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Assessment of gully erosion process dynamics for water resources management in a semiarid catchment of Swaziland (Southern Africa)

MICHAEL MÄRKER

Centre for Environmental Systems Research, Kassel University, Kurt-Wolters-Str. 4, 34119 Kassel, Germany

maerker@usf.uni-kassel.de

ALEKSEY SIDORCHUK

Geographical Faculty, Moscow State University, 119899 Moscow, Russia

Abstract In southern African countries, soil erosion and related problems like water quality issues or decreasing soil productivity are increasingly affecting the inhabitants of rural and urban areas. Problems related to soil erosion therefore have received increased attention in the recent past. Gully erosion processes especially play an important role for sediment production in many southern African catchments. Nevertheless, gully erosion phenomena have been widely neglected in erosion modelling. This study concerns the identification of spatially distributed erosion forms and processes in the Mbuluzi River catchment (Kingdom of Swaziland), with particular attention to gully erosion phenomena. The modelling of gully erosion was done successfully with models accounting for the two stages of development of a gully. The input data were obtained using remote sensing techniques and GIS-analyses. The example from Southern Africa shows that the methods applied are suitable for identifying and simulating the relevant erosional processes.

Key words gully erosion; gully erosion modelling; response units; Swaziland

INTRODUCTION

Soil erosion is one of the major environmental problems in southern Africa, and is likely to become even more severe due to population growth and climatic changes. *In situ* land degradation caused by soil erosion includes the loss of fertile topsoil, and the reduction of soil productivity as a result of lowered soil fertility, which is directly perceived through decreased harvests. In addition, the eroded soil material, i.e. sediment, reduces the water quality in a river network. Apart from having direct impacts such as reservoir sedimentation, such sediments are a carrier for chemical, physical and biological pollutants, which are stored by adhesion on their active surfaces. Consequently, such a reduction in water quality must be viewed as being an indirect effect of soil erosion. Furthermore, progressive land degradation by erosion aggravates water management problems in semiarid regions of Southern Africa where water scarcity is frequent. These interactive dynamics generate the need for the evaluation of suitable methods of land-use management that can lead to a reduction of soil erosion and, subsequently, sediment yield. However, before remediation and prevention of excessive soil erosion can be undertaken, the spatial extent of the problem has to be established.

For integrated water resources management, knowledge of soil erosion processes active within the landscape is of fundamental importance. Particularly gully erosion contributes significantly to the total sediment yield of a catchment. Nevertheless, gully erosion phenomena have often been neglected in erosion modelling (Bull & Kirkby, 1997; Poesen *et al.*, 1998) because the development of erosion models was focused on regions with intense agriculture in developed countries and because of the spatial and temporal heterogeneity of gully erosion.

The study presented here deals with the identification and modelling of gully erosion features and processes in the Mbuluzi River catchment in the Kingdom of Swaziland. Erosional processes and forms caused by water are mainly influenced and interlinked by the hydrological dynamics of a drainage basin. An innovative approach to characterize erosional processes caused by water and their integrated dynamics was introduced by Märker *et al.* (1999, 2001) and Flügel *et al.* (1999) with the concept of *erosion response units* (ERUs).

In this study, the ERUs are used to identify areas subject to gully erosion processes and dynamics, and as modelling entities for gully erosion simulations. Remote sensing techniques were applied to obtain information about the distributed physiographic and anthropogenic catchment characteristics such as land use, settlements and elevation models. This information was used for the parameterization of the physically-based gully erosion models which have been developed for similar environmental conditions (Sidorchuk, 1998, 1999; Sidorchuk *et al.*, 2003). These models account for two developmental stages of a gully. During the period of gully initiation, channel formation, following the drainage network, is very rapid and consequently morphological characteristics are far from stable. This stage comprises only about 5% of the entire gully lifetime (Zorina *et al.*, 1978), but already >90% of gully length, 60% of its area and 35% of the gully's volume are formed in this period. In the remaining 95% of the gully's lifetime, the morphologic conditions are nearly stable. In this study, the dynamic gully erosion model was applied to simulate the first stage of gully development, whereas the stable gully model was used to simulate the final gully morphology (Sidorchuk, 1998, 1999). Model validation and verification were carried out using detailed information on gully system time series and by ground checks.

MATERIALS AND METHODS

Location and physiography of the study catchment

The study catchment is drained by the Mhlambanyoni River, which has a drainage area of 42 km^2 and is a tributary of the Mbuluzi River (Fig. 1). The catchment area is located in the physiographic region of the upper Middleveld, with altitudes ranging from 610 to 760 m a.s.l. and median slopes of 12%. The geology of the Middleveld consists of granite and granitic gneisses, with outcrops of dolerite and gabbro. The region is characterized by deep, acid, well-drained, red and yellow ferrisolic and ferrallitic soils, often with stone lines (Murdoch, 1970). The mean annual rainfall ranges from 700 to 1200 mm (905 mm at Kwaluzeni), with the main rainfall occurring in summer (October–March). Kiggundu (1986) calculated a rainfall erosivity (EI_{30}) of 450 kJ mm m^{-2} h^{-1} (Wischmeier & Smith, 1979).

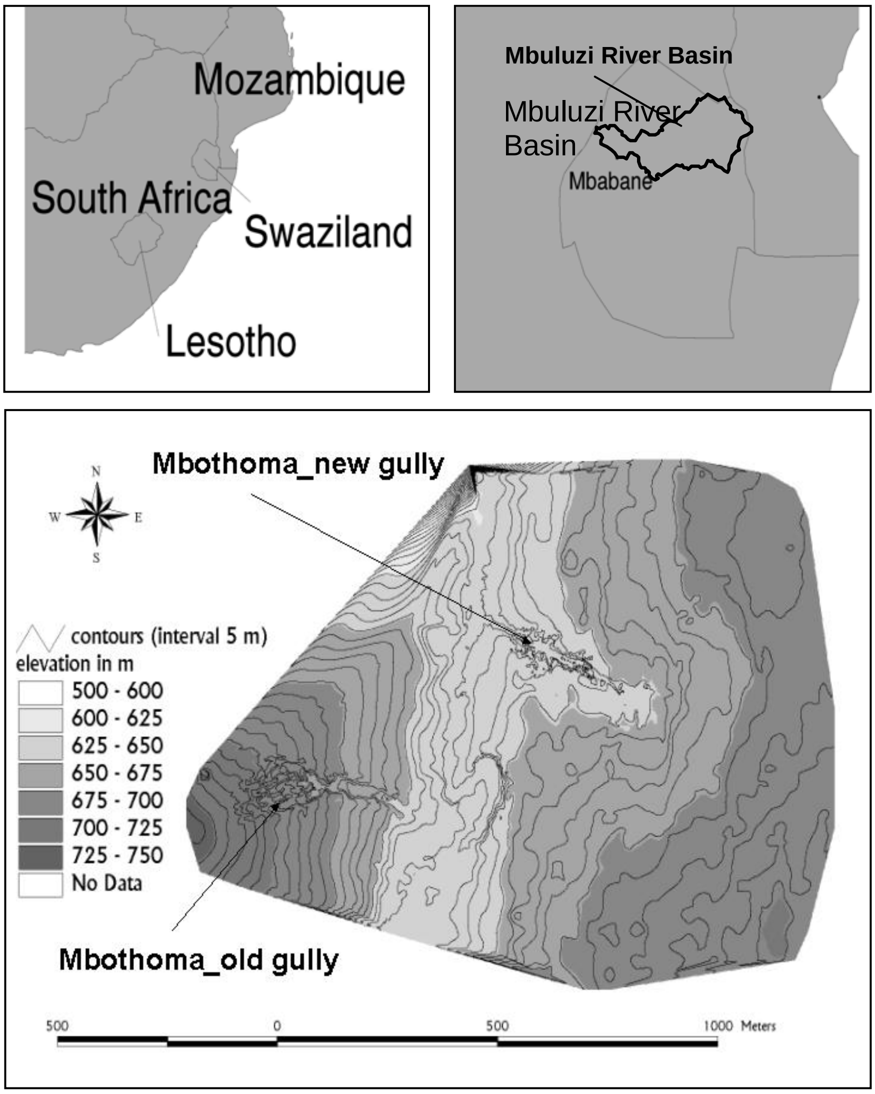

Fig. 1 Location of study sites.

Within the Mhlambanyoni catchment, the Mbothoma area, ~15 km north of Manzini (26°20′S; 31°23′E), was chosen as a characteristic test site for gully erosion studies. It is a densely populated area, and overgrazing is widespread. The dominant land use on this subsistence, small-scale farming land is pasture (Fig. 2). The lithology is composed of a thick granodioritic saprolite layer and a system of amphibolite and serpentite dykes (Felix-Henningsen *et al.*, 1993; Hunter *et al.*, 1984; Mushala *et al.*, 1994; Scholten *et al.*, 1995).

Methods

The concept of erosion response units was used to identify areas affected by gully erosion (Märker *et al.*, 1999; Flügel *et al.*, 1999). The ERUs provide information about the spatial distribution and intensities of erosion features and processes active within

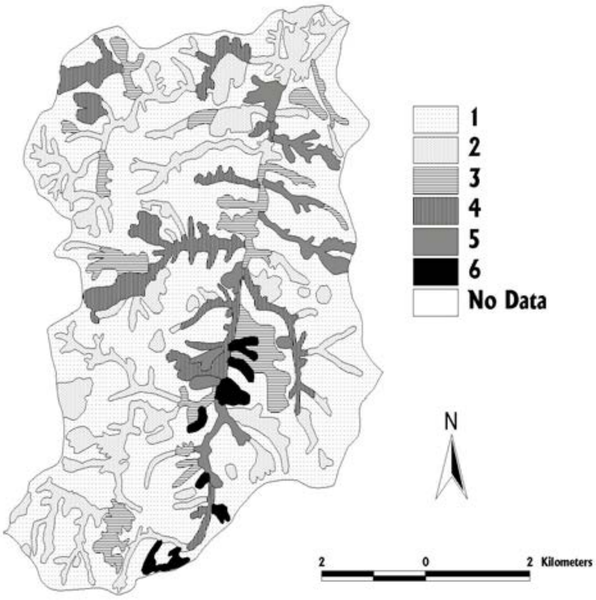

Fig. 2 Map of ERU information for the Mhlambanyoni catchment. (1) no erosion; (2) slight rill interrill erosion; (3) rill interrill, shallow gully erosion; (4) medium gully rill erosion; (5) deep gully rill erosion; (6) very deep gully erosion badlands.

the study area. ERU delineation in the Mbuluzi River catchment was carried out based on analyses of stereo-aerial-photographs, orthophotos and GIS. Therefore the adapted method of Van Zuidam (1985) was applied (see Märker *et al.*, 2001). Within the Mhlambanyoni catchment, the Mbothoma gullies (Figs 1 and 3) were chosen for a more detailed study of the active gully erosion processes and their dynamics.

Fig. 3 Old, stable Mbothoma gully system.

From laboratory experiments it is known that 90% of a gully's whole length can develop in 5% of a gully lifetime, and 90% of gully depth and area can develop in 20% of a gully's lifetime (Sidorchuk *et al.*, 1996, 1999, 2003). The evolution of the active Mbothoma gully system (Fig. 3) subsequently has been modelled using physically-based gully erosion models to account for the two phases of gully evolution. The dynamic gully erosion model simulates the first dynamic phase of gully development, and is based on the solution of the equations of mass conservation and gully bed and wall deformation. Gully-side wall inclination was predicted with a straight stable slope model. The stable gully model applied in this study calculates the final stage of development of the gully flowline network. It is based on the assumption of the final morphological equilibrium of gully bottom and gully walls, implying that gully bottom elevation and width do not change through time. Both models were developed and applied to the similar environmental conditions of Australia (Sidorchuk, 1998). Model validation and verification were carried out using detailed information on gully system time series and by ground checks (Sidorchuk *et al.*, 2003).

The input data necessary for the dynamic gully model and stable gully model consists of geomorphic and geological data, derived from terrain morphology, lithological composition (including vegetation cover), and hydrological information. For derivation of the morphological parameters, high resolution DEMs with a resolution of 1 m × 1 m have been used. A photogrammetric stereoanalyser (Planicomp P33, Carl Zeiss Jena) was utilized to get digital elevation data from the 1960s, 1970s and 1990s aerial photograph series. Georeferencing was done with 1:5000 orthophoto maps. The DEM of the Mbothoma site consists of *c.* 13000 measurement points. The DEMs were used for flowline network evaluation. For the GIS-based work, ArcInfo software was used. The spatial distribution of the surface and subsurface materials was obtained by triangulation of measured soil profiles and soil profile information from the literature (Hunting Technical Services, 1983; Murdoch, 1970; Mushala *et al.*, 1994; Scholten *et al.*, 1995; WMS Associates, 1988). Table 1 shows characteristic values of soil and substratum properties. The surficial material of the Mbothoma gully catchment is a granodioritic saprolite, and soil texture does not change along the flowline, but only with depth. The value of the shear stress has to be changed along the flowlines during the calculations, mainly at the points of the texture change.

The dynamic model uses daily values of discharge, whereas the stable gully model uses the entire range of discharges which form the gully cut. Consequently, annual maximum runoff values and their probability have to be estimated. Daily runoff was

Table 1 Texture of the lithological layers in Mbothoma gully catchments.

	Topsoil (*c.* 0.2 m deep)	Subsoil (up to 1.5 m deep)	Saprolite (more than 60 m deep)
Sand (%)	30	40	50
Silt (%)	20	30	40
Clay (%)	50	30	10
Bulk density (g cm^{-3})	1.1–1.5	1.1–1.5	1.2
Cohesion (kPa)	4.5–9.0	4.5–9.0	3.14
Saturated hydraulic conductivity (cm day^{-1})	0.5–1.8	0.5–1.0	1.0–4.4

simulated with the "Agrohydrological Modelling System" (ACRU) (Smithers & Schulze, 1995) for a period of 45 years. In the stable gully model, two main empirical relationships are used: flow width/depth ratio *vs* discharge, and stable bottom width *vs* discharge. Given the great difference in regime formulas and the absence of local empirical data, for the calculation of the stable Mbothoma gully the value 8.4 was used as width/depth ratio. This value was measured by Sidorchuk & Fogarty (unpublished data, communication from Sidorchuk) in the gullies of the Snowy River Basin (Victoria, Australia) that are eroded in granite saprolite.

There are three main empirical parameters in the stable gully model and in the dynamic gully model: critical flow velocity, flow bed roughness coefficient (Manning's *n*) and inclination of the stable gully walls. For the Mbothoma gully, this last parameter (angle of repose) was derived by measuring the slope of the stable Mbothoma gully (see Fig. 3).

RESULTS AND DISCUSSION

The ERUs delineated in the Mhlambanyoni catchment and the upper Mbuluzane River basin demonstrate the high density of gullies in this region (Fig. 2). The Mbothoma area is especially affected by intense gully erosion. This was the reason for a more detailed study of these processes. The dynamic gully model was applied to predict the rapid evolution of the active Mbothoma new gully, while the stable gully model was used to calculate the gully's final morphology. Longitudinal profiles, gully depth and bottom width were calculated for the basin of the Mbothoma new gully with both models. During the calculation with the two models, the same flowlines (over 100 m long) were used.

The results of calculations with the dynamic gully model are shown in Fig. 4(a)–(f) for 30-year steps (1960–2110). In the year 2110 the simulated (active) Mbothoma new gully system will have a dendritic pattern, with the main trunk about 1200 m long and three major, dendritic tributaries. The tributaries and the main gully will be up to 15 m deep in their central sections, and will have trapezoidal cross-sections with flat bottoms of 25–30 m widths and steep (>45°) sidewalls. The maximum gully length of ~1200 m is calculated to be > 95% of the gully catchment's length along this flowline. In the final stage, 79% of the entire contributing area will be affected by gully incision. The volume of the gully will be 1 040 000 m^3 for the gully catchments and the surrounding areas (total area: 70 ha). The dynamics of gully growth are characterized by a rapid increase of the gully's maximum length (Fig. 5, lower part), followed by gully area, mean depth and growth rate. The dynamics of gully evolution are qualitatively the same as in the study of Kosov *et al.* (1978). In the dynamic gully model, the erosion coefficient and the magnitude of water discharge mainly affect the rate of gully incision. The critical flow velocity for initiation of erosion and the water discharge distribution along the flowlines determine the shape of the gully bed. The critical flow velocity for initiation of erosion of the topsoil layer also controls gully length. These characteristics must be carefully calibrated with a set of experiments, or with backward calculations using existing information about gully longitudinal profile evolution in similar conditions. The old stable gully was used (Fig. 3) to derive these parameters by backward calculation.

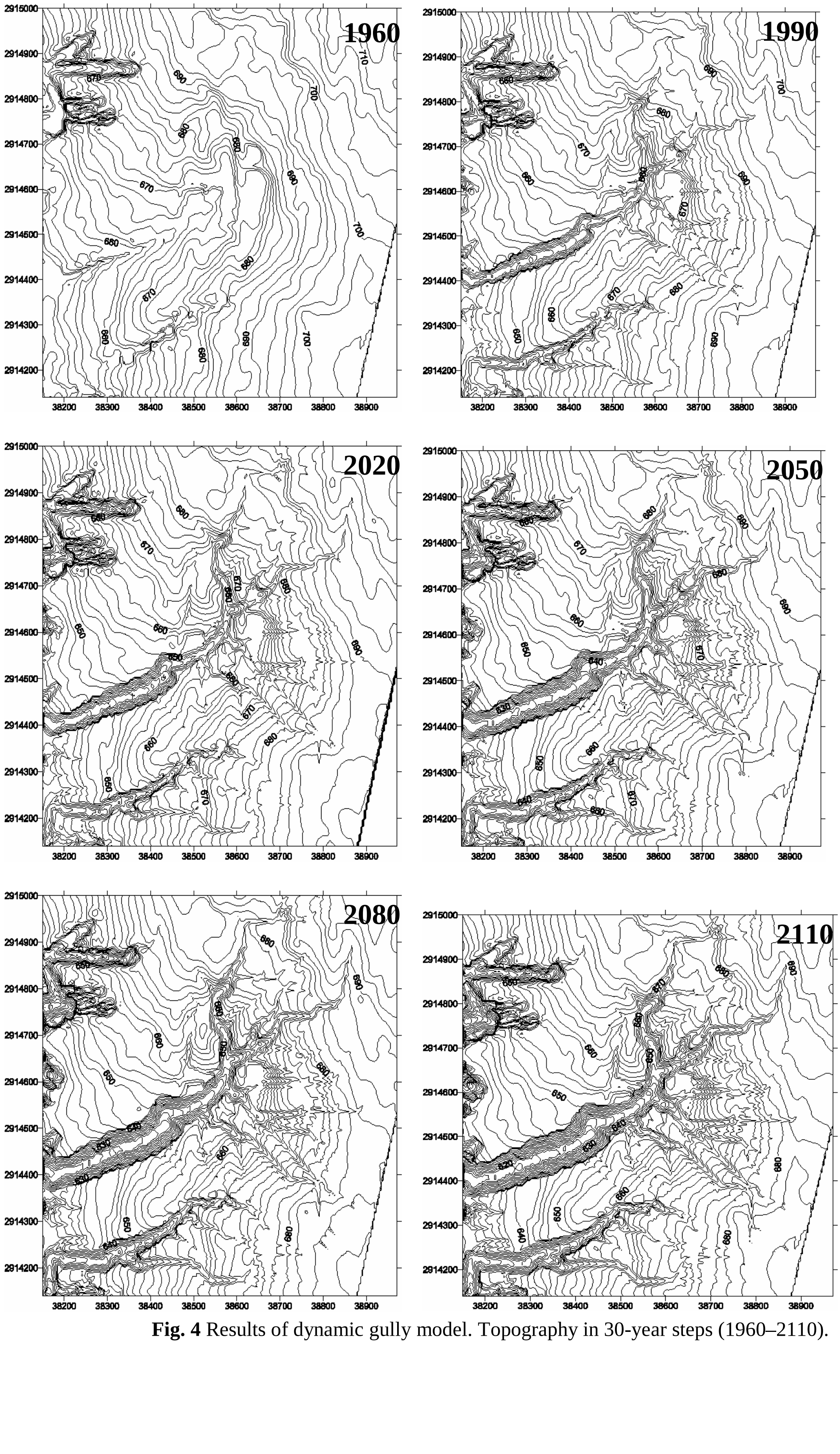

Fig. 4 Results of dynamic gully model. Topography in 30-year steps (1960–2110).

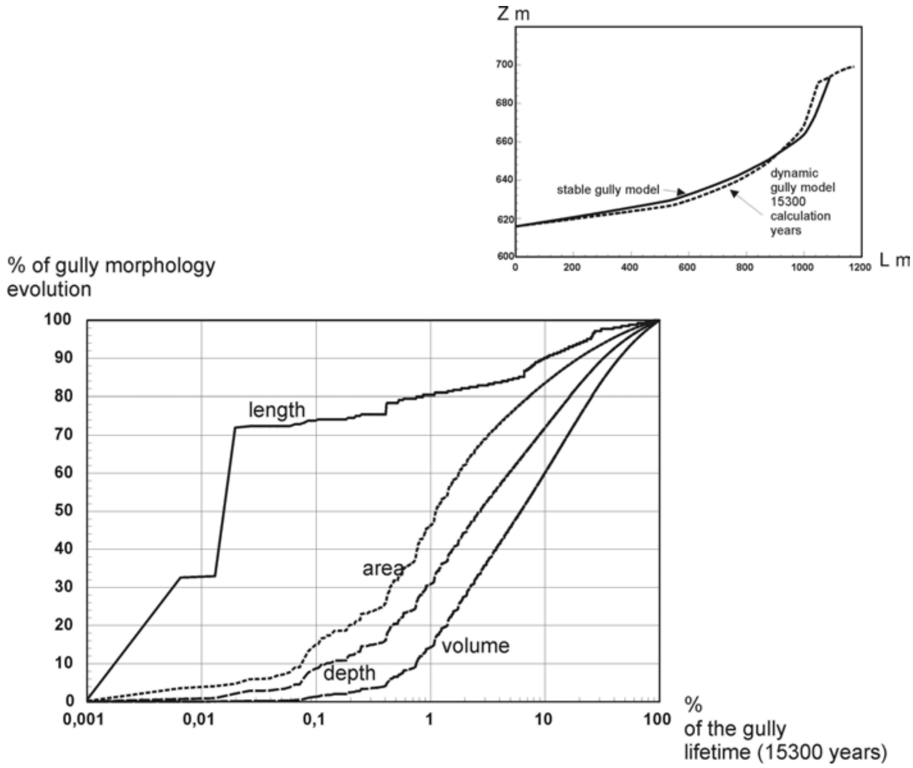

Fig. 5 Dynamic evolution of gully morphology calculated with the dynamic model (lower left) over 15 300 years and comparison of stable and dynamic model predictions for the main flow line evolution (upper right).

The stable gully model describes the final morphology of the gully. It is based on the assumption that the flow velocity is less than the critical value for erosion initiation but greater than the critical velocity of wash load sedimentation. This criterion of stability means that the main expression for the estimation of gully stable slope is the well-known reverse relation between slope and discharge (or its surrogates), which is extensively used in gully erosion investigations (e.g. Desmet *et al.*, 1999).

The application of the stable gully model for the Mbothoma new gully system shows that this system will have a dendritic drainage pattern, with a main trunk about 400 m long, and six main tributaries of 270–560 m in length. The maximum gully length of ~960 m is calculated to be >95% of the gully catchment's length along this flowline. In the final stage, 54% of the contributing area will be affected by gully incision. The volume of the stable gully will be 1 900 400 m^3. Each flowline derived from the DEM was separately processed in the model using its particular parameters. The final positions of the gully flowlines are provided as spatial *x*,*y*,*z* data. Figure 6 shows the elevation differences between the initial surface and the calculated, final surface of the gully system. As it is carefully calibrated, the stable gully model is a powerful expert tool for a very quick estimation of the final gully morphology. Furthermore, the stable model results can be used to validate the dynamic gully model. The dynamic model therefore was run for a 15 300 year period for the Mbothoma new gully, and results were compared to the predictions of the stable gully model. It was assumed that the climate would not change so that the generated discharges could be used. The morphometric parameters develop according to Kosov *et al.* (1978) over this

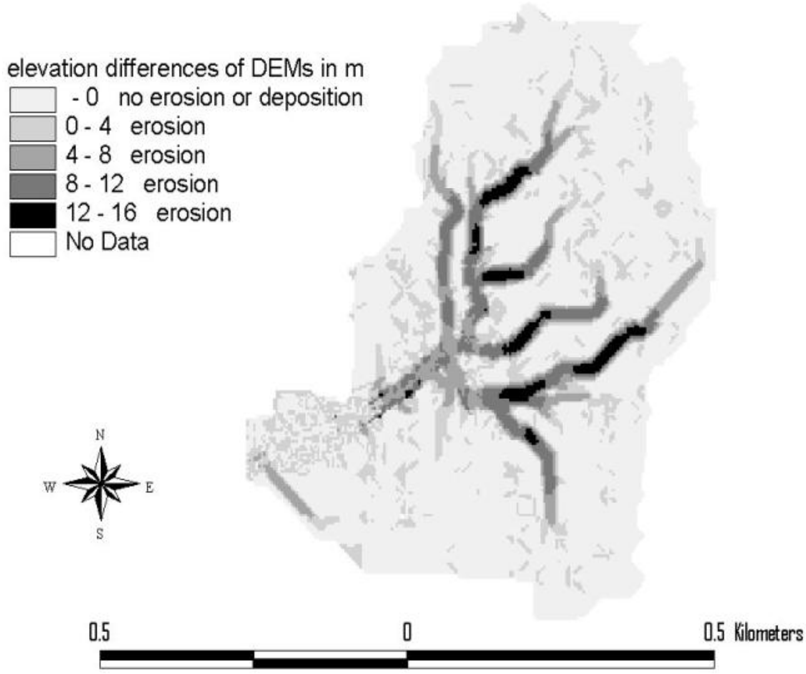

Fig. 6 Elevation differences (m) between the initial and final stage of gully development.

15 300 year period. A comparison of the gully longitudinal profile shows a general good fit of both curves, even though the dynamic gully model underestimates the elevations in the headwaters of the contributing area, but overestimates in the lower parts (Fig. 5; upper right). To validate the dynamic model, especially in the first dynamic phase, the model results were compared to observed gully profiles (Fig. 7). The simulated (1971, 1990) and observed profiles (1960, 1998) show a very good fit. Figure 7 also shows the 2100 simulation and the final profile of the stable model.

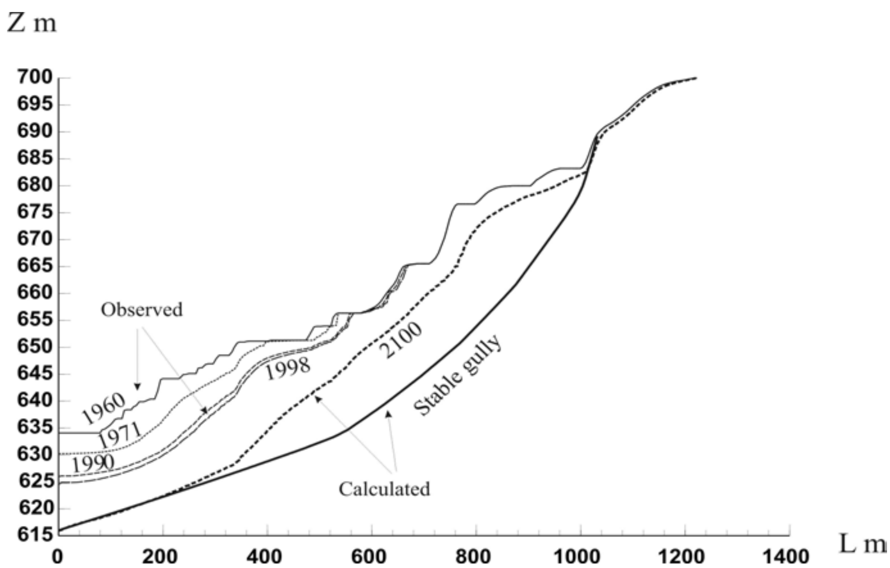

Fig. 7 Evolution of the Mbothoma new gully. Observed (1960, 1998) and calculated (1971, 1990, 2100, stable gully) longitudinal profiles.

The results of this analysis demonstrate that gully evolution involves rapid and intense erosion during the first phase of development. During this phase, huge amounts of sediment are delivered to the river network. This sediment causes off-site damage such as reservoir sedimentation and water pollution, and gully erosion thus greatly influences water quality. Consequently, water resources management has to consider these processes, and methods such as the erosion response units concept (Märker *et al.*, 2001) should be applied to allow an integrated assessment of all active erosional processes.

CONCLUSIONS

In this study, the concept of ERUs was used to identify areas subject to gully erosion. The distribution of gully erosion in the study area clearly shows that this process must be included in the calculation of sediment yield, especially where the surficial material (saprolite) is highly vulnerable to erosion. Nevertheless, in traditional models such as the USLE, gully erosion is almost completely neglected. Once the gully erosion sites were identified, a typical gully system was chosen to simulate the gully erosion processes and their dynamics. The dynamic gully model was applied to simulate the first quick phase of gully development, and the stable gully model was used to predict the final gully morphology. Both models deliver accurate and reliable results. Consequently, the models can be used to assess the dynamics of gully erosion processes and can deliver valuable information to water managers.

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