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Modelling Infiltration on Arable Lands

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Abstract

Prediction and estimation of soil erosion are of great importance in soil conservation. There are numerous soil erosion models, aimed at realizing these goals. Attempts have been made to adopt some of these to Hungarian conditions as well. The aim of our research was the calibration of the EUROSEM soil erosion model to Hungarian conditions, but because of the algorithmic mistakes of the model, significant problems have been encountered in fitting the modeled and measured data. Hence came the idea to make a new model suited for a new infiltration conception, while keeping the usable equations from the EUROSEM. Individual rainfall events can be modeled on homogeneous plots with the help of this new model.

This article describes the vegetation and infiltration submodel of this newly developed model mentioned above. These are based on exact physical and mathematical equations and can be applied to the majority of arable land conditions, characterized by the presence of a more compacted plough-pan beneath the cultivated upper soil layer with favourable hydrologic properties. The vegetation submodel gives us the temporal distribution of the rainfall reaching the surface as “net rainfall”. This “net rainfall” becomes the input of the infiltration submodel. The infiltration submodel can compute with equalizing the water amounts needed to fill the soil layers until field capacity and maximum soil moisture with definite integrations derived from the Hortonian equation. The model works to determine the following points of time: the initiation of surface runoff, the wetting front reaches the plough-pan, the plough-pan is saturated, the topsoil is saturated. All intervals between these moments can be ordered different functions of the infiltration and runoff. The model was programmed in Maple V.

Keywords: soil erosion, modeling, Hortonian infiltration

1. INTRODUCTION

Water erosion on agricultural lands is a global problem. The natural erosion is only 0.1-0.3 t/ha as contrasted with the so-called accelerated erosion caused by the permanent land use which can be 6-100 times greater (GOUDIE, A. 1995). Erosion exceeding the rate of soil formation leads to serious economical and ecological problems. The direct measurement of erosion includes expansive and difficult methods, therefore dozens of infiltration and erosion models are worked out which attempt to describe more or less exactly the erosional processes (WISCHMEIER, W. H. et al. 1978, DE ROO, A. P. J. et al. 1992, GRAYSON, R. B. et al. 1992, MORGAN, R. P. C. et al. 1993, FLANAGAN, D. C. 1994, YOUNG, R. A. et al. 1994, SCHRÖDER, R. 2000). Unfortunately, the measurement of numerous input parameters influencing erosion is not without problems, and even if any parameters can be measured accurately, their spatial and temporal variability yields further uncertainties. Consequently, it is necessary to set up standards for each model, which include the typical values of parameters depending on soil texture or vegetation type. These tables based on thousands and thousands measured data have limited spatial usability. They can be used only in similar geographical settings to which they were originally applied. The basic condition to use the models in other areas is the adoptation of these tables, or nomograms, as the calibration of the model is called, for local conditions.

More and more models are adopted to different regions in order to estimate any changes in erosion conditions (e.g. QUINTON, J. N. 1997). There are some models (e.g. USLE, WEPP, EPIC) which were calibrated in Hungary and they have been used for many years in our country as well (KERTÉSZ, Á. et al. 1997, HUSZÁR, T. 1998, KERTÉSZ, Á. et al. 2000, CENTERI, CS. et al 2003). The first step of this research was the calibration of the EUROSEM soil erosion model to Hungarian conditions. It is an event based dynamic model for plots and small catchments worked out for European Countries (MORGAN, R. P. C. et al. 1998).

During the process of the calibration it was shown that the EUROSEM has got some algorithmic, conceptional and other problems. Fitting the modeled and measured data was practically impossible (BARTA, K 2001). Hence came the idea to prepare a new model based on the EUROSEM. The basic concept of the new model is that it should avoid the problems encountered in the EUROSEM while keeping the usable part of the same model. So the major aim of the present work was to develop a dynamic mathematical model, which is suitable to model the effect of a rainfall event on a plot to the infiltration, runoff and erosion.

2. THE STRUCTURE OF THE NEW MODEL

2.1. The Basic Concept

The most typical conditions occurring on an arable land were chosen as the theoretical basis of the new model, namely where the upper part of the soil consists of two different layers: the cultivated topsoil and the more compacted plough-pan beneath. They can have different physical and hydrological properties in the model. This first version of the model can be used only in the case of permanent rainfall intensity and deep soil water table with no effect to the infiltration. The model consists of four submodels (Fig.1.):

1. The vegetation submodel describes the way of the rainfall until the surface (direct throughfall, leaf drainage, interception storage). The newness of this part of the model is that it can avoid the main algorithmic problem of the EUROSEM, taking into account the maximum interception storage of the vegetation in good sense.

2. The infiltration submodel can show the temporal distribution of the surficial rainfall between the infiltration and runoff. It was founded on absolutely new bases. The most important features of the submodel are the following:

- The infiltration is determined by the characteristics of the different soil layers, for e.g. saturated/unsaturated hydraulic conductivity, soil moisture, different water capacities.
- Only measurable or calculable soil parameters are used almost exclusively as an input.
- The measurement methods to each applied parameters are fixed and ordered.
- The hydraulic conductivity for each soil layer is described by the Hortonian function (HORTON, R. E. 1933).
- Based on the Hortonian equation, the saturation and infiltration of the different soil layers is characterized via mathematical functions.

3. The runoff sub-model describes the runoff intensity in space and time. It is based on the EUROSEM's equations.

4. The erosional part of the model was adopted from the EUROSEM as well. The sediment yield is given by the product of the water runoff and the sediment concentration (MORGAN, R. P. C. et al. 1998).

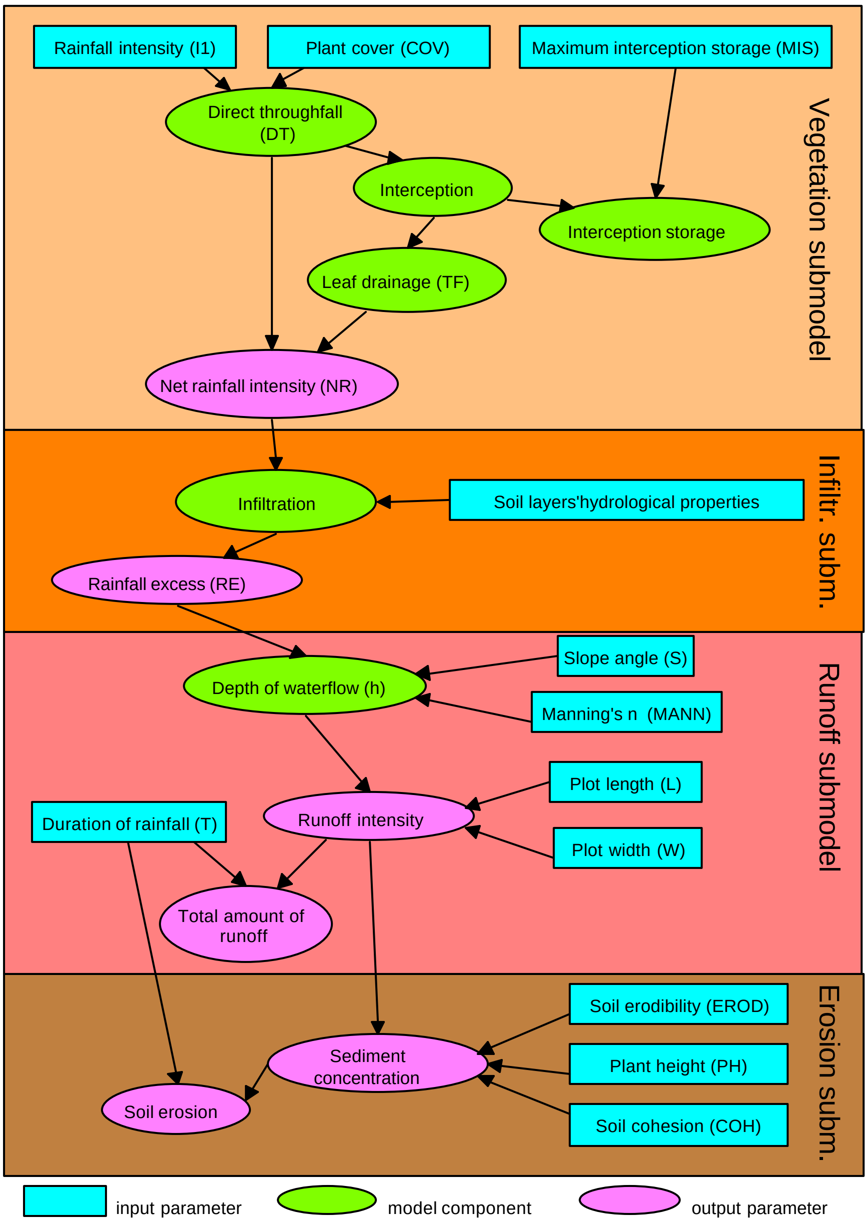

Fig.1. The algorithm of the model.

The first two submodels are described in the following parts of this article.

2.2. The Vegetation Submodel

The vegetation submodel describes the way of the rainfall until the surface. Besides the direct throughfall, a part of the rain remains on the leaves of plants filling up its interception storage. The other part forms the throughfall via the leaves. Thus, this submodel needs the following input parameters:

1. Plant cover (COV)
2. Maximum interception storage (MIS, mm)

There are lots of relationships explaining the temporal process of vegetation storage capacity fill up (WISCHMEIER, W. H. et al. 1978, KIRKBY, M. J. et al. 1980, MORGAN, R. P. C. et al. 1993, BERGSMA, E. 1996). Here we used the modified version of the equation derived from the EUROSEM (MORGAN, R. P. C. et al. 1998):

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

where I1 is the rainfall intensity in mm/min,
t is the time passed from the start of rainfall (min)
NR is the “net rainfall intensity“ reaching the surface (mm/min).
NR(t) means the output of the vegetation submodel and the input of the infiltration submodel.

2.3. The Infiltration Submodel

This submodel gives us the distribution of the net rainfall intensity between infiltration and runoff. The input parameters characterizing the physical and hydrological properties of both the topsoil and the plough-pan are summarized in Table 1. From this stage on *1* in subscript will highlight the parameters of the topsoil, and *2* in subscript will signify those of the plough-pan.

Table 1: Soil properties used as input parameters to the infiltration submodel

Parameter	***Mark***	***Unit***	***Notes***
Thickness of the layer	D	cm	
Maximal water content	P	v/v	
Field capacity	KP	v/v	
Gravity pores	GP	v/v	GP=P-KP
Initial average soil moisture	M	v/v	
Saturated hydraulic conductivity	K_c	mm/min	
Hortonian function of hydraulic conductivity	K(t)	mm/min	$K(t)=K_c+(K_0-K_c)e^{-At}$
(K_0: initial water absorption (mm/min), A: constant characteristic for the soil layer)			

With these parameters in hand the volume of water needed to fill up the pores of the given soil layer between the initial soil moisture and field capacity or between the field capacity and maximum soil moisture can be estimated using the following equations:

$$KT = 10*D*(KP-M) \quad (2)$$

$$GT = 10*D*(P-KP) = 10*D*GP \quad (3)$$

where KT is the amount of water necessary for reaching the field capacity from the initial soil moisture and GT is the amount of water necessary for reaching the state of full saturation from the field capacity. Both of them are in mm.

The saturation of the topsoil is carried out through the following four "significant moments" (Fig.2):

T_1 marks the place of the intersection of the NR(t) and K_1(t) functions, when the values of the net rainfall become greater than the water absorption of the topsoil. This is the initiation of runoff.

T_2 marks the moment when the topsoil reaches its field capacity corresponding to the initiation of the plough-pan's absorption.

T_3 means the start of the saturation of the gravity pores in the topsoil namely the absorption of the plough-pan decreases under the hydraulic conductivity of the topsoil then.

T_4 is the moment of the full saturation of the topsoil.

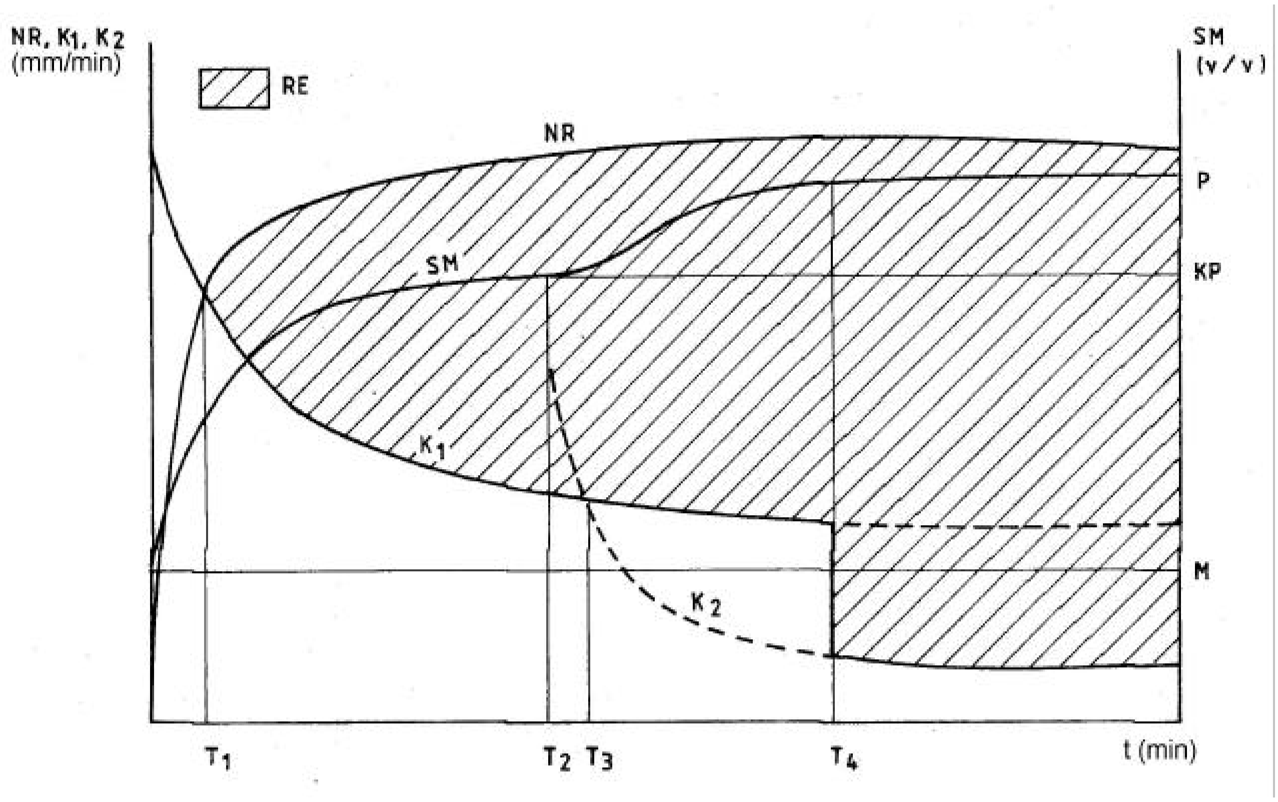

Fig.2. The saturation of the topsoil showing the "significant" moments. SM: moisture of the topsoil, RE: the uninfiltrated part of the net rainfall in mm/min (called rainfall excess, see later)

T_1 can be calculated by equalizing the Hortonian function of the topsoil with the net rainfall intensity:

$$NR(t) = K_1(t) \qquad (4)$$

T_2 is calculated by equalizing the amount of water necessary for reaching the field capacity (KT_1) with the function $K_1(t)$ integrated for the interval of (0;x) where the determination of the unknown x gives us T_2:

$$KT_1 = \int_0^x K_1(t)dt(= CK_1(x)) \qquad (5)$$

where CK_1 marks the cumulative amount of water infiltrated into the topsoil.

The existence of T_3 depends on the extent of differences between the hydrological properties of the two soil layers. Sometimes the initial water absorption of the plough-pan is lower than the hydraulic conductivity of the topsoil even at T_2. In this case defining T_3 makes no sense. In other cases T_3 can be determined by the solving the following equation:

$$K_1(t) = K_2(t-T_2) \qquad (6)$$

Water penetrating downwards starts to fill up the macro-pores in the topsoil at the moment T_3. Consequently T_4 can be calculated by equalizing the amount of water necessary for reaching the maximal water content from the field capacity (GT_1) with the following term:

$$\int_{T_3}^{x} K_1(t)dt - \left[\int_{T_2}^{x} K_2(t - T_2)dt - \int_{T_2}^{T_3} K_1(t - T_2)dt \right] = GT_1 \qquad (7)$$

where the first term is the total amount of water infiltrated into the soil from T_3 and the second term gives the part of the previous one that penetrated into the plough-pan.

The part of the net rainfall intensity that can not infiltrate into the soil gives the available amount of water for runoff. This is the most important output parameter of the infiltration submodel referred to as the “rainfall excess” (RE, mm/min – see Fig.2.). Based on the knowledge of the significant moments, the function RE can be given by different terms for different intervals:

$$RE(t) = 0, \qquad \text{if } 0 = t = T_1 \qquad (8)$$

$$RE(t) = NR(t)-K_1(t), \qquad \text{if } T_1 = t = T_4 \qquad (9)$$

This second equation means that the hydraulic conductivity of the topsoil can determine runoff until T_4. After T_4 the plough-pan’s properties play the most important role in runoff:

$$RE(t) = NR(t)-K_2(t-T_2) \qquad (10)$$

The difference between equations (9) and (10) causes a sudden change in rainfall excess which has no reality in the natural processes on arable lands. In order to remove this breaking point at T_4, the function RE was linearized between $0.95*T_4$ and $1.05*T_4$. The rightness of the choice of the interval's length should be controlled by field measurements in the future.

The rainfall excess will be one of the most important input parameters of the runoff submodel.

2.4. Technical Supports

These two submodels forming the basis of this article were programmed in Maple V. Maple gives us both the equation of function RE and its plotted graph. The runoff and erosion submodels can be run – suitably for its similarity of the EUROSEM – under the software of the EUROSEM. The main technical problem is to convert the intensity values of the rainfall excess into the data of the cumulative rainfall used in the EUROSEM's rainfall file. This last one can suppose only such a cumulative function which consists of linear sections, meaning that its derivative must be a step function.

Thus in the first step the function RE was integrated in order to make a cumulative function. Secondly it was divided into 4 and 2 linear sections between T_1 and T_2 and between T_4 and the end of the rainfall in Maple. Parallel with this, both the saturated hydraulic conductivity and the maximum interception storage of the vegetation as input parameters in the EUROSEM rainfall file must have zero values.

3. DISCUSSION

The model presented in this article is only an initial version of a model that will be suitable for a much more wide-scale use than this one. The main directions of the development can be summed up as follows:

- The embedment of the subsurface runoff that starts at the top of the plough-pan after T_3 into the model
- The use of even more input parameters to increase the accuracy and the reality of the model,
- The expansion of the applicability of the model to unsteady rainfall conditions as well,
- The testing of the model with comparison real measured and simulated data.

The main technical challenge is the programming of the model within a frame of any uniform software.

Naturally, it is possible to modify the model where there seem to be great differences between the real process and the algorithm of the model during the testing phase.

4. SUMMARY

The newly presented dynamic mathematical model is suitable to calculate runoff and erosion in plot scale. This first version can be used in the case of permanent rainfall intensity and assuming a layered soil profile with cultivated topsoil and more compacted plough-pan. The theoretical basis of the new model comes from the determination of some "significant"

moments during the infiltration with the help of differential equations. However, further developments are required to test and refine the model in the future.

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