ESTIMATION OF RUNOFF AND SEDIMENT YIELD OF UPPER EBONYI RIVER WATERSHED USING *MWAGNPS*

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ABSTRACT

Information about runoff and sediment exported from watersheds as well as related erosive processes are required by watershed managers and decision-makers. The event-based Agricultural Non-Point Source (AGNPS) pollution model is used extensively to simulate runoff, sediment yield and nutrient transport in agricultural watersheds. The present study estimated runoff and sediment yield of Upper Ebonyi River watershed using Mapwindow AGNPS (MWAGNPS). The materials used for the study include the Digital Elevation Map (DEM), the land use map and the soil map of the study area. The study was carried out using 13 rainfall-runoff events, 5 for calibration and 8 for validation, from Upper Ebonyi River watershed, Enugu State. The results obtained with MWAGNPS were compared with the observed data. After the analysis, the coefficient of performance between the observed and simulated runoff and sediment yield gave 1.3 and 1.4 respectively. Therefore, a calibrated MWAGNPS model could estimate runoff and sediment yield in the study area within an acceptable estimation error.

KEYWORDS: Watershed, runoff, sediment.

1. INTRODUCTION

The spatial distribution of water and the sediment it carries is difficult to assess. This is because normally the sediment concentration is measured at a point in the catchment, usually at an outlet where the sediments are lumped together. With the help of environmental models the spatial distribution of sediment can be considered. Simulations under various combinations of different factors of land and water management can provide comparative analysis of different options and then prove to be very useful guide as to what Best Management Practices (BMPs) can be adopted to minimize pollution from point and non-point sources (Shrestha, 2005). Many process-based models have been developed in the past for rainfall-runoff-erosion modelling. According to Rainis et al., (2002), these process-based models are advantageous as compared to the other methods of sediment yield estimation, particularly when the spatial and temporal distributions of net soil loss must also be determined for devising optimal soil conservation and management practices.

MWAGNPS is a MapWindow GIS interface for AGNPS. AGNPS (Agricultural Non-Point Source Pollution) Model was developed by the Agricultural Research Service, U.S. Department of Agriculture, in co-operation with Minnesota Pollution Control Agency and the Natural Resource Conservation Service (NRCS) (Rainis et al., 2002; Noor et al., 2012). The AGNPS model is an event-based model that simulates surface runoff, sediment, and nutrient transport primarily from agricultural watersheds. Borah and Bera (2003) summarized watershed-scale hydrologic and nonpoint-source pollution single-event models. Basic model components include hydrology, erosion, sediment, and chemical transport. In addition, the model considers point sources of water, sediment, nutrients, and chemical oxygen demand (COD) from animal feedlots, and springs. The model has the ability to output water results at intermediate points throughout the watershed network. This capability is based on the model's implementation of the 'cell'. Cells are uniformly square areas subdividing the watershed, and all watershed characteristics and inputs are expressed at the cell level. These Cells allows analysis at any point within the watershed. Each cell homogenously represents the environmental factors. Model components use equations and methodologies that have been well established. Runoff volume and peak flow rate are estimated using the SCS runoff curve number method. Upland erosion and sediment transport is estimated using a modified form of the Universal Soil Loss Equation, USLE. Sediment is routed from cell to cell through the watershed to the outlet using sediment transport and depositional relationship which is based on a steady-state continuity equation.

The AGNPS model is a simple routing runoff model based on the single storm event and very useful to identify the critical area, since the hydrologic components and nutrient loadings are provided based on the unit cell grids (Choi and Park, 1997). Kirnak (2002) compared Water Erosion Prediction Project (WEPP) model and the Agricultural Non-Point-Source Pollution Model (AGNPS) and found that there was no significant statistical difference between measured and predicted runoff and sediment data for both models (at $\mu = 0.05$ level). Parajuli et al., (2007) says that overall AGNPS model efficiency was found to be better than WEPP, especially in predicting sediment yields. Grunwald and Norton (1999), Panuska et al. (1991) concluded that sediment yield calculations were highly dependent on the quality of the peak flow calculations of the AGNPS model. The predicted sediment yield values ranged from a maximum under prediction of 60% to a maximum over prediction of 1.4% compared to measured sediment yield values. Though, testing and validation of AGNPS model using measured data is still scarce (Rainis et al., 2002; Grunwald and Norton, 1999).

Therefore, the objective of this study is to simulate runoff and sediment yield on Upper Ebonyi River watershed, Enugu state using MWAGNPS. The simulated values are compared with the observed data from the watershed.

2. METHODOLOGY

2.1 AGNPS Component Equations

Hydrologic Calculations

The peak flow is calculated using *TR55*. The *TR55* option uses the SCS unit hydrograph generation theory and assumes a rectangular shaped channel (top width and bankfull depth). The *TR55* method is an extension of the basic curve number theory including rainfall amount and distribution through the use of a unit hydrograph. The SCS curve number technique is a simplified method for estimating rainfall excess that does not require computing infiltration and surface storage separately. The excess rain volume (runoff) depends on the amount of precipitation and the volume of total storage (retention) predicted by the SCS (equation 1):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad \text{-------------------------------- (1)}$$

where Q is the runoff volume, P is the total rainfall from the storm and S is the retention factor, all with length dimensions [inches]. The retention factor S is obtained from (equation 2)

$$S = \frac{1{,}000}{CN} - 10 \quad \text{-------------------------------- (2)}$$

where CN is the curve number for the cell. These runoff curve numbers depend on the soil water content (moisture condition) and can be found as tabulated values for different land use descriptions. The SCS method uses the convolution of a triangular hydrograph for overland routing of excess rainfall where the peak time is the only parameter determining the shape of the hydrograph. The area under the unit hydrograph equals the unit volume of the rainfall excess.

Sediment Transport

Soil erosion affects downstream water bodies (Noor et al., 2012). The AGNPS model simulates the soil loss and sediment yield in a two-step process. For the soil erosion calculations it uses a modification of the Universal Soil Loss Equation, USLE. The modified USLE equation as used in AGNPS is (Young et al., 1989):

$$SL = (EI)\,KLSCP\,(SSF) \quad \text{------------------------} \; (3)$$

where SL is the soil loss, EI is the product of the storm total kinetic energy and maximum 30-minute intensity, K is the soil erodibility factor, LS is the topographic factor, C is the cover and management factor, P is the supporting practice factor, and SSF is a factor to adjust for slope shape within the cell.

2.2 Data Extraction

The process of extracting data from map sources is divided into two sections:

(a) topography related data using the DEM file,
(b) soil type and land cover data using the map files.

A digital elevation model (DEM) is used to derive slope, slope length, aspect, and other related parameters (He, 2003). For the DEM extraction, the calculations are performed in two steps. For the flow direction of each cell, the point of maximum flow accumulation within the intersection of the cell and the watershed is found. The cell with the largest of these maximum flow accumulations is the outlet cell for the watershed. Table 1 shows AGNPS variables as function of DEM and MAP.

Table 1: AGNPS Variables as Function of DEM and MAP

Variable	DEM[1]	LU[2]	S[3]
Receiving Cell Number	●		
Receiving Cell Subdivision	●		
Flow Direction	●		
SCS Curve Number		●	●
Land Slope	●		
Slope Shape (Def=1)	●		
Slope Length (Def=150)	●		
Overland Manning's		●	
K - Factor			●
C - Factor		●	
P - Factor (Def=1)		●	
Surface Condition Constant		●	
COD Factor		●	
Soil Texture ID			●

[1]DEM-Digital Elevation Model; [2]LU-Map File (landuse layer): [3]S-Map File (soil type layer)

2.3 The Study Area

Upper Ebonyi river watershed is shown as the study area in Figure 1 below. The gauging point is at Obollo-etiti, Nsukka. Two major landforms are found within the catchment: the sandstone escarpment of the Udi-Nsukka Cuesta; and the shale peneplains of the Cross River Plains (Campling et al., 2002). Meteorological data was collected from meteorological station, space centre, UNN. The main source files (in map form) of Upper Ebonyi river watershed used to implement MWAGNPS simulation are:

1) Watershed – polygon shape file (single boundary layer)
2) DEM – ascii raster file.
3) Soil – raster file and the plug-in converted it to a shape file.

4) Landuse – raster file and the plug-in converted it to a shape file.

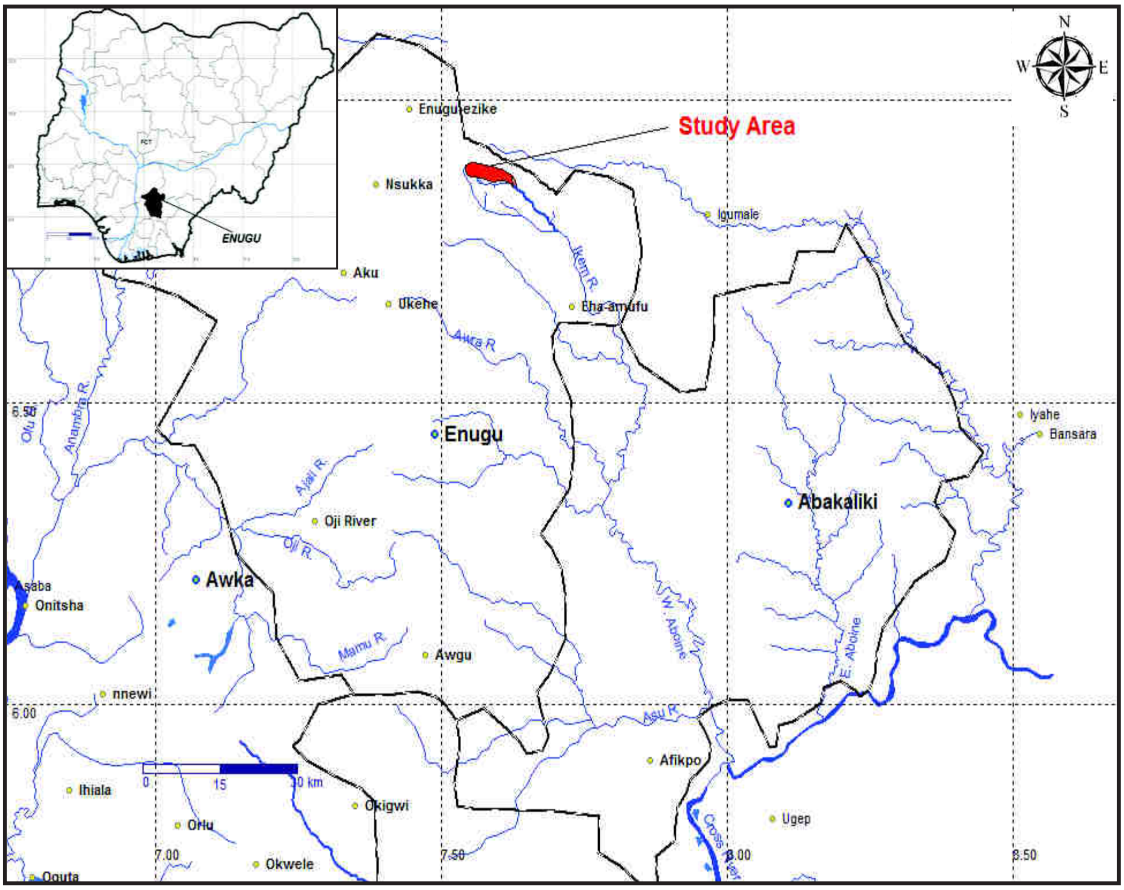

Figure 1: Map showing the study Area (Upper Ebonyi River Watershed)

2.4 Measurements and Model Parameters

MapWindow GIS serves as the main map engine used to display spatial information in the form of geographic layers and to extract the model data via the MWAGNPS plug-in. All the maps and the DEM data are stored in separate folders as shape and raster files. Also, all the modeled scenarios are stored as a combination of an Access database file with an associated grid as a shape file, both stored in the Scenarios folder. The model subdivides the study area into uniform grid cells similar to a raster-based GIS as specified. In this study, uniform grid system with cells was superimposed on the watershed, which generated 17 base cells. All watershed characteristics and inputs are expressed at the cell level. The cells are numbered consecutively from the upper left moving on the right direction and down automatically by the model.

The model requires two groups of input: watershed level and cell parameter (watershed element). At the watershed level, data required are as follows: watershed identification/description, precipitation (inches), precipitation duration, area of each cell (acres) and outlet cell number. For each watershed element (cell), AGNPS requires the following input data values (its distributed parameter information): cell number, number of the cell into which it drains, SCS curve number, average land slope (percent), slope shape factor (uniform, convex or concave), average field slope length (feet), average channel slope (percent), average channel side slope (percent), Mannings roughness coefficient for the channel, soil erodibility factor (K) for the USLE, cropping factor (C) for the USLE, practice factor (P) for the USLE, surface condition constant (factor based on land use), aspect (one of 8 possible directions indicating the principal drainage direction from the cell), soil texture (sand, silt, clay, peat), channel indicator (indicating existence of a defined channel within a cell). Geospatial databases built with geographic information systems (GIS) served as primary sources of input data to AGNPS. Elevation, land cover, and soil data for watershed are the base from which we extracted some input parameters required by the AGNPS.

Observed rainfall depth and the corresponding duration values were entered in the model (Table 2). Flow directions identified from digital elevation map (DEM) and field visits were assigned to the cells. The rainfall scenario for Upper Ebonyi River watershed was determined from rainfall recorded at the University of Nigeria Space Centre. From the records, rainfall events and their corresponding depth were selected with depths over 22.9mm. This approach was adopted because the AGNPS model, as input, uses rainfall depth and duration (hours) in each of its areal elements (Miklanek et al., 2004).

2.5 Model Calibration

The model was calibrated using 3 rainfall events and validated using 5 rainfall events as shown in Table 3. The surface runoff component of the model was calibrated by varying the 'Manning's roughness coefficient' parameter value. The sediment yield estimation was improved by proportionately varying the cropping factor (C) in the model.

Table 2: Observed rainfall depth and the corresponding duration values

Process	Event	Date	Rainfall (mm)	Duration of Rain (hr.)
Calibration	1	08-07-2013	32.8	7.6
	2	18-07-2013	32.9	2.4
	3	23-07-2013	45.4	3.7
Validation	4	25-07-2013	54.3	4.9
	5	08-08-2013	23	3.9
	6	21-08-2013	26.9	7.3
	7	27-08-2013	24.1	1.8
		28-08-2013	64.1	5.1

3. RESULTS AND DISCUSSION

For the purpose of calibration, the major results obtained after running the model are the peak runoff rate and the sediment yield. These results are shown in Tables 3 and 4 respectively.

Table 3: MWAGNPS model calibration and Validation results for Peak Flow

	Rainfall		Peak flow (m^3/s)	
	Event	Depth(mm)	Simulated	Observed
Calibration	1	32.8	0.0617	0.041
	2	32.9	0.0617	0.042
	3	45.4	0.1541	0.047
Validation	4	54.3	0.1204	0.105
	5	23	0.0014	0.036
	6	26.9	0.0210	0.030
	7	24.1	0.0085	0.034
	8	64.1	0.1031	0.134

Table 4: MWAGNPS model calibration and Validation results for Sediment Yield

	Rainfall		Sediment (t)	
	Event	Depth(mm)	Simulated	Observed
Calibration	1	32.8	0.45	0.758
	2	32.9	0.71	1.780
	3	45.4	9.84	3.461

Validation	4	54.3	8.11	3.241
	5	23	0.00	1.355
	6	26.9	0.03	1.877
	7	24.1	0.01	1.899
	8	64.1	10.10	9.210

The model performance was evaluated by calculating the coefficient of performance between observed and simulated parameters using Nash-Sutcliffe coefficient. The Nash-Sutcliffe coefficient describes how well the stream flows are simulated by the model. This efficiency criterion is commonly used for model evaluation, because it involves standardization of the residual variance, and its expected value does not change with the length of the record or the scale of runoff. The equation is described as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(Q_{Si} - Q_{Oi}\right)^2}{\sum_{i=1}^{N}\left(Q_{Oi} - \overline{Q_O}\right)^2} \quad \text{----------------------------- (4)}$$

After the analysis, the coefficient of performance between the observed and simulated runoff and sediment yield gave 1.3 and 1.4 respectively. A value of NSE = 1.0 indicates that the pattern of model estimation perfectly matches the measured data. The farther away from 1 the NSE value becomes, the larger the error in the predicted pattern when compared with the measurements. Based on the past studies of environmental model applications an NSE value of greater than 0.50 and mean relative error (MRE) value of less than 25% are considered numeric ratings for satisfactory model performance (Du et al., 2009). Hence from the analysis, the coefficient of AGNPS performance on Upper Ebonyi river watershed is not far from the value of NSE = 1. Though the results indicates that there are errors but is still within the acceptable limit.

4. CONCLUSION

The spatial distribution of water and the sediment it carries is difficult to assess. This is because normally the sediment concentration is measured at a point in the catchment, usually at an outlet where the sediments are lumped together. With the help of models like AGNPS, the spatial distribution of runoff and sediment can be considered. The event-based Agricultural Non-Point Source (AGNPS) pollution model interfaced in Mapwindow GIS is used in this study to simulate runoff and sediment yield in agricultural watersheds. The results obtained shows that calibrated MWAGNPS model can estimate runoff and sediment yield in the Upper Ebonyi river watershed within an acceptable estimation error. The coefficient of performance between the observed and simulated runoff and sediment yield gave 1.3 and 1.4 respectively.

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