CALCULATING SEDIMENT YIELD USING HEC-HMS IN PILAN AND MATIAO WATERSHED IN SOUTHERN PHILIPPINES

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ABSTRACT: Soil surface erosion is a natural phenomenon that occurs when its causing factors such as precipitation and surface runoff are present. During rainfall in a watershed and land surface are saturated, water in the form of runoff flow through gullies then accumulate into the streams and eventually drains out to the shores. Overland runoff carries soil particles from the surface and transports it until some were settled and conveyed in the streams implying change in the river hydrology. This study presented the sediment modeling in Pilan Watershed, Sta. Cruz, Davao del Sur, and Matiao Watershed, Pantukan, Compostela Valley, Southern Philippines using Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) Version 4.2 developed by U.S. Army Corps of Engineers (USACE) with modified universal soil loss equation (MUSLE) method to compute for the sediment load supplied by the watersheds. MUSLE parameters in HEC-HMS are the soil erodibility, topography, cover management, practice factor and gradation curve. Pilan Watershed has a total drainage area of 66.61 square kilometers, 0.11% of it is built-up area and the rest are covered with shrub land, agro-forest and forest. Matiao Watershed on the other hand has 166.08 square kilometres of drainage area and only at most 0.44% is built-up. The sediment models were calibrated through matching the simulation results to the observed discharge and total suspended solids (TSS) and with the time series of precipitation recorded in the drainage areas. The comparison has shown that the Pilan Watershed sediment model has -22.75 PBIAS, 0.55 RSR, and 0.69 NSE, and that the Matiao Watershed sediment model has -13.97 PBIAS, 0.44 RSR, and 0.80 NSE which mean that the models have acceptable parameterization. A 1-year rainfall observation was simulated using the models. The Pilan Watershed sediment model has computed a total of 107.91 tonnes of sediment load on the entire watershed, and the Matiao Watershed sediment model computed a total of 549.71 tonnes. The Pearson product-moment correlation (r) of sediment yield to the cover, erodibility, and topographic factors were also calculated. It was found out that the calculated sediment yield values were highly correlated to the topographic factor (r = - 0.9535) for Pilan Watershed and to the cover factor (r = 0.7084) for Matiao Watershed.

1. INTRODUCTION

Soil surface erosion is a natural phenomenon that occurs when its causing factors such as precipitation and surface runoff are present. Overland runoff carries soil particles from the surface and transports it until some were settled and conveyed in the streams. These soil particles are mostly composed of clay, silt, and sand (Push et al., 2012). Sand particles are more abundant on top soil whereas silt and clay are mostly settled on subsoil layers (Tindall and Kunkel, 2009). During erosion, transportation and deposition processes, sand-size soils are easily settled than silt and clay due to larger size of the particles and the latter are suspended in the water longer (Isidro et al., 2018). The extent of this phenomenon is difficult to describe and quantify, i.e., the exact amount of eroded, transported and deposited soil particle, and its environmental effects, but can be estimated by setting up models to provide scientific information to be used for best management practices (BMPs) (Jaferi et al., 2016).

The HEC-HMS version 4 is able to calculate sediment transport for soil surface erosion from sub-basins, channel sediment transport, and erosion/deposition in reaches, and sediment trap efficiency in reservoirs. It requires subbasin, reach, junction and outlet elements to represent a watershed. The tool has two methods to compute for sediment yield: modified universal soil loss equation (MUSLE by Williams, 1975) and built-up/wash off (BUWO by Huber and Dickenson, 1988). MUSLE is used to simulate soil surface erosion from subbasin elements for pervious or rural areas while BUWO method for impervious or urban areas (Pak et al, 2015). MUSLE parameters include soil erodibility factor, topographic factor, cover factor, practice factor and gradation curve. The resulting estimates by HEC-HMS are time-series of sediment load classified by grain sizes, i.e., clay, silt, sand, and gravel, and sediment concentration in mass per volume units. Using the output time series, the sediment load rate in unit of mass per time for each sub-basin and reach was calculated and given by the product of sediment concentration rate and water discharge rate of the same time-series. The model estimates the rate amount of sediment load yield (tons) and runoff (m3/s) in the sub-basins and reaches over a period of time.

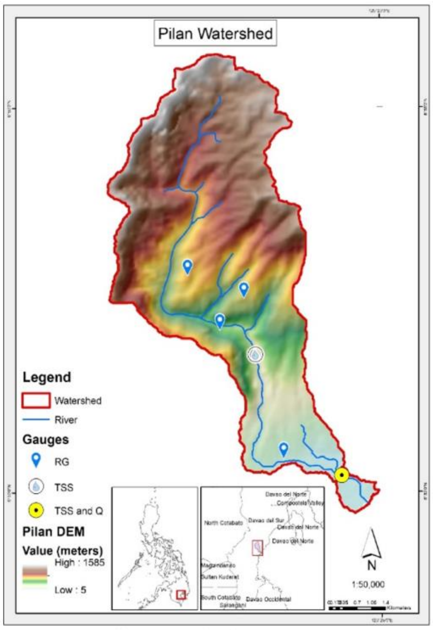
Pilan and Matiao Watershed hydrologic modelswere setup using HEC-Geospatial Hydrologic Modeling System (HEC-GeoHMS) to generate sub-basins, reaches, junctions and outlet elements of the watersheds. The modelswere supplied with required parameters to run the discharge simulation and were calibrated by importing the observed rainfall and discharge data taken from the installed stream and rain gauges in the watersheds. Pilan and Matiao Watershed sediment models in HEC-HMS were also setup and provided with the parameters in MUSLE to simulate sediment transport processes. The models were calibrated using observed total suspended solids (TSS) and rainfall data taken during a period of observation in the watersheds.

This research shows the application of HEC-HMS software sedimentation tool in computing the sediment yield of Pilan and Matiao Watersheds. The main objective of the study was to setup sediment models of the two watersheds. Specifically, to get initial MUSLE parameter values, to calibrate and validate sediment models and to run a 1-year simulation using 1-year rainfall data. The results display each particular area where sediments yielded. With the integration of geographic information system (GIS) tool, this study visualizes spatial information concerning sediment yield rate and transport.

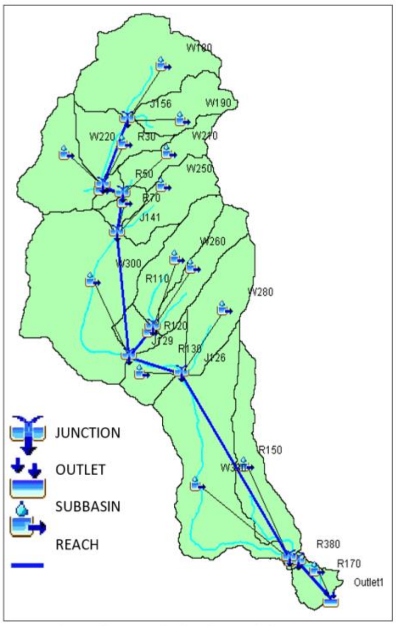
2. MATERIALS AND METHODS

2.1 Study Area

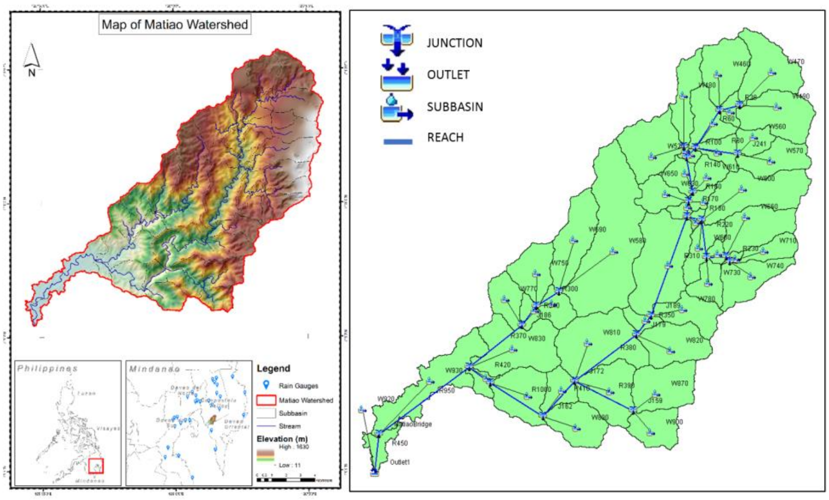
This study was conducted in Pilan Watershed located in the Municipality of Sta. Cruz, Davao del Sur, and in Matiao Watershed, Pantukan, Compostela Valley, Southern Philippines. Pilan Watershed covers an area of 66.61 square kilometers (km^2) where 73.77% of the area is agroforest, 20.80% is shrubland, 5.32% is forest and 0.11% is built-up area (Land Cover by DENR, 2012). There were 4 rain gauging stations, 2 TSS sampling stations and 1 discharge measurement station. Figure 1a shows the map of Pilan Watershed and the location of gauging stations. It has 18 subbasins, 8 junctions and 9 reaches as shown in figure 1b, the basin model of the watershed in HEC-HMS 4.2.Meanwhile, Matiao Watershed covers an area of 166.115 square kilometers (km^2) where 52.24% of the area is covered with forest, 35.54% with shrublands, 6.37% with crop lands, 5.41% with grasslands, and the remaining by built-up areas and inland water bodies(NAMRIA, 2015). There were 4 rain gauging stations, 2 TSS sampling stations and 1 discharge measurement station. Figure 1c shows the map of Matiao Watershed and the location of gauging stations. It has 47 subbasins, 24 junctions and 24 reaches as shown in figure 1d, the basin model of the watershed in HEC-HMS 4.2.



a. Pilan Watershed



b. Pilan Hydrologic Model



c. Matiao Watershed d. Matiao Hydrologic Model

Fig. 1. Location map of Pilan Watershed.

2.2 Data

The study made use of several datasets from various sources, as shown in Table 1.

Table 1. Dataset used in this study.

Data	Source	Date	Purpose
5-m Resolution DEM	DENR-NAMRIA	2017	Setup Hydrologic Model, Generation of Topographic Factor
Calibrated Hydrologic Model	HEC-HMS Calibration Processing	2018	Setup Sediment Model
Digital Soil Map of Pilan and Matiao Watershed	FAO/UNESCO	1971-1981	Generation of Erodibility Factor
Digital Landcover Map	DENR	2015	Generation of Cover Factor
Gradation curve	Soil sampling / Laboratory Analysis	August 2018	Gradation Curve Input
Total Suspended Solids	Water Sampling / Laboratory Analysis	December 2018 - March 2019	Calibration and Validation

The HEC-HMS sedimentation model using MUSLE requires a calibrated hydrologic model, rainfall and geographic data, such as land cover, soil class, topographic factor, etc., hence, the 5-meter resolution digital elevation model (DEM), land cover and soil maps, and the gradation curves were utilized. The calibrated hydrologic model was derived from HEC-HMS software using the 5-meter resolution DEM and stage-discharge curve. The input parameters for the stage-discharge curve of the river were velocity, stage, and cross-section data acquired during field survey. Davao City rainfall data from December 2015 to December 2016 was used for this study since no watershed rainfall data were available.

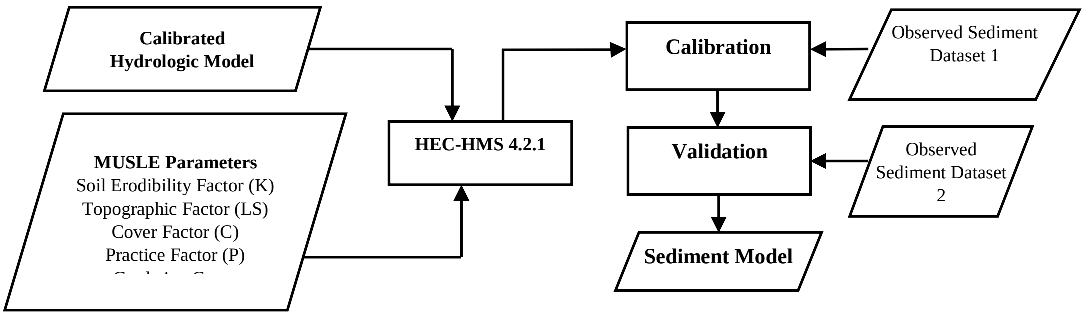
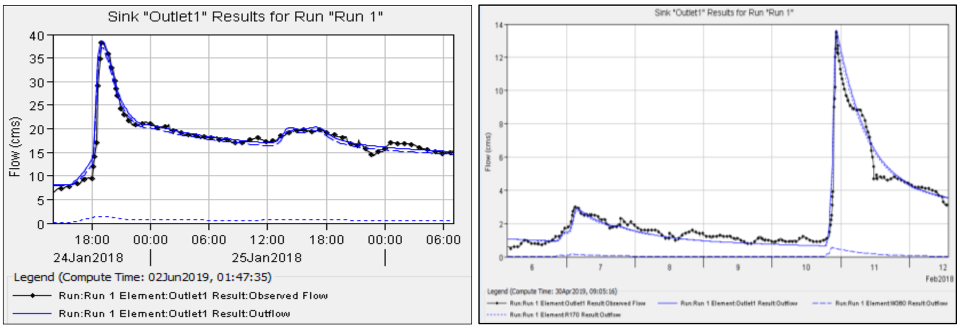


Figure 2. Level 0 of the data flow diagram for the sedimentation modeling using HEC-HMS.

2.3.1 Calibrated Hydrologic Model

HEC-HMS requires subbasin, reach and junction elements. HEC-GeoHMS plugin in ArcGIS was used to model thesubbasins, reaches and junctions based on the 5-meter resolution DEM (Ogania et al, 2019). Matiao hydrologic model has 47 subbasins, 24 junctions and 24 reaches with a total area of 166.59 square kilometer and Pilan hydrologic model has 18 subbasins, 8 joints and 9 reaches with a total area of 32.30 square kilometer. The models were configured as follows; SCS Curve Number for Loss method, Clark Unit Hydrograph for Transform method, Recession for Baseflow method and Muskingum-Cunge for Routing method. The hydrologic model calibration used measured hydrologic data such as discharge, water level and rainfall from field surveys.The observed discharge and water level were taken from the bridges and the rainfall on the upstream. These Pilan and Matiao field data were collected on February 6- 12, 2018 and on January 24-26, 2018, respectively, in 10-minute interval and were used to compare with the simulated discharge of the models. Calibration was done by parameterization and comparing the observed and simulated discharge curve from base flow, during an event flow and back to the base flow successively until such simulated discharge has reached close enough to the observed data.

After calibration, the models achieved very good model performance ratings (Moriasi et al., 2007) – i.e., Matiao Hydrologic Model attained a Nash-Sutcliffe Efficiency coefficient (NSE) equals 0.94, root mean squared error – standard deviation ratio (RSR) equals 0.24, and a percent bias (PBIAS) of -1.99, and for Pilan Hydrologic Model the NSE is 0.96, RSR is 0.21, and PBIAS is -0.01. Figure 3 shows the graph the HEC-HMS-simulated discharge versus the discharge field survey data.



(a) (b)

Fig. 3. Comparison of the simulated river discharge versus the field-surveyed discharge data of the (a) Matiao River from January 24 to 26, 2018 and (b) Pilan River on February 6- 12, 2018.

The calibrated hydrologic model which has calibrated parameters as shown in Table 2 was integrated into sediment yield computation by supplementing the required parameters of MUSLE in HEC-HMS.

Element	Parameter	Calibrated range of values or method		Notes
Subbasin	SCS Curve Number	Initial Abstraction Curve Number Impervious	0.13274-68.406 56.56-78.32 0%-42.64%	These values were changed during calibration.
	Clark Unit Hydrograph	Time of concentration Storage Coefficient	0.16768-1.16978 3.7626-26.2506	These values were changed during calibration.
	Recession Baseflow	Initial Type – Initial Discharge Recession Constant Threshold Type – Ratio to Peak	Discharge 0.0018652-0.20053 0.0213014-0.99491 Ratio to Peak 0.0411382-0.575218	Some values were changed during calibration.
Reach	Muskingum-Cunge	Time Step Method – Length Slope Manning’s n Shape – Width	Automatic Fixed Interval 208.99-5821.7 0.0022801-0.12286 0.05 Rectangular 7.1986-25.141	Some values were determined by the HEC-GeoHMS watershed delineation.

2.3.2 Modified Universal Soil Loss Equation (MUSLE)

Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) method is a good integration for the methods in HEC-HMS due to its runoff energy factor concept (Pak et al., 2008). HEC-HMS sediment calculation using MUSLE requires soil erodibility (K), topography (LS), cover management (C), practice factor (P), and gradation curve. The MUSLE is given by

$$Sed = 11.8(Q_{surf} \times q_{peak})^{0.56} K \cdot LS \cdot C \cdot P \qquad (1)$$

where Sed, Q_{surf}, and q_{peak} are the sediment yield for a given event, the surface runoff volume, and the peak runoff rate, respectively.

2.3.2.1 Soil Erodibility

The soil erodibility factor (K) identifies the capacity of the soil to erode. It requires the digital soil map of the world and the soil unit symbol provided by FAO/UNESCO (2003) which supplies the needed data to solve the K equation:

$$K = 0.1317 K_{USLE} \qquad (2)$$

$$K_{USLE} = f_{sand} \cdot f_{cl-si} \cdot f_{orgc} \cdot f_{hisand} \qquad (3)$$

where:

$$f_{sand} = 0.2 + 0.3\exp\left[-0.256 m_s \left(1 - \frac{m_{silt}}{100}\right)\right] \qquad (4)$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \qquad (5)$$

$$f_{orgc} = 1 - \left[\frac{0.7 orgC}{orgC + \exp\left(3.72 - 2.95 orgC\right)}\right] \qquad (6)$$

$$f_{hisand} = \left[1 - \frac{0.7\left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left(-5.51 + 22.9\left(1 - \frac{m_s}{100}\right)\right)}\right] \qquad (7)$$

where m_s, m_{silt}, m_c, and $orgC$ are the topsoil sand fraction, silt fraction, clay fraction, and organic carbon content, respectively.

2.3.2.2 Topographic (LS) Factor

The topographic factor (LS) requires the flow accumulation and the slope which were generated by analyzing geospatially the 5-m resolution DEM of the watershed. To define the capacity of the terrain in erosive force contribution due to length, slope, and runoff accumulation, the following equation developed by Moore and Burch (1986) was used:

$$LS = 1.4 \cdot \left(\frac{\alpha x \delta}{22.1}\right)^{0.4} \left(\frac{0.01745 \sin\theta}{0.09}\right)^{1.4} \qquad (8)$$

where α, δ, and ϕ are flow accumulation, resolution of the DEM, and the slope of the DEM.

2.3.2.3 Cover Factor

Table 3. Cover factor table based on land cover type (Kim, 2006).

Land Cover Type	Cover Factor
Water and Wetland	0.00
Urban	0.01
Forest	0.03
Paddy Field	0.06
Crop Land	0.37

Cover factor (*C*) defines the effect of vegetation to soil erosion, thus, land cover is the main data needed. The value of C ranges from 0 to 1, however, in the Philippine context, it only ranges from 0 to 0.37. This is based from the five general land cover types identified in the country, which are summarized in Table 3.

2.3.2.4 Practice Factor

The practice factor (*P*) defines the effect of soil conservation and management practices to soil erosion such as agricultural, construction, and urban practices. The value ranges from 0 to 1 where 0 signifies a perfect practice and 1 as no practice. According to Wall et al. (2002), general values for P values are: 1.00 for no support practice, 0.75 for cross slope farming, 0.50 for contour farming, 0.38 for strip cropping on cross slopes, 0.25 for strip cropping on contour.

2.3.2.5 Gradation Curve (Particle Size Distribution)

The gradation curve, also known as particle size distribution curve, determines the percentage distribution of soil particles that represents the whole sediment load. In determining such, soil samples were gathered within the watershed area and were analyzed in a laboratory through sieving.After generating the particle size distributions from the gradation curve, these were set as input to HEC-HMS and the sediment yield was then computed using the Modified Universal Soil Loss Equation. Note that, the MUSLE method of quantifying sediment yield in HEC-HMS requires rainfall data per watershed subbasin. Since, there were no rain gauges within Pilan Watershed, the rainfall data per sub-basin was interpolated.

2.3.3 Calibration and Validation

Calibration as well as validation of the HEC-HMS sediment model is necessary in order to determine its accuracy and usefulness in producing real-world estimates of sediment yield from surface erosion (White and Chauby, 2005). Parameterization of MUSLE in HEC-HMS was applied by comparing the simulated sediment yield and the observed sediment yield datasets. The threshold parameter of the HEC-HMS sedimentation model was set to 1.00, implying no sediment yield when overland flow does not reach 1.00 cubic meter per second (m^3/s). The observed sediment dataset for Pilan Watershed sediment model calibration were taken on December 30, 2018 to January 2, 2019 and another observed dataset for validation were taken on January 22-23, 2019, both were in 10-minute interval. For Matiao Watershed, calibration data were collected from February 11 to March 23, 2019.

3. RESULTS AND DISCUSSION

In the initialization of the MUSLE factors, the threshold value (m^3/s) was set to 1.0. This is by the assumption that there is no sediment yield when overland flow does not reach or exceed 1.0 m^3/s. The cover (C) factor values were derived using the DENR digital landcover data. The support practice (P) factor was also set to 1.0 due to the assumption that no management practices, e.g., cross slope and contour farming and strip cropping on contours and cross slopes, were applied anywhere within the two watersheds. The sediment calculation in HEC-HMS requires an exponent factor, this was set to 1.0 as an initial value. The erodibility (K) and topographic (LS) factor values were calculated based on equations [2] and [8], respectively.

The sediment modelswere calibrated by parameterization – i.e., by adjusting the MUSLE and Volume Ratio parameters. The Pilan sediment model was calibrated using TSS data gathered from Pilan Bridge, and the Matiao sediment model TSS data were collected from Matiao and Binugsayan Bridge.During calibration, the MUSLE factors and the volume ratio parameters were adjusted by comparing the observed TSS data with the simulated sediment yield of clay and silt. Sand and gravel sediment yield were excluded since they would most likely settle on the riverbed and only become suspended in water for a very short period of time (Isidro et al., 2018). After calibration, the Pilan Watershed sediment model was subjected to validation.The Pilan Watershed sediment model attained a coefficient of determination (R^2) of 85.07%, and a performance rating of very good after calibration, i.e., 0.40 for RSR, 0.84 for NSE, and -2.36 for PBIAS. And during validation, it attained a R^2 of 73.26%, and reached the performance ratings RSR equals 0.55, NSE equals 0.69, and PBIAS equals -22.75 which are good, good and satisfactory, respectively.Figures 4a and 4b shows the observed TSS versus the simulated sediment yield from the Pilan Watershed sediment model after calibration and validation, respectively. The same procedure was done for Matiao Watershed sediment model. TSS data were collected in Matiao and Binugsayan Bridge. The model attained a R^2 of 96.27, RSR of 0.44, NSE of 0.80, and a PBIAS of -13.97.Figures 4c and 4d show the graph of the simulated sediment yield versus TSS samples during calibration of Matiao Watershed sediment model in Matiao and Binugsayan Bridge, respectively.

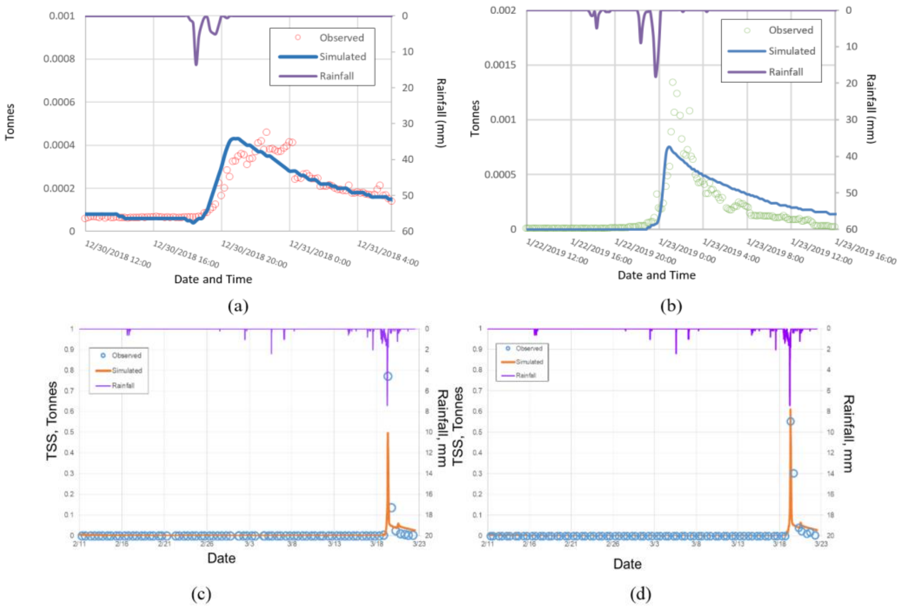


Fig. 4. Graphs of the HEC-HMS MUSLE sediment model simulated sediment yield and observed TSS during (a) calibration and (b) validation of Pilan Watershed sediment model, and calibration of Matiao Watershed sediment model at (c) Matiao and (d) Binugsayan Bridge.

After calibration, the sediment models were used to simulate a 1-year sediment yield scenario per subbasin and reach using Davao City rainfall data from December 30, 2015 to December 31, 2016. Figure 5 shows the sediment yield in particular subbasins and reaches of Pilan and Matiao Watersheds.

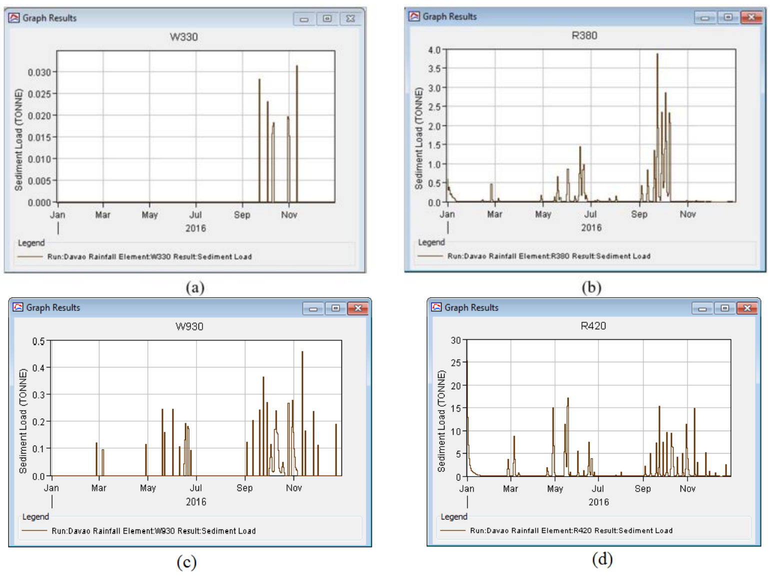
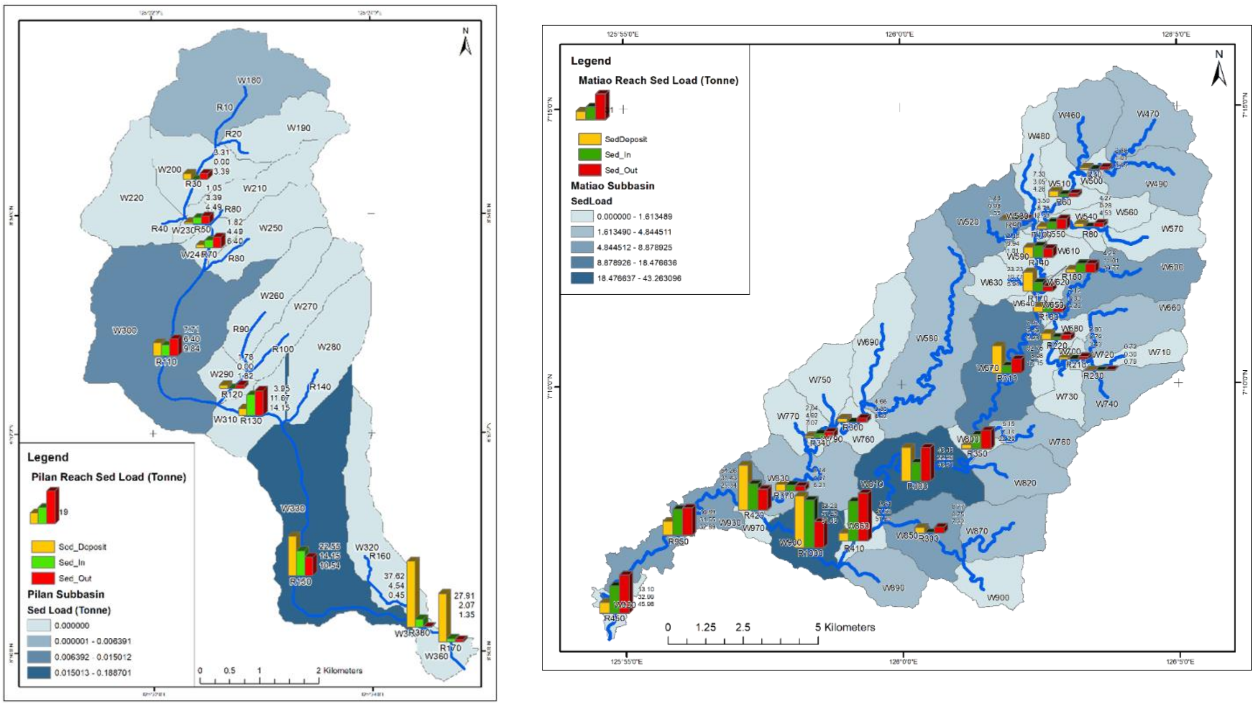


Fig. 5. Simulated sediment yield in Pilan Watershed (a) sub-basin W330 and (b) reach R380 and in Matiao Watershed (c) sub-basin W930 and (d) reach R420.

Results showed that sediment yield from W3330 and R380 of Pilan Watershed peaked during the third trimester of the year which agrees with the peaking of the rainfall data, and this is also the case for W930 of Matiao Watershed. However, a different pattern can be observed with R420 of Matiao. Sediment yields were evident in the first two trimesters which is possibly due to the characteristics of the sub-basins with respect to MUSLE.



(a) (b)

Fig. 6. Maps showing sediment yield (in tonnes) per reach and subbasin of (a) Pilan Watershed and (b) Matiao Watershed

The resulting simulated sediment yields were mapped using a GIS. Figure 6 shows the distribution of the calculated sediment model. The results of the sediment calculation using the calibrated sediment model showed that sediment deposits at lower stream reaches are greater than those in upper streams. Also, the results showed that the gravel and sand percentage of the sediment yield mainly compose the deposit and yield per reach of the rivers. For Pilan Watershed, W330 has the highest sediment yield among all the sub-basins. It is also important to note that sub-basins with the highest area, i.e., W180, W300, and W330, generated the highest sediment yield according to the model. The relationship between the sediment yield deposit per reach and the MUSLE factors per sub-basin adjacent to the reach was also investigated. The Pearson product-moment correlation (***r***) was calculated and it showed that sediment deposit is positively correlated with the K and C factors (***r*** = 0.9451 and 0.9188, respectively), and inversely with the LS factor (***r*** = -0.9535). For Matiao Watershed, W810 has the highest sediment yield among all the sub-basins. It is also important to note that sub-basins with more than 3 square kilometer in area, i.e., W750, W900 and W780 generated the sediment yield according to the model while those sub-basins with area below 3 sq. km. i.e., W680, W630 and W540 did not generate surface erosion. ***r***wasalso calculated. It showed that sediment deposit is also positively correlated with the K and C factors (***r*** = 0.2119 and 0.7084, respectively), and also inversely with the LS factor (***r*** = -0.0048).

4. CONCLUSION

This paper presented the process of setting up a sediment model of Pilan and Matiao Watershed using the modified universal soil loss equation (MUSLE) in HEC-HMS version 4.2.1. The initial input parameters of the models were derived from the watershed digital elevation model (DEM), watershed land cover data, watershed soil class data, soil sampling for grain size distributions, and the field-gathered and existing rainfall datasets. The models require hydrologic models calibrated using a stage-discharge curve. The set up Pilan and Matiao Watershed sediment modelswere calibrated and validated using observed sediment datasets, i.e., total suspended solids (TSS), collected in different periods of time. With the sediment models obtaining acceptable performance ratings, i.e., RSR equals 0.55, NSE equals 0.69, PBIAS equals -22.75 for Pilan Watershed, and a RSR of 0.44, NSE of 0.80, and a PBIAS of -13.97 for Matiao Watershed,the models were used in simulating a 1-year sediment load transport of the watershed based on the calibrated parameters and a 1-year rainfall data. The Pilan and Matiao Watershed sediment model calculated a total sediment yield of 107.91 and 549.71 tons, respectively, for the period of December 30, 2015 – December 31, 2016.

The sediment models were also able to compute sediment yields with respect to sediment grain size, i.e., clay, silt, sand, and gravel. Percentage distributions of each grain size classification per sediment yield per sub-basin was also based on the derived gradation curve. With the aid of GIS application, this study was able to determine probable areas where soil surface erosion occurs and where the yielded sediments are being deposited at a specific time period.

The TSS datasets used for calibration and validation or for training and testing the Pilan Watershed sediment model were collected from December 30, 2018 to January 2, 2019 and from January 22 to 23, 2019, respectively. TSS datasets for the calibration of Matiao Watershed sediment model were collected from February 11 to March 23, 2019. Thus, the 1-year simulation results were also based only on the given datasets. To obtain better results, the collection period of calibration and validation datasets can be extended. Also, the good determination of the gradation curve is recommended since resulting simulated sediment yield distribution is dependent on the input particle size distribution.

Calculation of exact sediment yield can be very difficult and tedious because of the countless factors to consider such as but not limited to anthropogenic operations, limitations of the resources, and technology being used, and unpredictability of natural phenomena; hence, utilization of automated models such as the HEC-HMS sedimentation model paired with observations from field survey can aid in capturing and approximating the condition of the watershed relative to surface erosion.

5. ACKNOWLEDGMENT

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