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Medium-term development of discontinuous gullies

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ABSTRACT

Intense gully erosion has sculptured remarkable channels into the Moldavian Plateau of eastern Romania, especially in its most representative subunit, the Bârlad Plateau covering >8000 km^2. The permanent gully types are: (1) discontinuous gullies, mostly located on hillslopes and (2) large continuous gullies in valley bottoms.
This study seeks to improve our understanding of the development of discontinuous gullies over variable timescales (mostly 17–30 years, but also including data collected since 1961) by providing quantitative information on gully evolution and processes. Several methods were used to accurately measure and estimate gully growth. These include intensive field monitoring between 1978 and 2000 using the 'stakes grid method,' repeated levelling until 2019, analysis of aerial photographs and Caesium-137 analysis.
The discontinuous gullies occur as single, successive (chains) or clusters. These are associated with small catchments (usually <100 ha in area) and ephemeral peak runoff discharges are usually ≤2 m^3 s^{-1}. The 'hydraulic radius at bankfull-channel' tended to decrease downstream of the gully head, accompanied by a gradual increase in gully bottom width. A salient tendency observed during major runoff events was for the hydraulic radius of the flow to progressively decrease downslope, accompanied by decreasing sedimentation rates on gully floors. The mean linear gully head retreat for 31 gullies was 0.97 m yr^{-1}, indicative of a relatively slow erosion rate. However, their 'pulsatory' development was mostly controlled by runoff accommodation when runoff enters and is conveyed through a gully. We especially discuss the changing runoff pattern or '*variable-geometry flow*.' The R^2 of the association between linear gully head retreat or areal gully growth and catchment area indicated a weak correlation for discontinuous gullies.

1. Introduction

A long-standing challenge is to understand processes governing gully development. An important feature of many gully systems is that they tend to form well-ordered dendritic networks. This suggests that while stochastic processes may play a role in gully growth and bifurcation, deterministic processes are also involved (Baird et al., 1992).

Thornes (1984) proposed an analytical model, assuming that gully growth is analogous to a 'shock-wave' migrating through the hillslope. He suggested that the relative magnitudes of forward and lateral/outward migration of gully walls may be critical in controlling branching, or bifurcation. When gully migration is controlled by overland flow processes, the 'shock' is 'supersonic' and long narrow gully channels develop, due to the limited opportunity for branching. When the widening of channels is mostly influenced by active mass failure, the likelihood of branching may increase, and the 'shock' is 'subsonic.'

A theoretical, digital model was proposed by Kemp (1990), by simulating headward migration of gullies, where the governing process is erosion by overland flow. This model illustrates how the growth and bifurcation of a gully may be critically controlled by the way in which the gully head geometry and slope topography influence particular processes.

Generally, rate of gully growth is more closely related to the topographic position of the gully head than to any other single factor (Brice, 1966). This logically implies that gully growth is mostly controlled by the size of the catchment area (CA). However, this parameter does not have a clear relation to hydraulic variables.

In order to increase the readability of this paper, Table 1 lists all gully variables (and acronyms) discussed in this paper.

In an analysis of data from western Iowa, Beer and Johnson (1965) correlated gully growth positively with surface runoff and negatively with gully length and distance from the catchment interfluve. Similarly, Piest et al. (1975) found that gully growth is strongly correlated with

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Table 1
List of discussed variables and their acronyms.

Variable	Description	Unit
ACS	Actual cross-section: the present-day visible CS of the discontinuous gullies	m^2
AGG	Areal gully growth rate in plan	$m^2\ y^{-1}$
CA	Catchment area: drainage area upstream of the gully head or at the gully outlet	ha
CS	Cross-section of gully channel measured perpendicular to its main axis	m^2
CSA	Cross-sectional area of gully channel	m^2
DDGH	Distance downstream of the gully head: the horizontal distance between the gully head and a specific downstream point/location	m
FCS	Filled cross-section: the CS of a discontinuous gully filled by recent sediment	m^2
FGD	Filled gully depth: mean vertical distance between the original gully bed and the present-day gully bed	m
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
GBW	Gully bottom width: the length of the straight line linking the edges of the gully floor	m
GTW	Gully top 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 to its 'wetted perimeter' (dummy variable)	m
LGHR	Linear gully head retreat rate: linear gully growth	$m\ y^{-1}$
WP	Wetted perimeter: the perimeter of the cross-sectional area of the flow that is 'wet'	m
WPBC	Wetted perimeter at 'bankfull-channel': the perimeter of the gully cross-section area that is 'wet' (dummy variable)	m
ST	Sediment thickness: thickness of very recent alluvia deposited on the gully floor or valley-bottom	m
MP	Moldavian Plateau of eastern Romania	
JRP	Jijia Rolling Plain: major sub-unit of the MP	
BP	Bârlad Plateau: major sub-unit of the MP	
CMP	Central Moldavian Plateau: sub-unit of the BP	
FH	Fălciu Hills: sub-unit of the BP	
TRH	Tutova Rolling Hills: sub-unit of the BP	

discharge. Some authors have advocated that decreased gully growth rate results from the associated decrease in gully CA and consequent runoff volume (e.g. Graf, 1979; Burkard and Kostaschuk, 1997; Poesen et al., 2002, 2003; Nachtergaele et al., 2002; Vandekerckhove et al., 2001). By using a simple regression, Rengers and Tucker (2014) observed no association between gully migration rate (as total travel distance within the path of the headcut) and drainage area at the current headcut location ($R^2 = 0.024$). Vanmaercke et al. (2016) presented a global meta-analysis of measured gully growth rates, which are significantly correlated with the runoff contributing area of the gully head ($r^2 = 0.15$; $n = 724$) and the 'rainy day normal' (RDN = mean rain depth during a rainy day; $r^2 = 0.47$).

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 (on the Eastern part of the Russian Plain). Nevertheless, the small mean value of LGHR (0.83 m yr^{-1} over 1978–2015) probably indicates that most of the studied gullies are discontinuous, including those located in the valley-bottoms. Some 67% of LGHR was triggered by snowmelt runoff over a 38 year period (1978–2015) within the Middle Volga region (2.4–4.1 °C mean air temperature and 530–560 mm yr^{-1} mean precipitation depth, of which 45% fell between October–March).

Gully erosion is an important environmental threat in the Moldavian Plateau (MP) of eastern Romania. Studies of gully evolution and control have received great interest over recent decades, mainly after the period 1968–1973, during which time land degradation has seen an unprecedented increase mainly due to higher precipitation than normal.

In a study of 38 gullies on the MP, detailed accounts of the factors causing gully development were reported by Rădoane and Rădoane (1992) and Rădoane et al. (1995, 1999). They concluded that gully growth depends on both lithology and catchment area (CA) upstream of the gully head. Also, they mapped two main areas of severe gully erosion in the MP and estimated that the average gully density between the Siret and Prut Rivers is 0.1–1.0 km km^{-2}, with maximum values exceeding 3 km km^{-2}.

The northern area includes the Jijia Rolling Plain (JRP), where small discontinuous gullies prevail, usually located on valley-sides. The southern area extends into the Bârlad Plateau (BP) and is typified by large, continuous, valley-bottom gullies (Ionita et al., 2021). However, most gullies are discontinuous. These gullies develop complex morphologies on the sandy-loamy substrata of the Fălciu Hills (FH), Tutova Rolling Hills (TRH) and northern half of Covurlui High Plain (CHP), known as the Covurlui Rolling Hills.

Ioniţă (1998, 2000, 2003, 2006) reported other results obtained on the BP and his main findings on discontinuous gullies are summarized as follows:

- The mean linear gully head retreat (LGHR) rate was 0.92 m yr^{-1} and the mean areal gully growth (AGG) was 17.0 $m^2\ yr^{-1}$ during a variable period of 6–18 years.
- The cold season between October–March, especially late winter freeze-thaw (nivation) processes during March, is responsible for ≤75% of discontinuous gully growth, but the critical period for gullying proceeds until mid-July.
- A new-channel shape factor has been identified, by relating actual cross-section (ACS) to filled cross-section (FCS) and value of 1.0 represents the threshold of hydraulic effectiveness of the discontinuous gullies.

Depending on the techniques used for measuring gully erosion, Poesen et al. (2003) distinguished the following time-scales: short time-scale (<1–10 years), medium time-scale (10–70 years) and long time-scale (>70 years), which implies use of historical data. There is a need for long-term monitoring of gully erosion to understand interactions between gully erosion and hydrological processes (Poesen et al., 2003; Valentin et al., 2005). Internal erosion and deposition processes within the gully complex below the scarp-face highlight the partially or fully transport-limited nature of the sediment yield (Shellberg et al., 2013).

In this study, we used medium-term (17–30 years) gully monitoring data from eastern Romania to better understand the development of discontinuous gullies. The main objective was to investigate the typology, flow characteristics and medium-term dynamics of discontinuous gully systems.

Gully growth is assessed by two parameters, which were precisely measured in the field, namely: linear gully head retreat (LGHR) and areal gully growth (AGG). Multiple associations were identified by plotting these indicators against gully geometry, selected ephemeral flow characteristics or contributing catchment area (CA).

2. Study area and methods

2.1. Study area

The BP is the most extended high subunit of the MP of eastern Romania and covers >8000 km^2. The BP is comprised of three major subunits: the Central Moldavian Plateau (CMP) in the north; the TRH, west of the Bârlad Valley; and the FH, east of the Bârlad Valley. Within the latter two subunits, the sedimentary substrata consist mainly of younger and relatively friable Late Miocene (Meotian/Tortonian and Pontian/Messinian) and Pliocene (Dacian/Zanclaen and Romanian) strata (Jeanrenaud, 1971). The sedimentary layers corresponding to

Meotian (Late Miocene) prevail on the lower and middle slopes and they comprises a succession of sands, clayey sands, clays, and shallow sandstone seams and are predominantly cross-bedded having a thickness of 150–180 m. On the upper slopes the Pliocene sands prevail, together with clay seams, accumulated in cross-bedded, coastal-deltaic facies (Jeanrenaud, 1971). A patchy loess-like mantle (usually <5 m deep) covers this area.

In the TRH, extending between the Racova, Bârlad and Siret valleys, these formations are incised by a consequent network of NNW-SSE oriented parallel valleys (Hârjoabă, 1968). Within this framework, a typical rolling hill landscape has developed, which is younger and fairly monotonous, with numerous long, rolling hills (collines).

East of the Bârlad Valley, in the FH, geological formations of similar age are split by short, subsequent, east-west oriented tributaries of the Bârlad River. They create typical asymmetrical valleys, where the left side has a northerly aspect cuesta front and the right side is a cuesta back-slope with a southerly aspect.

The climatological data were taken from the weather station located near Bârlad town (east Romania), in the middle of the study area, less than 15 km from the farthest investigated gully. Mean annual air temperature 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. Of the total amount, 178 mm (35%) falls during October–March and 330 mm (65%) falls during the warm season (April–September).

Bio-pedo-geographically, the higher areas are enclosed by deciduous forest, while sylvo-steppe is advancing within the Bârlad Valley. The native vegetation, especially forest, was drastically changed during the 19th Century; in particular forest was replaced by cropland, which remains the predominant land-use today. Accordingly, the zonal soils in the higher districts are Luvisols, with Cernisols in lower areas. Moreover, Ioniţă et al. (2015) noticed the importance on gully erosion of the widespread presence of duplex soils on the valley bottoms. Here, the gully banks show soils with two contrasting soil horizons. Usually, the topsoil of 2–3 m thick consists in a very recent alluvium blanket having a sandy loam to loamy sand texture. These sediments overlap a previous native soil having a thick Bt horizon, followed by the loam to sandy loam C horizon and usually loamy sand to sand D horizon.

The BP is the most representative subunit of the MP in terms of land degradation processes and has the most spectacular gully systems. Our study focuses on the development of nine gully systems (comprised of 31 discontinuous gullies) around the town of Bârlad, within an area of 1,520 km^2 (Fig. 1).

Across the entire BP, it is estimated that mean erosion rate varies between 20 and 30 t ha^{-1} yr^{-1} (Moţoc, 1983). For the 25,056 ha Racova catchment Niacşu et al. (2021) estimated a value of 24.8 t ha^{-1} yr^{-1}.

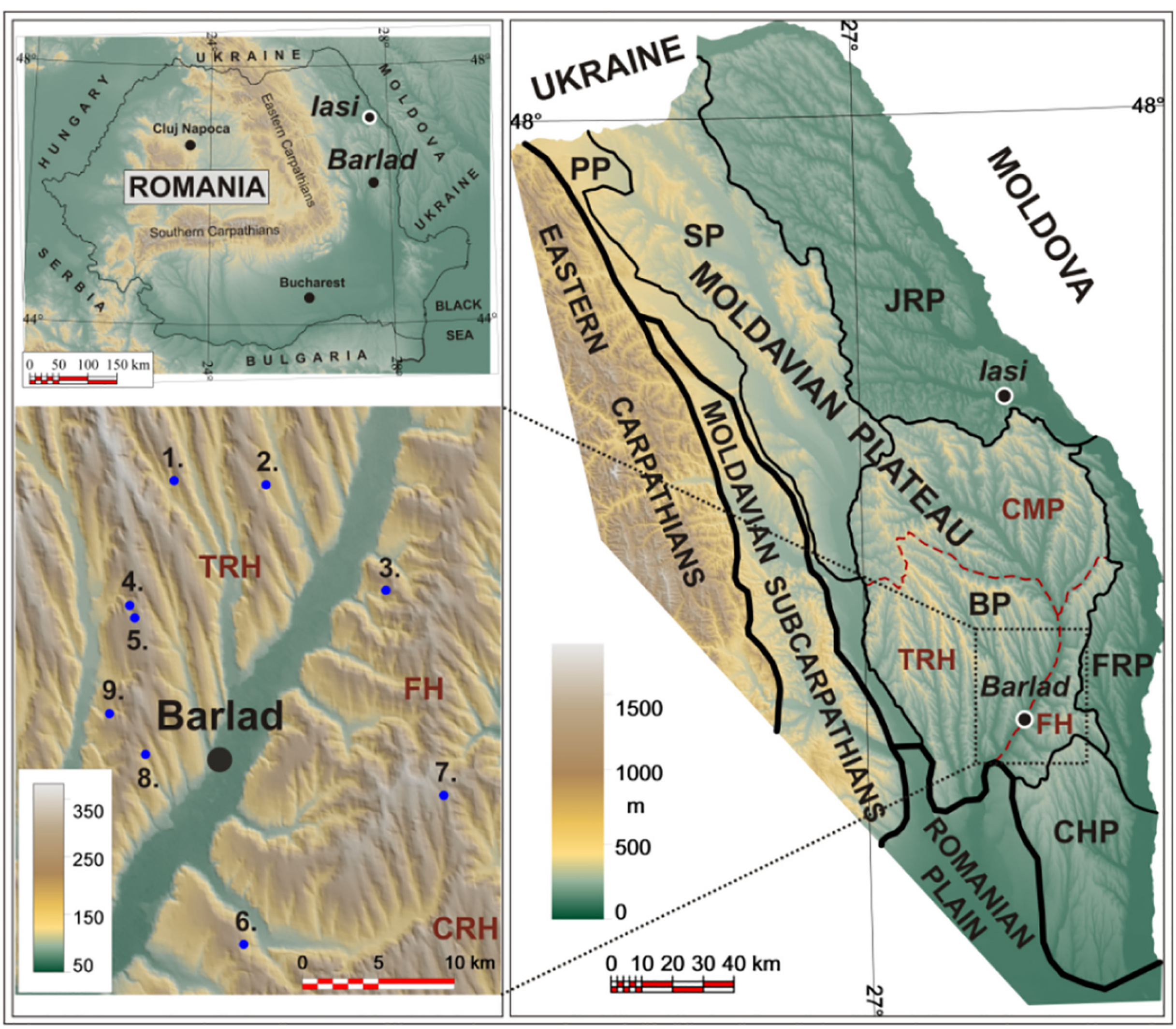

Fig. 1. Digital elevation model (DEM) of the study area and location of the gully systems.
No. of the gully systems: 1-Gornei, 2-Hârcioaia, 3-Larga, 4-Scrânghiţa (chain), 5-Scrânghiţa (cluster), 6-Timbru, 7-Puşca, 8-Căldarea, 9-Gheltag.

Therefore, the 'Perieni-Bârlad Research Station for Soil Erosion Control' was established in 1954. It became the 'Central Research Station' in 1970 and served as a model for soil and water conservation throughout Romania.

2.2. Methods

The first step in this study was to accurately determine gully development for a medium-term period of 17–30 years. Several methods have been deployed to accurately determine the most reliable gullying indicators, namely linear gully head retreat (LGHR) and areal gully growth (AGG), including:

1. Annual monitoring between 1979 and 2000 using the '*stakes grid method*' within the gully head area. This method 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 1:100 scale maps (Fig. 2). Large-scale field measurements were conducted in the discontinuous gully systems in several catchments, including Scrânghiţa-Roşcani, Timbru, Puşca, Hârcioaia, Gornei and Larga.

2. Stationary monitoring of gully growth by repeated levelling in combination with the analysis of aerial photographs from 1960 and 1970 and LiDAR in 2012.
3. Conventional measurements of sediment deposition, using iron plates on the floor of gullies during the 1987–1997period. Caesium-137 analysis of recently deposited sediments was made to provide chronological information on gully development. A soil auger set was also used to determine the thickness of recent sediments deposited along the floor of discontinuous gullies.

Runoff in most gully channels in the study area is ephemeral. Measurements of some peak flows were made mostly after runoff events, by measuring cross-sectional areas (CSA) of flow. At times, direct measurements of sediment concentration of flow were made during snowmelt.

In this paper, we only used the hydraulic radius (HR) data of the flow. Runoff discharges were not calculated because of the difficulties in selecting the appropriate Manning roughness coefficients to estimate the associated velocities. However, to better understand some characteristics of the geometry of discontinuous gullies, we also refer to 'hydraulic radius at bankfull-channel' (HRBC). Use of HRBC improved the classification of discontinuous gullies. Since these gullies are never entirely full with water, HRBC is a 'dummy variable.'

3. Results and discussion

3.1. Morphological characteristics of discontinuous gullies

Ioniţă (1998, 2000, 2003, 2006) distinguished three groups of discontinuous gullies: single, successive and batteries. This qualitative classification was based on data limited to gully morphology and the rate of gully floor aggradation; a typical process synchronous with gully channel incision. Now, this typology has been verified based on quantitative analysis, by including the variable 'bankfull geometry' of discontinuous gullies. The proposed classification of these gullies is: single, successive, and clusters (formerly termed 'batteries').

3.1.1. Single discontinuous gullies

Are relatively few in number, have a relatively isolated occurrence within small catchments and do not maintain a continuous channel between them. Their main morphological characteristics are decreasing channel depth downstream to their point of extinction (Leopold and Miller, 1956), while channel floor width increases due to sedimentation. Aggradation usually begins below the headcut area and migrates downstream, as the long gully floor progressively widens in the shape of 'long diffusor.' Under these circumstances, the depositional gully floor covers ~60% of the total gully area and the cross-sections (CS) of such gullies are typically trapezoidal as Sidorchuk et al. (2003) noticed also (Fig. 3). Consequently, the thickness of recent sediment deposited in such discontinuous gullies increases towards the gully outlet. Data on the 'bankfull geometry' of the Puşca and Căldarea gullies were collected as well (Table 2).

Based on surveys of 14 gully cross-sections (CS), levelled in March–July 1990 in the Puşca Catchment (156 ha), strong associations were evident between distance downstream of the gully head (DDGH) and both gully depth (GD; $r = -0.99$, $R^2 = 0.98$) and gully bottom width (GBW; $r = 0.98$, $R^2 = 0.97$) (Fig. 4). Other similar linear associations were found between gully length (GL) and sediment thickness (ST, in m), cross-sectional area (CSA, in m^2) and 'hydraulic radius at bankfull-channel' (HRBC, in m):

- $ST = 0.01GL + 0.16$, $R^2 = 0.91$, $n = 14$, $r = 0.95$.
- $CSA = 0.08GL + 51.51$, $R^2 = 0.89$, $n = 14$, $r = 0.94$.
- $HRBC = -0.004GL + 2.73$, $R^2 = 0.88$, $n = 14$, $r = 0.94$.

Within Căldarea gully (length 120 m, mean top width 8.2 m, mean depth 1.4 m; located within a 106 ha catchment), it was possible to distinguish between the actual cross-section (ACS) (13.8–1.1 m^2) and the cross-section filled with sediment (FCS) (14.2–5.8 m^2). The total CS was fairly constant (~17.7 m^2) along the gully, but the ACS/FCS ratio

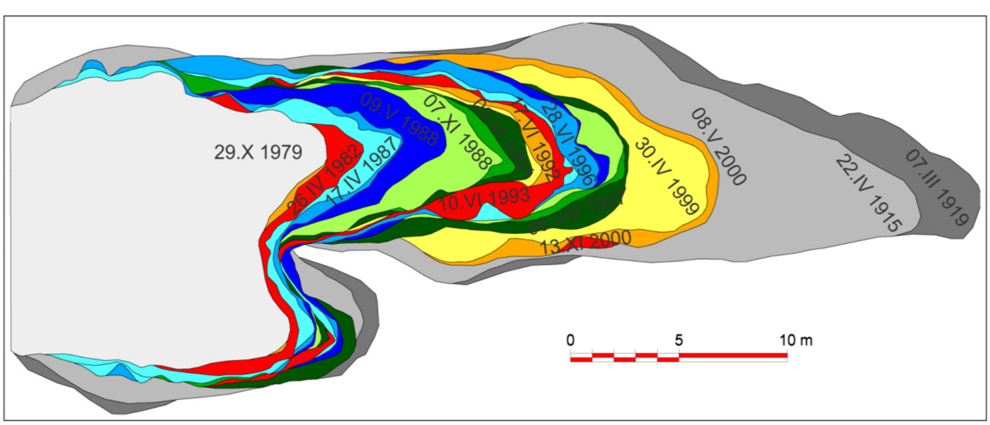

Fig. 2. Measured Gheltag discontinuous gully growth between 29 October 1979–07 March 2019 using both the '*stakes grid method*' and levelling. Labels refer to day, month and year of survey.

Fig. 3. Illustration of a single (isolated) discontinuous gully (Puşca gully in the Upper Jeravăţ Catchment, 03 May 2019).

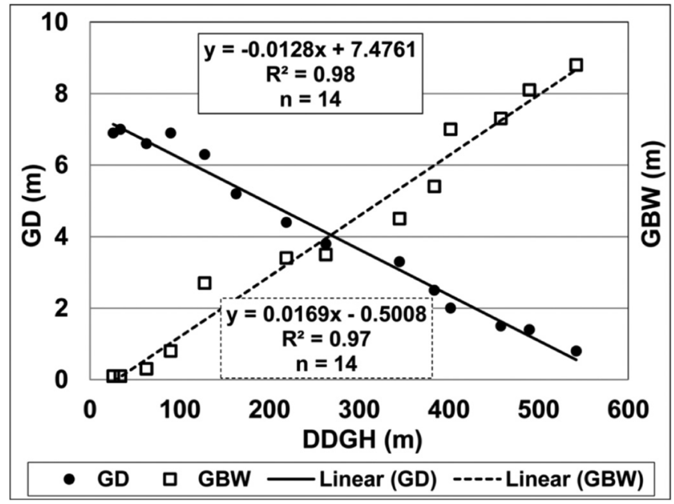

Fig. 4. Plot of gully depth (GD) and gully bottom width (GBW) with distance downstream of the gully head (DDGH) in Puşca gully.

decreased from 2.38 at 20 m DDGH to 0.08 at the gully outlet. Therefore, a strong negative correlation was found between this ratio and DDGH:

$$ACS/FCS = -0.02\ DDGH + 2.81, R^2 = 0.99, **P < 0.01, n = 4.$$

3.1.2. Successive (chain, cascade) discontinuous gullies

Have been categorized based on their rate of aggradation along the gully floor into *alluvial and erosional gullies*.

The ***successive alluvial gullies*** are the most common gullies in the study area, where deposition occurs following incision. Unlike the previous group, they succeed in maintaining a clear channel, so that the height of the gully banks never decreases to zero at the distal gully end (Fig. 5a & b).

They also have small catchments and appear mostly as divergent gullies, where the 'flaring' and short gully floor resembles a reverse funnel or 'short diffusor' (Fig. 5c). The trapezoidal CS shapes also prevail in these gullies due to sedimentation, but they alternate with triangular CS shapes in the gully head area, where net deposition is absent. The pattern of the mixed, alternative cross-sectional shapes, proceed upstream over time, as 'pulses' of sediment move through the channel, and a triangular CS eventually becomes a trapezoidal CS and vice versa.

The morphological features of five chain discontinuous gullies, along a 285 m channel reach with CAs of 81–97 ha within the Upper Scrânghiţa-Roşcani Catchment are presented in Table 3 and partly illustrated in Fig. 5b. These data are based on 37 cross-sections surveyed during 1980–1993.

These data reveal the contrast between the former/older broad, shallow CS and the present-day ones, which is reflected in the variability of the 'hydraulic radius at bankfull-channel' (HRBC). There are very small values (0.183–0.381 m) for former CS and values which are 3.5–5 times higher (0.908–1.940 m) for actual CS. These values progressively increase downstream. Furthermore, the maximum thickness of sediment recently deposited in these discontinuous chain gullies decreases downstream from 210 cm at the outlet of the first gully to 45–80 cm in the next two gullies, and sediments are almost absent in the last two gullies. The depositional gully floor covers 17–45% of the total gully area within the alluvial family of successive discontinuous gullies. Nevertheless, based on analysis of 17 CS surveyed by levelling in six 14–52 m long gullies in Timbru Catchment during May 1995, it was possible to identify a significant negative correlation between the ACS/FCS ratio and DDGH (Fig. 6).

In turn, there are relatively few ***successive erosional gullies***. These occur where erosion processes prevail and runoff is more contracted and competent to detach and evacuate more debris. Thus, deposited sediment progressively diminishes downstream and net aggradation is often absent, such as in the last two chain gullies of the Scrânghiţa reach. The CS of these gullies is triangular or slightly U-shaped, partly resembling some continuous gullies, but irregularities are still present in their longitudinal profile.

Table 2
'Bankfull geometry' of the single discontinuous Puşca gully, Upper Jeravăţ Catchment (1990).

No CS	DDGH (m)	GTW (m)	GBW (m)	GD (m)	F ratio TW/D (m)	CSA (m^2)	WPBC (m)	HRBC (m)	ST (m)
1	26	8.2	0.1	6.9	1.19	38.5	17.1	2.25	0
2	34	10.8	0.1	7.0	1.54	44.0	18.4	2.39	0
3	63	13.4	0.3	6.6	2.03	45.0	19.5	2.31	0.31
4	90	12.9	0.8	6.9	1.87	46.7	19.7	2.37	0.52
5	128	13.5	2.7	6.3	2.14	50.4	19.8	2.54	1.26
6	163	15.4	2.0	5.2	2.96	47.4	19.5	2.43	1.08
7	219	11.4	3.4	4.4	2.59	33.5	15.8	2.12	1.20
8	263	11.3	3.5	3.8	2.97	29.4	14.6	2.01	1.20
9	345	11.2	4.5	3.3	3.39	25.8	14.0	1.84	1.51
10	384	9.9	5.4	2.5	3.96	17.0	11.9	1.43	1.62
11	402	11.9	7.0	2.0	5.95	16.7	13.3	1.26	1.80
12	458	9.7	7.3	1.5	6.46	10.5	10.9	0.96	1.86
13	490	10.4	8.1	1.4	7.43	8.4	11.7	0.72	2.10
14	542	10.6	8,8	0.8	13.25	6.5	14.1	0.46	2.40

3.1.3. Clusters of discontinuous gullies

Combine features of the two previously discussed main groups (i.e. single and successive alluvial gullies). They typically consist of the combination of two short diffusors (represented by the upper gully branches) and a long diffusor as the main gully trunk. Clusters of discontinuous gullies are usually 'Y' shaped. An example is the upper Scrânghiţa-Roşcani Catchment, where four clusters have been identified within a drainage area of 10–52 ha (Fig. 7a).

They are located upstream of the above-mentioned stretch of chain gullies and are separated by small alluvial fans. In this case, there is almost a complete balance between erosion and sedimentation, since the calculated weight of the alluvial gully floor is 42% of the total area occupied by these gullies (Ioniţă, 1998, 2000, 2003, 2006).

When moving upstream and approaching small alluvial fans, developed between clusters of discontinuous gullies along the main drainage line, some headcuts bifurcate, if runoff conditions are suitable. For ***channel bifurcation*** to occur, the upstream fan axis must stand above the fan

Fig. 5. Successive (chain) alluvial gullies in a) Timbru Catchment on 27 April 1995 and b) in Upper Scrânghiţa-Roşcani Catchment on 25 April 1997. c) A chain of discontinuous gullies (n = 7–10) as 'short diffusors,' with slope gradients of 4.3–6.9% (Timbru gully system, Jeravăţ Catchment, 27 April 1995).

Table 3
'Bankfull geometry' of chain alluvial gullies in the Scrânghiţa-Roşcani Catchment. GH = gully head.

DDGH	No, type and year of CS	GTW (m)	GBW (m)	GD (m)	CSA (m^2)	WPBC (m)	HRBC (m)
54 m/old GH1	2 older CS (1980 + 1993)	9.7–11.3	–8.5	0.3–0.4	2.60–2.87	10.1–10.2	0.26–0.28
	8 CS (1981–1993)	4.0–5.5	0.1–3.0	2.05–2.8	6.04–9.93	6.65–8.4	0.91–1.18
32, 46, 63 and 73 m/old GH2	2 older CS (1993)	11.2–11.6	9.3–9.5	0.2–0.4	2.1–4.5	11.5–11.8	0.18–0.38
	8 CS (1985–1993)	7–10	0.3–2.2	3.3–4.7	16.1–28.9	11.0–14.9	1.33–1.94
2, 4, 22, 49, 54 and 66 m/GH3	2 older CS (1993)	10.8–12.9	8.2–9.3	0.3	3.1–3.5	10.3–12.8	0.27–0.30
	6 CS (1993)	9–12.9	0.2–2.6	3.3–5	19.7–26.3	12–16.5	1.29–1.44
5, 10, 16, 17, 22 and 30 m/GH4	6 CS (1993)	6.9–9.6	0.1–0.6	4.8–5.2	18–22.8	12.6–14.9	1.43–1.65
13, 14 and 20 m/GH5	3 CS (1993)	8.8–11.3	0.1–1.3	6–6.2	30.8–40.2	15.7–18	1.96–2.23

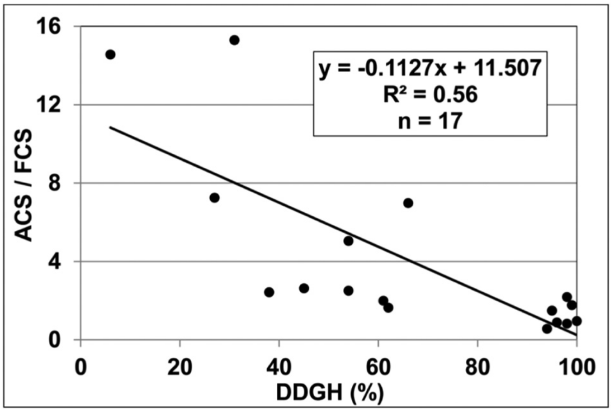

Fig. 6. Plot of Actual Cross-Section (ACS)/Filled Cross-Section (FCS) ratio to Distance Downstream of the Gully Head (DDGH) within successive alluvial gullies in Jeravăţ Catchment (Timbru Valley, BP).

edges, so that runoff splays and become divergent. The flows lines around the edges of an existing headcut have higher water discharges than those in the centre. Erosion in these flowlines is more than the central part and hence the former fan axis will become a promontory between new two gully channels (Fig. 7b). This type of headcut bifurcation within some discontinuous gullies, which is not usually triggered by tributaries, is symmetrical, when there is a balance between the retreat of the new gully branches, due to nearly equal runoff discharges along the fan edges (Fig. 7c). When the accommodation of flow mainly follows one line above the trunk gully head, headcut bifurcation becomes weak, resulting in asymmetrical branches.

The 'bankfull-channel' within the area of the Y-shaped gully cluster exhibit 'pulsatory' development (Fig. 7c, Table 4). For example, the value of HRBC is 0.140 m upstream of that gully cluster, as measured across a small alluvial fan of 24 m maximum width. At 'bankfull discharge,' HRBC increases three-fold, to 0.424 m, in the right gully branch at the base of its gully headcut. This value increases to 1.388 m at the outlet, 28 m downstream of the gully headcut (thus, tripling inside the same gully). Then, HRBC decreases to 0.810 m in the joint trapezoidal CS of both gully branches or above the main gully headcut. At this point, by notching the broad (17.1–12.4 m) wide gully bottom, the new CS becomes triangular and the hydraulic radius value increases three-fold, to 2.406 m, at 18 m downstream the trunk/main gully headcut.

Downslope, the gully CS becomes trapezoidal, due to aggradation of the gully floor. However, HRBC progressively increases to its peak value of 3.473 m at 38 m downstream of the main gully headcut, which accords with the highest GD of 8.2 m. From now on, the thickness of very recent sediment is >200 cm (≤350 cm at the distal end) and GBW becomes much broader (4.3–9.8 m). Hence, HRBC in the main gully drops <0.100 m at its outlet, and soon GD decreases to the point of extinction, similar to the distal end of the single discontinuous gullies. The maximum GTW of the Y-shaped gully cluster of 29 m occurs at the joint outlet from the upper gully branches and upstream of the headcut of the main gully trunk. It is located in the area where the previous alluvial fan, bordered by gully branches, was widest. Therefore, the

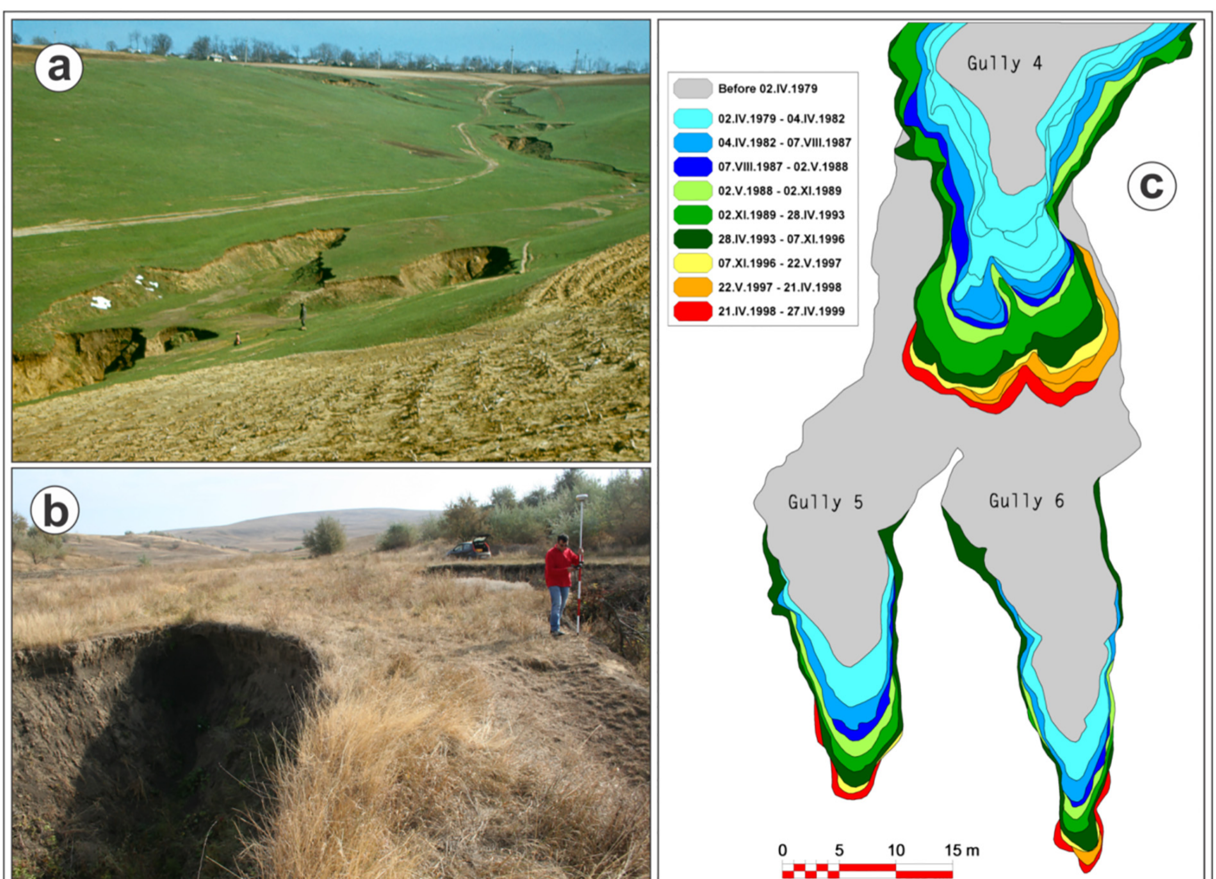

Fig. 7. a) Clusters of discontinuous gullies in Upper Scrânghiţa-Roşcani Catchment, within the upper reach of the 4th cluster in the foreground (20 April 1988). b) Gully head bifurcation on a small alluvial fan developed in the valley-bottom, middle Loava Catchment (BP, 23 October 2018). c) Development of Y-shaped gully cluster No. 4 in Scrânghiţa-Roşcani Catchment between 1979 and 1999, illustrating symmetrical bifurcation. Labels refer to day, month and year of survey.

Table 4
'Bankfull-channel' of gully cluster No. 4, Upper Scrânghiţa-Roşcani Catchment.

No of the CS	DDGH (m)	GTW (m)	GBW (m)	GD (m)	F ratio TW/D (m)	CSA (m^2)	WPBC (m)	HRBC (m)
Along the right branch of the gully cluster (08 August 1990)								
1	1.0	2.3	0.1	0.8	2.87	1.4	3.3	0.42
2	4.0	3.5	0.3	1.5	2.33	3.7	5.3	0.70
3	9.5	7.7	1.0	2.2	3.50	10.2	9.8	1.04
4	15.5	8.1	2.9	2.1	3.86	12.3	10.2	1.21
5	21	10.5	4.1	2.0	5.25	15.9	12.4	1.28
6	28	14.6	9.1	1.8	8.11	22.5	16.2	1.39
7	44 joint gully bottom of both branches	20.9	17.1	1.6	13.06	30.9	22.6	1.37
8	**59/0** joint gully bottom or above the main GH	15.2	12.4	0.9	16.89	12.8	15.8	0.81
Along the main gully trunk of the gully cluster (17 November 1988)								
9	18	10.5	2.6	7.4	1.42	47.4	19.7	2.41
10	27	17.0	2.3	8.2	2.07	86.4	25.1	3.42
11	38	19.0	1.0	8.2	2.32	91.7	26.4	3.47
12	88	20.9	5.9	6.7	3.12	89.4	26.1	3.42
13	103	17.6	4.5	5.6	3.14	61.6	22.1	2.78
14	156	12.5	4.3	3.5	3.57	28.5	15.2	1.87
15	168	13.0	4.7	2.7	4.82	25.2	14.8	1.70
16	199	12.2	8.6	1.2	10.17	11.2	13.0	0.86
17	242	10.5	9.8	0.2	52.50	0.91	10.3	0.09

decreased HRBC of gullies within the Y-shaped cluster is accompanied by a gradual increase in GBW (Fig. 8). This is characteristic for most discontinuous gullies on the MP, except for the successive erosional ones.

There were also other similar significant linear correlations between gully length (GL) and the following indicators:

- $GD = -0.04GL + 9.16$, $R^2 = 0.97$, $n = 9$, ***$P < 0.001$.
- $ST = 0.01GL + 0.88$, $R^2 = 0.94$, n = 9, ***$P < 0.001$.
- $CSA = -0.37GL + 91.74$, $R^2 = 0.72$, n = 9, **$P < 0.01$.

A much stronger inverse association between HRBC and DDGH is typical for wet long diffusors. An example is Hârcioaia gully, in Horoiata Catchment ($Y = 0.02x + 4.32$, $R^2 = 0.95$, ***$P < 0.001$, $n = 13$).

The strength of correlations between CSA and GTW are highly variable, except for the erosional gullies. For example, $R^2 = 0.11$ in Căldarea gully with uniform GTW; $R^2 = 0.33$ in Puşca gully; $R^2 = 0.73$ in Scrânghiţa gully (all three have dry gully floors) and $R^2 = 0.43$ in Hârcioaia gully, which has a wet gully floor. However, this correlation coefficient is negative ($r = -0.66$).

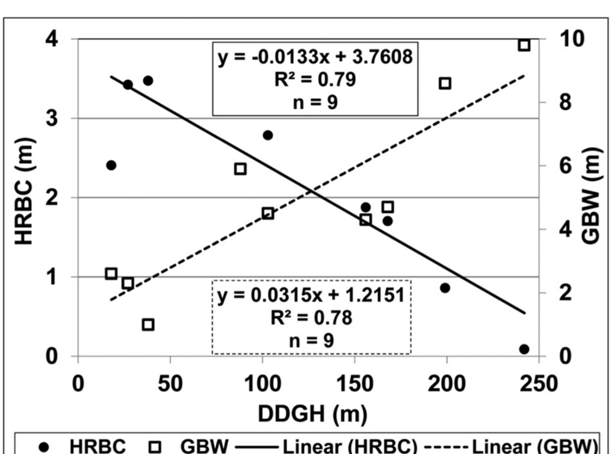

Fig. 8. Plot of 'Hydraulic Radius at Bankfull-Channel' (HRBC) and Gully Bottom Width (GBW) to Distance Downstream of the Gully Head (DDGH) of the main trunk (long diffusor) in the Y-shaped gully cluster, Scrânghiţa-Roşcani Catchment (1988–1990).

3.2. Flow characteristics in discontinuous gullies

Field observations and measurements enabled analysis of relationships between the classification of discontinuous gullies with the accommodation of the flow through each gully group. In this study, ***accommodation of the flow*** refers to how runoff is transferred/conveyed through the entire gully channel, from upstream when entering the gully head and downward towards the gully outlet. It is postulated that gully development is strongly controlled by runoff patterns (diverging/dispersing or converging/contracting). In turn, these patterns are controlled by the characteristics of gully cross-sections.

In single (isolated) gullies, runoff usually experiences contraction-expansion in plan. On the one hand, flow is divergent at the entrance to the gully, above the approaching headcut, and downstream of the headcut area, towards the gully outlet. This is because flow is becoming wider and shallower and thus energy is lost from the system. In turn, this causes sedimentation and aggradation of the gully floor. Consequently, the former gully CS is entirely filled with recent sediment at the point where the height of the gully banks decreases to zero. On the other hand, flow becomes convergent and thus narrower and deeper. The increased energy triggers erosion in the headcut area.

In successive (chain, cascade) alluvial gullies, the narrower, deeper flow cross-sectional areas, under converging flow, alternate several times with the wider, shallower cross-sections under diverging flow. The episodic streamflow typical for most discontinuous gullies is usually relatively low, with peak water discharges usually ≤2 $m^3 s^{-1}$. Field measurements during snowmelt showed that sediment concentrations in streamflow are high; ≤120 g L^{-1} in the gully headcut area. Then, the flow splays over the flaring and short gully floor (short diffusor) of the cascade alluvial gullies and sediment concentrations typically decrease to 30–50 g L^{-1} (Ioniţă, 1998, 2000, 2006).

Within clusters of discontinuous gullies, runoff tends to be diverging, both in the alluvial fan above the inlet and towards the cluster outlet. Thus, runoff tends to be wider and shallower, which is typical for single/isolated gullies. Inside the gully, flow becomes convergent, becoming narrower and deeper within the headcut area, which is typical within successive discontinuous gullies.

The spatial pattern of runoff accommodation is not generally incorporated into formulae or models of gully development, but it may assist in refining our understanding of gully development. The class of discontinuous gullies has a distinctive flow pattern, which we describe as '***variable-geometry flow***' (Fig. 9a). This approach is based on field observations and inductive analysis, as there are insufficient hydraulic data during active gully erosion. This was also observed and discussed in relation with the evolution of the continuous gullies by Ionita et al. (2021). Most of these continuous gullies are accompanied and fed by upper discontinuous gullies, that developed upstream from the main gully headcut (e.g. Tumba, Puriceni, Puriceni-Bahnari, Chira, Loava). These discontinuous developments upstream from the main gully headcuts govern runoff patterns (accommodation of the flow) towards and through the continuous gully heads and, implicitly, their growth (Fig. 9b).

Fig. 10 is associated with the flashy streamflow regime triggered by two major rain events in the main trunk of Y-shaped gully cluster No. 4 in the upper Scrânghiţa-Roşcani Catchment. Firstly, the 45.0 mm of heavy rainfall on 13 May 1996. Secondly, the exceptional series of four successive rain storms (36.3 + 32.4 + 29.3 + 33.5 mm), totalling 131.5 mm in 24 h at Perieni-Bârlad recorded on 22–23 June 1999. There was a tendency for hydraulic radius (HR) of the flow to progressively decrease downstream from the gully head ($R^2 = 0.73–0.79$). Thus, the flashy discharge within the gully splayed over the gully floor, with consequent progressive decreases in the CS area and the HR of the flow (and implicitly water unit discharge) to the gully outlet.

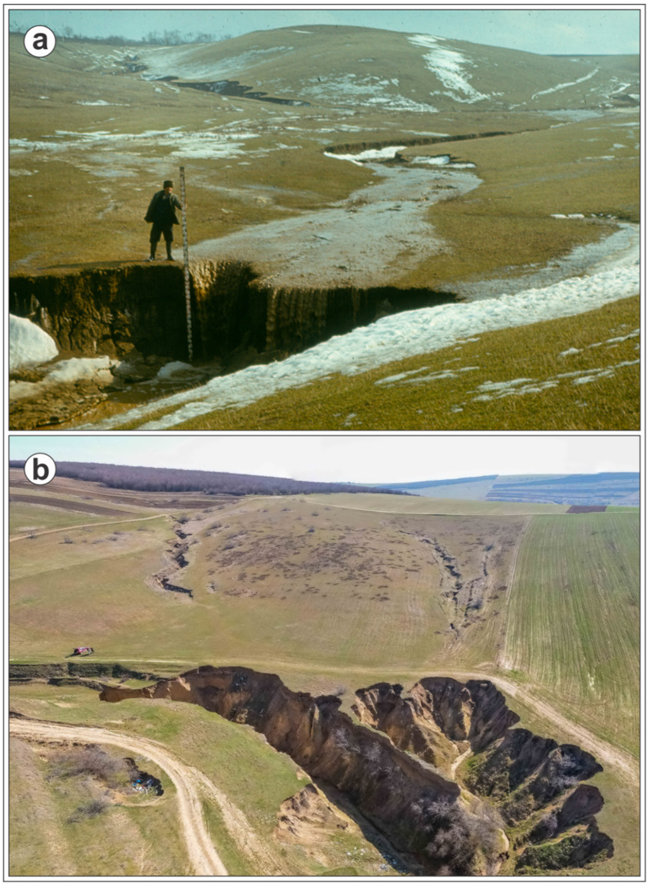

Fig. 9. a) 'Variable-geometry streamflow' during snowmelt runoff in Scrânghiţa-Roşcani Catchment (10 March 1980), with the headcut of the first chain gully in the foreground. b) Discontinuous gullies situated upstream Tumba continuous gully having an important role in water concentration and gully incision on the valley-bottom (photograph taken using a drone by Andrei Enea on 2 April 2021).

Comparison of the two almost parallel curves is informative in terms of the different hydrological responses during the two rain storms (Fig. 10). The mean HR of flow (0.222 m) during the successive rainfalls on 22–23 June 1999 was 1.75 times higher than during the 13 May 1996 event (0.127 m). Under these circumstances, the flow with higher

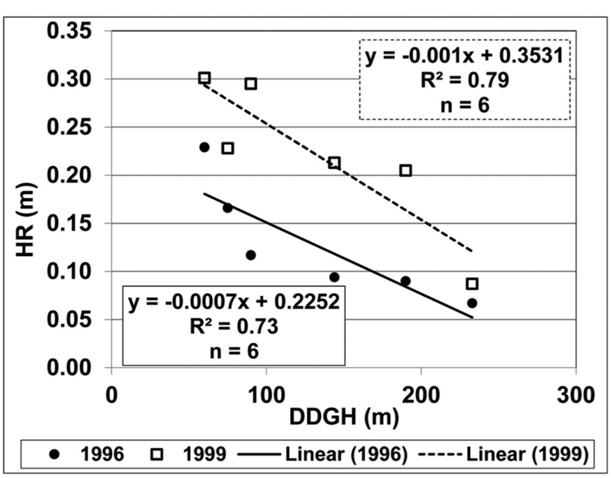

Fig. 10. Plot of the Hydraulic Radius (HR) of flow to Distance Downstream of the Gully Head (DDGH) in the upper Scrânghiţa-Roşcani Catchment during streamflow on 13 May 1996 and 22/23 June 1999.

sediment concentration in the active gully head area becomes broader/wider and shallower (diverging flow), promoting deposition of some sediment load.

The tendency for the HR of the flow to decrease results from both the progressively divergent shape of the gully floor and the variable pattern of sedimentation (Fig. 11a). In detail, sediment deposition below gully heads results in a 'steps and stairs' pattern. The 137-Cs depth profile was used to establish the mean sedimentation rate of 5.2 cm yr-1 over 10.5 years (April 1986–October 1997) at the half length of gully floor No. 4, in the main trunk (long diffusor) of the Y-shaped gully cluster within Scrânghiţa-Roşcani Catchment (Fig. 11b).

Repeated field measurements of sedimentation rates between August 1987–May 1997, using check-iron plates inside six cross-sections, revealed a notable repeating pattern of sedimentation within the same gully bottom. The highest sedimentation rates on the gully floor (exceeding the mean rate of 5 cm yr^{-1}) occurred in the upper reach, while lower values typified the lower reach (Ioniţă, 1998, 2000, 2006). However, in the context of the gully age, the thickness of recent sediment deposited on the gully floor is opposite to the value of aggradation rate, being highest at the gully outlet (350 cm) and least downstream of the gully head. In addition, strong negative correlations were found between the GD/FGD ratio and DDGH within the long diffusors in both the Puşca gully ($R^2 = 0.94$, $n = 10$, $^{***}P < 0.001$) and Hârcioaia gully systems (Fig. 12).

Data in Table 5 emphasize the variability of streamflow characteristics within the discontinuous chain/cascade gullies of the BP. Field measurements were conducted within two reaches of cascade gullies soon after the successive rainfalls of 22–23 June 1999. The first reach refers to the five successive gullies in the upper Scrânghiţa-Roşcani Catchment, located immediately downstream of Y-shaped gully cluster No. 4. The second reach is within one chain gully in the Timbru Valley. Since the first gully of the Scrânghiţa reach had a broad trapezoidal CS (Fig. 13a), the HR value during streamflow on 22/23 June 1999 was low (0.176 m).

The next two gullies show typical features of chain gullies; a variable CS, being triangular within the active gully head area, and a trapezoidal CS downslope due to deposition. Despite the gully floor tending to be divergent downward, the CS increases, with a consequent 3.3-fold increase in HR (mean 0.596 m). In turn, the last two gullies in that reach have an almost triangular or slightly U-shaped CS and thus the highest HR (mean 0.698 m). This is four-times more than the reference gully. Hence, these gullies look like typical successive erosional gullies, because the streamflow is competent to evacuate most of the detached debris. Furthermore, the maximum thickness of the recent sediment deposited along these discontinuous chain gullies decreased downstream from 210 cm at the outlet of the first gully (Fig. 13b) to 45–80 cm in the next two gullies, and was only a veneer of sediment in the last ones. That means streamflow was more constricted moving downstream and so the amount of scoured debris increased and hence the depth of deposited sediment progressively decreased.

In the Timbru Valley, the two measured wetted cross-sections were 10.7 m apart. Results highlight the variability of flow within the same successive chain gully with a short diffusor morphology. Thus, the HR of the flow was 3.5 times higher in the middle of the gully (0.217 m) compared to the distal end (0.061 m). Hence, the gully floor broadened downstream, due to sediment deposition. In contrast, in the context of the alluvial filling, gully depth (GD) decreases downstream (Fig. 14a). This figure also clearly illustrates both the size of filled cross-section (FCS). The FCS is darker in colour due to both higher soil moisture and humus contents at the outlet of gully No. 7, and the cantilever-like retreat of the head-cut of gully No. 8 in the Timbru Valley.

The thickness of sediment deposited at the outlet of gully no 7 was 163 cm (measured in December 1996). The associated 137-Cs depth profile exhibits two peaks: the first at 25–30 cm depth (139 Bq/kg), associated with the Chernobyl accident on 26 April 1986, and the second peak at 145–150 cm (6.3 Bq/kg), due to nuclear bomb tests in 1963

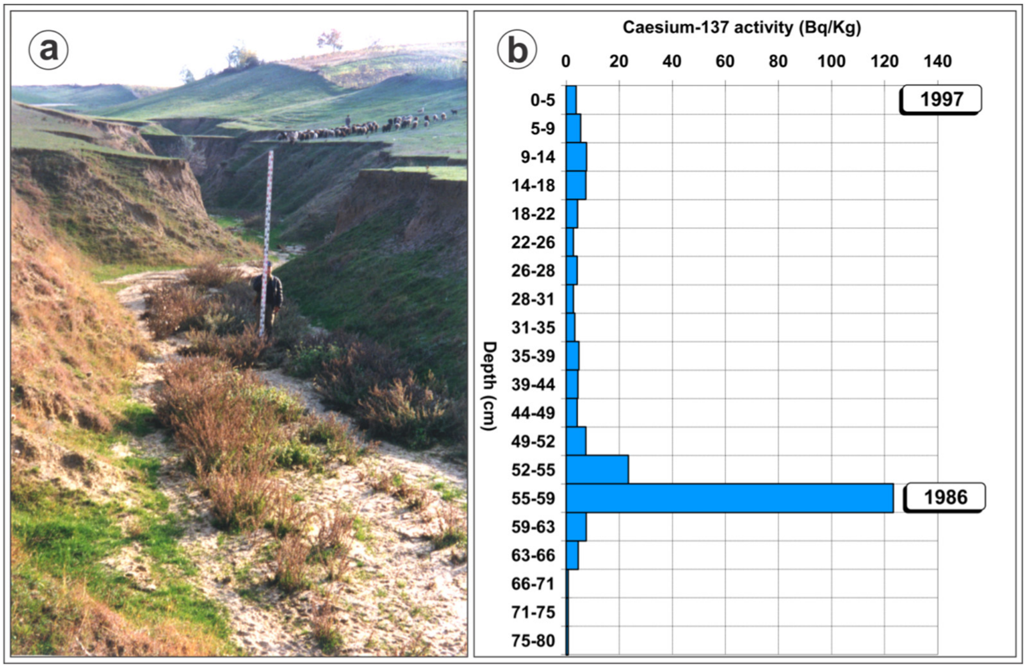

Fig. 11. a) Variations in recent sediment deposition patterns in the main trunk (long diffusor) of the Y-shaped gully cluster (19 October 1996) and b) depth distribution of 137-Cs within the alluvial fill of the main gully trunk No. 4 (10 October 1997), Scrânghiţa-Roşcani Catchment.

(Fig. 14b). Thus, the mean sedimentation rate was 2.5 cm yr^{-1} over the 10 year period 1986–1996, while between 1963 and 1986 the rate was double (5.2 cm yr^{-1}). This equates to a mean sedimentation rate of 4.4 cm yr^{-1} for the entire 34 year period and an age of ≥37 years for the 32 m gully length. Thus, it was possible to estimate an overall LGHR rate of 0.9 m yr^{-1} (Ioniţă and Mărgineanu, 2000). Therefore, the main characteristic of ephemeral flow passing through discontinuous gullies is the variability of both CS and HR. However, this field observation disagrees with the laboratory experiments of Apelt and Xie (1995), who concluded: "*despite irregularities of cross section due to contraction or expansion in channel width, the flow cross-sectional area remains essentially constant, or nearly so*."

The details of the effects of runoff within the gullies stress the differences between different types of discontinuous gullies. In comparing the influence of lithological and hydrological factors, hydrology appears dominant. The hydrological influence, represented by the '*variable-geometry flow*' pattern, is the most important factor controlling both flow accommodation through discontinuous gullies and their development. Without the hydraulic component, the broad variety of discontinuous gullies could not be explained.

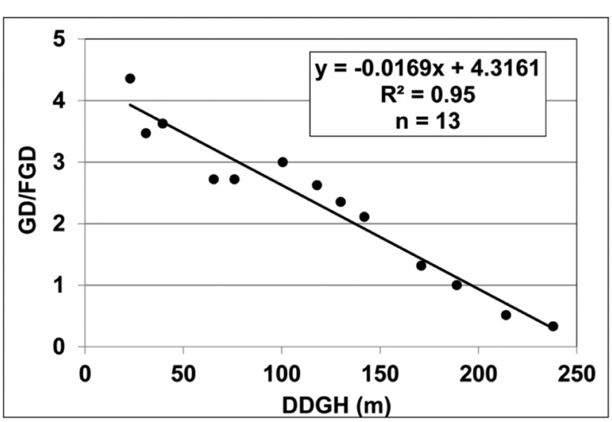

Fig. 12. Plot of Gully Depth (GD)/Filled Gully Depth (FGD) ratio and Distance Downstream of the Gully Head (DDGH) in Hârcioaia Gully No. 3, Horoiata Catchment, February 1990.

3.3. Head-cut retreat and areal growth rates of discontinuous gullies

Rădoane et al. (1995, 1999) reviewed the factors causing gully development in 38 gullies within very small catchments (CAs of 0.5–8.5 ha) on the MP. Of these gullies, 22 developed on clays (mostly in the northern area, in the Jijia Rolling Plain) and 16 on sands in the southern part, around the town of Bârlad.

Based on a multiple regression model, they indicated that the most important independent variable influencing LGHR rate is the CA upstream of the gully head, which explains 54% of data variance on clays and 68% on sands. Since the LGHR mainly depends on lithology, Rădoane et al. (1995, 1999) concluded that "*for a gully of the same length ($L = 50$ m) and width and the same basin drainage area upstream of gully head ($A = 1$ ha), the advancement rate is over 1.5 m yr^{-1} for gullies cut in sandy rocks and under 1 m yr^{-1} for the gullies cut in marls and clays*." They suggested that the trend-lines of these gully types are parallel, where the trend-line of gullies cut in sand is located ~0.5 m above that for gullies cut in clay. However, they did not present graphical evidence to support their argument.

Our medium-term field measurements on both the linear and areal gully growth of 31 discontinuous gullies on the BP are summarized in Table 6. The weighted mean LGHR rate of these gullies is 0.97 m yr^{-1} and the highest is ≤3.0 m yr^{-1}. Of all 31 gullies, 21 (68% of the total) had mean retreat rates <1 m yr^{-1}. The corresponding weighted mean rate of the AGG is 15.4 m^2 yr^{-1}.

By comparison, the mean LGHR of the continuous gullies over 60 years was almost 8 times higher (7.7 m yr−1) than the values of the discontinuous ones (Ionita et al., 2021). Moreover, the mean AGG of 213 m^2 yr^{-1} was 14 times higher.

There is a positive correlation between mean AGG and mean LGHR retreat ($r = 0.74$), but the independent variable only explains 55% of the variance of AGG (Fig. 15). The R^2 value of 0.55 is much less than the typical value for continuous gullies ($R^2 = 0.89$, $n = 83$). We postulate that this difference is triggered by ***the larger impact of the cold season***

Table 5
Characteristics of the wetted cross-sections in the chain discontinuous gullies.

Gully No.	Site of the wetted CS	Top width of flow (m)	Bottom width of flow (m)	Max depth (cm)	CSA (m^2)	WP (m)	HR	
							(m)	%
Upper Scrânghiţa-Roşcani Catchment (26 June 1999)								
G1	22 m downstream of the old GH1 + 46 m upstream of the old GH2	7.2	5.9	21.2	1.28	7.29	0.176	100
G2	67 m downstream of the old GH2 + 7 m upstream of the GH3	4.4	1.7	83.2	2.62	4.90	0.535	304
G3	56 m downstream of GH3 + 11 m upstream of GH4	6.3	2.8	102.2	4.50	6.85	0.657	373
G4	24 m downstream of GH4 + 8 m upstream of GH5	5.2	0.7	140.3	4.14	6.02	0.688	391
G5	20 m downstream of GH5	4.1	0.3	201.3	4.22	5.97	0.707	402
Timbru Valley (30 June 1999)								
G7	19.5 m downstream of GH7 + 16.3 m upstream of GH8	2.7	1.8	71.8	1.28	5.89	0.217	100
G7	30.2 m downstream of GH7 + 5.6 m upstream of GH8	4.9	4.2	15.6	0.61	9.93	0.061	28

(especially late winter freeze-thaw cycles) on the development of discontinuous gullies compared to continuous gullies (Ioniţă, 1998, 2000, 2006; Ionita et al., 2021). No significant correlations were found between slope gradient of the soil surface at the gully head and LGHR or AGG rates ($R^2 = 0.03$ and 0.05, respectively).

Generally, discontinuous gullies developed episodically into a 'pulse shape,' as exemplified by the first chain gully of the upper Scrânghiţa Catchment (Fig. 16). The gully headcut progressively retreated (0.6 m yr^{-1}) and enlarged (≤17 m width) during the 1970s. In Autumn 1981, small but prolonged flow discharges cut a notch into the upper part of this headcut, developed in recent alluvial fill, in the shape of a 'bottle-neck like' incision (2.1 m long and 1 m wide). Because of the combined effects of the saturation of the alluvial fill and streamflow generated by snowmelt, the new notch progressed upslope rapidly; some 11 m upslope from its previous position in March 1982. Then, in the next 10 years, LGHR rate decreased to 0.3 m yr^{-1}. These rates equate to an overall mean LGHR rate of 1 m yr^{-1} over the 22 year period (1970–1992). This pattern of gully evolution accords with Heede's (1975) opinion "*it appears that, in ephemeral gullies, time and duration of flow is more important than magnitude of flow*." At the same time, this comes into contradiction with the evolution of continuous gullies which is closely related to the pattern of annual precipitation (Ionita et al., 2021).

In terms of the ***contributing CA*** (which is often used as a surrogate measure for runoff discharge), mean CA is 107 ha and varies between 19.3 ha (Timbru Catchment) and 365.5 ha (Gheltag Catchment). Of all 31 gullies, 23 (74% of the total) have CA values <100 ha. Generally, slope gradients at the gully heads are gentle, with 23 gully heads having upstream slope gradients <6% and 19 gully heads (61% of the total) having gradients <4% (Fig. 17).

Since the time-scales of field measurements are uneven and Spearman correlation coefficients are higher than the corresponding Pearson values, a preliminary conclusion was that the statistical associations between mean LGHR or mean AGG and CA are non-linear. One outlier (No. 13 = gully 5 in the Larga system) was investigated and then omitted from the data-set with respect to each independent variable.

Two non-linear models best described the statistical associations between the variables; polynomial and power-function, respectively. Both models are statistically significant ($^*P < 0.05$). The power-function offers satisfactory results, but correlations are weak ($R^2 = 0.23$ for mean

Fig. 13. a) Variable-geometry streamflow (10 March 1980) and b) fresh sedimentation followed by fresh erosion in the first two chain gullies (01 April 1980), Scrânghiţa-Roşcani Catchment.

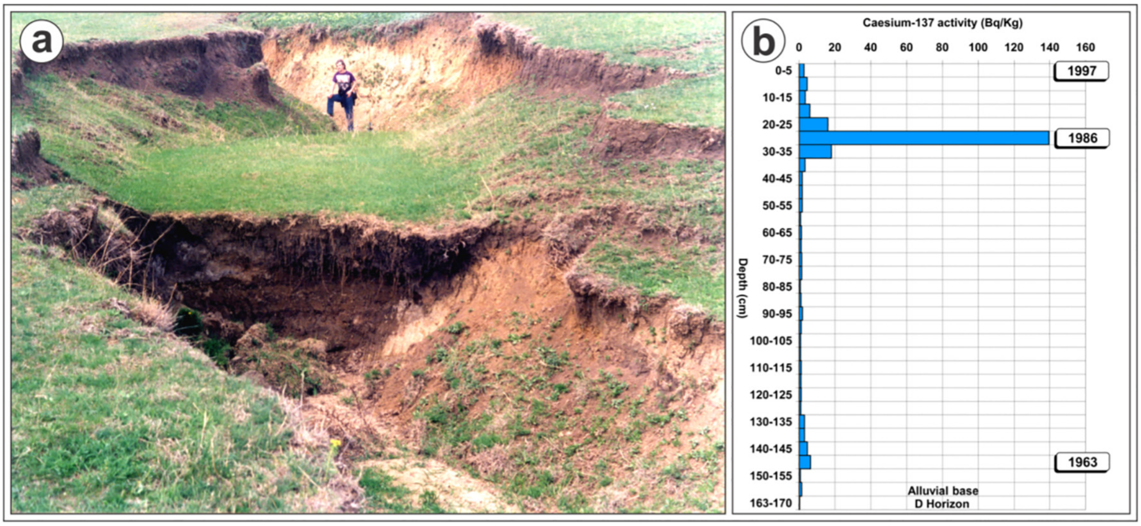

Fig. 14. a) Diverging floor of gully No. 7 and headcut of gully No. 8 (27 April 1995) and b) Depth distribution of 137-Cs in the alluvial headcut of gully No. 8 (13 December 1996), in the Timbru Valley, within Jeravăţ Catchment, Bârlad Plateau.

LGHR and $R^2 = 0.31$ for AGG, respectively), versus CA (Fig. 18). Therefore, the low R^2 values indicate that other factors are more important in controlling the development of discontinuous gullies. As discussed above, we firstly advocate the importance of runoff accommodation, in the shape of 'variable-geometry flow,' due to alternating divergent and convergent flow-lines (wide and shallow or narrow and deep) and vice versa through these gully systems. This particular process, along with sediment transport, predominates over the effect of contributing area (CA). Thus, it is apparent that, although a channel may be incising, it will cycle through periods of aggradation and degradation, as 'pulses' of sediment move through the gully channel.

Table 6
Gully development rates from nine discontinuous gully systems on the Bârlad Plateau.

No	Gully system	Gully	Time		Mean LGHR	Mean AGG	Mean CA
			Period	Years	(m yr^{-1})	(m^2 yr^{-1})	(ha)
1	1. Gornei	1	1990–2019	29	1.09	21.05	158.81
2		2			2.17	13.7	175.31
3		3			1.11	11.8	194.70
4		4			1.38	8.61	203.69
5		5			2.52	19.58	214.65
6	2. Hârcioaia	1	1990–2019	30	1.56	19.81	248.89
7		2			0.34	4.23	252.77
8		3			0.27	7.47	257.24
9	3. Larga	1	1961–2019	59	0.37	4.74	45.47
10		2			0.81	10.84	49.97
11		3			0.52	9.05	56.40
12		4			1.45	31.02	65.13
13		5			2.95	49.23	98.29
14	4. Scrânghiţa	1	1993–2019	26	0.65	7.02	80.48
15	(chain)	2			0.53	17.97	83.64
16		3			0.60	15.45	91.38
17		4			0.64	13.06	96.07
18		5			1.10	9.29	96.92
19	5. Scrânghiţa	4	1979–1997	18	1.00	22.2	41.34
20	(cluster)	5			0.50	5.10	39.54
21		6			0.60	6.10	39.39
22	6. Timbru	6	1995–2012	17	0.44	3.88	19.32
23		7			0.67	5.59	19.85
24		8			0.45	2.57	20.11
25		9			0.39	3.21	20.25
26		10			0.58	3.19	20.40
27		11			0.17	1.17	20.74
28		12			0.58	6.58	23.84
29	7. Puşca	1	1990–2019	29	0.89	27.76	148.91
30	8. Căldarea	2	1978–1983	5	0.48	2.70	64.07
31	9. Gheltag	2	1980–1997	17	0.82	7.99	365.49
Weighted mean					**0.97**	**15.40**	

4. Conclusions

- This study investigated the typology, flow characteristics and medium-term dynamics of discontinuous gullies. Gully morphological characteristics and sedimentation rates on gully floors were used to describe and distinguish three groups of discontinuous gullies: i.e. single, successive, and clusters.
- The most common cross-section (CS) shape of discontinuous gullies is trapezoidal, due to synchronous and variable sedimentation along the gully floor and the most common discontinuous gullies are successive (chain, cascade) alluvial gullies. Below the gully headcut, in the recent incised stretch of channel, erosion may prevail and CSs tend to be triangular in shape.
- A changing runoff pattern (accommodation of the flow when it enters the gully head) in the shape of 'variable-geometry flow,' due to alternating divergent and convergent flow-lines, is the main factor controlling the development and variety of discontinuous gullies.
- The decrease of 'hydraulic radius at bankfull-channel' (HRBC) of the gullies is accompanied by a gradual increase in gully bottom width (GBW), except in the case of successive erosional gullies, where recent

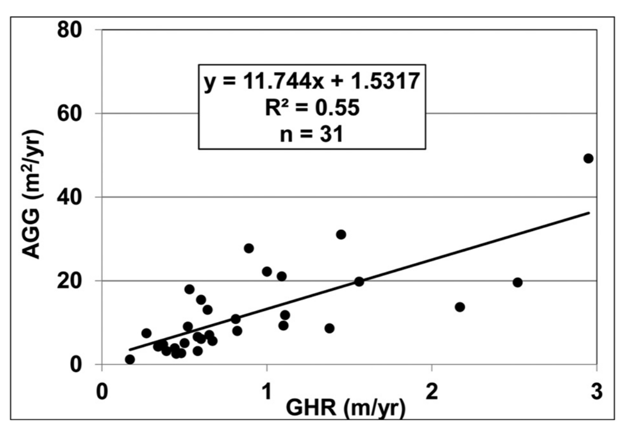

Fig. 15. Plot of mean Areal Gully Growth (AGG) and mean Linear Gully Head Retreat (LGHR) for 9 discontinuous gully systems on the Bârlad Plateau.

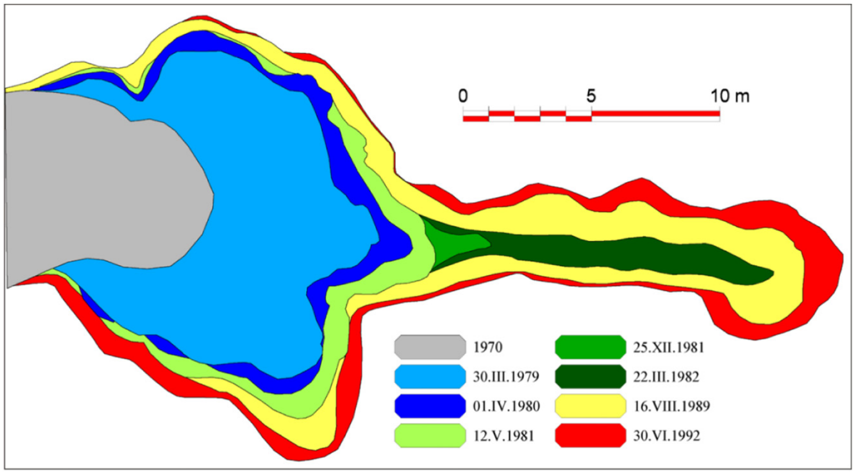

Fig. 16. Development of the first discontinuous chain gully in the shape of a 'bottle-neck' like incision, Upper Scrânghiţa Catchment (1970–30 June 1992). Labels refer to day, month and year of survey.

net deposition is usually absent. This tendency for the hydraulic radius (HR) of flow to decrease results from both the progressively divergent width of the gully floor and the variability of sedimentation patterns and rates within gully systems.

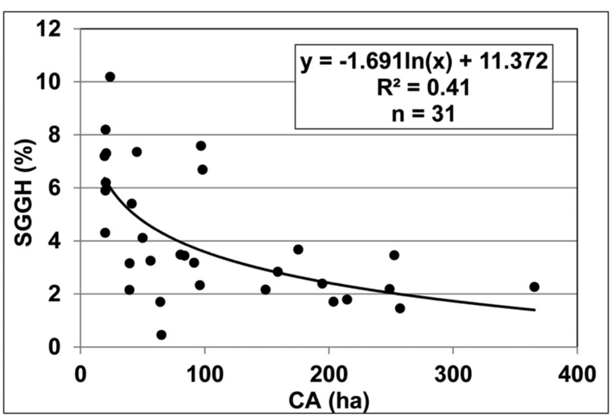

Fig. 17. Plot of Slope Gradient at the Gully Head (SGGH) and Catchment Area (CA) for 31 discontinuous gullies on the Bârlad Plateau.

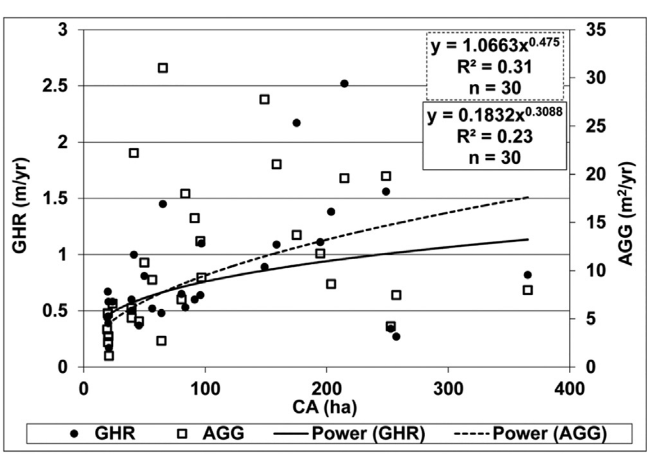

Fig. 18. Plot of mean annual Linear Gully Head Retreat (LGHR) rate and Areal Gully Growth (AGG) to Catchment Area (CA) for all 31 discontinuous gullies (omitting gully 13) on the Bârlad Plateau.

- Precisely measured gully characteristics, namely linear gully head retreat (LGHR) and areal gully growth (AGG), exhibited relatively low, but pulsatory, erosion rates.
- The correlation between mean LGHR or mean AGG and catchment area is weak, since CA only explains 23–31% of data variance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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RESEARCH ARTICLE

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

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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 m^2 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.

Piest 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 ($I_{30} \geq 25$ 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 southeastern 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 [CSAs] 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 continuous 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 Falciu 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 (Niacşu, 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 (Vanmaercke, 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 (*S*).
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	Falciu 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, Falciu 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).

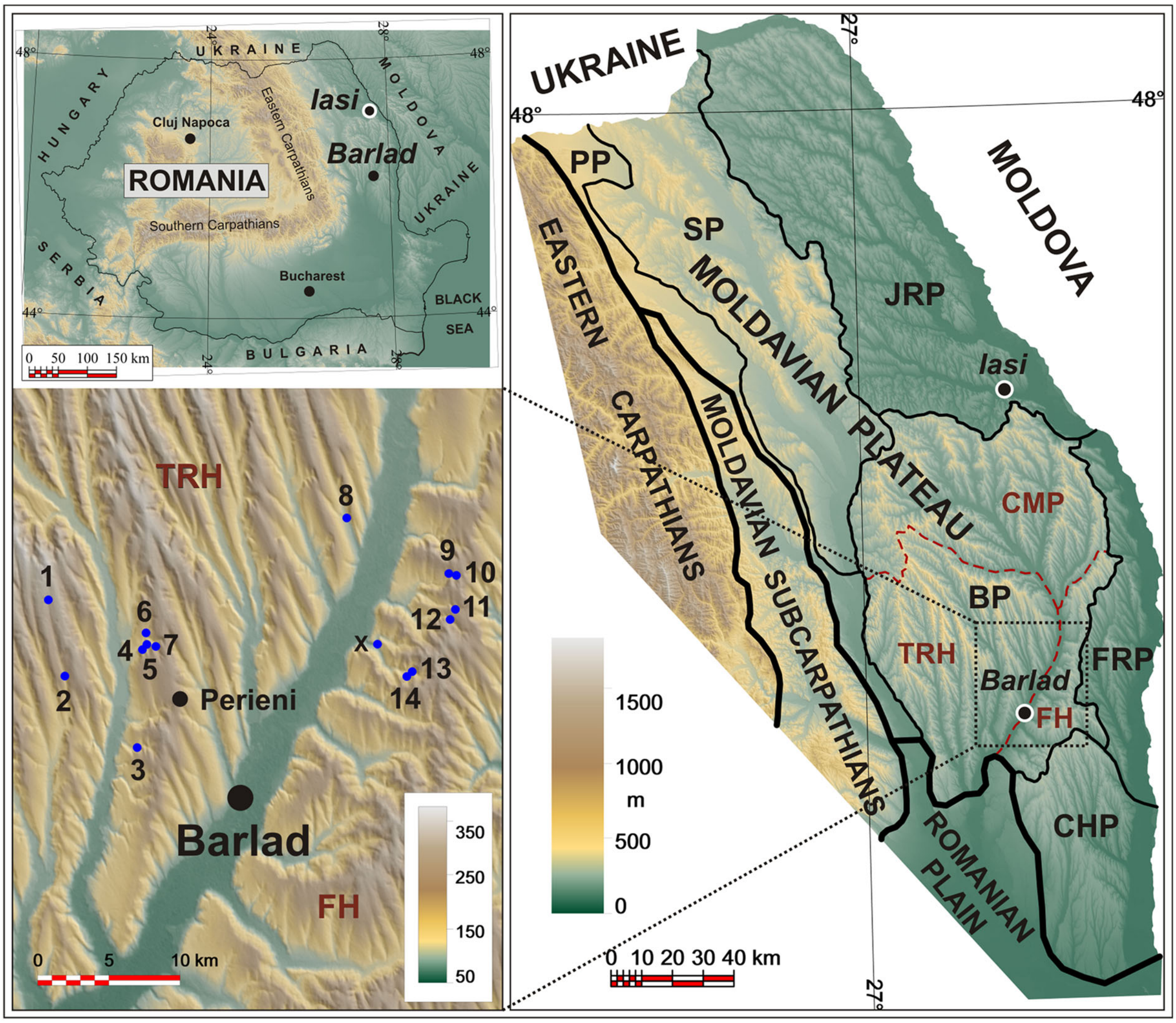

FIGURE 1 Digital elevation model (DEM) of study area and location of the main gullies. Gully number: 1, Angheluta; 2, Hreasca; 3, Gheltag; 4, Ursoi; 5, Langa; 6, Fagaras; 7, Scranghita; 8, Mitoc; 9, Puriceni gully 2, 10, Puriceni gully 1; 11, Valcioaia; 12, Tumba; 13, Recea; 14, Chira; X, Loava

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 sylvo-steppe 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

FIGURE 2 Valcioaia continuous valley-bottom gully developed after 1970 (photograph taken using a drone by Andrei Enea on 1 April 2021)

TABLE 2 Morphometric parameters of the studied catchments and sub-catchments

Number	Catchment			Gully contributing sub-catchment			Total gully length in 2020 (m)
	Area (ha)		Mean slope (%)	Total area at the outlet (ha)		Area in 1960 (ha)	
1	Chioara	2997	15.6	Valcioaia	598	414	2728
				Tumba	468	175	2615
				Puriceni 1	867	157	289
				Puriceni 2[a]	44	44	193
2	Banca	1614	20.3	Recea	481	481	473
				Chira[b]	71	71	153
3	Roscani	796	19.2	Scranghita-Poligon	229	127	950
				Fagaras[c]	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

[a]Since 1970;
[b]Since 1967;
[c]Since 1964.

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 gullying 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 temporary 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 Stoisesti 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.

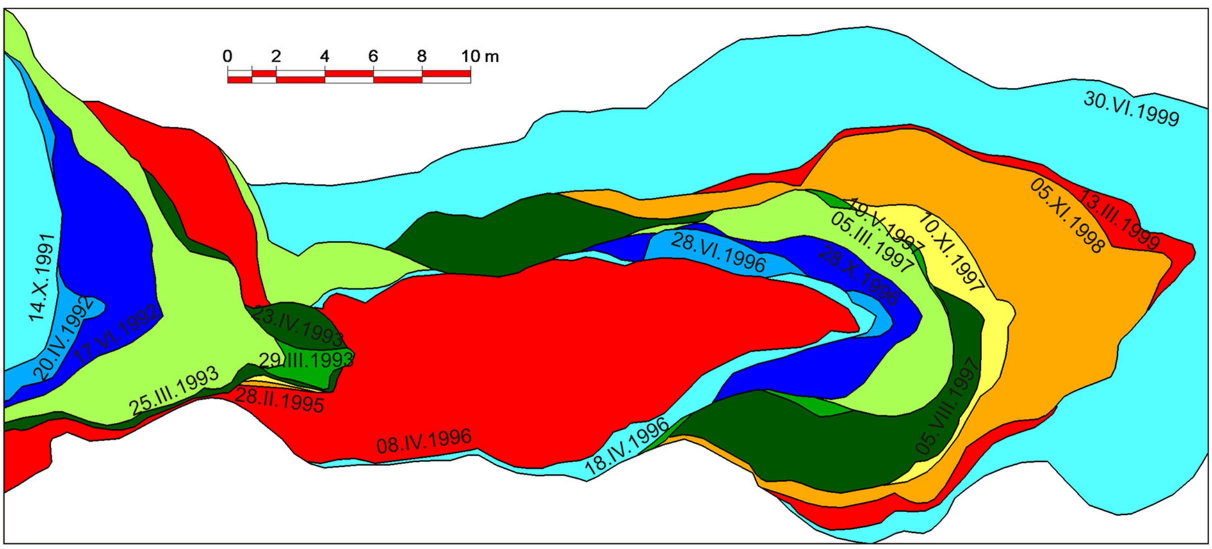

FIGURE 3 Measured growth of Gheltag continuous gully between 14 October 1991–30 June 1999 using the 'stakes grid method'. Labels refer to day, month and year of survey

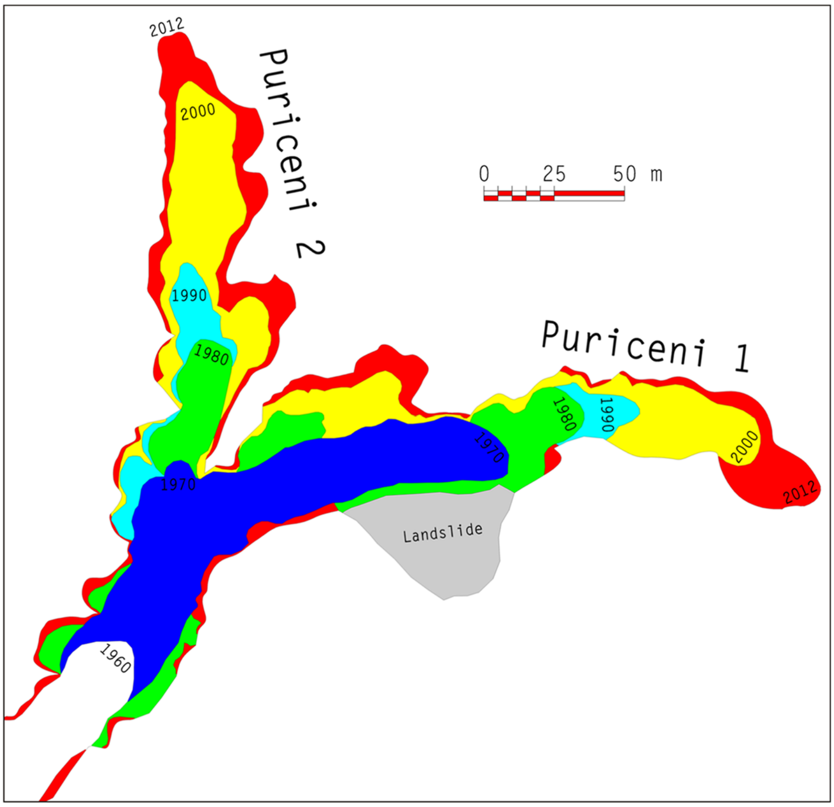

FIGURE 4 Development of the Puriceni gully system between 1961 and 2012 analysed using both aerial photographs from 1960 and 1970 and successive topographic levelling (Ionita, Niacsu, et al., 2015)

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 ~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

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

		Mean LGHR rate (m yr^{-1})						
Number	Gully	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	Scranghita	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.
[a]Minus 1985–1990 when the gully head was affected by a check-dam;
[b]Since 1964.
[c]Since 1970.
[d]Since 1967.

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

		Mean decadal precipitation				
			Cold season (October–March)		Warm season (April–September)	
Number	Decade	Total (mm yr^{-1})	(mm)	(%)	(mm)	(%)
1	1961–1970	581.8	222.6	38.3	359.2	61.7
2	1971–1980	568.8	169.9	29.9	398.9	70.1
3	1981–1990	419.4	135.6	32.3	283.8	67.7
4	1991–2000	496.0	164.3	33.1	331.7	66.9
5	2001–2010	492.2	172.3	35.0	319.9	65.0
6	2011–2020	490.9	205.8	41.9	285.1	58.1
7	Mean of 60 years	**508.2**	**178.4**	**35.1**	**329.8**	**64.9**

50 m^2 yr^{-1} for Ursoi gully and 999 m^2 yr^{-1} for Hreasca gully. When considering previous periods, the mean AGG rate of 476 m^2 yr^{-1} for the 20-year wet period 1961–1980 is 5.9 times larger than the mean AGG of 81 m^2 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, R^2 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 $n = 83$.

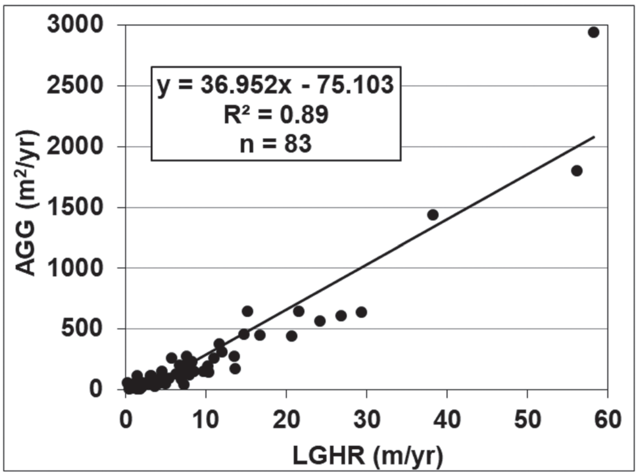

FIGURE 5 Plot of mean annual areal gully growth (AGG) versus mean annual linear gully head retreat (LGHR) rate measured over six decades between 1961 and 2020 for 14 continuous gullies

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, Gheltag, Langa, Puriceni gully 2 and Ursoi) do not exhibit any significant correlations between LGHR rate and CA. No significant correlations were found between decadal AGG and CA:

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

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

When considering the contributing CA multiplied by catchment slope (S) upstream of the gully head, correlations between mean LGHR and their product (CA $\times$ S) are also generally weak. The product CA $\times$ S is responsible for only 10% (n = 71) of the variance of LGHR when including 12 gullies with a 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, R^2 increases to 0.27 (n = 83). Again, no significant associations were evident between decadal AGG and CA $\times$ 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

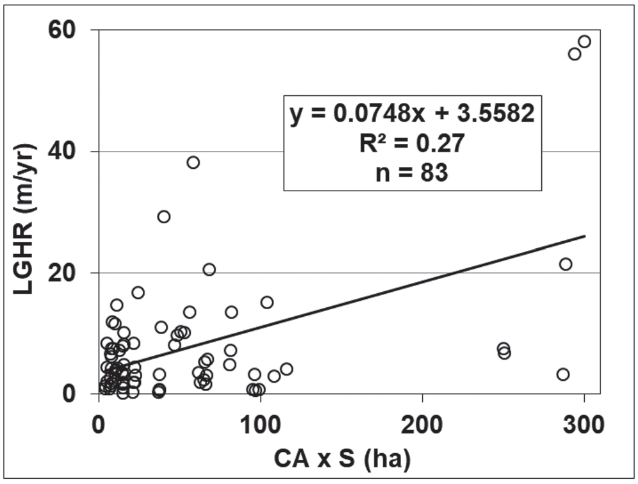

FIGURE 6 Plot of mean annual linear gully head retreat (LGHR) rate measured over six decades between 1961 and 2020 against catchment area (CA) multiplied by mean catchment slope (S) for 14 continuous gullies on the Barlad Plateau (BP)

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 Stoisesti 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 gullying rates of 3.7 to 4.0 m yr^{-1} were influenced by both soil moisture reserves from previous years and the impact of nivational 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 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 m^2 yr^{-1}) occurred in the 6 years with above average P values. The annual AGG peak-value of 287 m^2 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.

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

Year	Gully/annual LGHR (m yr^{-1})							Mean GHR (m yr^{-1})
	Gheltag	Valcioaia	Recea	Chira	Loava	Mitoc	Tumba	
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.

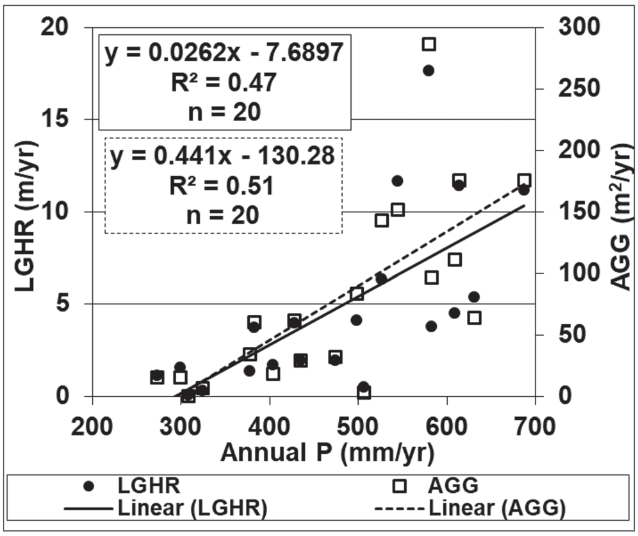

FIGURE 7 Plot of mean annual linear gully head retreat (LGHR) rate (closed circles) and areal gully growth (AGG) rate (open squares) versus annual precipitation depth (P) for seven gullies monitored over 20 years (1981–2000)

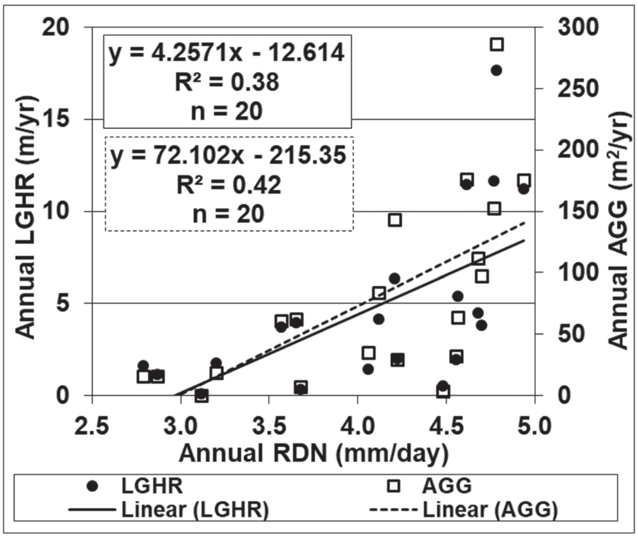

FIGURE 8 Plot of mean annual linear gully head retreat (LGHR) (closed circles) and areal gully growth (AGG) (open squares) against annual rainy day normal (RDN) for seven gullies over 20 years (1981–2000)

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 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 hanging incision developed in recent alluvia/colluvia (1.8 m thick), along the end reach of the upstream discontinuous gully. The 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:

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

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:

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

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 × *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

TABLE 6 Pearson correlation coefficient matrix for annual linear gully head retreat (LGHR) for seven gully heads between 1981 and 2000

Variables	Gheltag	Valcioaia	Recea	Chira	Loava	Mitoc	Tumba
Gheltag	**1**	**0.622**	0.416	0.146	0.209	0.230	0.198
Valcioaia	**0.622**	**1**	**0.748**	**0.553**	**0.626**	**0.813**	**0.742**
Recea	0.416	**0.748**	**1**	**0.725**	**0.670**	**0.817**	**0.614**
Chira	0.146	**0.553**	**0.725**	**1**	**0.802**	**0.755**	**0.665**
Loava	0.209	**0.626**	**0.670**	**0.802**	**1**	**0.670**	**0.774**
Mitoc	0.230	**0.813**	**0.817**	**0.755**	**0.670**	**1**	**0.690**
Tumba	0.198	**0.742**	**0.614**	**0.665**	**0.774**	**0.690**	**1**

Values in bold are significant at $p < 0.05$.

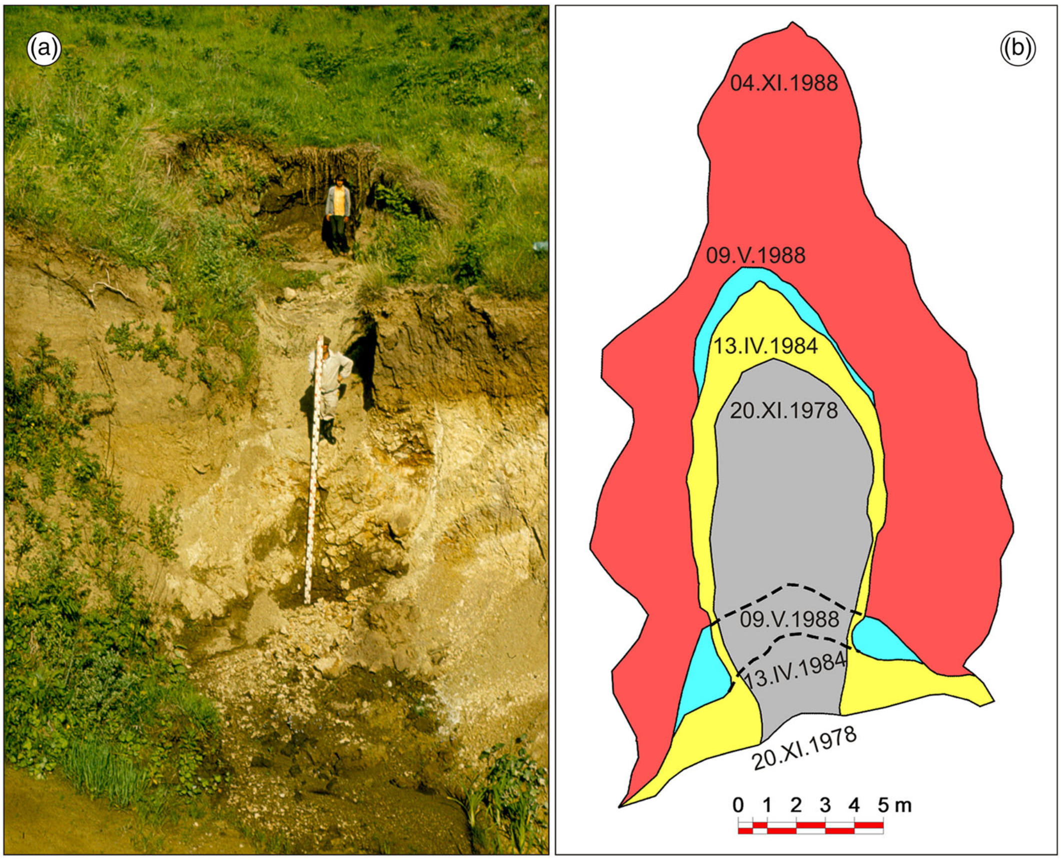

FIGURE 9 Bottle-neck shaped incision in the headcut of Gheltag continuous gully on 8 June 1979 (a) and gully development by 4 November 1988 (b)

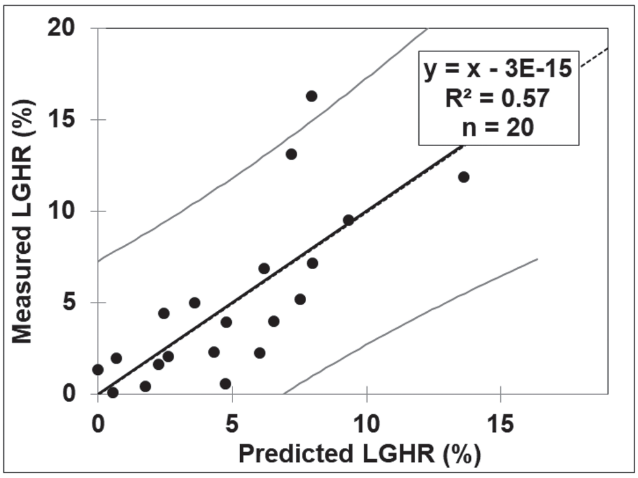

FIGURE 10 Measured versus predicted relative mean linear gully head retreat (LGHR)

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

(April–September). Mean snowfall is 38 cm yr^{-1} (equivalent to ~40 mm of water) and the depth of frozen soil is ≤ 100 cm.

Multiple annual field measurements on the growth of six continuous gullies (Recea, Chira, Loava, Mitoc, Tumba and Valcioaia) between 1981 and 2000 indicate that 57.4% (2.7 m yr^{-1}) of the mean LGHR rate (4.7 m yr^{-1}) occurred in the cold season (in late winter, especially due to nivation and snowmelt runoff). The remaining 42.6% of LGHR resulted from rainfall-induced runoff in spring and early summer (Table 7).

Three gully heads with drier bottoms had above average LGHR values in the cold season (October–March) (Tumba: 79%, Chira: 65%, Valcioaia: 59%). Both Mitoc and Recea gullies had the lowest LGHR rates (42% and 53%, respectively), due to their much wetter floors. Only Loava gully approximated the mean LGHR rate.

Very similar mean values (53.5% in the cold season and 46.5% in the warm season) were found for AGG over 1981–2000, when the mean rate was 78 m^2 yr^{-1}. Above average values were evident in four gully systems (Tumba and Chira: 71%, Loava: 63% and Valcioaia: 57%) in the cold season, while two gullies (Mitoc and Recea) had higher warm season values.

Figure 11 illustrates the impacts of snowmelt runoff and nivational activity on the growth of Tumba gully head during March–early April 1985, after a marked fall in mean air temperature to −8.2°C in January and −9.9°C in February. Large loamy 'blocks' of regolith (~11 m^3, 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 m^2 in 1988 (103 m^2 in late winter and 201 m^2 in the warm season) and 168 m^2 in 1996 (132 m^2 in late winter and 36 m^2 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 nivational 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 m^2) and ranged between 0.259 m for Valcioaia gully and 0.358 m for Tumba gully. Of all 122 wetted CSA, ~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 m^3 s^{-1} during streamflow fed by snowmelt (Ionita, 1998, 2000, 2008) and ~90 m^3 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

	Mean LGHR					
	(m yr^{-1})			(%)		
Gully	**Total**	**Cold season**	**Warm season**	**Total**	**Cold season**	**Warm season**
Recea	6.0	3.2	2.8	100	53.3	46.7
Chira	1.6	1.0	0.6	100	62.5	37.5
Loava	2.1	1.2	0.9	100	57.1	42.9
Mitoc	5.2	2.2	3.0	100	42.3	57.7
Tumba	2.9	2.3	0.6	100	79.3	20.7
Valcioaia	10.6	6.3	4.3	100	59.4	40.6
Mean	**4.7**	**2.7**	**2.0**	**100**	**57.4**	**42.6**

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.

FIGURE 11 The impact of nivation on Tumba gully head (19 April 1985). Note person for scale and the cross-section (CS) of the upstream discontinuity, mostly developed in recent alluvia

FIGURE 12 Snowmelt runoff at Valcioaia gully head area. Flow commenced at 1501 (EET) on 27 March 1996 (a) and ceased at 1720 (EET) on 2 April 1996 (b). Gully depth is 11.7 m at 35 m downstream of the gully headcut (a). Note significant aggradation of the former upstream discontinuity (b)

∼50% in the BP (eastern Romania) and ∼67% in the Middle Volga region (Russian Federation).

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).

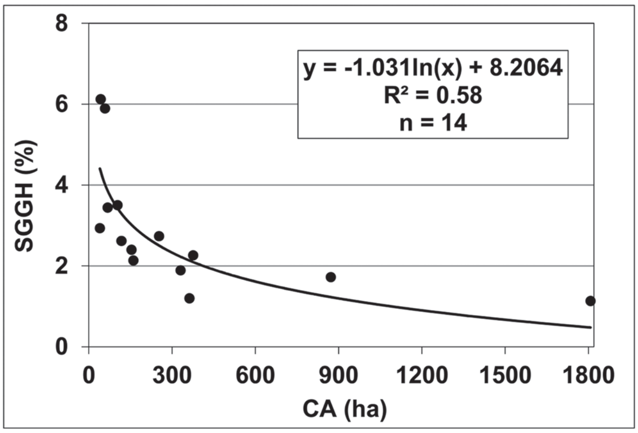

FIGURE 13 Plot of soil surface slope gradient at the gully head (SGGH) versus catchment area (CA) for 14 continuous gullies on the Barlad Plateau

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 Valcioaia, Hreasca and Tumba, these gullies are 0.3–1.2 m deep, have an actual CS of 0.4 to 9.4 m^2 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 m^2 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 51.2 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 timescales, 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 Valcioaia 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 m^2 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 m^2. 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_t horizon, the CS becomes V-shaped and the associated HR doubles. The B_t 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

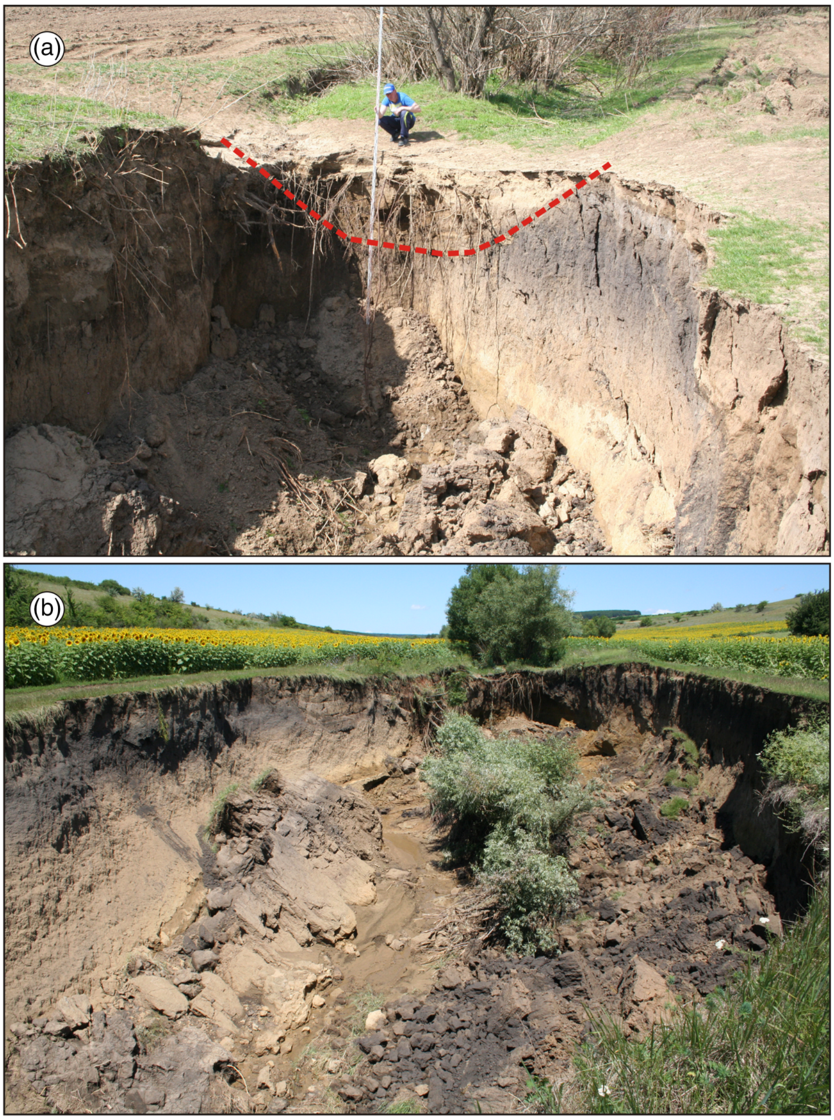

FIGURE 14 (a) Recent aggradation of the discontinuous gully located just upstream of the headcut of Hreasca continuous gully (11 April 2018). (b) Hreasca gully head after heavy rainfall, showing the impact of changing runoff patterns (3 July 2018)

both gullies occurred after their headcut entered a black locust (*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 ~1:7 or ~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.

5 | 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 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. 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 × *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 nivational 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.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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SUPPORTING INFORMATION

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

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