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ESTIMATING NON-POINT POLLUTANT LOADINGS—I: A GEOGRAPHICAL-INFORMATION-BASED NON-POINT SOURCE SIMULATION MODEL*

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ABSTRACT

This article is the first part in a two-article series. A geographical-information-based model, the Cornell Non-Point Source simulation model (CNPS), has been developed to help planners identify, analyze, and simulate the impacts of alternative land-use management policies and practices on non-point source pollutant loadings. It simulates hydrologic, erosion, and non-point source processes using spatial data from Geographic Information Systems. The model can be used 1) to simulate the erosion and runoff, sediment and the pollutant loadings at the watershed outlet, 2) to provide non-point water quality constituent loadings from a watershed to stream water quality model for comprehensive instream modeling, 3) to analyze the runoff quantity and quality for different land-use management alternatives, and 4) to study the relative changes in water quality of receiving water bodies associated with changes in land-uses. Part II of this series describes an application of the model to the Fall Creek watershed in New York, U.S.A.

INTRODUCTION

Throughout the United States and much of the world, major water quality impacts occur during short-term storm, high runoff events. This is particularly true for

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non-point source pollution from the land surfaces, because non-point source pollution takes place mainly during runoff and erosion producing storm events. Storm events also affect the mass of pollutants that can enter the aquatic system and cause water quality problems later during the critical flow conditions. The present research seeks improved ways of predicting the water quality impacts of these short-term events as a function of land topography, land cover, and land-use, in order to assess the effectiveness of various land-use management and policy alternatives. A number of models, such as SWMM [1], STORM [2], ARM [3], NPS [4], CREAMS [5], ANSWERS [6], HPSF [7], AGNPS [8] etc., are available for the aforesaid problem. They inevitably require an extensive amount of data and are generally not flexible enough to analyze various possible alternative control and management options. There is a need for improved tools which can be used under a wide variety of conditions and be based on data available from Geographic Information systems. The proposed model, the Cornell Non-Point Source simulation model, is an attempt in this direction.

THE CNPS MODEL

The CNPS model represents a geographic area as a matrix of grid cells [9]. Each grid cell represents a parcel of land of certain size and serves as the basic unit for quantification of various spatial parameters, representing the physical, topographical, meteorological, hydrological, and geological features. It will, therefore, require spatially distributed data. The spatial data used here include elevation, slope, soil, land-use, and watershed boundary. Here comes the role of a GIS package. The spatial data stored in a GIS is extracted in a format useful to the CNPS model. If GIS cannot write data files in a raster format, i.e., grid cell by grid cell basis, then suitable computer program writes ASCII grid files from binary GIS data.

The temporal data used for estimating non-point source pollutant loadings are precipitation, temperature, wind speed, and atmospheric pressure. Since precipitation, temperature, wind speed etc. are usually, not uniformly distributed over the geographic area and hence their spatial distributions are also needed. These are derived from the regression analysis of collected data over the geographic area.

The framework for the modeling approach is shown in Figures 1 through 3. The geographic information model and meteorological model are outside the CNPS model and provide the necessary data for the CNPS model. The CNPS model has three sub-models, one for each of the hydrologic response, erosion, and non-point source processes.

The hydrologic, erosion, and pollutant loading calculations are performed for each grid cell in the geographic area. The sub-models are applied starting with the highest grid cell in the watershed followed by each down stream grid cell in a

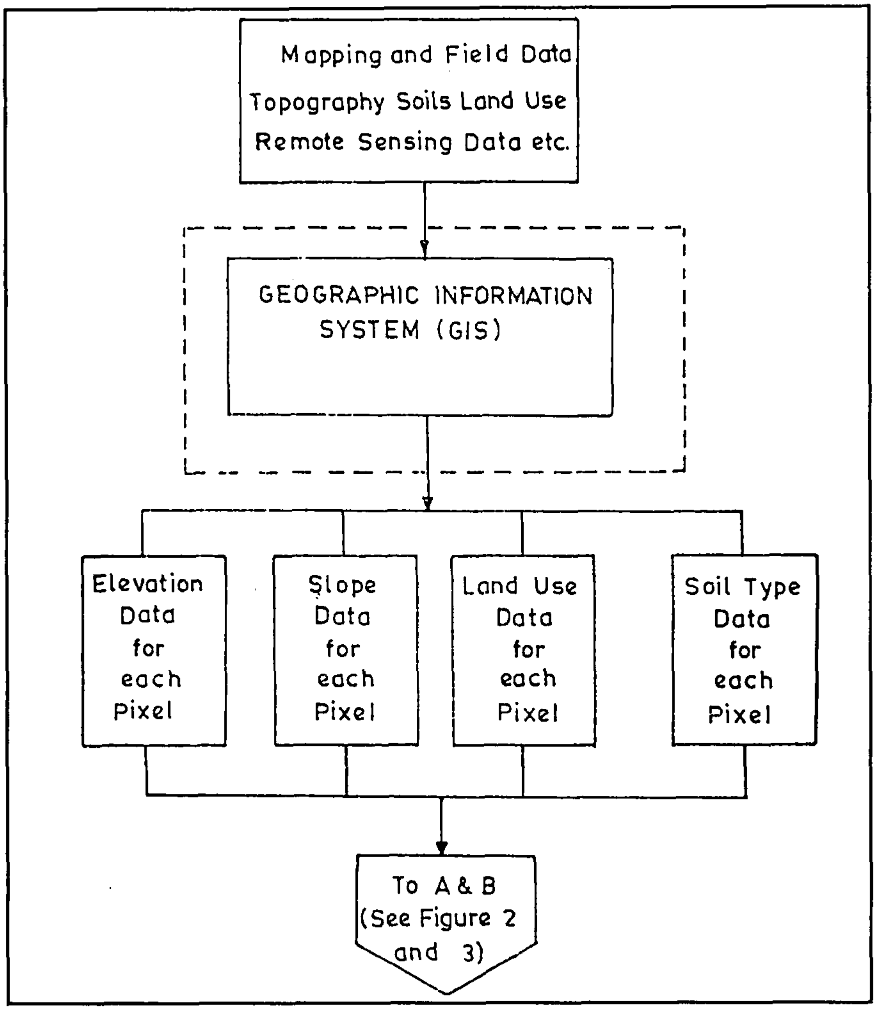

Figure 1. Geographic information model showing input and output data.

sequence until watershed outlet is reached. In following sections, the mathematics of sub-models have been discussed.

Hydrologic Response Sub-Model

The hydrologic response sub-model used here follows a three-dimensional topographic structure as shown in Figure 4. Various components of sub-model are the following.

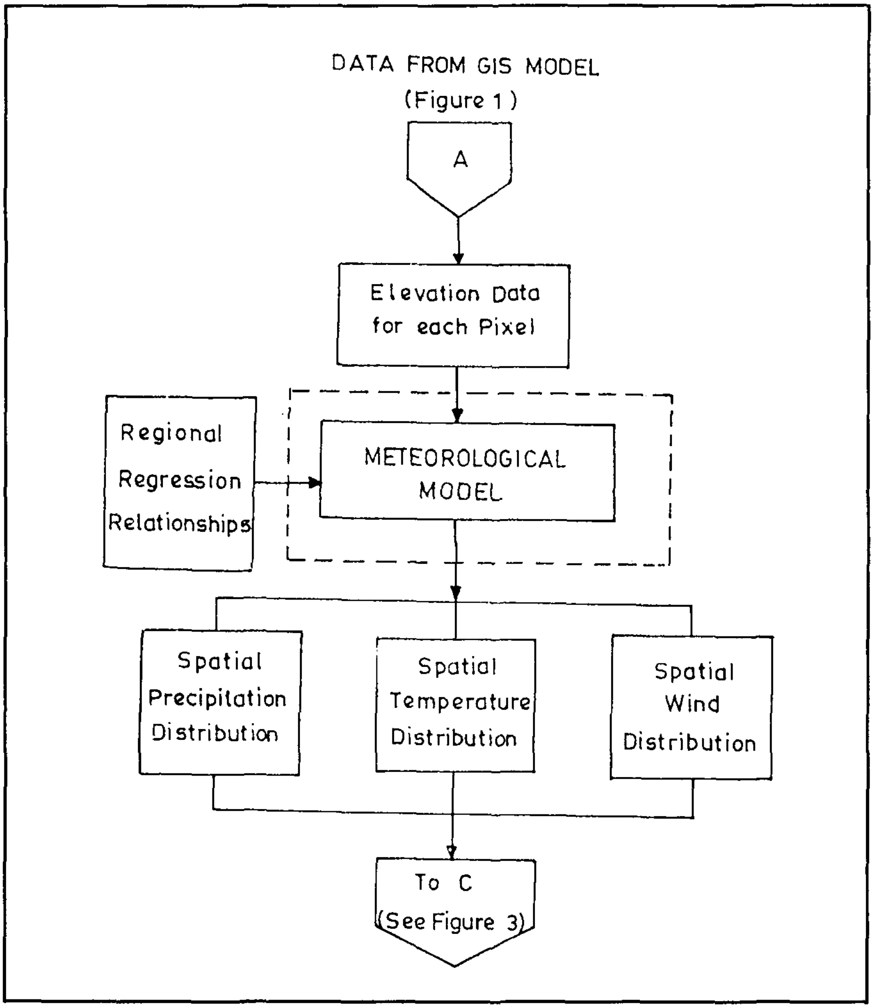

Figure 2. Input and output data of meteorological model.

Form of Precipitation

The precipitation can be rainfall and/or snowfall. The fraction as rainfall (f_r) and as snowfall (f_{sn}) are a direct function of mean air temperature [10].

$$R_t = f_r P_t$$
$$dSN_t = f_{sn} P_t$$

where P_t is precipitation on day t, R_t is rainfall and dSN_t is snowfall during day t.

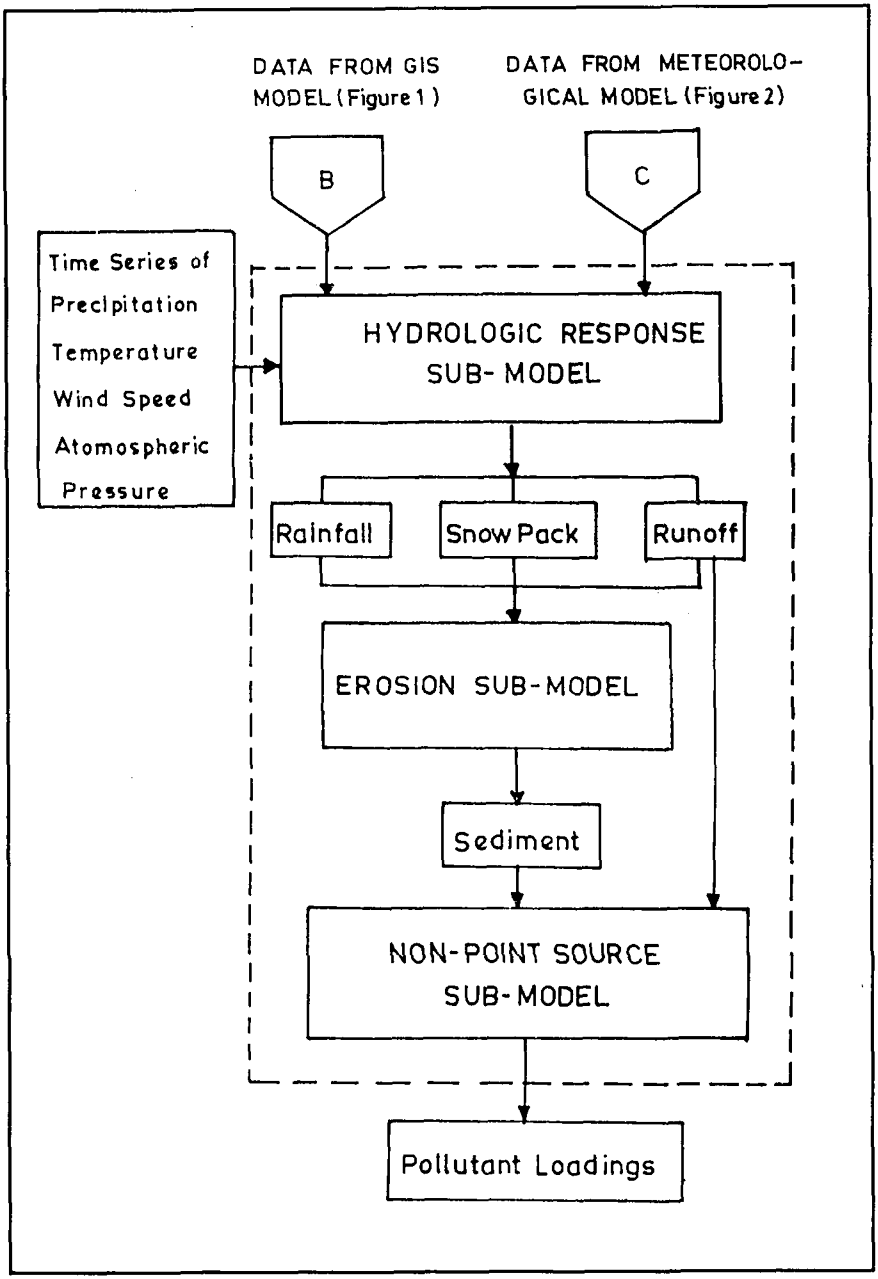

Figure 3. The CNPS model components showing input and output data.

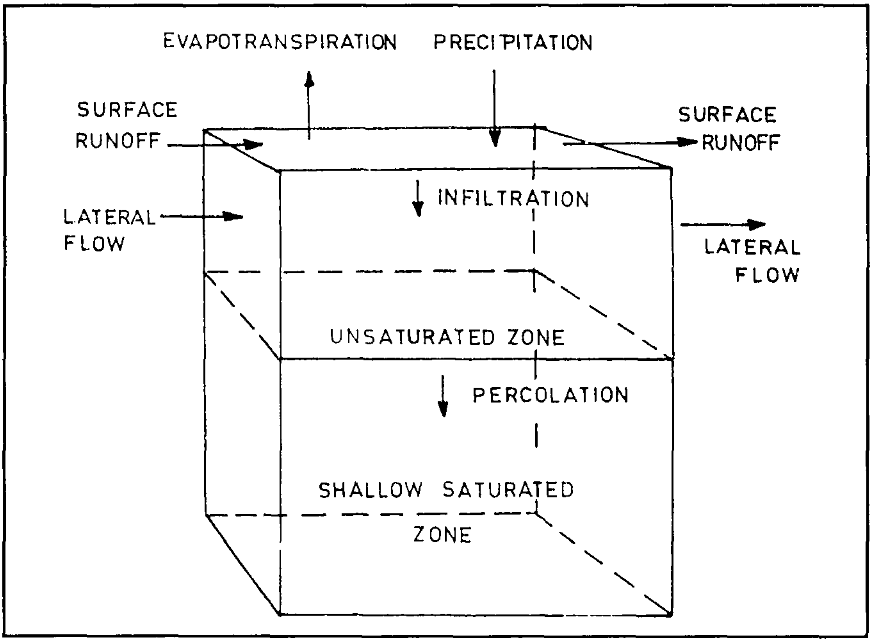

Figure 4. Hydrological processes for a typical grid cell.

Snowmelt

The computation of snow accumulation and snowmelt is based on explicit energy balance [11]. Snowmelt, M_t, during non-rainy periods with rainfall less than 10mm, is given by

$$M_t = M_f (T_t - T_{base})$$

where M_f is melt factor, T_t is mean air temperature in °C and T_{base} is base temperature usually taken as 0°C.

Snow melt during rainy days is given by

$$M_t = [0.028\, T_t + 7.5\, y_t\, f_t(u)\, T_t + 8.5\, y_t\, f_t(u)\, (v_t - 0.18) \\ + 0.007\, R_t\, T_t]$$

where y_t is the psychrometric constant, $f_t(u)$ is average daily wind function, and v_t is vapor pressure on day t.

Evapotranspiration

Evapotranspiration, E_t, on day t is calculated as a function of potential evapotranspiration, PE_t:

$$E_t = CV_t \, PE_t$$

where CV_t is cover coefficient on day t.

Potential evapotranspiration is given by Hamon's equation,

$$PE_t = 0.021 \, H_t^2 \, v_t \, / \, (273 + T_t)$$

where H_t is number of daylight hours on day t.

Surface Runoff

The surface runoff is computed using U.S. Soil Conservation Service's curve number method [12]. The surface runoff, Q_{kt}, from land-use k on day t is given by

$$Q_{kt} = (R_t + M_t - 0.2 \, W_{kt})^2 \, / \, (R_t + M_t + 0.8 \, W_{kt})$$

W_{kt}, the retention parameter on day t is given as

$$W_{kt} = 254 \, (100 \, / \, CN_{kt} - 1)$$

The suitable curve number, CN_{kt}, is selected as a function of root zone moisture as shown in Figure 5. The root zone moisture content, $MC_{s,t}$, is defined as

$$MC_{s,t} = (SM_{s,t} - WP_s) \, / \, (FC_s - WP_s)$$

where FC_s and WP_s are field capacity and wilting point of soil-type s.

The surface runoff could be channel flow, Q_{ct}, or overland flow, Q_{ot}–

$$Q_{ct} = DC \, Q_{kt}$$
$$Q_{ot} = Q_{kt} - Q_{ct}$$

where DC is drainage coefficient.

Percolation

If available water in root zone on day t is more than 75 percent of the available water at field capacity, percolation can occur. Percolation, PC_{st}, occurs at the rate of saturated hydraulic conductivity, SHC_s, of the soil s,

$$PC_{st} = SHC_s$$

Soil Moisture

The model maintains a continuous daily moisture balance for each grid cell in the watershed as

$$SM_{s,t+1} = SM_{s,t} + R_t + M_t - Q_{kt} - PC_{st}$$

where $SM_{s,t}$ is root zone moisture on day t.

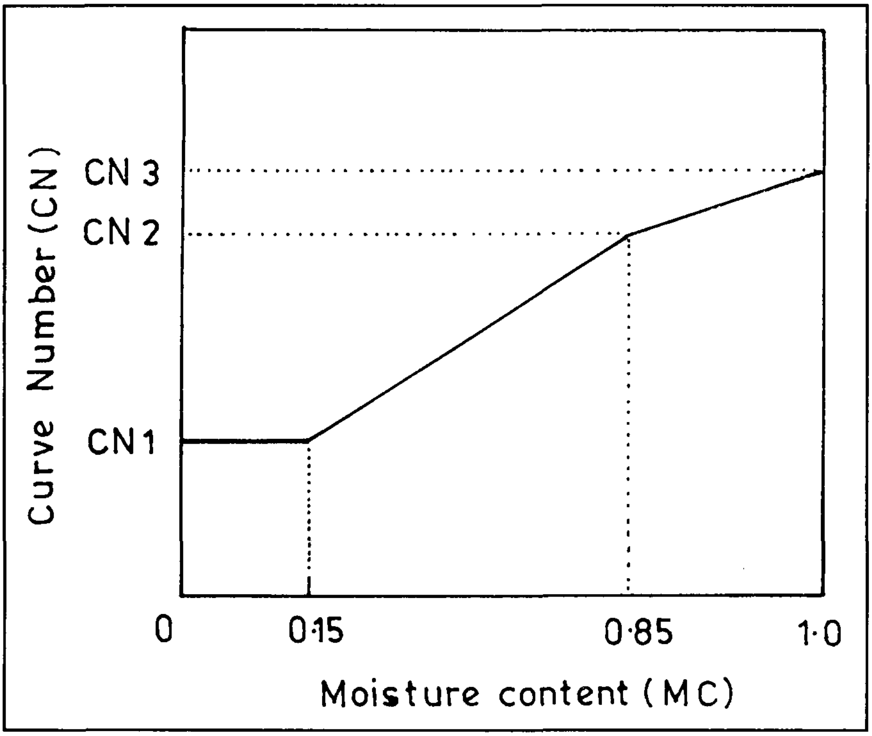

Figure 5. Curve number as a function of moisture content on a day.

Erosion Sub-Model

Upland Erosion

The soil erosion, X_t, on day t is given by modified universal soil loss equation:

$$X_t = 0.129\, RE_t\, A\, K\, ls\, C_t\, P$$

where A is the area of erosion source, RE_t is rainfall erosivity on day t, K, ls, C_t, and P are soil erodability parameter, topographic factor, cover factor, and supporting practice factor, respectively [13].

Sediment Yield

All the eroded soil does not reach the watershed outlet. Only a fraction of it, called sediment delivery ratio, actually finds its way to the watershed outlet. Daily sediment yields are calculated using the method proposed by Haith [14]. It is assumed that sediment transport capacity is proportional to $Q_t^{5/3}$ and that no sediment is left to be transported during the next water year.

The transport capacity TR_t on day t is calculated by

$$TR_t = Q_t^{5/3}$$

The sediment generated at the end of day t is available for transport from the next day until the end of the water year. Total transport capacity, TC_t, for day t is given by

$$TC_t = \sum_{j=t+1}^{N} TR_j$$

where N is the total number of days in the water year.

The sediment yield, Y_t, on day t is computed from the following equation:

$$Y_t = s_d \, TR_t \sum_{j=1}^{t} (X_j/TC_j)$$

where s_d is the watershed sediment delivery ratio [15].

Non-Point Sub-Model

The non-point sub-model is based on the concepts of generalized waste loading functions [16]. In this approach, the chemical properties of pollutants are assumed to be known or they are estimated with the help of empirical methods. The pollutants are either dissolved in runoff draining the landscape or adsorbed to the sediment particles.

Loadings from Rural Runoff

The pollutant loadings from rural runoff, DR_t^i, for pollutant i on day t is computed as the total mass of the pollutants carried by runoff from respective rural land-uses.

$$DR_t^i = \sum_{k \varepsilon R} CD_k^i \, Q_{kt}$$

where CD_k^i is dissolved concentration of quality constituent i in the runoff from rural land-use k and R is set containing all rural land-uses in the watershed.

Loadings from Urban Runoff

It is assumed that dissolved loads in urban runoff are zero. All pollutant loadings are in the solid phase form. It is calculated from linear daily pollutant accumulation model. The pollutant accumulation, $A_{k,t+1}^i$, on urban land-use k for day t+1 is given as pollutant i accumulated so far, $A^i_{k,t}$, plus the pollutant build-up, dA^i_k, for that day less pollutant washed off the surface, $QL^i_{k,t}$, along with the runoff, Q_{kt},

$$A^i_{k,t+1} = A^i_{k,t} + dA^i_k - QL^i_{k,t}$$

The pollutant washed off the urban land-use k is a fraction, w_{kt}, of pollutant available for that day:

$$A^i_{k,t+1} = w_{k,t}\,(A^i_{k,t} + dA^i_k)$$

The wash off fraction, $w_{k,t}$, on day t is given by,

$$w_{k,t} = 1 - \exp(-1.81\ Q_{k,t})$$

The solid phase loadings, SU^i_t, can be calculated by summing amount of pollutant i washed from all urban land-uses, U.

$$SU^i_t = \sum_{k\,\varepsilon\,U} QL_{kt}$$

Loadings from Rural Sediments

Watershed loadings of pollutant i carried by sediment, SR^i_t, on day t from rural land-use surfaces is given as the product of sediment pollutant concentration, CS^i, and the sediment yield, Y_t, on day t.

$$SR^i_t = CS^i\ Y_t$$

Total Watershed Loadings

Total dissolved waste loadings for pollutant i, D^i_t, is sum of dissolved loadings, DP^i_t, form point sources and dissolved loadings, DR^i_t, carried by rural runoff.

$$D^i_t = DP^i_t + DR^i_t$$

Total solid phase waste loadings for pollutant i, S^i_t, is sum of solid phase loadings, SP^i_t, SR^i_t, SU^i_t, carried by point sources, rural sediments and urban runoff respectively,

$$S^i_t = SP^i_t + SR^i_t + SU^i_t$$

Total loadings, T^i_t, for pollutant i on day t is sum of dissolved and solid phase loadings, i.e.,

$$T^i_t = D^i_t + S^i_t$$

PARAMETERS EVALUATION FROM GIS DATA

A GIS system not only provides spatial data required for the CNPS model, but it also provides a mechanism to evaluate or choose all parameters associated with soil as well as land-use distribution in the watershed. Soil and land-use distribution files contain the information about soil type and land-use class for each grid cell in the geographic area being modeled. The parameters associated with physical and hydrologic properties of soils and land-uses are assumed to be known precisely or their best determined laboratory values are available. These parameter values are specified for each soil type and land-use class in the soil and land-use database (SOILTYPE.DBS AND LANDUSE.DBS). Then these are automatically chosen for each grid cell whenever the model may require them.

Other parameters, viz., melt factor, antecedent temperature index parameter, negative melt factor, seasonal cover coefficients, drainage coefficients, and sediment delivery ratio cannot be evaluated from GIS data. These should be either selected based on local topographic and meteorological features or through model calibration. Since there are three sub-models, hence hydrologic parameters should be calibrated first, followed by the erosion sub-model and finally non-point sub-model.

CNPS DATA REQUIREMENTS AND OPTIONS

The CNPS model has currently three options available: 1) hydrologic simulation only, 2) hydrologic and sediment simulation, and 3) hydrologic, sediment, and non-point source simulation.

In addition to the model parameters, the model requires spatial/geographic data, temporal/meteorological data, parameter databases, and quality data.

Geographic Data

Watershed specific data about elevation, slope, soil, land-use, and watershed boundary are stored in five separate files with extension .GRD. These files store the entries for a specific attribute for each grid cell in raster format, i.e., line by line.

Meteorological variables, viz., precipitation, temperature, wind speed could be assumed to be uniformly or non-uniformly distributed over the space. One or more auxiliary GRD files are needed, only if a particular meteorological variable varies across the geographic area. In order to provide the change in spatial distribution over time to represent seasonal variations, the file names are used as PRECIP_XXXX.GRD, TEMP_XXXX.GRD, etc., where XXXX indicates the time-step from which another distribution is to be used.

Temporal Data

Model requires daily data for precipitation, temperature, wind-speed, and atmospheric pressure which are specified as files PRECIP_TS.DAT, TEMP_TS.DAT, WIND_TS.DAT, and ATM_TS.DAT. Of these, the first two data files are essential. If daily information about wind-speed and atmospheric pressure is not available, model could either use standard default values of zero Kmph and 766 mm of mercury, or seasonal average values could be specified.

Parameter Databases

Three databases—one each for soil properties, land-use properties, and water quality—provide automatic interpolation and use of most of the parameter values required by the model. These databases store properties and parameters specific to soil type, land-use, and quality constituents respectively for a given watershed. To reflect the different sets of local physical, meteorological, and hydrological features, a new set of databases must be assembled for a specific geographic area.

MODEL OPERATION AND APPLICATION

The CNPS model is designed to continuously simulate hydrologic, erosion, and non-point source processes on a daily time-step. It may also be used on a shorter simulation time-step, provided temporal data for that resolution is available. It is also possible to use the model to simulate isolated storm event, but in this case, antecedent watershed conditions are to be specified precisely.

In order that a user may effectively grasp and understand watershed behavior, spatially varying inputs and model outputs can be presented as color coded images, maps, and graphs at any desired time-step before, during, and after the simulation.

The model has been applied to the Fall Creek watershed situated near Ithaca, New York, United States. The complete data preparation and model application is discussed in Part II of this two-article series.

CONCLUSIONS

The proposed model, CNPS, is a geographic-information-based non-point source simulation model. It incorporates spatial parameters and temporal inputs, hydrologic, erosion, and non-point sub-models and possible interaction between and among inputs and sub-models. The model is suitable for continuous simulation of watershed behavior on daily time-step. Its effectiveness as a tool to assess the non-point source pollutant loadings impact of alternative land-use management policies and practices, shall be illustrated in Part II of the series.

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