CHILD EVALUATION WITH A FIELD DATA SET

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Abstract One of the main processes driving gully initiation and development is gully headcut retreat. This process contributes significantly to total soil losses and it can cause severe land degradation. Nevertheless, headcut retreat is not always included in gully models, and none of these models has been tested against field data. In this paper, we calibrate and validate the Channel-Hillslope Integrated Landscape Development (CHILD) Model and use it to predict gully development. We evaluate CHILD with field data from Bardenas, Northeastern Spain.

The headcut retreat module of CHILD was calibrated by fitting the shape factor parameter to fit the observed linear retreat and volumetric soil loss of one gully during 36 years period, using reported field data to parameterize the rest of the model. To validate the calibrated model, estimates of CHILD of the headcut retreat of 4 other neighboring gullies were compared to observations. The differences in retreat rates between the computed and monitored observations were less than 5 cm/year, on average, with standard deviations of these differences smaller than 10 cm/year. These results are the first evaluation of the headcut retreat module implemented in CHILD with a filed data set. The model is a valuable tool for simulation long-term gully evolution due to plunge pool erosion.

INTRODUCTION

Gully erosion is an important soil loss process that cause great damage to the environment (Poesen *et al.*, 2003) and to the infrastructure (Hanson *et al.*, 2001).

The gully activity varies with time. Sidorchuk (1999) described two main developmental stages of gully evolution: active and stable. The active gully stage constitute only about 5% of the entire gully lifetime, but, at that moment, over 90% of gully length, 60% of its area and 35% of its volume forms. In this stage three processes govern gully growth: the retreat of the headcut upstream, which is the most important; the deepening of the bottom; and the widening of the channel cross-section. Different processes dominating gully growth have been investigated. The development and application of gully erosion models incorporating these processes into their simulation are of great importance, because they allow the study of gullying in different backgrounds.

Among currently available models for the analysis of the landscape evolution (see models revision by Coulthard, 2001), and, in particular, of soil erosion processes (Aksoy and Kavvas, 2005), there are few dedicated to gully erosion. The most important models are. EGEM (Merkel *et al.*, 1998) which simulates a single, non-bifurcating ephemeral gully on a planar surface, AnnAGNPS (Gordon *et al.*, 2007), which, based on the EGEM, improves it, among in the migration of headcuts and bank failure in permanent gullies or stream systems, using the CONCEPTS model (Langendoen and Simon, 2008), and CHILD (Flores-Cervantes *et al.*, 2006) simulating multiple and bifurcating gullies with headcut retreats fro plunge pool erosion and bank failure.

But if models are scarce, there are even fewer of them tested against field data (Valentin *et al.*, 2005). Nachtergaele *et al.* (2001) and Capra *et al.* (2005) used EGEM to simulate gullies observed in several place in Europe. In general, the EGEM performed poorly in predicting the area dimensions of ephemeral gullies ad total soil losses and its application to field data was problematic. Gordon *et al.* (2007) compared measured and simulated dimensions of ephemeral gullies with AnnAGNPS at four agricultural field sites in central Mississippi for single storm events, finding a reasonably good prediction of lengths but a less favourable one of breadths. Those investigations deal with the position and sizes of ephemeral gullies in one agricultural year. However, those tools were not programmed to simulate detailed growing processes of gullies, like gully headcut retreats and bank failure, nor the evolution of gullies in time scales larger than a year. Therefore, the purpose of this work is to evaluation of the headcut retreat module implemented in CHILD with historical field data.

MERIALS AND METHODS

Study area and field data set The Bardenas Reales Natural Park (Navarre, Spain), a World Biosphere Reserve, is located in the central sector of the Tertiary Ebro Basin. In the erosive depression of the northern sector of Bardenas Reales, a 300ha semi-arid watershed named *El* Cantalar was selected for this study (Figure 1). *El Cantalar* formed by incision and erosion mechanisms triggered by the downcutting of the Ebro and Aragon Rivers (Sancho *et al.*, 2008). The watershed has a flattened bottom, located around 340 m a.s.l., overlain by several Upper Pleistocene-Holocene alluvial morphosedimentary units originating from the erosion of surrounding clayey Tertiary bedrock.

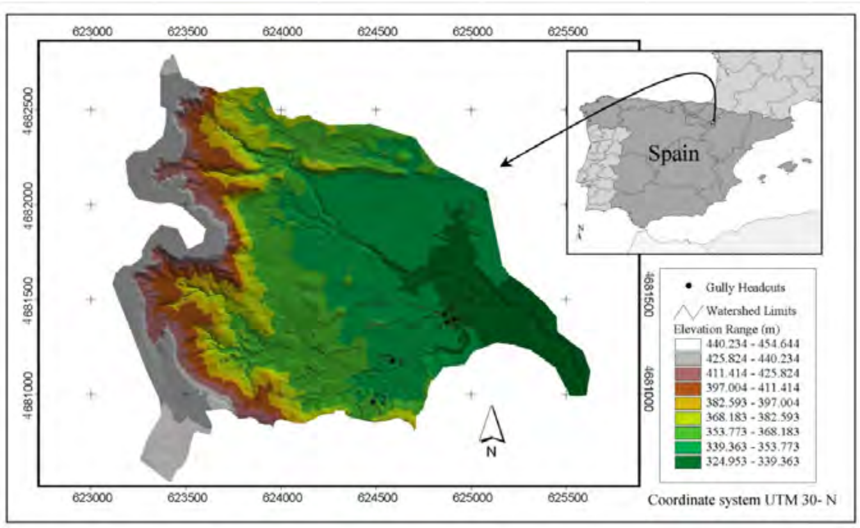

Figure 1 Location of *El Cantalar* watershed and each gully headcut used.

Five gullies from *El Cantalar* were selected for this study (Figure 1). These gullies have a headcut with a plunge pool and develop in soil, not on bedrock. The geometry of each gully was measured and samples of the soil profiles were collected at the site. Headcuts heights are between 1.7 m and 3.2 m, widths between 2.0 m and 3.8 m in width (see Table 1). Particle size analyses of the first 30 cm indicate a high percentage of silt and clay, with values never lesser than 60%. Measured bulk densities have a mean value of 1.4 Mg/m^3.

Table 1 Main morphologic characteristics of gully headcuts.

Gully	Headcut characteristics (2003)			Contributing area characteristics (1967)		
	Depth	Width	Textural class	Area	Upstream slope	Cropland fraction
	m		(0-0.3 m)	ha		
1	1.7	2.4	Silt loam	0.25	0.250	0.036
2	2.1	3.8	Silt loam	0.78	0.219	0.446
3	2.3	2.4	Silt loam	8.51*	0.096	0.246
4	3.2	2.7	Silty clay loam	0.12	0.055	0.536
5	2.4	2.0	Silty clay loam	0.73	0.044	0.624

* In 2003 it was 0.85 ha.

The long-term 3D evolution of these gully headcuts was based on multitemporal aerial photographic stereo-pairs from 1967 (1:17,500 scale) and 2003 (1:20,000), according with the approach proposed by Derose *et al.* (1998). For every year, contour line, break lines and characteristic points were obtained by manual restitutions. This restitution was made by experts from the Tracasa team (a Spanish surveying and mapping public company). The geometric transformation produced a Root Mean Square error of 0.13 m in both x and y directions and of 0.18 m in z (altitude). By means of a triangular interpolation of the topographic information, TINs (Triangular Irregular Networks) for each year were obtained, and derived in 1m-resolution DEMs (Digital Elevation Model). From the aerial photos and the DEMs, ortho-photographs with a 0.40 m resolution were made.

Based on the break lines and the ortho-photographs, the linear gully headcut retreat rates were estimated (Table 2). During the 36 years, then mean linear headcut retreat rate was 0.35 m/year with a maximum value of 0.93 m/year. The maximum value correspond to the gully (gully 3) with the largest contributing area (8.51 ha). This value would be higher if watershed area had been constant. In the early 1990's was constructed a spillway (ditch) upstream of the gully 3, modifying the stream pathway and drastically reducing its contributing area to 0.85 ha.

Table 2 Measured (normal font) and simulated by CHILD (italic) linear and volumetric retreat rates of gully headcuts.

	Gully Headcut						
Linear retreat (m/y)	1	2	3	4	5	Mean	SD
1967-2003	0.11	0.37	0.93	0.05	0.47	0.39	0.35
	0.11	*0.33*	*1.61*	*0.06*	*0.50*	*0.52*	*0.63*
Volumetric retreat (m^3/y)							
1967-2003	0.27	2.00	5.36	0.10	1.26	1.80	2.14
	0.33	*1.54*	*5.05*	*0.22*	*2.52*	*1.93*	*1.98*

There are not precipitation data at subdaily scale in the surrounding area. Caparroso station, located at 14 km, has daily data from 1991 onwards. The station with the longest subdaily precipitation data is El Yugo station, located 10 km away from the site. Data is only available from 1992 onwards.

Model Description The main characteristics of the mathematical model of the evolution of the landscape selected are briefly described, focussing on the headcut retreat module implemented in the model, whose performance under field conditions is analyzed in this work.

CHILD is a computational framework that simulates the evolution of a 3-D topographic surface driven by a number of erosion and sedimentation processes, given a set of initial and boundary conditions (Tucker *et al,* 2001). Topography is discretized as a set of points connected to form a triangulated irregular mesh, in which each node in the triangulation is associated with a Voronoi polygon.

Each Each Voronoi polygon is treated as a finite-volume cell, where changes in elevation are expressed mathematically as

$$dz/dt=U(x,y,t)-\Delta q \tag{1}$$

where $U(x,y,t)$ represents the base level change or tectonic uplift and can be variable in space and time, Δq is the sediment flux divergence, which is a function of different geomorphic sediment transport laws (Dietrich *et al*., 2003), the spatial coordinates are x, y, and z, and t represents time. The processes are fluvial erosion and deposition, soil creep and mass wasting mechanisms, that currently include landslides, slope instability failures (Istanbulluoglu *et al.*, 2005) and headcut retreat due to plunge pool erosion (Flores-Cervantes *et al.*, 2006). In this study landslides or slope instability failures are not considered.

The gully headcut retreat module implemented in CHILD (Flores-Cervantes *et al.*, 2006) is based on previous studies of headcut retreat in flume experiments (see Alonso *et al.*, 2002). The model calculates the retreat rate of a headcut dX/dt as a function of the rate of vertical deepening of the plunge pool, dD/dt, divided by a shape factor, Sf, as

$$dX/dt= dD/(S_f \cdot dt) \tag{2}$$

where X is the horizontal retreat length. The shape factor is the ratio of depth D to the pool's mid length Xm, $S_f=D/Xm$ (see Figure 2). This formulation assumes that, as the headcut retreats, the shape of the pool remains constant. Eq. 4 is applied to gully headcuts, which are defined by the model as the locations where slopes are steeper than 80 % and where such lope is twice the downstream channel slope.

The deepening rate is estimated as a function of:

$$dD/dt=k(\tau-\tau_{cr})^p \tag{3}$$

where τ is the maximum shear stress produced at the bottom of the pool, τ_{cr} is the critical shear stress required for the scouring of the soil, k is the soil erodibility and p is an empirical exponent, commonly 1, for cohesive soils (Alonso *et al.,* 2002).

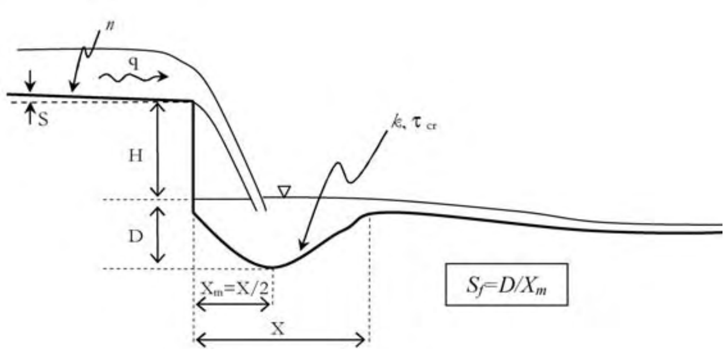

Figure 2 Sketch of the headcut-plunge-pool system.

The shear stress at the bottom of the pool can be calculated following the approach of Alonso *et al.* (2002), as a function of the bottom velocity, which can be calculated in terms of the flow velocity at the brink, the pool geometry and the headcut height.

In short, given all the above, the retreat rate is related to the flow conditions at the brink, the headcut height, the pool's shape and soil characteristics.

In previous versions of CHILD, the rainfall engine was a stochastic method to represent rainfall variability, based on the Poisson Model developed by Eagleson (1978). The latter, although it addresses the role of event magnitude and frequency in drainage evolution, is not enough to deal with high intensity storms that occur in semiarid landscapes (Rodríguez-Iturbe *et al.*, 1987) and the reproduction of important features of the rainfall process in other time-scales.

Therefore, in order to overcome these limitations, CHILD has been implemented with an improved stochastic model, called modified Bartlett-Lewis (MBL) (Rodríguez-Iturbe *et al.*, 1987). The model MBL has six parameters; λ,κ, ϕ, μ_x α and γ as it is described in detail by Bo *et al.* (1994).

RESULTS AND DISCUSSION

Calibration The Modified Barlett-Lewis (MBL) assumes two wet periods, one for the spring and one for the autumn, and two dry periods. The six parameters of MBL for each of these periods are estimated using the method of moments as it is described by Bo *et al.* (1994). The resulting parameters are shown in Table 3. With these parameters 36 years of synthetic rainfall are generated and used in the simulations. For the whole period studied, synthetic and real daily precipitations have similar descriptive statistics.

Table 3 Estimated parameters of MBL model.

Season	Duration	λ y^{-1}	κ	ϕ $\times 10^2$	μ_x m/y	α	ν $y\times 10^5$
Wet(i)	3/1-6/30	114.10	0.92	9.91	7.91	3.49	10.4
Wet(ii)	9/1-12/31	192.81	0.14	3.07	36.17	2.99	4.36
Dry	Rest of the year (121 days)	45.70	0.13	5.79	136.67	9.03	5.27

The gully model was calibrated using the synthetic rainfall and field measurements (gully 1 described in Table 1 and Table 2). For this purpose, the linear headcut retreat and the volume of soil eroded were used as objective variables for the calibration, with the form factor of the plunge pool, S_f as a calibration parameter. This variable was selected as a calibration parameter mainly for two reasons. First, it is one of the parameters to which the headcut retreat is most sensitive (Flores-Cervantes *et al.*, 2006) (see equation 2). Second, this parameter is the only one specific of headcut retreat module, because it does not affects any other process simulated by CHILD. Values of the shape factor reported in literature range between (0.02 and 0.42) (Flores-Cervantes, 2004). The rest of the model parameters (*c, n, p,* τ_{cr} and *k*) are provided in Table 4.

Table 4 Parameter values used in gully headcut retreat model simulation.

Parameter	Value
Shape factor, S_f	0.3
Soil erodibility, *k*, $m^3\ (N{\cdot}y)^{-1}$	0.8
Critical shear stress, τ_{cr}, Pa	5
Erosion exponent, *p*	1
Manning's roughness, *n*	0.05
Grid size, *c*, m	2

To estimate the water discharge per unit width, a channel width needs to be estimated. In this case the channel with is assumed equal to the length of the edge between two Voronoi cells, which is approximated to the node spacing. In the set of simulations discussed here, that is c and is 2 m. This assumption affects q, and thus headcut retreat rate. Measured headcut widths vary between 2 and 3.8 m. Thus, 2 m is representative of channel width in the simulations.

The selected value of the coefficient *n* is 0.05, and corresponds to a flood plain with light brush and weeds (Arcement and Schneider, 1989). *p* is set to 1 (e.g. Flores-Cervantes *et al.*, 2006). The values of τ_{cr} and *k* used in the simulations fall within the ranges of values measured in the field (Knapen *et al.*, 2007).

Gully 1 experienced a retreat of 3.9 m and that resulted in the erosion of 9.7 m^3 in the 36 years of the total period of study (Table 2). With a S_f of 0.3 CHILD estimated a retreat of 4 m and an associated eroded soil volume of 11.8 m3 (Table 2). Thus this value is selected as the calibrated parameter. The S_f selected for CHILD is similar to the average value of the measured S_f (0.35 m) in the study area.

The evolution of gully 1 in CHILD is shown in Figure 3. Figure 3a shows the location of the gully in the basin, and gully retreat with blue. Warm tones indicate deposition. Figure 3b shows the longitudinal profile of the evolution of the gully in CHILD and the measured evolution of the gully. As can be seen, the original outline of the headcut in the 1967 measurement data was more vertical than that simulated at a time zero of the simulation. This is due to the 2 m resolution used in the simulations. Taking as a reference point the top bank of the headcut, it is observed how its advance rate measured and obtained after the 36 years study is the same with a difference lower than 2%.

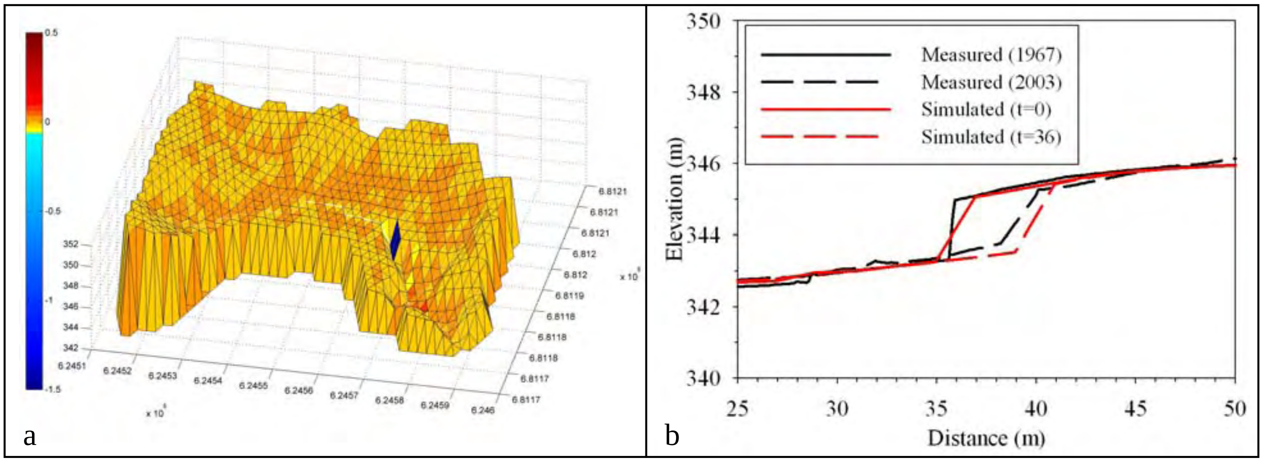

Figure 3 Evolution of the calibration watershed used in CHILD, with S_f= 0.3. a) Final DEM after 36 years of simulation using CHILD. Vertical legend shows total erosion (-) and sedimentation (+) values (m). b) Measured and simulated gully headcut longitudinal profiles in different years.

The eroded soil volume resulting from the headcut retreat in the 36 years of simulation was overestimated by 22% by the model. This difference is partly due to the structure of the retreat model. In the field, headcut retreat occurs in discrete events of magnitudes of a few cm per event. In CHILD the elevation field only changes when the accumulated retreat of the headcut exceeds the length of one of its modeling elements. Therefore, it occurs at discrete events of grid size, 2 m, equivalent to 5.75 m^3 in gully 1 (H = 1.7 m). This factor restricts the resolution of erosion and retreat in the model.

Validation The parameters estimated above are used to simulate the evolution of gullies 2-5. The results are provided in Table 2, and Figures 4 and 5. As is apparent in Figure 4, the model predicts well the measured retreat at year 36 with the exception of gully 3. This is attributed to the construction of a spillway upstream of the gully in the 1990's as discussed in Material and Methods. Moreover, in gully 3 after the 20th simulation year, the model simulated erosion as fluvial erosion instead of plunge pool erosion. It is explained because the topography does not fit with the condition that define a headcut (see model description). This bug would be improved using local information, like wavelet filtering (Lashermes *et al.*, 2007).

Figure 5 gives, for each headcut the retreat rates monitored vs. the values simulated by the CHILD model, including the calibration headcut. For the whole of the period analyzed, 36 years, there was a good linear relationship between the total advance rates derived from the DEMs and those simulated by the model: the coefficient of determination, R^2, is 0.94, with a 46% overestimation of them by the model. The differences in retreat rates between the model and observations for these five gullies, on average, were less than 20 cm y^{-1} and the standard deviation of these differences was 40 cm y^{-1}. If headcut no. 3 is not considered due to its measured retreat corresponding to approximately 26 years instead of the 36 years simulated as seen above, the linear relationship improved, with a R^2=0.99, being obtained. In this case, the differences in retreat rates between the model and observations dropped to less than 5 cm y^{-1}, and with a standard deviation of these differences of less than 10 cm y^{-1}. Secondly, in Figure 5, the volume of the soil eroded from the headcut retreat has been plotted against the simulated volume.

The same as happened with the linear retreat, the volume of eroded soil followed a linear relation with a 2% overestimation, R^2= 0.90. In general terms, the behavior of the volume is identical to that followed by the linear retreat, so that the model gave an adequate prediction of the volume of soil eroded resulting from the retreat of the headcut for the 36 years.

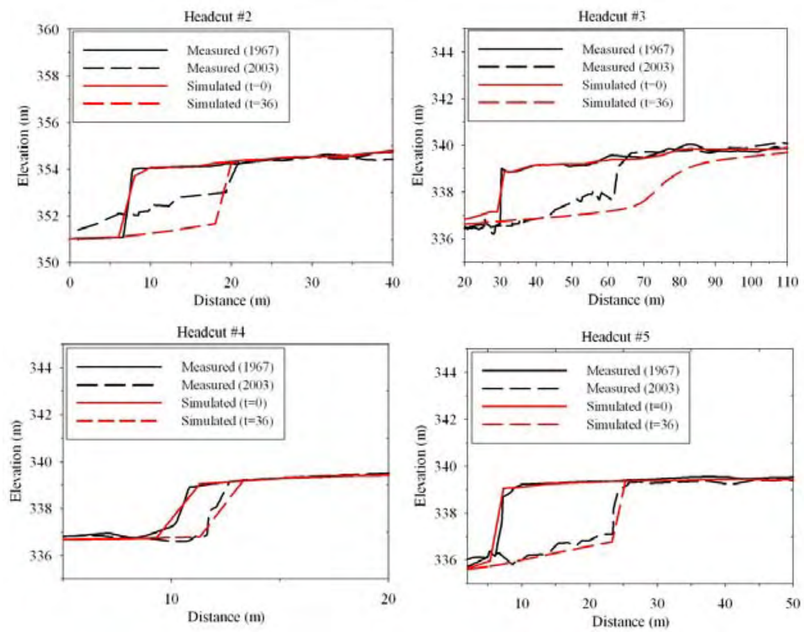

Figure 4 Evolution of the measured and simulated longitudinal profile of each of the studied gully headcuts.

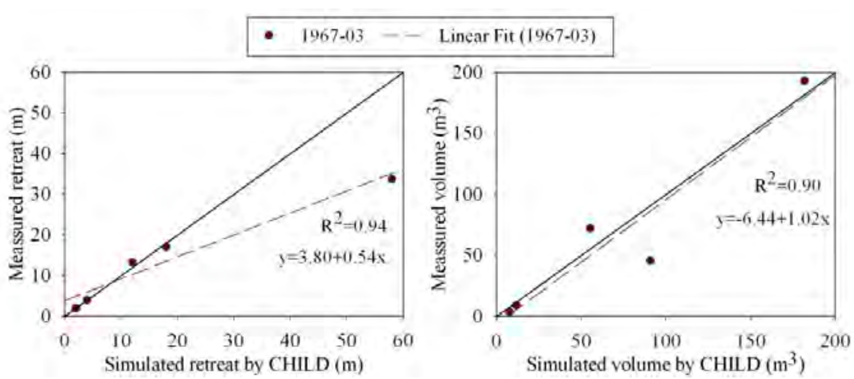

Figure 5 Objective variables (lineal and volumetric retreat) selected for the calibration: measured vs. simulated.

CONCLUSIONS

In this technical paper we have evaluated a gully headcut retreat model due to a plunge pool with a field data set. The model was calibrated with the shape factor, that in agreement with field measurements in the region of Bardenas. The retreat rates were good.

In base on the rainfall model adaptation, to simulate high intensity storms, typical of certain periods in arid environments (Rodríguez-Iturbe *et al.*, 1987), the model has a better simulation of precipitation and allows to simulated future long term.

This study has provided a first evaluation of the model of gully headcut retreat due to plunge pool erosion, implemented in CHILD (Flores-Cervantes *et al.*, 2005), with field data pertaining to long periods of time. Taking into account that the model represents a simplified image of reality (Bras *et al.*, 2003) and that the results of the model may constitute an aid to decision-making, the gully headcut retreat module set up in CHILD is presented as a potential tool for the planning and management of areas with gullies, in which the main growth process of the gullied area is plunge pool erosion.

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