Controls on the development of continuous gullies: A 60 year monitoring study in the Moldavian Plateau of Romania

Ion Ionita1 | Lilian Niacsu1 | Jean Poesen2,3 | Michael A. Fullen4

1Department of Geography, Alexandru Ioan Cuza University, Iași, Romania
2Division of Geography and Tourism, Department of Earth and Environmental Sciences, KU Leuven, Heverlee, Belgium
3Faculty of Earth Sciences and Spatial Management, Maria-Curie Skłodowska University, Lublin, Poland
4Faculty of Science and Engineering, The University of Wolverhampton, Wolverhampton, UK

Correspondence
Lilian Niacsu, Department of Geography, Faculty of Geology and Geography, Alexandru Ioan Cuza University, Carol I Blvd 24, 700505 Iași, Romania.
Email: lilianniacsu@yahoo.com

Abstract
Gully erosion is a major environmental threat on the Moldavian Plateau (MP) of eastern Romania. The permanent gully systems consist of two main gully types. These are: (1) discontinuous gullies, which are mostly located on hillslopes and (2) large continuous gullies in valley bottoms. Very few studies have investigated the evolution of continuous gullies over the medium to longer term. The main objective of this study was to quantitatively analyse the development of continuous gullies over six decades (1961–2020). The article aimed at predicting temporal patterns of gully head erosion based on field data from multiple gullies.

Fourteen representative continuous gullies were selected near the town of Barlad, most of them having catchment areas < 500 ha. Linear gully head retreat (LGHR) and areal gully growth (AGG) rates were quantified for six decades. Two main periods were distinguished and compared (i.e., the wet 1961–1980 period and the drier 1981–2020 period). Results indicate that gully erosion rates have significantly decreased since 1981. The mean LGHR of 7.7 m yr⁻¹ over 60 years was accompanied by a mean AGG of 213 m² yr⁻¹. However, erosion rates between 1961 and 1980 were 4.0 times larger for LGHR and 5.9 times more for AGG compared to those for 1981–2020.

Two regression models indicate that annual precipitation depth (P) is the primary controlling factor, explaining 57% of LGHR and 53% of AGG rate. The contributing area (CA) follows, with ~33%. Only 43% of total change in LGHR and 46% of total change in AGG results from rainfall-induced runoff during the warm season. Accordingly, the cold season (with associated freeze–thaw processes and snowmelt runoff) has more impact on gully development. The runoff pattern, when flow enters the trunk gully head, is largely controlled by the upper approaching discontinuous gully.

KEYWORDS
areal gully growth, cold season, hydraulic radius, linear gully head retreat, runoff pattern

1 | INTRODUCTION

Generally, the rate of gully growth is most closely related to the topographic position of the gully head than to any other single factor (Brice, 1966). Logically, this means that gully growth is mainly controlled by the size of the catchment area (CA) upstream of the gully head. Some authors have advocated that the decrease in gully growth rate results from the associated decrease in gully CA and consequent runoff volume (e.g., Burkard & Kostaschuk, 1997; Graf, 1979; Nachtergaele et al., 2002; Poesen et al., 2002, 2003; Vandekerckhove et al., 2001).

By monitoring gully erosion over 4 years, under the highly seasonal tropical climate of northern Australia, Wilkinson et al. (2018) reported that annual variations of net sediment yield in the gully head...
area were strongly dependent on annual rainfall ($R^2 = 0.30$) and runoff ($R^2 = 0.51$). In a similar environment on the east coast of Australia, Saxton et al. (2012) estimated that areal gully growth (AGG) rates are positively correlated with the contributing CA multiplied by slope ($r^2 = 0.67; n = 18, p < 0.005$).

Rengers and Tucker (2014) noted a strong power-relationship ($R^2 = 0.87$) between gully migration rate in the West Bijou Creek, Colorado (USA), as total travel distance within the path of the headcut and accumulated drainage area (the sum of the drainage area at each cell along a headcut path). However, by using simple regression, they observed a weak association between those variables ($R^2 = 0.024$) when the accumulated drainage area is substituted by drainage area at the current headcut location.

Plest et al. (1975) monitored the growth of one gully in a 30 ha catchment near Treynor, Iowa (USA) during 1965–1971. The estimated mean gully erosion values were: 7.3 m yr$^{-1}$ linear gully head retreat (LGHR), 135 m$^2$ yr$^{-1}$ AGG and soil losses of 500 t yr$^{-1}$.

Thomas et al. (2004) agreed that decreasing runoff was responsible for decreased gully growth rates with time. However, they concluded that despite the significant correlation between gully growth rates and runoff volume ‘decreasing growth rates did not result from a decrease in catchment area’. The decreasing rate of gully growth resulted from the steadily decreasing ratio of runoff to base-flow in western Iowa.

Rieke-Zapp and Nichols (2011) reported a power-relationship ($R^2 = 0.89$) between gully retreat rate with the product of contributing drainage area and areal precipitation (P) for rainfalls exceeding a threshold intensity ($I_{th} \geq 25$ mm h$^{-1}$) in the Walnut Gulch Experimental Watershed, Arizona (USA).

By studying a permanent gully formed in an agricultural catchment within the Lublin Uplands of southeast Poland (7.6°C mean air temperature and mean P = 538 mm yr$^{-1}$ for the 1936–2011 period) during 2003–2006, Rodzik et al. (2009) qualitatively observed that snowmelt runoff is the main variable explaining spatial patterns of gully development, while pluvial runoff is mainly responsible for ‘cleaning out’ the previously produced debris, including gully deepening.

Li et al. (2015) estimated gully bank retreat rates under different land-use types in 30 small catchments (mean size 39 ha) in the southeast-eastern part of the Loess Plateau of China. The highest rates ranged between 0.23 and 1.08 m yr$^{-1}$, with a mean of 0.5 m yr$^{-1}$ between 2003 and 2010. The effect of topographic factors on gully bank erosion decreased as vegetation cover increased, especially when cover exceeded 60% in the upslope drainage areas.

Two valley-bottom and three hillslope gullies, incised in two gently sloping small catchments (160 and 129 ha) in Nenjiang County, Heilongjiang Province, northeast China, were monitored by Dong, Wu, et al. (2019) over a short period (2005/2006–2010). Four indices were used to express gully erosion rates. They found that freeze-thaw (nivation) processes significantly influenced gully development and that snowmelt runoff often occurs from late March to mid-April. Mean LGHR was high (7.1 m yr$^{-1}$) and AGG was small (45 m$^2$ yr$^{-1}$), but they observed that gully lengthening was mainly controlled by rainfall.

Based on aerial photographs and field observations (measuring the distance from the gully head to a fixed reference point), Rysin et al. (2017) conducted long-term monitoring of LGHR over 56 years (1959–2015) in the Udmurt Republic, on the Eastern Russian Plain. Their results showed that, in the context of global warming, LGHR decreased from 2.4 m yr$^{-1}$ during 1959–1997 to 0.3 m yr$^{-1}$ between 1998 and 2015.

Sharifullin et al. (2019) observed that mean LGHR in the Republic of Tatarstan (Russia) decreased from 1.6 m yr$^{-1}$ (1983–1994) to 0.4 m yr$^{-1}$ (2015–2018). The impacts of land use and soil conservation practises were found to be less important than increased air temperatures.

Vanmaercke et al. (2016) presented a global analysis of measured gully head retreat (GHR). The data-base showed considerable variability, both in terms of gully dimensions (cross-sectional areas [CAS] ranging between 0.11 and 816 m$^2$ with a median of 4 m$^2$) and volumetric GHR rates (ranging between 0.002 and 47,430 m$^3$ yr$^{-1}$ with a median of 2.2 m$^3$ yr$^{-1}$). LGHR rates varied between 0.01 and 135 m yr$^{-1}$ (median: 0.89 m yr$^{-1}$), while areal GHR rates varied between 0.01 and 3628 m$^2$ yr$^{-1}$ (median: 3.12 m$^2$ yr$^{-1}$). Results show that measured GHR rates are significantly correlated with the runoff contributing area of the gully heads ($r^2 = 0.15; n = 724$) and the rainy day normal (RDN, i.e., the mean rain depth on a rainy day; $r^2 = 0.47$).

Gully erosion is of particular concern on the Moldavian Plateau (MP), which occupies most of eastern Romania. There is also much evidence of soil erosion, landslides, aggradation via sedimentation along floodplains, and reservoir siltation. Investigations of gully evolution and control have been a major research focus of the national agro-environmental community over recent decades, mainly after the period 1968–1973, during which time $P$ amounts were well above average.

Detailed accounts of gully distribution and factors causing gully development were given by Radoane and Radoane (1992) and Radoane et al. (1995, 1999). They mapped two main areas of severe gully erosion on the MP and estimated that average gully density between the Siret and Prut Rivers is 0.1–1.0 km km$^{-2}$, with maximum values > 3 km km$^{-2}$. The northern area of the MP includes the Jijia Rolling Plain, where there are many small discontinuous gullies, usually located on valley-sides. The southern area extends around the town of Barlad and is typified by large, continuous, valley-bottom gullies. However, most gullies are discontinuous. Gullying is much more limited on the Central Moldavian Plateau (CMP) because of more erosion-resistant substrata and forest cover compared to the other subunits of the MP. The authors concluded that gully growth depends on both lithology and the contributing catchment area upstream of the gully head.

Ionita (1998, 2000, 2006) reported additional observations in the Barlad Plateau (BP) and his main findings on discontinuous gullies were:

- Gully erosion rates have decreased since the 1960s, but still remain problematic, since the mean LGHR and AGG for 13 gullies were 12.5 m yr$^{-1}$ and 367 m$^2$ yr$^{-1}$, respectively, between 1961 and 1990.
- During 16-years of monitoring (1981–1996) 57% of total gully growth occurred during the cold season, with the remainder occurring during the warm season.
- Most gully erosion occurs during the 4 months between 15 and 20 March and 15–20 July.

A strong linear correlation between the mean annual LGHR and mean annual eroded volume excavated by gullying was observed in...
the Fălcu Hills (FH) over five successive decades (Ionita, Niacsu, et al., 2015). Another similar linear association \((R^2 = 0.91)\) was found between annual sediment yield from the catchments in which gullies are located and mean annual LGHR during the same 52 year period (1961–2012).

Ionita (2000, 2006, 2008) measured very high sediment concentrations in stream-flow during snowmelt and this scenario is very similar for some heavy rainfalls and intense successive rainfalls. During such extreme events, the sediment concentration curve had a ‘pulse’ shape, usually reaching 100–300 g L\(^{-1}\), but there was no evident debris-free period. This is not consistent with the study of Piest et al. (1975), who measured sediment transport from the Treynor (Iowa) gullies during severe storms and found debris-free periods (‘breaks’) in gully sediment discharges. Niacsu and Ionita (2011) identified 847 gullies within the Pereschiv Catchment, covering 512 ha (2.2% of the total CA). The estimated mean GHR and AGG for the valley-bottom gullies were 7.5 m yr\(^{-1}\) and 168 m\(^2\) yr\(^{-1}\), respectively (Niacs\&c, 2012).

Despite the decreasing intensity of gully erosion and decreasing gully catchment areas over the last half-century, gullying still remains problematically high on the MP. If these gully systems were indeed initiated by human activities, the gullied catchments of the BP probably represent some of the most important case-scenarios of human impacts on soil erosion in Europe (Vanaemerce, 2013).

In this study, we used long-term (60 years) gully monitoring data from east Romania to better understand the development of continuous valley-bottom gully systems. The main objectives were:

1. To determine the mean annual rates of gully growth for 14 continuous gullies over six decades (1961–2020) and to investigate relationships between mean LGHR and AGG versus contributing CA or the product of CA and mean catchment slope (5).
2. To derive regression models for predicting the contribution of \(P\) and \(CA\) as the main factors controlling gully growth, based on annual monitoring of seven continuous gullies during 20 years (1981–2000).
3. To investigate relationships between continuous gullies and upstream discontinuous gullies, focusing on runoff patterns (runoff accommodation) when flow enters the trunk gully head and the associated influence on gully erosion rates.
4. To estimate the large-scale impacts of both cold and warm seasons on gully development.

Gully growth is expressed by two major parameters: LGHR and AGG. These were accurately measured in the field. Multiple associations were found by plotting these indicators versus selected parameters describing gully geometry, selected ephemeral flow characteristics or contributing \(CA\) and \(P\). In order to increase the readability of this article, the acronyms of both the main variables and the local landform units are presented in Table 1.

### Table 1: Overview of the considered variables and acronyms

| Variable Description | Unit |
|----------------------|------|
| ACS Actual cross-sectional area: the present-day visible cross-section of the discontinuous gullies located above the head of continuous gullies | m\(^2\) |
| AGG Areal gully growth in plan | m\(^2\) yr\(^{-1}\) |
| CA Catchment area: area draining towards the gully head | ha |
| CS Cross-section of gully channel in general, measured perpendicular to its main axis | m\(^2\) |
| CSAF Cross-sectional area of flow: the cross-sectional area that is ‘wet’ within the gullies | m\(^2\) |
| FCS Filled cross-sectional area: the cross-section of a discontinuous gully filled by recent sediments, located above the head of continuous gullies | m\(^2\) |
| GD Gully depth: the mean vertical distance from the gully bed to the line linking the gully edges (i.e., the original soil surface) | m |
| GL Gully total length: the distance between the gully head and the gully outlet | m |
| GW Gully width: the horizontal length of the straight line linking the gully edges | m |
| HR Hydraulic radius of the flow: ratio of the flow’s cross-sectional area to its wetted perimeter | m |
| HRBC Hydraulic radius at ‘bankfull-channel’: ratio of the gully cross-sectional area (CSA) to its ‘wetted perimeter’ (dummy variable) | m |
| LGHR Linear gully head retreat: linear gully growth | m yr\(^{-1}\) |
| P Precipitation depth | mm |
| RDN Rainy day normal: the mean rain depth per rainy day | mm |
| SGGH Slope gradient (of the soil surface) at the gully head | % |
| WP Wetted perimeter: the perimeter of the flow’s cross-sectional area that is ‘wet’ | m |
| WPBC Wetted perimeter at ‘bankfull-channel’: the perimeter of the gully cross-sectional area (CSA) that is ‘wet’ (dummy variable) | m |
| MP Moldavian Plateau of eastern Romania |
| BP Barlad Plateau: major sub-unit of the Moldavian Plateau |
| CMP Central Moldavian Plateau: sub-unit of the Barlad Plateau |
| FH Fălcu Hills: sub-unit of the Barlad Plateau |
| TRH Tutova Rolling Hills: sub-unit of the Barlad Plateau |

### 2 | STUDY AREA AND METHODS

#### 2.1 | Study area

Extending over ~27,000 km\(^2\), the MP is the broadest and most typical plateau of Romania. Its major units are the Suceava Plateau, Jijia Rolling Plain in the north, Fălcu Rolling Plain (FRP) in the east and the BP and Covurlui High Plain (CHP) in the central-southern area. The BP is the most extensive high subunit of the MP of eastern Romania. It covers > 8000 km\(^2\) and comprises three major subunits: the CMP in the north; the Tutova Rolling Hills (TRH), west of the Barlad Valley; and the FH, east of the Barlad Valley (Figure 1).
The BP is the most representative subunit of the MP in terms of land degradation processes and has the most spectacular gullies. The continuous gullies form and evolve under relatively large peak runoff discharges (up to a few tens of cubed metres per second) and are mainly located in valley-bottoms (Figure 2).

The outcropping sedimentary substrata consist mainly of younger and more friable Late Miocene and Pliocene layers. These cross-bedded, sandy-clayey strata dip gently to the south-southeast with a gradient of 7 to 8 m km$^{-1}$ (Jeanrenaud, 1971). A patchy loess-like mantle covers the BP and is usually < 5 m thick.

These strata are incised by a consequent network of north-northwest–south-southeast oriented parallel valleys in the TRH. Here, a typical but fairly monotonous rolling hill landscape has developed, with a series of narrow hilltops (peaking at 561 m on Dorosanu Hill) and steep slopes (Harjoaba, 1968). East of the Barlad Valley, in the FH, geological formations of similar age are split by short, subsequent, east–west oriented tributaries of the Barlad River. They create typical asymmetrical valleys, where the left side represents a north-facing cuesta front and the right side is a south-facing cuesta back-slope.

The climate is temperate continental, with a mean annual temperature range between 7.5 and 10.2°C and mean annual P is 460–700 mm yr$^{-1}$, with 60–75% falling during the warm season (April–September).

The higher areas are covered by deciduous forest, while sylvosteppe is advancing on lower areas. Accordingly, the zonal soils in the higher districts are Luvisols, with Cernisols in lower areas. However, the native forest vegetation was mainly converted to cropland during the 19th century, and this land use still prevails today. The marked land-use change by large-scale deforestation resulted in a sharp decline in forest cover within the TRH, from 47% in 1832 to 22% in 1893 (Poghirc, 1972). A similar pattern is evident in the FH, where forest cover is now only 13% of the total (Ionita, Niacsu, et al., 2015).

Soil erosion data collected in the TRH over 30 years (1970–1999) using runoff plots, located on slightly eroded cambic Chernozems, reveal a mean soil loss of 33.1 t ha$^{-1}$ yr$^{-1}$ for continuous fallow and 7.7 t ha$^{-1}$ yr$^{-1}$ for maize, while on severely eroded Luvisols soil loss doubles (Ionita et al., 2006). Across the entire BP, it is estimated that mean erosion rates usually vary between 20 and 30 t ha$^{-1}$ yr$^{-1}$ (Motoc, 1983).

Our study focuses on monitoring gully development around the town of Barlad, within an area of 1960 km$^2$. Some 14 gullies were first sampled near Barlad, most having contributing CAs < 500 ha. They
are located in the following catchments: Chioara, Banca, Roscani, Hreasca, Gheltag and Albia-Mitoc. Table 2 shows selected morphometric parameters of the studied catchments and sub-catchments. Additionally, Roscani valley-bottom gully is 2450 m long (downstream of the junction between the Scranghita-Poligon and Fagaras gullies), Banca gully is 4956 m long (downstream of the junction between Recea and Chira gullies) and Puriceni gully is 2225 m long (downstream of the junction between Puriceni gully 1 and Puriceni gully 2).

Duplex soils are generally characteristic of sites with U-shaped gullies on the BP. The gully banks often expose soil horizons with contrasting textures and about half of the gully cross-sections are cut into parent material. Down-valley from the actively eroding gully reach, the continuous gullies have fairly stable channels and are usually 8–30 m wide and 6–16 m deep (maximum depth 25 m).

### 2.2 Methods

Field data on gully development were divided into at least two or three intervals, which increased the number of independent samples, depending on the techniques used for measuring gully erosion. Poesen et al. (2003) distinguished the following timescales: short timescale (< 1–10 years), medium timescale (10–70 years) and long

| Number | Catchment | Area (ha) | Mean slope (%) | Gully contributing sub-catchment | Total area at the outlet (ha) | Area in 1960 (ha) | Total gully length in 2020 (m) |
|--------|-----------|-----------|----------------|----------------------------------|-------------------------------|------------------|-------------------------------|
| 1      | Chioara   | 2997      | 15.6           | Valcioaia                        | 598                          | 414              | 2728                          |
|        |           |           |                | Tumba                            | 468                          | 175              | 2615                          |
|        |           |           |                | Puriceni 1                       | 867                          | 157              | 289                           |
|        |           |           |                | Puriceni 2                      | 44                           | 44               | 193                           |
| 2      | Banca     | 1614      | 20.3           | Recea                            | 481                          | 481              | 473                           |
|        |           |           |                | Chira                            | 71                           | 71               | 153                           |
| 3      | Roscani   | 796       | 19.2           | Scranghita-Poligon               | 229                          | 127              | 950                           |
|        |           |           |                | Fagaras                          | 270                          | 270              | 329                           |
|        |           |           |                | Langa                            | 67                           | 66               | 275                           |
|        |           |           |                | Ursoi                           | 45                           | 44               | 154                           |
| 4      | Hreasca   | 1203      | 12.7           | Hreasca                          | 1203                         | 987              | 2770                          |
|        |           |           |                | Angheluta                        | 357                          | 198              | 2010                          |
| 5      | Gheltag   | 521       | 18.2           | Gheltag                          | 521                          | 386              | 1377                          |
| 6      | Albia-Mitoc | 2338   | 12.1           | Mitoc                            | 2338                         | 2013             | 1030                          |

*aSince 1970;  
*bSince 1967;  
*cSince 1964.

**FIGURE 2** Valcioaia continuous valley-bottom gully developed after 1970 (photograph taken using a drone by Andrei Enea on 1 April 2021) [Color figure can be viewed at wileyonlinelibrary.com]
timescale, which implies use of historical data. Since large-scale gully monitoring could only be performed after the Second World War, this study advocates modified timescales for gully monitoring: short-term (< 10 years), medium-term (10–30 years) and long-term timescales (30–70 years).

Several methods have been deployed to precisely determine two gully indicators, namely LGHR and AGG. Adopted techniques include:

1. Annual, intensive monitoring between 1978/1981 and 2000 using the ‘stakes grid method’ within the active gully head area. This consisted of installing four stable, concrete or metal landmarks around the gully head enclosing a rectangle (e.g., 40 m long and 20 m wide). During field measurements, small wooden stakes are temporarily placed 1 m apart both on the gully sides and along the reference line upstream of the gully head. One metal tape is used to measure distances from the stakes to the gully edges and two tapes for measuring gully depth (GD). Although this method is time-consuming, it was deployed several times throughout the year, namely at the start and end of winter and after notable rainfall events, in order to increase the accuracy of data plotted on maps at a scale of 1:100 or 1:50 (Figure 3). The level of accuracy corresponds to that of current global positioning systems (i.e., ±1–2 cm). Seven continuous gullies were surveyed over that period: that is Valcioaia: 45 surveys, Loava: 43, Gheltag: 42, Recea: 39, Mitoc: 35, Tumba: 31 and Chira: 26 surveys. By using this method, LGHR and AGG annual rates were estimated for seven continuous gullies over 20 years (1981–2000).

2. Long-term stationary monitoring of gully growth using repeated levelling (topographic surveying, starting in 1978 and mostly after 2001), usually with a Theo 020A, Leica 407 TCR, Trimble M3 and GPS South 82 V-Trimble. Thus, it was possible to obtain longitudinal profiles and cross-sections of gullies at > 210 sites, and map them at a scale of 1:500 or 1:250. Gully perimeters were surveyed as follows: Valcioaia: 14 times, Recea: 12, Tumba: 12, Mitoc: 8, Chira: 7, Gheltag: 7 and Loava: 4 times.

3. Using aerial photographs (1960 and 1970 at a scale of 1:5000 or 1:2000) to locate and plot the positions of all gully headcuts on the maps produced by levelling. Occasionally, the 2005 and 2009 ortho-images with a pixel resolution of 0.5 m, 2012 LiDAR (light detection and ranging) and reliable local information have been collected and analysed to enhance the reconstruction of gully development (Figure 4). Topographical plans at a scale of 1:5000 were used to calculate the size of CAs.

By combining the described methods, both LGHR and AGG rates were quantified for 14 continuous gullies over 60 years (1961–2020) and over six timescales (1961–1970, 1971–1980, 1981–1990, 1991–2000, 2001–2010 and 2011–2020).

Regression analysis was used to investigate relationships between LGHR and AGG versus contributing CA or CA multiplied by catchment slope (S) and P over time.

Runoff in most gully channels is ephemeral. Measurements of some peak flows were occasionally made after flow events by measuring ~200 CSAFs. The top of the weeds that were bent or covered by sediments or the upper edge/line of the bare gully bank that was quickly washed off by the flow (i.e., flow marks) provided a reference line indicating the peak water surface elevation. At times, direct measurements of sediment concentration in runoff, surface velocities and the cross-sectional area of flow (CSAF) were made during snowmelt. In this article, we only used the hydraulic radius (HR) data. Runoff discharges were not calculated because of difficulties in selecting representative Manning roughness coefficients to estimate the associated velocities.

Daily P data from Barlad Meteorological Station were provided by the Romanian National Meteorological Administration for the period 1961–2020. Daily P was also measured between 1981 and 2000 at a rain gauge in Stoisésti village, Vaslui County, FH.

In this study, gully head comprises both the headcut, applied to the scarp (and not to a point at the head of a gully bounded mostly by orthogonal flow-lines), and the usually active gully sides, where some runoff is deflected and thus enters the gully at a slight angle.

---

**Figure 3** Measured growth of Gheltag continuous gully between 14 October 1991–30 June 1999 using the ‘stakes grid method’. Labels refer to day, month and year of survey (Color figure can be viewed at wileyonlinelibrary.com)
3 | RESULTS

3.1 Development of 14 continuous gullies during 60 years (1961–2020)

Gully evolution over 30-years (1961–1990) has been described by Ionita (1998, 2000, 2006). If compared to the 13 initially selected gullies for 1961–1990, there are only some minor changes. These have little impact on the multi-annual mean values, namely: replacing Loava gully (Banca Catchment) by new-born Puriceni gully 2 (from the neighbouring Chioara Catchment). This was due to large and heavy concrete blocks being thrown in the gully head after 1990. Further modifications include incorporating Angheluta gully data and revising Fagaras gully retreat data for the first decade.

Results obtained for LGHR are presented in Table 3. The mean multi-annual LGHR rate is 7.7 m yr\(^{-1}\) over 60 years (1961–2020) and the annual mean values range between 2.1 m yr\(^{-1}\) for Ursoi gully and 26.0 m yr\(^{-1}\) for Hreasca gully. These data indicate a strong trend of decreasing LGHR after 1980.

The trend of decreasing mean annual LGHR rate is quite similar to the annual P distribution (Table 4). Indeed, the mean long-term (1961–2020) P at Barlad is 508 mm yr\(^{-1}\), with a higher value of 575 mm yr\(^{-1}\) between 1961 and 1980 and a lower mean of 475 mm yr\(^{-1}\) for the drier 40-year period of 1981–2020.

Since the mean LGHR rate during the 1980s (4.3 m yr\(^{-1}\)) was much closer to the three subsequent decades, it is more informative to divide the LGHR data series into two periods: 1961–1980 and 1981–2020. The notable P decreases by \(~\sim\)100 mm yr\(^{-1}\) resulted in significantly lower LGHR rates, namely: 15.3 m yr\(^{-1}\) for the period 1961–1980 versus 3.8 m yr\(^{-1}\) (4.0 times greater) for the period 1981–2020.

The largest mean annual LGHR values occurred during the early decades, namely: 18.4 m yr\(^{-1}\) in the 1960s and 12.3 m yr\(^{-1}\) in the 1970s (Table 3). However, it is surprising that the gullies received similar amounts of P: mean value of 582 mm yr\(^{-1}\) during the 1960s and 569 mm yr\(^{-1}\) during the 1970s. The noticeable margin of 6.1 m yr\(^{-1}\) for LGHR during the 1960s resulted from the seasonal distribution of P. The first decade received 223 mm (38% of annual P) during the cold season (October–March) and 359 mm (62% of annual P) in the warm season (April–September). In turn, the second decade showed only 170 mm (30% of the annual P) during the cold season and 399 mm (70% of annual P) during the warm season. We presume that the unequal distribution of seasonal P during these two decades resulted in more soil moisture content at the gully heads during late winter in the first decade, including more prolonged and greater volumes of snowmelt runoff and higher LGHR rates. The highest mean annual LGHR for individual gullies occurred during the 1960s, namely: 58 m yr\(^{-1}\) for Hreasca gully and 38 m yr\(^{-1}\) for Valcioaia gully. There are strong negative correlations between LGHR rate and the six time-series. There were high coefficients of determination, from R\(^2\) = 0.79 (linear-function) to R\(^2\) = 0.96 (power-function). There were considerable variations in LGHR rates for specific gullies over time. For example, the very high mean retreat rate of Hreasca gully (51.2 m yr\(^{-1}\) between 1961 and 1984/1990) dropped to 5.9 m yr\(^{-1}\) after 1990. Besides the impact of decreasing annual P, other factors explain decreased rates of gully development. These include a small rise in the gully base-level triggered by the concrete remnants of the former check-dam structure (built in June 1984 and destroyed by streamflow damage by August 1991) and changing flow patterns (accommodation of the flow) being conveyed through the gully head after 1991.

The mean AGG rate exhibits a similar pattern to LGHR. Its value is 213 m\(^2\) yr\(^{-1}\) for the 60-year period 1961–2020, ranging between
50 m² yr⁻¹ for Ursoi gully and 999 m² yr⁻¹ for Hreasca gully. When considering previous periods, the mean AGG rate of 476 m² yr⁻¹ for the 20-year wet period 1961–1980 is 5.9 times larger than the mean AGG of 81 m² yr⁻¹ for the last drier four decades (1981–2020). Figure 5 illustrates the strong positive association between mean decadal values of AGG and LGHR over the 60-year period, 1961–2020. Correlations between mean LGHR and CA upstream of the gully head are weak. The independent variable is responsible for only 12% (n = 83) of the variance of LGHR, when including all 14 gullies having CA < 2000 ha or 17% when analysing 12 gullies (omitting Mitoc and Hreasca gullies) with a CA < 500 ha. When considering 13 gullies (omitting Mitoc) each having a CA of < 1000 ha, R² increases to 0.34 (n = 77); (see Supporting Information Figure S1). It should be noted that n = 71 and not 72, because Puriceni gully 2 appeared in 1970 (Figure 4; Table 3) and so is absent in the first decade. This note also applies for n = 77 and n = 83.

### TABLE 3 Mean linear gully head retreat (LGHR) rate for the six decades and for the period 1961–2020

| Number | Gully        | Mean LGHR rate (m yr⁻¹) |
|--------|--------------|-------------------------|
|        | 1961–1970    | 1971–1980    | 1981–1990    | 1991–2000    | 2001–2010    | 2011–2020    | 1961–2020    |
| 1      | Hreasca a    | 58.2        | 56.1        | 21.5        | 3.3         | 6.9         | 7.5         | 26.0        |
| 2      | Valcioaia    | 38.2        | 13.5        | 10.2        | 10.3        | 9.7         | 8.1         | 15.0        |
| 3      | Mitoc        | 24.1        | 26.8        | 6.9         | 3.6         | 1.9         | 0.7         | 10.7        |
| 4      | Angheluta    | 14.7        | 11.6        | 7.5         | 12.0        | 6.2         | 7.6         | 9.9         |
| 5      | Recea        | 15.1        | 13.6        | 7.2         | 4.9         | 2.0         | 3.6         | 7.7         |
| 6      | Tumba        | 20.6        | 5.7         | 3.2         | 1.7         | 5.4         | 2.4         | 6.5         |
| 7      | Fagaras b    | 29.3        | 11.0        | 3.3         | 0.6         | 0.8         | 0.4         | 6.4         |
| 8      | Gheltag      | 8.4         | 4.9         | 1.6         | 7.9         | 3.3         | 3.6         | 5.0         |
| 9      | Puriceni 1   | 16.7        | 3.1         | 2.0         | 4.5         | 2.0         | 0.4         | 4.8         |
| 10     | Scraghita    | 7.3         | 4.3         | 4.0         | 4.0         | 3.6         | 2.1         | 4.2         |
| 11     | Langa        | 8.2         | 10.2        | 0.2         | 1.8         | 2.0         | 1.1         | 3.9         |
| 12     | Puriceni 2 c | –           | 4.3         | 2.7         | 6.7         | 1.4         | 1.0         | 3.2         |
| 13     | Chira d      | 8.4         | 4.5         | 2.1         | 1.0         | 1.4         | 1.8         | 2.6         |
| 14     | Ursoi        | 4.1         | 3.0         | 0.8         | 0.7         | 3.3         | 0.8         | 2.1         |
| Mean   |              | 18.4        | 12.3        | 4.3         | 4.5         | 3.6         | 3.0         | 7.7         |

Note: The bold mean values have been calculated as weighted means.
aMinus 1985–1990 when the gully head was affected by a check-dam;
bSince 1964.
cSince 1970.
dSince 1967.

### TABLE 4 Distribution of precipitation between 1961 and 2020 at Barlad, Romania

| Number | Decade  | Total (mm yr⁻¹) | Cold season (October–March) | Warm season (April–September) |
|--------|---------|----------------|-----------------------------|------------------------------|
|        |         | (mm)           | (mm) (%)                    | (mm) (%)                     |
| 1      | 1961–1970 | 581.8         | 222.6                      | 38.3                         |
| 2      | 1971–1980 | 568.8         | 169.9                      | 29.9                         |
| 3      | 1981–1990 | 419.4         | 135.6                      | 32.3                         |
| 4      | 1991–2000 | 496.0         | 164.3                      | 33.1                         |
| 5      | 2001–2010 | 492.2         | 172.3                      | 35.0                         |
| 6      | 2011–2020 | 490.9         | 205.8                      | 41.9                         |
| 7      | Mean of 60 years | 508.2         | 178.4                      | 35.1                         |

Figure 5 Plot of mean annual areal gully growth (AGG) versus mean annual linear gully head retreat (LGHR) rate measured over six decades between 1961 and 2020 for 14 continuous gullies.
Within individual gullies, only Chira and Fagaras gullies exhibit strong and positive associations, although they have the smallest decrease in CA (due to upstream gully head migration) from their initial CA. 5% (3.6 ha) and 7.8% (21.1 ha) from 71 ha and 270 ha, respectively. Overall, the relative mean CA reduction is 18% (70.7 ha) between 1961 and 2020. Of all 14 gullies, five gullies (Tumba, Ghetlag, Langa, Puricieni gully 2 and Uros) do not exhibit any significant correlations between LGHR rate and CA. No significant correlations were found between decadal AGG and CA:

\[
AGG = 0.24 CA + 134.71, \quad R^2 = 0.07, \quad n = 83, \quad \text{for all 14 gullies.}
\]

\[
AGG = 0.54 CA + 58.04, \quad R^2 = 0.10, \quad n = 71 \quad \text{for 12 gullies.}
\]

When considering the contributing CA multiplied by catchment slope (S) upstream of the gully head, correlations between mean LGHR and their product (CA × S) are also generally weak. The product CA × S is responsible for only 10% (n = 71) of the variance of LGHR when including 12 gullies with CA < 500 ha or 0.08% (n = 77) when considering 13 gullies each having a CA of <1000 ha. Figure 6 illustrates that when analysing all 14 gullies having CA < 2000 ha, R² increases to 0.27 (n = 83). Again, no significant associations were evident between decadal AGG and CA × S, namely: \( R^2 = 0.047, n = 71 \), for 12 gullies, \( R^2 = 0.006, n = 77 \), for 13 gullies and \( R^2 = 0.044, n = 83 \), for all 14 gullies.

3.2 Annual monitoring of the evolution of seven continuous gullies over 20 years (1981–2000)

Results obtained by processing multiple annual field measurements, undertaken using the ‘stakes grid method’ over 20 years (1981–2000), adds to our knowledge of gully development. These data are unique in that the same seven gullies were intensively monitored over the medium-term.

LGHR data reveal the considerable variability in annual gully growth rates, with ‘pulses’ of erosion activity, interspersed with periods of stagnation. The peak value (43.1 m yr⁻¹) was measured in Valcioaia gully during 1988 (Table 5). The mean recorded in the study area was 474 mm yr⁻¹, representing a mean value P between 458 mm yr⁻¹ at Barlad Meteorological Station and 490 mm yr⁻¹ at Stoiaesti village in the Chioara Catchment, FH.

Mean LGHR over the 20-years is 4.7 m yr⁻¹, but mean annual values better illustrate the ‘pulsating’ nature of gully development, which was strongly controlled by P distribution. Ten of the 20 years (1981–2000) were relatively dry and LGHR was ≤2 m yr⁻¹. However, sometimes there was no LGHR, as in 1983 (P = 308 mm), 1986 (299 mm), 1990 (324 mm) and 1994 (273 mm). In 1995, despite 526 mm of P, mean LGHR was only 0.5 m yr⁻¹, which is attributed to the severe drought of 1994. Two other years were also relatively dry: 1985 (382 mm) and 1982 (427 mm). However, their gully rates of 3.7 to 4.0 m yr⁻¹ were influenced by both soil moisture reserves from previous years and the impact of nival activity.

The major changes (69% of the total for the 20 year period) in the LGHR occurred during 6 years, representing 30% of the 20 year period, when the study area received a mean of P of 596 mm yr⁻¹ (544 mm in 1981, 630 in 1984, 579 in 1988, 686 in 1991, 613 in 1996 and 526 mm in 1999). During the remaining 14 years, mean P was 419 mm yr⁻¹, ranging between 273 mm in 1994 and 608 mm in 1997.

By far, the largest mean LGHR value of 17.7 m yr⁻¹ was measured during 1988, when Valcioaia gully head retreated by 43.1 m (24.2 m during the cold season and 18.9 m due to warm season rainfall). This value was followed by Recea gully (32.9 m) and Mitoc gully (23.3 m). In terms of the hydrological response and associated gully growth during spring 1988, the most erosive rains causing GHR were: 62 mm in mid-April (10 mm on 17 April and 52 mm on 18 April), 91 mm in the last week of May during six rains ranging between 10 and 24 mm and 55 mm in early June (11 mm on 2 June and 44 mm on 3 June). Therefore, the lengthening of these gullies illustrates the non-linear gully expansion confined to years with above average P (see Figure S2).

The trend of gullying differs from the trend of soil losses (by sheet and rill erosion), which revealed two peaks of ~60 t ha⁻¹ yr⁻¹ (1988 and 1999) under continuous fallow on the reference erosion plot (Ionita et al., 2006). The high gully rates from 1991 and 1996 do not correspond to the erosion plot soil loss of ~60 t ha⁻¹ yr⁻¹. Moreover, most gully erosion occurs during the 4 months between mid-March and mid-July. In contrast, most sheet and rill erosion occur during the 2 months between mid-May and mid-July.

Some 60% of total changes in the AGG (mean 79 m² yr⁻¹) occurred in the 6 years with above average P values. The annual AGG peak-value of 287 m² yr⁻¹ (18% of the total) occurred during 1988. Similarly to the six decades (1961–2020), there is a stronger positive association between mean annual AGG and LGHR (\( R^2 = 0.86, n = 140, p < 0.001 \)) than over 1981–2000 (see Figure S3). When analysing the corresponding mean values, then \( R^2 = 0.94, n = 20, p < 0.001 \). Moreover, moderately strong positive correlations were found between both mean annual AGG (\( R^2 = 0.51 \)) and mean annual LGHR (\( R^2 = 0.47 \)) and annual P (Figure 7). Analysis of associations between mean annual AGG or mean annual LGHR for Romanian gullies and corresponding RDN (Vanmaercke et al., 2016) yielded lower \( R^2 \) values (i.e., 0.42 for AGG and 0.38 for LGHR) (Figure 8).

Fitting both power and exponential relations between these variables yielded even lower \( R^2 \) values.

![Figure 6](image-url)  
**Figure 6** Plot of mean annual linear gully head retreat (LGHR) rate measured over six decades between 1961 and 2020 against catchment area (CA) multiplied by mean catchment slope (S) for 14 continuous gullies on the Barlad Plateau (BP).
3.3 Predicting linear gully head retreat (LGHR) and areal gully growth (AGG)

We investigated whether decreasing P and decreasing contributing CA or CA multiplied by catchment slope (CA × S) upstream of the gully head better explain the decline in gully erosion rates over time.

Multiple regression analyses investigated associations between LGHR and AGG (as dependent variables, y) with contributing CA upstream of the gully head and P (as independent variables, x). All individual, annual data were normalized for each of the seven gullies over 20-years (1981–2000) to produce a correlation matrix and develop a regression model. They were entered into computation as relative

### TABLE 5 Annual and mean linear gully head retreat (LGHR) of seven continuous gullies between 1981 and 2000

| Year | Gheltag | Valcioala | Recea | Chira | Loava | Mitoc | Tumba | Mean GHR (m yr⁻¹) |
|------|---------|-----------|-------|-------|-------|-------|-------|------------------|
| 1981 | 0.4     | 23.7      | 23.7  | 5.1   | 8.1   | 13.9  | 6.8   | 11.7             |
| 1982 | 0.7     | 7.6       | 4.7   | 3.5   | 2.1   | 6.7   | 2.6   | 4.0              |
| 1983 | 0.0     | 0.0       | 0.0   | 0.0   | 0.0   | 0.8   | 0.0   | 0.1              |
| 1984 | 0.3     | 11.1      | 4.3   | 2.8   | 5.6   | 6.5   | 7.2   | 5.4              |
| 1985 | 0.2     | 8.1       | 3.0   | 2.1   | 2.3   | 7.3   | 3.2   | 3.7              |
| 1986 | 0.2     | 3.9       | 0.9   | 1.7   | 0.2   | 2.9   | 1.5   | 1.6              |
| 1987 | 0.8     | 3.5       | 1.8   | 0.9   | 1.0   | 2.8   | 1.5   | 1.8              |
| 1988 | 8.9     | 43.1      | 32.9  | 4.0   | 3.7   | 23.3  | 7.8   | 17.7             |
| 1989 | 4.6     | 1.2       | 0.9   | 0.4   | 1.1   | 4.7   | 1.0   | 2.0              |
| 1990 | 1.3     | 0.3       | 0.0   | 0.2   | 0.0   | 0.6   | 0.1   | 0.4              |
| 1991 | 22.3    | 36.1      | 6.5   | 0.2   | 2.9   | 6.3   | 4.2   | 11.2             |
| 1992 | 4.2     | 2.1       | 3.5   | 0.3   | 1.0   | 1.3   | 1.6   | 2.0              |
| 1993 | 7.7     | 12.1      | 2.4   | 0.5   | 1.5   | 2.1   | 2.7   | 4.1              |
| 1994 | 0.1     | 0.3       | 3.3   | 0.1   | 0.9   | 2.2   | 1.1   | 1.1              |
| 1995 | 0.1     | 0.6       | 0.7   | 0.2   | 0.3   | 1.5   | 0.2   | 0.5              |
| 1996 | 21.6    | 16.9      | 25.5  | 3.7   | 3.7   | 5.6   | 3.2   | 11.5             |
| 1997 | 3.8     | 13.1      | 1.7   | 2.0   | 2.1   | 2.4   | 6.5   | 4.5              |
| 1998 | 6.2     | 9.0       | 1.9   | 1.0   | 0.7   | 3.7   | 4.2   | 3.8              |
| 1999 | 11.4    | 14.9      | 2.0   | 3.2   | 2.8   | 8.6   | 1.6   | 6.4              |
| 2000 | 1.5     | 3.5       | 0.4   | 0.3   | 1.0   | 1.4   | 1.8   | 1.4              |
| Mean | 4.8     | 10.6      | 6.0   | 1.6   | 2.1   | 5.2   | 2.9   | 4.74             |

Note: The bold mean values have been calculated as weighted means.
values; namely: LGHR ($y_1$) and AGG ($y_2$) in percentage of the total value, CA ($x_1$) in percentage of the total loss of the CA and $P$ ($x_2$) in percentage versus mean. Table 6 shows the generally strong correlations between gully advance rates. The exception is Gheltag gully, which grew relatively slowly between November 1978–May 1988.

During the early 1970s, the Gheltag gully head (which was then 5.1 m deep) incised into a more erosion-resistant clay/marl seam. The LGHR rate dropped notably and then streamflow incised a narrow ‘bottle-neck’ shaped channel in the upper part of the headcut. This incision triggered converging (narrower and deeper) runoff and, consequently, the harder seam was progressively incised until spring 1988 (Figure 9). Then, the LGHR rate increased markedly, due to both the shape of the valley-bottom and changing flow patterns. The valley-bottom above the approaching discontinuous gully was 22 m wide and runoff usually splits, resulting in an asymmetrical bifurcation of the gully head and a decreased LGHR rate. In turn, downslope of the gully head of the approaching discontinuous gully, the valley floor width reduced by half. Accordingly, on 22/23 June 1999, the HR of runoff was 2.6 times higher (0.548 m) at 10 m upstream of the continuous gully head, compared to 0.210 m upstream of the approaching discontinuous gully.

The following regression model was obtained by analysing the relative LGHR data:

$$\text{LGHR(\%)} = -5.997 + 0.197\text{CA(\%)} + 0.100P(\%).$$

Since we are dealing with different measurement units (hectares for CA and millimetres for $P$), normalized coefficients were used. The catchment area loss (CA %) and annual precipitation ($P$ %) data were converted as follows:

Firstly, every annual CA loss (in hectares) for each gully was converted to a percentage by setting the total CA loss (in hectares) of one gully equal to 100%. Then, CA (%) was entered into the model as a mean of the 20 annual CA losses in percentage of those seven gullies.

Secondly, $P$ (%) was calculated as a percentage of the annual $P$-values versus the mean $P$ (473.7 mm yr$^{-1}$) for 1981–2020. Annual $P$-values ranged between 57.5% (1994) and 144.9% (1991).

By computing normalized coefficients, it was possible to estimate that annual $P$ is the primarily controlling factor, explaining 57% of variability in the dependent variable (LGHR). Then, the contributing CA follows (33%). This subordinate contribution is similar to that found through linear regression of data for 13 gullies, each having a CA < 1000 ha. Moreover, Figure 10 illustrates a strong correlation between the predicted and measured LGHR values, which supports the validity of the proposed regression model. In terms of the relative mean AGG, minor changes were noticed if compared to LGHR. The associated contributions on the AGG are 53% for $P$ and 32% for CA, and the regression model is:

$$\text{AGG(\%)} = -5.220 + 0.191\text{CA(\%)} + 0.093P(\%).$$

Multiple regressions do not improve the level of explanation when using the product of CA and catchment slope ($S$) upstream of the gully head, instead of CA. Thus, annual $P$ explains 59% of LGHR and 54% of AGG, while associated contributions to AGG are 54% for $P$ and 30% for the product of CA $\times$ $S$. This similarity can be explained by the very small variation of slope gradients over 20 years (1981–2000).

Both simple linear regression and multiple regression models indicate that the main factor controlling gully growth on the BP is $P$, sometimes coupled with air temperature. It is logical that, when $P$ decreases, gully expansion decreases or even ceases, irrespective of CA. These models also indicate that the joint contribution of $P$ and CA explains 85–90% of gully growth rates.

4 | DISCUSSION

4.1 | Comparative role of rainfall and snowmelt in controlling gully growth

Gully lengthening is believed to be mainly triggered by severe rainstorms and resultant runoff events. However, the impact of late winter (especially snowmelt runoff) on gully development is often overlooked.

Rysin et al. (2017) estimated that the mean LGHR rate was 1.30 m yr$^{-1}$ over 1978–1997 and 0.32 m yr$^{-1}$ between 1998 and 2015 in the Udmurt Republic, eastern Russian Plain. Nevertheless, the relatively small mean LGHR value (0.83 m yr$^{-1}$ over 1978–2015) probably indicates that most studied gullies are discontinuous, including those located in valley-bottoms. They observed that 81% of LGHR over 20 years (1978–1997) was induced by snowmelt runoff in March and April. Then, this contribution dropped to 53% between 1998 and 2015. That means that 67% of LGHR were triggered by snowmelt
runoff over 38 years (1978–2015) within the Middle Volga region (2.4–4.1°C mean air temperature and $P = 530$–$560$ mm yr$^{-1}$, of which 45% fell between October and March). Decreased LGHR after 1997 was associated with increased air temperatures, in the context of global warming. This resulted in less snowmelt runoff contribution to gully development, probably resulting from decreased depth of frozen soil and less frequent heavy rainfall events > 50 mm (Rysin et al., 2017; Golosov et al., 2018; Sharifullin et al., 2019). Although mean air temperature increased by 0.8°C, from −8.1°C (1950–2017) to −7.3°C (1981–2010) during November–March at Kazan, Tatarstan, winter temperatures remained sub-zero. Thus, it can be expected that increased air temperature resulted in a shorter duration of snowmelt runoff. Generally, LGHR rates increase with the duration of snowmelt runoff.

Xu et al. (2019) studied one 239 m long gully, located in a gently sloping 5.7 ha catchment on Mollisols in Hailuny, Heilongjiang Province (China). Based on snowmelt runoff and sediment transport data during March 2017, they concluded that snowmelt-induced erosion greatly impacts on gully erosion and development. LGHR was 2.3 m and total AGG 57 m$^2$. However, mean $P$ over November–March is 29 mm (5% of the annual $P$ of 550 mm) and the mean air temperature is −13.8°C (2.5°C is the mean annual temperature at Hailun). Accordingly, we assume that the impact of the snowmelt runoff on gully extension is limited and, over the long term, probably minimal in northeast China. Using data published by Piest et al. (1975), it was possible to calculate a cold season contribution of 25% for both LGHR and AGG in western Iowa. Over the 7 year period, mean $P$ between October and March accounted for 23% (193 mm) of the annual total (828 mm yr$^{-1}$). Nevertheless, in nearby Omaha, eastern Nebraska, that $P$ fraction increased to 27% of the annual total (778 mm yr$^{-1}$) during 1981–2010. Here, mean air temperature is 10.6°C and a sub-zero mean monthly air temperature of −3.4°C occurs during December–February.

Mean annual air temperature at Barlad (Romania) is 10.2°C, which rises from −2.5°C in January to 21.6°C in July (1961–2020). Mean annual $P$ is 508 mm, with a monthly peak of 75 mm during June and a minimum of 24.8 mm in February. Some 178 mm (35% of annual $P$) falls October–March and 330 mm (65%) falls during the warm season.

**FIGURE 9** Bottle-neck shaped incision in the headcut of Gheltag continuous gully on 8 June 1979 (a) and gully development by 4 November 1988 (b) [Color figure can be viewed at wileyonlinelibrary.com]

**FIGURE 10** Measured versus predicted relative mean linear gully head retreat (LGHR)

$y = x - 3E-15$

$R^2 = 0.57$

$n = 20$
Mean linear gully head retreat (LGHR) rate for six continuous gullies between 1981 and 2000 values have been calculated as weighted means. Note: Gheltag gully data were excluded due to its disturbed growth pattern between November 1978 and April 1985, after a marked fall in mean air temperature to –9.9 °C in February. Large loamy ‘blocks’ of regolith (~11 m³, 4.4 m long, 1.1 m wide and 2.3 m thick) collapsed into the gully one-week after the cessation of snowmelt runoff, associated with rapid warming.

Precipitation distribution, air temperature and the stage of vegetation cover throughout the year are important for estimating the relative impact of cold and warm seasons on gully growth. For example, when comparing the mean values of these six gullies during two wetter years (P = 579 mm in 1988 and 613 mm in 1996) and gully growth, mean LGHR was 19 m in 1988 (of which 7 m was in late winter and 12 m in spring) and 10 m in 1996 (of which 8.5 m was late winter and 1.5 m in the warm season). The same pattern was observed in terms of mean AGG: 304 m² in 1988 (103 m² in late winter and 201 m² in the warm season) and 168 m² in 1996 (132 m² in late winter and 36 m² in the warm season). Cold season values are similar, but major differences are due to the timing of erosive rains. For instance, 215 mm fell during spring 1988, when the widely-spaced crops (mainly maize and sunflowers) had not yet developed a protective vegetation cover and consequently erosion was severe. In contrast, 250 mm fell during August–September 1996, when the vegetation cover was well developed. Hence, relatively little erosion occurred.

The calculated 1-in-10 year daily rainfall at Barlad is 80 mm. However, the largest recorded 24-h rainfall total was 131.5 mm on 22 June 1999 at Perieni Research Station. The daily total consisted of four successive rainstorms of 36.3, 32.4, 29.3 and 33.5 mm. These storms caused the highest gully growth rates in a single day. However, the cumulative longer-term contribution of the cold season (especially nival processes and snowmelt runoff during late winter) exceeds the impact of rainfall on gully development.

Over time, the hydraulic parameters of the flow for 122 wetted CSAs, associated with the main rain and snowmelt events, have been measured upstream of the trunk head of five continuous gullies (Valcioaia, Tumba, Recea, Chira and Loava). The mean weighted value of the HR of the flow was 0.338 m (flow width = 2.74 m; flow depth = 0.5 m; CSAF = 1.04 m²), and ranged between 0.259 m for Valcioaia gully and 0.358 m for Tumba gully. Of all 122 wetted CSAs, ~50% had HR values < 0.201 m, 32% between 0.201 and 0.400 m, 14% between 0.401 and 0.600 m and 5% > 0.600 m.

Most streamflow events generated by snowmelt were included in the first category (HR < 0.201 m), which comprises small and prolonged runoff events. This finding agrees with Heede (1975) that ‘in ephemeral channels, sediment loads are often more closely related to time and duration of flow than to magnitude of flow’. However, they are very efficient, because the flow always falls at the headcut base and triggers more extensive undermining during late winter (Figure 12).

Peak runoff discharges at the outlet of the 2997 ha Chioara Catchment rose to 6 m³ s⁻¹ during streamflow fed by snowmelt (Ionita, 1998, 2000, 2008) and ~90 m³ s⁻¹ due to heavy rains, such as those in early July 1997 and late June 1999 (Ionita, Niacsu, et al., 2015).

Based on data collected from different locations in the temperate zone of the Northern Hemisphere, it is possible to postulate that the relative contribution of the cold season to the linear GHR is highly variable and is closely related to climatic conditions. Thus, the contribution is very small in northeast China, ~25% in western Iowa (USA),

Table 7 Mean linear gully head retreat (LGHR) rate for six continuous gullies between 1981 and 2000

| Gully    | Total (m yr⁻¹) | Cold season (%) | Warm season (%) |
|----------|---------------|----------------|-----------------|
| Recea    | 6.0           | 3.2            | 2.8             |
| Chira    | 1.6           | 1.0            | 0.6             |
| Loava    | 2.1           | 1.2            | 0.9             |
| Mitoc    | 5.2           | 2.2            | 3.0             |
| Tumba    | 2.9           | 2.3            | 0.6             |
| Valcioaia| 10.6          | 6.3            | 4.3             |
| Mean     | 4.7           | 2.7            | 2.0             |

Note: Gheltag gully data were excluded due to its disturbed growth pattern between November 1978–May 1988, as already described. The bold mean values have been calculated as weighted means.
4.2 | Relationships between continuous gullies and upstream discontinuous gullies

The increased depth of some gullies may be due to geomorphic factors, especially changes in longitudinal slope over time. However, it is unclear which factors are responsible for slope gradients upstream of continuous gully headcuts. Of all 14 continuous gullies, 12 (86%) have slope gradients at the gully head (SGGH) between 1.1% and 3.5% (Figure 13).

Most continuous gullies are fed either by upper discontinuous gullies, developed several tens to hundreds of metres upstream from the main gully headcut (e.g., Tumba, Puriceni [gullies 1, 2 and 3], Puriceni-Bahnari, Chira, Loava) or by small channels located in very recent alluvium/colluvium along valley bottoms (e.g., Recea, Valcioaia).
These channel developments upstream from the main gully headcuts are much smaller than continuous gullies, but they play an important role. Their characteristics largely govern runoff patterns (accommodation of the flow) towards and through the continuous gully heads and, implicitly, their growth.

When the approaching discontinuous gullies develop in recent alluvial/colluvial fill they result in a trapezoidal or U-shape CS. The sizes of these CS are highly variable. For example, above the head of the trunk gully of Valcoiaoa, Hreasca and Tamba, these gullies are 0.3–1.2 m deep, have an actual CS of 0.4 to 9.4 m² and a hydraulic radius at bankfull-channel (HRBC) of 0.094 to 0.836 m. However, two processes inducing morphological changes along the approaching discontinuous gullies have been noticed: that is (1) a decreased CS due to sediment deposition or (2) an increased CS due to channel incision. Usually, these processes within the approaching discontinuous gullies result in smaller growth rates of the trunk continuous gullies than expected.

Firstly, the progressive sedimentation on the discontinuous gully floor can be highlighted by comparing actual CS values with their total CS (actual CS + filled CS) values 1.7–3.2 m depth, 5.3–24.2 m² area and 0.835–1.734 m HRBC. That means current values represent only 8–39% of total CS and 11–48% of total HRBC.

A typical example is Hreasca gully head, where high LGHR over 1960–1984/1990 (mean 512 m yr⁻¹) decreased 8.7-fold between 1991 and 2020 (mean 5.9 m yr⁻¹). This is a typical case of gully erosion as both a natural and human-induced hazard (Ionita, Fullen, et al., 2015). More precisely, since 1991, due to decreased sheep farming, forest vegetation regrew along the upstream discontinuous gully. Increased vegetation cover increased channel roughness and sedimentation, which is emphasized by an alluvial ridge within the channel axis. The current size of the actual CS represents only one-quarter of the original total area (Figure 14a). Additionally, two broad and shallow furrows and ridges progressively formed due to soil tillage parallel and close to gully banks (ploughing has caused the outward inversion of soil). Consequently, these new topographic irregularities triggered major changes in how flow enters and is conveyed through Hreasca gully head (runoff accommodation). Runoff is now partly deflected towards the gully sides and this decreases flow concentration and, implicitly, leads to slower gully head retreat.

Based on a flow-scouring experiment (including 11 tests with two runoff discharges) Dong, Xiong, et al. (2019) found that for individual runoff events, GHR rates could not be predicted by flow hydraulics alone, because of the considerable contribution of GHR to mass failures. For longer time scales, however, the influence of soil collapse at the gully head is less and flow hydraulics becomes dominant in terms of predicting GHR.

Field measurements of flow geometry, associated with a major rainfall event of 38.2 mm on 1 July 2018 revealed that the HR within the central CS was 0.341 m at 2 m upstream of the gully headcut, while at 39 m downstream HR was over double (i.e., 0.707 m). Under these circumstances, only about one-third of the upstream flow entered the Hreasca gully headcut orthogonally and the other two-thirds were deflected downstream (Figure 14b).

A very similar situation occurred in Valcoiaoa gully. Until the late 1980s, arable land on the right valley-side was generally cultivated along the contour. Based on hydraulic indicators of streamflow measured on 27 July 1984, it was estimated that only 63% of water flowed orthogonally to the gully headcut (0.441 m HR and 1.55 m² CSAF of the almost full upstream discontinuity). The remaining 37% of flow was deflected. After the late 1980s, runoff patterns were altered by the adoption of an up-and-down slope farming system. Small side colluvial fans almost clogged the former discontinuity upstream of the gully head and CS decreased < 0.5 m². Thus, the much smaller ACS frequently favours deflection of some runoff along the left broad channel, and LGHR decreased to 9.4 m yr⁻¹ between 1991 and 2020 (about half of the 1961–1990 LGHR value).

Secondly, the increased CS of the approaching discontinuous gully, by deepening the gully floor, triggers the cutting of notches in the trunk gully headcut. When gully flow cuts into the B horizon, the CS becomes V-shaped and the associated HR doubles. The B horizon material is 3–4 times more resistant to concentrated flow erosion than the A or C soil horizons (Poesen & Govers, 1990). When gully flow cuts into the weaker C horizon, it undermines the overhanging B horizon and the most intense stage of gully growth develops, triggering regular increases in gully area (Ireland et al., 1939).

Based on field observations and measurements, it was found that relationships between the deepening of the upstream channel and the LGHR rate of the trunk gully during the process of gully fusion is non-linear. Two stages can be identified. One of a larger LGHR, when the larger the HR, the more efficient the upstream channel is, and the trunk headcut height accelerates gully growth (ascendant type). The other type is of a smaller LGHR that still maintains a large HR, but the main headcut height and LGHR are decreasing (descendent type). In this type, there is usually no deflection of flow; the gullies merge and it is often difficult to distinguish the new location of the former gully head-scarp (e.g., Puriceni gully 1 in 2015).

Other typical examples of the evolution of approaching discontinuous gullies above the trunk gully head are in the Fagaras, Angheluta, Scranghita-Poligon and Chira gullies. Thus, Fagaras GHR decreased markedly to a mean 0.6 m yr⁻¹ over 1991–2020 (vs. 12.1 m yr⁻¹ weighted mean between 1964 and 1990) because of almost complete gully fusion. Angheluta gully headcut has been visibly notched during the last decade and its height decreased from 3 to 1 m in 10 years (see Figure S4). These changes and the decreased growth rates of
both gullies occurred after their headcut entered a black locust 
(\textit{Robinia pseudoacacia}) buffer strip. The presence of small trees in the 
thalweg forced runoff to split and flow became divergent and more 
prolonged. Therefore, there is a threshold between these stages of 
gully deepening and, intuitively, it can be expressed as the ratio 
between the CS geometry upstream and downstream of the trunk 
gully headcut. Important ratios include the ACS or the GD of the 
upstream discontinuous gully, versus the CS or GD of the main gully 
head. However, these ratios vary considerably, depending on local 
conditions.

The optimum ratio between upstream and downstream channel 
depth (GD), capable of maintaining the highest LGHR during 
channel deepening is \(\sim 1:7\) or \(\sim 1:10\) between upstream CSA and 
downstream CSA at the point along the gully bed that is free of recent 
debris. For example, in May 1984, the total vertical height of Puriceni 
gully 1 headcut was 9.0 m, of which the head-scarp height was 4.9 m 
(54\% of the total) and the remaining 4.1 m was the depth of the 
approaching discontinuous gully. After 8 years (June 1992), the depth 
of the discontinuous gully had increased to 5.4 m (60\% of the total), 
with its floor now incised into the C horizon. Then, incision cut into 
the loamy D horizon and, by 2015, the former impressive gully head- 
scarp had almost disappeared.

\section{Conclusions}

This study reports one of the longest continuous field monitoring 
studies of gully development in Europe, extending from 1961 to 
2020. Changes in the mean annual LGHR and mean annual AGG were 
measured in 14 gullies. Effectively, 325 individual field measurements 
were performed during 1978–2020, using the ‘stakes grid method’
and topographical surveying. Furthermore, the database includes 
information extracted from four series of aerial photographs 
(i.e., 1960, 1970, 2005 and 2009) and LiDAR (light detection and 
ranging) data (2012).

Results show that the mean LGHR of 7.7 m yr\(^{-1}\) over 60 years 
was accompanied by a mean AGG of 213 m\(^2\) yr\(^{-1}\). The gully head ero-
sion rates between 1961 and 1980 were 4.0 times larger for LGHR 
and 5.9 times more for AGG compared to those for 1981–2020. 
However, this decreasing trend corresponds closely to the pattern of 
decreasing annual \(P\).

Temporal distribution of annual \(P\) is the primary controlling factor, 
explaining 57\% of the variability in total LGHR and 53\% of the total 
AGG. Contributing CA is the next important factor, explaining 33\% of 
LGHR and 32\% of AGG, respectively. When using the product of CA 
and mean catchment slope (CA \(\times\) S), instead of CA, similar predicted
values of LGHR and AGG resulted, attributable to the very small variation of slope gradients calculated for the tributary catchment of each successive gully head. Locally, important changes are linked to both human activity (i.e., land-use changes, building check-dams) and natural conditions (e.g., litho-pedological properties).

The article contributes to our understanding of: (1) the comparative role of rainfall and snowmelt in controlling gully growth and (2) the relationships between continuous gullies and upstream discontinuous gullies.

In the first case, most flow events generated by snowmelt are associated with HR values < 0.201 m, which comprises of prolonged low-volume runoff events. Nevertheless, such events are very efficient, as runoff water falling at the headcut base causes intense plunge pool erosion and triggers notable gully wall undermining and subsequent collapse during late winter. Thus, 57% of mean LGHR and 54% of mean AGG occurred in the cold season (due to nival processes and snowmelt runoff) between 1981 and 2000.

In the second case, continuous gullies are usually fed either by upper discontinuous gullies or by small channels (swales) located in very recent alluvium along valley bottoms. They play important roles in determining runoff patterns when flow enters the trunk gully head and notable ‘pulses’ of GHR often result. This is due to the alternation of sectors with sediment deposition and with channel incision along the discontinuous gully floors. On the one hand, morphological changes related to sediment deposition induces runoff deflection towards the gully sides and this decreases flow concentration and, implicitly, leads to decreased gully head retreat. On the other hand, channel incision above the trunk gully headcut leads to runoff concentration, triggering regular increases in gully head area.

ACKNOWLEDGEMENTS

Many thanks are expressed to the Department of Geography, University of Iași, for financial support of field measurements over the last 3 years. The authors thank the Romanian National Meteorological Administration for providing precipitation data from Barlad Station. They also express their gratitude to the National Administration for providing precipitation data from Barlad Station last 3 years. The authors thank the Romanian National Meteorological Administration for providing precipitation data from Barlad Station. The data that support the findings of this study are available due to privacy or ethical restrictions.

REFERENCES

Brice, J.C. (1966) Erosion and Deposition in the Loess-Mantled Great Plains, Medicine Creek Drainage Basin, Nebraska. Geological Survey Professional Paper 352-H: 255–339. US Geological Survey, Reston, VA.

Burkard, M. & Kostaschuk, R. (1997) Patterns and controls of gully growth along the shoreline of Lake Huron. Earth Surface Processes and Landforms, 22(10), 901–911. https://doi.org/10.1002/(SICI)1096-9837(19971022)22:10<901::AID-ESP430>3.0.CO;2-6

Dong, Y., Wu, Y., Qiu, W., Guo, Q., Yin, Z. & Duan, X. (2019) The gully erosion rates in the Black Soil region of northeastern China: Induced by different processes and indicated by different indexes. Catena. 182, 104–146.

Dong, Y., Xiong, D., Sua, Z., Duan, X., Luc, X., Zhang, S. & Yuana, Y. (2019) The influences of mass failure on the erosion and hydraulic processes of gully headcuts based on an in situ scouring experiment in a dry-hot valley of China. Catena. 176, 14–25. https://doi.org/10.1016/j.catena.2019.01.004

Golosov, V., Yermolaev, O., Rysin, I., Vannaeckere, M., Medvedeva, R. & Zaytseva, M. (2018) Mapping and spatial-temporal assessment of gully density in the Middle Volga region, Russia. Earth Surface Processes and Landforms, 43(13), 2818–2834. https://doi.org/10.1002/esp.4435

Graf, W. (1979) The development of montane arroyos and gullies. Earth Surface Processes, 4(1), 1–14. https://doi.org/10.1002/esp.3290040102

Harjoaba, I. (1968) Relieful Colinelor Tutovei. Editura Academiei R.S. Romania, Bucharest, Romania.

Heede, B.H. (1975) Stages of development of gullies in the West. Present and Prospective Technology for Predicting Sediment Yields and Sources. USDA-ARS, 5-40, 155–161.

Ionita, I. (1998) Studiul geomorfologic al degradarilor de teren din bazinul mijlociu al Barladului. Teza de doctorat. Universitatea “Al. I. Cuza,” Iasi.

Ionita, I. (2000) Formarea si evolutia ravinei din Podisul Barladului. Iasi, Romania: Editura Corson.

Ionita, I. (2006) Gully development in the Moldavian Plateau of Romania. Catena, 68(2–3), 133–140. https://doi.org/10.1016/j.catena.2006.04.008

Ionita, I. (2008) Sediment movement from small catchments within the Moldavian Plateau of Eastern Romania. In: Schmidt, J., Cochrane, T., Phillips, C., Elliot, S., Davies, T. & Basher, L. (Eds.) Sediment Dynamics in Changing Environments. Wallingford, UK: International Association of Hydrological Sciences Publication 325, IAHS Press, pp. 316–320.

Ionita, I., Fullen, M.A., Zglobicki, W. & Poensen, J. (2015) Gully erosion as a natural and human-induced hazard, Editorial. Natural Hazards, 79 (Suppl. 1), 1–5. https://doi.org/10.1007/s11069-015-1935-2

Ionita, I., Niacsu, L., Petrovici, G. & Blebea-Apostu, A.M. (2015) Gully development in eastern Romania: A case study from Fâlcu Hills. Natural Hazards, 79(Suppl. 1), 113–138. https://doi.org/10.1007/s11069-015-1732-8

Ionita, I., Radoane, M. & Mircea, S. (2006) Ch. 1.15 Romania. In: Boardman, J. & Poensen, J. (Eds.) Soil Erosion in Europe. Chichester, UK: John Wiley & Sons, pp. 155–166.

Ireland, H.A., Sharpe, C.F.S. & Eagle, D.H. (1939) Principles of gully erosion in the Piedmont of South Carolina. USDA Technical Bulletin 633. USDA, Washington, DC.

Jennraenud, P. (1971) Geologia Moldovei centrale dintre Siret si Prut. Rezumatul tezei de doctorat, Universitate “Alexandru Ioan Cuza,” Iasi.

Li, Z., Zhang, Y., Zhu, Q.K., He, Y.M. & Yao, W.J. (2015) Assessment of bank gully development and vegetation coverage on the Chinese Loess Plateau. Geomorphology, 228, 462–469. https://doi.org/10.1016/j.geomorph.2014.10.005

Motoc, M. (1983) Ritmul mediul de degradare erozionala a solului in R.S.R. Bul. Inf. 2: 67–73. ASAS, Bucharest, Romania.

Nachtgeraede, J., Poensen, J., Oostwood Wijdenes, D. & VandeKerkhove, L. (2002) Medium-term evolution of a gully developed in loess-derived soil. Geomorphology, 46(3-4), 223–239. https://doi.org/10.1016/S0169-555X(02)00075-2
Niacsu, L. (2012) Bazinul Pereașchiu lui (Colinele Tutovei). Studiu de geomorfologie și pedogeografie cu privire specială asupra utilizării terenurilor. Iasi, Romania: Editura Universității Alexandru Ioan Cuza.

Niacsu, L. & Ionita, I. (2011) Gully erosion in the Pereașchiu catchment of eastern Romania. Landform Analysis, 17, 135–137.

Piest, R.F., Bradford, J.M. & Sperer, R.G. (1975) Mechanisms of Erosion and Movement from Gullies. In: Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S-40. Washington, DC: Agricultural Research Service, USDA, pp. 162–176.

Poens, J. & Govers, G. (1990) Gully Erosion in the Loam Belt of Belgium: Typology and Control Measures. In: Boardman, J., Foster, I. & Dearing, J. (Eds.) Soil Erosion on Agricultural Land. Chichester, UK: John Wiley & Sons, pp. 513–530.

Poens, J., Nachtergaele, J., Verstraeten, G. & Valentin, C. (2003) Gully erosion and environmental change: importance and research needs. Catena, 502-4), 91-133. https://doi.org/10.1016/S0341-8162(02)00143-1

Poens, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G. & van Wesemael, B. (2002) Gully erosion in dryland environments. In: Bull, L.J. & Kirkby, M.J. (Eds.) Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels. Chichester, UK: John Wiley & Sons, pp. 229–262.

Poghiric, P. (1972) Satul din Colinele Tutovei. Studiu geografic. Bucharest, Romania: Editura Stiintifica.

Radoane, M., Ichim, I. & Radoane, N. (1995) Gully distribution and development in Moldavia, Romania. Catena, 24(2), 127–146. https://doi.org/10.1016/0341-8162(95)00023-L

Radoane, M. & Radoane, N. (1992) Areal distribution of gullies by the grid square method. Case study: Siret and Prut interfluve. Revue Roumaine de Géographie, 36, 95–98.

Radoane, M., Radoane, N., Surdeanu, V. & Ichim, I. (1999) Ravenele. Forme, procese, evolutie. Cluj Napoca, Romania: Editura Presa Universitară Clujeana.

Rengers, F.K. & Tucker, G.E. (2014) Analysis and modeling of gully headcut dynamics, North American high plains. Journal of Geophysical Research – Earth Surface, 19, 983–1003.

Rieke-Zapp, D.H. & Nichols, M.H. (2011) Headcut retreat in a semiarid watershed in the southwestern United States since 1935. Catena, 87 (1), 1–10. https://doi.org/10.1016/j.catena.2011.04.002

Rodič, J., Furtak, T. & Zglobicki, W. (2009) The impact of snowmelt and heavy rainfall runoff on erosion rates in a gully system, Lublin Uplands, Poland. Earth Surface Processes and Landforms, 34(14), 1938–1950. https://doi.org/10.1002/esp.1882

Rysin, I., Grossiev, L., Zaytseva, M., Golosov, V. & Sharfullin, A. (2017) Long-term monitoring of gully erosion in Udmurt Republic, Russia. Proceedings of the International Association of Hydrological Sciences, 375, 1–4. https://doi.org/10.5194/plahs-375-1-2017

Saxton, N.E., Olley, J.M., Smith, S., Ward, D.P. & Rose, C.W. (2012) Gully erosion in sub-tropical south-east Queensland, Australia. Geomorphology, 173-174, 80–87. https://doi.org/10.1016/j.geomorph.2012.05.030

Sharfullin, A., Gafurov, A., Medvedeva, R., Golosov, A., Dvinshikh, A., Gusarov, A. & Eissuman-Quainoo, B. (2019) Contemporary gully erosion trend in the northern part of the forest-steppe zone of the Russian Plain: A case study from the Republic of Tatarstan, European Russia. Proceedings of the International Association of Hydrological Sciences, 381, 21–24. https://doi.org/10.5194/plahs-381-21-2019

Thomas, J.T., Iverson, N.R., Burkart, M.R. & Kramer, L.A. (2004) Long-term growth of a valley-bottom gully, western Iowa. Earth Surface Processes and Landforms, 29(8), 995–1009. https://doi.org/10.1002/esp.1084

Vandekerckhove, L., Poens, J., Wijdenes, D.O. & Gyssels, G. (2001) Short-term bank gully retreat rates in Mediterranean environments. Catena, 44(2), 133–161. https://doi.org/10.1016/S0341-8162(00)00152-1

Vanmaercke, M. (2013) 6th International Symposium on Gully Erosion in a Changing World (6th ISGE) held in Iasi (Romania), 6–12 May 2013. In: European Society for Soil Conservation Newsletter 2013 (2): 22–25.

Vanmaercke, M., Poens, J., Van Mele, B., Demuzere, M., Bruyneels, A., Golosov, V., et al. (2016) How fast do the gully heads retreat? Earth Science Reviews, 154, 336–355. https://doi.org/10.1016/j.earscirev.2016.01.009

Wilkinson, S.N., Kinsey-Henderson, A.E., Hawdon, A.A., Hairsine, P.B., Bartley, R. & Baker, B. (2018) Grazing impacts on gully dynamics indicate approaches for gully erosion control in northeast Australia. Earth Surface Processes and Landforms, 43(8), 1711–1725.

Xu, J., Li, H., Liu, X., Hu, W., Yang, Q., Hao, Y., et al. (2019) Gully erosion induced by snowmelt in Northeast China: A case study. Sustainability, 11(2088), 1–14.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Ionita, I., Niacsu, L., Poens, J. & Fullen, M.A. (2021) Controls on the development of continuous gullies: A 60 year monitoring study in the Moldavian Plateau of Romania. Earth Surface Processes and Landforms, 46(13), 2746–2763. Available from: https://doi.org/10.1002/esp.5204