Landform Analysis, Vol. 17: 81–86 (2011)

Simulation of gully erosion using the SIMWE model and GIS

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Abstract: Current soil erosion models do not solve the impact of gully erosion on the landscape changes but only its spatial distribution and intensity. Distributed process-based model SIMWE (Mitas & Mitasova 1998) and landscape evolution module (Burton et. al. 2010) was used for simulation of gully erosion consequences in GIS environment. The results of simulation within the assigned initiation condition in the past showed the real situation at the present time. Simulation process corresponded with the theoretical knowledge about gully development. Modification and combination of selected module procedure and of erosion model has shown the potential of the presented method to predict effectively the genesis of gullies.

Keywords: simulation, gully erosion, SIMWE, r.landscape.evol, modeling, GIS

Introduction

Soil erosion modeling identifies potential erosion risk locality, but they do not solve the impacts of this phenomenon on the spatial pattern and character of the land surface. The spatial changes caused by sheet erosion are almost invisible in short period of time. However gully erosion has a significant impact on the land surface pattern. Therefore it is important not only to predict the locality of potential gully, but also to simulate the consequences of this process on the changes of surface pattern based on the modeled erosion values.

Gullies are predominately associated with water-converging geomorphological forms (e.g. valley bottoms), eventually on straight, steep slopes with strong kinetic energy of flowing water. The inception of gully erosion and incision of gullies was determined by human activity via land use change that exposed the soil and substratum to flowing water. In many cases, this land use change is associated with deforestation and subsequent agricultural use of the land (Valentin 2005).

The objective of this contribution is a temporal-spatial simulation of gully formation and development in the study area and the consequences of this process on the changes in landscape. The simulation is based on a physical model SIMWE and it is implemented in an open source geographic information system GRASS. The simulation of gully erosion was tested in the territory where a relict permanent gully is located nowadays. The gully development was computed for anticipated past conditions during the incision of gully. The results of simulation were compared with the existing gully.

Methods

Methodological conception of gully erosion simulation is based on distributed, process-based model SIMWE (*Simulation of Water Erosion*; Mitas & Mitasova 1998) and GRASS module *r.landscape.evol* (Burton et al. 2010).

SIMWE Model

Model SIMWE simulates hydrologic overland flow and sediment transport using path sampling method. The solution is based on duality between the particles and field representation of spatially distributed phenomena. The inputs and outputs of simulation are represented by continual multivariation functions (scalar or vector fields) in contradiction to homogenous slope segments or polygons used in traditional approaches. The model solves overland water flow and sediments transport by means of two-dimensional vector field (Mitasova et al. 1996a). Model solution is based on duality of particles representing particular solution of differential equations

Table 1. Input parameters of simulation by *r.landscape.evol* and SIMWE model

Land cover	Rainfall intensity [mm min^{-1}]	Soil infiltration [m s^{-1}]	Rainfall excess [m s^{-1}]	Manning's roughness coefficient [m$^{-1/3}$ s]	Sediment transport capacity [s]	Detachment capacity [s m^{-1}]	Critical shear stress [Pa]
Arable land	3.5	0.00000525	0.00005308	0.03	0.0006	0.000557	2.43

Source: Flanagan & Nearing 1995; Hofierka et al. 2002.

describing the movement of water and sediments and their spatial representation by a physical field.

The model is implemented in GIS GRASS by means of *r.sim.water* module (Neteler & Mitasova 2002), which represents a simulation model of water overland flow, determined for the spatially variable area, soils and rainfalls and *r.sim.sediment* module, representing the simulation model of soil erosion, transport and deposition of sediments caused by flowing water (Neteler & Mitasova 2002). Input parameters (Table 1) are derived for the SIMWE model on the basis of WEPP model methodology (Flanagan & Nearing 1995).

The simulation of gully erosion

Gully erosion simulation is based on the transformation of erosion values according to modeling results on the changes of elevation as a result of material loss caused by water flow erosion. For this reason we used the methodology for GRASS module of landscape evolution in time – *r.landscape.evol*, based on the USPED model (Mitasova et al. 1996a, 1996b).

The source code of the module is available on the internet. The script is licensed as a free software of GNU General Public License. Isaac Ullah and Michael C. Barton from the Arizona State University, USA are the authors of the script. The script of module uses a raster data model and creates a new map where each raster cell carries a numerical value, which represents the simulated meters of erosion or deposition estimated for that cell.

This map is then added to (for deposition) or subtracted from (for erosion) the topography map (DEM) of the previous temporal step. The module has the ability to run recursively, looping over several iterations. Time interval is represented by each iteration; their number is conditioned by the size of input environmental variables.

The change of erosion model (from USPED to SIMWE) in *r. landscape.evol* script required a significant modification of the script source code because we needed to recalculate the algorithm of erosion/deposition and the conversion of its values depending on the change in elevation for each cell of raster. From the original script we used only the algorithm for simulation repetition according to the chosen number of iterations.

Significant change is related also to the conversion of erosion/deposition values to elevation change in meters. While in the original script this conversion is realized by map algebra (*r.mapcalc*) directly from the given USPED equation, in this case we shifted this conversion behind the net erosion/deposition calculation by means of *r.sim.sediment* module. Output values of erosion/deposition are defined according to SIMWE model in kg m^{-2} s^{-1}.

Due to this fact, was used the density of soil as a value for algorithm of conversion (Koco 2009):

$$h = \frac{ED \times nl \times r}{\rho \times 1000} \qquad (1)$$

where:
h is the change in elevation at each cell [m],
ED is erosion/deposition according to SIMWE [kg m^{-2} s^{-1}],
nI is the number of iterations within the iteration cycle of *r.sim.sediment* [second] module,
r is the raster resolution and ρ is the density of soil [t m^{-3}].

The modified script *r.landscape.evol* calculates the change in elevation as a result of erosion/deposition according to SIMWE model within one iteration in the following steps:
1. calculation of partial derivations of first order for the determination of overland flow direction and sediment transport by means of *r.slope.aspect* module,
2. calculation of the depth of overland water flow by means of *r.sim.water* module,
3. calculation of net erosion/deposition according to SIMWE model (Mitas & Mitasova 1998) by means of *r.sim.sediment* module,
4. conversion of net erosion/deposition values from kg m^{-2} s^{-1} on the change of elevation in meters by means of map algebra (*r.mapcalc*),
5. calculation of elevation changes (DEM) as a result of erosion/deposition by means of map algebra (*r.mapcalc*).

Study area

The simulation was tested in the basin of a gully of total area 0.26 km^2 with the relict gully on its bottom, situated in the south-western part of Velký

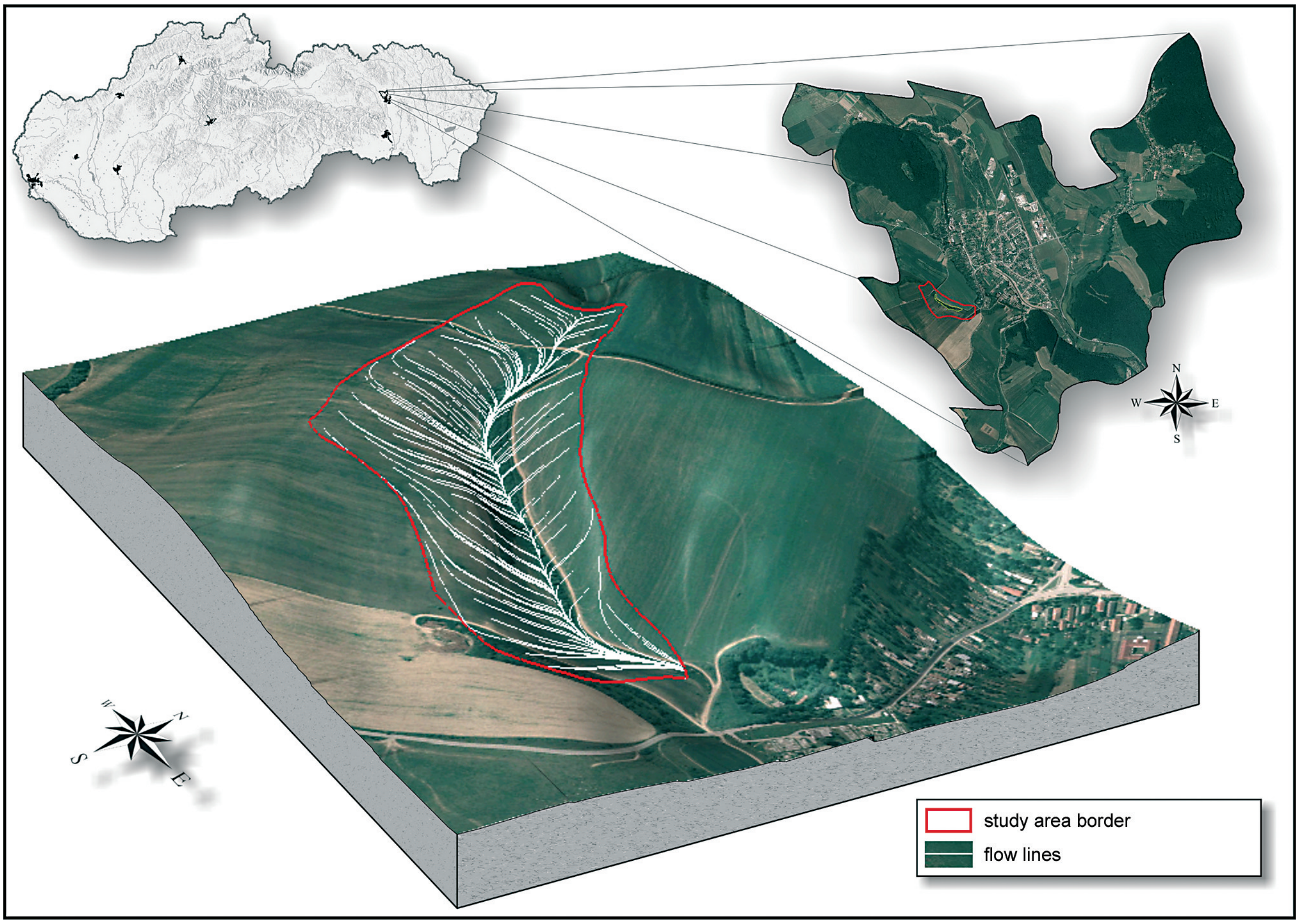

Fig. 1. Location of the study area

Šariš cadastre area, 10 km north-east from the regional capital Prešov (Fig. 1).

The highest point of the area is located in north-eastern part, near the westernmost point of the territory with the elevation of 361.74 above the sea level and its lowest point is located in the south-eastern part, close to the easternmost point, with the elevation of 290.06 meters above the sea level. Orthometric height then reaches 71.68 m. Generally, the elevation raises from the south-east to the north-west.

The geological structures are formed by the Central Carpathian Paleogene flysh rocks which are very inclined to landslides and all forms of water erosion. Regarding the geomorphologic division, it is a part of Spišsko-šarišské medzihorie. Average annual precipitation is 662.4 mm. Whole area belongs to the basin of Šarišský stream, which is a right-side tributary of Torysa river. According to pedogeograhic regionalization of Slovakia, the study area belongs to the regions with significant release of ferric oxides and aluminium oxides with partial move of disintegrated clay. The soil types of the territory are Stagni-Haplic Luvisols and Eutric Cambisols.

Input data

The input parameters were optimized for possible conditions of study area in the time of gully inception. Analysis of military maps from the Habsburgh Empire period showed that the existing gully was formed between 1782 and 1832 (Fig. 2). However the information about conditions related to the gully erosion are insufficient from this period. Therefore, the input data were set to possible conditions the most suitable for gully erosion initialization; for combination of extreme rainfalls and minimal protection of soil by vegetation.

Parameters deepening on rainfalls were derived from the value of rainfall intensity 3.5 mm min^{-1} (historically the highest value of rainfall intensity measured in Slovakia; Lukniš et al. 1972). On the map of 1st military mapping the study area is completely deforested. However we don't know what kind of non-forest vegetation it is. We assumed the arable land in the whole area (Table 1) because this type of land use protects soil against the effect of erosion the least. Soil parameters were obtained from the complex soil survey in Slovak Republic. Several soil probes were taken from in our study area within this survey.

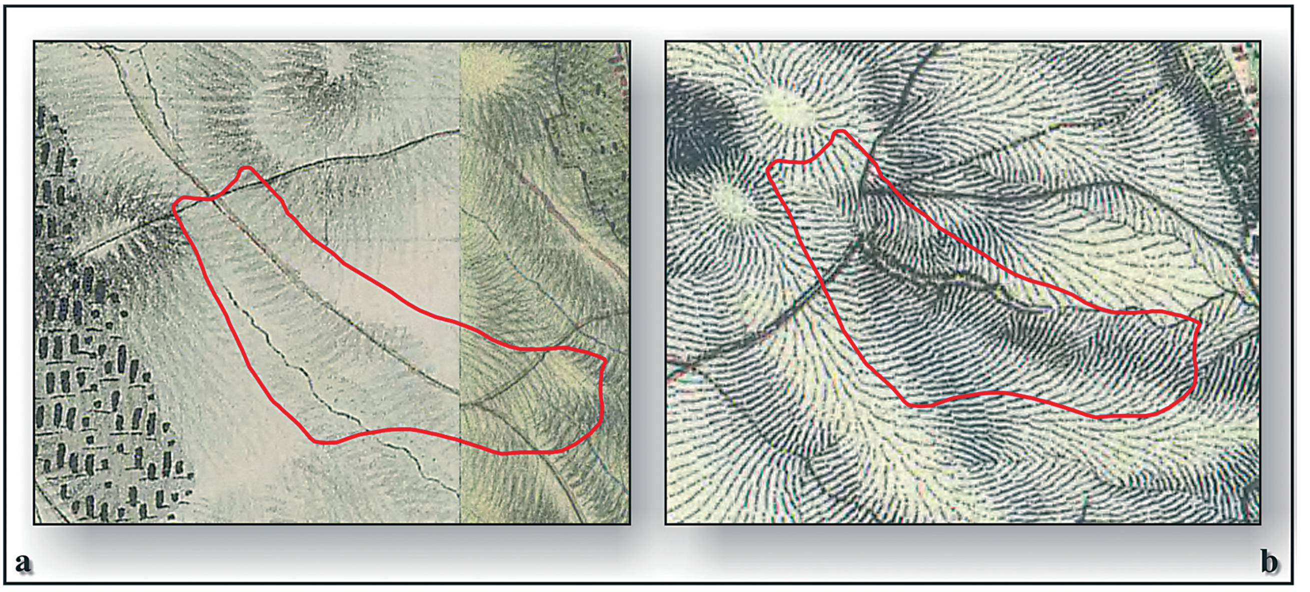

Fig. 2. Study area on the maps of 1st (a) and 2nd (b) military mapping from the Habsburg Empire period

Land surface properties substantially influence the processes of gully erosion and present a main component of the input in most of gully erosion models. Land surface in GIS is represented by a digital elevation model (DEM) with an array of spatially distributed values of elevation and topographic parameters. Topographic parameters express geometric properties of the land surface. The DEM is usually computed by spatial interpolation using input elevation data points. In our analysis, the primary elevation data source were geodetic measured points with information about coordinates and elevation. We have assumed that conditions before the incision of gullies included no sharp cut-outs in the land surface now representing gullies. Geodetic points in this part of territory were modified to anticipated conditions of surface at the time of gully formation.

On the basis of these conditions we determined input data for simulation. The input data for simulation in GIS GRASS were represented by raster maps of elevation for the period before the gully formation (DEM), rainfall excess, infiltration excess of soil, Manning's roughness coefficient, coefficient of sediment transport capacity, coefficient of detachment capacity, critical shear stress with the resolution of 1 meter.

Parameter of soil density was assigned a numerical value of 1.35 t m^{-3} directly. Also number of iterations and number of walkers for SIMWE model were assigned directly. Walker represents the particle for which SIMWE model calculates the direction of particle movement during one iteration, depending on the configuration of relief.

Results

The results of simulation within the assigned conditions showed gully formation and development similar to real situation at present time. During the simulation the gully was increasing regressively in phases. Final maps of simulated erosion/deposition (Fig. 3a, 3b, 3c) show that with the increasing number of iterations, the values of erosion/deposition in the place of flow concentration on the bottom of the basin are increasing, too. At the same time, we can see the continual spread of concentric line of higher values of erosion/deposition in reverse direction from the end of the gully to the gully head. Simulation shows the formation of a gully in the lower part of the territory already after the third iteration (Fig. 3, 4 and 5).

After the fifth iteration the gully undercuts the area above the existing lower part and deepens and widens in its lower part. After the seventh iteration the simulation of gully formation reaches the place of present head of the gully. The analysis of cross section of newly formed gully in three transects show that in the lower part the present depth was reached already after the sixth iteration, in the middle part after the fifth iteration and in its upper part after seventh iteration.

Simulation within the given conditions has shown a periodical development of the gully, represented by gully headcut retreat. The simulation results are similar to the current state of gully and gully formation and development carried out according to the theoretical knowledge about gully erosion. The simulation proved that this kind of model is able not only to identify the areas with higher potential for gully formation, but also we can apply the result values in the simulation of elevation change as a result of accumulation and deposition of material.

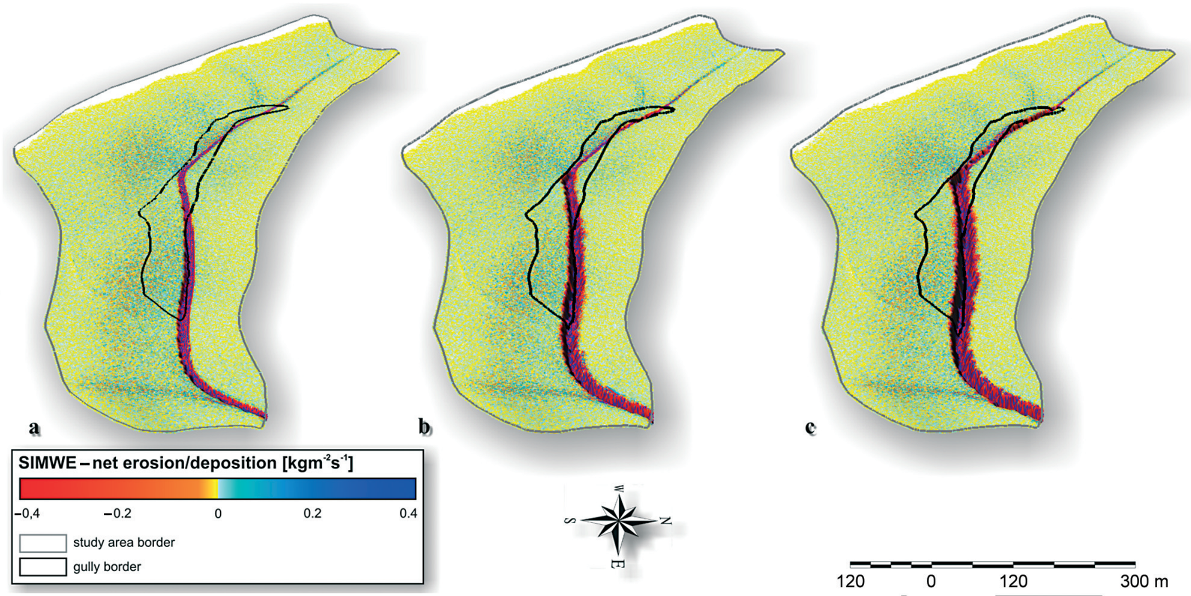

Fig. 3. Erosion/deposition development by SIMWE model for 3th (a), 5th (b) and 7th (c) iteration of gully erosion simulation

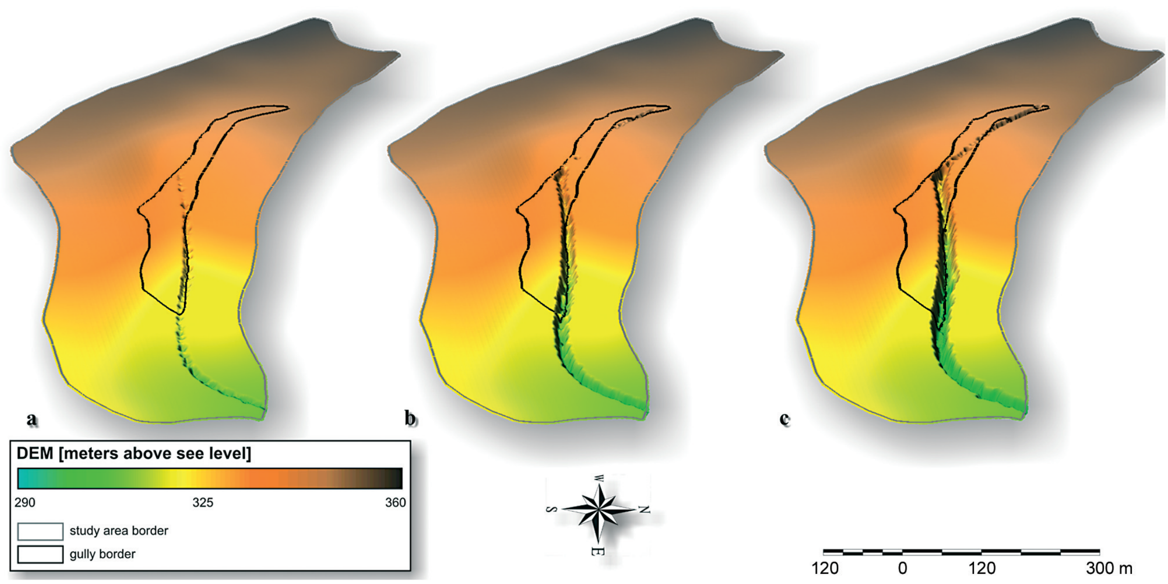

Fig. 4. Changes in elevation by SIMWE model for 1st (a), 3th (b) 5th (c), and 7th (d) iteration of gully erosion simulation

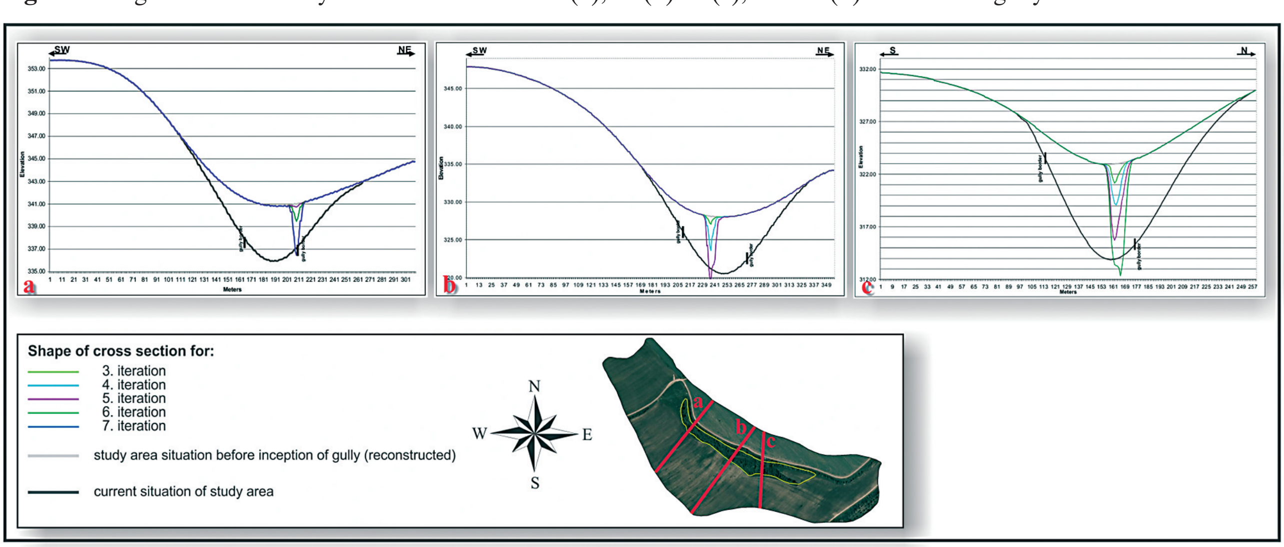

Fig. 5. Simulation of gully erosion by SIMWE model and changes in vertical profile

Conclusion

SIMWE model is a dynamic model, in which the input values define the initial conditions for the process of erosion/deposition. Within its iteration sequences, the model is able to calculate not only the amount of overland water flow, but also its direction and the change of water flow amount in time. This is important in relation to transport and deposition of eroded material, mainly in the case of gully erosion, where the transport of eroded material outside the area of the gully itself, is crucial.

The aforesaid method and results of simulation in the modeled area proved wide possibilities of SIMWE model usage, which enables due to its variability to model the manifestation of gully erosion although it as originally developed for sheet erosion.

Modification and combination *r.landscape.evol* module procedure with SIMWE model has shown the potential of the method to predict effectively the genesis of gullies. The application of this method can be used to model topographic changes caused by gully erosion, not only to identify the location of gullies. Moreover, exact development of gully means that the assumed input parameters could be similar to the conditions during the incision of gully. The results has also shown that geographic information systems is an effective tool for landscape modelling using various scenarios including the anticipation of past, current and future environmental conditions and human activities.

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