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LISEM: a new physically-based hydrological and soil erosion model in a GIS-environment, theory and implementation

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Abstract A new physically-based hydrological and soil erosion model has been developed, which can be used for planning and conservation purposes: the LImburg Soil Erosion Model (LISEM). The LISEM model is one of the first examples of a physically based model that is completely incorporated in a raster Geographical Information System. This incorporation facilitates easy application in larger catchments, improves the user friendliness by avoiding conversion routines, and allows remotely sensed data to be used. Processes incorporated in the model are rainfall, interception, surface storage in micro-depressions, infiltration, vertical and lateral movement of water in the soil, overland flow, channel flow, detachment by rainfall and throughfall, detachment by overland flow, and transport capacity of the flow. Special attention has been given to the influence of tractor wheelings, small roads, and surface sealing. Vertical and lateral movement of water in the soil is simulated using the Richard's equation. For the distributed flow routing, a four-point finite-difference solution of the kinematic wave is used together with Manning's equation. Validation results of the mode are still being processed. Preliminary results are satisfactory.

INTRODUCTION

Soil erosion and surface runoff have always been problems concomitant with intensive agricultural land use in hilly areas. There are many reports of the causes and damaging effects of surface runoff and soil erosion. However, quantitative information on soil erosion rates and the effects of conservation strategies is often not available. Local and provincial policy makers and parties concerned (both farmers organizations and environmental groups) need a quantitative evaluation of the extent and the magnitude of the soil erosion problems and the possible management strategies on a regional basis, as is the case in South-Limburg, The Netherlands. Therefore, field measurements are necessary. Also, quantitative simulation models of surface runoff and soil erosion, which can be used to evaluate alternative strategies for improved land management, not only in the monitored areas, but also in ungauged catchments, are useful.

THE LISEM MODEL

In 1991, a soil erosion project started in three catchments in the loess area of South-Limburg, funded by local, provincial and national authorities. The Departments of Physical Geography of the Utrecht University, the University of Amsterdam, and the Soil Physics Division of the Winand Staring Centre in Wageningen cooperated to develop and validate a new physically-based hydrological and soil erosion model, which can be used for planning and conservation purposes: the LImburg Soil Erosion Model (LISEM).

The LISEM model is one of the first examples of a physically based model that is completely incorporated in a raster Geographical Information System. Incorporation means that there are no conversion routines necessary, the model is completely expressed in terms of the GIS command structure. This approach was introduced by Van Deursen & Kwadijk (1990) and the principles were demonstrated in RHINEFLOW, a water balance model for the river Rhine (Van Deursen & Kwadijk, 1993). PC-Raster Van Deursen & Wesseling, 1992) is used as the GIS to prototype these ideas. Furthermore, the incorporation facilitates easy application in larger catchments, improves the user friendliness, and allows remotely sensed data from airplanes or satellites to be used, such as demonstrated by De Jong (1994). If required, the model can be linked easily with other GIS's.

The development and structure of the LISEM model is based on the experiences with the ANSWERS model (Beasley *et al.*, 1980; De Roo *et al.*, 1989; De Roo, 1993a,b) and SWATRE (Belmans *et al.*, 1983), but process descriptions are changed totally. The advantages of linking a model with a GIS have been described also in De Roo *et al.* (1989) and De Roo (1993). The main reasons for using a GIS is that runoff and soil erosion processes vary spatially, so that cell sizes should be used that allow spatial variation to be taken into account. Also, the data for the large number of cells required is enormous and cannot easily be entered by hand, but can be obtained by using a GIS. The main advantage of incorporating models in GIS is that the "source code" of the model then resides on the comprehensible abstraction level of one or two lines of source code, a GIS command, per process (e.g. interception, infiltration and sediment routing). Such a high level of abstraction simplifies model modification, maintenance and reusability of parts of the model in other models. The current implementation of LISEM is less than 200 lines (exclusive of comments). The GIS must contain a set of tools to build such models (Van Deursen & Kwadijk, 1990). Therefore PC-Raster contains tools to query and report time series, routing tools such as drain, accumulate and kinematic wave (Chow *et al.*, 1988) and equation solvers such as Newton's method.

Besides the availability of the right set of tools to create a model, the GIS must have advanced scripting facilities. While most temporary GI systems are capable of scripting series of commands that could make up a model, often their scripts suffer from an inefficient data transfer mechanism and a lack of abstraction level desired for modelling complicated processes. Especially the data transfer between the various commands makes it practically impossible to run models, since each command output is written to the database or file system and then read by some other command despite the fact that most information is only used local in the model. In other words intermediate output that is written is only used in some succeeding step and then discarded. For example, modelling an event of 9 h with a time step of 15 s by a 200 line model would result in a data transfer of 432 000 raster maps.

LISEM is written in a prototype GIS modelling language currently developed at the Utrecht University. The language comprises all PC-Raster commands as statements with exactly the same syntax as the command form of these statements. When compiled, an efficient run time mechanism eliminates redundant data transfer.
Processes incorporated in the model, which are described below, are rainfall, interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and throughfall, detachment by overland flow, and transport capacity of the flow. Also, the influence of tractor wheelings, small paved roads (smaller than the pixel size) and surface sealing on the hydrological and soil erosion processes is taken into account.

Rainfall

Data from multiple raingauges can be entered in an input data file. A map is used as input to define for each pixel which raingauge must be used. For every time increment during the simulation of a storm, the model generates a map with the spatial distribution of the rainfall intensity. Thus, the model allows for spatial and temporal variability of rainfall. In the future, this approach allows for the input of e.g. radar data indicating rainfall intensity patterns changing in space and time: e.g. to simulate a thunder storms which moves over a catchment.

Interception

Interception by crops and/or natural vegetation is simulated by calculating a maximum storage capacity, which is filled during rainfall. The maximum interception storage capacity is estimated using an equation developed by Von Hoyningen-Huene (1981):

$$\mathrm{SMAX} = 0.935 + 0.498 * \mathrm{LAI} - 0.00575 * \mathrm{LAI}^2 \qquad (1)$$

where SMAX = maximum storage capacity (mm) and LAI = leaf area index.

Cumulative interception during rainfall is simulated using an equation developed by Aston (1979), which is modified from Merriam (1960):

$$\mathrm{CINT} = \mathrm{SMAX} * \left[1 - e^{-(1-p) * \frac{\mathrm{PCUM}}{\mathrm{SMAX}}}\right] \qquad (2)$$

where CINT = cumulative interception (mm), PCUM = cumulative rainfall (mm) and p = correction factor, equals (1 − 0.046 * LAI).

This equation simulates throughfall already before SMAX is reached. The factor k, equal to $(1 - p)$, was introduced by Aston (1979) to incorporate the effect of slower interception when the vegetation is dense. Simultaneously, this factor incorporates the fact that only that part of the cumulative rainfall which falls on the vegetation (PCUM * PER, where PER is the soil coverage by vegetation) can contribute to the interception storage. From the cumulative interception equation, interception rate is calculated by subtracting the CINT at time = $(t - 1)$ from CINT at time = t.

Infiltration and soil water transport

Infiltration and soil water transport in soils are simulated by a solution of the well known Richards equation, which combines the Darcy equation and the continuity equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} K(h) \left[\frac{\partial h}{\partial z} + 1 \right] \tag{3}$$

where K = the hydraulic conductivity (m s^{-1}), h = the pressure (matric) potential (m), θ = the volumetric water content (m^3 m^{-3}), z = the gravitational potential or height above a reference level (m) and t = time (s).

Using the soil water capacity $C(h) = d\theta(h)/dh$ (the slope of the soil water retention curve $\theta(h)$, the unsaturated flow equation is derived:

$$C(h) \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} K(h) \left[\frac{\partial h}{\partial z} + 1 \right] \tag{4}$$

where C = the soil water capacity.

The Mualem/Van Genuchten equations (Mualem, 1976; Van Genuchten, 1980) are used to predict the soil-water retention curves and the unsaturated hydraulic conductivity, which are needed to solve the equation above. In the basins, soil profile types are defined, and for each characteristic soil horizon, the van Genuchten parameters are determined. Optionally, the measured K-θ-h relations can be used. The equations are solved by explicit linearization using the so-called Thomas (tridiagonal) algorithm (see e.g. Remson *et al.*, 1971). The submodel operates with a variable time increment depending on pressure head changes.

Storage in micro-depressions

Storage in micro-depressions is simulated by a set of equations developed by Onstad (1984) and Linden *et al.* (1988). The random roughness variable is used as a measure of microrelief. Surface storage in depressions is simulated by (Onstad, 1984):

$$\text{RETMAX} = 0.112 * \text{RR} + 0.031 * \text{RR}^2 - 0.012 * \text{RR} * S \tag{5}$$

where RETMAX = maximum depression storage (cm), RR = random roughness (cm) and S = slope gradient (%).

The rainfall excess (rainfall + overland flow − interception − infiltration) required to fill all depressions is calculated using the equation (Onstad, 1984):

$$\text{RETRAIN} = 0.329 * \text{RR} + 0.073 * \text{RR}^2 - 0.018 * \text{RR} * S \tag{6}$$

where RETRAIN = rainfall excess needed to fill depressions (cm).

Moore & Larson (1979) identified three possible stages during a rainfall event:

(a) micro-relief storage occurring, no runoff;
(b) additional micro-relief storage accompanied by runoff;
(c) runoff only with the micro-relief storage.

To determine the transition from stage (a) to stage (b), the data of Onstad (1984) were analysed. From this analysis the following equation was developed, simulating the starting point of runoff:

$$\text{DETSTART} = \text{RETMAX} * [0.0527 * \text{RR} - 0.0049 * S] \quad (7)$$

where DETSTART = rainfall excess needed to start runoff (cm).

Thus, during stage 1, all excess rainfall becomes depression storage. Then, from point DETSTART to point RETMAX both overland flow and further depressional storage occur, based on a linear filling of the depressions until RETMAX. After RETMAX, all excess rainfall becomes runoff. Thus, using these relationships the actual storage in depressions (RET) can be calculated.

Also, using the same input data, the maximum fraction of the surface covered with water can be calculated (Onstad, 1984):

$$\text{FWAMAX} = 0.152 * \text{RR} - 0.008 * \text{RR}^2 - 0.008 * \text{RR} * S \quad (8)$$

where FWAMAX = the maximum fraction of the surface covered with water.

The actual fraction surface covered with water is calculated using a relationship based on the work of Moore & Larson (1979) and Onstad (1984):

$$\text{FWA} = \text{FWAMAX} * \left[\frac{\text{RET}}{\text{RETMAX}}\right]^{0.6} \quad (9)$$

where FWA = the actual fraction of the surface covered with water.

Based on the findings of Linden *et al.* (1988), some depressions are (temporarily) isolated and do not contribute to overland flow. From their data it was determined that if the storage (RET) was less than 75% of the RETMAX, 20% of the depressions are isolated. If RET is between 75% and 100% of RETMAX then the following equation was derived:

$$\text{FWAISO} = 0.20 * \text{FWA} * \left[1 - \frac{\frac{\text{RET}}{\text{RETMAX}} - 0.75}{0.25}\right] \quad (10)$$

where FWAISO = the fraction of the isolated depressions.

Overland flow and channel flow

For the distributed overland and channel flow routing, a four-point finite-difference solution of the kinematic wave is used together with Manning's equation. Procedures of the numerical solution can be found in Chow *et al.* (1988) and Moore & Foster (1990).

Splash detachment

Splash detachment is simulated as a function of soil aggregate stability, rainfall kinetic energy and the depth of the surface water layer. This submodel is calibrated by field experiments (Cremers *et al.*, submitted). The kinetic energy can arise from both direct throughfall and drainage from leaves. The following equation is used:

$$\text{DETR} = \left[\frac{2.07}{\text{AGGRSTAB}} * \text{KE} * \exp^{-1.48 * \text{DEPTH}} + 2.20\right] * (P - I) * \frac{(\mathrm{d}x)^2}{\mathrm{d}t} \quad (11)$$

where DETR = splash detachment (g s^{-1}), AGGRSTAB = soil aggregate stability (median number of drops), KE = rainfall kinetic energy (J m^{-2}), DEPTH = depth of the surface water layer (mm), P = rainfall (mm), I = interception (mm), dx = size of an element (m) and dt = time increment (s).

Transport capacity

The transport capacity of overland flow is modelled as a function of unit stream power (Govers, 1990). For loess soils, the following equation, valid for D_{50} = 50 μm is used:

$$\mathrm{TC} = 0.063 * [S * V - 0.4]^{0.56} \tag{12}$$

where TC = volumetric transport capacity (cm^3 cm^{-3}), S = slope gradient (m m^{-1}), V = mean flow velocity (cm s^{-1}).

Rill and interrill erosion

Flow detachment and deposition are simulated using equations from the EUROSEM model (Morgan *et al.*, 1992). Whenever the transporting capacity, calculated using equation (12), is less than the available sediment from splash, from upslope areas and from previous time steps, deposition occurs at the following rate (Morgan *et al.*, 1992):

$$\mathrm{DEP} = w * v_s * [\mathrm{TC} - C] \tag{13}$$

where DEP = deposition rate (kg m^{-3}), w = width of the flow (m), v_s = settling velocity of the particles (m s^{-1}), TC = transport capacity (kg m^{-3}) and C = sediment concentration in the flow (kg m^{-3}).

If the transporting capacity of the flow exceeds the sediment concentration in the flow, detachment by the flow takes places and is calculated using the following equation (Morgan *et al.*, 1992):

$$\mathrm{DF} = y * w * v_s * [\mathrm{TC} - C] \tag{14}$$

where DF = flow detachment rate (kg m^{-3}), y = efficiency coefficient.

The efficiency coefficient in equation (14) is determined by (Morgan *et al.*, 1992; Rauws & Govers, 1988):

$$y = \frac{u_{\mathrm{gmin}}}{u_{\mathrm{gcrit}}} = \frac{1}{0.89 + 0.56 * \mathrm{COH}} \tag{15}$$

where u_{gmin} = minimum value required for the critical grain shear velocity (cm s^{-1}), u_{gcrit} = critical grain shear velocity for rill initiation (cm s^{-1}) and COH = cohesion of the soil at saturation (kPa).

LISEM OUTPUT

The results of the LISEM model consist of:

- a text-file with totals (total rainfall, total discharge, peak discharge, total soil loss etc.);

– an ASCII data file which can be used to plot hydrographs and sedigraphs.
– PC-Raster maps of soil erosion and deposition, as caused by the event;
– PC-Raster maps of overland flow at desired time intervals during the event.

Examples of these are given in Figs 1 and 2.

VALIDATION OF THE LISEM MODEL

The distributed hydrological and soil erosion model LISEM is currently being validated in three catchments in The Netherlands by comparing measured and simulated values of discharge and sediment concentration at the catchment outlet and at two sub-catchment outlets. Furthermore, spatial soil erosion patterns are evaluated using ^{137}Cs (De Roo, 1991; Quine & Walling, 1991). Thus, the distributed model is evaluated in a distributed way.

APPLICATIONS AND USE OF LISEM

One of the applications of LISEM is for planning and evaluating various strategies for controlling pollution from intensively cropped areas. Within the LISEM project, several possible scenarios, of which a few control measures are seriously considered to be

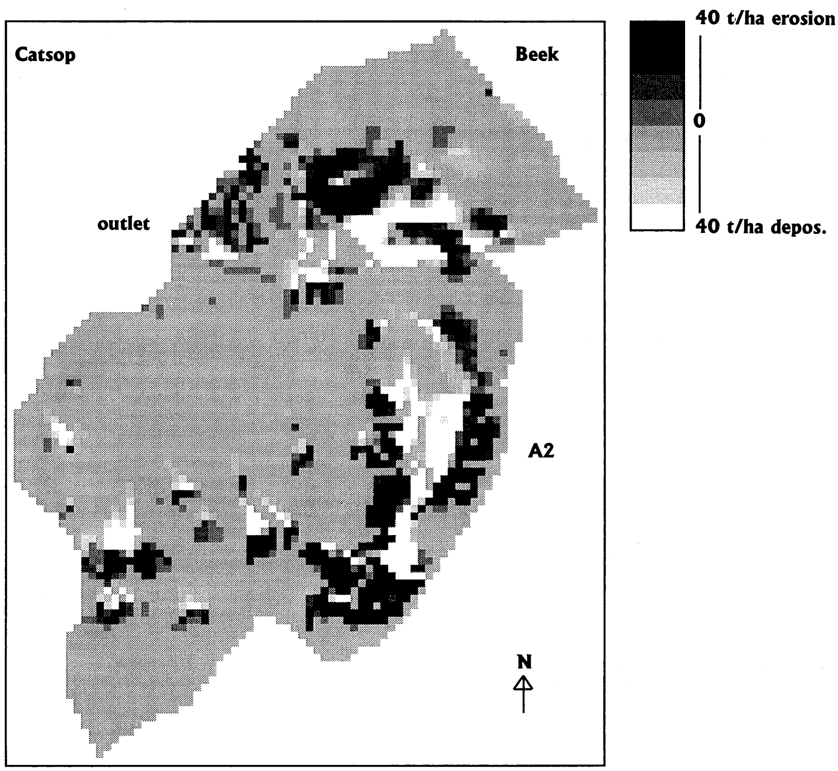

Fig. 1 Example of a LISEM erosion map.

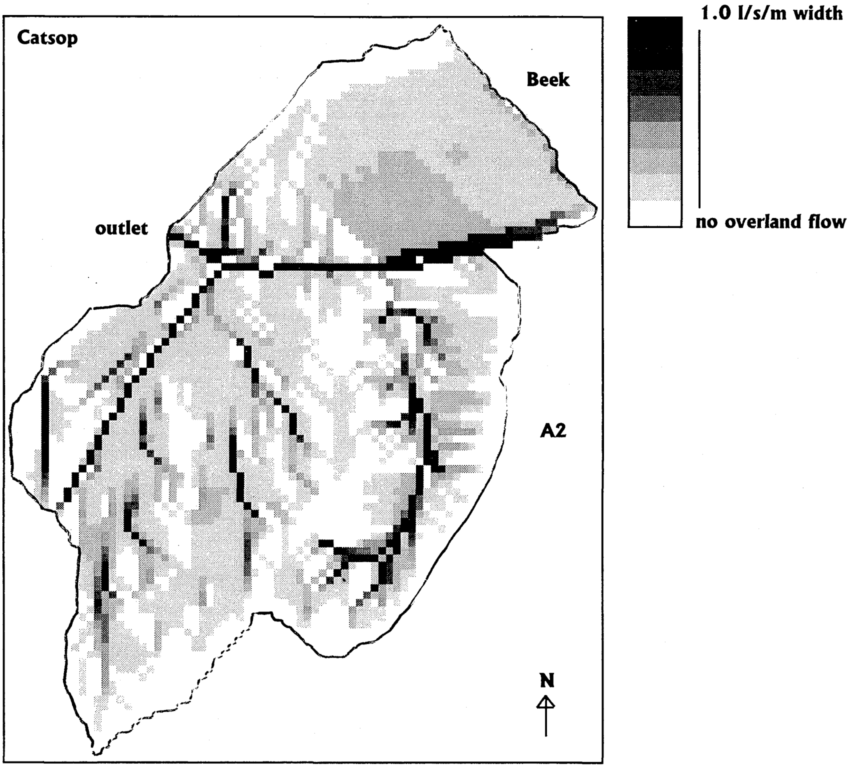

Fig. 2 Example of a LISEM overland flow map.

implemented, are evaluated. Also, using the model the best possible locations for the measures can be determined.

Maps of soil erosion and sedimentation of the scenarios are compared by subtraction. These simulations indicated where possible control measures would have the greatest positive and negative consequences. Planners can decide to combine the positive elements from several scenarios and leave out the negative elements and develop new scenarios. The advantage of using LISEM is that this operation can be done very quickly: combining maps in the PC-Raster GIS which accompanies LISEM is a standard operation. The map database can easily be updated with new data (such as field and laboratory measurements), followed by new interpolations to produce maps.

CONCLUSIONS

LISEM is a powerful model which simulates hydrological and soil erosion processes during single rainfall events on a catchment scale. Using LISEM it is possible to calculate the effects of land use changes and to explore soil conservation scenarios. Driven with hypothetical storms of known probability of return, LISEM is a valuable tool for planning cost-effective measures to mitigate the effects of runoff and erosion. LISEM produces detailed maps of soil erosion and overland flow that are useful for planners. The integration of LISEM in a raster-based GIS, which holds the many data on the distributions of land attributes, is very useful.

Other advantages of LISEM are the use of physically-based mathematical relationships, the ease with which newly developed relationships can be incorporated, the incorporation of information about the spatial variability of land characteristics, and the detailed spatially displayed output of the model, useful for planners.

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