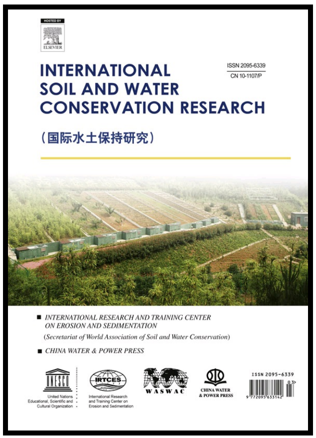

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Modelling the Impacts of Structural Conservation Measures on Sediment and Water Yield in Thika-Chania Catchment, Kenya

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Abstract

Recently, there have been a growing need to implement soil and water conservation measures in order to control sediment and water yield from agricultural areas. The objective of this study was to use a modelling approach to evaluate the impacts of structural conservation measures on water and sediment yield from Thika-Chania catchment in Central Kenya. SWAT model was calibrated and validated for stream flow and sediment yield at selected gauging station in the catchment. The calibrated model was run to create a base scenario for the simulation structural conservation methods i.e. terraces and grassed waterways. Model simulation results indicated that terraces and grassed waterways would significantly impact on water and sediment yield at the catchment outlet. Terraces were found to provide the greatest reduction in sediment yield by 80.7% from the baseline scenario while grassed waterways reduced sediment yield by 53.90%. Terraces indicated a reduction in surface runoff by 30.25% from the base annual average value of 202.28 mm. This was attributed to the increased infiltration that was indicated by increase in base flow by 8.35%. However, grassed waterways did not indicate any significant reduction in water yield. The results of this study show that structural conservation measures could reduce sediment yield from cultivated areas by more than 50% at the sub-catchment level. Results also indicated that the effectiveness of structural conservation measures can be increased by implementing more than one method. Structural conservation measures studied in the current study were found to have a positive impact in controlling water and sediment yield in the catchment. However, further studies need to be conducted to evaluate the costs and benefits of implementing them at small scale level.

Keywords: Terraces, grassed waterways, SWAT, conservation measures, sediment yield

1. Introduction

Across the world, soil erosion is an ecosystem problem that greatly reduces the productivity of soil and water quality leading to ecosystem degradation. Approximately more than half of the agricultural lands in the world are impacted by soil erosion leading to deterioration of water flow regulation and purification (Cohen, Brown, & Shepherd, 2006). In Africa, studies indicate that approximately 5 t/ha of top soil are washed to the water bodies annually (Angima, Stott, O'Neill, Ong, & Weesies, 2003). Due to degradation of water resources from soil erosion and unsustainable utilization of catchments, Kenya spends approximately USD 30M annually to mitigate water resources degradation (Mogaka, Gichere, Davis, & Hirji, 2006). A baseline survey conducted in Thika-Chania catchment shows that soil erosion is a major problem especially in coffee growing areas where more than half of the inhabitants have observed deteriorating water quality particularly in rain seasons (Leisher, 2013).

Soil erosion and sedimentation has led to deterioration of water quality and loss of water storage volume in downstream reservoirs in Thika-Chania catchment that subsequently affects hydropower generation (Archer, 1996; Hunink & Droogers, 2015). Bathymetric survey conducted in the catchment indicate that Masinga and Kamburu reservoirs located downstream of Thika-Chania catchment have observed annual average sedimentation rate of 8.03 and 1.1 Mton, respectively (Hunink & Droogers, 2011). While the catchment provides 90% of water to Nairobi and adjoining areas, soil and water conservation is crucial for the sustainability of these services.

Research conducted in the catchment recommended the implementation of soil and water conservation measures to reduce sediment yield and improve water quality (Hunink, Immerzeel, Droogers, & Kauffman, 2012). However, physical determination of the effectiveness of conservation methods at the farm level is challenging and time consuming. Modelling biophysical processes in the catchment is one approach to determine the impact of implementing structural conservation measures on water and sediment yield.

Modelling soil and water conservation methods have been effective in other studies to assess the impacts of contour farming and vegetative filter strips which among others constitute non-structural conservation measures (Brunner, Park, Ruecker, & Vlek, 2008; Kyalo, Zhunusova, & Holm-müller, 2014; Parajuli, Mankin, & Barnes, 2008). However, little has been reported on evaluating the existing structural conservation measures (i.e. terraces and grassed waterways) in the catchment and their impacts on water and sediment yield. Inadequate knowledge on the impacts of structural conservation measures and inadequate incentive programs to implement them have also led to their low adoption rate (Gathagu, Isiah, Oduor, & Mourad, 2017).The objective of this study was to evaluate the impact of implementing terraces and grassed water ways on sediments and water yield. A combination of the two methods was also assessed to determine their integral effects on water and sediment yield.

1.1. Model review

Different biophysical tools including VIC, InVEST and SWAT have been applied across the globe to model water and sediment yield from catchments (Liang, Wood, & Lettenmaier, 1996; Tallis & Polasky, 2009; Vigerstol & Aukema, 2011). In the present study, SWAT- a physically based model, was used due to its extensive application across the world, combines both the simulation of sediment and water yield and has a good user support. The model has also successfully been applied elsewhere in modelling ecosystem services (Arabi, Frankenberger, Engel, & Arnold, 2008; Bracmort, Arabi, Frankenberger, Engel, & Arnold, 2006; Tuppad, Kannan, Srinivasan, Rossi, & Arnold, 2010). SWAT was further selected because sediment yield estimation uses the MUSLE equation that accounts for antecedent soil moisture and can therefore assess sediments from a single storm (Humberto & Rattan, 2008; Neitsch, Arnold, Kiniry, & Williams, 2005).

1.2. Terraces

Terraces are earthen embankment that are constructed on the dominant slope partitioning the field in uniform and parallel segments (USDA NRCS, 2015). They are mainly installed to reduce sheet and rill erosion from agricultural areas (Bracmort et al., 2006). Terraces implementation in Black Creek sub-watersheds significantly reduced predicted sediment and phosphorus from upland areas (Bracmort et al., 2006). Terraces have also been found to improve soil composition, moisture level and also increase yields due to reduced erosion and improved soil fertility in the Ulugurus mountains in Tanzania (Branca, Mccarthy, Lipper, & Jolejole, 2011).

1.3. Grassed waterways

Grassed waterways are channels of water having grass established along drainage pathways to reduce surface runoff velocity and sediment yield (Humberto & Rattan, 2008). Vegetation planted along the waterways reduce the velocity of surface runoff hence deposition of sediments along the channel. Grassed waterways are implemented in areas where runoff concentrates and then convey it to the outlet (Fiener & Auerswald, 2006).

2. Materials and Methods

2.1. Study area

Thika-Chania catchment covers an area of 840 km^2 and spans over 3 counties in Kenya i.e. Kiambu, Murang’a and Nyandarua as shown in Fig. 1. The catchment lies between latitude 36.58º and 37.58º E and 0.58º and 1.17º S. The main rivers include Thika and Chania that has a confluence at the catchment’s outlet.

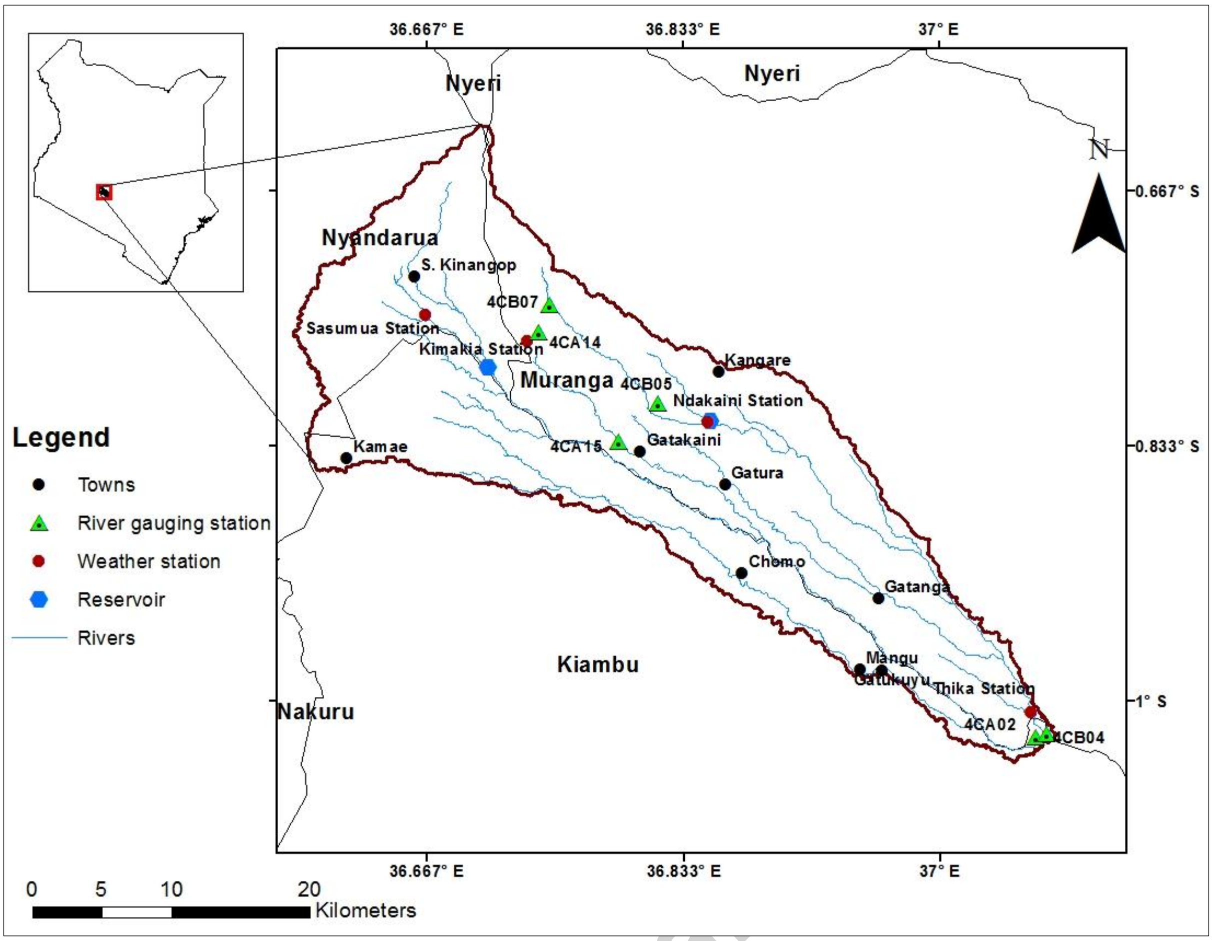

Fig. 1. Location of Thika-Chania catchment.

Slopes in the catchment varies from gentle to very steep while the predominant slopes ranges between 0-20%. Dominant slopes in cultivated range from 0-30% while steeper slopes greater that 30% are found in forests and tea zones. The forested areas in the catchment covers 35.6% of the total catchment area while 28.1% and 19.6% of the area is on coffee and general agriculture respectively. Population increase in the catchment has led to conversion of forests, wetlands and riparian areas to small holder agricultural farms increasing the susceptibility of the catchment to soil erosion (Hunink & Droogers, 2015; Vogl et al., 2017). According to Hunink et al. (2013), the increase in small holder rainfed agriculture from the previously uncultivated areas is approximately 60% of the overall land use. This implies that with unsustainable farming methods in these areas, sedimentation of reservoirs and deterioration of water quality will persist. Farmers in the catchment experience loss in soil fertility due to soil erosion further leading to reduction in crop yields (Gathagu et al., 2017; Kauffman et al., 2014). The major crops under rainfed agriculture in the catchment are coffee, corn, horticultural crops and tea (Mwangi, Shisanya, Gathenya, Namirembe, & Moriasi, 2015). The steep slopes coupled with intensive farming increases the vulnerability of the catchment to soil erosion leading to deterioration of ecosystem services. Distribution of rainfall in the catchment is bimodal with high peaks beginning from March and May and short rains coming in October to December as shown in Fig. 2.

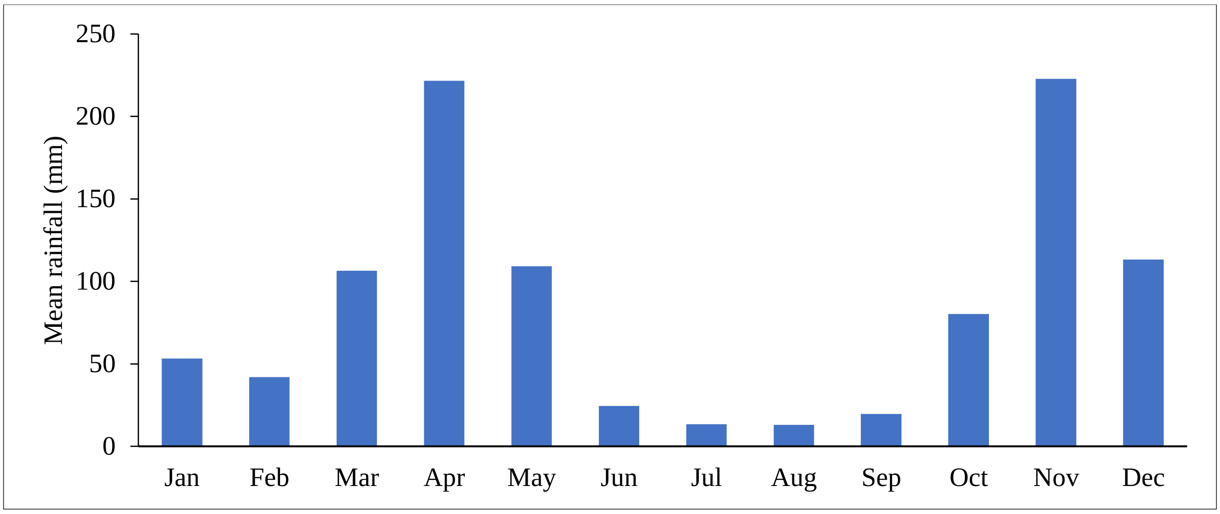

Fig. 2. Bimodal rainfall distribution in the catchment.

Rainfall varies from 800 mm in low altitude areas to 2200 mm in high altitude areas of the catchment. Dominant soils in the catchment are Mollic Andosol and Humic Nitisols whose physical and chemical properties vary spatially and also between soil layers.

2.2. Model setup

The datasets used to build the model are presented in Table 1. The catchment was delineated by taking the catchment outlet as the confluence of Thika and Chania Rivers. The critical source area was selected such that the average sub-catchment area fell within 2-5% of the total catchment area for effective sediment yield simulation (Jha, Gassman, Secchi, Gu, & Arnold, 2004). Land use and soils maps were then uploaded to the SWAT interface. Saturated hydraulic conductivity and soil erodibility factor were key parameters missing in the SOTER database. These parameters were computed using the method of Jabro (1992) and Williams (1995), respectively (Jabro, 1992; Neitsch et al., 2005). Hydrologic Response Units (HRU) were defined after classification of threshold percentage for land use, soil and slopes. Daily weather data obtained from the Kenya Meteorological Department (KMD) and Nairobi City Water and Sewerage Company (NCWSC) were used. The SCS curve number was applied to compute the surface runoff while flow routing through the stream was analyzed using the Muskingum routing method. To determine the evapotranspiration rate from the sub-catchments, the Penman Monteith formula was used in this study.

Table 1 Data used in SWAT model set up.

Datasets	Details	Sources
Digital elevation model	30 m resolution	SRTM
SOTER-UT soils map	Scale 1:250000	ISRIC-WISE
Land use map (2009)	30 m resolution	ISRIC-GWC
Meteorological data	Daily (1996-2013)	KMD, NCWSC
Stream flow data	Daily (1996-2013)	WRMA, NCWSC
Bathymetric survey data	Thika dam, Sasumua dam, Masinga dam	(Hunink & Droogers, 2011)

2.3. Model parameter sensitivity analysis, calibration and validation

Parameter sensitivity analysis was conducted to guide the calibration process and to identify the precision parameters for calibration and validation (Winchell, Srinivasan, Di Luzio, & Arnold, 2013). SWAT Calibration and Uncertainty Program (SWATCUP SUFI2) was used to perform global sensitivity analysis (Abbaspour, 2015) after one run of the Latin hypercube sampling. The defined objective functions were then evaluated depending on the defined thresholds.

Observed stream flow into Ndakaini dam was split into two where one set was used for calibration and the other for validation. The first two years (1996-1997) were used as model warm up period while calibration and validation of stream flow was conducted between 1998-2005 and 2006-2013, at gauging at gauging station 4CB05, respectively. Nash-Sutcliffe coefficient, Percent Bias and coefficient of determination were used to compare the variation between observed and the simulated variables. Data from a bathymetric survey conducted within the catchment in 2011 was used to calibrate and validate the model for sediments. Results from other studies carried out within the catchment were also used to spatially validate the output of the model simulation. Similar methodology was applied in other studies in absence of adequate continuous sediment data (Mwangi et al., 2015; Vogl et al., 2017). The calibrated and spatially validated model was run to form the base scenario for simulation of impacts of terraces and grassed waterways on water and sediment yield.

2.4. Simulation of terraces

Terraces were assumed to be implemented in parallel based on the methodology adopted in other studies (Arabi et al., 2008). To simulate the effects of terraces in conserving soil erosion and therefore reducing sediment yield, HRUs slope length (TERR_SL) with slopes greater than 2.3% was adjusted. Reducing the slope length in HRU where the slope is less than 2.3% would result in higher erosion estimate (Arabi et al., 2008). TERR_P values were modified based on the respective HRU slopes obtained in Table 2.

The SCS curve number (TERR_CN) were reduced by six units for the calibration value. These parameters were adjusted simultaneously for every simulation.

Table 2 USLE P for simulating terraces.

Slope (%)	TERR-P
1-2	0.12
3-5	0.1
6-8	0.1
9-12	0.12
13-16	0.14
17-20	0.16
21-25	0.18

Source: (Arabi et al., 2008; Wischmeir & Smith, 1978).

The slope length indicated in SWAT as (TERR_SL) in the terraces management option 1 (MGT_OP1) was modified based on equation (1)

$$SLSUBBSN = (x \times SLOPE + y) \times \frac{100}{SLOPE} \quad (1)$$

Where x is a dimensionless variable with values from 0.12-0.24. A value of 0.24 is used for low rainfall areas and 0.12 used for high rainfall areas. Based on the climatic conditions in the catchment an average value of 0.18 was used. The dimensionless variable y is influenced by soil erodibility and crop management system. The variable can take values of 0.3, 0.6, 0.9 or 1.2 (Arabi et al., 2008) as shown in Table 3.

The low y value of 0.3 is used for highly erodible soil with conventional tillage and little residue, while the high value of 1.2 is used for soil with very low erodibility and with a residue of more than 3.3 t/ha or no-till management condition. Thika-Chania has soil erodibility values ranging from 0.07-0.24. In agricultural areas, harvesting of crops leaves little or no crop residue on the lands hence an assumed ground of 40% was adopted in this study. Interpolation of values in Table 3 gave a y value of 0.75. Approximately 50% of the total catchment which includes areas on coffee, corn and general agriculture were simulated with terraces.

Table 3 Typical values of the dimensionless variable y.

Ground cover (%)	Soil erodibility factor		
	0-0.2	0.2-0.28	0.28-0.64
10	0.75	0.53	0.30
40	0.98	0.75	0.53
80	1.20	0.98	0.75

Source: *(USDA NRCS, 2015).*

2.5. Simulation of grassed waterways

Grassed waterways were simulated in small seasonal channels and drain ways that convey water from agricultural lands and towns (Arabi et al., 2008; Secchi et al., 2007). The methodology used in this study was based on grassed waterway modelling option in SWAT 2012 (Winchell et al., 2013). Grassed waterways were modelled in SWAT by modifying parameters in scheduled management option (MGT_OP 7). The Manning’s roughness factor “n” (GWATn) for the main channel was also adjusted based on the recommendation of Arabi et al. (2008). A value of 0.1 was used to represents channel roughness and control the energy of the streams. This value also represents dense grasses under non-submerged conditions.

Based on the waterways installed along the farmland and road sections in the catchment, a uniform channel width (GWATW) of 2.5 m and a depth (GWATD) of 0.3 m was adopted in this study. The linear parameter for determining sediments re-entrained in channel sediment routing (GWATSPCON) was taken as 0.005 (Waidler et al., 2009). The average slope of the grassed waterway (GWATS) was determined based on the average slope of the main channel (Waidler et al., 2009).

2.6. Simulating the integration of terraces and grassed waterways

A combination of terraces and grassed waterways was simulated to evaluate their effectiveness on water and sediment yield when implemented together. This was achieved by running the model after adjusting respective simulation parameters for terraces and grassed waterways. The use of an integration of soil and water conservation methods have been shown to improve yields and water productivity in other studies (Ouattara, Serme, Bongoungou, & Zombre, 2017). Simulation results were then compared to those when individual conservation practice is implemented. The effectiveness of conservation methods was computed by comparing model outputs before and after implementation of the conservation method as shown in equation 2.

$$E = \frac{a_1 - a_2}{a_1} \times 100 \tag{2}$$

Where E is the effectiveness of the conservation practice, a_1 and a_2 are model simulation before and after implementation of the conservation method, respectively.

3. Results and Discussion

The average sub-catchment. area was found to be 19.53 km^2 and represents 2.3% of the total catchment area. The entire catchment was subdivided into 43 sub catchments as shown in Fig. 3.

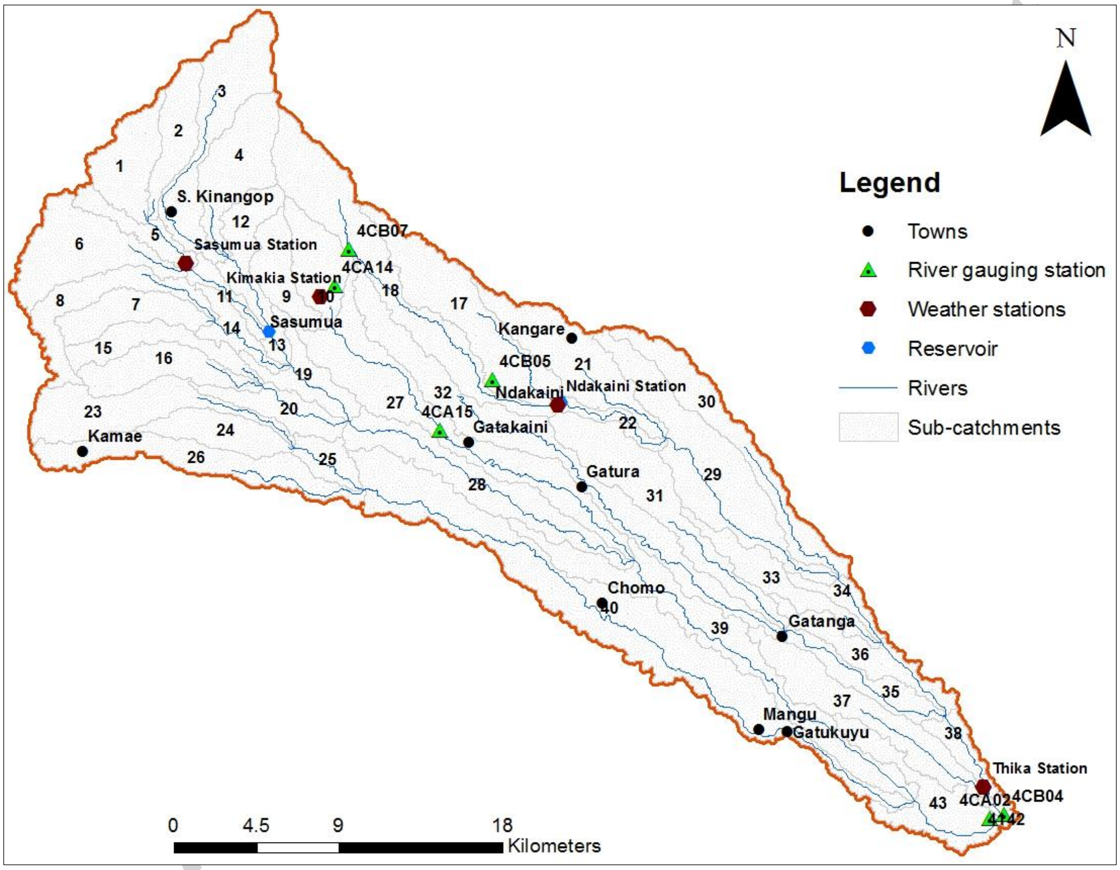

Fig. 3 Thika-Chania sub-catchments, weather and river gauging stations.

3.1. Sensitivity analysis

Global sensitivity analysis was conducted using SWATCUP SUFI-2 model after 500 simulations and the results are presented in Table 4. In global sensitivity analysis, the bigger the absolute value of the t-stat the more sensitive the parameter is (Abbaspour, 2015). The p-values also tests the null hypothesis that the parameter is not sensitive. Therefore, low p-values implies that the null hypothesis is rejected and hence the respective parameter is sensitive to streamflow. Sensitivity analysis for sediments indicated that curve number (CN2), SPEXP, SPCON, CH_N2 and slope are the main sensitive parameters to sediments.

Table 4 Parameters description and sensitivity analysis.

Parameter	Description	t-Stat	P-Value
ALPHA_BF	Base flow alpha factor (days)	23.48	0.00
SOL_AWC	Available water capacity of the soil layer	14.42	0.00
CN2	SCS runoff curve number factor	9.51	0.00
CH_N2	Manning's "n" value for the main channel	1.94	0.05
CH_COV2	Channel cover factor	1.22	0.22

3.2. Calibration and validation of streamflow and sediments

Stream flow was calibrated after 5 iterations with each iteration having 500 simulations. After the fifth iteration, the model enveloped 70% of the observed data within the 95 percent prediction uncertainty (95PPU) (Fig. 4.). The p and r factor were found to be 0.70 and 0.67, respectively.

According to Abbaspour (2015), a p-factor greater than 0.70 and r-factor less than 1.5 are recommended for stream flow calibration. The uncertainty range within which the respective parameters were calibrated are presented in Table 5. Statistical methods e.g. NS efficiency (R^2), coefficient of determination and the percent bias (PBIAS) were found to be 0.66, 0.69 and 10.3, respectively. The closer the values of NS and R^2 to one, the better the match between the observed and simulated results (Abbaspour, 2015). If the NS value is between 0.65-0.75 and PBIAS value between ±15-25, then the model results are deemed as good in simulating streamflow (Moriasi et al., 2007).The model can be judged as satisfactory if the NS value is greater than 0.5 and PBIAS is within ± 25% for stream flow (Moriasi et al., 2007). Considering the values of NS and PBIAS in the current study, the model performance was good for stream flow calibration. An R^2 greater than 0.5 have been reported to represent a good match between the observed and the simulated flow (Moriasi et al., 2007; Santhi et al., 2001). Therefore, with an R^2 of 0.69 in this study, the model results were considered acceptable.

The calibrated parameters and their uncertainty ranges were used for the validation of streamflow between 2006 and 2013 and results are presented in Fig. 5. Validation of streamflow indicated that NS, R^2 and PBIAS as 0.73, 0.75, and 7.2 respectively. The p-factor and r-factor for the validation period were 0.61 and 0.45 respectively. The NS, R^2 and PBIAS improved after the validation but the p-factor reduced 9% which implies lesser observed data bracketed within 95PPU band. The latter case was attributed to the gaps in the observed data, uncertainty in data collection and/or gap filling during the model validation period. Other studies by Briak, Moussadek, Aboumaria, & Mrabet (2016) observed an NS value of 0.67 and PBIAS of -14.44 during model validation using SUFI2 and reported it as good model performance.

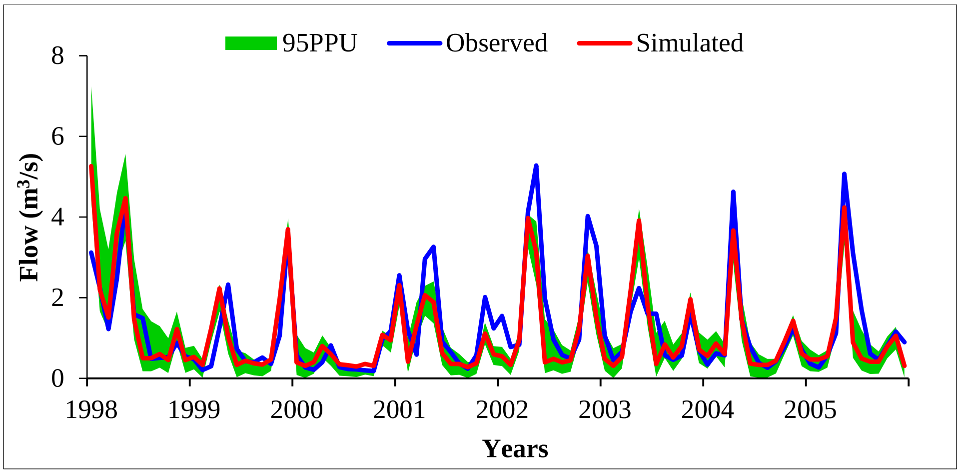

Fig. 4. Monthly streamflow calibration results for gauging station 4CB05.

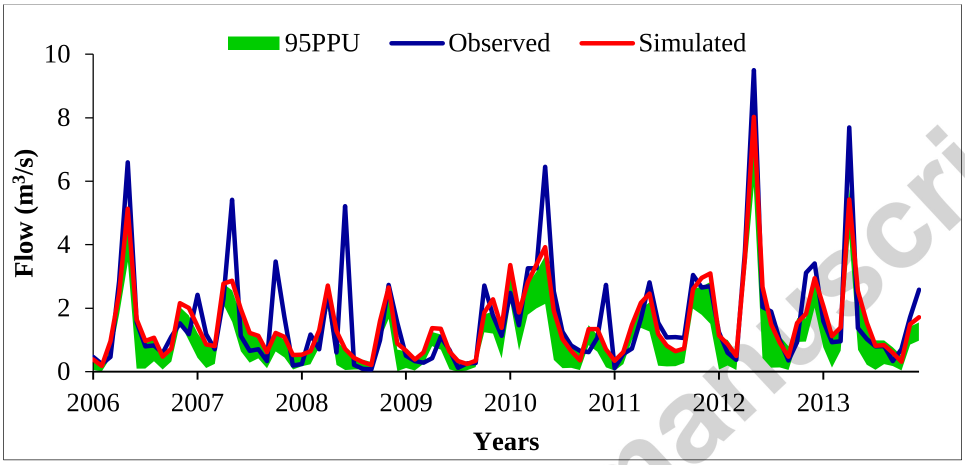

Fig. 5. Monthly streamflow validation results for gauging station 4CB05.

Table 5 Parameters qualifiers and uncertainty range

Parameter Name	Qualifier	Fitted value	Min_value	Max_value
CH_COV2	v	0.099	0.028	0.149
CH_N2	v	0.658	0.292	0.661
CN2	r	0.386	0.156	0.542
SOL_AWC	r	-0.179	-0.949	-0.095
ALPHA_BF	v	0.001	-0.103	0.107

*****r refers to the relative change in a specified parameter where the given value is added to one and the multiplied by the initial value of the parameter. v refers to the replacement of a parameter by the given value.

Sediments calibration involved calibration of the SPCON, SPEXP, curve number, USLE_P and the average slope which were among the most sensitive parameters. Results indicated a close match between the observed and the simulated values. Abbaspour et al. (2007) reported similar results in a parameter sensitivity analysis for sediments calibration using SWAT model in Thur catchment, Switzerland. The uncertainty range within which sediment yield were calibrated and subsequently used for validation are presented in Table 6.

Sediments calibration and validation results exhibited a close match between the observed data and the simulated values (Table 7). The mean annual sediment outflow from the catchment was compared with the simulated sediment yield. Results showed that the simulated annual sediment yield from the entire catchment is 21.507 t/ha. These results matched the observed sediment yield of 21.45 t/ha at the outlet of the catchment from the bathymetric survey data. Therefore, the model accurately simulated the sediments yield at the catchment outlet. Similarly, model results during validation were compared with those of the bathymetric survey and findings from other studies. The results were considered satisfactory for simulating the effectiveness of terraces and grassed waterways on sediment and water yield.

After calibration and validation of sediments, the results for the spatial distribution of erosion rate was plotted in a map as shown in Fig. 6 This provided the base scenario where the average sediment yield from the catchment was 21.507 t/ha/yr. Sub-catchments where coffee, corn and general agriculture is practiced indicated the highest sediment yield that were classified between high and very severe (Singh, Babu, Narain, Bhushan, & Abrol, 1992). Tea growing zones had relatively less sediment yield which was attributed to the extensive ground cover and minimal soil disturbance. Areas with the largest percentage on forests had slight sediment yield. These areas were excluded in the simulation terraces and grassed waterways. The base annual total water yield was simulated as 922.36 mm where surface and base flow was 202.28 mm and 638.20 mm, respectively. These results formed the base scenario for evaluating impacts of the structural conservation methods on water and sediment yield.

Table 6 Calibrated parameters for sediments in Thika-Chania catchment.

Parameter Name	Qualifier	Fitted value	Min_value	Max_value
CH_COV1	v	0.3	0.1	0.30
SPEXP	v	1.4	1.0	1.60
SPCON	v	0.005	0.001	0.005
CH_COV2	v	0.3	0.10	0.30
CN	v	50-88	36	98
USLE-P	v	0.95-1	0.80	1

* v means the parameter was directly replaced by the respective fitted value.

Table 7 Observed and simulated average annual sediment yield in Thika-Chania catchment.

Reservoir/catchment	Observed sediment yield (t/ha)	Simulated sediment yield (t/ha)	Source
Sasumua reservoir	0	0.60	Hunink & Droogers (2011)
Ndakaini reservoir	0	0.67	
Sasumua sub-catchment	10.3	11.0	Mwangi et al. (2015);
Thika-Chania catchment	21.45	21.507	Hunink & Droogers (2011)

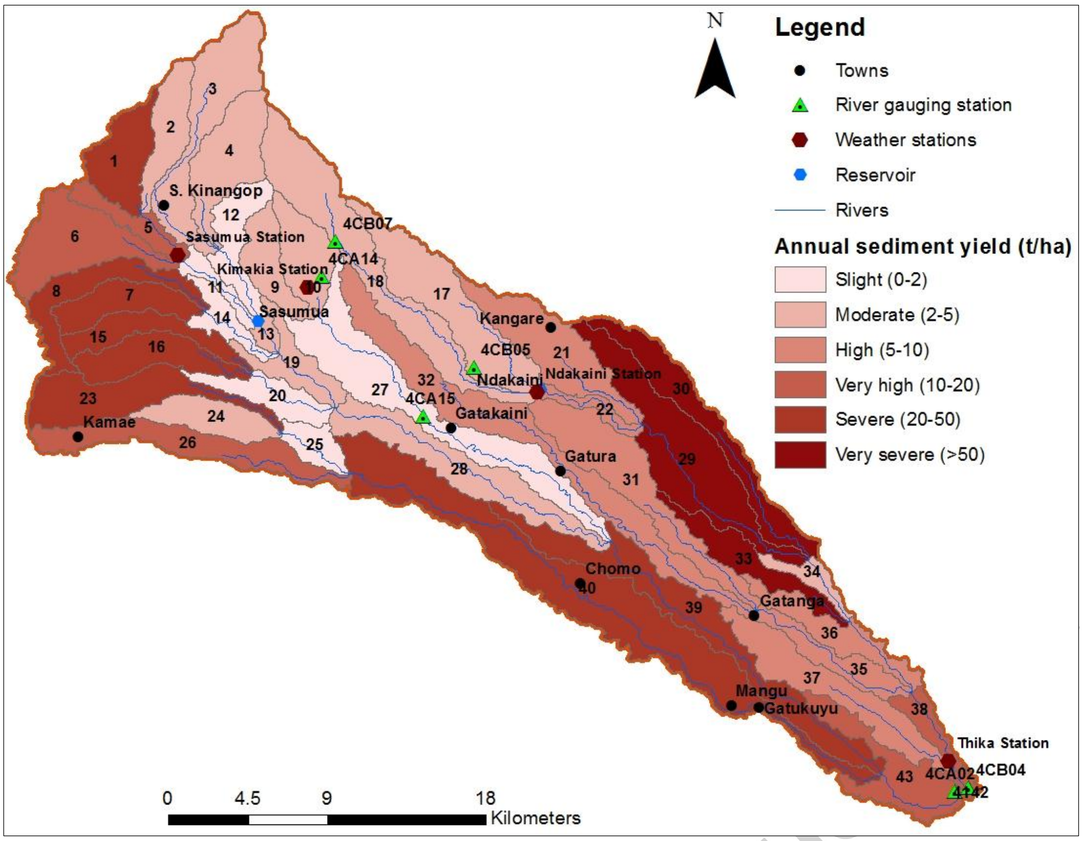

Fig. 6 Spatial distribution of sediment yield across sub-catchments.

3.3. Impact of terraces

Terraces were simulated in all HRUs except in forest and tea zones. Despite these areas being characterized by steep slopes, they have extensive ground cover that reduces soil erosion. Results indicated that implementing terraces particularly in agricultural lands would reduce sediment yield by 80.7% at the catchment outlet thus reducing the amount of sediments into reservoirs and water infrastructure. The percent reduction of sediment at each sub-catchment where terraces were implemented is shown in Fig. 7. This indicates the level of intervention and prioritization required in every management unit in the catchment. Sediment reduction above 50% was observed in agricultural areas and areas that have steep slopes. Only sub-catchment 43,38 and 5 had sediment yield reduction of less than 50%. This was attributed to the presence of rangelands in the three sub-catchments where terracing was not simulated. Rangelands have good grass cover thus reducing the susceptibility of the soil to erosion. The results showed that terraces are able to reduce sediment yield more than non-structural conservation methods e.g. contour farming and vegetative filter strips assessed in other studies (Mwangi et al., 2015). According to Mwangi et al. (2015), contour farming implemented at the sub-catchment level in Thika-Chania catchment reduced 15.2% of sediment yield from the base scenario. Therefore, implementation of terraces would have the greatest benefit in terms of per hectare sediment reduction from uplands where agriculture is the main land use. The greatest beneficiary of terraces is the coffee growing zones where erosion rates were modelled to be highest and also characterized by slopes greater than 20%. Terraces reduce the slope lengths thereby decreasing the runoff velocity thus reducing the amount of sediments in surface runoff.

The current study agrees with research conducted by Gassman et al. (2006) where more than 60% sediment reduction was observed when terraces are implemented in an agricultural catchment. A study conducted in Bosque River watershed in Texas found that sediment yield could be reduced at the HRU level by a magnitude of between 57 and 95% (Tuppad et al., 2010).

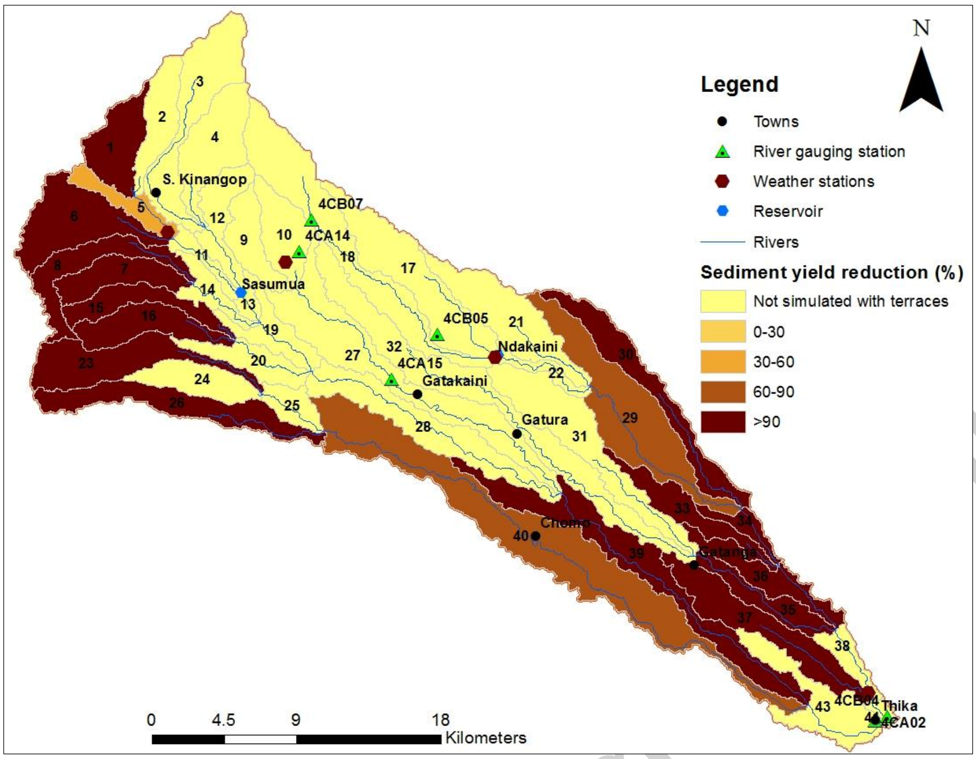

Fig. 7. Percent sediment reduction after terracing.

Surface runoff was reduced by 30.25% from the base value of 202.28 mm while base flow was increased by 8.38%. Shallow aquifers recharge increased by 5.08% from 76.75 mm. Although the flow components were observed to change from the baseline scenario, the total water yield from the catchment reduced by only 0.40%. This shows that terraces would be very useful in reducing flashfloods associated with peak surface runoff through enhanced water infiltration. By increasing the amount of runoff retained within the terraced fields, the amount of water available to recharge shallow groundwater aquifers is also increased. However, when surface runoff is used to feed reservoirs, then other methods that do not significantly reduce surface runoff should be implemented. Fig. 7 shows the sub-catchments within which terraces could be implemented and the respective estimated percent reduction in sediment yield. These results shows that terraces can effectively be used both as control for soil erosion and peak runoff rates.

Other research has shown that implementing terraces reduce both surface runoff and sediment yield (Arnáez, Lana-Renault, Lasanta, Ruiz-Flaño, & Castroviejo, 2015; Lemann et al., 2016). When it rains, terraces cause ponding of water on the flat surfaces hence increasing infiltration. The results of this study are also consistent with other research findings where terraces implemented on a slope greater than 5% could reduce sediment and water yield by 90% and 43% respectively (Schmidt & Zemadim, 2015).

3.4. Impact of grassed waterways

Simulation results of grassed waterways in seasonal tributaries and channels conveying water from agricultural lands shows that sediment yield can be reduced by 53.90% from the base simulation of 21.507 t/ha/yr. at the outlet of the catchment as shown in Fig. 8.

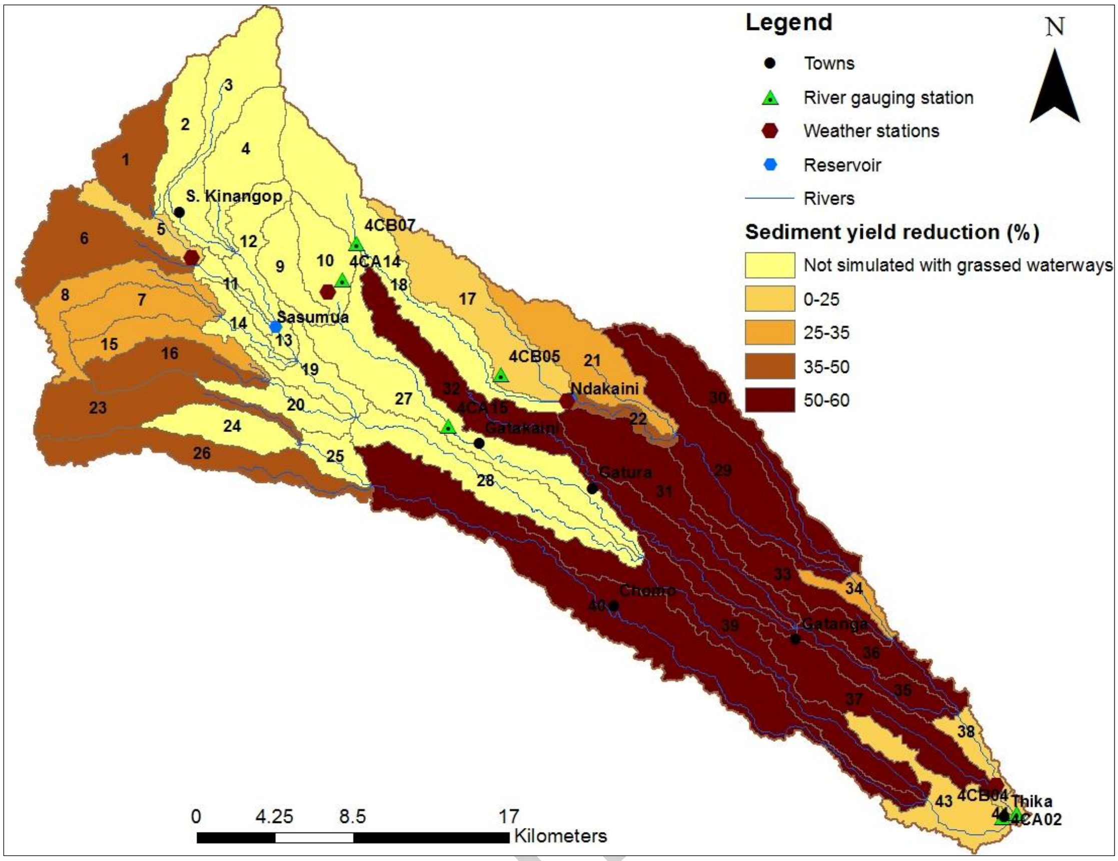

Fig. 8. Percent sediment reduction after implementing grassed waterways.

Sediment trapping from surface runoff flowing into Ndakaini and Sasumua reservoir would be reduced by 56.70% and 38.06%, respectively when grassed waterways are implemented. This shows that grassed waterways are effective in reducing the amount of sediments in surface runoff by creating channel roughness that facilitate deposition of soil particles. Simulation of grassed waterways was done with Manning's channel roughness factor of 0.1 which signifies a grassed waterways under poor conditions (Arabi et al., 2008). The results of this study imply that if implemented and maintained properly, the effectiveness of grassed waterways would be improved hence the annual average sediment yield would decrease.

The annual average surface runoff showed no significant change from the base scenario hence the total water yield did not change. Elsewhere, studies have shown that grassed waterways reduced sediment yield in upper Maquoketa watershed by 45.9% (Gassman et al., 2006). The authors also found that the total flow rate reduced by 3% from the base simulation thus facilitating the deposition of sediments. A study conducted by Mwangi et al. (2015) found that grassed waterways could reduce sediment yield by 54% from the base scenario. However according to the authors, no significant change in total water yield was observed.

3.5. Impact of combining grassed waterways and terraces

Simulation results of grassed waterways and terraces indicated that when they are implemented together on the same land, sediment yield can be reduced by 88.72% from the average annual sediment yield of 21.507 t/ha. This depicts an increment of 8% from 80.7% sediment reduction when terraces are implemented individually. Based on these results, grassed waterways did not greatly impact on sediment yield when they are combined together with terraces. However, Fiener & Auerswald (2006) recommended the use of grassed waterways to discharge surface runoff from terraces and other water concentration points that may cause erosion and flooding.

The average annual surface runoff from the catchment decreased by 30.25%. This value however does not reflect the influence of grassed waterways on water yield when the two conservation methods are implemented together. However, a combination of grassed waterways and terraces can reduce more sediments at the catchment outlet compared to when individual methods are implemented.

4. Conclusion

SWAT model was successfully calibrated and validated to model the impacts of implementing structural conservation measure on water and sediment yield. The model produced good results with an NSE value of 0.66 and 0.75 during calibration and validation, respectively. The model also bracketed 70% and 61% of the observed data with 95 PPU band in calibration and validation, respectively. However, continuous data collection and sampling should be prioritized in the catchment to facilitate further scientific research e.g. nutrient modelling and also improve plausibility of results.

Terraces were the most effective in sediment reduction (80.7%) while grassed waterways indicated sediment reduction of 53.97% from the base scenario. The total water yield decreased by 0.40% when terraces were implemented. Terraces increased the base flow by 8.38% while recharge in the shallow ground water aquifer increased by 5.08%. Terraces therefore had a greater impact on both sediment and water yield in the catchment. However, simulation of the implementation of grassed waterways indicated no change in the total water yield. In both structural conservation methods, more that 50% sediment reduction was achieved. It can be concluded therefore that structural conservation measures are effective in reducing sediment yield in agricultural catchments. A combination of terraces and grassed waterways resulted in more sediments reduction compared to when an individual method is used. Further studies however need to conducted to evaluate the cost and benefits associated with implementing structural conservation measures at smallholder level and their adoption rate by famers with/without grants or incentives. Small holder farmers need to be capacity built on the effectiveness of structural conservation methods and supported both financially and technically in implementing them.

Revision Notes/Responses

1. **As the study is just a very standard modeling assessment of a watershed, the paper title now looks too general and it should include something like "... in a ??? watershed in Central Kenya".**

The title of the paper was modified to read: “Modelling the Impacts of Structural Conservation Measures on Sediment and Water Yield in Thika-Chania Catchment, Kenya”

2. More information of the study basin such as land use and cover should be given to justify and highlight the practcal significance of the study.

   Additional information on land use/cover and the impact of demographic changes in the catchment was added. We have included reports that indicates increase in rainfed agriculture from previously uncultivated areas leading to more production of sediments. Intensive farming and the topography of the region also increases vulnerability to soil erosion. Information on slopes in the agricultural areas has been explained in details. The major crops grown in the region include coffee, corn, tea, and vegetables. An analysis of the land use map showed that areas where these crops are grown has the highest sediment yield. This information is given in the results section (Pg 9).

3. Why is the model calibration period so short (only 2 years from 1996 to 1997) compared to the validation period of 8 years (2006-2013)? Are the data of 1998-2005 not available?

   The 2 years (1996-1997) were used as the model warm-up period. The calibration period was from 1998-2005 while that for the validation was between 2006-2013. This information has been clarified in the paper.

4. More results showing the model performance in the calibration and validation periods should be presented and discussed.

   Model results during calibration and validation has been added in figure 4 and 5, respectively. The p and r factors were included and discussed based on the recommendation of Abbaspour, (2015). Statistical results for the calibration and validation period has also been added and discussed according to the recommendations of Moriasi et al. (2017) and Santhi et al. (2001). In this regard, we have described what the model results are and what they imply as far as simulation results are concerned. We have also included the results of other studies to justify our results. More results/discussion has been made for sediments calibration.

5. In Table 5, it is not necessary to show 6 digits after the decimal point. Three digits should be enough.

   The figures in Table 5 were changed to 3 digits after the decimal point.

6. Non-structural conservation measures are mentioned a few times in the paper. What are they? Better to briefly discuss their applicability and effectiveness in your study basin.

   Non-structural measures include the agronomic measures that do not involve putting up physical structure to control runoff and erosion. In this context we were referring to contour farming and vegetative filter strips. We have discussed their application in the study area from results of other studies in the catchment. We have compared their effectiveness to those of structural conservation methods like terraces.

7. Some data are given without source and explanation, such as soil erodibility from 0.07 to 0.21 on p. 4.

   The information on soil erodibility in page 4 has been deleted because it has been repeated in page 6. However, soil erodibility values from 0.07-.021 are based on the calculation we made using the method of Williams (1995). The values were sorted in excel thus coming up with the range of soil erodibility.

8. Two minor editorial problems: (i) inconsistency in citing references (list of multiple authors vs. et al.), and (2) better to be consistent in using % and percent.

   We have edited the list of references for consistency on multiple authors vs. et al. We have been guided by the authors guide and other publications by the journal. We have also changed the use of “percent” to “%” for uniformity.

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