Research article

Application of Soil and Water Assessment Tool (SWAT) Model to Predict Streamflow and Sediment Yield in Wahig-Inabanga Watershed, Bohol, Philippines

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Abstract The study applied the Soil and Water Assessment Tool (SWAT) model -- to predict streamflow and sedimentation in Wahig-Inabanga Watershed, Bohol, Philippines. The applicability of the SWAT model was evaluated and its output was integrated to GIS to generate sedimentation hazard map. The result of the SWAT model performance evaluation on stream flows was satisfactory given prediction efficiency values: NSE = 0.6578; R^2 = 0.7038; PBIAS = 14.94%; and RSR = 0.5850. Satisfactory result was also achieved in model validation with model accuracy values on NSE, R^2, PBIAS and RSR of 0.41, 0.57, 25.09%, and 0.71, respectively. However, the model did not provide precise estimates of sediment yield in sub-basins and hydrological response units (HRU) especially with corn as single land use or one of the landuses even on flat to gently rolling terrain. Inaccuracy issue on sediment yield prediction deferred further analysis including thesedimentation risk valuation which supposed to provide baseline information for watershed management and land use planning.

Keywords Soil and Water Assessment Tool, SWAT, streamflow, sediment yield

INTRODUCTION

The Philippines is very vulnerable to natural disasters because of its natural setting (Palao et al., 2013; Principe, 2012; Luna, 2001), its socioeconomic, political, and environmental context, and especially its widespread poverty (DepEd et al., 2008; Lasco et al. [undated]). Moreover, the country is prone to geologic and natural hazards mainly because of its geographic, geologic, and tectonic setting. Disasters, whether natural or human-induced, have caused tremendous losses in the country's national economy. Storms, landslides, floods, and sometimes the combination of all three at once, displace as many as 8 million people every year. The National Disaster Risk Reduction and Management Council (NDRRMC) under the Office of the Civil Defense, Department of National Defense (OCD-DND) has recorded more than 15 major disasters to have devastated different parts of the country in the last five years alone, including typhoon Haiyan ("*Yolanda*"), said to be the greatest typhoon ever recorded in Philippine history. Being mountainous and rugged in topography, the Philippines is no doubt prone to massive erosions and landslides. These two, together with floods, typhoons, and fire, account for billions of pesos of government spending annually for disaster rehabilitation programs.

Soil erosion alone has been considered as a major threat to sustainable agriculture and to the environment (Paningbatan et al., 1995) especially in the developing world particularly the Philippines (Genson, 2006; Bantayan, 2006; Bantayan, 1997). According to a report from PCARRD (1999), some 74 to 81 million tons of soil is lost annually, affecting 63% to 77% of the country's total land area. Using the Global Assessment of Soil Degradation (GLASOD) database, FAO (2000) as cited by Genson (2006) confirmed the severity of land degradation giving an estimate of about 79%. Indeed, land degradation is a major environmental and development issue in the Philippines. Its process is advancing at an alarming rate due to deforestation and inappropriate agricultural activities in fragile and highly sensitive mountainous environments. This is further aggravated by frequent cyclones and thunderstorms due to climate change and weather extremes which somehow explain the very high sediment yield rates throughout the country (Palao et al., 2013; Principe, 2012; PCARRD, 2008).

The integration of SWAT and GIS in streamflow and sediment yield modeling in Wahig-Inabanga Watershed, Bohol, Philippines, is perceived to be of great advantage in terms of improved procedures and analyses, and yield outputs both for sub-basin and hydrological response unit (HRU) scale. Evidence of GIS and SWAT integration are the availability of several readily downloadable SWAT add-ins compatible with selected GIS software packages. One particular SWAT add-in used in this study was ArcSWAT, the SWAT geo-spatial interface in ArcGIS.

OBJECTIVES

The study aimed to apply and evaluate the performance of the Soil and Water Assessment Tool (SWAT) model in streamflow and sedimentation modeling in the Wahig-Inabanga Watershed using ArcGIS as the platform of geo-spatial analysis.

METHODOLOGY

Study Site

The Wahig-Inabanga Watershed, also known as Wahig-Inabanga River Watershed Forest Reserve (WIRWFR), is the biggest watershed in the province of Bohol, Philippines. From the Northwest Bay of Inabanga, the river dissects the central part of the island embracing a total land area of more than 610 km^2 (Figure 1). This watershed is about 15.20% of the total land area of the province.It is geographically located between 124^{o}3’36” and 124^{o}23’24” East longitude, and between 9^{o}43’48” to 10^{o}4’48” North latitude (GCS Luzon-Philippines 1911 datum).

Fig.1 Location of the study area: (a) map of the Philippines showing the Central Visayas; (b) map of the Central Visayas showing Bohol; and (c) map of Bohol showing the study area

SWAT Modeling

The SWAT model, being physical-based, claims for more complex types of input data in order to become operationally functional. In the study, there were several types of data (database input files, GIS required and optional input layers, and the observed or acquired measured data on streamflow) obtained from different reliable sources. The database input files which were used included: 2000-2012 climatic data from Bohol Experiment Station (BES); soil physical and chemical data from the Bureau of Soil and Water Management (BSWM); and daily rainfall datafrom two rainfall stations within the watershed, all of which need to be preprocessed and organized into a format readable by the SWAT model. In addition, the required GIS input layers were land cover (LULC) and soil, including a digital elevation model of the watershed in which the manual definition of slope was based. Other optional input layers like watershed mask and stream network were also used to reduce the processing time during watershed and sub-basins delineation. Unluckily, in the study area only streamflow dataset was available and this was applied for sensitivity analysis, calibration and validation of the model.

ArcGIS was used to preprocess some of the various SWAT model parameters observed and collected from the real watershed condition into a format that is acceptable by the model. Only the manual calibration method was applied in this study after parameterization. It was done by manually adjusting values of identified significant parameters. This was followed by model validation which aided in demonstrating whether a given site-specific model was capable of making sufficiently accurate simulations or otherwise. Results of the model simulation included the estimates on streamflow and sediment yield in sub-basin and HRU levels. Acceptance of the model was based on the satisfactory values of the model efficiency indicators such as Nash-Sutcliffe efficiency, coefficient of determination, root mean square error–observations standard deviation ratio, and percent bias. Computation, however, was done outside the GIS interface. The ArcSWAT2009 version 488, unfortunately, does not directly provide spatio-temporal erosion maps. However, since the SWAT simulation was run within the GIS setting, visualization of the outputs was obtained by adding the sediment yield estimates in the attributes of sub-basin and HRU layers.

RESULTS AND DISCUSSION

Sensitivity Analysis

Auto-sensitivity analysis was performed on 20 relevant stream flow parameters for the period 1986-1991. The absence of sediment yield data limited the sensitivity analysis only to streamflow-related parameters. Based on parameter sensitivity scale rating of Lenhart et al. (2002), out of the 20 parameters evaluated, half were found significant on simulated vs. observed output.

Table 1 Ranking of significant flow parameters after sensitivity analysis with observed data

Parameter	Description	Rank	Sensitivity Index
CN2	Curve number for moisture condition II	1	0.9960**
CH_K2	Effective hydraulic conductivity in main channel (mm/hr)	2	0.8000**
ESCO	Soil evaporation compensation factor	3	0.7720**
ALPHA_BF	Baseflow alpha factor (days)	4	0.1920*
CH_N2	Manning's N value for the main channel	5	0.1660*
BLAI	Maximum potential leaf area index	6	0.0693*
GWQMN	Shallow aquifer threshold water depth (mm H_2O)	7	0.0665*
CANMX	Maximum canopy storage (mm H2O)	8	0.0542*
SOL_AWC	Available water capacity of the soil layer (mm H_2O/mm soil)	9	0.0512*

Note: Sensitivity Rating (Lenhart et al., 2002): **= high; * = medium (moderate)

Table 1 shows the result of the analysis ranked according to sensitivity index values. The first three parameters were highly sensitive based on Lenhart et al. (2002) sensitivity rating while the rests were medium sensitive.Those parameters with less than 0.05 sensitivity index values were considered negligible based on Lenhart et al. (2002) sensitivity rating and, thus, were not included in model calibration.

Stream Flow Model Calibration and Validation

SWAT stream flow model calibration was performed using the 9 significant parameters during the same simulation period (1986-1991). Model validation, on the other hand, was done for the period 1991-1996. Each run was evaluated using model efficiency indices such as NSE (Nash-Sutcliffe efficiency coefficient), R^2 (coefficient of determination), PBIAS (percent bias), and RSR (root mean square error – observations standard deviation ratio). The results of the simulation passed the model efficiency criteria as required by each of the pre-identified indices. Summary results of the stream flow (runoff) initial run, calibration and validation evaluation are presented in Table 2.

Table 2 Summary result of model prediction efficiency evaluation of the stream flow model for Wahig-Inabanga Watershed

SIMULATION	PERIOD	NSE	R^2	PBIAS	RSR
Initial Run	1986-1991	0.5035	0.6831	25.2796	0.7046
Calibration	1986-1991	0.6578	0.7038	14.9373	0.5850
Validation	1991-1996	0.4106	0.5699	25.0883	0.7083

Several SWAT users (Principe, 2012; Duan et al., 2009) suggested that models with NSE of more than 0.4 and R^2 greater than 0.5 for both calibration and validation can still realistically simulate basin's hydrological processes. Thus, based on the calibration and validation results, it was assumed that the model captures the actual stream flow condition in the study area. According to the SWAT user group [https://swat.tamu.edu/media/82492/swat-user-group], it is a requirement that a SWAT model intended for soil erosion prediction through sediment yield must fulfill this condition.

Basin-Level Water Balance Tradeoff and Sediment Yield

The water balance tradeoffs and the resulting changes in sediment yield of Wahig-Inabanga Watershed as outputs of model calibration for streamflow are presented in Table 3. Results show a considerable decreasing pattern on sediment yield as values of significant parameters were adjusted from their default or assigned values. Out of the 121 sub-basins of Wahig-Inabanga Watershed, 47 exceeded the soil tolerable loss of 11.2 tons/ha/yr (Figure 3). The tolerable soil loss is based from Hudson (1995) and Lal (1994). It was noticed that all 47 sub-basins had CORN as a single land use or in combination with some other land uses. This only revealed that the model may have over predicted the SYLD for CORN, and perhaps on some other LULCs, irrespective of slope class. In this regard, a comprehensive assessment is required in the HRU-level output of the model. Sub-basins with CORN as its single LULC had annual averages ranging from 31.38 tons/ha to 55.21 tons/ha, while those sub-basins with several other LULCs in addition to CORN had annual averages of about 11.81 tons/ha to 138.58 tons/ha.

Table 3 Basin-level water balance trade-off of Wahig-Inabanga Watershed during streamflow model calibration

SIMULATION	PARAMETER ADJUSTED	PRECIP	PET	ET	SW	PERC	SURQ	GWQ	LATQ	WYLD	SYLD
Initial run		1787.38	796.52	604.01	2055.93	405.91	563.37	383.43	217.32	1164.12	5444.37
Calibration	CN2	1787.38	796.52	604.52	2095.12	702.93	177.64	674.66	306.30	1158.60	1968.05
	CH_N2	1787.38	796.52	604.52	2095.12	702.93	177.64	674.66	306.30	1158.60	1968.05
	BLAI	1787.38	796.52	608.42	2087.86	700.50	176.80	672.39	305.65	1787.38	1949.72
	GWQMN	1787.38	796.52	608.42	2087.86	700.50	176.80	655.87	305.65	1138.32	1949.72
	CANMX	1787.38	796.52	643.89	2204.95	701.34	175.01	654.16	270.33	1099.50	1942.39
	SOL_AWC	1787.38	796.52	655.43	2754.11	667.04	169.89	619.60	298.15	1087.63	1868.54

Note: PRECIP = average annual precipitation (mm)
PET = average annual potential evapotranspiration (mm)
ET = average annual evapotranspiration
SW = average annual soil water (mm)
PERC = average annual percolation (mm)
SURQ = average annual surface runoff (mm)
GWQ = groundwater flow (mm)
LATQ = lateral flow (mm)
WYLD = water yield (mm)
SYLD = total average annual sediment yield (ton/h) for the whole watershed

CN2 = curve number for moisture condition II
CH_N2 = Manning's N value for the main channel
BLAI = maximum potential leaf area index
GWQMN = Shallow aquifer threshold water depth (mm H_2O)
CANMX = maximum canopy index (mm)
SOL_AWC = available water capacity of the soil layer (mm H_2O/mm soil)

HRU-Level (LULC) Water Balance and Sediment Yield

Another important output of each simulation in SWAT is the HRU-level water balance and sediment yield. Rearrangement of the output was purposely done to determine which among the LULC types have been mis-predicted by the model in terms of sediment yield prediction. Table 4 presents the water balance and sediment yield after having adjusted all flow sensitive parameters.

Table 4 HRU-level water balance and sediment yield (ton/ha) of calaibrated flow model using flow sensitive paramerets summarized by landuse and land cover

LULC	PRECIP	PET	ET	SW	PERC	SURQ	GWQ	LATQ	TLOSS	WYLD	$SYLD_A$	$SYLD_{MN}$	$SYLD_{MX}$
URBN	1818.29	787.47	613.93	2570.17	496.54	622.16	459.93	86.82	7.10	1161.81	16.91	0.63	66.53
CORN	1797.33	789.69	563.08	2427.83	606.64	205.91	557.43	422.98	1.50	1184.82	91.68	1.86	481.18
FRST	1787.98	790.65	727.55	2242.42	487.00	122.74	434.35	452.23	0.92	1008.40	0.22	0.00	1.11
OILP	1765.20	793.10	766.30	2289.35	525.68	133.58	476.59	341.77	0.85	951.09	1.43	0.00	12.34
RICE	1810.38	788.30	562.01	2528.71	716.84	184.21	669.88	348.85	1.40	1201.54	4.98	0.21	26.20
RNGB	1695.28	800.50	575.96	2518.90	548.75	106.86	499.18	464.04	2.23	1067.85	3.12	0.01	17.46
RNGE	1768.66	792.69	579.93	2388.19	550.46	155.12	504.11	484.13	2.87	1140.48	8.44	0.01	33.39
WATR	1692.91	1170.35	819.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WETF	1482.25	823.39	696.12	4337.22	382.87	386.60	321.46	0.97	0.72	708.26	0.01	0.00	0.02

Note: Water Balance Component:

PRECIP = precipitation (mm)
PET = potential evapotranspiration (mm)
ET = evapotranspiration (mm)
SW = soil water content (mm)
PERC = percolation (mm)
SURQ = surface runoff (mm)
GWQ = groundwater flow (mm)
LATQ = lateral flow (mm)
TLOSS = transmission loss (mm)
WYLD = water yield (mm)
$SYLD_A$ = average annual sediment yield (ton/ha)
$SYLD_{MN}$ = minimum sediment yield (ton/ha)
$SYLD_{MX}$ = maximum sediment yield (ton/ha)

SWAT Landuse and Land Cover:

URBN = urban for built-up
CORN = corn
FRST = forest mixed
OILP = oil palm for perennial cultivated and plantations (dominated by coconuts and other perennial crops)
RICE = rice
RNGB = range-brush for wooded grassland
RNGE = range-grasses for grassland
WATR = water
WETF = wetland forested for mangrove

The spatial distribution of the predicted average annual soil erosion rates in terms of sediment yield (tons/ha) in sub-basin and HRU-levels are presented in Figures 2 and 3. The soil erosion (sediment yield) values for the whole watershed were divided into six levels: slight (< 2 tons/ha/yr); acceptable (2-11 tons/ha/yr); moderate (12-25 tons/ha/yr); high (26-50 tons/ha/yr); severe (51-80 tons/ha/yr); and very severe (> 80 tons/ha/yr). This classification, accordingly, is based from the tolerable erosion rate of 10 to 12.5 tons/ha/yr adopted from Paningbatan (1987) as cited by PCARRD (1991) and was also used by several local researchers in the Philippines.

The overall output of the model and given the limited available input data used in the simulations, it can still be assumed that the model is able to predict stream flow. However, it is not accurate in estimating sediment yield for some of the sub-basins and HRUs, particularly those with corn as a landuse. The inaccuracy in sediment yield estimation using the SWAT model deferred its risk quantification and valuation.

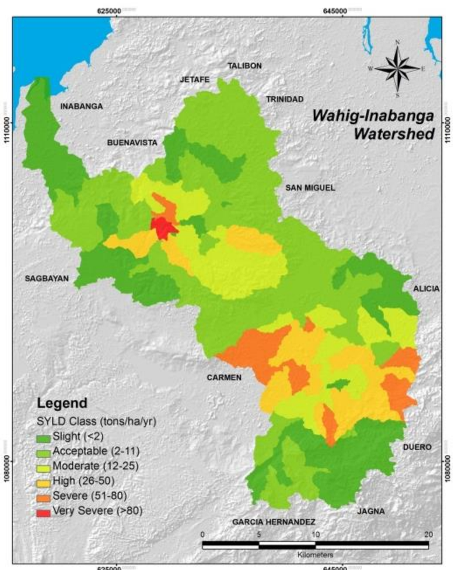

Fig. 2. Sub-basin-level sediment yield class ratings of Wahig-Inabanga Watershed

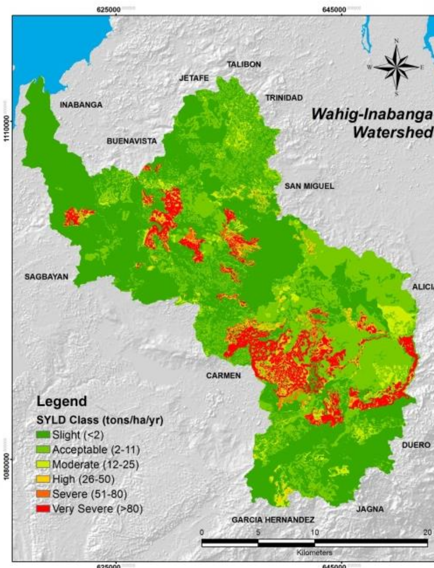

Fig. 3. HRU-level sediment yield class ratings of Wahig-Inabanga Watershed

CONCLUSION

The study validated the applicability of the SWAT model only in simulating flow discharge dynamics of the watershed based on the satisfactory values of the statistical measures of model efficiency. However, it does not provide accurate estimates of the annual sediment yield in some LULCs such as grassland, rice, perennial cultivated crops, and especially corn, on flat to gently sloping areas in the watershed. The model, on the other hand, somehow precisely predicted annual sediment yield for built-up, open forest, mangroves, and inland water. The absence of sediment yield data restricts the calibration and validation only to streamflow-related parameters. The sediment yield input data, supposedly, should have been included in the sensitivity analysis with measured data for more efficient model calibration in case sediment yield prediction is the intention of the study.

RECOMMENDATIONS

In order to fully appreciate the utility of the SWAT model, its application must be employed only in watersheds with at least minimum required input data. Assumptions on the values of important parameters, if not provided quantitatively, will just complicate the interpretation of the results.

Acquired, measured or observed data on discharges (stream flows) and sediment yields are needed especially if the intention of using the model is for sediment yield prediction. The absence of acquired data on sediment yield in the present study which is supposed to be included in sensitivity analysis and used in calibration may have affected the results of sediment yield estimation. Therefore, subsequent or related studies, using the same model, are only suggested if these data are all available.

Parameters in the crop database must be studied well. The over-predicted values of sediment yield in corn and some other LULCs demand further examination of the crop database to determine which parameters need iteration. In addition, it is possible in the current and latest SWAT versions to delete, edit, update and add a specific crop type or LULC (e.g. agroforestry) which is not available in the crop database as long as matching parameter values taken in the field will also be provided. This is suggested primarily to address difficulty in model parameterization.

Fine-tuning of parameters in the SWAT model is generally a stumbling block to new users of the software. The task would be more tedious especially when some critical parameters need to be precisely adjusted to minimize error and increase accuracy of the model. Therefore, auto-calibration which was not performed in the study is suggested only for the identified sensitive parameters.

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