into SWAT with 100% overlay and a look-up table prepared for land cover classes, with SWAT codes used to fill a SWAT land use classification table. The major land uses identified were; forest (SWAT code 42 FRSE), wetland (92 WETN) and agriculture (82 AGRR). Finally, the representative land cover classes were reclassified to be fed into the SWAT project.

Projected soil layer was then loaded into SWAT, with 100% overlap and a look-up table was used to fill the SWAT soil classification table.

The SWAT model accepts a slope range of 0 to 99%, and five classes were created and reclassified for the study area; 0-5%, 5-15%, 15-25%, 25-35% and 35-99%.

2.5. Running SWAT

The initial simulation before calibration and validation covered the period 1 January 1997 to 31 December 2009. This included 3 years for model warm up, so output began on 1 January 2000. Rainfall distribution was considered skewed normal.

The large number of model parameters prevented normal calibration, as in other models. Instead, SWAT CUP (SWAT Calibration and Uncertainty Procedures), a parameter sensitivity analysis procedure developed for SWAT was used [12]. The analysis was performed to evaluate the influence of input parameters on output and decide if calibration is possible with user modification of selected input parameters.

2.6. Model Calibration and Validation

SWAT CUP, SUFI-2 program (Sequential Uncertainty Fitting, program version -2) linked to SWAT provides an auto-calibration option. The model was calibrated hydrologically with the monthly stream flow from the gauging station from 2000 to 2004. It was validated with the data covering the period 2005 to 2009.

2.7. Performance Evaluation of the Model

Model performance was evaluated to assess how its simulated values fitted with those observed. The coefficient of determination (R^2), which is commonly used, was employed. It describes the proportion of the total variance in the measured data that can be explained by the model. It ranges from 0.0 to 1.0, with higher values indicating better agreement. (1);

$$R^2 = \left[\frac{\sum_{i=1}^{N}[O(i)-O_{avg}][S(i)-S_{avg}]}{\left[\sum_{i=1}^{N}(O(i)-O_{avg})^2\right]^{0.5}\left[\sum_{i=1}^{N}(S(i)-S_{avg})^2\right]^{0.5}}\right]^2 \quad (1)$$

where, *O(i)* is the *ith* observed parameter, *Oavg* is the mean of the observed parameters, *S(i)* the *ith* simulated parameter, *Savg* the mean of the model-simulated parameters, and *N* the total number of events.

The other model performance index used was the Nash–Sutcliffe efficiency (NSE). This, in addition to R^2, is the most widely used method for hydrologic model calibration and validation [13]. NSE values range from negative infinity to one, an NSE of zero or below indicates that the simulation cannot predict discharge, while a value between 0 and 1 indicates that performance falls within an acceptable range of uncertainty. (2);

$$NSE = 1 - \frac{\sum_{t=1}^{N}[q_{obs}(t)-q_{sim}(t)]^2}{\sum_{t=1}^{N}[q_{obs}(t)-\bar{q}_{obs}]^2} \quad (2)$$

Where $q_{obs}(t)$ is the t^{th} observed parameter, $q_{sim}(t)$ the t^{th}

simulated parameter, $\bar{q}_{obs}$ the mean of the observed parameters, and N the total number of events.

2.8. Land Use Change Scenario Analysis

The calibrated model was used for scenario analysis. A single scenario analysis was defined; a change in land use, but terracing was introduced subsequently as a management operation option on agricultural land, for further analysis. The simulation period for the model was the eight years, 2002 to 2009, for which flow data were available, and various land use updates were made on 1 January 2004 for scenario analysis.

2.9. Data Analysis

ArcGIS 10.2.2 was used for geospatial analysis and ArcSWAT 2012 extension, a graphical user interface for SWAT, for modelling. Notepad and Excel were used for data interpretation, presentation, and reporting in tabular and graphical form.

The simulation database was stored in a geographic information database management system and related software. It included: SRTM DEM (30 x 30 m resolution) Kimwarer Catchment, soils, slope, climate data, land use maps and stream flow data for the river.

3. Results and Discussions

3.1. Catchment Delineation and HRU Development

The watershed was fully delineated at Tallal 35°33'40.273" E, 0°15'38.993" N, the selected discharge point from the catchment. The delineated catchment resulted in 93 sub-basins and 714 HRUs. The major land use shown on the maps was agricultural (cultivated row crops, pasture and settled areas) occupying more than 60% of the catchment. The dominant soil type is humic nitisols on KENSOTER map overlay. Slopes in the catchment range from 0 to 35%, with the majority being between 5 and 15% (Table 1). The elevation range is between 2,400 and 2,800 m.a.s.l.

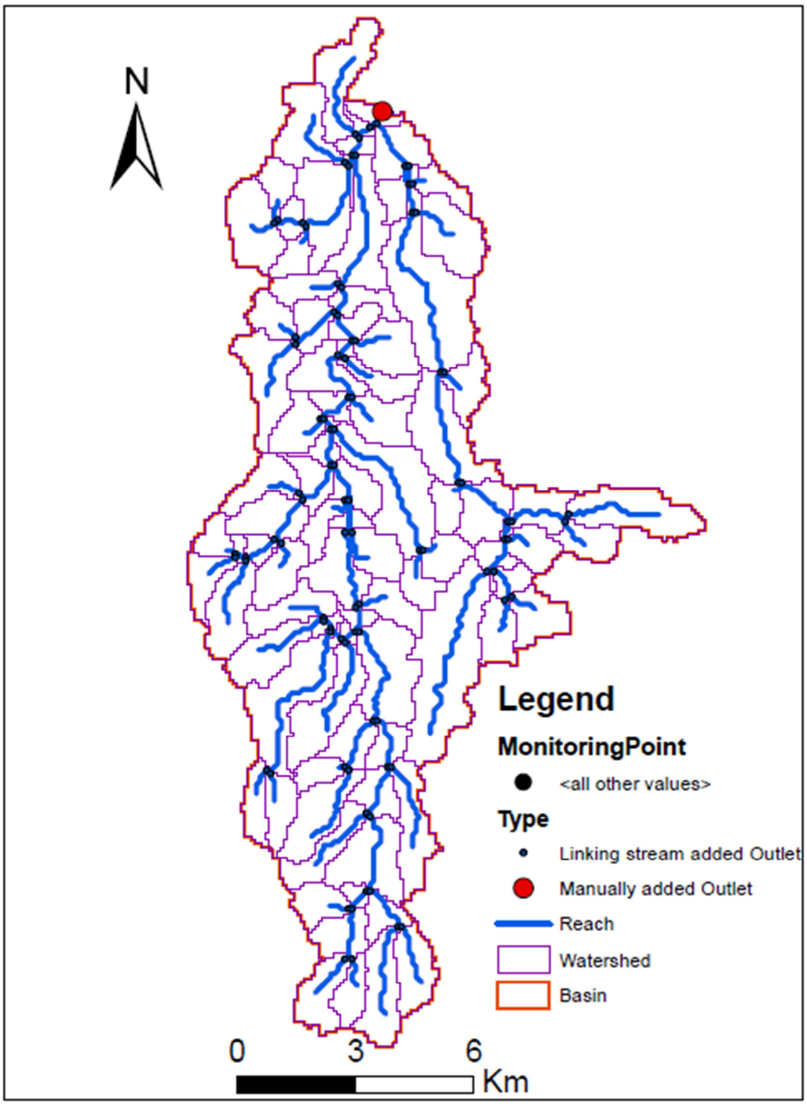

Figure 2. *Delineated catchment showing sub-basins and reach, and discharge gauging station.*

Table 1. *HRU report summary.*

SWAT Model simulation Date: 9/16/2016 12:00:00 AM
MULTIPLE HRUs Land Use/Soil/Slope OPTION THRESHOLDS : 0 / 0 / 0 [%]
Number of HRUs: 714
Number of Sub basins: 93

		AREA [HA]	AREA [ACRES]	%WAT. AREA
WATERSHED		13820	34150	100.00
LANDUSE:				
Wetlands-Non-Forested --> WETN		1502	3711	11
Forest-Evergreen --> FRSE		1611	3981	12
Agricultural Land-Row Crops --> AGRR		10707	26459	77
SOILS:	Humic Nitosols	13820	34150	100.00
	0-5	2282	5638.37	16.51
	5-15	7859	19421.04	56.87
%SLOPE:	15-25	3255	8042.23	23.55
	25-35	379	936.73	2.74
	35-99	45	112.07	0.33

3.2. Model Calibration and Validation

The five most sensitive parameters found were; runoff curve number (CN2 mgt), saturated hydraulic conductivity of soil layer (mm/hr) (Sol_K), groundwater delay (days) (Gw_Delay. gw), base flow alpha factor (ALFA_BF. Gw), and threshold depth of water in the shallow aquifer required for return flow (GWQMN. gw). Any small change in these parameters results in a significant change in the catchment's hydrology.

3.2.1. Model Calibration Results

After several iterations of SUFI-2, a good fit was found for each of the five most sensitive parameters – see Table 2.

Table 2. *Fitted parameter values for calibration.*

Parameter	Cn2. mgt	Sol_K. sol	Gw_Delay. gw	ALFA_BF. gw	GWQMN. gw
Calibrated value/s	80.04	Layer 1; 288 Layer 2; 450 Layer 3; 400 Layer 4; 150	72	0.9	1.4

Figure 3 shows the comparison of observed and simulated monthly flow for the calibration period (2000 to 2004). The model could predict flows with values for R2 and NSE of 0.79 and 0.31, respectively, during calibration. In other words, the performance was low but acceptable. The low performance could be associated with input data deficiencies, especially the simulated weather data from station 2356, which may not have been a good representation for the catchment. The other factor that could have affected performance was the accuracy of observed flow data from the gauging station.

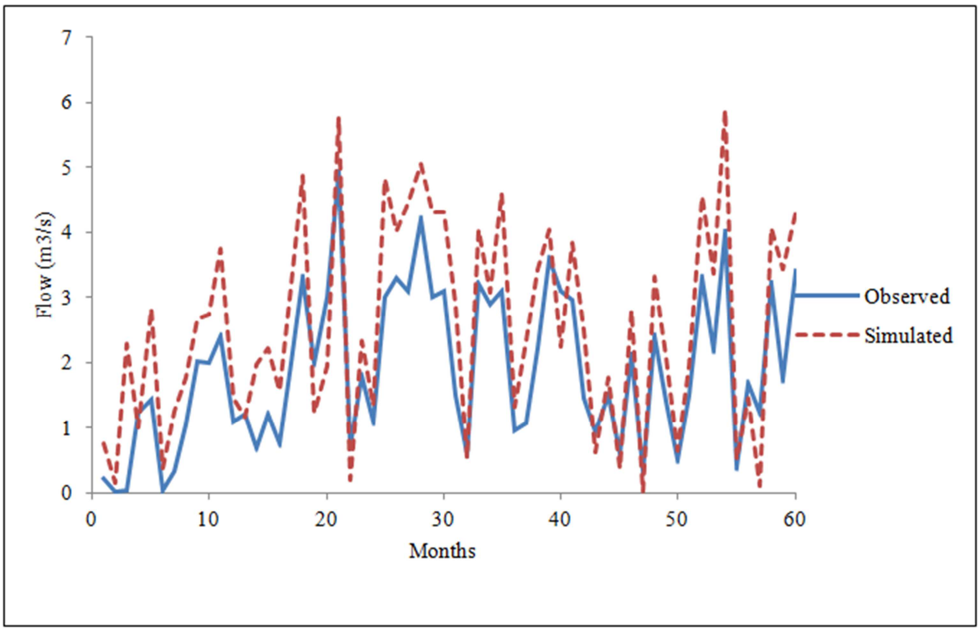

Figure 3. *Outflow graphs for observed versus simulated flow after model calibration.*

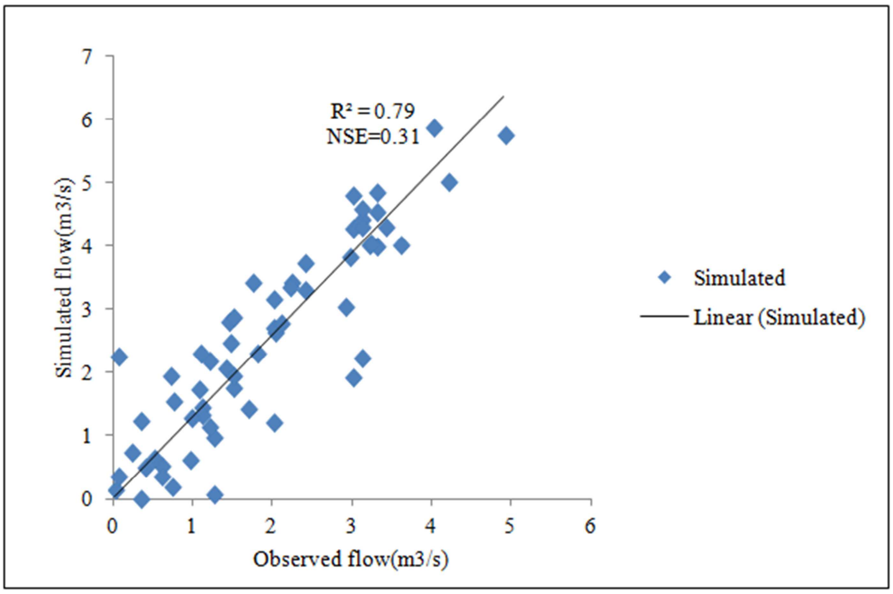

Figure 4. *Scatter diagram of simulated flow on observed flow after model calibration.*

3.2.2. Model Validation

Figure 5 shows the comparison of observed and simulated monthly flows during model validation (2005-2009). The model could predict flow with R^2 and NSE values of 0.70 and 0.50, respectively – i.e., the model simulated flow fairly well for most months. Generally, the model simulated higher flows than were observed.

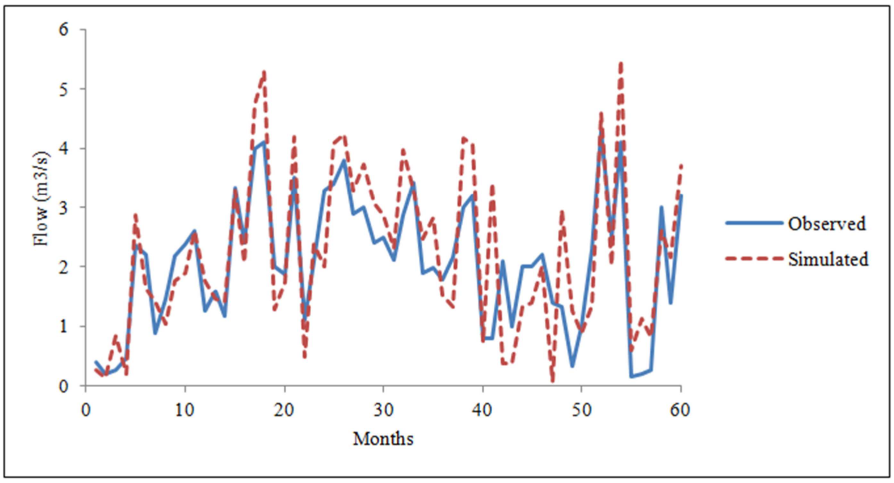

Figure 5. *Outflow graphs for observed versus simulated flow after model validation.*

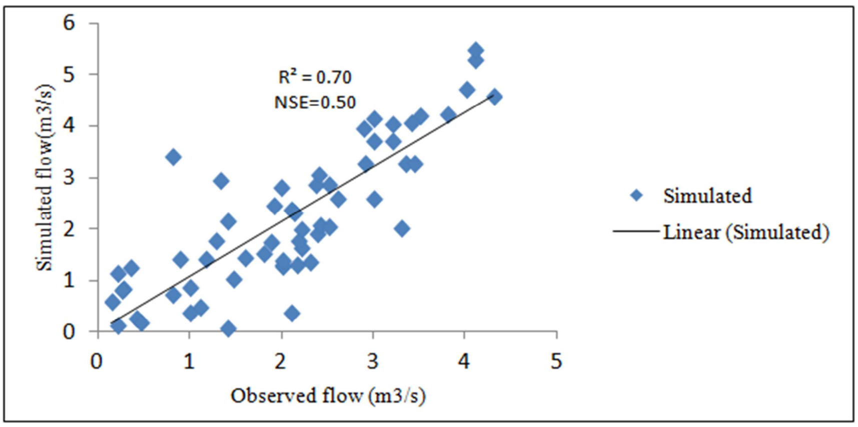

Figure 6. *Scatter diagram of simulated flow on observed flow after model validation.*

3.3. Scenario Analysis for Land Use Change

The annual hydrology are presented in terms of; potential evapo-transpiration (PET), evapo-transpiration, precipitation, surface runoff, lateral flow, return flow, percolation to shallow aquifer, recharge to deep aquifer and “REVAP” from shallow aquifers. REVAP refers to the fraction of water that can be moved from a shallow aquifer into the overlying, unsaturated soil layer.

Six land use scenarios were observed;

84.5% agriculture, 9.7% forest and 5.8% wetland.
100% of agricultural land converted to forest.
50% of agricultural land converted forest.
25% of agricultural land converted forest.
100% of forest land converted to agriculture.
50% of forest land converted to agriculture.

The annual hydrological values determined for the different land use scenarios are presented in Table 3.

Table 3. *Results of hydrologic modelling for different land use scenarios (annual basis).*

Scenario No.	Runoff (mm)	Lateral flow (mm)	Return flow (mm)	Percolation to shallow aquifer (mm)	REVAP from shallow aquifer (mm)	Recharge to deep aquifer (mm)
1	305.87	17.00	9.49	24.61	34.05	1.23
2	206.41	24.32	31.39	59.94	34.05	3.00
3	256.14	20.66	20.44	42.27	34.05	2.11
4	281.14	18.83	14.96	33.44	34.05	1.67
5	327.93	15.05	5.36	17.37	34.05	0.87
6	316.9	16.01	7.42	20.99	34.05	1.05

Table 4 presents the effects of changes in the proportion of forest cover on runoff, lateral flow and base flow. Agricultural land was gradually replaced with forest cover.

Table 4. *Annual water yield with varying forest cover.*

% Forest cover	0	4.85	9.7	30.83	51.95	94.2
Runoff (mm)	327.93	316.9	305.87	281.14	256.14	206.41
Lateral flow mm)	15.05	16.01	17	18.83	20.66	24.32
Base flow (mm)	5.36	7.42	9.49	14.96	20.44	31.39

Forest cover varied from 0 to 94.2% interchangeably with agriculture, while the area of wetland in the catchment remained constant at 5.8%.

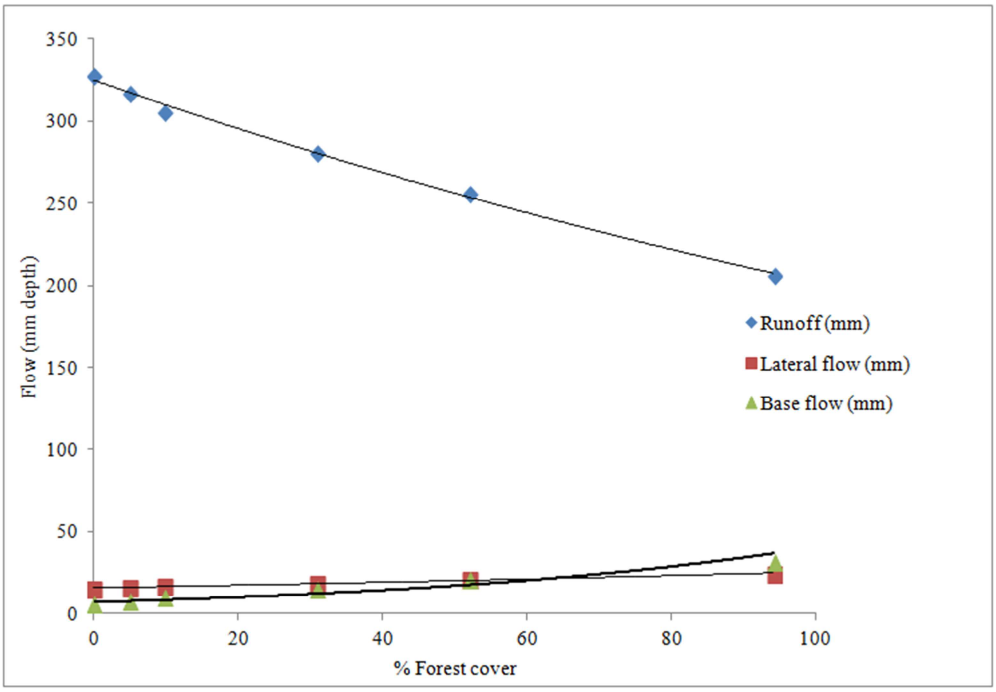

Figure 7. *Combined graphs for runoff and base flow versus percentage change in forest cover.*

Annual hydrological values given by the model for the same six land use scenarios but involving terraced agricultural land are presented in Table 5.

Table 5. *Results of hydrologic modelling for different land use scenarios, including terraced agricultural land (annual basis).*

Scenario No.	Runoff (mm)	Lateral flow (mm)	Return flow (mm)	Percolation to shallow aquifer (mm)	REVAP from shallow aquifer (mm)	Recharge to deep aquifer (mm)
1	165.47	24.65	33.59	63.33	34.05	3.17
2	206.41	24.32	31.39	59.94	34.05	3.00
3	185.94	24.48	32.45	61.64	34.04	3.10
4	175.71	24.56	33.04	64.49	34.05	3.13
5	156.36	24.97	33.99	63.96	34.03	3.2
6	196.18	24.40	31.94	60.79	34.05	3.04

The area of terraced agricultural land (SL; 50 m) area varied from 0 to 94.2%, and wetland remained constant at 5.8%. The effects are summarized in Table 6.

Table 6. *Annual water yield for different LU scenarios of varying terraced agricultural land.*

%Terraced agricultural land	0	21.15	42.25	63.37	84.5	94.2
Runoff (mm)	206.41	196.18	185.94	175.71	165.47	156.36
Lateral flow mm)	24.32	24.40	24.48	24.56	24.65	24.97
Base flow (mm)	31.39	31.94	32.45	33.04	33.59	33.99

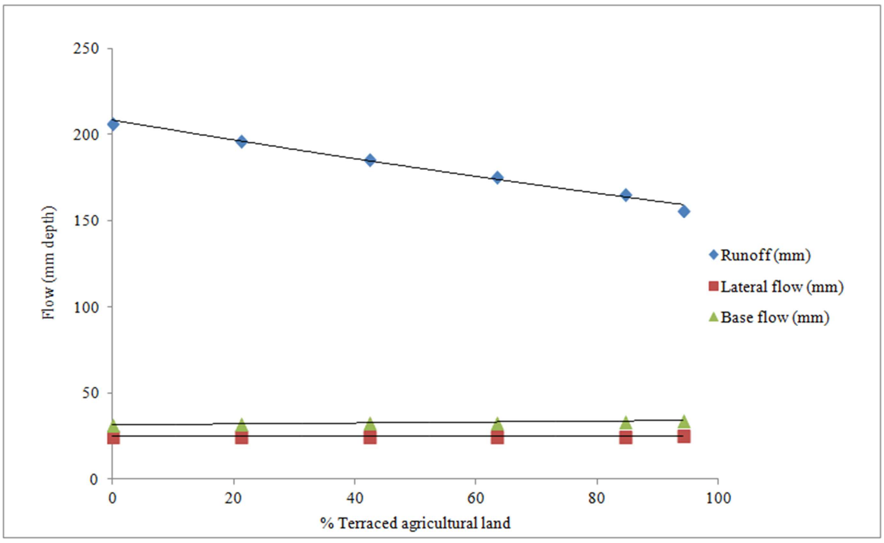

Figure 8. *Combined graphs for runoff, base flow and lateral flow versus percentage change in forest cover; (Terraced agricultural land varied interchangeably with forest cover).*

From scenario analysis on land use change, the model predicted higher runoff when a large proportion of the catchment was under agriculture, with reduced runoff when agriculture was replaced by forest cover (Figure 7). Scenario trends indicate that a 10% increase in forest yielded 4 mm depth increase in baseflow and 22 mm decrease in runoff (Figure 7). The introduction of terraces to manage agricultural land reduced runoff by 46% (Figure 8). Both lateral- and base- flow were low in these scenarios. In a related study on parameterization of the effects of terraces on surface runoff, [14] found that local terraces established on 50% of the watershed reduced surface runoff by 19%.

4. Conclusions

A SWAT model was successfully calibrated and validated for stream flow prediction. The modeling results indicate that catchment hydrologic parameters can be modeled effectively using SWAT.

Modelling different scenarios showed that high runoff occurs when a large proportion of the catchment is under agriculture, with reduced runoff when agriculture is replaced by forest. The model predicted lower runoff when agricultural land was terraced, and that both forest cover and agricultural terraces are effective in controlling runoff.

Acknowledgements

This study was made possible by the contributions of many people. First, I am sincerely grateful to all my supervisors in the study, Dr. J. K. Kollongei and Dr. C. K. Kiptum for continual guidance from the inception of the research to final writing. I also wish to acknowledge the contribution of Prof. E. C. Kipkorir for the technical assistance, insightful comments, and suggestions that enabled me to improve the quality of this research. The contribution of University of Eldoret, directorate of board of postgraduate studies , was instrumental in the overall process.

The encouragement from my family and friends was heartfelt. Finally to the almighty God for in Him we live.

Appendix

Table A1. *Observed runoff quantities from different land use scenarios.*

% Forest cover (interchanged with agricultural land)	0	9.7	30.83	51.95	73.05	94.2
Runoff with unterraced agricultural land (mm)	327.93	305.87	281.14	256.14	231.30	206.41
Runoff with terraced agricultural land (mm)	156.36	165.47	175.71	185.94	196.18	206.41

Table A2. *Monthly observed and simulated flows (m^3/s) – 2000 to 2004 (calibration period).*

Month	1	2	3	4	5	6	7	8	9	10	11	12
Observed	0.21	0.02	0.04	1.24	1.43	0.04	0.33	1.06	2.02	2.0	2.4	1.1
Simulated	0.76	0.15	2.28	1.00	2.83	0.38	1.25	1.76	2.66	2.73	3.75	1.46

Month	13	14	15	16	17	18	19	20	21	22	23	24
Observed	1.2	0.7	1.2	0.75	2.0	3.29	2.0	3.0	4.91	0.72	1.79	1.1
Simulated	1.16	1.97	2.21	1.56	3.19	4.86	1.24	1.94	5.77	0.2	2.32	1.34

Month	25	26	27	28	29	30	31	32	33	34	35	36
Observed	3.0	3.3	3.1	4.2	3.0	3.1	1.5	0.6	3.2	2.9	3.1	0.96
Simulated	4.83	4.01	4.45	5.04	4.30	4.32	2.89	0.54	4.04	3.07	4.61	1.31

Month	37	38	39	40	41	42	43	44	45	46	47	48
Observed	1.08	2.22	3.6	3.1	2.95	1.45	0.94	1.50	0.60	2.10	0.33	2.40
Simulated	2.32	3.43	4.03	2.25	3.84	2.49	0.63	1.77	0.38	2.81	0.02	3.32

Month	49	50	51	52	53	54	55	56	57	58	59	60
Observed	1.40	0.50	1.50	3.30	2.20	4.00	0.39	1.68	1.24	3.21	1.74	3.41
Simulated	2.08	0.65	1.96	4.55	3.36	5.89	0.51	1.45	0.10	4.07	3.44	4.31

Table A3. *Monthly observed and simulated Flow (m^3/s) - 2005 to 2009 (validation period).*

Month	1	2	3	4	5	6	7	8	9	10	11	12
Observed	0.41	0.21	0.27	0.46	2.37	2.21	0.89	1.47	2.18	2.38	2.60	1.27
Simulated	0.28	0.13	0.85	0.2	2.87	1.64	1.42	1.05	1.77	1.91	2.60	1.77

Month	13	14	15	16	17	18	19	20	21	22	23	24
Observed	1.59	1.17	3.34	2.41	4.00	4.10	2.00	1.88	3.50	1.10	2.10	3.29
Simulated	1.46	1.41	3.29	2.07	4.74	5.3	1.28	1.74	4.20	0.5	2.38	2.02

Month	25	26	27	28	29	30	31	32	33	34	35	36
Observed	3.40	3.80	2.90	3.00	2.40	2.50	2.12	2.88	3.43	1.91	1.99	1.80
Simulated	4.09	4.24	3.29	3.73	3.07	2.87	2.32	3.98	3.29	2.47	2.82	1.53

Month	37	38	39	40	41	42	43	44	45	46	47	48
Observed	2.16	3.00	3.20	0.80	0.80	2.10	1.00	2.00	2.00	2.20	1.40	1.32
Simulated	1.32	4.17	4.05	0.74	3.42	0.38	0.38	1.32	1.40	2.01	0.08	2.96

Month	49	50	51	52	53	54	55	56	57	58	59	60
Observed	0.34	1.00	2.30	4.30	2.50	4.10	0.15	0.21	0.26	3.00	1.40	3.20
Simulated	1.27	0.88	1.36	4.59	2.04	5.5	0.59	1.14	0.82	2.60	2.16	3.71

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