Sensitivity analysis in sediment yield modelling

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Abstract The Universal Soil Loss Equation (USLE) is widely used in mathematical models for predicting sediment yield. The models are based on regression equations for describing rill and inter-rill detachment and apply input parameters to account for external forcing. Uncertainty in estimation of input parameters as well as internal model parameters (e.g. in regression equations) gives rise to uncertainty in the modelling result. In order to clarify the magnitude of this uncertainty and to identify the most crucial factors influencing the simulation output, the sensitivity and uncertainty model UNCSAM was implemented. The sensitivity study was carried out for barley and grass fields. Two soil types were selected, namely silty clay and silt. In all, the sensitivity of 45 parameters (input and internal parameters) to erosion was studied. Besides slope, erosion seemed to be controlled by the internal parameters (i.e. regression factors in the rill erosion and sediment transport equations), while the composition of soil texture, for example, was of minor importance. If snow melted and accumulated in several periods, the parameters affecting snowmelt gained importance. Furthermore, the choice of the uncertainty measure had only minor effects on the ranking of sources, while the initial assumption of correlation between the input parameters had an effect on the outcome. The years differ largely in their hydrology and this requires that UNCSAM runs have to be performed with output data representing varying hydrological conditions.

INTRODUCTION

Sediment yield is a result of numerous complex interactions among hydrological (rainfall intensity and surface runoff) and landscape (e.g. soil, vegetation) properties. The deterministic modelling of the annual erosion requires a lot of data and carries a considerable amount of uncertainties. In the model, the parameter values can be based on measurements (Puustinen, 1994), on literature values (Vehviläinen, 1992) and on regression equations (Knisel, 1980; Foster *et al.*, 1977). Due to the heterogeneity of soil as well as vegetation properties, the parameter values can vary largely. Therefore, a systematic sensitivity analysis is worthwhile in many respects. Firstly, it forces the user to become acquainted in detail with the process descriptions and parameters involved. Secondly, the sensitivity analysis produces the dominant sources of sediment yield and thus can help to interpret the model outputs in changing situations. This is particularly important in order to provide accurate estimates of sediment-associated nutrient and contaminant transfer. In this study, UNCSAM (a software package for uncertainty and sensitivity analysis) (Janssen *et al.*, 1993), which applies a Monte Carlo simulation connected with Latin Hybercube sampling in combination with regression and correlation analysis, was used to analyse the sensitivity and uncertainty of the ICECREAM model output concerning sediment losses from agricultural fields.

MATERIAL AND METHODS

The ICECREAM model

The ICECREAM model (Tattari *et al.*, 2000), is a field-scale mathematical simulation model predicting water transport, soil and nutrient losses at the edge of the field and out of the root zone. It is an extension of the CREAMS/GLEAMS models (Knisel, 1980, 1993; Leonard *et al.*, 1987), originally developed in the USA to assess and compare the impact of different management practices on soil and nutrient losses. The hydrology and crop growth calculations have been further developed by Rekolainen & Posch (1993).

The hydrology component of ICECREAM simulates daily runoff using a modification of the Soil Conservation Service Curve Number method (USDA-SCS, 1972), which relates to soil texture and structure, land use and management practice. The matrix flow in soil is described by a simple "tipping bucket" system using the user-defined hydraulic conductivity and pF-curve values for porosity, field capacity and wilting point. Evaporation is calculated by a model presented by Ritchie (1972). Erosion is computed using the modified Universal Soil Loss Equation (MUSLE: Foster *et al.*, 1977):

$$A = R \cdot K\left(\frac{x}{\lambda_u}\right)^n \cdot \left(a_1 \cdot s^2 + a_2 \cdot s + a_3\right) \cdot C \cdot P \tag{1}$$

where A is the average soil loss per unit area, R is the rainfall and runoff erosivity factor, K is the erodibility factor, x is field length, λ_u is the length of unit field (22 m), s is the sine of the slope angle (α), C is the cover and management practices factor, and P is the supporting conservation practices factor.

Erosion is divided into five processes: detachment and transport of sediment caused by rainfall or runoff and deposition. Erosion produced by rainfall is pronounced in the upper part of the slope while the runoff typically cumulates in the direction of slope and is thus dominant in the lower part of the slope. Deposition of sediment occurs when the transport capacity is less than the sediment load. Typically, the fine grained particles remain in suspension and are transported considerable distances.

In ICECREAM, two types of erosion are distinguished, namely sheet erosion, also called inter-rill erosion, and rill erosion. The sediment transport capacity for each particle size class, based upon the potential sediment load, is computed using Yalin's sediment transport equation (Yalin, 1963). All of these equations contain regression coefficients which have been computed based on measured local erosion data (e.g. Foster *et al.*, 1977, 1980).

The equation for inter-rill erosion ($\overline{D_i}$) is:

$$\overline{D_i} = b_1 \cdot ei \cdot \left(s + b_2\right) \cdot K \cdot C \cdot P \cdot \frac{q_p}{Q} \tag{2}$$

where *ei* is the rainfall factor, b_1, b_2 are regression coefficients, q_p is the peak runoff rate and Q is daily runoff. The peak runoff rate is calculated as follows:

$$q_p = P_1 \cdot A^{c_1} \cdot s^{c_2} \cdot wlw^{c_3} \cdot Q^{c_4 \cdot A^{c5}} \tag{3}$$

where *wlw* is the width–length ratio of the field, A is the drainage area, and $c_{1\text{-}5}$ and P_1 are regression coefficients. The equation for rill erosion is similar to the inter-rill erosion equation, but more strongly dependent on the slope:

$$\overline{D}_r = m \cdot \left(P_2 \cdot q_p^{\frac{4}{3}} \right) \cdot \left(P_3 \cdot s^2 \right) \cdot \left(\frac{x}{\lambda_u} \right)^{m-1} \cdot K \cdot C \cdot P \tag{4}$$

where m is a coefficient determined as a function of slope. Shear stress equations are needed to compute the transport capacity, $\tau_{1,u}$:

$$\tau_{1,u} = P_{4,5} \cdot \left(q_{1,u} \cdot x \cdot \frac{n_{\text{bov}}}{s_{1,u}} \right)^{0.6} \cdot \gamma_w \cdot s_{1,u} \cdot \left(\frac{n_{\text{bov}}}{n_{\text{cor}}} \right)^{0.9} \tag{5}$$

where $q_{1,u}$ is the peak runoff rate, n_{bov} and n_{cor} are Manning's n for bare soil and over soil covered by vegetation, respectively, γ_w is the mass density of fluid, and P_4 and P_5 are regression coefficients.

The UNCSAM model

UNCSAM is a software package for performing sensitivity and uncertainty analyses for a mathematical model. It applies a Monte Carlo simulation technique in conjunction with standard statistical analysis to determine the sources of sensitivity and uncertainty in the model (Janssen *et al.*, 1992). The source can be either the input parameters or the internal model parameters. The Latin Hypercube sampling technique (Iman & Conover, 1982) was included in the software package and was utilized in the analyses.

For the analyses, nominal values of parameters with their ranges and distributions are given. In addition, correlations between selected parameters can be specified. Numerous statistical descriptors are used in UNCSAM to express sensitivity and uncertainty. They are based either on correlation or on regression analysis. In this study, two descriptors, the Semi-Partial Correlation coefficient (SPC) and RooT of Uncertainty (RTU), were utilized. The coefficient SPC is based on correlation and RTU on regression analysis. Root of uncertainty takes into account the specified correlations between the parameters, which may lead to a situation where a "weak" parameter can notably rise in the ranking list provided it correlates with a "strong" parameter. In both cases, a good linear relationship between the parameters and the model output is required.

Parameter selection

The selection of parameters for the sensitivity analysis is always a subjective choice, if it is not possible to study all the model parameters. Besides the traditional input parameters, the parameterization of physical processes produces typically regression equations with coefficients, which are based on local measurements and thus not necessarily valid for different locations. The choice of the parameters for sensitivity analysis can be based on, for example, the prevailing knowledge of the erosion mechanism and on the process descriptions in the model. The USLE is very sensitive to slope steepness. Furthermore, parameters such as soil erodibility, soil type and hydraulic properties of the soil undoubtedly affect yearly sediment loss. Dense vegetation cover may substantially decrease sediment losses and thus parameters having an influence on leaf area index and biomass growth will affect erosion losses. Since a large number of erosion events in Finland occur during the snowmelt period and in late autumn, the parameters controlling snowmelt are also studied. Altogether 45 parameters, including five internal model parameters were selected for the analysis. Some influential parameters together with their range and distribution are presented in Table 1. The sensitivity analysis was performed for two soil types (silty clay and silt soil) and for two crops, namely barley and grass.

Table 1 Examples of parameter distributions and ranges for silty clay soil with barley vegetation.

Parameter	Explanation	Distribution	Minimum	Maximum
ksoil	soil erodibility	normal	0.15	0.3
om	fraction of organic matter in soil (m^3 m^{-3})	normal	0.04	0.12
cc	fraction of clay in soil (m^3 m^{-3})	normal	0.3	0.6
θ_{fc}	field capacity (m^3 m^{-3})	uniform	0.35	0.5
k_{sat}	saturated hydraulic conductivity (mm h^{-1})	logarithmic	0.05	2.0
f_0	degree day factor (mm °C^{-1} d^{-1})	uniform	1.9	7.6
T_0	threshold temperature for melting (°C)	uniform	–0.3	2.1
n_{bov_u}	Manning's *n* after tillage in autumn	normal	0.022	0.028
ω	growth parameter	normal	1	3
h_{max}	maximum canopy height (m)	uniform	0.7	1.1
β_w	maximum canopy width (m)	uniform	0.15	0.35
R_{dm}	maximum root depth (m)	uniform	0.35	0.85
P_1	regression coefficient in peak runoff equation (2)	uniform	0.2	1.8
P_2	regression coefficient in rill erosion equation (3)	uniform	1	27
P_3	regression coefficient in rill erosion equation (3)	uniform	5	500
P_4, P_5	regression coefficient in rill erosion equation (4)	uniform	0.2	1.4

RESULTS

Traditional parameters

The sensitivity analysis was conducted with erosion data representing an average year in proportion for precipitation and erosion. The absolute value of 0.20 was chosen for RTU and SPC as a threshold value above which the influence of a specific parameter was considered significant. A relatively high value (0.20) was chosen in order to point out only the most affecting parameters. The ranking list of controlling parameters on erosion for two soil types and for two crops is presented in Table 2. Slightly different parameters dominate for silty clay soil and silt soil. For silty clay soil, the sensitivity analysis gives only two influential parameters: n_{bov}_u and cc (see Table 1). For silt soil, a larger number of parameters affects the simulated output. Instead of clay content, sand and organic matter content as well as soil erodibility gain significance. This is presumably due to the narrower range of clay content for silt soil (cc = 0–15%) than for silty clay soil (cc = 30–60%). In addition to soil type, the crop used in the simulation also affects the ranking list order of the most influential parameters. For permanent grass crop, the parameters which are connected to biomass growth play an important role. A high mutual correlation was given between h_{max} and R_{dm} (see Table 1) and, presumably, it resulted in higher ranking of R_{dm} on the RTU list than on the SPC list. It is also noteworthy that more parameters are affecting the simulated sediment yield for grass than for barley. Unexpectedly, the parameters affecting the surface runoff, such as field capacity and wilting point, are negligible for simulated sediment yield (Bärlund & Tattari, 2000).

Internal regression coefficients and snowmelt parameters

The years differ largely in their hydrology and, because of this variability, the sensitivity analysis may introduce quite different factors in the ranking list when the simulated output variable represents e.g. extreme hydrological conditions. In addition, the internal regression coefficients (e.g. P_1–P_5 in equations (1)–(5)) have been shown to affect simulated erosion sums even more than the traditional user defined parameters (Tattari & Bärlund, 2000). Moreover, the snowmelt parameters (e.g. f_0, T_0) might be important depending on the prevailing snowmelt and precipitation events (Tattari & Bärlund, 2000). Figure 1 shows the annual erosion losses from a barley field (2% slope, silty clay soil) with an unchanged parameter set and with changing parameter values. The changed parameters (f_0, n_{bov}_u, cc, P_3

Table 2 RTU and SPC ranking of the most influential parameters for yearly cumulative sediment yield.

RTU ranking	RTU value	SPC ranking	SPC value
Silty clay soil, barley, slope 2%:			
cc	0.7	n_{bov}_u	0.65
n_{bov}_u	0.65	cc	0.62
Silty soil, barley, slope 2%:			
n_{bov}_u	0.74	n_{bov}_u	0.71
ksoil	0.44	*ksoil*	0.36
sc	0.29	*sc*	0.21
om	0.22		
Silty clay soil, grass, slope 2%:			
h_{max}	0.48	ω	0.44
ksoil	0.45	*ksoil*	0.36
ω	0.45	β_w	0.26
R_{dm}	0.39	h_{max}	0.26
cc	0.32	cc	0.23
β_w	0.31		
om	0.21		

See Table 1 for definition of parameters.

and ω) are the ones which turned out to be the most influential according to the sensitivity studies. On the whole, the impact of a specific parameter varies from year to year. For example, the degree-day factor is controlling erosion losses during 1988 and 1990 but seems not to be significant during 1989 and 1991. In contrast, the effect of clay content is almost constant during the four year period. Due to the Finnish tillage practice (typically in late August), soils are bare until planting in early May, resulting in strong impact of Manning's *n* value for the simulated output. An uniform distribution was given for parameter P_3, which probably led to under-estimation of its influence compared to the normal distribution set for clay content, Manning's *n* value and degree-day factor (see Fig. 1).

CONCLUSION

The UNCSAM model was implemented to study the influence of input parameters and internal regression coefficients on erosion. In all cases, slope steepness had the most significant effect on erosion. The importance of snowmelt parameters was dependent on the prevailing snowmelt and precipitation events. In general, the impact of a specific snowmelt parameter varied from year to year. Completely different parameters were influential for barley and for grass. When slope was neglected from the analysis, the clay content of soil and Manning's *n* after tillage gained importance for barley, whereas for grass, the parameters affecting crop growth were the most important. The internal regression coefficients were without exception significant.

The UNCSAM model is capable of ranking the most influential parameters for simulated output variables. However, the ranking order is highly dependent on the initial presumptions. For example, the number of input parameters in ICECREAM is large. This means that the modeller has to select the most important parameters for the analysis. This makes it possible to discard important parameters from the UNCSAM parameter list. In addition, the modeller has to specify the range as well

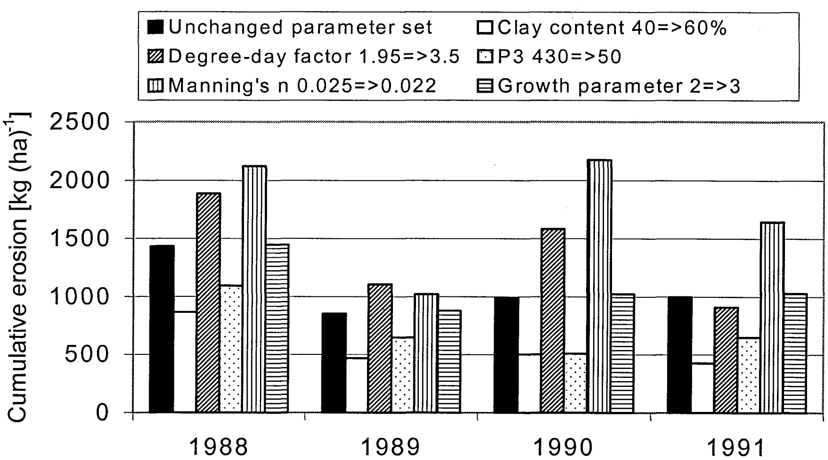

Fig. 1 The influence of the change in a specific parameter value on yearly cumulative erosion.

as the distribution for the parameters. Based on the limited number of measurements, this is a presumable source of error.

In order to get reliable ranking lists for a certain output variable, the UNCSAM runs have to be performed with different soil as well as crop data. The same applies for the simulated output variable; years with extreme hydrological and meteorological conditions emphasize different parameters from those of an average year. As a whole, the UNCSAM result contributed to better understanding the functioning of the ICECREAM model.

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