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EXPERIENCES WITH SOIL EROSION MODELS

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AGNPS (Agricultural Non-Point Source Pollution Model) PART I

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1. Introduction

The event-based simulation model AGNPS (Agricultural Non-Point Source Pollution Model) version 5.0 was developed mainly by the United States Department of Agriculture - Agricultural Research Service (Young et al., 1987, 1994). It is a distributed parameter soil erosion model which uses relatively simple and robust approaches for calculating surface runoff, peak flow rate, and sediment yield. Hence the number of input parameters required is not very high. The objective for the development of AGNPS has been the identification of non-point source pollution in medium to large sized watersheds (I - 10' kin 2). It is also used as a simulation model for studying the impacts of land use management on the movement of water, sediment, and nutrients at broad scales. Applications of AGNPS are given by Hession et al. (1989), Mitchell et al (1993), Vieux et al. (1993), Tim et al. (1994), Srinivasan et al. (1994), Rode (1995), and Grunwald et al. (1997).

2. Model description

2.1 AGNPS

Below a brief description of the key routines in AGNPS is presented. Further details are given in the manual by Young et al. (1987, 1994). AGNPS calculates surface runoff for each grid-cell separately by using Curve Number (CN) method (SCS, 1972). The CN method can be written as:

$$Ia = 0.2 * S \quad (1)$$

$$S = \left(\frac{1000}{CN} - 10\right) * 25.4 \quad (2)$$

$$Q_D = \frac{(P - Ia)^2}{P + S - Ia} \qquad (3)$$

where:

Q_D: *surface runoff [mm]*

P: *storm precipitation [mm]*

S: *potential maximum retention [mm]*

Ia: *initial abstraction [mm]*

CN: *Curve Number [-]*

Surface runoff is treated as equivalent to direct runoff which is total runoff volume in a channel corrected for base flow. After calculating surface runoff in each grid-cell, it is routed through the watershed, based on flow directions from one grid-cell to the next until a drainage outlet is reached.

For each grid-cell peak flow rate is calculated by equation (4) (Smith et al., 1980). To describe concentrated flow within each grid-cell it is modeled a triangular rill or channel with varying depth and width of water flow. The cross-sectional area of the channel times the flow velocity equals channel flow.

$$Q_{max} = 3.79 * A_{EO}^{\ 0.7} * J^{0.16} * \left(\frac{Q_D}{25.4} \right)^{(0.903 * A_{EO}^{\ 0.017})} * \left(\frac{L^2}{A_{EO}} \right)^{-0.19} \qquad (4)$$

$$W = 2.38 * z^{-0.625} * (1 + z^2)^{0.125} * \left(Q_{max} * \frac{n}{c^{0.5}} \right)^{0.375} \qquad (5)$$

$$T = \frac{z * W}{2} \qquad (6)$$

$$v = \frac{\left(\frac{1.49}{n} \right)^{0.75} * z^{0.25}}{0.743 * (2 * (1 + z^2)^{0.5})^{0.5} * c^{0.375} * Q_{max}^{\ 0.25}} \qquad (7)$$

$$Aq = T * W * 0.5 \quad (8)$$

$$Q_{ch} = Aq * v \quad (9)$$

where:

Q_{max}; *peak flow rate* $[m^3/s]$

Q_{ch}; *channel flow* $[m^3/s]$

A_{EO}: *drainage area* $[km^2]$

QD: *surface runoff [mm]*

P: *average channel flow [%]*

L: *length of the drainage path [km]*

W:. *channel width [m]*

Z: *channel side slope [%]*

n: *Manning's roughness coefficient* $[m^{1/3}/s]$

c: *channel slope [%]*

T: *depth of channel [m]*

V: *flow velocity [m/s]]*

Aq: *cross-sectional area of channel* $[m^2]$

Optionally there is a second method for peak and channel flow calculations in AGNPS, which is based on Soil Conservation Service (SCS) TR55 method assuming a rectangular cross-sectional area for channel flow (SCS, 1986). Soil loss (A) is calculated by a modified Universal Soil Loss Equation (USLE) (Wischmeier et al., 1978), which includes the energy-intensity value and a slope shape factor. A is given by:

$$A = EI * K * L * S * C * P * SSF \tag{10}$$

where:

A: *soil loss [t/ha]*

EI: *energy-intensity value [N/h]l*

K: *soil erodibilityJactor [(t/h) * (ha/N]*

L: *slope-length factor [-]*

S: *slope-steepness factor [-]*

C: *cover and management factor [-]*

P: *support practice factor [-]*

SSF: *slope shape factor [-]*

Sediment transport is calculated by the approach of Foster et al. (1981) and Lane (1982) using transport capacity equation by Bagnold (stream power equation) (Bagnold, 1966). The sediment routing is done on a per cell and per particle-size basis, where five different particle sizes are considered. For calculation of sediment discharge at the cell outlet the sediment input from adjacent grid-cells are routed into the grid-cell considered, deposition within the grid-cell is calculated, and afterwards a comparison is made between the sediment yield Qs(X) within the cell and the effective sediment transport capacity gs(x). If Qs(x) is smaller than gs(x) the particles are routed to the next grid-cell. The deposition rate is given by:

$$D(x) = \frac{Vss}{q(x)} * \left[qs(x) - gs(x) \right] \tag{11}$$

where:

*D(x): sediment deposition rate [kg/(s *m^2)]*

q(x): discharge per unit width [m/s]

*qs(x): sedimentflow, rate [kg/(s*m)]*

*gs(x): effective sediment transport capacity [kg/(s*m)]*

The effective sediment transport capacity (Bagnold, 1966) is given by:

$$gs = et * k * ss * \frac{V_G^2}{Vss} \qquad (12)$$

where:

gs: *effective sediment transport capacity [kg/(s*m)]*

et: *effective transport factor*

k: *transport capacity factor*

ss: *sheer stress [kg/m^2]*

V_G: *average channel velocity [m/s]*

Vss: *particle fall velocity [m/s]*

Sediment discharge calculated for each particle size (i) at the cell outlet is given by equation (13)

$$Qs_i(x) = \left(\frac{2 * q(x)}{2 * q(x) + dx * Vss_i} \right) * \left[Qs_i(o) + Qs_{Li} - \frac{Wm * dx}{2} * \left[\frac{Vss_i}{q(o)} * \left(qs_i(o) - gs_i(o) \right) - \frac{Vss_i}{q(x)} * gs_i(x) \right] \right] \qquad (13)$$

$Qs_i(x)$: *particle discharge at the cell outlet [kg/s]*

Qsi(o): particle discharge into the cell [kg/s]

Qs_{Li}: *lateral particle discharge into the cell [kg/s]*

$q_i(o)$: *discharge per unit width into the cell [m/s]*

$qs_i(o)$: *particle discharge per unit width into the cell [kg/(s *m)]*

q(x): discharge per unit width at the cell outlet [m/s]

q(o): discharge per unit width into the cell [m/s]

Wm: average width of channel [m]

dx: down slope distance [m]

Vss_i: *particle fall velocity [m/s]*

$gs_i(o)$: *effective sediment transport capacity into the cell [kg/(s*m)]*

$gs_i(x)$: *effective sediment transport capacity out of the cell*

2.2 AGNPSm

In the AGNPSm version (AGNPS modified) (Grunwald, 1997) modifications were carried out on the hydrological and sediment routines of the AGNPS model in order to adjust to Western European climate and land use conditions (model transfer), as well as to improve simplified modeling routines. Therefore the model complexity is raised, but only few more input parameters are necessary. Changes made to the source code of AGNPS include the following:

- surface runoff calculated by Lutz (1984),
- LS factor calculated by Moore et al. (1986) based on stream power theory,
- linkage of channel erosion by individual categories of particle size to flow velocity,
- and grid-based precipitation input (Chaubey et al., 1997; Grunwald, 1997).

In the following, there is a brief summary of the Lutz Method (Lutz, 1984). C values (maximum discharge values) are calculated based on a combination of hydrologic soil groups, land use data, average antecedent soil moisture condition (H), and an extreme rainfall event of 250 mm. They correspond to Curve Numbers. Calculation of surface runoff by Lutz (1984) as modified by Rode (1995) is given by:

$$Ia = 0.03 * S \tag{14}$$

$$S = 25.4 * \left(\frac{10}{C} - 10 \right) \tag{15}$$

$$a = C1 * e^{(-C2/WZ)} * e^{(-C3/Q_B)} * e^{(-C4*D)} \tag{16}$$

$$Q_D = (P - Ia) * C + \frac{C}{a} \left(e^{-a(P-Ia)} - 1 \right) \tag{17}$$

where:

Q_D: *surface runoff [mm]*

Ia: *initial abstraction [mm]*

P: *storm precipitation [mm]*

C: *maximum discharge value*

S: *potential maximum retention [mm]*

a: *factor of proportionality [1/mm]*

C1, C2, C3, C4: *weighting parameters for optimization (calibration factors)*

WZ: *week value [-]*

QB: *base flow [1/(s*km^2)]*

D: *duration of precipitation [h]*

Initial abstraction *(1a) (Eq. 14)* is calculated such as *Ia* in *Eq. 1 (CN method)* but *S* (potential maximum retention) is weighted with a fixed factor of 0.03. This means that initial abstraction calculated by Lutz method is smaller than by CN method and therefore larger surface runoff is computed *(Eq. 17)*.

The week value (WY) represents a simplified crop growth factor varying during a year, which acts on hydrology. They can be derived from lookup tables (Lutz, 1984). Week values are low in summer time (high crop growth), which refers to a low tendency for surface runoff generation. WZs are high in winter time because of low crop growth and/or bare soils after harvest, which refers to a higher tendency for surface runoff generation. The factor C2 is for optimization (calibration factor) to fit measured and predicted surface runoff *(Q_D)* best. The higher C2 the lower the factor of proportionality *(a)* and the lower surface runoff generation *(Eq. 16 and 17)*.

Baseflow (Q_B) is used to characterize the initial soil moisture condition before a rainfall-runoff event takes place. Lutz (1984) assumes that base flow is approximately equal all over a watershed, hence base flow at the drainage outlet is representative for the entire watershed. This is true for watersheds uniform in bedrock geology, which applies more typically to smaller watersheds than to large ones. A high *QB* has the tendency to generate higher surface runoff compared to low *QB* values. The C3 factor is a calibration factor weighting the influence of baseflow to surface runoff. The higher C3 the lower the factor of proportionality *(a)*, and the lower surface runoff generation *(Eq. 16 and 17)*.

The duration of precipitation (D) characterizes the type of rainfall event, that is the distinction between short heavy thunderstorms or long lasting rainfall events of low intensity. The shorter a precipitation event the higher the factor of proportionality *(a)* and the higher surface runoff generation. The C4 factor also serves as a calibration factor. The higher C4 the lower the factor of proportionality *(a)*, and the lower surface runoff *(Eq. 16 and* 17). Lutz points out that C4 factor may often be neglected (fixed to 0.0) because of low sensitivity for surface runoff calculation. The Cl calibration factor is most sensitive for surface runoff calculation *(Eq. 16)* and in calibration procedure it should be focused on.

Soil detachment and transport by flowing water can be described by stream power theory (Yang, 1972). Water on the soil surface has potential energy by virtue of its elevation above some arbitrary datum. This energy becomes available to detach and transport soil particles as the water moves down slope. Yang (1972) defined the time rate of potential energy expenditure per unit weight of water as the unit stream power. The LS factor based on stream power theory is given by (Moore et al, 1986):

$$f = \frac{A_{pwa}}{b * l_{pwl}} \tag{18}$$

$$Lsp = \left(\frac{f * l_{pwl}}{22.14} \right)^{0.4} \tag{19}$$

$$Ssp = \left(\frac{\sin s_x}{0.0896} \right)^{1.3} \tag{20}$$

where:

f: *form parameter [-]*

A_{pwa}: *partial watershed area [m^2]*

b: *width of contour element [m]*

i_{pwl}: *partial watershed length [m]*

Lsp: *L factor (stream power theory)*

Ssp: *S factor (stream power theory)*

Sx: *slope [degrees]*

The form parameter f accounts for the effect of overland flow convergence (f > 1) or divergence (f < 1) on the length-slope factor derived from unit stream power theory. Equation *(18)* implies that for watersheds of equal area, a converging partial watershed will produce more sediment than a diverging partial watershed (Moore et al., 1986).

In AGNPS the user has to flag (activate (1) or deactivate (0)) for each particle size the scouring within each grid-cell. To make such a decision is difficult or impossible for the user. Calibration is necessary to find out which particle size should be scoured**.** Because the detachment and transport of particles is dependent on critical flow velocity or shear stress (Anderson, 1988) they can be used to improve calculations of channel erosion. In AGNPSm the scouring of particles is linked to flow velocity. If the calculated sediment discharge is smaller than the effective sediment transport capacity a comparison is carried out between the flow velocity and a critical flow velocity for each particle size. Based on this comparison a decision is made for the channel scouring of each particle size. Critical flow velocities for each particle size were obtained from the literature (Grunwald, 1997).

2.3 AnnAGNPS

AnnAGNPS (annualized AGNPS) is the continuous simulation, surface runoff pollutant loading model developed by the United States Department of Agriculture - Agricultural Research Service based on former versions of AGNPS. The model (beta version) and model information can be downloaded from the internet:
http://www.sedlab.olemiss.edu/cwp_unit/AnnAGNPS_prj.html. This continuous version includes the calculation of potential evapotranspiration *(Etpot)* by the Penman-Monteith equation. The actual evapotranspiration is calculated as a function of *Etpot* and soil moisture content. A synthetic weather generator can be used to generate the precipitation and min/max air temperatures for AnnAGNPS. However, historic records would have to be used to complete the remaining required weather parameters (relative humidity, percent sky cover, and wind speed). The soil profile is considered a two-layer system, whereas top layer is fixed to a constant thickness of 20 cm representing a tillage layer. Certain properties of the top layer may vary due to tillage operation such as bulk density. The second layer has static properties and does not exceed a 2-meter depth from the surface. Daily soil moisture accounting considers runoff, evapotranspiration, and percolation in maintaining a water budget for the 2-layer soil system. Surface runoff is calculated by the Curve Number method, accounting for different antecedent soil moisture conditions. Percolation occurs at the rate of the hydraulic conductivity corresponding to the soil moisture content, calculated according to the Brooks-Corey equation. Winter routines include provisions for snow, snowmelt and frozen soil. A thermal energy balance is maintained to track the soil and any snow pack temperatures daily. Sheet and rill erosion is calculated using Revised

Universal Soil Loss Equation (RUSLE). A flow net generator calculates stream reach characteristics (stream network, length, elevation, and slope), grid-cell data (drainage area, elevation, aspect, and receiving reach), and flow directions based on digital elevation model data.

3. Conclusions

AGNPS, AGNPSm (modified AGNPS), and AnnAGNPS (annualized AGNPS) are distributed soil erosion parameter models varying in complexity. Model complexity addresses the issues of the selection of model routines (empirical or physical ly-based equations), the description of all processes and interactions between processes (including the time component), and the dimensions (one, two, three dimensions). Increasing model complexity is associated with rising parameter input.

The description of processes (water flux and sediment transport) is less complex in AGNPS resulting in limited parameter input. Compared to physically-based soil erosion models such as WEPP (Flanagan et al., 1990) or KINEROS (Woolhiser et al., 1990) the structural error describing all processes within a landscape is higher (not accounting e.g. detailed spatial varying infiltration or initial soil moisture). Only processes occurring during a rainfall-runoff event are included in the model, i.e. the user has to input the border conditions before a rainfall-event takes place. AGNPS uses rather lumped, empirical equations such as CN method or USLE, which makes the model applicable to large watersheds, because parameterization is simple. Because AGNPS is a distributed parameter soil erosion model high spatial precision might be reached by using small grid-sizes for simulations, which depend on the available quality of spatial input data.

In AGNPSm (modified AGNPS) the model complexity is increased but only few additional input variables are required. Processes such as soil erosion are described with more detail. Model adjustment to land use, soil, and climate conditions in Germany are made by using Lutz method for runoff volume calculation.

In ArmAGNPS (annualized AGNPS) the complexity is increased because additional processes are included, e.g. evapotranspiration, snowmelt, and equations with higher complexity are used, e.g. RUSLE. The border conditions before a rainfall-runoff event are calculated by the model rather than by individual user input. Additionally long term simulations are possible.

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