

GULTEM - The Model to Predict Gully Thermoerosion and Erosion (Theoretical Framework)

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ABSTRACT

The three-dimensional hydraulic model GULTEM was developed to predict the rapid changes of gully morphology in the early stages of gully development. It is based on the digital elevation model's analysis of flowlines; calculations of runoff due either to snowmelt or to rainfall; and the solution of the equations of mass conservation and gully-bed deformation for different types of soil (including frozen soil). The model of the shallow landslide stability was used to predict the gully's sidewall inclination. The stochastic method of detachment rate estimation used in GULTEM is based on calculation of the probability of excess driving forces above resistance forces in the flow, which erode cohesive soil. The method explains the substantial difference in the types of relationships between detachment rate and flow velocity (or shear stress and stream power) for different soils. The model can be used to choose the appropriate system of land conservation measures and to fit sustainable land-use conditions to catchments with high gully-erosion potential.

INTRODUCTION

The soil conservation to sheet and rill erosion approach is fundamentally different how we approach to gully erosion. In the first case, a soil conservation schedule includes field morphological, hydrological and soil investigations, laboratory analysis of soil erosion properties, laboratory experiments, and engineering calculations before the solution for soil conservation measures can be found. A large number of field and laboratory methods can be found in handbooks, and many mathematical models are available for soil erosion calculations.

In the second case, soil conservation measures are designed with less information. Field investigations consist mainly of morphological measurements in the gullies. Engineering calculations include stable slope estimations for gully sides and infilling. The number of mathematical models necessary to predict gully erosion is very much less than for sheet and rill erosion calculations.

A practical reason for these differences is not clear. The significance of gully erosion has been well documented. The volume of the gullies on the Russian Plain is about 4×10^9 m³, i.e. about 4% of the whole volume of erosion since 1700 AD (Sidorchuk, 1995). In Australia, with mainly pasture land, the volume of gully erosion amounts to 16×10^9 t a⁻¹

(Wasson et al., 1996). In Western Europe, ephemeral gully erosion can measure up to 30-40% and up to 80% of the total erosion volume (Poesen et al., 1996). Gullies destroy the fertile topsoil layer, and the surrounding lands are damaged with more severe sheet and rill erosion.

A gully is a linear deep erosion feature with an active head cut, unstable side walls, subject to mass movement, and a non-graded longitudinal profile, with temporal water flow. A gully is often a transient form of relief: It can be initiated as a rill on a slope, can be transformed into an ephemeral gully, and, if not cultivated, enlarge into a typical gully. After long-term evolution a gully becomes stable. Such a mature linear erosion feature with a graded profile and stable sidewalls is called "balka" in Russia. With a good ground water supply, a stable gully can become a small creek. During periods of active bottom and head cut erosion, a "balka" or creek can be transformed into a reactivated gully, and during an accumulation period, a gully can be completely filled with sediment, thus becoming a shallow elongated depression at the slope (so called "zero-order valley" or "lozhbina").

There are two main stages of gully development, controlled by different sets of geomorphic processes. At the first stage of gully initiation, hydraulic erosion (and thermoerosion in areas with permafrost) is predominant at the gully bottom, and rapid mass movement occurs along the gully sides. During this period, when the morphological characteristics of the gully (length, depth, width, area, and volume) are far from stable, gully channel formation is very intense. In the later stage, sediment transport and sedimentation are the main processes in the gully bottom. The gully's width increases due to lateral erosion, and slow mass movement transforms the gully sides. The experiments of B. Kosov, I. Nikol'skaya and Ye. Zorina (1978) on gully formation in sand show that the first stage is relatively short and takes about 5 % of the gully's lifetime. More than 90 % of gully length, 60 % of gully area and 35 % of gully volume are formed at this period. Gully morphology at the last stage (the greatest part of a gully's life) is nearly stable.

One of the main areas of recent intensive anthropogenic gully erosion is the Yamal Peninsula in Western Siberia, in the areas of gas fields with permafrost. The rate of gully growth is as much as 20-30 to 200 m year⁻¹ (Sidorchuk, 1996; Sidorchuk and Grigor'ev, 1998). These gullies are a real danger for construction and gas transportation facilities, and their activity has led to a regional ecological

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catastrophe. In recently exploited gas fields of the Yamal Peninsula the initial stages of gully development are typical: for example, a gully near the main exploitation camp (called PBB) did not exist in 1986, but a 240-m - long shallow, elongated depression on the slope did. After the camp construction in 1986-87, erosion and thermoerosion were initiated due to the increase in surface runoff. In 1988, the gully length was 450 m. In 1989 it was 740 m, and in 1990 the length was 940 m. The head of the gully reached the camp buildings. Filling of the gully head by heavy loam from the banks by bulldozers attempted to stop the gully growth. Nevertheless, in 1995, the gully was 25 m longer, than in 1990.

GULTEM model

The 3D hydraulic gully thermoerosion and erosion model GULTEM was developed for the initial stage of gully evolution. At this stage, erosion (and thermoerosion at the areas with permafrost) is predominant at the gully bottom, and rapid shallow landslides occur on the gully sides. Gully channel formation is very intensive, and the morphological characteristics of the gully (length, depth, width, area, and volume) are far from stable. On the marine terraces of the Yamal Peninsula, composed from frozen loam and sands with substantial ice content, this stage lasts 4-10 years and anthropogenic gullies cut into the terrain to cover their entire length.

The GULTEM is based on a net of flowlines, evaluated from a topographical digital elevation model (DEM). The multi-layered soil texture (including topsoil with the vegetation cover) is derived from DEMs of the top surfaces of each layer with a similar texture. The runoff due to snowmelt and rainfall is calculated with physical-based hydrological models. The input to the GULTEM model includes topographic, hydrologic, hydraulic and soil mechanics data. Topography is described by elevations and distance from the gully mouth along the longitudinal profile of each flowline on initial slope (including existing gullies). The runoff along these flowlines is calculated with the hydrological model. The multi-layer soil properties are used in the model. The input for each layer includes: the elevations of the base of the layer along the same flowlines; soil bulk density; soil cohesion, angle of internal friction and fatigue to rupture; the size of the water stable aggregates; soil moisture and thin vegetation roots content (for a topsoil).

During a snowmelt or rainstorm event, flowing water is assumed to erode a rectangular channel in the topsoil or at the gully bottom. The longitudinal profile transformation in space and time and gully bed widening are calculated in terms of the mass-conservation equation with Lax-Wendroff predictor-corrector scheme. The stability criterion is determined for each calculation step. The numerical scheme stability is obtained by change of a time step: At each time

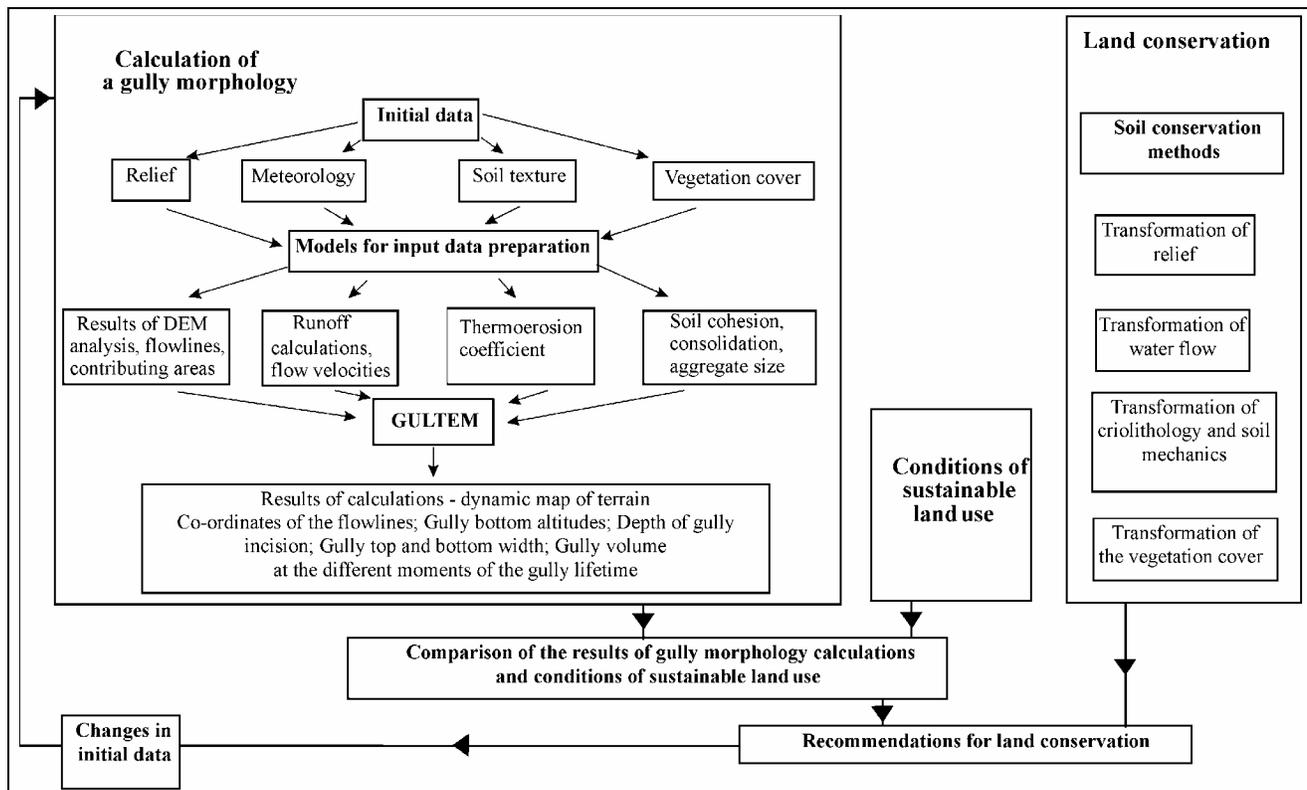


Figure 1. System of models for gully morphology prediction in conditions of sustainable land use.

step, width, depth, velocity and critical shear stress for the soils both in the gully bed and in the banks are calculated, along the flow. This allows calculation of the soil aggregates' detachment rate, and the rate of the flow incision and widening. Between water flow events, a gully cross - section is quickly transformed by shallow landslides. After each flood event, the model transforms the rectangular bottom trench to a trapezoidal shape with a shallow landslide stability model. Numerical experimentation shows that the model describes the real process of gully longitudinal and cross-section profile evolution in time and space on a gully basin. As it is sensitive to of soil erodibility variations, field investigations and careful calibration of the model are necessary to predict gully erosion.

The main parameters, controlling GULTEM calculations of erosion and thermoerosion (relief, water flow, soil mechanics, and vegetation cover), correspond to the main arguments for soil conservation measures. The numerical experiments provided by the model can be used to choose the correct land conservation measures and to fit sustainable land-use conditions to catchments with high gully-erosion potential (Fig. 1).

The system of models used for preparation of input data for GULTEM and for gully morphology calculation, was described in the paper of A. Sidorchuk and A. Sidorchuk (1998). The basic principles of soil erosion used in GULTEM are presented here.

Theoretical framework of GULTEM

The rate of gully erosion is controlled by water flow parameters (velocity, depth and turbulence) and soil texture (mechanical pattern and protection by vegetation). These characteristics are combined in equations of mass conservation (1) and deformation (2), which can be written in the form:

$$\frac{\partial Q_s}{\partial X} + \frac{\partial AC}{\partial t} = C_w q_w + M_0 W + M_b D - C V_f W \quad (1)$$

$$(1 - \varepsilon) \frac{\partial Z}{\partial t} = C V_f - M_0 \quad (2)$$

Here $Q_s = QC$ is sediment discharge (m^3/s), Q = water discharge (m^3/s); X = longitudinal co-ordinate (m); t = time (s); C = mean volumetric sediment concentration; A = flow cross-section area (m^2); C_w = sediment concentration of the lateral input; q_w = specific lateral discharge; M_0 = upward sediment flux (m/s); M_b = sediment flux from the channel banks (m/s); Z = gully bed elevations (m); W = flow width (m); D = flow depth (m); V_f = soil aggregates fall velocity in the turbulent flow (m/s); ε = porosity of the soil at the gully bed.

The first term in the left part of equation (1) defines the sediment budget in the channel reach, the second term is the sediment storage in the flow. The right part of (1) defines the sediment flux: the first term is lateral flux, the second one is upward flux, the third is sediment flux from the banks, and the fourth is downward flux. Equation (2) defines the change of gully-bottom elevation according to the sediment budget.

The sediment storage in the flow is usually very small and can be neglected. The fall velocity in highly turbulent flow in the young gullies is often close to zero, and the rate of sedimentation for these environments is also negligible. In this case, equation (1) is a first-order ordinary differential equation, and equation (2) is a first-order partial differential equation with variable coefficients. The solution of these equations depends on the form of the terms that describe sediment fluxes. To understand the erosion process, the upward flux of soil aggregates and particles (detachment rate) is of major importance.

Upward flux (detachment rate)

The detachment rate (D_r) is the product of the concentration (C_Δ) of active soil aggregates in the bed layer with the thickness Δ and the mean vertical velocity of soil aggregates (U_\uparrow):

$$D_r = C_\Delta U_\uparrow \quad (3)$$

Sediment concentration is the ratio between the volume of active soil aggregates V_a and the volume of the fluid V in the near bed layer (with the thickness Δ and the unit area S): $C_\Delta = V_a / (\Delta * S)$. The volume of active soil aggregates can be written as the product of the number of active soil aggregates N on their mean volume V_m : $V_a = N V_m$. The unit area can be presented as the product of the number of soil aggregates M , exposed at the flow bed on the unit area, on their mean area S_m : $S = M S_m$. Therefore, near bed sediment concentration can be represented as:

$$C_\Delta = \frac{N V_m}{M S_m \Delta} \quad (4)$$

The ratio N/M is the probability (P_d) of soil aggregate detachment for a given unit time $dt = \Delta / U_\uparrow$, and the ratio V_m / S_m is some measure of the mean soil aggregate height D_m .

$$C_\Delta = \frac{D_m P_d}{\Delta} \quad (5)$$

For the near bed layer with thickness Δ equal to aggregate height D_m , the probability of detachment is equal to the sediment concentration in the near bed layer. After H. A. Einstein (1942), it is a function of the measure of the transport rate for the case of non-cohesive sediments. Mirtschoulava (1988), Nearing (1991), Larionov (1993), Wilson (1993a, 1993b) and Lisle et al. (1998) formulated probabilistic concepts of detachment for cohesive soils. The following theoretical stochastic description of soil erosion is an amplification of the models listed above, with the significant addition of the stochastic variables that govern this complicated process.

The probability of soil aggregate detachment is equal to the probability of the excess of driving forces above resistance forces in the flow. Driving forces are drag force (F_d), lift force (F_l), negative turbulent dynamic pressure (F_{dp}), and pore water pressure (F_{pw}). Resistance forces are submerged weight (F_w), friction force (F_f), static pressure (F_{sp}), positive turbulent dynamic pressure (F_{dp}) and cohesion (F_c). After Mirtskhoulava (1988) and Borovkov (1989):

$$F_d = C_R \rho S_d \frac{U^2}{2} \quad (6)$$

$$F_l = C_y \rho S_u \frac{U^2}{2} \quad (7)$$

$$F_{dp} = 3.5 \lambda \rho S_b \frac{U_m^2}{2} \quad (8)$$

$$F_{pw} = g \rho S_b z_p \quad (9)$$

$$F_w = g V_u (\rho_s - \rho) \quad (10)$$

$$F_f = f_t g V_u (\rho_s - \rho) \quad (11)$$

$$F_{sp} = g \rho S_b d \quad (12)$$

$$F_c = C_0 S_b \quad (13)$$

Here C_R is the coefficient of drag resistance; C_y is the coefficient of uplift; U is the actual near-bed flow velocity, and U_m is its mean value; λ is the coefficient of hydraulic resistance; S_d is the cross-section area of soil aggregate, perpendicular to flow; ρ_s and ρ are the soil aggregate density (containing pores) and water density respectively; S_u is the cross-section area of soil aggregate, parallel to the flow (vertical projection); S_b is the area of soil aggregate that is solid with native soil and other aggregates; z_p is capillary pressure height; f_t is the friction coefficient; d is water depth; C_0 is soil cohesion.

A probability of detachment is greater than zero, when the sum of the driving forces is more than the sum of resistance forces:

$$F_d + F_l + F_{pw} - F_{dp} - F_w - F_f - F_{sp} - F_m - F_c > 0 \quad (14)$$

or

$$\Psi = U^2 + k_{pw} z_p \frac{S_b}{S_u} - k_{dp} \lambda \frac{S_b}{S_u} U_m^2 - k_{wf} D_m \frac{(\rho_s - \rho)}{\rho} - k_{sp} d \frac{S_b}{S_u} - k_c \frac{C_0}{\rho} \frac{S_b}{S_u} > 0 \quad (15)$$

The values of the coefficients can be obtained from Mirtskhoulava (1988) and Borovkov (1989):

$$k_{pw} = \frac{2g}{(k_{CR} + C_y)} \approx 40; k_{dp} = \frac{3.5}{(k_{CR} + C_y)} \approx 7; k_{wf} = \frac{2(1+f_t)g}{(k_{CR} + C_y)} \approx 42; k_{sp} = \frac{2g}{(k_{CR} + C_y)} \approx 40; k_m = \frac{24}{k_{CR} + C_y} \approx 48; k_c = \frac{2}{(k_{CR} + C_y)} \approx 4. \quad (16)$$

Driving and resistance forces are stochastic variables, and their sum Ψ has some stochastic distribution with the probability density function p_Ψ . Therefore, probability of detachment P_d can be calculated with the formula:

$$P_d = \int_0^\infty p_\Psi d\Psi \quad (17)$$

The vertical velocity of soil aggregates is the second component of the formula (3) for the detachment rate calculation. The moment of aggregate detachment acceleration can be derived from the expression:

$$D_m \frac{(\rho_s - \rho)}{2\rho} \frac{\partial U_\uparrow^2}{\partial z} = \Psi \quad (18)$$

In the near bed layer of the flow with thickness Δ , an aggregate accelerates from zero velocity to its maximum value, U_\uparrow . The integral of (18) gives a simple expression for the near bed vertical velocity of aggregates:

$$U_\uparrow = \sqrt{\Psi \frac{\Delta}{D_m} \frac{2\rho}{(\rho_s - \rho)}} \quad (19)$$

In turbulent flow with random vertical velocity, its mean value in the sum of the fields of positive forces may be calculated with the formula:

$$\overline{U_\uparrow} = \frac{\int_0^\infty p_\Psi \sqrt{\Psi \frac{\Delta}{D_m} \frac{\rho}{(\rho_s - \rho)}} d\Psi}{\int_0^\infty p_\Psi d\Psi} \quad (20)$$

Theoretical analysis of the stochastic mechanics of soil aggregate erosion in water flow shows that in the field of random driving and stabilizing forces the detachment rate can be calculated as product of Eqs. (17) and (20) as:

$$D_r = \int_0^\infty p_\Psi \sqrt{\Psi \frac{\Delta}{D_m} \frac{\rho}{(\rho_s - \rho)}} d\Psi \quad (21)$$

It is important to note, that in the case of the initial stage of gully evolution, the rate of sedimentation is very small and the detachment of the aggregates and particles occurs from the surface of native soil. The role of sedimentation can be important at the later stages of gully growth, and here the recommendations of Hairsine and Rose (1991) must be taken into account.

The probability of a function of stochastic variables can be calculated if the probabilities of the individual variables are known (Gnedenko, 1954). A probability of product Z of stochastic variables X and Y is derived with the integrals:

$$p_Z(Z) = - \int_{-\infty}^0 X^{-1} p_X(X) p_Y\left(\frac{Z}{X}\right) dX + \int_0^\infty X^{-1} p_X(X) p_Y\left(\frac{Z}{X}\right) dX \quad (22)$$

A probability of sum Z of stochastic variables X and Y is derived from the function:

$$p_Z(Z) = \int_{-\infty}^\infty p_X(X) p_Y(Y) dX = \int_{-\infty}^\infty p_X(X) p_Y(Z-X) dX \quad (23)$$

We shall work out a simplified case, where four characteristics are taken as stochastic variables: velocity U , cohesion C_b , aggregate size D_m and soil consolidation $I_s = S_b/S_u$, and all others are parameters. Therefore the probability density functions for stochastic variables must be estimated theoretically or experimentally.

A probability density function p_U for actual near bed velocity U with mean value U_m and standard deviation σ_U is often described by the normal distribution (Mirtskhoulava, 1988). Then frequency of $z = U^2/\sigma^2$ will be defined by first order non-central χ^2 distribution (Pugachev, 1979). Borovkov (1989) showed that σ_U is related to dynamic velocity: $\sigma_U = 3.0 u_*$.

The ratio of the soil aggregate area S_b , where aggregate

is solid with the native soil or other aggregates, to the aggregate vertical projection area S_u : $I_s = S_b/S_u$ is the measure of the soil consolidation. The difference between these two areas is the area of micro-cracks, which cut loose individual aggregate from native soil. Such micro-cracks filled with the ice are often formed in the frozen soil. The relative volume of micro-cracks is approximately the difference between bulk soil porosity and structural within aggregate porosity. The soil consolidation is opposite to soil fatigue, generated in the soil under a dynamic action of turbulent flow (Mirtskhoulava, 1988), and mainly due to flow velocity oscillation and dynamic pressure rapid change. Its distribution depends on soil texture, cohesion and the intensity of turbulent oscillations. Overview of laboratory and field experiments of Mirtskhoulava (1988) shows that for a wide range of different soils, $(I_s)_{mean}$ has an asymmetrical distribution. Beta-distribution will therefore be used in further calculations. It is evident that the soil consolidation or fatigue, as defined above, needs for further investigations.

Analysis of the laboratory data of Mirtskhoulava (1988) shows that a gamma-distribution can be used to describe the distribution of cohesion within a sample of soil. Mirtskhoulava's data also showed that the coefficient of variation $C_v = \sigma_c/C_m$ for this distribution is constant and equals ~ 0.2 for wide range of soil characteristics. In this case, the distribution curve for actual cohesion is determined only by one parameter: mean cohesion of soils.

The distribution density of soil aggregate size within a sample of soil generally fits a lognormal distribution with the parameters, related to mean aggregate diameter D_m and its standard deviation σ_D .

The parameters of distribution curves for flow velocity, soil cohesion, consolidation and aggregate size vary in space at the flow bed and in the soil profile. These parameters can also change in time during the process of erosion. Mirtskhoulava (1988) defines four stages in cohesive soil erosion: 1) rapid erosion of the initially weakened soil surface; 2) slow erosion of the native soil body; 3) acceleration of erosion due to the increase of soil fatigue in the oscillating turbulent flow; 4) the erosion rate stabilization. It is evident that two last stages can be repeated in a series for each freshly exposed layer of eroded soil. The parameters of the flow velocity distribution curve may change in these series due to soil surface roughness variability. Flow turbulence can increase at the beginning of accelerated erosion stages, when the soil surface becomes more irregular, and decrease at the slow erosion stages of due to smoothing of the soil surface. Soil consolidation will decrease with the increase of the flow turbulence due to higher lever of dynamic influence of the drag and lift forces on soil aggregate stability. With the rapid removal of the weakened aggregates consolidation increases. This self-organising interconnection of eroding flow and eroded soil needs further investigations, which can be more useful by stochastic approach.

RESULTS AND DISCUSSION

The analytical form of (21) is rather complicated, and has to be solved numerically with a certain set of input data. A FORTRAN program (available from the author) was written for these calculations. The input data consisted of mean bed velocity U_m , mean soil cohesion C_0 , mean soil consolidation I_s , mean aggregate diameter D_m and its standard deviation σ_D . The hydraulic resistance coefficient λ , flow depth d , pore water pressure height z , aggregate density (with porosity) ρ_s also must be known. Numerical experiments were carried out to analyze the influence of these four stochastic factors on the detachment rate. A first-order non-central χ^2 distribution was used to describe a probability of square of velocity, a gamma distribution was used for soil cohesion, a lognormal distribution was used for aggregate size, and a beta-distribution was used to describe a probability of soil consolidation. The range of flow bed velocity was 0.1-2.0 m s⁻¹, the range of cohesion was 1-60 kPa, soil consolidation ranged from 0.1 to 0.9, aggregate mean size from 1 to 10 mm. Other parameters were constant: flow depth was 0.01 m, pore pressure height was 0.001 m, the hydraulic resistance coefficient was 0.01, aggregate density was 1600 kg m⁻³, and aggregate size standard deviation was $0.3D_m$.

The detachment rate increased with flow velocity (Fig. 2). This increase in erosion rate cannot be described with an often-used simple power function $D_r \sim U_m^n$. Theoretical calculations showed that in the relatively low velocities, the detachment rate increases more rapidly than in the relatively high velocities. A similar effect was described by Larionov (1993) and by Nearing et al. (1997) on the basis of observations of empirical soil erosion measurements. The current theory explains this phenomenon. The detachment rate increase is controlled by soil cohesion (Fig. 2a), by aggregate size (Fig. 2b) and, very significantly, by soil consolidation (Fig. 2c). Detachment rate increased more rapidly with flow velocity for more consolidated soil with high cohesion, large aggregates, and high soil consolidation. Decrease of soil consolidation and the aggregates size led to a decrease of the exponent in power law of detachment rate versus flow velocity.

Calculations also show great differences in the type of soil erosion in the relatively high and relatively low flow velocities. When flow velocities are relatively high and driving forces increase significantly over stabilizing forces, soil properties (cohesion, aggregate size, soil consolidation) are less important in determining the soil-erosion rate (Fig. 2). This implies that the time and space random variability of these factors, which always exist in natural conditions, will not lead to major changes in erosion rate. When flow velocities are relatively low and driving forces only slightly increase over stabilizing forces, soil properties are very important in determining soil erosion rates. Even the small time and space random variability of these properties may lead to significant changes in erosion rate.

To verify the theoretical results, two sets of data were

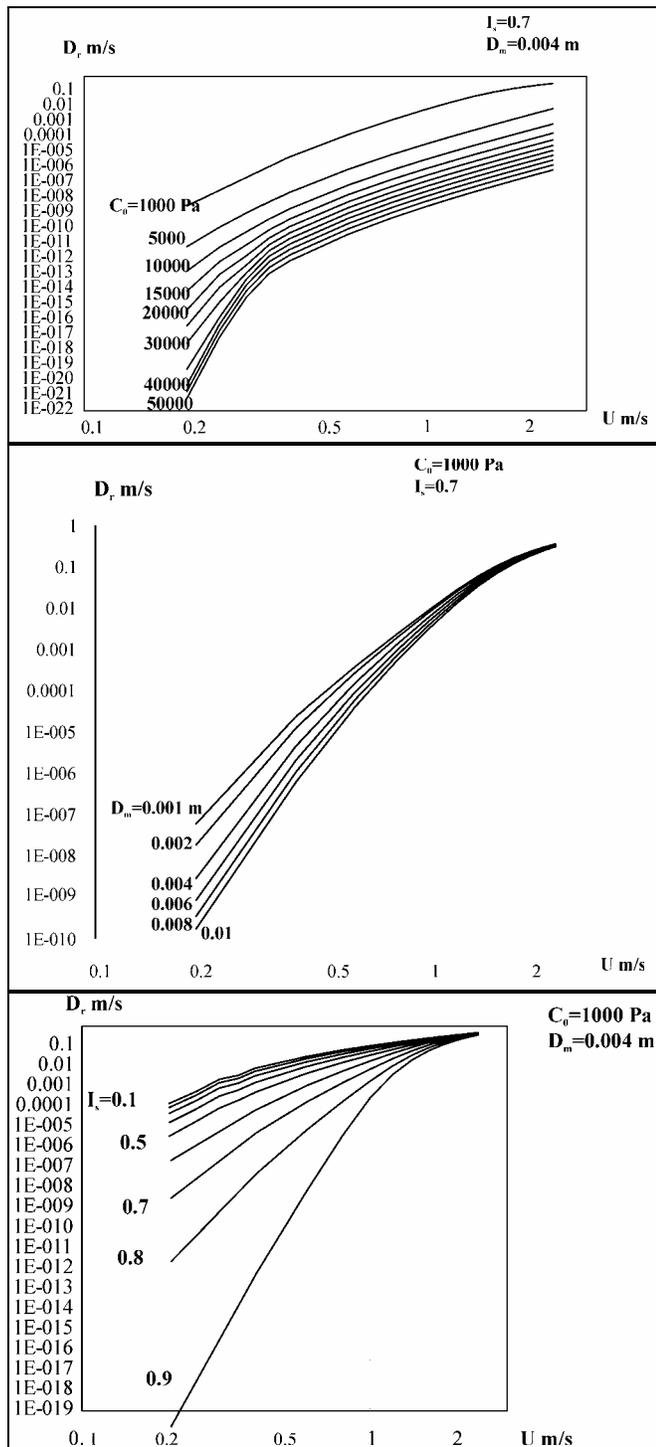


Figure 2. Influence of (a) soil cohesion C_0 , (b) aggregates size and (c) soil consolidation I_s on the relationship between detachment rate and flow velocity.

used: the laboratory measurements of Nearing et al. (1991) of the detachment rate for the Russell silt loam (fine-silty, mixed, mesic Typic Hapludalf) and Paulding clay (very-fine, illitic, nonacid, mesic Typic Haplaquept) in the USA, and the field measurements of the detachment rate for pebbly loam in Brook Creek gully, Australia (Sidorchuk,

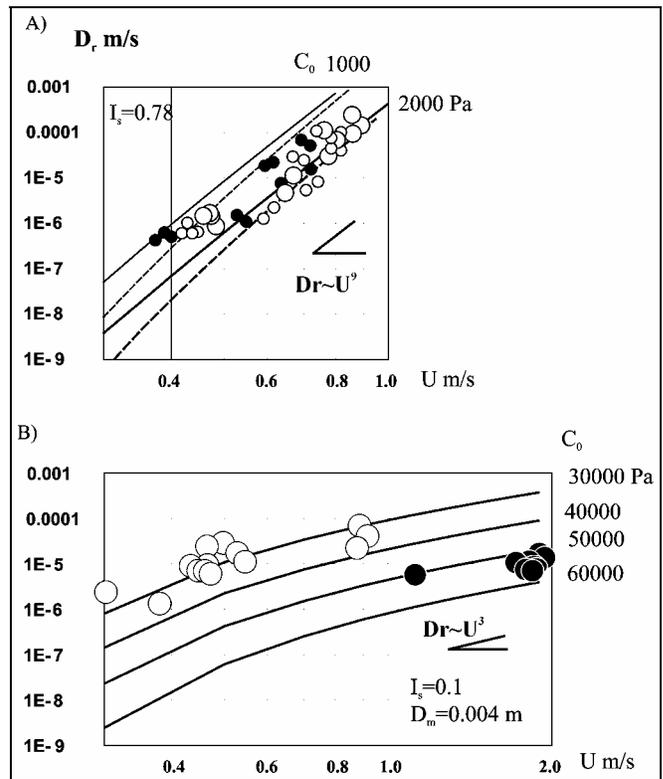


Figure 3. Comparison of calculated (lines) and measured (circles) rates of detachment of active soil aggregates in near bed layer for (A) laboratory experiments of Nearing et al. (1991) and (B) field experiments in Brook Creek gully (Sidorchuk, 1998). Different soil consolidation I_s causes different types of relationship between the detachment rate D_r (m/s) and near bed flow velocity U (m/s). The cohesion of Paulding and Russel soils in the laboratory varied from 1 kPa (thin lines, white circles) to 2 kPa (thick lines, black circles), the aggregate size varied from 0.47 mm (solid lines, small circles) to 2.07 mm (broken lines, large circles). The cohesion of soils in the Brook Creek gully varied from 20-30 kPa (white circles) to 50-60 kPa (black circles).

1998). The detachment rate, hydraulic flow parameters, soil cohesion and aggregate size were published for these experiments. Soil consolidation is unknown for both data sets. Optimisation calculations were performed to estimate unknown soil consolidation values. The same procedure of optimization was used by Wilson (1993b) for unknown parameters of similar type. A best fit of measured detachment rates in Nearing et al.'s (1991) experiments with calculated ones (Fig. 3a) was obtained for $(I_s)_{mean} = 0.78$. Although the soil cohesion was rather low (1-2 kPa), the consolidation of these soils was rather high. That led to very rapid changes of detachment rate with velocity: $D_r \sim U^{9-10}$. The influence of aggregates size was not so obvious. A best fit of measured detachment rates in natural conditions in Brook gully with calculated ones (Fig. 3b) was obtained for $(I_s)_{mean} = 0.1$. Although the soil cohesion was rather high (30-50 kPa), a consolidation of natural soils in the gully was low. That led to less exponent in the power law between detachment rate and velocity: $D_r \sim U^{2.5-3}$.

CONCLUSION

The stochastic method of detachment rate estimation was used in the gully erosion and thermoerosion model GULTEM. It is based on calculation of the probability of excess of driving forces above resistance forces in the flow that erode cohesive soil. The explicit relationships of the hydraulic characteristics of the flow (actual flow velocity, water depth, dynamic pressure) and the mechanical properties of the soil (cohesion and consolidation) with the soil aggregates detachment rate allow to give an explanation of a great difference in types of relationship between detachment rate and flow velocity (shear stress, stream power) for different soils. In high flow velocities, when driving forces increase significantly above stabilizing forces, the rate of erosion increase with flow velocity is relatively low. The influence of soil properties (cohesion, aggregate size, soil consolidation) variability is also less important in determining the soil erosion rate of high relative flow energy (Fig. 2). This may be the main reason for the greater predictive capability of existing soil erosion models for high-energy events. With low flow velocities and with driving forces only slightly increased above stabilizing forces, the erosion rates speedily increase with flow velocity. Soil property variability causes significant changes in soil erosion rates, and this influence grows with the increase of soil cohesion, consolidation and soil aggregates size. Even minor spatial and temporal random variability of these properties may lead to significant changes in erosion rate. This may be the reason why rather high errors in soil erosion calculations are found even with detailed physical based models for low erosion rates.

The explicit use of the main parameters that control calculations of erosion and thermoerosion (relief, water flow, soil mechanics, and vegetation cover) in GULTEM model allow the model to be used as a tool for establishing of soil conservation measures. Numerical experiments with the variable input can be used to choose the correct land conservation measures for catchments with high gully erosion potential. The stochastic component in the model gives the opportunity to take into account the spatial and temporal variability of the main erosion and soil conservation factors.

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