Model for estimating gully morphology

ALEKSEY SIDORCHUK

Laboratory of Soil Erosion and Fluvial Processes, Geographical Faculty, State University of Moscow, Moscow 119899, Russia

ANNA SIDORCHUK

Department of Statistics, Faculty of Applied Mathematics, State University of Moscow, Moscow 119899, Russia

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 a choice of flow lines; 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 the inclination of the side walls of a gully. The model was verified on data of a gully's morphology and dynamics at the Yamal Peninsula (north of Western Siberia, Russia).

INTRODUCTION

The significance of gully erosion has been well documented. The volume of gullies on the Russian Plain is about 4×10^9 m^3, i.e. about 4% of the whole volume of erosion since 1700 AD (Sidorchuk, 1995). In Australia where the land use is mainly pasture the gully erosion amounts to 14×10^9 t year^{-1} (Wasson *et al.*, 1996). In Western Europe ephemeral gully erosion can account for up to 40–80% of the whole volume of erosion (Poesen *et al.*, 1996). Gullies completely destroy the fertile topsoil layer, and the surrounding lands are damaged by severe sheet and rill erosion.

One of the main places of recent intensive anthropogenic gully erosion is the Yamal Peninsula in areas of gas field exploitation. The rates of gullies grows by 20–30 and up to 200 m year^{-1} (Sidorchuk, 1996). These gullies are a real danger for construction and gas transportation facilities their presence can result in a regional ecological catastrophe.

Notwithstanding the importance of predicting gully erosion 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 & Govards, 1990), the rate of gully head growth (Trofimov & Moskovkin, 1983; US Soil Conservation Service, 1966), and gully longitudinal profile transformation (Sidorchuk, 1996).

The proposed three-dimensional hydraulic gully erosion model was developed for the first stage of gully development. At this stage the erosion (and thermo-erosion in areas with permafrost) is predominant at the bottom of the gully 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 change rapidly. On the marine terraces of the Yamal Peninsula, composed of frozen loams and sands, this stage lasts 4–10 years and anthropogenic gullies cut the terrain for their whole length.

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

MODELLING GULLY EROSION

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

(a) Flowing water during a snowmelt or rainstorm event 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 to a trapezoidal cross-section in the period between water flow events.

The rate of gully incision is controlled by water flow velocity, depth, turbulence, temperature and by soil texture, soil mechanical pattern and level of protection by

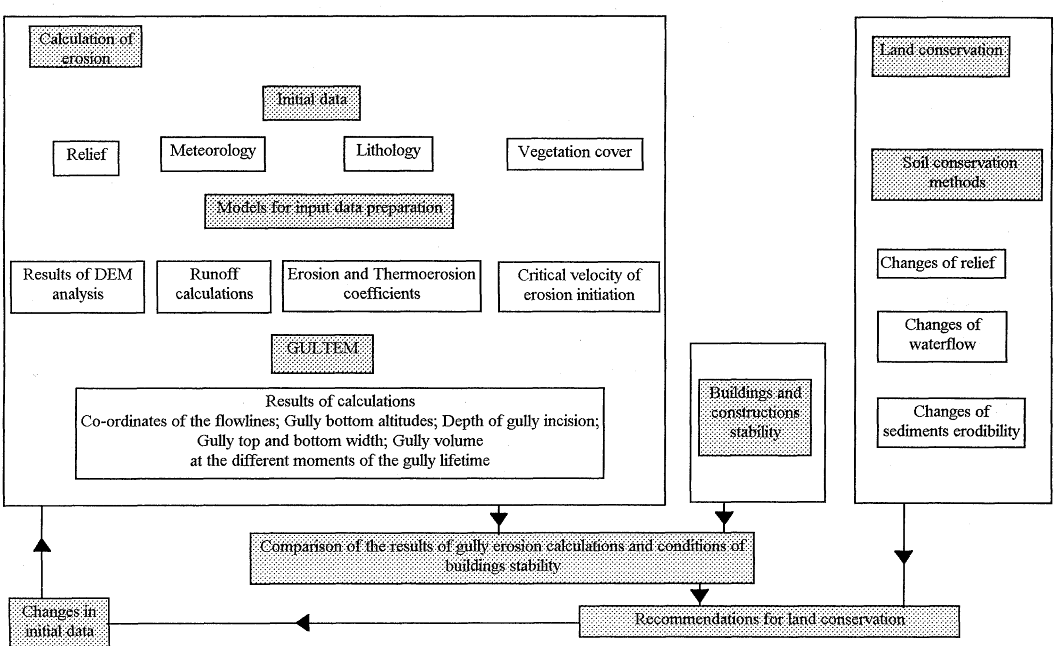

Fig. 1 System of models of gully morphology prediction and land conservation.

vegetation. These characteristics are combined in the equations of mass conservation and deformation:

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

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

Here $Q_s = Q\ C$ is sediment discharge ($m^3\ s^{-1}$), Q = water discharge ($m^3\ s^{-1}$); X = longitudinal coordinate (m); t = time (s); C = mean volumetric sediment concentration; C_w = sediment concentration from the lateral input; q_w = specific lateral discharge ($m^2\ s^{-1}$); M_0 = upward sediment flux (m s^{-1}); M_b = sediment flux from the channel banks (m s^{-1}); Z = gully bottom elevations (m); W = flow width (m); D = flow depth (m); V_f = sediment particle fall velocity in the turbulent flow (m s^{-1}), ε = soil porosity.

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

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

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:

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

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 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 significant 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, mesh with 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 the top 5 cm 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 a soil with permafrost (so called thermo-erosion) water temperature becomes the main factor of erosion. Field and laboratory experiments of Poznanin (1989) showed that as a first approximation the soil detachment rate is equal to the rate of soil thawing and linearly related with water temperature T°C:

$$M_{0t} = k_{te}T \tag{6}$$

The value of the coefficient of thermo-erosion k_{te} is about 5.2×10^{-5} for thin sands and 0.55×10^{-5} for loams but it is highly variable due to changes in the 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 predicting the inclination of the gully sides. If the depth of incision D_v becomes greater than the critical value

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

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

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

Here w is volumetric water content in the soil and 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 information and meteorological measurements.

DEM analysis

DEMs were used for elevations, flow-line directions and gradients and catchment area evaluation. The contour lines from topographical and lithological maps were scanned to raster image and then vectored with the "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, originating 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 preferred direction was provided to estimate the influence of out-of-scale features like small roads or ploughing up. The terrain gradient at a point, taking account of a pixel shape, was calculated from two elevations at the operating point and one from neighbour point as the possible maximum gradient. The catchment area of any point was calculated as the sum of pixel areas of all flow lines, linked to the point above it.

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

Runoff calculations

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

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

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

The rate of snow thawing m (m s^{-1}) can be calculated by formula of the heat budget (Kuz'min, 1961):

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

Here W_r is heat flux from solar 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 melting ice, 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 formulae of Kuz'min (1961).

The evaporation E_v (m s^{-1}) during the snow thawing is calculated as:

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

Here ρ is the density of air, $K_0 = 0.38$ is the aerodynamic constant, e_2 is humidity of the air at height 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 on the measurement units, u_1 is wind velocity at height z_1 above the snow surface.

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

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

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

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

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

Here Θ is volumetric water content, $\rho_w(\partial\Theta/\partial t)$ is moisture flow, ρ_w is water density, K is hydraulic conductivity of soil, K_Θ is effective saturated hydraulic conductivity, z is the vertical coordinate, $D_0 = K_\Theta(\partial\psi/\partial\Theta)$ is the coefficient of capillary diffusion, ψ is the soil moisture potential. 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 the formula (Budagovskiy, 1952):

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

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

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

(here Θ_{min} is minimal moisture).

The infiltration rate (m s^{-1}) is calculated as

$$I = \int_0^H \frac{\partial \Theta}{\partial t} \mathrm{d} z \tag{15}$$

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 the formula of Popov (1956):

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

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 from the crops and natural vegetation P is calculated by the formulae:

$$D_p = P_M - H_p$$

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

$$H_p = P - E_p$$

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 Runoff is described by the equation of the kinematic wave together with the formula of Manning, solved on the network of flow lines.

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

Here A is the channel cross-section area, R is 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 formulae:

$$W = 3.0 * Q^{0.4} \tag{19}$$

and

$$D = 0.48 Q^{0.45} \tag{20}$$

based on data from the Yamal Peninsula.

VERIFICATION OF THE GULLY EROSION MODEL

The gully thermo-erosion and erosion model was verified using data about gully

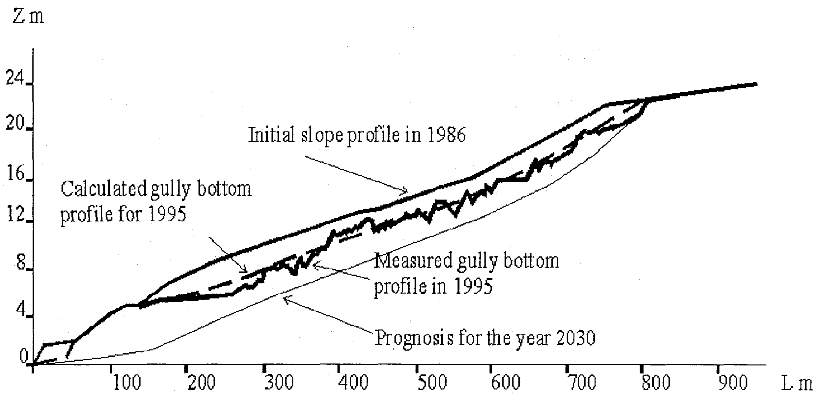

Fig. 2 Gully erosion model verification: case study of longitudinal profile evolution and prediction for the gully N9 on the Yamal Peninsula (Russia).

development on the Yamal Peninsula, in conditions of deep permafrost, snowmelting and rainfall. One of these gullies (N9), for which both initial and actual longitudinal profiles are available, is situated at the right-hand bank of Se-Yakha River. Before 1986 there was a shallow linear depression with dense vegetation cover and ephemeral flow. In 1986 an exploration camp was built at the top of the basin. Surface destruction and increase of meltwater flow lead to intensive gully erosion. A gully of 840 m in length (measured along the gully valley) was formed. In 1991 and 1995 the longitudinal profile of the 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 basis of meteorological data from the Marre Salye station. The coefficients k in formula (3) and k_{te} in formula (6) were calibrated with data from the 1986–1991 period. The calculated and observed altitudes of the gully bottom in 1995 are close (Fig. 2). The solution is mainly controlled by the value of τ_{cr}, which is a function of the soil aggregates size, soil cohesion and vegetation cover density. The next important factor is water discharge.

LAND CONSERVATION IN THE CONDITIONS OF THE GULLY THERMO-EROSION 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 under conditions of continuous permafrost. Several methods to stop gully growth were used in the Bovanenkovskoye gas field of the west central Yamal Peninsula. A check dam was constructed at the head of gully N9 but a new gully head had passed around the check dam in 1995. The erosion cut was filled with sediments from the gully sides by bulldozers, but every year it was renewed by gully erosion. Several wall cuts in gully N9 were covered by technical textiles. Cuts with small subcatchments were stabilized but in most of them the cover was destroyed by erosion that took place around the covers.

These cases highlight that human activities in the Arctic tundra, accompanied by deterioration of the vegetation and an increase of runoff cause intensive erosion. This

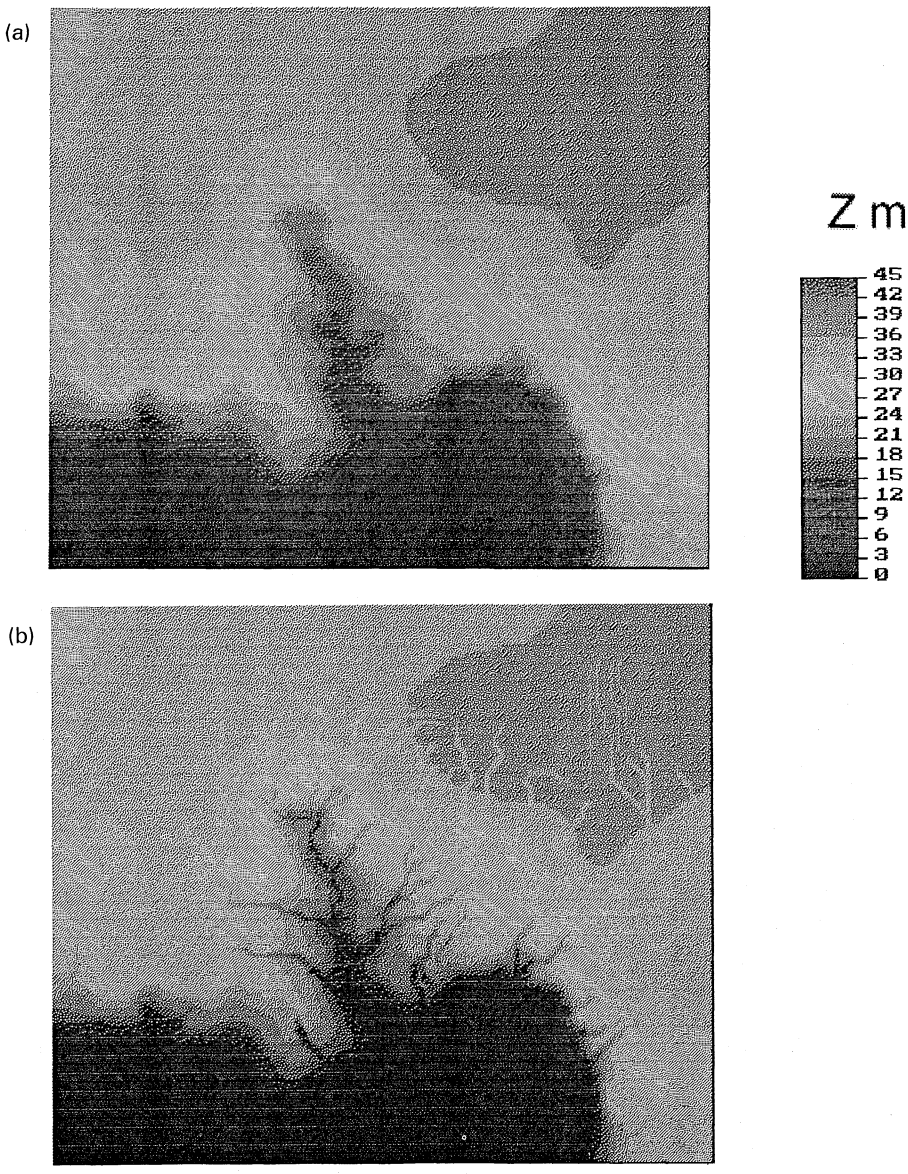

Fig. 3 Effect of land conservation on gully erosion. (a) Initial terrain in 1986 before camp building and in conditions of thaw water drainage or vegetation cover recultivation. (b) gully growth in conditions of thaw water increase and vegetation cover deterioration.

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 thermo-erosion. To minimize 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 the vegetation cover.

All these measures led to a decrease in water discharge and an increase in critical shear stress of erosion initiation. As GULTEM includes 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 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. 3(b). To stop gully erosion (Fig. 3(a)) all the snow has to be removed from the camp at the end of the winter or the quality of the vegetation cover has to be high enough to provide a density of thin roots not less than 23 kg m^{-3} for clays, 35 for loam and 47 for loamy sands.

CONCLUSION

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

The GULTEM was realized using a network of flow lines, evaluated from a topographical DEM. The multi-layered soil texture (including the 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 physically-based hydrological models.

The main parameters, which control calculations of erosion and thermo-erosion with GULTEM, correspond 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 stabilize buildings and constructions on the catchments with high gully erosion potential.

Acknowledgement The work for this paper was partly supported by RFBR Grant 96-04-48478 and by the scientific programme Yamal of RSC GAZPROM.

REFERENCES

Apollov, B. A., Kalinin, G. P. & Komarov, V. D. (1960) *Gidrologicheskie Prognozy* (Hydrological prognosis) (in Russian). Gidrometeoizdat, Leningrad.

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

Kaluzhny, I. L. & Pavlova, K. K. (1981) *Formirovanie Poter' Talogo Stoka* (Thaw water losses formation) (in

Russian).Gidrometeoizdat, Leningrad.

Kuz'min, P. P. (1961) *Process Tayaniya Snezhnogo Pokrova* (The process of snow cover thawing) (in Russian). Gidrometeoizdat, Leningrad.

Mirtskhulava, Ts. Ye. (1988) *Osnovy Fiziki i Mekhaniki Erozii Rusel* (Principles of physics and mechanics of channel erosion) (in Russian). Gidrometeoizdat, Leningrad.

Poesen, J. & Govers, G. (1990) Gully erosion in the loam belt of Belgium: typology and control measures. In: *Soil Erosion on Agricultural Land* (ed. by J. Boardman, I. D. L. Foster & J. A. Dearing), 513-530. John Wiley, Chichester, UK.

Poesen, J., Vandaele, K. & van Wesemael, B. (1996) Contribution of gully erosion to sediment production on cultivated lands and rangelands. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. Walling & B. Webb) (Proc. Exeter Symp., July 1996), 251-266. IAHS Publ. no. 236.

Palagyn, E. G. (1981) *Matematicheskoe Modelirovanie Agrometeorologicheskykh Uslovyi Perezimovki Ozimykh Kultur* (Mathematical modelling of agrometeorologyc conditions of winter crops) (in Russian). Gidrometeoizdat, Leningrad.

Popov, Ye. G. (1956) *Analiz Formirovaniya Stoka Ravninnykh rek* (Analysis of river flow formation) (in Russian). Gidrometeoizdat, Leningrad.

Poznanin, V. L. (1989) L'distost' grountov i ee vliyanie na termoeroziyu (The ground ice content and its influence on the thermo-erosion process) (in Russian). In: *Materialy Glyatsiologicheskikh Issledovaniy* (Materials of glaciological research) **59**, 11-31.

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 Russian). In: *Vodokhozyaistvennyye Problemy Ruslovedeniya (Water resources management and problems of fluvial science)*, 74-83. Izd AVN, Moscow.

Sidorchuk, A. (1996) Gully erosion and thermo-erosion on the Yamal Peninsula. In: *Geomorphic Hazards* (ed. by O. Slaymaker), 153-168. John Wiley, New York.

Trofimov, A. M. & Moskovkin, V. M. (1983) *Matematicheskoye Modelirovaniye v Geomorfologii Sklonov* (Mathematical modelling in geomorphology of slopes). Izd. Kazan Univ., Kazan.

US Soil Conservation Service (1966) *Procedures for Determining Rates of Land Damage, Land Depreciation and Volume of Sediment Produced by Gully Erosion.* Tech. Release no. 32, US Dept Agric., Washington.

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 yield during floods) (in Russian). Gidrometeoizdat, Leningrad.

Wasson, R. J., Olive, L. J. & Rosewell, C. J. (1996) Rates of erosion and sediment transport in Australia. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (ed. by D. Walling & B. Webb) (Proc. Exeter Symp., July 1996), 139-148. IAHS Publ. no. 236.

Zorina, Ye. F.(1979). Raschetnyye metody opredeleniya potentsiala ovrazhnoy erozii (Methods of calculating gully erosion potential). In: *Eroziya Pochv i Ruslovyye Protsessy* (Soil erosion and channel processes) (in Russian) (ed. by R. S. Chalov), vol. 7, 81-90. Moscow Univ. Press.