Comparison of Soil Erosion Models for Application in the Humid Tropics

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Abstract

Soil erosion by water has contributed significantly to the degradation of lands and impoverishment of the lives of people, especially those living in the humid tropics. Soil erosion models coupled with geographical information systems have a major advantage in that they can represent the spatial variability of catchment characteristics. This study compared the performances of three erosion models, namely, AGNPS, WEPP and SWAT, applied on different watersheds based on model predictions and efficiency. WEPP applications were found to provide good capability to simulate sediment yield followed by SWAT as shown by the high values of E_{NS} and R^2, while AGNPS applications were satisfactory as shown by the average values of E_{NS} and R^2. Therefore, the application of these models is highly recommended in the humid tropics to reduce environmental degradation due to soil erosion.

Keywords: AGNPS, WEPP, SWAT, Models, Soil Erosion

Introduction

Soil erosion is a common feature during wet seasons in humid tropical regions, such as south-eastern Nigeria, due to marked seasonality of hydro meteorological phenomena which characterizes the humid tropical environment (Mbajiorgu, 2001). Sediment resulting from soil erosion is the major pollutant of surface water in rural and agricultural watersheds (Mbajiorgu, 2004). Sediment transport studies have been receiving worldwide attention amongst soil and water scientists because its estimates are needed for various purposes. Knowledge of sediment yield from a catchment is needed to estimate the quantity of sediment delivered to a downstream reservoir (Xu et al., 2009).

Soil erosion and its attendant ills have already contributed very significantly to the degradation of lands and impoverishment of the lives of people, especially those living in the humid tropics. Zeleke (2001) reported that various studies carried out in Ethiopia considered soil erosion as a major cause of land degradation. Kaur et al. (2003) also reported that sheet erosion exists throughout the whole of India and estimated the annual rate of soil loss at about 16.75 t/ha, far above the permissible soil erosion rates of 7.5 – 12.5 t/ha/yr for various regions in India. In the Piracicaba river basin in Brazil, Bacchi et al. (2000) reported that the high erodibility of the soils coupled with the intense cultivation with sugarcane led to high erosion rates which caused severe silting of a water reservoir, reducing its original volume to only 25%, and generating several sediment deposits within the watersheds.

Understanding the processes of soil erosion, its causes and impacts on our environment is needed in other to devise effective control mechanisms and appropriate land management practices. Monitoring of soil erosion processes requires installations of various gauging stations, which is rather expensive and time-consuming and often unaffordable. Recent scientific developments have demonstrated that knowledge of soil erosion processes can be successfully gained by applying soil erosion prediction technologies (Zeleke, 2001). Soil erosion models coupled with geographical information systems have a major advantage in that it can realistically represent the spatial variability of catchment characteristics. Many hydrological models currently in use can simulate sediment transport in agricultural watersheds. This study aims at comparing applications of different physically-based, distributed, watershed hydrologic models (AGNPS (Young et al., 1989, 1994), WEPP (Nearing et al., 1989) and SWAT (Arnold and Allen, 1996)) based on their output in order to demonstrate their strengths and weaknesses in assessing the impact of agricultural land management practices on sediment transport and yield.

Soil Erosion Models

Mbajiorgu (2001) reported that hydrologic models were being developed to aid understanding of hydrologic and erosion processes which occur on watersheds. Licciardello (2007) also reported that among the different structural and non-structural measures to control negative impact of erosion processes, reliable prediction models can help in solving erosion problems and land use planning. Watershed models are considered a cost-effective and time-efficient method for the assessment of pollutant load and management practices in an effort to address non-point source pollution (Shrestha et al., 2005). These models include the USLE (Wischmeir and Smith, 1978), CREAMS (Knisel, 1980), ANSWERS (Beasley et al., 1980), EPIC (Williams et al., 1982), SWRB (Williams et al., 1985), GLEAMS (Leonard et al., 1987), WEPP (Nearing et al., 1989), AGNPS (Young et al., 1989, 1994), AnnAGNPS (Cronshey and Theurer, 1998), PESTFADE (Clemente et al., 1993), HSPF (Donigian et al., 1995), WRM (Mbajiorgu, 1995) and SWAT (Arnold and Allen, 1996). Some of these models share a common base in their attempt to incorporate the heterogeneity of the watershed and spatial distribution of topography, vegetation, land use, soil characteristics and climate (Setegn et al., 2008). Merritt et al. (2003) gave a detailed review of several erosion models, which differ in terms of their complexity, inputs and requirements, the processes they represent and the manner in which these processes are represented, the scale of their intended use and types of output information they provide. The use of physically-based distributed hydrological models and geographical information systems (GIS) can assist watershed managers to identify the most vulnerable erosion prone areas of a catchment and to select appropriate management practices (Xu et al., 2009).

Brief Description of Selected Soil Erosion Models

AGNPS Model

Agricultural Nonpoint Source Pollution Model (AGNPS) was created by the USDA - Agricultural Research Service and the Natural Resources Conservation Service in order to compare the effects of different watershed pollution control management practices. AGNPS simulates sediment and nutrient loadings from agricultural watersheds for single storm events (AGNPS) or for continuous data input (AnnAGNPS). It has the capabilities of evaluating non-point source pollution at any point predicting site-specific sedimentation within catchments.

AnnAGNPS is a continuous-simulation, watershed-scale model intended to be used as a tool to evaluate non-point source pollution from agricultural watersheds ranging in size up to 300,000 ha (Bosch et al, 1998). It is an expansion of the capabilities of single event based

AGNPS and as such shares many similarities to the original model. It is designed to aid in the evaluation of watershed response to agricultural management practices (Cronshey and Theurer, 1998). The model can be used to study the effects of alternative cropping and tillage systems including the effects of fertilizer, pesticide, irrigation application rate as well as point source yields and feedlot management (Bosch et al., 1998).

The AGNPS model comprises 3 major basic components: hydrology (runoff volume, peak discharge), sediment (sediment yield, sediment concentration, sediment particle sizes, deposition, enrichment ratio) and chemical transport (nitrogen, phosphorous, COD).

Runoff volume and peak flow rate are estimated by SCS method (Mbajiorgu, 2004):

$$Q = {(P - 0.2\,S)^2}\Big/{(P + 0.8\,S)} \qquad (1)$$

where Q = runoff volume, P = rainfall, S = retention parameter

The retention parameter is defined in terms of a curve number (CN) which depends on land use, soil type and hydrologic soil condition (Mbajiorgu, 2004). But:

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad (2)$$

where CN = curve number

Peak flow rate is calculated as in Mbajiorgu, (2004):

$$q = \frac{0.0021QA}{T_P} \qquad (3)$$

where q = peak flow rate in m/s, A = drainage area in ha, Q = runoff volume in mm
T_P = time of peak in hours.

Upland erosion for single storms, in erosion and sediment transport component, is calculated from modified form of USLE (Mbajiorgu, 2004) as follows:

SL = (EI) KLSCP (SSF) (4)

where
SL = soil loss,
LS = topographic factor,
C = cover and management factor,
P = supporting practice factor,
SSF = slope shape factor,
K = soil erodibility factor, and
E I = the product of the storm total kinetic energy and maximum 30-minute intensity.

Chemical transport component estimates N, P and COD. The calculation of this component is divided into soluble and sediment-absorbed phases.

WEPP Model

The Water Erosion Prediction Project (WEPP) was initiated in 1985 to develop a new generation water erosion prediction technology for use in soil and water conservation and in environmental planning and assessment (Abaci and Papanicolaou, 2009). The model is a distributed parameter, continuous simulation, and erosion prediction model, implemented as a set of computer programs for personal computers (Flanagan and Livingstone, 1995). The model was developed to predict erosion effects from agricultural management practices and to accommodate spatial and temporal variability in topography, soil properties, and land use conditions within small agricultural watersheds (Ascough et al., 1995). The model is used to calculate runoff and erosion on hillslopes or watersheds on a daily basis, and for agriculture, forestry and rangeland management (Flanagan and Nearing, 1995). The WEPP model is based on the fundamentals of infiltration theory, hydrology, soil physics, plant science, hydraulics and erosion mechanics (Nearing et al., 1989). It consists of nine components: climate generation, winter process, irrigation, hydrology, soils, plant growth, residue decomposition, hydraulics of overland flow, erosion and deposition. The surface hydrology component of WEPP computes the surface runoff and peak discharge using the kinematic wave equation. The WEPP erosion model computes soil loss along a slope and sediment yield at the end of a hillslope. Interrill and rill erosion processes are considered and it uses a steady state sediment continuity equation as a basis for the erosion computations. The steady state sediment continuity equation is used to compute net detachment and deposition (Foster et al., 1995).

$$\frac{dG}{dx} = D_f + D_i \qquad (5)$$

where

x = distance down slope (m), G = sediment load (kg/s^{-1}.m^{-1}),

D_i = the interrill sediment delivery to the rill (kg/s^{-1}.m^{-2}), and

D_f = the rill erosion rate (kg/s^{-1}.m^{-2}).

The detailed mathematical representations of the channel hydrological processes are presented in technical manual of WEPP model (Flanagan and Nearing, 1995). The application of WEPP to a watershed requires that hillslopes be delineated and channels identified (Baffaut et al., 1997). Each hillslope (represented as a rectangle in WEPP) consists of a representative length (L), width (W) and slope profile. Hillslope drain into the top, left side, or right side of a channel, eventually leading to a watershed outlet. In the WEPP model, the smallest possible watershed includes one hillslope component and one channel. Runoff, detachment and deposition are first calculated on each hillslope with the hillslope component of WEPP for the entire simulation period. Then the model combines simulation results from each hillslope and performs runoff and sediment routing through the channels and impoundments. It is intended for use on small watershed in which the sediment yield at the outlet is significantly influenced by hillslope and channel processes. An advantage of WEPP over other existing models, such as the popular Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), is that the soil loss and deposition of sediment is estimated spatially along a profile. In other words, soil loss deposition on a complete simulation hillslope profile can be calculated, which is important in watershed modelling because it enables enhanced prediction of sediment yield to channels and to the watershed outlet.

The reason behind the development of the WEPP watershed model is that watershed sediment yield is a result of detachment, transport, and deposition of sediment on overland (rill and interrill) flow areas and channel flow areas. That is, erosion from both hillslope areas and concentrated flow channels must be simulated by the watershed version (Ascough et al., 1995). Soil erosion on a hillslope is represented as two components in the WEPP model: soil particle detached by raindrop and transport by a thin sheet flow, known as interrill erosion; and soil particle detached by shear stress and transport by concentrated flow, known as rill erosion (Pudasaini et al., 2004). The model most notably is known for its capability in (a) identifying zones of sediment deposition and detachment within permanent channels or ephemeral gullies, (b) accounting the effects of backwater on sediment detachment, transport and deposition within channels and (c) representing spatial and temporal variability in erosion and deposition processes as a result of agricultural management practices (Ascough II et al. 1995). In addition, the WEPP model is very sensitive to management and crop performance, making the model useful when the evaluation of agronomic practices is one of the objectives of a hydrological study. The WEPP model helps in evaluating and selecting the alternative land use and management practises for soil and water conservationist in environmental planning and assessment.

SWAT Model

The SWAT model is a continuous time, physically-based, spatially distributed model designed to stimulate water, sediment, nutrient and pesticide transport at a catchment scale on a daily time scale (Setegn et al., 2008). It was developed over 30 years ago by the United States Department of Agriculture (USDA). Full details of the model are given in Neitsch et al. (2001). The components of the SWAT model include hydrology, erosion, climate, soil temperature, plant growth, nutrients, pesticides and land management. It uses hydrologic response units (HRUs) that consist of specific land use, soil and slope characteristics to simulate the water balance in a given watershed (Setegn et al., 2008). Input data required include spatial data sets of soil, landuse, slope and daily climate data.

The soil-water balance is the primary equation used in the SWAT model, which is represented as:

$$SWt = SW_{\circ} + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad (6)$$

where

SW_t = final soil water content (mm water),

$SW_{\circ}$ = initial soil water content in day i (mm water),

t = time (days),

R_{day} = amount of precipitation in day i (mm water),

Q_{surf} = amount of surface runoff in day i (mm water),

E_a = amount of evapotranspiration in day i (mm water),

W_{seep} = amount of water entering the vadose zone from soil profile in day i (mm water),

Q_{gw} = amount of return flow in day i(mm water)

The SWAT model estimates sediment yield using the Modified Universal Soil Loss Equation (MUSLE) developed by Wischmeier and Smith (1978). Sediment deposition in the channel and floodplain in based on the sediment particle settling velocity as a function of its diameter is determined using Stocke's law (Chow et al., 1988). Channel degradation is based on Bagnold's stream power concept (Bagnold, 1977). The Modified Universal Soil Loss Equation is given as:

$$Sed = 11.8 \times \left(Q_{surf} \times q_{peak} \times area_{hru}\right)^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG \qquad (7)$$

where
Sed = sediment yield on a given day (metric tons),
Q^{surf} = surface runoff volume (mm/ha),
q_{peak} = peak runoff rate (m^3/s),
$area_{hru}$ = area of HRu (ha),
K_{USLE} = USLE soil erodibility factor,
C_{USLE} = USLE cover and management factor
P_{USLE} = USLE support practices factor, LS_{USLE} = USLE topographic factor
CFRG = support practices factor

Comparison of Models for Soil Erosion Simulation

Xu et al. (2009) reported that the basic requirement of a hydrological model is to simulate surface runoff adequately. This naturally affects soil erosion and the transport of sediments. Benaman and Shoemaker (2005) noted that model performance in relation to sediment simulation is very important when trying to quantify non-point source pollution. Results of model applications in different study areas for AGNPS, WEPP and SWAT models are presented below.

Results

Tables 1, 2 and 3 show the key results of applications of AGNPS, WEPP and SWAT models respectively, as compared for various watersheds. These models performed reasonably well based on their predictions, model efficiency and statistical analyses.
Mbajiorgu (2004) concluded that given basic measurable watershed data, AGNPS model has utility for fine-tuning water quality management best practices in rural areas of the humid tropics. Similar conclusions were made for the other models, by Mbajiorgu and Ogbu (2011) for the WEPP model, and by Ogbu and Mbajiorgu (2011) for the SWAT model. It is noteworthy that such conclusions are made possible by the process nature of the models being compared.

Discussion

The results of AGNPS, WEPP and SWAT models applications were compared to one another. The statistical coefficient of determination, R^2, and the Nash and Sutcliff, (1970) coefficient of model efficiency, $E_{NS,}$ were also presented. Simulation results are considered good for values of E_{NS} greater than or equal to 0.75, satisfactory for values of E_{NS} between 0.75 and 0.36, and unsatisfactory for values below 0.36 (Van liew and Garbrecht, 2003). Therefore, WEPP model applications generally provided good capability to simulate sediment yield at the outlet followed by SWAT models as shown by the high values of E_{NS} and R^2 while AGNPS applications were satisfactory as shown by the average value of E_{NS} and R^2. In line with this comparison, the statistical evaluation of the WEPP and AGNPS by Kirnak, (2002) showed that WEPP predicted sediment yield better than AGNPS. However, according to (Kirnak, 2002), AGNPS gives better prediction for lager scales than other models. Hence, the results obtained from these model applications showed that AGNPS, WEPP and SWAT models could be used to simulate runoff and sediment in agricultural watersheds.

Table 1: AGNPS Model Applications

S/N	Source	Study Area	Watershed Size	GIS Interface	Predicted Runoff	Predicted Sediment Yield	Model Perfomance
1.	Apaydin and Ozturk, (2010)	Guvenc Basin, Ankara, Turkey	16 km^2	ArcGIS	166.5 mm/yr	35.83 t/ha/year	(Runoff) E = 0.77 RMSE = 18.8 MRE = 0.06
2.	Rainis et al. (2002)	Sungai Air Terjun (Waterfall River) Watershed, Penang Hill, Malaysia	4.98 km^2	Arc View 3-D Analyst extension	-	429.55 tons/km^2 (mean)	(Sediment Yield) E_{NS} = 0.57
3.	Shrestha et al. (2005)	Masrang Khola Watershed, Siwalik Hill, Nepal	130.8 ha	Arc View GIS	-	0.63 tons/month	(Sediment Yield) R^2 = 0.59 CP_A = 0.47
4.	Mbajiorgu, (2004)	Upper Nyaba watershed in Enugu State, Nigeria.	2853.26 ha	-	32.26 mm (1.27 inches)	2.05 × 10^5 kg (226.22 tons)	-
5.	Mbajiorgu ,(1997)	Upper Nnom watershed in Enugu State, Nigeria	6,523.764 ha	-	55.1 mm (2.17 inches)	2.1 × 10^6 kg (2318.54 tons)	-

Table 2: WEPP Model Applications

S/N	**Source**	**Study Area**	**Watershed Size**	**GIS Interface**	**Predicted Runoff**	**Predicted sediment yield**	**Model performance**
1.	Mbajiorgu and Ogbu, (2010)	Nsukka, Southeastern, Nigeria	6.7 m^2	-	9.05mm (for single event)	0.007kg/m^2 (for single event)	-
2	Pandey et al., (2008)	Karso watershed in Damodar Barakar catchment, India	175 ha	Arc View	226.43mm	2.69t ha^{-1}	(Runoff) R^2= 0.95 E_{NS}= 0.92 (Sediment Yield) R^2 = 0.90 E_{NS}= 0.85
3	Zeleke, (2001)	Anjeni Research unit, Gojam North eastern Ethiopia	-	-	479.38mm/yr	8.06kgm^{-2}/yr	(Runoff) R^2= 0.69 ME= 0.43 (Sediment Yield) R^2= 0.79 ME= 0.72
4	Pandey et al., (2009)	Karso watershed, India	2793 ha	Arc/Info	-	30.39t ha^{-1}	-

Table 3: SWAT Model Applications

S/N	Source	Study Area	Watershed Size	GIS Interface	Predicted Runoff yield	Predicted Sediment yield	Model Performance
1.	Kaur et al. (2003)	Damodar-Barakar basin, India	92.46km^2	AVSWAT	383.37 mm/yr	21.28 t/ha/yr	(Runoff) E_{NS} = 0.54, R^2 = 0.83 (sediment Yield) E_{NS} = 0.70, R^2 = 0.65
2.	Xu et al. (2009)	Miyun Reservoir watershed, china	15 788 km^2	AVSWAT	Outlet 1: 0.42 billion m^3/yr Outlet 2: 0.38 billion m^3/yr	Outlet 1: 281000 t/yr Outlet 2: 208000 t/yr	(Runoff) R^2 = 0.93, E_{NS} = 0.91 R^2 = 0.90, E_{NS} = 0.87 (sediment Yield) R^2 = 0.96, E_{NS} = 0.84 R^2 = 0.98, E_{NS} = 0.97
3.	Phomcha et al. (2009)	Lam Sonthi watershed, Central Thailand	357km^2	AVSWAT	-	4807 t/month	(Runoff) R^2 = 0.71, E_{NS} = 0.70 (sediment Yield) R^2 = 0.78, E_{NS} = 0.79
4	Omani et al. (2007)	Gharasu river basin, Iran	5793Km^2	AVSWAT	-	3.4 ton/ha/yr	(sediment Yield) R^2 = 0.82, E_{NS} = 0.82
5.	Ogbu and Mbajiorgu (2011)	Ebonyi River watershed, Southeast Nigeria.	3765 km^2	Map Window	24.32 m^2/s (Daily average over 1 year period)	341.3 tons (daily average over 1 year period)	-

Conclusion

Soil erosion poses great problems in the humid tropics mostly as a result of the marked seasonality of hydro-meteorological phenomena. Over time, many hydrologic models have been developed to allow for better understanding of the hydrologic and erosion processes which occur on agricultural watersheds. In the humid tropics which are characterized by seasonality of meteorological and hydrologic events, the application of these hydrological models is not only possible but imperative. Also, due to the heterogeneous, spatial and temporal characteristics of the physical environment (soil, topography and land use), it is even more imperative to adopt process/physically-based, distributed and continuous hydrologic models to better understand the environment. This study compared such applications of AGNPS, WEPP and SWAT models in different watersheds. The models are useful research and management tools. They were found to be capable of identifying high soil-loss producing areas in a watershed to assist watershed managers to select appropriate BMPs to reduce soil erosion and environmental degradation.

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