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MODELING RUNOFF AND INFILTRATION ON PLOUGH FIELDS

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Abstract

Erosional investigations have a very important role in soil conservation. There are dozens of infiltration and erosion models attempting to describe these processes more and more accurately. The aim of the present paper is to introduce a dynamic mathematical model, which is suitable for modeling the effects of a rainfall event on infiltration and runoff at the scale of parcels. As a theoretical base, the most typical and simple conditions were chosen that we are faced with on a plough field. Namely the model is applicable to soils with two different layers; i.e. a cultivated topsoil, and a more compacted plough-pan beneath. The model consists of three submodels. The vegetation submodel determines the net rainfall reaching the surface directly, or through the vegetation. The infiltration one can show the temporal distribution of the net rainfall between the infiltration and the runoff. Finally the runoff submodel describes the runoff intensity in space and time. The model can compute with equalizing the water amounts needed to fill the soil layers until field capacity, and the maximum soil moisture with definite integrations derived from the Horton's equation. It determines the following points of time: the start of surface runoff, the wetting front reaching the plough-pan, the plough-pan damming back water, the topsoil becoming saturated. All intervals between these moments can be ordered to different functions of the infiltration and the runoff. Programming was done in Maple 8.

Introduction

Understanding and controlling the hydrodynamic processes of the Hungarian arable lands is of primary importance, regarding both the conservation of soil quality, as well as the plants cultivated. The most important factors determining the physical properties and the quality of soils are the water absorbing capacity and permeability of soils, influencing potential infiltration and runoff. Furthermore, they are an important asset, mostly via runoff, to one of the most significant erosion process: soil degradation. Several theoretical and practical models have been proposed for determining infiltration, runoff and the degree of the resulting soil degradation so far (WISCHMEIER et al., 1978; KIRKBY et al., 1980; GRAYSON et al., 1992; MORGAN et al., 1993; YOUNG, 1994; FLANAGAN, 1994; BEVEN, et al., 1995).

These models included abstract mathematical approaches, empirical equations for inter-relationships and display a large-scale variety regarding the spatial and temporal extensions of the modeled area. Unfortunately, even the most commonly used soil models carry a large degree of uncertainty and error deriving from the high spatial and temporal variance of the soil properties and the hardships encountered during the quantification; i. e. the measurement of these as well (QUINTON, 1997; VEIHE et al., 2000). Measurements of soil erosion and the adaptation of soil erosion models are quite relevant at several Hungarian institutes today (VERŐNÉ, 1996; HUSZÁR T., 1998; CSEPINSZKY et al., 1999; CENTERI, 2002).

Testing and calibrations of the EUROSEM soil erosion modeling system (MORGAN et al. 1993, 1998) started in 1998 at our department (BARTA, 2001). This work has revealed several problems in the algorithm of the EUROSEM which prevented the appropriate calibration. In order to eliminate these errors, the development of a new model was initiated.

The aim of the present paper is to introduce a dynamic mathematical model which is suitable for modeling the amount of surface water deriving from the rainfall and irrigation, as well as its distribution between infiltration and runoff at the scale of parcels.

Since the final goal is the development of a complete soil erosion modeling system, via the enhancement of the previously mentioned mathematical model, the spatial distribution of surface runoff was determined as accurately as possible even at this stage.

The theoretical basis and the input parameters of the model

As a first step, a model was developed for rainfall events with permanent intensity (I1, mm/min). The intensity of surface runoff is calculated with the help of three distinct, yet closely interdependent submodels (**Figure 1.**). Consequently, the parameters used in the models can be divided into three distinct groups as well:

1. Vegetation parameters: determine the amount of "net rainfall"; the actual amount of precipitation reaching the surface in case of a rainfall event with permanent intensity.
2. Soil parameters: determine the distribution of net rainfall between infiltration and runoff.

The calculation of the rate of infiltration was carried out with the help of the Horton's equation (HORTON, 1933). At this stage our model is applicable only for the most simple and typical conditions we are faced with on ploughlands, not a comprehensive situation involving an arbitrary number of soil layers. Namely, for soils with two different layers; i.e. cultivated topsoil and a more compacted plough-pan beneath, characterized by less favorable hydrological properties.

Since normally we can find layers with higher hydraulic conductivity beneath this latter horizon, presuming their homogeneity, only the two uppermost layers should be considered in our model. As the development began on the basis of soil erosion investigations, the capillary effects of the groundwater were neglected in this model.

In contrast to previous infiltration models describing the total water absorption of soils with the help of a single equation, a new aspect of our model is that here absorption and discharge is calculated for the individual soil layers. Furthermore, only such parameters were utilized as an input which can actually be measured or calculated.

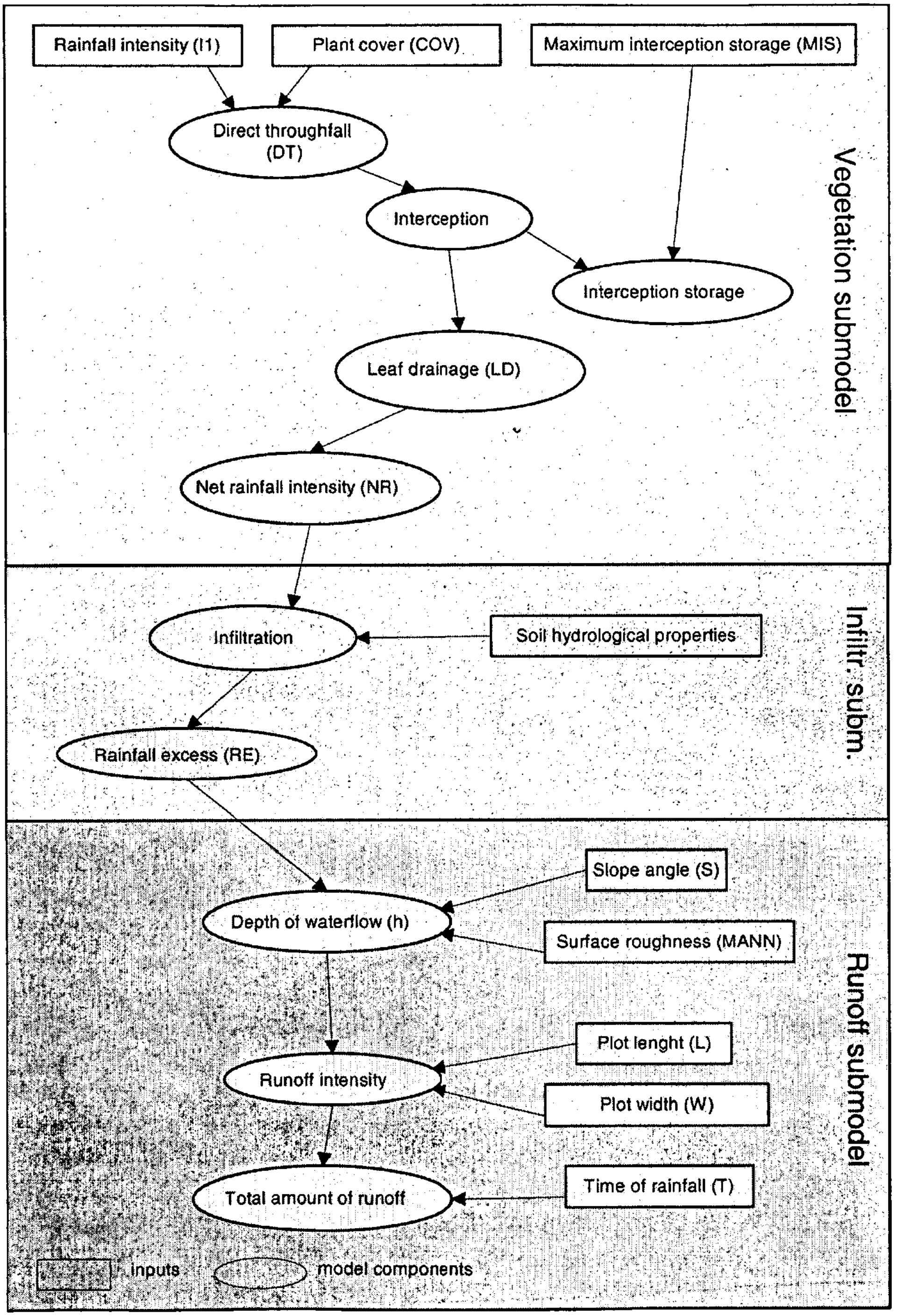

Figure 1. The algorithm of the model

3. Micro-relief parameters: determine the intensity, velocity and capacity of sheet wash among given relief conditions, i. e. the temporal distribution of runoff in the area.

The following vegetation parameters have been utilized:

- Surface vegetation cover (COV),
- The maximum interception storage of the vegetation (MIS, mm).

The following physical and hydrological properties should be taken into account as inputs for both soil layers under investigation:

- layer thickness(D, cm),
- maximum water content (P, v/v),
- field capacity (KP, v/v),
- gravity pore space (GP = P-KP, v/v),
- initial average soil moisture (M, v/v),
- saturated hydraulic conductivity (Kc, mm/min),
- the function of water absorption-permeability for the given soil layer.

This latter is given by the Horton's equation (DE ROO et al., 1992; SCHRÖDER, 2000):

$$K(t) = K_c + (K_0 - K_c)\, e^{-At} \tag{1}$$

where

K(t): is the water absorption capacity and the hydraulic conductivity of the soil layer in relation to time (t, min) measured from the initiation of saturation (mm/min)

K_0: the initial water absorption (mm/min)

A: a constant parameter characteristic for the soil layer

Hereunder parameters related to the top cultivated soil are marked with a subscript 1 in the text, while those related to the plough-pan are marked with a subscript 2.

The calculation of the K(t) functions are carried out on the field with the help of a double-framed hydraulic conductivity meter upon the surface of the individual soil layers. Naturally the implementation of this 6-hour measuring process is not feasible preceding all rainfall events. Therefore, measurements should take place among conditions characterized with the lowest achievable water content in the soil, in order to be able to widen the scale of applicability of the function. Knowing such a function enables the control of the intensity of water absorption from the state of actual initial water content. It is supposed that the zero point of the function represents the state of actual initial water content.

The following micro-relief parameters have been utilized:

- the length of the plot (L, m),
- the width of the plot (W, m),
- the slope of the plot (S, m/m),
- the Manning value representing the roughness of the surface (MANN, $m^{1/6}$).

The vegetation submodel

Several equations are used to describe the process of how rainfall reaches the surface; i. e. the intensity of net rainfall (WISCHMEIER, 1978; KIRKBY et al., 1980; MORGAN et al., 1993; BERGSMA, 1996). The intensity of net rainfall, as a result of the process depicted in **Figure 1.**, can be calculated in relation to time with the help of the following equation adopted from the EUROSEM model (modified after MORGAN et al., 1998):

$$NR(t) = I1\times(1-e^{-I1\times t/(MIS\times COV)}) \qquad (2)$$

where NR(t) marks the net rainfall intensity in mm/min. Several practical tables have been prepared for capturing the maximum interception capacity of the vegetation (WISCHMEIER et al., 1978; KIRKBY et al., 1980; MORGAN et al., 1993). Unfortunately, the majority of these do not give any details on the rate of surface vegetation cover considered. Thus it should be noted here that equation (2) is applicable for the calculation of maximum interception capacity only if the vegetation cover is 100%. Without this, the *COV* component should be neglected in the denominator of the exponent of *e* in equation (2).

The final outcome of the vegetation model, i. e. NR(t) is taken as the input for the infiltration submodel.

The infiltration submodel

This submodel is a completely new development without any elements adopted from other models. In order to create a dynamic model, infiltration was determined in relation to time in all cases. Rainfall starts at time t = 0, and the following significant time periods could have been distinguished in the fluctuations of infiltration and runoff:

T_1: the increasing values of NR(t) exceed the decreasing values of $K_1(t)$, i. e. water absorption is reduced below the net rainfall intensity. This results in a rainfall excess (RE(t), mm/min) on the surface and the initiation of surface runoff.

T_2: as a result of water absorption the topsoil reaches the limit of field capacity. It bears no effect on the amount of rainfall excess however, the lower plough-pan starts taking up water from this time onwards

T_3: The rapidly decreasing water adsorption of the plough-pan becomes less intensive than the hydraulic conductivity of the topsoil. This results in the saturation of the gravity-pore space of the cultivated layer thanks to the backwater effect of the plough-pan.

T_4: The topsoil reaches the limit of saturation. From this point on surface runoff is determined by the water absorption capacity and hydraulic conductivity of the plough pan.

The order of the above-mentioned events is only theoretical, there might be certain discrepancies. In reality T_1 very often equals 0, i. e. surface runoff is induced even at the initial stage of absorption. Even more frequently, the hydraulic conductivity of the cultivated soil exceeds the rate of initial water absorption of the plough-pan, resulting in the elimination of T_3.

In order to determine the above mentioned T time periods, the total water volumes necessary for reaching the given rates of field moisture were calculated in two different ways for the two soil layers:

1. based on layer thickness, water content, plough field capacities and porosity and
2. with the help of integrals derived from the Horton's equation.

In this latter case the upper limits of the integral ranges define the unknown T-s, thus by solving the equations received by the equalization of the two different types of calculations the T values could be determined.

Calculation of the volumetric water content

The amount of water necessary for reaching the state of initial field moisture, field capacity and maximal rate of saturation was given in mm, i. e. l/m^2.

The parameter of initial field moisture given in mm (MT) is not considered in the present version of the model. It will be significant at the correction of the function for water absorption later on during the process (see earlier):

$$MT = 10 \times D \times M \tag{3}$$

The amount of water (KT, mm) necessary for reaching the state of field capacity from the stage of initial field moisture can be calculated with the help of the following equation:

$$KT = 10 \times D \times (KP - M) \tag{4}$$

Similarly the amount of water (GT, mm), required for reaching the maximal rate of saturation from the stage of field capacity is calculated as follows:

$$GT = 10 \times D \times (P - KP) = 10 \times D \times GP \tag{5}$$

The determination of the significant time periods (T)

T_1 is received by solving the equation:

$$NR(t) = K1(t) \tag{6}$$

There is no rainfall excess between the time periods t = 0 and t = T_1; i. e. RE(t) = 0.

The rainfall excess between T_1 and T_2 is

$$RE(t) = NR(t)\text{-}K1(t) \tag{7}$$

T_2 is calculated as follows: the amount of water necessary for reaching the field capacity (equation (4)) is equalized with the function $K_1(t)$ integrated for the interval of (0, t). The unknown x (time in min) is then calculated by solving this new equation:

$$KT_1 = \int_0^x K_1(t)dt(= CK_1(x)) \tag{8}$$

The water absorption of the plough-pan starts at time T_2. If we suppose that this initially exceeds the rate of hydraulic conductivity in the topsoil we get to

$$K1(t) = K2(t\text{-}T2) \tag{9}$$

By solving this equation we receive the time period T_3 marking the initiation of backwater into the topsoil. In case equation (9) cannot be solved, or $T_3 < T_2$, then T_3 is taken to be equal with T_2. The development of rainfall excess happens in accordance with equation (7) during the period between T_2 and T_3.

This process will last as long as the period T_4, marking the limit of maximal water content (see equation (5)). T_4 is received by solving the following equation for x:

$$\int_{T_3}^{x} K_1(t)dt - \left[\int_{T_2}^{x} K_2(t - T_2)dt - \int_{T_2}^{T_3} K_1(t - T_2)dt \right] = GT_1 \tag{10}$$

The first term gives the total amount of water infiltrated into the soil from T_3, while the last two terms give the part that managed to infiltrate into the lower plough-pan. The pace of rainfall excess formation changes after T_4. It happens in accordance with the equation:

$$RE(t) = NR(t)\text{-}K2(t\text{-}T2) \tag{11}$$

There is a sudden change in the formation of rainfall excess at T_4, which is normally weakened under natural conditions. In order to make RE(t) continuous, the function was linearized between 0,95×T_4 and 1,05×T_4. The length of the interval defined by this linear equation can be modified later on depending on the outcome of control measurements.

The runoff submodel

When the net amount of rainfall exceeds infiltration, this results in the formation of rainfall excess on the surface (RE(t)). This excess rainfall starts moving down the slope in accordance with the law of gravity, influenced by such factors as the angle of the slope and surface roughness. The thickness of the water film is given by the equation h, derived from solving the following binary differential equation containing partial derivates and adopted from the EUROSEM model (MORGAN et al., 1993):

$$\frac{dh(x,k)}{dk}+\frac{5}{3}\cdot\frac{S^{0,5}}{MANN}\cdot h(x,k)^{\frac{2}{3}}\cdot\frac{dh(x,k)}{dx}=1000\cdot MRE(k) \tag{12}$$

where:

x: is the distance measured from the upper end of the parcel (m)

k: is the time elapsed from the initiation of rainfall in sec (k = t×60)

h(x, k): is the thickness of the water film at a distance of *x* m from the upper end of the plot at time *k* (m)

MRE(k): is the amount of excess rainfall in relation to time given in sec (mm/min)

As the amounts under examination are independent of the width of the plot they are given for a unit size parcel (width = 1 m). The equation can be solved by a four-point implicit method utilizing the Newton-Raphson technique. The initial criterion is h(0, 0) = 0. By knowing the function h(x, k), the velocity of the downward moving water film can also be determined:

$$v(x,k)=\frac{S^{0,5}}{MANN}\cdot h^{\frac{2}{3}}(x,k) \tag{13}$$

where v(x, k) marks velocity in m/s.

Furthermore, the discharge can also be calculated:

$$MQ(x,k)=\frac{S^{0,5}}{MANN}\cdot h^{\frac{5}{3}}(x,k) \tag{14}$$

where MQ is the discharge rate in m^3/s for a unit size plot with a width of 1m (MORGAN, R. P. C. et al. 1993).

The following section describes the outputs that are important for the users of this submodel:

1. the intensity of runoff as a dynamic output (discharge):

$$\frac{Q(L,t)\cdot 1000}{L} \tag{15}$$

in mm/min or

$$Q(L,t)\cdot W \tag{16}$$

m^3/sec (for the whole plot),

where Q is the runoff from a unit size plot (width = 1 m) in relation to time given in minutes (m^3/s).

2. The total runoff in mm (17) or in m^3 (18), when the whole area is considered, as a static output:

$$\frac{1000}{L}\cdot\int_0^T Q(L,t)dt \tag{17}$$

$$W\cdot\int_0^T Q(L,t)dt \tag{18}$$

where T is the length of rainfall duration in minutes.

Summary of results and further possibilities

This article introduced a dynamic mathematical model bearing the following characteristics:

- suitable for the characterizing infiltration and runoff in ploughfields
- applicable for homogenous ploughfields at parcel scale
- applicable for a single event, i. e. capable of characterizing the effects of intensive downpour lasting only for minutes or seconds and longer mild showers as well
- the description of the temporal saturation of the cultivated layer and the backwater effect of the plough-pan gives the theoretical basis of the model

The model presented herein gives the basis for of a newer soil erosion model, with the following development stages:

- inclusion of rainfall events characterized by varying intensities
- determine the load concentration of the surface runoff by having the rate of soil erodability at hand
- and determine the rate of soil erosion with the help of the above.

The final step involves the calibration, testing and refinement of the model via the long-term comparison of theoretical and practical results gained from on location.

References

BARTA K. (2001) A EUROSEM talajeróziós modell tesztelése hazai mintaterületen. In: A földrajz eredményei az új évezred küszöbén. Magyar Földrajzi Konferencia. Szeged, 2001. október 25-27. (CD)

BERGSMA, E. (ed.) (1996) Terminology for soil erosion and conservation. Wageningen.

BEVEN, K. – LAMB, R. – QUINN, P. – ROMANOWICZ, R. – FREER, J. (1995) TOPMODEL. In: Computer Models of Watershed Hydrology (ed: Singh, V. P.). Water Resources Publications, pp. 627-668.

CENTERI, CS. (2002) Importance of Local Soil Erodibility Measurement in Soil Loss Prediction. Acta Agronomica Hungarica 50 (1), pp. 43-51.

CSEPINSZKY B. – JAKAB G. (1999) Függelék a Vízgazdálkodási és Meliorációs Tanszék történetéhez. In: Csepinszky Béla: A Vízgazdálkodási és Meliorációs Tanszék története. Keszthely. pp. 78-87.

DE ROO, A. P. J. – RIEZEBOS, H. Th. (1992) Infiltration Experiments on Loess Soils and Their Implications for Modelling Surface Runoff and Soil Erosion. Catena 19, pp. 221-239.

FLANAGAN, D. C. (ed.) (1994) Water Erosion Prediction Project. Erosion Prediction Model v94.7 User Summary. USDA-ARS NSERL, West Lafayette – USA.

GRAYSON, R. B. – MOORE, I. D. – McMAHON, T. A. (1992) Physically Based Hydrologic Modeling 1-2. Water Resources Research 26-28, No. 10, pp. 2639-2666.

HORTON, R. E. (1933) The role of infiltration in the hydrologic cycle. Trans. Am. Geophys. Union 14. pp. 446-460.

HUSZÁR T. (1998) A talajerózió térképezése és modellezése magyarországi mintaterületeken térinformatikai módszerekkel. PhD értekezés tézisei. Budapest.

KIRKBY, M. J. – MORGAN, R. P. C. (ed.) (1980) Soil Erosion. J. Wiley & Sons, New York.

MORGAN, R. P. C. – QUINTON, J. N. – RICKSON, R. J. (1993) EUROSEM: A User Guide. Silsoe College.

MORGAN, R. P. C. – QUINTON, J. N. – SMITH, R. E. – GOVERS, G. – POESEN, J. W. A. – AUERSWALD, K. – CHISCI, G. – TORRI, D. – STYCZEN, M. E. (1998) The European Soil Erosion Model (EUROSEM): A Dynamic Approach for Predicting Sediment Transport from Fields and Small Catchments. Earth Surface Processes and Landforms 23. pp. 527-544.

QUINTON, J. N. (1997) Reducing predictive uncertainty in model simulations: a comparison of two methods using the European Soil Erosion Model (EUROSEM). Catena 30. pp. 101-117.

SCHRÖDER, R. (2000) Modellierung von Verschlämmung und Infiltration in landwirtschaftlich genutzen Einzugsgebieten. Bonner Geographische Abhandlungen 101. Asgard-Verlag, Sankt Augustin

YOUNG, R. A. – ONSTAD, C. A. – BOSCH, D. D. – ANDERSON, W. P. (1994) Agricultural Non-Point-Source Pollution Model (AGNPS). User´s Guide (Version 4.03). USDA, Agricultural Research Service, Washington.

VEIHE, A. – QUINTON, J. (2000) Sensitivy analysis of EUROSEM using Monte Carlo simulation I: hydrological, soil and vegetation parameters. Hydrological Processes 14. pp. 915-926.

VERŐNÉ WOJTASZEK MALGORZATA (1996) Távérzékelés alkalmazása talajerózió becslésében pázmándi mintaterületen. Agrokémia és talajtan 45/1-2. pp. 31-41.

WISCHMEIER, W. H. – SMITH, D. D. (1978) Predicting Rainfall Erosion Losses. Agricultural Research Service Handbook No. 282. United States Department of Agriculture, Washington.

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