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Estimation of Sediment Yield and Runoff from
Small Watershed using WEPP

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ESTIMATION OF SEDIMENT YIELD AND RUNOFF FROM SMALL WATERSHED USING 'WEPP' MODEL

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1.0 Introduction

Soil erosion is the removal of surface material by wind or water. When rain drop falls on a surface, the soil particles are splashed. Higher is the velocity of impact, greater is the amount of soil splashed. The detached soil particles are then carried further, either by runoff or wind. This whole process is known as erosion. The soil erosion affects the infiltration rates, crop production, water holding capacity, removal of organic matter and plant nutrients. Further, transported sediments lead to decrease in water quality, increasing eutrophication, and reduce the life of reservoirs.

The process of sediment yield is a natural phenomenon, which occurs whenever the flow of sediment carrying river is impounded by any kind of obstacle. This results in reduction of storage capacity, water supply capability, power generation, discharge control, etc. of reservoirs, rivers, or catchments. The erosion in catchment changes groundwater regime and results in lowering of water table at some places and rise at the other with the formation of arid zones and marshes respectively. The fertility of soil and its chemical composition will also be changed due to erosion.

The soil loss and sediment yield problems are important in India, because of varying topographical and geological conditions, pressure of human and animal population on the land resources, and small land holdings. This is further aggravated by improper land use and faulty land management practices being adopted in the upland watersheds. It is estimated that at present 150 million ha. (about 45 % of total area of the country) of land under agriculture, forests, grass lands, and other land uses, is in need of soil conservation.

Problems associated with soil erosion and sedimentation may be divided into those which are on-site and off-site in character. On-site problems are associated with a net loss of sediment, and off-site problems, with a net gain of sediment. These types of problems are;

On-site Problems: Loss of plant nutrients, Loss of organic matter, Damage to soil structures, Subsoil exposure.

Off-site Problems: Siltation of streams, rivers & estuaries, Siltation of dams, Damage to crops, roads, culverts, etc., Deposition of soil pollutants.

Factors affecting erosion and sediment yield are;

Hydrology:	rainfall and runoff
Catchment Characteristics:	size and slope of the catchment and length of overland flow
Soil Characteristics:	soil erodibility, soil transportability, soil texture and soil structure
Land use Cover:	plant canopy, mulches, plant residue
Management Practices:	tillage, soil conservation structures, terraces, diversions, bunds, etc.

Of all the factors mentioned above, rainfall and runoff provide the basic energy input to drive the erosion process. Steepness of slope plays an important role in the process of erosion. Soil properties such as soil texture, structure, and the land cover also have a major role in erosion process.

The effects of land use on sediment yield are closely linked to those of climate and physiography, since the latter may exert a major control on land use practice. Where the effect can be isolated, it is clear that the major contrasts in sediment yield may be attributed to the influence of land use. The precise sequence and timing of land use change within a basin will exert a strong control on the resultant pattern of sediment yield.

Scientific study of soil erosion has a long history in the geographic and geomorphic sciences, where much of the emphasis is on erosion as one of the natural landscape forming processes. Human activity, and expanding activities of agriculture, has led to an acceleration of soil erosion commonly associated with agricultural practices. Therefore, early agriculturally focused research on soil erosion depends on successful agronomic research methodologies. These methodologies were typified by planned experimentation followed by quantitative (often statistically guided) analysis of the results obtained.

Later on, researchers tried alternative methodologies in which more emphasis is being made on physical theory to provide a framework in which experimental data are analysed. In this approach, parameters were used, which have to be experimentally determined and which are more closely related to the processes to be involved in erosion and deposition. This new approach to soil erosion and deposition proved useful at the scale of runoff plots and small agricultural plots and efforts are being made at a rapid pace to utilise this approach to interpret erosion and deposition processes on larger scales.

There is growing recognition of combining erosion experimentation with the development of models of the processes involved. Experimentation is essential to provide the database which models must be able to comprehend. However, models of erosion processes are not simply based on data, but on basic physical theory applied to the interpretation of such processes. Nevertheless, the experience of interacting models based on theory with experimental data has been shown to be most helpful, and progress in such interaction is taking place most rapidly in slope erosion studies.

2.0 Common Techniques for Estimating Sediment Yield

Sediment yield estimating techniques vary in their complexity depending on a large part upon the objective of the investigation and the availability of data. The methods commonly used in estimating sediment yield and some comments regarding problems of using each are given below (Renard, 1985);

The sediment rating curve/flow duration method : This method is highly dependent upon the accuracy of sediment concentration measurements at field locations. Meaningful data are difficult to obtain from this method on small watersheds because discharge of water and sediment vary rapidly and there is not enough time to sample accurately without sophisticated, permanent sampling equipment.

The sediment delivery ratio method : Sediment delivery ratio is a percentage relationship between sediment yield and gross erosion in a watershed. Sediment delivery ratios have been determined for many areas and it is found that they are related to the drainage area.

Reservoir sediment deposition surveys : Sediment yield is estimated by adding the estimated amount of sediment that have passed through the reservoir, based on the reservoir's trap efficiency. These estimates can be used to relate sediment yield to drainage area. This approach provides information about magnitude and variation of average annual sediment yield, but has little value for forecasting sediment yield over a short time.

Field measurements of erosion and deposition : The difference between erosion and deposition estimates or measurements can be used to estimate sediment yield. The uncertainty of both erosion and deposition measurements can lead to large error.

Bedload relationships : The coarse fraction of sediment yield can be estimated using bedload relationships. Most of these relationships were developed primarily from laboratory flume studies.

Mathematical simulation models : Such models use relationships for the process of soil detachment, transport and deposition. These relationships are incorporated into a hydrologic model to estimate sediment yield. This method, widely used in research, is undoubtedly an important method. However, there are many limitations concerning parameter definition, extensive data requirement and computer cost.

Predictive equations based on watershed parameters such as drainage area, runoff, temperature, slope, soils, and cover : Eventhough such equations apply to a limited range of conditions, they are frequently used. Such predictive equations can be grouped into two categories; statistical and parametric.

3.0 WEPP Model

The USDA - Water Erosion Prediction Project (WEPP) model represents a new erosion prediction technology based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics. It is a continuous simulation computer program, which predicts soil loss and sediment deposition from overland flow on hill slopes, soil loss and sediment deposition from concentrated flow in small channels, and sediment deposition in impoundments. In addition to the erosion components, it also includes a climate component which uses a stochastic generator to provide daily weather information, a hydrology component which is based on a modified Green-Ampt infiltration equation and solutions of kinematic wave equations, a daily water balance component, a plant growth and residue decomposition component, and an irrigation component.

A watershed is defined in WEPP as one or more hill slopes draining into one or more channels and/or impoundments. The smallest possible watershed includes one hillslope and one channel. Fig.1 shows the schematic representation of a hillslope and watershed for WEPP application.

The controlling variables, which affect hillslope erosion are rainfall intensity, rainfall duration, peak flow rate, and flow shear stress. Processes considered in hillslope profile model application include rill and interrill erosion, sediment transport and deposition, infiltration, soil consolidation, residue and canopy effects on soil detachment and infiltration, surface sealing, rill hydraulics, surface runoff, plant growth, residue decomposition, percolation, evaporation, transpiration, snow melt, frozen soil effects on infiltration ad erodibility, climate, tillage effects on soil properties, effects of soil random roughness, and contour effects including potential overtopping of contour ridges. The model accommodates the spatial and temporal variability in topography, surface roughness, soil properties, crops, and landuse conditions on hill slopes.

The primary purpose of the hillslope component is to supply the erosion calculations with peak discharge, duration of runoff, and flow shear stress. Infiltration is computed using a formulation of the Green-Ampt equation for the case of unsteady rainfall. Rainfall excess is defined as the difference between rainfall and infiltration during the period when the infiltration rate is less than the rainfall rate. The peak runoff rate at the bottom of the hillslope is estimated by a method based on a semi-analytical solution of the kinematic wave equation for overland flow or by using regression equations derived from the kinematic solution for a range of slope steepness and lengths, surface roughness coefficients, soil textural classes, and rainfall distributions. Soil erosion is described on overland flow areas as interrill detachment of soil particles by raindrop impact and sediment transport by sheet flow, and rill detachment, transport, and deposition of soil particles by concentrated flow. The interrill erosion is taken as a function of soil detachment by raindrop impact, sediment delivery to rill flow areas by broad sheet flow, and rill erosion as a function of the flow's ability to detach sediment, sediment transport capacity and the existing sediment load in the flow

In watershed applications, the model allows linkage of hillslope profiles to channels and impoundments. The model is made up of three major components; hillslope, channel, and impoundment. The channel erosion and deposition calculations are similar to those of the hillslope with the major difference that only entrainment, transport, and deposition by concentrated flow are simulated, and the flow shear is calculated based on the spatially varied flow equations. Channel infiltration is calculated by either using the Green-Ampt or a transmission loss equation. Watershed peak discharge rate is calculated by a method based on a semi-analytical solution of the kinematic wave equation. Flow depth and hydraulic shear stress along the channel are computed by regression equation based on a numerical solution of the steady state spatially varied flow equation. Detachment, transport, and deposition within permanent channels or ephemeral gullies are calculated by a steady state solution to the sediment continuity equation. The impoundment component computes deposition and sediment yield from terrace and reservoir impoundments.

3.1 Basic Concepts

The basic concept guiding the development of WEPP model is that sediment yield from a watershed is the result of detachment, entrainment, transport, and deposition of sediment on overland (rill and interrrill) flow areas. Interill erosion is described as a process of soil detachment by raindrop impact, transport by shallow sheet flow, and sediment delivery to rill channels. Sediment delivery rate to rill flow areas is assumed to be proportional to the product of rainfall intensity and interrill runoff rate. Rill erosion is described as a function of the flow's ability to detach sediment, sediment transport capacity, and the existing sediment load in the flow.

Overland flow processes are conceptualised as a mixture of broad sheet flow occurring in interrill areas and concentrated flow in rill areas. Broad sheet flow on an idealised surface is assumed for overland flow routing and hydrograph development. Overland flow routing procedures include both an analytical solution to the kinematic wave equation and regression equations derived from the kinematic approximation for a range of slope steepness and lengths, friction factors, soil textural classes, and rainfall distributions. Once the peak runoff rate and the duration of runoff have been determined, steady state conditions are assumed at the peak runoff rate, for erosion calculations.

The erosion equations are normalised to the discharge of water and flow shear stress at the end of a uniform slope and are then used to calculate sediment detachment, transport, and deposition at all points along the hillslope profile. Net detachment in a rill segment is considered to occur when hydraulic shear stress of flow exceeds the critical shear stress of the soil and when sediment load in the rill is less than sediment transport capacity. Net deposition in a rill segment occurs whenever the existing sediment load in the flow exceeds the sediment transport capacity.

In watershed applications, detachment of soil in a channel is predicted to occur if the channel flow shear stress exceeds a critical value and the sediment load in the flow is below the sediment transport capacity. Deposition is predicted to occur if channel sediment load is above the flow sediment transport capacity. Flow shear stress in channel is computed using regression equations that approximate the spatially varied flow equations. Deposition within the sediment discharge from impoundments is modeled using conservation of mass and overflow rate concepts.

3.2 Model Components

Weather Generation : The climate component generates mean daily precipitation, daily maximum and minimum temperature, daily solar radiation, and daily wind direction and speed. The number and distribution of precipitation events are generated using a two-state Markov chain model. Given the initial condition that the previous day was wet or dry, the model determines stochastically if precipitation occurs in the current day.

Winter Processes : The winter processes which the WEPP model simulates are frost and thaw development in the soil, snow accumulation, and snow melting. In order to make more accurate predictions, the average daily values for temperature, solar radiation, and precipitation are used to generate hourly temperature, radiation and snow fall values.

Irrigation : The irrigation component accommodates stationary sprinkler systems and furrow irrigation systems. Four irrigation schemes are available: a) no irrigation, b) depletion-level scheduling, c) fixed-date scheduling, and d) combinations of the second and the third options.

Infiltration : The infiltration component is based on the Green-Ampt equation modified by Mein and Larson (1973), with the ponding time calculation for an unsteady rainfall. The infiltration process is divided into two distinct stages; a stage in which the ground surface is ponded with water and a stage without surface ponding.

Overland Flow Hydraulics : Surface runoff is represented in two ways in WEPP. a) Broad sheet flow is assumed for the overland flow routing and hydrograph development. Once the peak runoff rate and the duration of runoff have been determined, steady state conditions are assumed at the peak runoff rate for rill erosion and transport calculations, and b) The proportion of the area in rills is represented by a density statistics and an estimated rill width. Depth of flow, velocity and shear stress in the rills are calculated assuming a rectangular channel. The erosion calculations are then made for a constant rate over a characteristic time to produce estimates of erosion for the entire runoff event.

Water Balance : This component of the hillslope model is based on the water balance component of SWRRB (Simulator for Water Resources in Rural Basins) with some modifications for improving estimation of percolation and soil evaporation parameters.

This maintains a continuous balance of soil moisture on a daily basis. It uses information generated by the weather generation, infiltration, and plant growth components.

Plant Growth : It simulates plant growth for crop land and rangeland conditions. The purpose of this component is to simulate changes in plant variables that influence the runoff and erosion processes.

Residue Decomposition : This component estimates decomposition of flat residue mass, submerged residue mass, and dead root mass. Decomposition parameters must be specified in the management input file.

Soil Parameters : Soil parameters that influence hydrology and erosion are updated in the soil component, and include: random roughness, oriented roughness, bulk density, wetting front suction, hydraulic conductivity, interrill erodibility, rill erodibility, and critical shear stress.

Hillslope Erosion and Deposition : Soil erosion is represented in two ways in WEPP applications; a) soil particle detachment by rain drop impact and transport by sheet flow on interrill areas, and b) soil particle detachment, transport and deposition by concentrated flow in rill areas. Calculations within the erosion routines are made on a per unit rill width basis and subsequently converted to a per unit field width basis.

Watershed Channel Hydrology and Erosion Processes : This component was developed to predict erosion effects from management practices and to accommodate spatial and temporal variability in topography, soil properties and land use conditions within small agricultural watersheds. The watershed model is capable of ; a) identifying zones of sediment deposition and detachment within constructed channels or concentrated flow gullies, b) accounting for 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.

Watershed Impoundment Component : Impoundments can significantly reduce sediment yield by trapping as much as 90% of incoming sediment, dependent upon particle size, impoundment size, and inflow and outflow rates. This component calculates outflow hydrographs and sediment concentration for various types of outflow structures suitable for both large or small impoundments.

3.3 Limitations

The WEPP model is developed for use on small agricultural watersheds in which the sediment yield at the outlet is significantly influenced by hillslope processes. Model application is constrained by the following limitations of application of the model; 1) no partial area response, 2) no headcutting, 3) no bank sloughing, and 4) no perennial streams. Also the currently available version of WEPP (March 1997) does not include forest and road options in the management file builder.

4.0 Methodology

Preparation of input files forms the base of this model. Number of input files required for WEPP, depend on the application for which it is being applied. However, the major input files for any WEPP model application is climate, cropping/management, soil and slope files. The optional input files include irrigation, channel and impoundment characteristics, and watershed configuration.

In climatic input file, it is possible to provide either a single storm event or a continuous rainfall series. Actual data can be supplied, or where only rainfall statistics are available, a program called CLIGEN is provided in the model which can be used to generate data series of any length. Similarly, for the preparation of other data files, input file builders are provided in the model. The slope file builder has the added advantage of allowing the user to graphically preview the slope shape. Information on soil properties to a maximum depth of 1.8 meters (upto 8 different soil layers) can be input to the model through soil input file. The management file builder contains a large number of built in cropping pattern and management practices, which can be easily brought into our data file to suit the prevailing conditions on each overland flow elements within a hill slope.

First step in the application of WEPP is the process of dividing the study area into a number of hill slopes and channels. Each hill slopes are made up of one or more overland flow elements (OFE). OFE is an area of uniform cropping, management, and soil characteristics. The current version of WEPP allows simulation of upto 10 OFEs on an individual hill slope. The input files are prepared for each hill slopes. Soil, slope, and management parameters for each OFE on the hill slope profile are provided in the input files. The model run has been done for individual hill slopes and runoff and sediment yield calculated at the foot of the hill slope. In the watershed modelling option, these are routed through channels and the quantities are calculated at the outlet of the watershed.

The WEPP program produces many kinds of output, in various quantities. The most basic output contains the runoff and erosion summary information, on a storm-by-storm, monthly, annual, or average annual basis. The output gives detachment or deposition at each of a minimum of 100 points on a hill slope.

4.1 Hillslope Model

Soil characteristics for each hillslope, including type of soil, hydraulic conductivity, soil albedo, initial saturation, number of soil layers, thickness, bulk density, sand, clay, and organic matter percentage, etc. have to be provided in Soil input file. Number, length and width of each OFEs and slope detail are to be specified in Slope input file. Cropping pattern/management types are to be provided in the Management input file. Various levels of data input can be handled by the model. For a larger watershed, where prcise details about soil and land use are not available, an approximate estimate can be obtained. For a specific study on a hillslope, it is possible to provide very accurate data on soil and management, which will give a more realistic result.

For inputting the climate data, either daily rainfall data or event rainfall data can be given to simulate runoff and erosion processes from a hill slopes. Alternately, using CLIGEN program and average climatological parameters for the study area, a climate file can be created for any number of years. The CLIGEN climate generator reads climate statistics (such as monthly average rainfall, temperatures, solar radiation, probability of wet day, etc.) for a given station, and from these statistics, builds a stochastic climate data of any length. The most important variables are the monthly average rainfall amounts and the likelihood of rainfall occurring.

4.2 Watershed model

For the application of the watershed version of the WEPP model, the study area has been divided into a combination of hill slopes and channels. The runoff and sediment output from the upstream hillslope is allowed to enter the upstream channel and routed through the network of hillslopes and channels. The cumilative effect of the whole process of erosion and deposition can be compted at the outlet of the watershed.

In addition to the slope, soil and management characteristics of the hill slopes, channel properties such as width and depth of channels, hydraulic properties, channel bank management details, soil characteristics, etc. has to be given as input data.

5.0 Conclusions

The WEPP model is a distributed, continuous, small agricultural watershed erosion model. Its' intended purpose is to simulate the effects of management practices and land use changes on the spatial and temporal variability of the erosion processes within a watershed system. The major features of this model are the ability to;
(i)delineate areas of detachment and deposition on a hillslope or along a channel reach,
(ii) account for the effects of management and land use changes on the erosion process,
(iii) account for the effects of backwater on detachment, transport, and deposition processes within channels.

WEPP is capable of simulating erosion and deposition processes on hillslope or along a channel course. It gives precise locations of erosion and deposition, so that proper management strategies can be taken up to tackle these problems. Using the various components of the WEPP, a large amount of details can be obtained about the watershed behaviour for a set of climatological, soil, slope and management inputs. Since it gives an idea of the overland flow on hill slopes and progress of these outflows from the hill slopes through the channels, it can also be used as a rainfall-runoff model for small watersheds.

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