The Model for estimating of the Gully morphology.

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Abstract. The three-dimensional hydraulic model GULTEM to predict rapid changes of gully morphology at the first period of gully development is based on digital elevations model analysis and flowlines choice; calculations of runoff due to snowmelt or rainfall; solution of the equations of mass conservation and gully bed deformation for different types of soil (including frozen soil). The model of straight slope stability was used for prediction of gully's side walls inclination. The model was verified on the data of gully's morphology and dynamics at Yamal peninsula (north of the Western Siberia, Russia).
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Introduction

The significance of gully erosion has been well documented. The volume of the gullies on the Russian Plain is about 4 10^9 m^3, i.e. about 4 per cent of the whole volume of erosion since 1700 AD (Sidorchuk, 1995). In Australia with mainly pasture land the volume of gully erosion amounts to 14 10^9 m^3 (Wasson et al., 1996). At the Western Europe the part of ephemeral gully erosion can measure up to 30-40% of the whole volume of erosion (Poesen et al., 1996). The gullies destroy completely the fertile topsoil layer, and the surrounding lands are damaged with more severe sheet and rill erosion.

One of the main places of the recent intensive anthropogenic gully erosion is Yamal peninsula at the areas of gas fields exploitation. The rates of gullies grows are 20-30 and up to 200 m $year^{-1}$ (Sidorchuk, 1996). These gullies cause real danger for constructions and gas transportation facilities, their activity can led to regional ecological catastrophe. Notwithstanding with the importance of gully erosion prediction the number of gully erosion models is surprisingly low. There are several models to predict stable gully morphology (Zorina, 1979, Mirtskhulava, 1988), the conditions of ephemeral gully initiation (Poesen and Govards, 1990), the rate of gully head grows (Trofimov, Moskovkin, 1983, US SCS,1966), gully longitudinal profile transformation (Sidorchuk, 1996).

The posed three-dimensional hydraulic gully erosion model was developed for the first stage of gully evolution. At this stage the erosion (and thermoerosion at the areas with permafrost) is predominant at the gully bottom and rapid mass movement occurs on the gully sides. Gully channel formation is very intensive and morphological characteristics of the gully (length, depth, width, area, volume) are far from stable and rapidly change. At the marine terraces of Yamal peninsula, composed from frozen loams and sands, this stage lasts 4-10 years and anthropogenic gullies cut the terrain to their whole length.

The main application of any soil erosion model is the system of soil conservation measures. At the most cases of sheet and rill erosion those are methods to conserve erosion-prone agricultural lands. At the case of gully erosion not only agricultural lands can be destroyed, but also buildings and constructions can be damaged. The system of models for gully morphology prediction and land conservation for the latter case include three main branches: 1) modelling of gully erosion; 2) estimation of optimal interrelations between erosion forms and constructions; 3) gully erosion conservation methods (fig.1). The main purpose of the proposed system is to choose the sequence of soil conservation methods, which can reduce gully erosion down to the level, optimal for buildings and constructions stability.

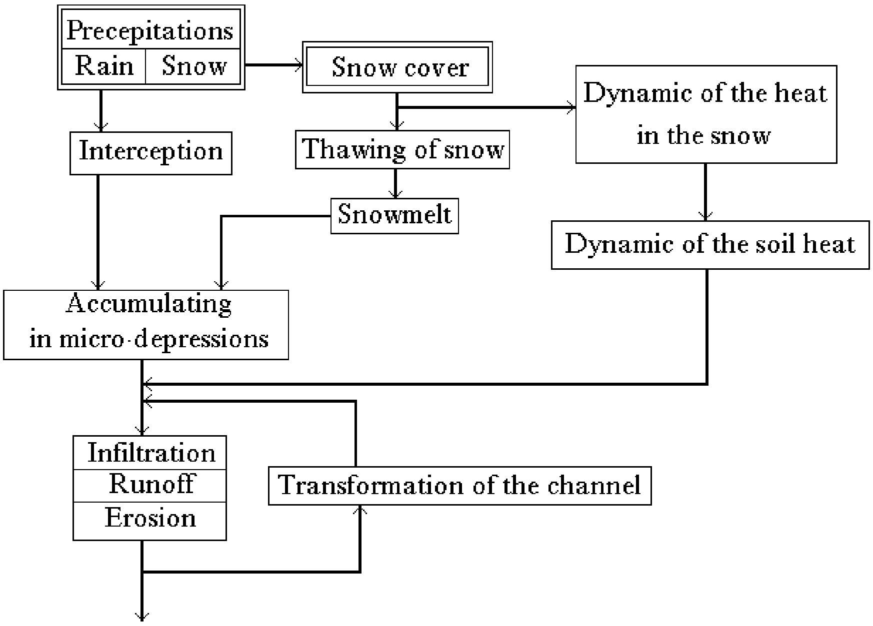


Fig.1. System of models of gully morphology prediction and land conservation.

Modelling of the gully erosion

At the first, quick stage of gully development the following main processes occur:

a) During the snowmelt or rainstorm event the flowing water erodes a rectangular channel in the topsoil or at the gully bottom.

b) The vertical walls of this trench can be unstable. Shallow landslides transform a rectangular gully cross - section shape to trapezoidal along the period between adjacent water flow events.

The rate of gully incision is controlled by water flow velocity, depth, turbulence, temperature, and by soil texture, soil mechanical pattern, level of protection by vegetation. These characteristics are combined in equations of mass conservation and deformation

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

$$\left(1-\varepsilon\right) W \frac{\partial Z}{\partial t} = -\frac{\partial Q_s}{\partial X} + M_b D + C_w q_w \qquad (2)$$

Here Q_s = Q C 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; C_w- sediment concentration of the lateral input; q_w- specific lateral discharge(m^2/s); M_0 = upward sediment flux (m/s); M_b = sediment flux from the channel banks (m/s); Z=gully bottom elevations (m); W = flow width (m); D = flow depth (m); V_f = sediment particles fall velocity in the turbulent flow (m/s), ε= soil porosity.

The analysis of the experiment results in the gullies of Yamal shows, that in the conditions of steep slopes and cohesive soils, common for gullies, the rate of soil particles detachment (upward sediment flux) is linearly correlated with the product of bed shear stress $\tau = g\rho DS$ and mean flow velocity U:

$$M_0 = kU \frac{\tau}{\tau_{cr}} \qquad (3).$$

Here S is gully bottom slope, g is acceleration due to gravity. Experiments show, that for loam and clay with the cohesion 20-40 kPa the erosion coefficient k equals to 1.9 10^{-6}. Mirtskhulava (1988) showed, that critical shear stress τ_{cr} is controlled by the forces of friction and cohesion:

$$\tau_{cr} = 0.06\left(d/D\right)^{1/3}\left[\left(\rho_s - \rho\right)gd + 0.62C_f^n\right] \qquad (4).$$

Here ρ_s and ρ are sediment and water density (kg/m^3); d is mean diameter of soil aggregates (m). C_f^n is soil fatigue strength to rupture and it is the function of soil cohesion C_h (Pa): $C_f^n = 6.7*10^{-7} C_h^2$ after our experiments, or $C_f^n = 0.035 C_h$ after Mirtskhulava (1988).

One of the sufficient factors of soil cohesion is the content of grass roots in the soil. Thin (less that 1 mm in diameter) living and dead roots penetrate into the soil aggregates, gather them to each other and increase the soil cohesion. The field and laboratory experiments show, that the bulk soil cohesion C_h increases rapidly with the content of thin roots R (kg m^{-3}) in top 5 centimetres of the soil:

$$C_h = C_0 \exp(0.05R) \quad (5).$$

Here C_0 is cohesion of the same soil, but without vegetation roots.

For the case of gully erosion in the soil with permafrost (so called thermoerosion) water temperature becomes the main factor of erosion. Field and laboratory experiments of Poznanin (1969) showed, that as first approximation the soil detachment rate is equal to the rate of soil thawing and linearly related with water temperature T°C:

$$M_{0t} = k_{te} \mathrm{T} \quad (6).$$

The coefficient of thermoerosion k_{te} value is about 5.2 10^{-5} for thin sands and 0.55 10^{-5} for loams, but its variability is rather high due to changes in soil cryogenic texture and ice content (Sidorchuk, 1996).

If bed shear stress in the flow is less than its critical value for erosion initiation τ_{cr} , then M_0 and M_{0t}=0.

The side walls of the gully become practically straight after rapid sliding, following the incision. In this case a model of straight slope stability can be used for prediction of gully sides inclination. If the depth of incision D_v becomes more than critical value

$$D_{vcr} = \frac{2.0C_h}{g\rho_s}\cos(\varphi)\Big/\sin^2\frac{1}{2}\left(\varphi+\frac{\pi}{2}\right) \quad (7),$$

then gully walls inclination ϕ can be calculated with the help of the formula:

$$\frac{C_h}{g\rho_s D_v} = \frac{\rho_s - w\rho}{\rho}\tan(\varphi)\cos^2(\phi) - \frac{\sin(2\phi)}{2} \qquad (8).$$

Here w is volumetric water content in the soil, φ is the angle of internal friction.

When the bottom width, wall inclination and whole volume of incision V_0 are known, the shape of the gully cross-section can be transformed into a trapezium with bottom width W_b, depth $D_t = \left(\sqrt{W_b^2 + \frac{4V_0}{\tan(\phi)}} - W_b\right)\frac{\tan(\phi)}{2}$ and top width $W_t = W_b + \frac{2.0D_t}{\tan(\phi)}$.

Input data for GULTEM and the models for their preparation

The input information to run GULTEM consists of data, obtained from terrain topography and lithological composition (digital elevation models and soil mechanics parameters), from vegetation cover features and meteorological measurements.

DEM analysis

DEMs were used for elevations, flowlines directions and gradients, catchment areas evaluation. The contour lines from topographical and lithological maps were scanned to raster image and then vectored with “EASY TRACE” tracer program. Altitudes on equal-distance grid were evaluated with SURFER procedures. The interactive procedure was elaborated for filling or linking of closed depressions, originated from the errors of interpolation of initial relief. The algorithm choosing one of eight possible directions of flow with maximum gradient was used for flow path estimation. The ability to set the preferable direction was provided to estimate influence of out-of-scale features like small roads or ploughing up. The terrain gradient in a point with account of a pixel shape was calculated from two elevations in operating point and in one of neighbour point as possible maximum gradient. The catchment area of any point was calculated as sum of pixel areas of all flowlines, linked to this point above it.

The elevations of top surface were estimated from DEMs for each lithologicaly similar layer and the main parameters of soil mechanics were evaluated from direct measurements or tables.

Runoff calculations

Main processes that must be taken into account in surface runoff calculations are:

1. Precipitation in form of snow or rainfall.
2. Interception of water by crops and natural vegetation.
3. Dynamics of the heat in the snow, thawing of snow and melt water output.
4. Water storage in micro-depressions and on the vegetation.
5. Infiltration

<u>Snow thawing.</u>

The melting of snow was described by Palagyn (1981). The melt water from upper snow layers enters the lower layers and freezes with emission of the heat. This process increases the snow temperature up to 0^oC. During some period there are two layers in the snow cover: upper one with the stored water and temperature equal to 0^oC and lower cold and dry layer. The further income of water results in decreasing of lower layer depth and increasing of snow-water ratio. Runoff occurs when snow-water ratio becomes more than critical water-retaining capacity of snow (about 15% of dry snow mass). In the conditions of low winter temperatures and formation of a deep permafrost layer the infiltration of the water into soil is very low.

The rate of snow thawing m (m/s) can be calculated by formula of the heat budget (Kuz'min, 1961):

$$m = \frac{10}{L} \cdot \int_{t_s}^{t_f} S(W_r - W_t - W_i - W_s - W_h)dt \qquad (9)$$

Here W_r is heat flux from sun radiation, W_t is the turbulent heat flux; W_i is the heat flux due to evaporation, W_h is heat flux, spend on change of the snow cover temperature and W_s is heat exchange with the soil (J s^{-1} m^{-2}), L is the latent heat of the ice melting, S is the part of surface, covered by snow, %, t_s is beginning of thawing and t_f is end of thawing. The components are calculated with formulas of Kuz'min (1961).

The evaporation E_v (m/s) during the snow thawing is calculated as

$$E_v = \delta\rho K_0{}^2 \frac{u_1}{\ln\frac{z_1}{z_0}} \frac{e_2 - e_0}{\ln\frac{z_2}{z_0}} \qquad (10).$$

Here ρ is the density of the air, $K_0 = 0.38$ is aerodynamic constant, e_2 is humidity of the air at the level z_2 above the snow surface, e_s is maximal steam resiliency at the temperature of the snow surface, z_0 is height of roughness of the snow surface, δ is the coefficient depending to the measure units, u_1 is wind velocity at the level z_1 above the snow surface.

The water flow from the snow cover m_1 can be calculated with the formula (Appolov *et al.*, 1960)

$$m_1 = \left(\frac{m}{1-\alpha} + x - Ev\right) \cdot S \qquad (11)$$

Here α is snow moisture, corresponding to m at the present snow structure, and x is rainfall depth. It is assumed that the waterflow beginning coincides with the moment when the snow moisture riches it's water-retaining capacity.

Runoff during the rainfall.

The infiltration into the soil can be described by the following equation:

$$\rho_w \frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}\left(D_0 \frac{\partial \Theta}{\partial z} - K \right) \qquad (12)$$

Here Θ is volumetric water content, $\rho_w \frac{\partial \Theta}{\partial t}$ is a moisture flow, ρ_w is water density, K is hydraulic conductivity of soil, K_Θ is effective saturated hydraulic conductivity, z is the vertical co-ordinate, $D_0 = K_\Theta \frac{\partial \psi}{\partial \Theta}$ is coefficient of capillary diffusion, ψ is the soil moisture potential. The equation (12) can be solved numerically with the aim of scheme suggested by Vershinina *et al.* (1985). The dependencies $\psi=\psi(\Theta)$ and $K_\Theta = K_\Theta(\Theta)$ can be calculated by formula (Budagovsky, 1952):

$$K_w(\Theta) = K\left(\frac{\Theta - \Theta_{wt}}{\Theta_{\max} - \Theta_{wt}} \right)^4 \qquad (13),$$

(here Θ_{wt} is withering moisture, Θ_{max} is critical moisture), and by formula of Kaluzhny & Pavlova (1981)

$$\psi = 10220 \exp\left(-3.58 \frac{\Theta - \Theta_{wt}}{\Theta_{\min} - \Theta_{wt}} \right) \qquad (14),$$

(here Θ_{min} is minimal moisture).

The infiltration rate (m/s).is calculated as

$$I = \int_0^H \frac{\partial \Theta}{\partial t} dz \qquad (15),$$

where H is the lower boundary with constant moisture.

Water storage in micro-depressions and on the vegetation

The depth of the water stored in micro-depressions H_0 can be calculated by formula of Popov (1963)

$$H_0 = D'\left(1 - \exp\left(-\frac{H_q}{D_M'}\right)\right) \quad (16).$$

Here H_q is the depth of the flow, D′ is available volume of storage, and D'_M is maximal storage. D′ is calculated from the following equation: $D' = \min\begin{cases} D' - H_0 + H'_{ef} \\ D'_M \end{cases}$, where H'_{ef} is the depth of infiltration and evaporation from pools.

Water loss on the crops and natural vegetation P is calculated by formulas

$$D_p = P_M - H_p,$$

$$P = D_p\left(1 - \exp\left(-\frac{H}{P_M}\right)\right) \qquad (17),$$

$$H_p = P - E_p.$$

Here D_p is deficit of moisture on the plants, P_M is maximal water-retaining capacity of plant cover, E_p is the depth of evaporation from wet plants, H is the depth of rainfall.

Runoff

The runoff is described by the equation of the kinematic wave together with formula of Manning, solved on the net of the flowlines.

$$\begin{cases} \dfrac{\partial A}{\partial t} + \dfrac{\partial Q}{\partial x} = (R - I - H_0 - P)W \\ v = \dfrac{\sqrt{S}}{n} D^{\frac{2}{3}} \end{cases} \qquad (18).$$

Here A is the channel cross-section area, R - rainfall, S is the channel slope, n is Manning’s roughness coefficient.

The width and depth of the flow in gullies can be calculated with the empirical formulas:

$$W = 3.0 * Q^{0.4} \quad (19)$$

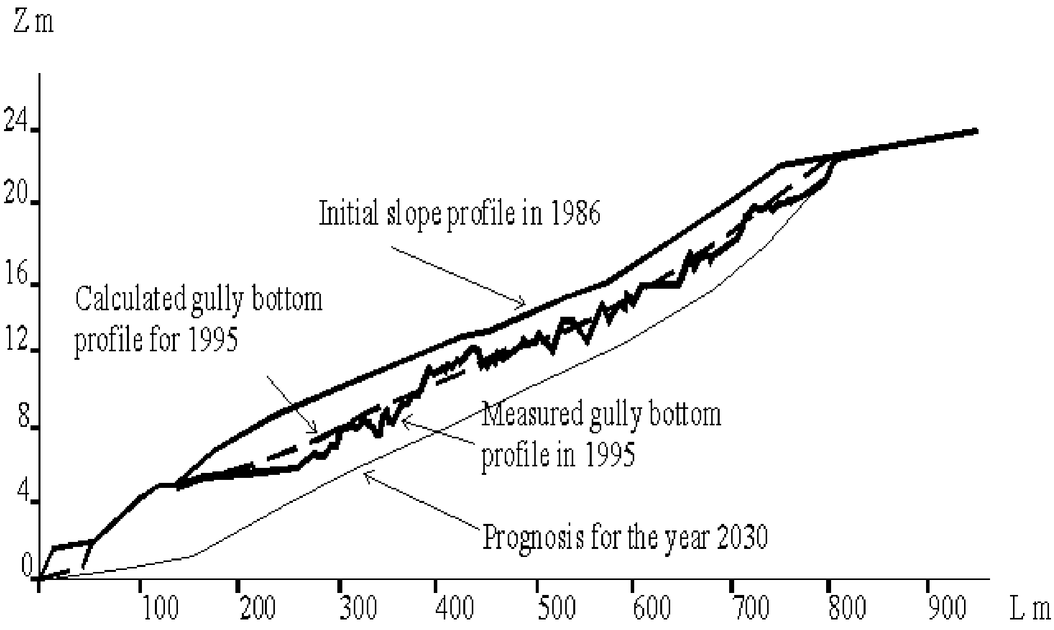
and

$$D = 0.48 Q^{0.45} \quad (20)$$

based on data from Yamal peninsula.

Results of the gully erosion model verification.

The gully themoerosion and erosion model was verified using data about gullies development on the Yamal Peninsula, in the conditions of deep permafrost, snowmelting and rainfall. One of these gullies (N 9), for which both initial and actual longitudinal profiles are available, is situated at the right bank of Se-Yakha River. Before 1986 there was shallow linear depression with dense vegetation cover and ephemeral flow. In 1986 the exploitation camp was built at the top of the basin. Surface destruction and increase of melt water flow lead to intensive gully erosion. The gully 840 m long (measured along the gully valley) was formed. In 1991 and 1995 the longitudinal profile of gully was investigated. The initial profile was available from the large scale map. The depths of runoff for thaw and rainfall periods for 1986-1995 were calculated on the base of Marre Salye station meteorological data. The coefficients k in formula (3) and k_{te} in formula (6) were calibrated with the data of 1986 - 1991 period. The calculated and observed altitudes of the gully bottom in 1995 are rather close (fig.2). The solution is mainly controlled by the value of τ_{cr}, which is function of the soil aggregates size, soil cohesion and vegetation cover density. The next important factor is water discharge.



. Dynamic gully erosion model verification: case study of longitudinal profile evolution and prediction for the gully on the Yamal Peninsula (Russia)

Fig.2 Gully erosion model verification: case study of longitudinal profile evolution and prediction for the gully N 9 on the Yamal peninsula (Russia).

Land conservation in the conditions of the gully thermoerosion and erosion in permafrost.

The main methods for soil and water conservation have been designed for the Temperate Zone, and there is no experience of their application in the conditions of continuous permafrost. Several methods to stop gully growth were used on the territory of Bovanenkovskoye gas field of the west central Yamal peninsula. The check dam was constructed at the head of gully N 9, but a new gully head had passed around the check dam in 1995. The erosion cut was filled with sediments from gully sides by bulldozer, but every year it was renewed by gully erosion. Several wall cuts in gully N 9 were covered by technical textiles. Cuts with small subcatchments were stabilised, but in most of them the cover was destroyed by erosion that took place around the covers.

These cases highlight, that human developmental activities in the arctic tundra, accompanied by deterioration of the vegetation and an increase of runoff causes intensive erosion. This is due to low permafrost permeability, high runoff, high erodibility of bare soils with high ice content, and low slope stability. For existing gullied basins, it is very difficult to stop erosion and thermoerosion. To minimise it several methods can be tried: mechanical removal of the snow from gully catchments; vertical drainage of industrial and rainfall waters; covering of disturbed slopes with a peat layer; filling of the gullies with heavy loam and a peat cover; recultivation of vegetation cover.

All these measures led to water discharge decrease and critical shear stress of erosion initiation increase. As GULTEM include these parameters, the effectiveness of land conservation measures can be checked by the numerical experiments.

The main results of these experiments are shown at fig.3. In the conditions of full vegetation cover deterioration on the territory of exploitation camp and of snowmelt volume increase due to snow storage near buildings (contemporary situation) the gully heads will reach the centre of the camp and most constructions will be disturbed (fig. 3b). To stop gully erosion (fig. 3a) all the snow have to be removed from the camp territory at the end of the winter or the quality of the vegetation cover have to be high enough to provide the density of thin root not less than 23 kg m^{-3} for clays, 35 for loam and 47 for loamy sands.

Conclusion

The gully thermoerosion and erosion model GULTEM describes the first, quick stage of gully development, which is coincided with the main changes in gully morphology.

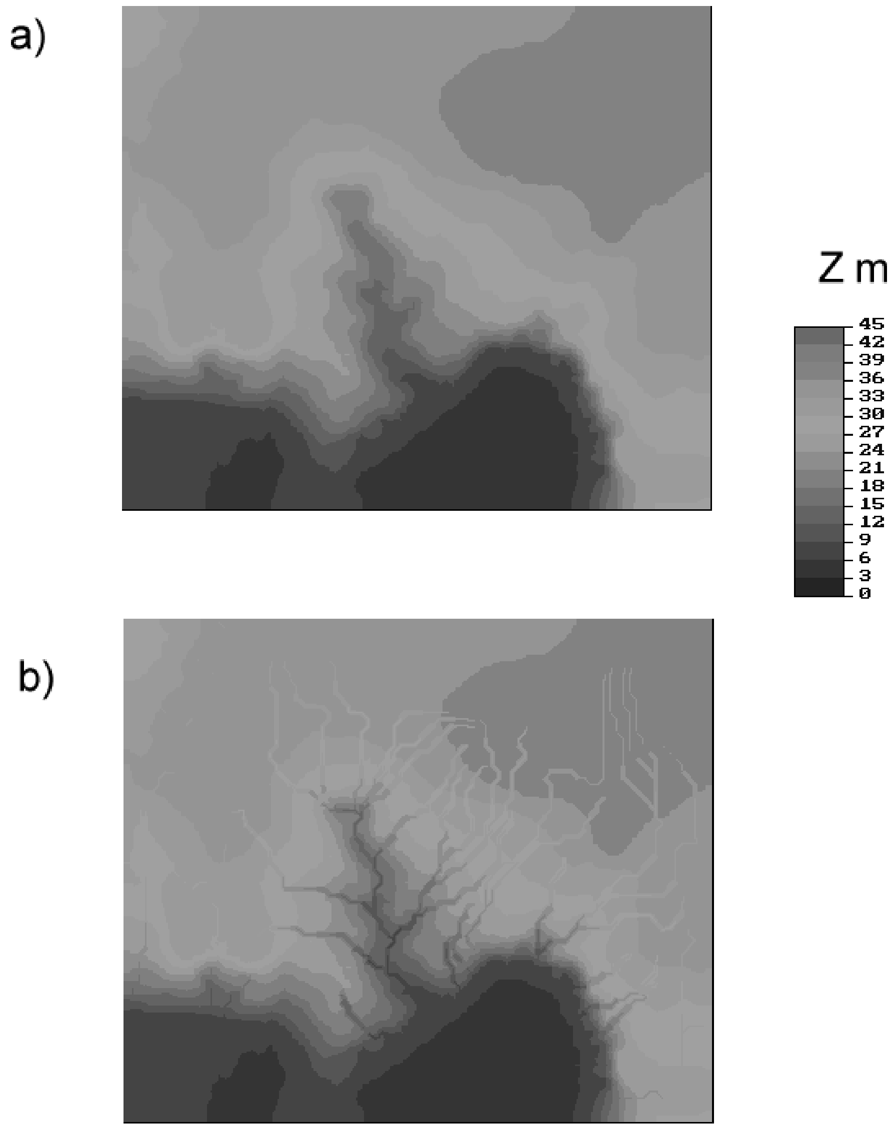


Fig.3 Effect of land conservation on gully erosion. a) Initial terrain in 1986 before exploitation camp building and in the condition of thaw water drainage or vegetation cover recultivation.; b) gully growth in the condition of thaw water increase and vegetation cover deterioration.

During the snowmelt or rainstorm event the flowing water erodes a rectangular channel in the topsoil or at the gully bottom. At the period between water flow events shallow landslides transform quickly gully cross - section shape to trapezoidal. Numerical experiments show, that the model in whole describes the real process of gully longitudinal and cross-section profiles evolution in time and space. It is sensitive to change of the soil erodibility, so field investigations and careful calibration of the model are necessary for accurate prediction of gully erosion.

The GULTEM was realised on the net of flowlines, evaluated from topographical DEM. The multy-layered soil texture (including top layer with the vegetation cover) was derived from DEMs of the top surfaces of each layer with similar lithology. The runoff due to snowmelt and rainfall was calculated from meteorological information with physical-based hydrological models.

The main parameters, which control calculations of erosion and thermoerosion with GULTEM, corresponds to the main arguments of soil conservation measures. The numerical experiments provided with the model can be used to choose the system of land conservation measures and to stabilise buildings and constructions on the catchments with high gully erosion potential.

References

Apollov, B.A., Kalinin, G.P., Komarov, V.D. (1960) Gidrologicheskie prognozy (Hydrological prognosis). Gidrometeoizdat, Leningrad, 506 p (in Russian).

Budagovskiy, A.I. (1952) Issledovaniye protsessov infiltratsii vody v pochvu (Investigation of the water infiltration into the soil). PhD Thesis, Moscow, 20 p.

Graham, O.P. (1988). Land Degradation Survey of N.S.W. Soil Conservation Service of N.S.W. Tech.Rep. 7, 47 p.

Kaluzhny, I.L. & Pavlova, K.K.(1981) Formirovanie poter’ talogo stoka (Thaw water losses formation).Gidrometeoizdat, Leningrad, 160 p.(in Russian).

Kuz’min P.P. (1961) Process tayaniya snezhnogo pokrova (The process of snow cover thawing). Gidrometeoizdat, Leningrad, 345 p. (in Russian).

Mirtskhulava, Ts.Ye. (1988). Osnovy fiziki i mekhaniki erozii rusel (Principles of Physics and Mechanics of Channel Erosion). Leningrad, Gidrometeoizdat, 303 p. (in Russian). Motovilov Yu. G.(1980) Raschet osnovnoi gidrologicheskoi khakteristiki pochv po dannym o pochvenno-gidrologicheskikh konstantakh (Calculation of the basic hydrophysical soil characteristic from data of soil-hydrological constants). *Meteorologia i Gidrologia* **12**, 93-101. (in Russian).

Poesen J. and G. Govers. (1990) Gully Erosion in the loam belt of Belgium: Typology and Control Measures. In J.Boardman, I.D.L. Foster and J.A.Dearing (eds). Soil Erosion on Agricultural Land. J.Wiley and Sons, pp. 513-530

Poesen J., Vandaele K., van Wesemael B. (1996) Contribution of gully erosion to sediment production on cultivated lands and rangelands. In: Walling D, Webb B. (ed). *Erosion and Sediment Yield: Global and Regional Perspectives*. IAHS Publ. N 236, pp.251-266.

Palagyn E.G. (1981) Matematicheskoe modelirovanie agrometeorologicheskykh uslovyi perezimovki ozimykh kultur.(Matematical modellind of agrometeorologyc conditions of winter crops wintering). Gidrometeoizdat, Leningrad, 191 p. (in Russian).

Popov, Ye.,G. (1956) Analiz formirovaniya stoka ravninnykh rek (Analysis of river flow formation). Leningrad, Gidrometeoizdat, 132 p. (in Russian).

Poznanin V.L. (1989) L’distost’ grountov i ee vliyanie na termoeroziyu (The ground ice content and its influence on the thermoerosion process). In: *Materialy* *glyatsiologicheskikh issledovaniy (Materials of glaciologic research),* v.59,p.11-31 (in Russian).

Sidorchuk, A.Yu. (1995) Erozionno-akkumulyativnyye protsessy na Russkoy pavnine i problemy zaileniya malykh rek (Erosion-sedimentation processes on the Russian Plain and the problem of aggradation in the small rivers). In: *Vodokhozyaistvennyye problemy ruslovedeniya (Water Resources Management and Problems of Fluvial Science).* Moscow, Izd AVN, 74-83 pp. (in Russian).

Sidorchuk A. (1996) Gully Erosion and Thermoerosion on the Yamal Peninsula. In: O.Slaymaker ed. *Geomorphic Hazards*, J.Wiley and Sons, pp. 153-168.

Trofimov, A.M., Moskovkin, V.M. (1983) Matematicheskoye modelirovaniye v geomorfologii sklonov (Mathematical modelling in geomorfhology of slopes). Kazan, Izd. Kazan Univ., 213 p.

US Soil Conservation Service (1966) Procedures for Determing Rates of Land Damage, Land Depreciation and Volume of Sediment Produced by Gully Erosion. Tech. Release N 32, USDA, Washington, 27 pp.

Vershinina L.K., Krestovsky O.I., Kaluzhny I.L. & Pavlova K.K.(1985) Otsenka poter' talykh vod i prognozy ob'ema stoka polovodya (Thaw water losses estimation and water yeild during flads). Gidrometeoizdat, Leningrad, 189 p. (in Russian).

Wasson R.J., Olive L.J., Rosewell C.J. (1996) Rates of erosion and sediment transport in Australia. In: Walling D, Webb B. (ed). *Erosion and Sediment Yield: Global and Regional Perspectives*. IAHS Publ. N 236, p.139-148.

Zorina Ye.F.(1979). Raschetnyye metody opredeleniya potentsiala ovrazhnoy erozii (Methods of gully erosion potential calculating). In R.S. Chalov (ed), *Eroziya pochv i ruslovyye protsessy (Soil erosion and channel processes),* v.7, Moscow Univ.Press, pp 81-90. (in Russian)