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Research article

Application of APEX Model in Evaluating Streamflow and Sediment Yield in Stung Chinit Catchment

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Abstract Streamflow and sediment yield are important indicators to understand the alterations in hydrological processes as well as the supply and transformation of nutrients and biological productivity in the ecosystem. The main objective of this study was to evaluate the performance and applicability of the APEX model in estimating streamflow, sediment yield, and quantifying the soil erosion in Stung Chinit Catchment. The result indicates that the APEX model performed well in accurately simulating the monthly streamflow and annual sediment yield in the watershed. The overall statistical indicators (NSE, R^2, and PBIAS) of streamflow calibration (1997-2015) were 0.60, 0.62, and 2.50%, respectively. The validation statistical indicators (NSE, R^2, and PBIAS) for streamflow were 0.71, 0.80, and 28.22%, respectively. The mean annual surface runoff was 212.03 mm; varied from 72.56 mm to 435.59 mm. The average annual sediment yield varied from 10.21 tons/ha/year in the lowlands of the Stung Chinit catchment main river channel to 68.2 tons/ha/year in the highlands, with an annual average of 29.2 tons/ha/year. Most of the sediment yield came from the eastern part and near the outlet of the Stung Chinit catchment.

Keywords APEX model, sediment yield, streamflow, Stung Chinit catchment

INTRODUCTION

Soil erosion is a major environmental problem which affects people by degrading water quality, depositing sediment in the channel, decreasing the reservoir effective capacity and increasing the risk of flooding (Umit et al. 2018). Due to some human activities such as forest burning, overgrazing, deforestation, recreation, soil erosion rates have been increased above natural levels, a phenomenon known as accelerated erosion. Accelerated surface erosion is a severe matter that reduces agricultural productivity, finite arable lands, and reservoir capacity. Erosion and sedimentation in a catchment are closely associated with natural processes which is mainly driven by rainfall and runoff processes. Erosion is the movement and detachment of soil particles by natural forces, primarily caused by water and wind. Sediment yield is the amount of soil that is transported to surface water bodies within a time scale over a specific area (Issaka and Ashraf, 2017).

Sediment yield in a watershed varies spatially, depending on several contributing factors such as topography, soil types, catchment area, climate (i.e., precipitation, wind, temperature, etc.), vegetation cover, human-influenced soil erosion, forest fires, river discharge (Francipane et al. 2015). In a watershed, the amount of sediment transported by a river system depends on the supply of sediment and transport capacity of the flow. Therefore, the accuracy of the estimate of the sediment yield from any watershed relies on understanding and representation of the multiple contributing factors such as rainfall, runoff, and erosion processes. More discussion on sedimentation processes can be found in earlier publications (Wilkinson and McElroy 2007; Francipane et al. 2015). Most physical models normally require hydro-meteorological, topographical, soil, and land use data as the input data for the model. Besides these data, models such as APEX, DSSAT, EPIC, and SWAT (Ayele et al, 2017; Jeong et al. 2010) also require crop management data. APEX is capable of evaluating the effects of various water and land management practices on watershed hydrology, sediment yields and water quality at various environmental issues (Luo and Wang, 2019; Assefa et al. 2018; Van Liew et al., 2017; Ayele et al, 2017; Tuppad et al. 2010)

The Stung Chinit catchment is one of the major tributaries of Tonle Sap Lake. There is an intensified economic activity in the catchment, including major land concessions, infrastructure developments and demographic pressures (CNMC, 2012). As a result, some soil erosion may occur eroded from the upstream to the downstream of the catchment due to agricultural land expansion by encroaching to the forest land. Moreover, farmers suffer abnormal storms, floods and multiple kinds of droughts (meteorological, hydrological and agricultural), making them and their communities highly vulnerable to water scarcity.

OBJECTVIES

The research aims to evaluate the performance and applicability of the APEX model in estimating streamflow and sediment yield as well as identifying the soil erosion in Stung Chinit Catchment, Cambodia.

MATERIALS AND METHODS

Study Area

Stung Chinit catchment covers an area of about 8,236 km^2 and composed of the Stung Chinit and Stung Taing Krasaing Rivers and other small streams that drain from the north. The mainstream, Stung Chinit, flows 264 km south-westwards to the gentler slopes downstream before discharging into the Tonle Sap Lake (CNMC, 2012). A measuring stream gauge is located in the middle of the river along National Road 6, Kampong Thmar (Fig. 1).

Rainfall in the catchment increases with elevation, while the spatial distribution of annual average rainfall ranges from 1200 to 1500 mm. Over 90% of the catchment's annual rainfall is received during the wet season, from May to October, and the highest rainfall occurs in August (MOWRAM, 2014). Daily temperatures vary from 20°C in the coolest months of December to January up to 35°C during the hottest months of April and May (CNMC, 2012). Farmers in Stung Chinit and Taing Krasaing mainly cultivate traditional wet season rice and some dry season rice. A large proportion of the catchment has poor quality soil, Acrisols, which covers 60.75% of the entire catchment (CNMC, 2012). Agricultural land occupies 28.9% of the total catchment area (238,020 ha), located mostly on poor Acrisols. Another 46.3% of the catchment area (381,327 ha) is occupied by forestland, grassland, shrubland, soil and rock, urban settlements and water bodies. Of the total agricultural land, rice takes up 154,014 ha, annual crops 49,197 ha, perennial crops 22,938 ha and village garden crops 7331 ha (CNMC, 2012).

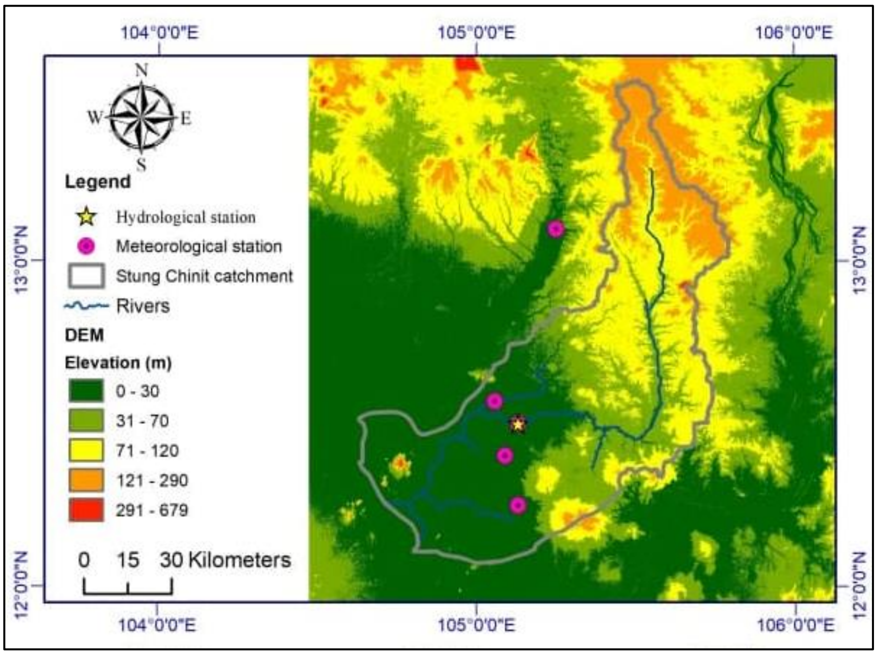


Fig. 1 Topography, hydrological and meteorological stations, and rivers of the study area

The APEX Model Application, Data Inputs and Model Setup to Predict Hydrology

The APEX model is an extension of the Environmental Policy Integrated Climate (EPIC) model (Williams, 1998), which is capable of evaluating the effects of various soil and water management practices on the hydrology of the system, crop growth, and other environmental factors (Wang et al., 2014; Steglich et al., 2018). The APEX simulates watershed processes based on weather data, soil characteristics, topography, vegetation, and management practices (Wang et al., 2012). Multiple options are available in the APEX model in estimating evapotranspiration, surface runoff, peak runoff rate, and available soil water capacity to derive hydrology of the system (Wang et al., 2012).

The APEX model requires some input data, including Geographic Information System (GIS) data layers, climatic data, and management practices. The GIS data layers are digital elevation model (DEM), soil, and land use or crop covers (Table 1). A 30 m DEM was obtained from the United States Geographical Survey (USGS) website. The land use data was received from the Cambodia National Mekong Committee (CNMC), 2015 (Fig. 2d). A harmonized world soil map prepared by the Food and Agricultural Organization (FAO) with two levels were used for soil database preparation of APEX (Fig. 2b).

During the model setup process, the APEX version 1501, developed by Texas A&M AgriLife Research, Temple, Texas, USA, was used and divided into three steps. The first step was the process of setting up the APEX model and began with the processing of GIS data layers to delineate the watershed boundary, subareas, and derive watershed characteristics from the Digital Elevation Model (DEM). The land use, soil data and slope was overlaid and used the dominant landuse/soil/slope, while the land use of paddy rice was modified in the management file of APEX file based on the schedule of tradition rice cropping system which people mostly cultivate in the catchment (Table 2). The dominant land uses in the catchment are evergreen forest (52.94%), paddy rice (26.82%), grassland (6.23%), marsh/swarm (4.56%), shrubland (4.36%), agricultural land (3.6%) and deciduous forest (1.49%) (Fig. 2d), while The dominant soils are Acrisols (55.13%), Gleysols (34.92%) and Vertisols (9.95%) (Fig. 2b). The second step was to integrate weather data of 12 catchments of Stung Chinit provided by WinRock International (Fig. 1) through the Arc-APEX model interface. The third step was the process of performing an initial model run and complete model setup procedures to create APEX model output files for further analysis.

The APEX can simulate all the key water balance components of the system. Precipitation, snow melts, and irrigation are the main inputs to the system, which are then disseminated into various components: surface runoff, subsurface/tile drainage flow, soil water, percolation, and evapotranspiration (Williams, et al. 2006). In APEX, the key landscape processes across hydrological connected units are called subareas. The subareas are the smallest unit in APEX with homogenous watershed characteristics, such as soil types, land use/crop cover, slope, and management. There are two options to estimate the runoff volume (Williams, et al. 2006) which are the modified Soil Conservation Service (SCS) (NRCS, 2004) curve number (CN) and Green and Ampt infiltration (Green and Ampt, 1911) methods used in the APEX model. The SCS-CN runoff estimate method is a function of rainfall and retention parameter. The curve number is a function of land use, hydrologic soil group and management practices. The subsurface flow is a function of the vertical and horizontal flow and simulated as a simultaneous process (Wang et al., 2012). The horizontal flow consists of a lateral flow, whereas the vertical flow (percolation) adds to groundwater storage, which is then subjected to return flow or deep percolation. The vertical component of percolation is calculated as a function of soil water content, field capacity, and travel time. There are five options available to estimate the potential evapotranspiration such as Penman, Penman–Monteith, Baier and Robertson, Priestly and Taylor, and Hargreaves methods (Williams, et al. 2006). The Hargreaves method is dynamic and requires a lower data, and is a function of solar radiation, latent heat of vaporization, and temperature.

Table 1 Some required input data for APEX model setup

Data	Source
DEM (30×30m) resolution	ASTER-GDEM, USGS
Soil type FAO/UNESCO in 1984	http://www.fao.org/soils-portal/data-hub
Land use and Land Cover	Cambodia National Mekong Committee (CNMC), 2015
Meteorological data (1990 – 2017) Streamflow data (1997 – 2017)	Rainfall data of 12 catchments and streamflow data provided by Soparith Tes from Winrock International.

Table 2 Major crop management activity and cropping pattern in Stung Chinit catchment

Types of crop	Management practices	Date
Medium wet season rice	1st tillage	25-April
	2nd tillage	5-May
	3rd tillage	15-May
	DAP fertilizer application	15-May
	Sowing	15-May
	1st stage fertilizer application after planting	30-June
	2nd stage fertilizer application after planting	30-July
	Harvest	10-November

Sensitivity Analysis, Model Calibration, and Validation

Model sensitivity analysis is a method of identifying key parameters that affect model performance and are essential for model parametrization. The APEX model has huge sets of parameters related to hydrology, sediment, nutrients, crops, and other environmental factors. Sensitivity analysis is the first step for hydrological models, which helps to diagnose and narrow down the enormous sets of parameters for calibration. Model calibration is a process in which model parameters are modified so that a model output mimics observed data, whereas validation is the use of modified parameters to simulate another set of observed data. The APEX auto-calibration and uncertainty estimator (APEX-CUTE) was used to perform sensitivity analysis and auto-calibration for the APEX hydrology model (Wang et al., 2014), followed by manual adjustment of a few parameters. The first step was to examine the APEX hydrology model outputs for modifications. Some default methods and input parameters might need modification to get better simulation prior to sensitivity analysis and calibration (Williams, et al. 2008). The second step included a sensitivity analysis, calibration, and validation of the APEX hydrology model. Streamflow was recorded at Kampong Thmar Station located in the middle of Stung Chinit catchment from 1990 - 2017, while the sediment yield was done in 2005 - 2008. Model warm-up period (1990-1996) was used to initialize model parameters and obtain better predictions. Streamflow records were split into two periods: calibration (1997 - 2015) and validation (2016 - 2017). The APEX hydrology model was verified in monthly basis for the Stung Chinit catchment from the measuring gauge to the upstream of the watershed. Most of the parameters considered during calibration were related to soil properties and climate. The third step includes evaluating the APEX model. The APEX model performance in predicting hydrology of the system was evaluated using commonly used statistical measures such as Nash–Sutcliffe efficiency (NSE), determination of coefficient (R^2), and percent bias (PBIAS). NSE is a normalized statistical measure that was proposed in Reference (Chad et al. 2015). PBIAS measures the deviation of model prediction as an under- or overestimation from observation, while R^2 is a statistic that will give some information about the goodness of fit of a model.

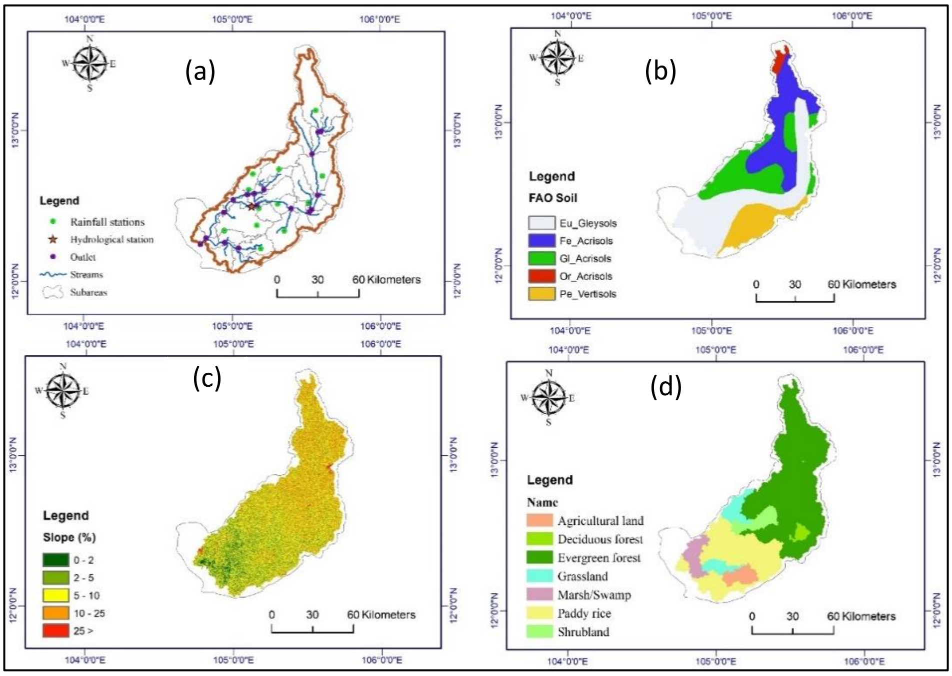


Fig. 2 Model input data in the Stung Chinit catchment

(a) meteorological and hydrological stations, rivers, outlets, and subareas;
(b) FAO soil; (c) slope classifications;
(d) land use and land cover in 2015 from CNMC

RESULTS AND DISCUSSION

APEX Sensitivity Analysis, Calibration, and Validation for Streamflow

All relevant parameters for APEX hydrology components were included in the sensitivity analysis in accordance with the reference (Wang et al., 2014). The results of the sensitivity analysis in the Stung Chinit catchment illustrated that streamflow was sensitive to the following parameters: Return flow ratio (RFPO), Groundwater residence day (RFTO), Hargreaves potential evapotranspiration (PET) equation exponent (PARM-34), Groundwater residence day (PARM-40), SCS curve number index coefficient (PARM-42), runoff volume adjustment factor (PARM-92), runoff CN initial abstraction (PARM-20) and soil evaporation coefficient (PARM-12), in order of decreasing influence (Table 3). The most sensitive parameters were associated with soil characteristics, groundwater residence day and climatic conditions. The parameter PARM-42 was found to be the most sensitive parameter for streamflow followed by PARM-34, possibly because ET was the second most-dominant hydrological process after rainfall. Feng et al. (2015) showed that ET affecting the water yield of the catchment in their scenario analysis, while Assefa et al. (2018) depicted that ET could be able to impact on hydrology. Variable CN nonlinear CN/SW with depth soil water weighting method (NVCN = 0), which is a function of soil water content and is directly linked with ET, was used. Parameters PARM-92 and PARM-20 were found to be the third and fourth most sensitive parameters for streamflow prediction. Parameters APM and PARM-90 and PARM-92 were less sensitive and thus not used for calibration.

Table 3 APEX sensitive parameters and final calibrated values for streamflow calibration

Parameters	Description	Range	Default value	Optimal value
RFPO	Return flow ratio: (Return flow)/(Return flow + Deep percolation)	0.05 – 0.95	0.5	0.85
RFTO	Groundwater residence day	10 – 50	30	60
PARM (12)	Soil evaporation coefficient	1 - 2	2	1.5
PARM (17)	Soil evaporation plant cover factor	1.5 – 2.5	1.5	2.5
PARM (20)	Runoff CN initial abstraction	0.8 – 1.5	1	1
PARM (34)	Hargreaves PET equation exponent	0.5–0.6	0	0
PARM (40)	Groundwater residence day	10 - 50	30	60
PARM (42)	SCS curve number index coefficient	0.3 -2.5	0.4	0.4
PARM (49)	Groundwater storage threshold	0.001 - 1.0	0.25	0.99
PARM (90)	Subsurface flow factor	1–100	1	1
PARM (92)	Runoff volume adjustment factor	0.1–2.0	1	1

The APEX hydrology model was calibrated by using the 18 years of the measured streamflow data (1997 - 2015) (Fig. 4a) followed by validation (2016 - 2017) using the monthly parameters in Fig. 4b. Model parameter initialization was carried out prior to calibration (warm-up period: 1990-1996). Final calibrated values of sensitive parameters are listed in Table 3. Based on statistical performance measure ratings of Moriasi et al, (2007) as shown in Table 4, the simulation of APEX model in identifying the water discharge showed very good agreement with the observed monthly streamflow both calibration and validation for a monthly time step of NSE = 0.60, R^2 = 0.62 and PBIAS = 2.50%, and NSE = 0.71, R^2 = 0.80 and PBIAS = 28.22% for model calibration and validation, respectively (Table 5 and Fig. 3).

Table 4 Model performance evaluation rating

Statistic	Evaluation rating			
	Unsatisfactory	Satisfactory	Good	Very good
R^2	< 0.50	0.50 – 0.60	0.60 – 0.70	0.70 – 1
NSE	< 0.50	0.50 – 0.65	0.65 – 0.75	0.75 – 1
PBIAS	> ±25	±15 < PBIAS < ±25	±10 < PBIAS < ±25	< ±10

Table 5 APEX model performance on a monthly basis of observed and simulated streamflow calibration (1997–2015) and validation (2016–2017) in Stung Chinit Catchment

Station Name	Component	NSE	R^2	PBIAS (%)
Kampong Thmar	Calibration	0.60	0.62	2.50
	Validation	0.71	0.80	28.22

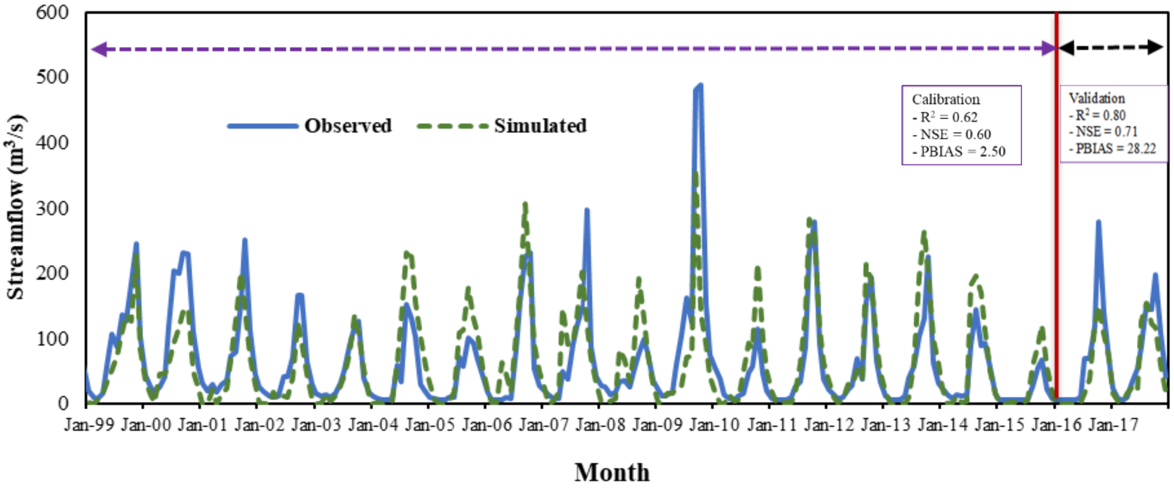
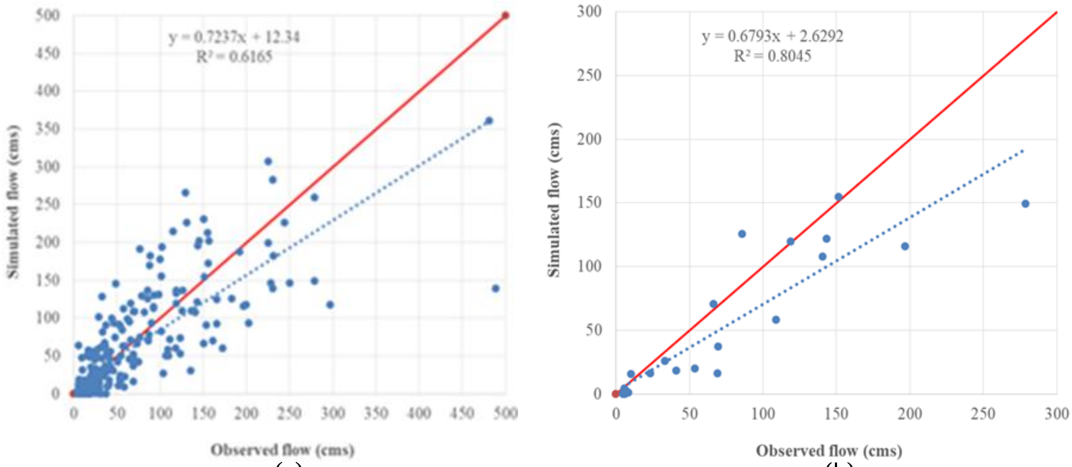


Fig. 3 The monthly comparison of time series measured and simulated streamflow and corresponding precipitation data for Stung Chinit Catchment



(a) (b)

Fig. 4 The monthly comparison of measured and simulated streamflow for (a) calibration (1997-2015), and (b) validation (2016-2017) periods for Stung Chinit Catchment

We illustrated a scatter plot with line 1:1 and regression lines to compare the results between the observed and simulated monthly streamflows during calibration and validation (Fig. 4). The model overpredicted the flow when the observed values were less than approximately 320 m^3/s (Fig 4a). The model had a large error of prediction when it predicted a monthly streamflow peak greater than 490 m^3/s. During validation, the low-flow values (<150 m^3/s) were scattered near the 1:1 line, but most of the high-flow values (> 250 m^3/s) were underpredicted (Fig. 4b).

APEX Annual Sediment Simulation

Due to the limited data of sediment yield for the model calibration, we could not do the calibration on the sediment yield. The annual suspended sediment load was just estimated as shown in (Table 6). The annual sediment yield is mainly varied with the amount of surface runoff in the catchment. The severe sediment rate of 68.14 ton/ha/year occurred in 1999. This can be the result of forest decline due to the land encroachment and forest-logging in the catchment. Since then, the sediment yield is declining dramatically. The huge erosion occurred in 2011 and 2013 because the country experienced the flooding across the study area at that time; resulted in severe sediment occurrence.

Variability of Surface Runoff and Sediment Yield in the Catchment

The mean annual surface runoff was 212.03 mm (varied from 72.56 mm to 435.59 mm). The sediment yield varied from 10.21 ton/ha/year in the riparian lowlands of the Stung Chinit main river channel to 68.14 ton/ha/year primarily in the mountain highlands from, with an average sediment yield rate of 29.62 ton/ha/year for the entire basin (Table 6).

Table 6 Water balance and sediment components

Year	PRECIP (mm)	QSS (mm)	QSW (mm)	QTS (mm)	YW (t/ha)
1997	1279	176.33	176.28	286.97	16.95
1998	1182	192.46	192.39	306.70	21.88
1999	1910	435.59	435.43	708.31	68.14
2000	1550	243.49	243.36	495.76	37.46
2001	1521	209.23	209.11	439.94	26.88
2002	1196	112.45	112.4	243.95	11.18
2003	1261	126.65	126.59	301.3	16.13
2004	1271	172.61	172.48	489.18	29.90
2005	1019	97.83	97.79	385.16	10.21
2006	1581	313.98	313.76	659.87	40.67
2007	1517	261.03	260.86	566.53	29.34
2008	1412	171.64	171.55	363.78	20.75
2009	1640	284.64	284.47	532.77	40.07
2010	1468	217.74	217.60	446.53	30.06
2011	1592	347.19	346.97	641.92	52.52
2012	1447	234.73	234.61	475.51	26.57
2013	1616	355.71	355.49	652.86	58.56
2014	1352	189.38	189.24	442.01	35.66
2015	931	72.56	72.52	184.78	12.76
2016	1167	134.26	134.19	295.92	16.00
2017	1095	103.16	103.09	257.83	20.25
Mean	1381	212.03	211.91	437.03	29.62

PRECIP = Precipitation; QSS= Surface runoff; QSW = Watershed outflow; QTS= Total flow from all subarea and YW= Watershed sediment yield

CONCLUSION

Our results showed that the Stung Chinit catchment experienced soil loss during 2011 and 2013 due to the big flooding occurrence in the catchment area. A calibrated and validated APEX model was able to estimate streamflow and sediment yield. The model also provided a good qualitative description on the effects of land uses and geographic indicators on streamflow and sediment estimation. The mean annual surface runoff was 212.03 mm varied from 72.56 mm to 435.59 mm, while the sediment yield varied from 10.21 tons/ha/year in the lowlands of the Stung Chinit catchment main river channel to 68.2 tons/ha/year in the highlands, with an annual sediment yield of 29.2 tons/ha/year. Most of the sediment yield came from the eastern part and near the outlet of the the Stung Chinit catchment. Land use management in lowlands could be improved while practising some soil erosion control methods in highlands and minimizing inappropriate tillage practices in areas with slopes greater than 25 to prevent soil loss. Due to our data limitations, we did not compare the impact of land use change on streamflow and sediment load in this watershed, but it is important to determine how the drivers of streamflow and sediment load will be changed in response to land use change and climate change in the watershed. Nevertheless, this research should be able to develop a reliable physically-based streamflow model, which is capable of illustrating and defining the critical source areas and conditions of sediment yield.

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