Earth-Science Reviews 154 (2016) 336–355

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Invited review

How fast do gully headcuts retreat?

Matthias Vanmaercke [a,b,*], Jean Poesen [a], Bert Van Mele [a], Matthias Demuzere [a,b], Amber Bruynseels [a], Valentin Golosov [c,d], José Fernando Rodrigues Bezerra [e], Sergey Bolysov [c], Aleksandr Dvinskih [d], Amaury Frankl [f], Yulia Fuseina [c], Antônio José Teixeira Guerra [g], Nigussie Haregeweyn [h], Ion Ionita [i], Fils Makanzu Imwangana [j,k], Jan Moeyersons [l], Itshack Moshe [m], Aliakbar Nazari Samani [n], Lilian Niacsu [i], Jan Nyssen [f], Yoshinori Otsuki [o], Maria Radoane [p], Ivan Rysin [q], Yuri V. Ryzhov [r], Oleg Yermolaev [d]

[a] Division of Geography and Tourism, Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium
[b] Research Foundation Flanders (FWO), Brussels, Belgium
[c] Faculty of Geography, Moscow State Lomonosov University, Moscow, Russia
[d] Institute of Ecology and Environmental Sciences, Kazan Federal University, Kazan, Russia
[e] Geography and History Department, State University of Maranhão, São Luís City, Brazil
[f] Department of Geography, Ghent University, Ghent, Belgium
[g] Department of Geography, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil
[h] International Platform for Dryland Research and Education, Tottori, Japan
[i] Department of Geography, "Alexandru Ioan Cuza" University of Iasi, Iasi, Romania
[j] Laboratoire de Géomorphologie et Télédétection, Centre de Recherches Géologiques et Minières, Kinshasa, Congo
[k] Department of Geosciences, Faculty of Sciences, University of Kinshasa, Kinshasa, Congo
[l] Royal Museum for Central Africa, Tervuren, Belgium
[m] Forestry and Soil Conservation Division, Keren Kayemeth LeIsrael, Southern Region, Gilat, Israel
[n] Faculty of Natural Resources, University of Tehran, Tehran, Iran
[o] Institute of Geography, Tohoku University, Sendai, Japan
[p] Department of Geography, 'Stefan cel Mare' University, Suceava, Romania
[q] Department of Ecology and Environmental Sciences, Udmurt State University, Izhevsk, Russia
[r] Institute of Geography, Siberian Branch, Russian Academy of Sciences, Irkutsk, Russia

ARTICLE INFO

Article history:
Received 4 November 2015
Received in revised form 18 January 2016
Accepted 20 January 2016
Available online 23 January 2016

Keywords:
Gully erosion
Data compilation
Global analysis
Model
Climatic impact
Temporal variability

ABSTRACT

Gully erosion has important on and off site effects. Therefore, several studies have been conducted over the past decades to quantify gully headcut retreat (GHR) in different environments. Although these led to important site-specific and regional insights, the overall importance of this erosion process or the factors that control it at a global scale remain poorly understood. This study aims to bridge this gap by reviewing research on GHR and conducting a meta-analysis of measured GHR rates worldwide. Through an extensive literature review, GHR rates for 933 individual and actively retreating gullies have been compiled from more than 70 study areas worldwide (comprising a total measuring period of > 19 600 years). Each GHR rate was measured through repeated field surveys and/or analyses of aerial photographs over a period of at least one year (maximum: 97 years, median: 17 years). The data show a very large variability, both in terms of gully dimensions (cross-sectional areas 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 $year^{-1}$ with a median of 2.2 m^3 $year^{-1}$). Linear GHR rates vary between 0.01 and 135 m $year^{-1}$ (median: 0.89 m $year^{-1}$), while areal GHR rates vary between 0.01 and 3628 m^2 $year^{-1}$ (median: 3.12 m^2 $year^{-1}$). An empirical relationship allows estimating volumetric retreat rates from areal retreat rates with acceptable uncertainties. By means of statistical analyses for a subset of 724 gullies with a known contributing area, we explored the factors most relevant in explaining the observed 7 orders of magnitudes of variation in volumetric GHR rates. Results show that measured GHR rates are significantly correlated to the runoff contributing area of the gully ($r^2 = 0.15$) and the rainy day normal (RDN; i.e. the long-term average annual rainfall depth divided by the average number of rainy days; $r^2 = 0.47$). Other factors (e.g. land use or soil type) showed no significant correlation with the observed GHR rates. This may be attributed to the uncertainties associated with accurately quantifying these factors. In addition, available time series data demonstrate that GHR rates are subject to very large year-to-year variations. As a result, average GHR rates measured over short (<5 year) measuring periods may be subject to very large (>100%) uncertainties. We integrated our findings into a weighted regression model that simulates the volumetric retreat rate of a gully headcut as a function of upstream drainage area and RDN. When

---

* Corresponding author at: KU Leuven, Division of Geography and Tourism, Celestijnenlaan 200E, 3001 Heverlee, Belgium.
E-mail address: matthias.vanmaercke@ees.kuleuven.be (M. Vanmaercke).

http://dx.doi.org/10.1016/j.earscirev.2016.01.009

weighing each GHR observation proportional to its measuring period, this model explains 68% of the observed variance in GHR rates at a global scale. For 76% of the monitored gullies, the simulated GHR values deviate less than one order of magnitude from their corresponding observed value. Our model clearly indicates that GHR rates are very sensitive to rainfall intensity. Since these intensities are expected to increase in most areas as a result of climate change, our results suggest that gully erosion worldwide will become more intense and widespread in the following decades. Finally, we discuss research topics that will help to address these challenges.

Contents

1. Introduction

Several studies reported that gully development leads to important losses of land and damage to infrastructure (e.g. Poesen et al., 2003; Valentin et al., 2005; Makanzu Imwangana, 2014). Furthermore, gullies are often a major source of sediments at the catchment scale, can strongly increase catchment sediment connectivity and can have strongly negative impacts on the hydrological functioning of catchments (e.g. Poesen et al., 2003; Avni, 2005; de Vente and Poesen, 2005; Vanmaercke et al., 2011a,, 2012a). Understanding this erosion process is therefore highly relevant, both from a geomorphic and environmental point of view (e.g. Poesen et al., 2003). Over the past decades, several studies focussed on identifying the topographic, climatic, lithologic and land use conditions under which gullies form and this has been the subject of other review articles (e.g. Poesen et al., 2003, 2011; Torri and Poesen, 2014).

Gullies are often characterized by actively retreating headcuts. A gully headcut is a natural, nearly vertical drop in gully channel-bed elevation (Poesen et al., 2003). Since, gully headcut retreat (GHR) is the major process of gully expansion, various studies have measured gully GHR rates for specific gullies (Poesen et al., 2011). Although these studies have provided us with important findings, their results remain specific for the study areas where they were conducted and can therefore not be easily extrapolated. Our understanding about the magnitude and controls of GHR rates can therefore strongly benefit from a review and analyses of these site-specific studies. Moreover, many field data on GHR rates risk to get lost as recently demonstrated for other type of legacy data (Vines et al., 2014). Hence, the objectives of this study were: (i) to review studies measuring GHR rates and to compile previously reported retreat rates; (ii) to explore the factors explaining the variability in GHR rates at a global scale based on a meta-analysis of these compiled data in a database; and (iii) to identify and discuss scopes for further research to improve our understanding of GHR.

Section 2 provides a brief literature review on what is currently known about the processes and factors driving GHR. Section 3 explains the compilation of a global database of GHR rates from literature, while Section 4 provides an overview of the available measurements. The compiled database itself is included in appendix. In Section 5 we examine the factors controlling the spatial variability of GHR at a global scale, explore the role of temporal variations in GHR and propose a model that allows simulating volumetric GHR rates based on commonly available data. In our conclusions (Section 6) we highlight some important implications of our work and discuss a number of promising areas for further research.

2. A brief review of processes and factors controlling gully headcut retreat rates

Several studies have already explored the role of different processes and factors controlling gully headcut retreat and proposed empirical models that allow simulating GHR rates (Poesen et al., 2011; Table 1). These studies show large discrepancies in the factors they report as controlling GHR rates. This is likely attributable to the different environments in which these studies were conducted. In addition, also the type of retreat rate considered varies. For example, depending on the study, GHR rates are reported as linear retreat rates (i.e. the distance along the slope [m] over which the gully head retreated per unit of time), as areal retreat rates (i.e. the areal expansion [m^2] of the gully head over time), as volumetric retreat rates (i.e. the eroded volume [m^3] of soil per unit of time) or the mass retreat rate (i.e. the mass [t] of eroded soil material per unit of time). Likewise, some studies focussed on the GHR during specific (rainfall or snowmelt) events while others provided data on long-term average retreat rates (Table 1). Nonetheless, these studies provide valuable insights into the factors that may potentially control GHR. We start with reviewing the processes that cause a gully headcut to retreat (Section 2.1). Next, we discuss the factors that control (often indirectly) the GHR rate. A distinction is made between factors indicative for the erosive forces that cause headcut retreat (Section 2.2) and factors reflecting resistance forces that prevent, or slow down, GHR retreat (Section 2.3).

2.1. Processes controlling gully headcut retreat

Once a gully channel is formed (mostly by hydraulic erosion), several processes lead to channel expansion: i.e. tension crack development, piping, plunge pool and splash erosion, fluting and mass failure (i.e. creep, soil fall, toppling and sliding). These processes, summarized below, contribute in various degrees to the retreat of a gully headcut (Poesen et al., 2002).

The erosion or undercutting of cohesive gully banks commonly involve significant tensile strains. These strains often lead to deep soil cracks, parallel to the gully walls. Such tension cracks typically occur in well-developed tension zones of brittle soils (Poesen et al., 2002). Piping (subsurface concentrated flow erosion due to bypass flow) is mainly controlled by soil characteristics at depth, particularly the presence of differential porosity, solubility and strength. Also soil surface features allowing concentrated penetration of overland flow into deep tension cracks or desiccation cracks enhance soil piping (Harvey, 1982).

At the gully headcut the dissipation of the kinetic energy of the flowing water causes intense splash and hydraulic erosion, leading to a deepening and widening of the gully channel (Poesen et al., 2002). Plunge pools are formed by falling water at the base of vertical gully headcuts. Plunge pool erosion is essentially controlled by flow erosivity (which in turn depends on water fall height and unit flow discharge) and soil erodibility. Field observations reveal that the development of plunge pools in gully channels often undermines the gully walls and, hence, decrease their stability (Harvey, 1982; Poesen et al., 2002).

Gully head and gully wall collapse are a composite and cyclical process resulting from downslope creep, tension crack development, saturation of soil cracks by overland flow, gully head or wall collapse, followed by debris erosion during runoff events which facilitates the next failure (Collison, 1996). In areas where dispersible soils occur, also fluting can cause pronounced gully wall retreat. Flutes are vertically elongated grooves, generally tapering towards the top that furrow into the wall of the gully and result predominantly from the action of flowing water (Poesen et al., 2002).

There are two common types of mass failure in homogenous, cohesive gully banks (Alonso and Combs, 1990). One is a progressive, continuous failure by creep movements over long periods of time. The other is a catastrophic shear failure of the bank which is the most frequent mode of failure in cohesive gully banks. Rapid movement usually occurs when the shear strength along a slip surface is exceeded, either because of a reduction in the shear strength of the bank material (caused by an increase in pore water pressure, weathering, …) or by an increase in stress due to soil saturation or human activities (e.g. due to overloading; Poesen et al., 2002). In contrast to non-cohesive gully banks which are maintained at the natural angle of repose and where stability is independent of bank height, the stability of cohesive gully banks strongly depends on both the slope and height of the bank (Alonso and Combs, 1990). Most often failure occurs by a deep-seated slip, although shallow slips also occur. Failure mechanisms most frequently associated with gully banks are rotational slips, plane slips in association with tension cracking and cantilever failures (Alonso and Combs, 1990).

Gully headcut retreat results from a combination of several of these processes (although typically not all of them) which renders accurate prediction of headcut retreat rates using physics-based models very difficult (Poesen et al., 2011). As an alternative, most studies followed a more empirical approach by directly linking GHR rates to environmental factors. These factors are discussed below.

2.2. Factors reflecting erosive forces

These factors generally reflect controls on the runoff volume and flow intensity that causes the headcut to retreat. A first commonly considered erosive factor is the size of the upstream area (A) draining to the gully headcut. As larger areas can produce larger runoff volumes, a positive correlation between A and GHR rates is widely reported (Table 1). Nonetheless, depending on rainfall characteristics and the spatial configuration of land use and soil characteristics, only certain parts of the drainage area may actually contribute runoff (Rossi et al., in press; Moeyersons et al., 2015). Hence, the upstream drainage area of a gully provides a maximum area that may contribute runoff to the headcut and will therefore generally overestimate the actual runoff contributing area (Rossi et al., in press).

A potentially relevant factor related to A, is the shape of the drainage area. Travel distances in elongated catchments are generally longer than in catchments with a more circular form of the same size, resulting in relatively smaller peak flow discharges (Summerfield, 2014). As GHR is mainly caused by these runoff peaks cause GHR (Nachtergaele et al., 2002b; Moeyersons et al., 2015), the shape of the drainage area is expected to influence GHR rates. Nevertheless, no studies have investigated this.

Evidently, weather and climate conditions also play an important role in runoff production and may therefore be expected to also influence GHR rates. Especially factors relating to rainfall intensity (e.g. the sum of rainfall events exceeding a certain intensity threshold) have been reported to explain differences in GHR rates (e.g. Beer and Johnson, 1963; Thompson, 1964; Stocking, 1980; Rieke-Zapp and Nichols, 2011; Table 1). However, some studies also indicate that antecedent soil moisture content (e.g. Stocking, 1980, 1981; Karimov et al., 2014), soil thawing and snowmelt runoff (e.g. Archibold et al., 2003; Ionita, 2000, 2006, 2008; Rodzik et al., 2009; Ionita et al., 2015; Moeyersons et al., 2015) can play an important role. Surprisingly, however, relatively few of the proposed GHR models actually consider weather and climate conditions as a driving factor (Table 1). This may be explained by the fact that most studies focussed on differences in average retreat rates in relatively small areas with a limited climatic variability. GHR models that do include a climate or weather factor were calibrated with either time series of retreat rates (allowing to account for temporal variations in rainfall; e.g. Stocking, 1980) or with data from several locations throughout the USA (e.g. Thompson, 1964; US Soil Conservation service, 1966).

Also land cover and soil characteristics can influence gully initiation through their effect on runoff production (e.g. Hawkins et al., 2009; Nyssen et al., 2010; Maetens et al., 2012a; Torri and Poesen, 2014). As a result, land use and soil conditions that promote runoff may also increase GHR rates. A typical example are gullies that result from strongly increased runoff production due to soil compaction and/or road construction in urbanized environments (e.g. Makanzu Imwangana et al., 2014; Moeyersons et al., 2015). Some studies also indicated that variability in GHR rates can be linked to land use (e.g. Kosov, 1970; Rysin, 1998). Nonetheless, with the exception of studies by Beer and Johnson (1963) and of Li et al. (2015), most local GHR rate models do not include a land use related factor (Table 1). Nevertheless, the role of land use was evaluated in several studies but reported to have no or only a very limited effect (e.g. Vandekerckhove et al., 2001b). This may be partly attributed to the difficulties associated with accurately quantifying the effects

Table 1
Overview of studies reporting site and region-specific empirical models to simulate gully headcut retreat rates. Note that the ‘Considered factors’ only indicate factors that were included in the proposed models.

Continent	Study area	Dominant soil types	Type of retreat	Number of observations	Considered factors						Reference
					Climate	Maximum contributing area	Topography	Land use	Soil characteristics	Gully age	
Africa	Ethiopia (northern Highlands, near Mekele)	Clayey soils (Vertisols)	Volumetric	33	/	Drainage area above gully head (+)	/	/	/	/	Frankl et al. (2012)
	South Africa (KwaZulu – Natal Province)	Sandy loam (Acrisols and Luvisols)	Volumetric	15	/	Drainage area above gully head (+)	/	/	/	/	Grellier et al. (2012)
	Zimbabwe (Central Zimbabwe)	Fine sandy soils (Sodium rich)	Volumetric (events)	66	Event rain depth (+); antecedent moisture index (+)	Drainage area above gully head (+)	Height of the headcut (+)	/	Piping Index (+)	/	Stocking (1980, 1981)
Asia	China (Caijiachuan basin, SE loess plateau)	Loess	Areal (total of multiple headcuts in small catchment)	30	/	Upslope drainage area (+)	Local Slope gradient (+)	Proportion of the upslope drainage area with less than 60% vegetation cover (+)	/	/	Li et al. (2015)
	Iran (Hableh Rood basin, Semnan Province)	Sandy, Ca-rich	Linear	16	/	Drainage area above gully head (+)	/	/	Fraction of soluble minerals (+)	/	Nazari Samani et al. (2010)
	Israel (Southern Israel)	Loess	Linear	35	/	Drainage area above gully head (+)	/	/	/	/	Seginer (1966)
Europe	Romania (Moldavia)	Marls and clays	Linear	22	/	Drainage area above gully head (+)	Relief energy of the drainage basin (+); drainage basin inclination (−)	/	/	Length of the gully at the beginning of the period (+)	Radoane et al. (1995)
	Romania (Moldavia)	Sandy material	Linear	16	/	Drainage area above gully head (+)	Relief energy of the drainage basin (−); drainage basin inclination (−)	/	/	Length of the gully at the beginning of the period (+)	Radoane et al. (1995)
	Spain (SE Spain)	Sandy loam & clay	Volumetric	46	/	Drainage area above gully head (+)	/	/	/	/	Vandekerckhove et al. (2001a, 2001b)
	Spain (SE Spain)	Sandy loam & clay	Volumetric	9	/	Drainage area above gully head (+)	/	/	/	/	De Luna Armenteros et al. (2004)
	Spain (SE Spain)	Sandy loam & clay	Volumetric	9	/	Drainage area above gully head (+)	/	/	/	/	Marzolff et al. (2011)
N-America	Canada (Eastern shoreline of Lake Huron)	Glacial and glaciolacustrine clays	Areal	44	/	Drainage area above gully head (+)	/	/	/	/	Burkard and Kostaschuk (1997)
	USA (Western Iowa)	Loess	Areal	61	Index of surface runoff (+); deviation in precipitation from normal (−)	Distance from gully head to catchment divide (−)	/	Amount of terraced area in the catchment (−)	/	Length of the gully at the beginning of the period (+)	Beer and Johnson (1963)
	USA (Minnesota, Iowa, Alabama, Texas, Oklahoma, Colorado)	Clayey, silty and sandy soils	Linear	210	Sum of all rainfall with an intensity >12.7 mm/day (+)	Drainage area above gully head (+)	/	/	Fraction of clay of the eroding profile (+)	/	Thompson (1964)
	USA (East of Rocky mountains)	Clayey, silty and sandy soils	Linear	210	Sum of all rainfall with an intensity >12.7 mm/day (+)	Drainage area above gully head (+)	/	/	/	/	US Soil Conservation Service (1966)
	USA (Walnut Gulch, Arizona)	Gravelly sandy loams	Linear	8	Sum of all rainfall with an intensity >12.7 mm/day (+)	Drainage area above gully head (+)	/	/	/	/	Rieke-Zapp and Nichols (2011)

Factors that are not listed (‘/’) were either not considered by the authors or found to be insignificant.

of land cover on runoff, as also spatial and temporal patterns of land cover may play an important role in this (e.g. Rossi et al., in press). Furthermore, the lack of a detectable land use effect also suggests that this factor may be only of limited importance for explaining differences in GHR rates. This does not imply that land cover conditions are irrelevant for gully erosion. Land use can play a dominant role in the initiation of gullies (e.g. Poesen et al., 2003; Vanwalleghem et al., 2003; Torri and Poesen, 2014). But, given the fact that a gully headcut is present, differences in (often already erosion-prone) land cover conditions may be not necessarily crucial for explaining differences in GHR rates. A similar reasoning can be followed in explaining why the effects of soil characteristics on runoff production are not considered by empirical GHR rate models (Table 1). An additional reason for this might be that soil characteristics not only influence runoff production, but also the resistance of a headcut to erosion (see further). These effects may in some cases counteract each other. For example, sandy materials are often highly permeable (leading to lower runoff production) but also have little cohesion (facilitating GHR).

Finally, also topography can be considered as an erosive factor as slope gradient directly controls runoff erosivity (e.g. Knapen and Poesen, 2010). Several of the empirical GHR models do include a topographic factor (e.g. Stocking, 1980; Radoane et al., 1995; Li et al., 2015). However, here too it is noteworthy that most models do not (Table 1). As with land use and soil characteristics, it is possible that topography mainly controls the initiation of gullies (Poesen et al., 2003; Torri and Poesen, 2014) and less the GHR.

2.3. Factors reflecting resistance forces

Factors that control resistance to GHR are vegetation and soil properties. As discussed above, these factors can also control runoff volume and hence runoff erosivity. However, their role in flow erosivity is mainly determined by how they occupy the upstream drainage area, while their role in resisting GHR occurs at or nearby the actual headcut.

The presence of vegetation at a gully headcut can strongly decrease GHR rates in various ways (e.g. reducing flow velocity by increasing hydraulic roughness), but mainly by increasing the cohesion of the soil (e.g. Stokes et al., 2007; De Baets et al., 2008; Mao et al., 2012; Vannoppen et al., 2015). Whereas the effects of vegetation in reducing surface water erosion and runoff are mainly determined by the vegetation cover, its effects on reducing gully erosion mainly depend on the extent and architecture of its root systems (e.g. Gyssels et al., 2005; Knapen et al., 2007; Vannoppen et al., 2015). Given the difficulties associated in measuring belowground biomass characteristics such as root (length) density, relatively few data on the effects of root systems on concentrated flow erosion rates are available (Vannoppen et al., 2015). As a result, the effectiveness of vegetation in reducing GHR rates remains difficult to quantify. This also explains why empirical GHR rate models do not explicitly consider vegetation at the gully headcut (Table 1).

In terms of soil properties, mainly soil cohesion can be expected to influence GHR rates, with more cohesive soils resulting in lower soil erodibility (Poesen, 1992). This cohesion depends on various parameters including soil texture, organic matter content and chemical properties that prevent or promote the dispersion of soil aggregates (e.g. Sanchis et al., 2008). Also here, the effects of these properties on soil erodibility remain difficult to quantify or predict (Sanchis et al., 2008). Nonetheless, a number of studies do report a significant influence of soil properties on GHR (e.g. Thompson, 1964; Stocking, 1980; Radoane et al., 1995; Nazari Samani et al., 2010; Table 1). Most of the variables used to quantify these soil properties at gully heads mainly relate to the susceptibility of the soils to dispersion and piping. Also the rock fragment content of soils may influence GHR rates. Evidence for this is provided by laboratory experiments that show that soils with a large proportion of rock fragments are less likely to be incised by concentrated runoff (Poesen et al., 1999; Rieke-Zapp et al., 2007) and by compilations of field surveys, showing that gully incision thresholds are generally higher in stony soils (Torri and Poesen, 2014). Nonetheless, there are currently very few studies that directly demonstrate an impact of soil stoniness on GHR rates. Also previously proposed GHR rate models do not account for soil stoniness (Table 1).

2.4. Time and other potential controls

Apart from the factors listed above, some other elements may also potentially influence GHR rates but are not easily classified as 'erosive' or 'resistance' factors. One of these is seismicity. Cox et al. (2010) demonstrate that the spatial patterns of large erosional gullies in Madagascar are strongly correlated to patterns of earthquakes. This suggests that gully initiation and perhaps GHR may in some cases also be influenced by seismicity. Nonetheless, the processes explaining this correlation are poorly understood. Seismicity may potentially alter soil properties and hence decrease the soil resistance for GHR (Cox et al., 2010). However, seismicity may also cause landslides that predispose areas for gully erosion (e.g. by generating a steep drainage area devoid of vegetation). In addition, seismicity is often associated with uplift that may cause river incision and hence trigger gully erosion due to base level lowering (e.g. Menéndez-Duarte et al., 2007).

Another currently poorly understood factor is time. As the gully head retreats, the slope of the soil surface at the headcut and its drainage area may decline, resulting in a reduction of runoff erosivity. Additionally, the gully may stabilize through the development of vegetation in the gully channel and near the headcut or through human interventions that actively aim to stop the gully headcut from retreating (e.g. runoff diversion, headcut stabilization). For these reasons, one may expect that GHR rates will in general decline with the age of the gully. Some studies indeed report that average GHR rates decrease as the measuring period increases (e.g. Sobolev, 1948; Graf, 1977; Rutherford et al., 1997; Zorina et al., 1998; Nachtergaele et al., 2002a; Vanwalleghem et al., 2005; Makanzu Imwangana et al., 2015). Nonetheless, the overall effects of time on GHR rates remain poorly quantified, mainly due to a lack of sufficiently long time series of observations. As a result, none of the currently proposed empirical GHR models explicitly considers the age of the gully (Table 1). Some reported models do include the gully length at the beginning of the measuring period as a controlling factor (Beer and Johnson, 1963; Radoane et al., 1995). Gully length can be expected to correlate with gully age. Surprisingly, however, both Beer and Johnson (1963) and Radoane et al. (1995) include gully length as a factor that positively influences GHR rates. This further illustrates our limited understanding of the role of time in explaining GHR rates.

3. Data selection criteria and data compilation

Many studies on gully development produced valuable data on gully headcut retreat rates. These include linear, areal, volumetric and in a few cases mass measurements (Poesen et al., 2003). Overall, volumetric measurements are the best compromise as they avoid difficult considerations of bulk density of soils no longer in situ (Stocking, 1980).

We compiled a dataset on linear, areal and volumetric GHR rates based on an extensive literature review. We only retained GHR data that were actually measured at individual gully headcuts (i.e. no modelled/predicted values or gully erosion rates that reflect the average of multiple gullies) and that met the following selection criteria: (i) the retreat rate of the gully was measured over a known measuring period of at least one year; (ii) the cross-sectional area of the gully was at least one square foot (Poesen et al., 2003); and (iii) the gully headcut was actively retreating during the observation period. Regarding the last criterion, the difference between active and stabilized gully headcuts can easily be recognized in the field (see Oostwoud Wijdenes et al., 2000 for criteria). As a result, it was mostly clearly reported in the source that the gully headcut was active. However, some studies did not make this distinction and reported the retreat of all gullies in a given area, including some stabilized gullies (e.g. Rysin and Grigoriev, 2007). In those cases, we only retained the gullies with a reported linear retreat rate exceeding 1 cm/year, an areal retreat rate of >30 cm^2/year or a volumetric retreat rate of >900 cm^3/year.

Apart from the measured linear, areal and/or volumetric retreat rate, we included at least the following information: the original source of the data; the start date, end date and the duration of the measuring period; the latitude and longitude of the location of the gully headcut or (if unavailable) the latitude and longitude of the center of the study site; and the type of measuring procedure used to obtain the GHR rates. For the latter, we made a distinction between retreat rates obtained from field surveys (FS), retreat rates obtained from the analyses of aerial photographs, LIDAR, or other remote sensing techniques (AP) or a combination of both (FS + AP).

We also included the width, depth and cross-sectional area of the headcut, as well as the area of the catchment draining to the headcut (A) if this was reported or could be derived from the data. Likewise, we included (when available) information on the dominant land use in the catchment draining to the GH and the soil type/soil texture in which the GH developed. Information on the latter was often limited and difficult to compare between different studies. Therefore, we used a simple classification based on the dominant soil-textural class in which the gully developed, i.e. sandy, silty or clayey. Also other potentially relevant information (e.g. on important rainfall or snowmelt events during the measuring period, on vegetation characteristics at the gully headcut or on the local topography) was initially included in our dataset. However, such details were only reported for a small number of studies and did not allow for a systematic analysis.

4. Description of the compiled gully data

4.1. Overview of the gully head measurements

We compiled GHR rates for 933 individual gullies from 68 different data sources (Table 2; see appendix). These data represent measurements from 25 countries on six continents (Fig. 1). Especially Russia (208 gullies), Spain (131 gullies), Iran (110 gullies) and Romania (105 gullies) are well represented in our dataset (Table 2). As a result, the database reflects a wide range of environmental conditions (e.g. climate, land use, topography, lithology and seismicity) and gully dimensions. Fig. 2 illustrates some contrasting examples of gullies in study areas where GHR rates have been measured.

Most GHR rates were derived from either field surveys or a combination of field surveys and aerial photo analyses (e.g. to determine the initial extent of a gully). Based on these field surveys, a measured annual volumetric retreat rate (RR_V) was reported for about 72% of our data (672 gullies). Annual areal retreat rates (RR_A) were available for 714 gullies, while an annual linear retreat rate (RR_L) was available for 822 of the 933 gullies. While ca. 230 gullies were monitored over a period of five years or less, the majority of gullies were monitored over much longer periods with an average of 21 years (min: 1 year, max: 97 years, median: 17 years; Fig. 3). The sum of the measuring periods for all 933 gullies in our database yields a total of 19 656 'gully-years' of observations (Table 2). Most GHR rates were measured since the 1960s (Fig. 3). However, for ca. 50 gullies (mostly in N-America) the measuring period dates back to the 1930s (Fig. 3).

4.2. Gully dimensions

Fig. 4 displays the cumulative distributions of the gully widths (W), depths (D), cross-sectional areas (CS) and drainage areas (A) of all gullies in the dataset for which these variables were reported (note that the number of observations per cumulative distribution varies, due to the fact that these data were not systematically reported in each study). As seen in the examples shown in Fig. 2, the gullies represented in our dataset display a very large range in terms of dimensions (Fig. 4). Gully widths range between 0.4 and 104 m (mean: 9 m, median: 3.2 m), depths vary between 0.2 and 35 m (mean: 2.1 m, median: 1.3 m) and cross-sectional areas range between 0.11 and 816 m^2 (mean: 20.8 m^2, median: 3.7 m^2). Also the reported upstream areas draining to the gully headcut display a very large variability (0.001–10 000 ha) with a mean of 59.1 ha and a median of 4.3 ha.

Previous studies have shown that a fairly good correlation can be expected between the channel width of a gully and the runoff discharge passing through the channel (e.g. Nachtergaele et al., 2002b). Since drainage area is generally considered to be a proxy for runoff discharge (see Section 2.2), also a correlation between A and W can be expected. A weak but significant trend is indeed apparent (Fig. 5). However, the variance explained by this trend is small. Also the cross-sectional area of a gully headcut showed only a weak correlation with its corresponding upstream drainage area, while subdividing these relationships according to the dominant soil texture at the gully head did not improve these trends (Fig. 5). As a result, the area draining to a gully headcut cannot be straightforwardly estimated from the dimensions of the gully headcut, based on the data we collected. This lack of a strong correlation can be attributed to several reasons. Firstly, drainage area is only a crude proxy for runoff discharge. The actual discharges draining to the gully head will also depend on the shape and topography of the catchment, the (spatial distribution) of land use and soil characteristics and rainfall properties (e.g. Nachtergaele et al., 2002b; Vandekerckhove et al., 2003; Rossi et al., in press; Moeyersons et al., 2015). Especially at a global scale, these other factors influencing runoff discharge may vary strongly, while the relative importance of drainage area for runoff discharge may be larger at local scales. Secondly, the gully headcut widths (and cross-sectional areas) compiled in this study were not always measured using the same standardized method. Whereas runoff discharge will mainly influence the channel width (i.e. the width at the bottom of the gully; Nachtergaele et al., 2002b), a large (but unknown) fraction of the reported gully widths most likely reflects the top width of the gully, which may be the result of a combination of hydraulic erosion and mass movement processes on the gully banks (see Section 2.1). This gives further reason to interpret with caution the relationship between W and A shown in Fig. 5. Better correlations were observed between measured gully widths and gully depths and, consequently, between the width and cross-sectional area of gully headcuts (Fig. 5). Here too, differences in dominant soil texture at the gully head appeared to have little influence on the observed relationships. Given its high explained variance and the large number of observations involved, the relationship between W and CS (Fig. 5) might be useful to make robust, first-order assessments of gully cross-sectional areas in cases were only a gully width is reported.

4.3. Gully headcut retreat rates

As shown in Fig. 6, the variation of our compiled GHR rates worldwide is very large. Linear retreat rates vary between 0.01 m $year^{-1}$ (our arbitrarily set minimum, see Section 3) and 135.2 m $year^{-1}$, with a median of 0.89 m $year^{-1}$ and an average of 5.0 m $year^{-1}$. Areal retreat rates vary between 0.01 and 3628 m^2 $year^{-1}$, with a median of 3.1 m^2 $year^{-1}$ and an average of 131 m^2 $year^{-1}$. Volumetric retreat rates vary over 7 orders of magnitude (0.002–47 430 m^3 $year^{-1}$) with a median of 2.2 m^3 $year^{-1}$ and an average of 358.6 m^3 $year^{-1}$.

Fig. 7 displays relationships between linear, areal and volumetric retreat rates, based on all gullies for which at least the linear and areal, areal and volumetric or linear and volumetric retreat rates were measured. As could be expected, linear retreat rates are strongly correlated to their corresponding areal retreat rate ($r^2 = 0.83$) and to a lesser extent with their corresponding volumetric retreat rate ($r^2 = 0.53$). However, especially between areal (RR_A) and volumetric

Table 2
Overview of the collected gully headcut retreat data and their sources.

Continent	Country	# AP (Tot. MP)	# FS (Tot. MP)	# AP + FS (Tot. MP)	#Total (Tot. MP)	References
Africa	Angola	3 (23)	N.A.	N.A.	3 (23)	Bruynseels (2015)
	Burkina Faso	2 (6)	N.A.	N.A.	2 (6)	Marzolff and Ries (2007)
	D.R. Congo	57 (961)	N.A.	N.A.	57 (961)	Bruynseels (2015), Makanzu Imwangana (2014), Makanzu Imwangana et al. (2014), Makanzu Imwangana et al. (2015)
	Ethiopia	N.A.	45 (121)	18 (489)	63 (610)	Frankl et al. (2012), Haregeweyn et al. (2011), Nyssen et al. (2006)
	Kenya	N.A.	9 (27)	N.A.	9 (27)	Oostwoud and Bryan (2001)
	Morocco	1 (3)	N.A.	N.A.	1 (3)	Marzolff and Ries (2007)
	Nigeria	14 (74)	7 (19)	N.A.	21 (93)	Bruynseels (2015), Ehiorobo and Izinyon (2012), Olofin (1990)
	Rwanda	2 (14)	N.A.	N.A.	2 (14)	Bruynseels (2015)
	South Africa	N.A.	N.A.	13 (39)	13 (39)	Grellier et al. (2012)
	Swaziland	1 (8)	N.A.	N.A.	1 (8)	Sidorchuk et al. (2003)
	Tunisia	N.A.	N.A.	8 (304)	8 (304)	El Maaoui et al. (2012)
	Zimbabwe	5 (120)	N.A.	N.A.	5 (120)	Withlow and Firth (1989)
Asia	China	N.A.	37 (300)	N.A.	37 (300)	Hu et al. (2007, 2009), Li et al. (2007), Otsuki et al. (2008), Wang et al. (2008), Wu and Cheng (2005), Wu et al. (2008), Otsuki and Saijo, 2015
	Iran	N.A.	6 (18)	104 (3726)	110 (3744)	Mehdipour et al. (2007), Nazari Samani et al. (2010), Nazari Samani (pers. Comm.)
	Israel	36 (540)	9 (135)	4 (96)	49 (771)	Avni (2005), Ithshack (1998), Nir and Klein (1974), Seginer (1966)
	Nepal	N.A.	N.A.	3 (84)	3 (84)	Ghimire et al. (2006)
	Russia (Asian part)	N.A.	17 (82)	N.A.	17 (82)	Bazhenova et al. (1997), Ryzhov (1995, 1998)
Europe	Belgium	N.A.	18 (63)	N.A.	18 (63)	Nachtergaele et al. (2002a), Van Mele (2013)
	Poland	N.A.	N.A.	1 (64)	1 (64)	Schmidt and Heinrich (2011)
	Romania	38 (532)	16 (352)	51 (2136)	105 (3020)	Ionita (2006), Niacsu and Ionita (2011), Radoane et al. (1995)
	Russia (European part)	N.A.	191 (2973)	N.A.	191 (2973)	Bolysov (1982), Bolysov et al. (1985), Bolysov and Tarzaeva (1996), Dedkov et al. (1990), Rysin and Grigoriev (2007, 2009, 2010), Yermolaev (2014)
	Spain	65 (2117)	54 (256)	12 (376)	131 (2749)	Campo et al. (2007), Campo et al. (2010), De Luna Armenteros et al. (2004), Marzolff et al. (2011), Vandekerckhove et al. (2001a, 2001b, 2003)
N-America	Canada	48 (2976)	3 (23)	N.A.	51 (2999)	Archibold et al. (2003), Burkard and Kostaschuk (1995, 1997), Godin and Fortier (2012)
	United States	N.A.	6 (135)	N.A.	6 (135)	Leopold et al. (1966), Rieke-Zapp and Nichols (2011), Thomas et al. (2004)
Oceania	Australia	3 (87)	9 (12)	N.A.	12 (99)	Blong (1985), Brooks et al. (2009)
S-America	Brazil	7 (226)	10 (139)	N.A.	17 (365)	Coelho Netto et al. (1988), Francisco and Nunes (2009), Guerra et al. (2007), Lessa et al. (2007), Viero et al. (2005), Vrieling et al. (2005)
Total		282 (7687)	437 (4655)	214 (7314)	933 (19,656)	

For each country, the number ('#') of gully headcuts for which retreat rates have been measured are listed, while the value between brackets indicates the sum of their measuring periods in years ('Tot. MP'). 'AP', 'FS' and 'AP + FS' indicate gullies for which the retreat rate was respectively obtained from aerial photographs, field surveys or a combination of both. 'N.A.' means not available.

retreat rates (RR_V) a very strong correlation can be observed ($r^2 = 0.88$, $n = 550$; see Fig. 7):

$$RR_V = 1.2\ RR_A^{1.16} \qquad (1)$$

For only 10 out of the 550 gullies included in this relationship, the observed RR_V deviates more than a factor ten from the volumetric retreat obtained with Eq. (1). The volumetric retreat rates obtained with Eq. (1) deviate less than a factor 5 for 92% of the gullies included, while for 67% of these gullies the deviation is smaller than a factor 2. Similar to the gully headcut dimensions (Fig. 5), we found no evidence that the relationship between areal and volumetric retreat rates is strongly affected by the dominant soil texture at the gully headcut (Fig. 7). Given its large predictive value and the large number of observations worldwide on which this trend is based, Eq. (1) provides an easy way to robustly estimate the volumetric retreat rate of a gully head when only the areal retreat rate is measured (e.g. from aerial photographs).

Comparably, studies have proposed widely-used power relationships that allow estimating the volume of landslides based on their areal extent (e.g. Guzzetti et al., 2009; Larsen et al., 2010). However, recent studies have demonstrated that applying such relationships to landslide inventories can lead to large volume overestimations due to landslide amalgamation (i.e. the mapping of several adjacent landslides as a single polygon; Marc and Hovius, 2014). Since Eq. (1) has an exponent larger than one, this relationship may lead to similar overestimations when not correctly applied. It is therefore important to stress that Eq. (1) was calibrated only with data from individual gully headcuts and can only be used this way. For example, applying Eq. (1) to the areal expansion of an entire gully network may lead to large overestimations of the eroded volume.

5. Factors controlling gully headcut retreat rates at a global scale

5.1. Methodology

As discussed in Section 4.3, GHR rates at a global scale vary tremendously. Whereas several local and regional studies have already explored the factors controlling GHR rates (Table 1), a global analysis of GHR rates is currently lacking (see Section 2). We therefore explored the factors explaining the observed variability in our RR_V database, by means of standard statistical techniques.

We focussed our analyses only on volumetric retreat rates, as these relate most closely to the actual erosion rate, whereas the RR_L and RR_A only provide a proxy for the actual volume of eroded soil. GHR rates expressed as a mass per time unit also directly reflect erosion rates. However, such data are rarely reported and are subject to additional uncertainties associated with estimating the bulk density of the soil material. Therefore, only gullies with a reported volumetric or areal retreat rate were considered for further analyses. In those cases where only RR_A was reported, each individual retreat rate was converted into a volumetric retreat rate using Eq. (1). As discussed in Section 4.3, the

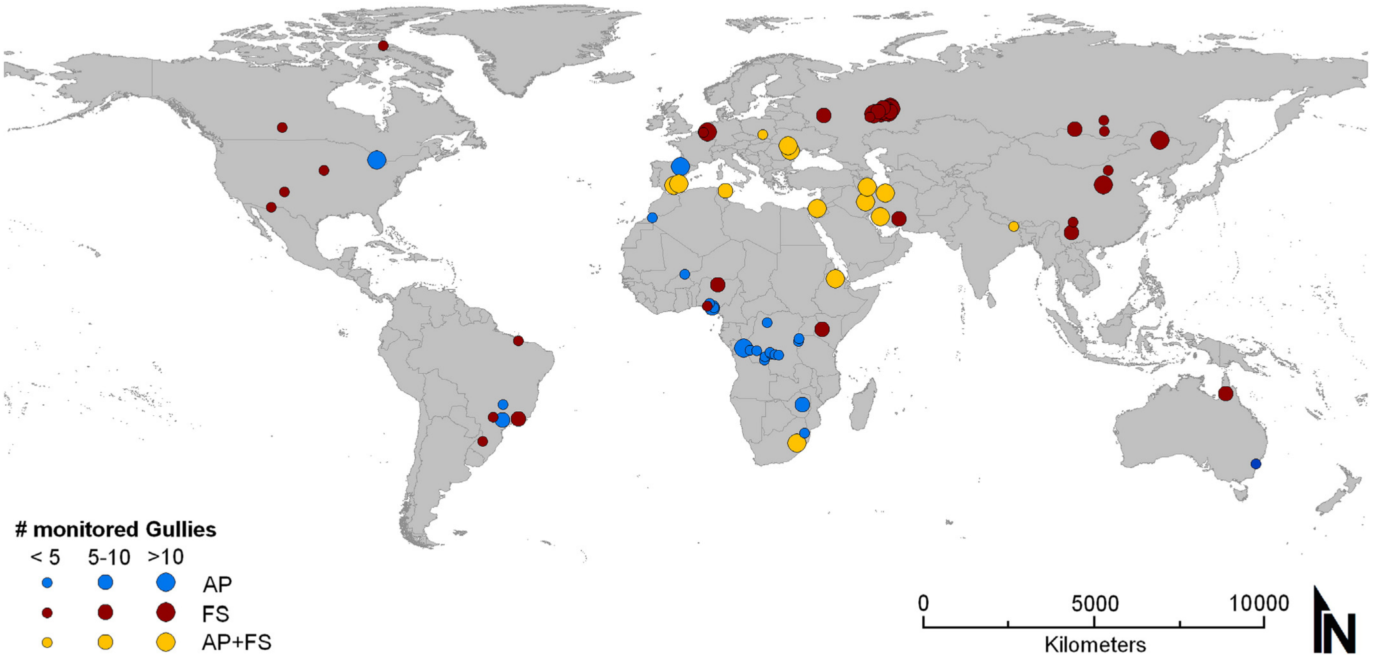

Fig. 1. Overview of the study site locations for which gully headcut retreat rates were reported. The size of each symbol indicates the number of gullies at the study site for which the headcut retreat rate was measured, while the symbol colours indicate the method used to derive the gully headcut retreat rates (AP = aerial photos, FS = field surveys, AP + FS: aerial photos combined with field surveys). The assignment of a gully to a specific study site was to some extent arbitrary (e.g. due to differences in accuracy of reported gully headcut locations). However, as a general rule, we considered two gullies to belong to the same study site if their geographical coordinates deviated less than half a degree from each other.

uncertainties associated with this conversion are expected to be small. No volumetric estimates were made from gullies with only a linear retreat rate reported, since the uncertainty associated with such estimations were expected to be too large (Fig. 7). In addition, since the area draining to the headcut is generally considered to be the most important factor influencing GHR (Table 1; Section 2), we only selected those gullies for which this drainage area was measured and reported. In total, 724 gullies met these criteria. For 80 of these gullies (studied by Burkard and Kostaschuk, 1997 and Bruynseels, 2015; see Table 2) the RR_V was obtained from the measured areal retreat rate, using Eq. (1). For the other 644 gullies, the volumetric retreat rate was directly measured and reported.

Based on our literature review (Section 2), we extracted a set of variables for each of our 724 gully headcuts (see Table 3). Their potential role in explaining the observed spatial variability in RR_V values was assessed by means of regression analyses, as well as by normal and partial correlation analyses. Partial correlation measures the degree of association between two considered variables, with the effect of other controlling variables removed (Fisher, 1924; Steel and Torrie, 1960). This is done by conducting a regression between each of the considered variables and the control variables and then calculating the correlation between the residues of these two regressions. Given the fact that RR_V (i.e. the dependent variable) and several of our considered independent variables (Table 3) vary over several orders of magnitude, we used the non-parametric Spearman's rank correlation coefficients for our correlation analyses, while our regression analyses were based on least-square linear fits on the logarithmically transformed data. This was done in order to obtain results that were as robust as possible.

Several of the considered variables (Table 3), including drainage area and measuring period, were directly derived from the original data sources and were also considered in previous studies exploring the factors controlling GHR rates (Table 1). However, since information about the topography, seismicity and air temperature and rainfall conditions was not reported for most of the gully headcuts, variables relating to these factors were extracted from global gridded datasets (see Table 3).

Reported information on soil characteristics at the gully head varied greatly between the different studies (from a general description of the soil type to detailed information on soil texture and chemistry). Due to these differences, we could only classify the soil at each gully head as dominantly sandy, silty or clayey. Whereas this only provides a rough description and may not capture other potentially relevant soil characteristics (e.g. the actual grain-size distribution, the organic matter content, the susceptibility to dispersion), it was the only way to allow for a systematic comparison between the selected gullies.

Also reported information about the land cover in the catchment draining to the gully head varied greatly between the different studies considered. In order to allow for a comparison between different studies, we made a quantitative estimate of the potential role of land use in producing runoff based on the SCS Curve Number model (Hawkins et al., 2009). This empirical model simulates the daily runoff of a catchment based on daily rainfall and a Curve Number (CN). The latter depends on land use and soil type of the drainage area and can be determined based on lookup tables (Hawkins et al., 2009). Despite several shortcomings, the model is widely used due to its conceptual simplicity while often performing at least as good as more complex models (e.g. Loague and Freeze, 1985; Jakeman and Hornberger, 1993). Also several studies focussing on gully erosion have used CN-values in order to quantify the role of land use (e.g. Vandekerckhove et al., 2001b; Rossi et al., in press).

In this study, CN-values for each catchment draining to a gully head were determined, based on tables provided in Hawkins et al. (2009). The relevant Hydrological Soil Group (HSG) was selected based on the dominant soil texture (see above; HSG A for 'Sandy', HSG B for 'silty', HSG for 'Clayey') and assuming average antecedent moisture conditions ('class II'; Hawkins et al., 2009). The CN-value best describing the land use conditions in the catchment draining to the gully head were selected based on the information provided in the original data source. Where

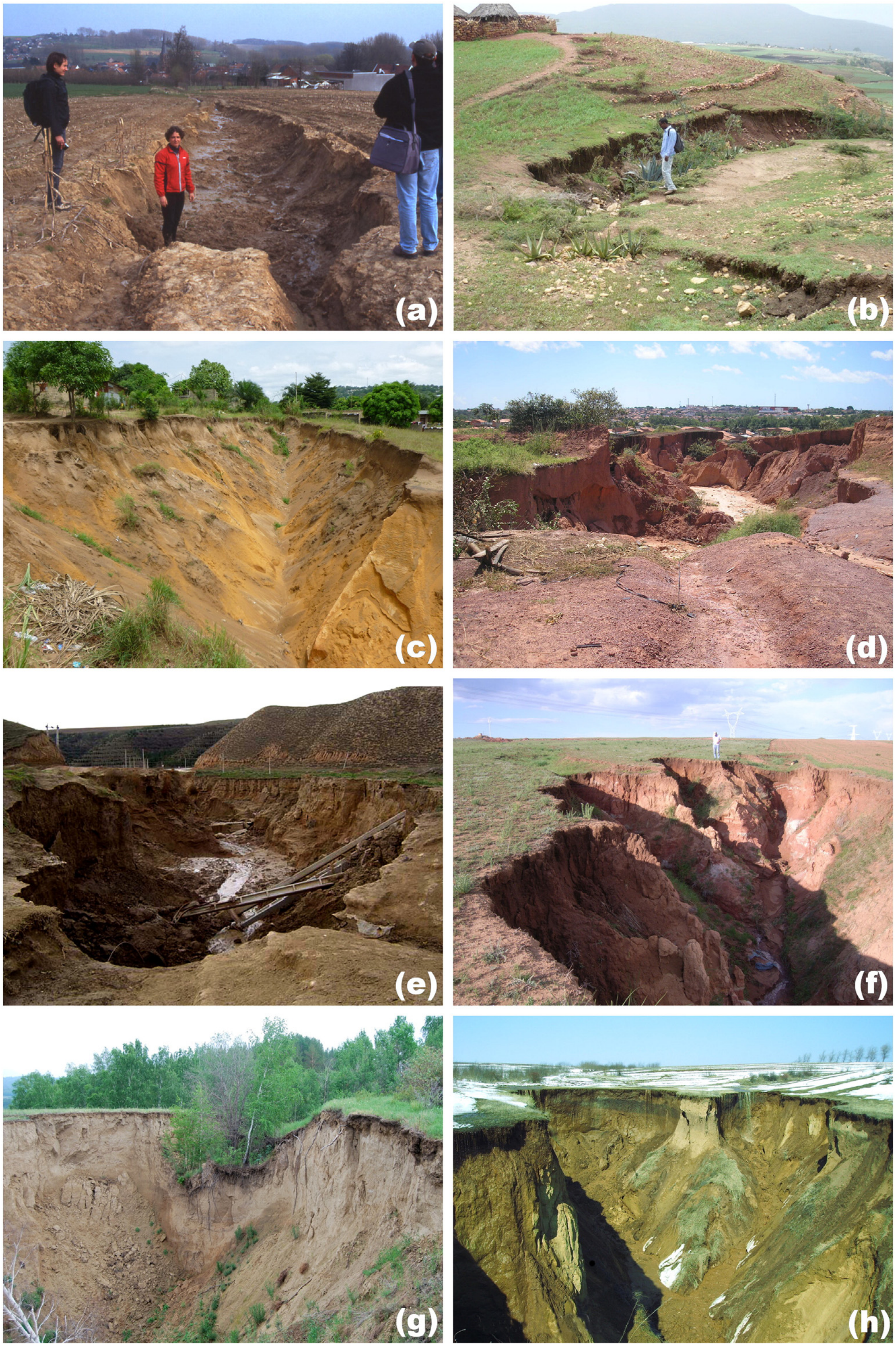

Fig. 2. Examples of gullies from contrasting study areas for which gully headcut retreat rates were reported. (a) Gully head in Michelbeke, Belgium. Mean width (W): 3 m, mean depth (D): 1.20 m mean depth, silt loam (loess). Photo: J. Poesen, 04.04.2003. (b) Gully head at Adi Kwolakol, Tigray, Ethiopia. W = 2.5 m, D = 1.5 m, sandy loam. Photo: A. Frankl, 04.08.2010. (c) Gully head near Camp Badiadingi, Kinshasa, DR Congo. W = 4 m, D = 2 m, sandy soil. Photo: F.M. Imwangna, 25.02.2012. (d) Coeduc Gully head, São Luís city, Brazil. W = 12 m, D = 1.80 m, sandy loam. Photo: J. F. Rodrigues Bezerra, 12.08.2009. (e) Gully head near Chenarly Village, NE Iran. W = 6 m, D = 8 m, silt loam (loess). Photo: Sayadi Jamil, Nov. 2000. (f) Gully head at Jizuiyingzi, Huhhot City, Inner Mongolia, China. W = 12 m, D = 4.4 m, sands and fine pebbles (including granules). Photo: Y. Otsuki, 30.06.2008. (g) Gully head near Kyitun village, Republic of Buryatia, Russia. W = 17.5 m, D = 9.0 m, loamy sand (loess). Photo: Y.V. Ryzhov, 16.07.2012. (h) Puriceni-Bahnari gully head, Falciu Hills, Eastern Romania. W = 21 m, D = 12 m, loam to sandy loam; Photo: I. Ionita, 20.03.2006.

possible (i.e. if the exact location of the headcut was known and good aerial imagery was available), we supported our decision by studying available images of the catchment in Google™ Earth. To avoid as much as possible subjectivity, all CN-values were assigned by at least two of the authors without knowing the retreat rate of the gully head. For catchments where the assigned CN-value differed between the authors, the available information was re-evaluated and discussed until a consensus was reached.

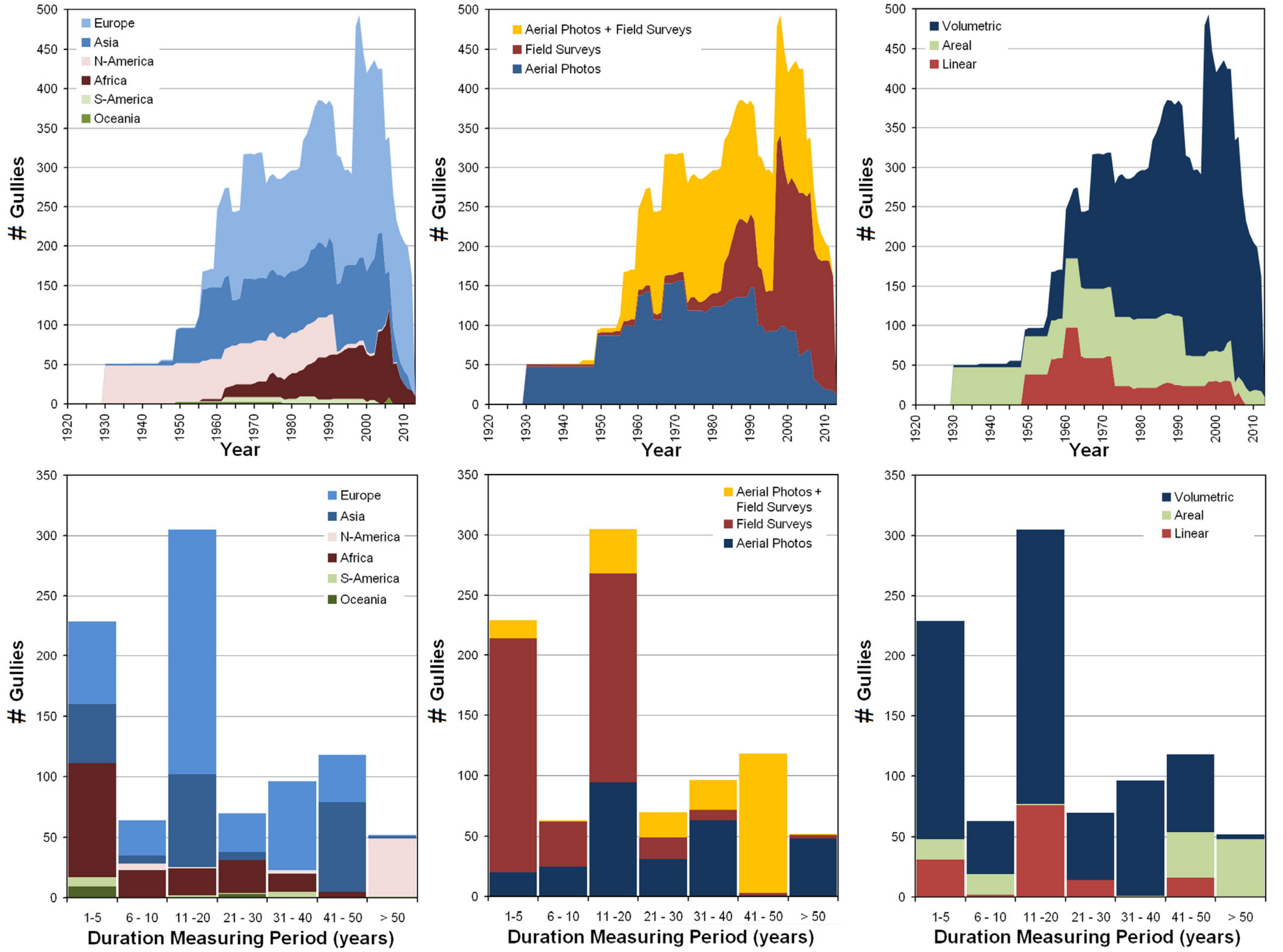

Fig. 3. Temporal distribution of the number (#) of reported gully headcut retreat (GHR) rates. The upper charts show for how many gullies the GHR measuring period includes the indicated year. The lower charts show the frequency distribution of the gullies according to the length of the GHR measuring period. In both cases, data are stacked and subdivided according to continent (left), measuring method (central) and the type of retreat rate available (right).

5.2. Spatial variability in gully headcut retreats

5.2.1. Climatic factors

Of all variables considered (Table 3), the rainy day normal (RDN; i.e. the average rainfall depth on a rainy day) clearly showed the highest Spearman's rank correlation coefficient with RR_V (Table 4). Partial correlation analyses showed that this variable remained highly significant ($p < 0.0001$) after correcting for any of the other considered variables. RDN is a variable commonly used in landslide and debris flow research and can be expected to be strongly correlated to the occurrence of intense rainfall events (e.g. Wilson and Jayko, 1997; Guzzetti et al., 2008). Fig. 8a shows the results of a least-square regression of RDN versus RR_V. Other variables relating to rainfall (i.e. P_a, P_m, P_{day99}; see Table 3) also show significant correlations with RR_V, with P_m (i.e. the average rainfall depth in the wettest month) showing only a slightly lower correlation than RDN (Table 4). However, P_a (i.e. the total average annual rainfall depth) and P_{day99} (i.e. the estimated daily rainfall depth that has an exceedance probability of 1%) show clearly weaker correlations with RR_V.

The fact that especially RDN and P_m show a much stronger correlation with RR_V than P_a concurs with several earlier studies indicating the importance of rainfall intensity as a factor controlling GHR rates (see Table 1; Section 2). However, in this context, it may appear surprising that P_{day99} shows a much weaker correlation, as this measure relates more directly to the highest daily rainfall intensity. This may be attributed to errors on estimated P_{day99} values, resulting both from uncertainties on the daily rainfall depth values and the coarse spatial resolution of the dataset (Table 3; Ashouri et al., 2015). The errors on RDN values can be expected to be smaller due to the higher spatial resolution and smaller uncertainties on the source data used to calculate this variable (New et al., 2002). An additional reason might be that, contrarily to P_{day99}, RDN not only relates to the highest recorded rainfall event but provides an integrated proxy on the overall occurrence of intense precipitation events that may cause GHR. In that sense, RDN is highly similar to rainfall proxies used in models that were used to predict GHR for gullies in the US (i.e. the sum of all rainfall events with an intensity exceeding 12.7 mm day^{-1}; see Table 1). However, RDN offers the advantages that it is easier to calculate and avoids a (somewhat arbitrary) rainfall threshold.

Apart from rainfall variables, also T (i.e. the average annual air temperature; see Table 3) shows a clearly significant correlation with RR_V. This might be attributed to the fact that regions with a high mean annual air temperature often are more likely to experience extreme rainfall events of higher intensity (Berg et al., 2009), which is also indicated by the strong correlation between T and RDN (Table 4). Whereas previous studies did not consider mean air temperature as a potential factor explaining gully headcut retreat rates (Table 1), Zanchi and Torri (1980) indicated that air temperature can indeed be a good

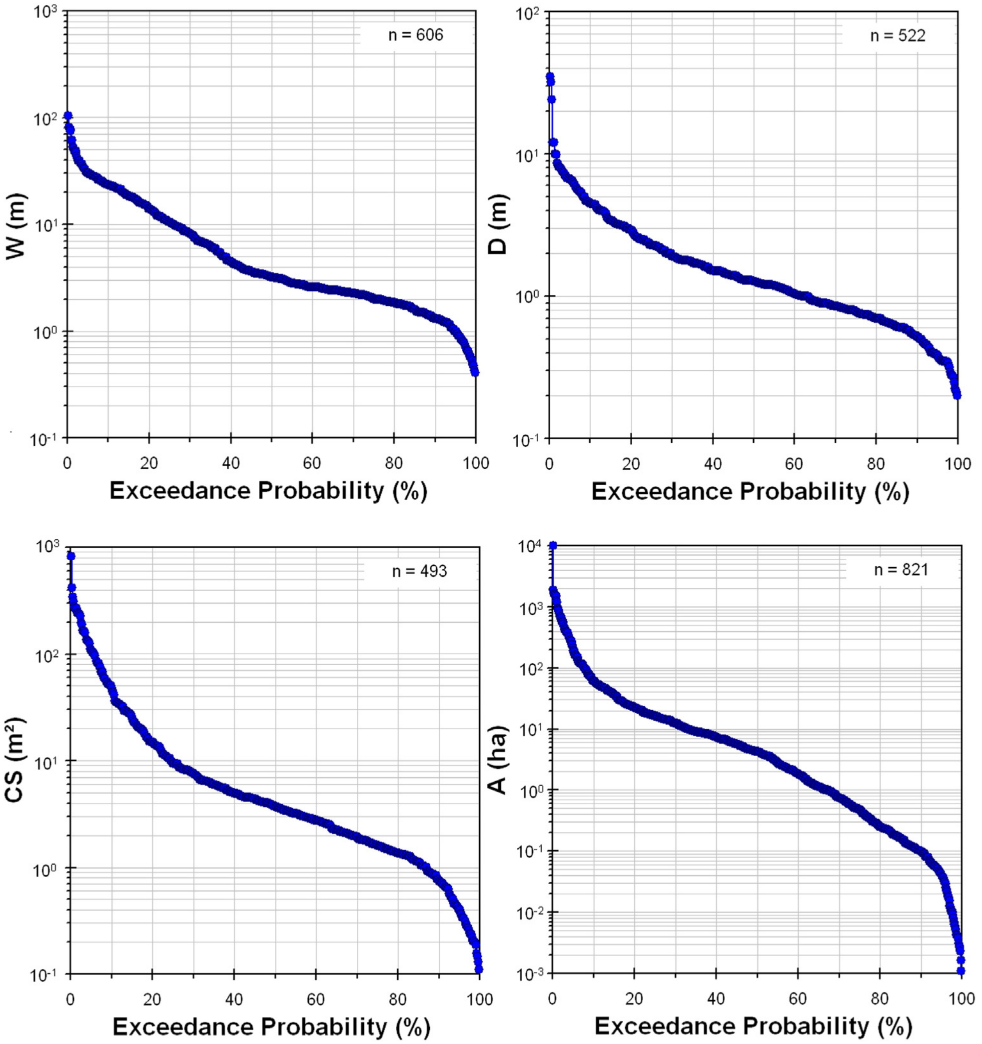

Fig. 4. Exceedance probabilities of the average gully width (W), depth (D), cross-sectional area (CS) and contributing area (A) at the gully headcut. Each exceedance probability plot is based on all gully headcuts for which W, D, CS or A was reported or could be calculated in a non-spurious way. 'n' indicates the number of gullies.

proxy for rainfall erosivity and runoff production. Likewise, several studies at the catchment scale observed highly significant positive correlations between T and sediment yield (e.g. Syvitski & Milliman, 2007; Vanmaercke et al., 2015). Hence, it is likely that T is a proxy for the occurrence of torrential rainfall with significant geomorphic impacts (Zanchi and Torri, 1980; Berg et al., 2009; Vanmaercke et al., 2015).

We found no meaningful correlation between the snowmelt variable ('SNOW', see Table 3) and RR_V (Table 4). Although this is likely partially due to the crude nature of this variable (i.e. a boolean variable indicating whether snowmelt is potentially important or not), it indicates that snowmelt plays only a limited role in explaining patterns of gully headcut retreat at a global scale. This does certainly not imply that snowmelt is an irrelevant process. Studies in temperate and cold regions did indicate that snowmelt is a main driver of gully expansion, with often more than half of the observed GHR being caused by the effects of snowmelt (e.g. Bolysov et al., 1985; Bolysov and Tarzaeva, 1996; Dedkov et al., 1990; Ionita, 2000, 2006; Archibold et al., 2003; Rysin and Grigoriev, 2007, 2010; Ionita et al., 2015). Nonetheless, these reported impacts of snowmelt are relatively limited when compared to the large variations in average retreat rates at a global scale (e.g. Fig. 8).

5.2.2. Drainage area and other catchment characteristics

Apart from RDN and several of the other climatic variables discussed above, also the area draining to the gully headcut (A) shows a highly significant correlation with RR_V (Table 4). This correlation remains highly significant after correcting for RDN (Partial Spearman r: 0.55, $p < 0.0001$). Nonetheless, the variance explained by A is relatively low (Fig. 8b) compared to RDN (Fig. 8a). This might seem surprising, given that A is generally identified as the most important factor controlling GHR rates (see Section 2; Table 1). Nonetheless, as discussed above, most of these earlier studies focused on specific regions in areas having often a limited spatial variability in climatic conditions. Whereas small differences in rainfall conditions appear less important than A for explaining GHR rates at a local scale, the role of climate likely overrules the role of A at larger spatial scales.

Our estimated CN-values showed only a weak correlation with RR_V (Table 4; Fig. 8c). Partial correlation analyses indicates that this correlation was no longer significant ($p > 0.05$) after correcting for RDN. This at first sight counterintuitive result may to some extent be attributed to errors on the estimated CN values, since they were in many cases estimated with only limited information on the actual soil and land use conditions (see Section 5.1). Nonetheless, it is noteworthy that also few local studies identified land use as a significant factor controlling GHR rates (Table 1). For example, Vandekerckhove et al. (2001a, 2001b) also reported that CN-values explained only very little of the observed variance in GHR rates, despite the fact that their estimated CN-values were based on detailed field surveys of land use in the gully catchments. Several reasons may explain the apparently limited impact of land use

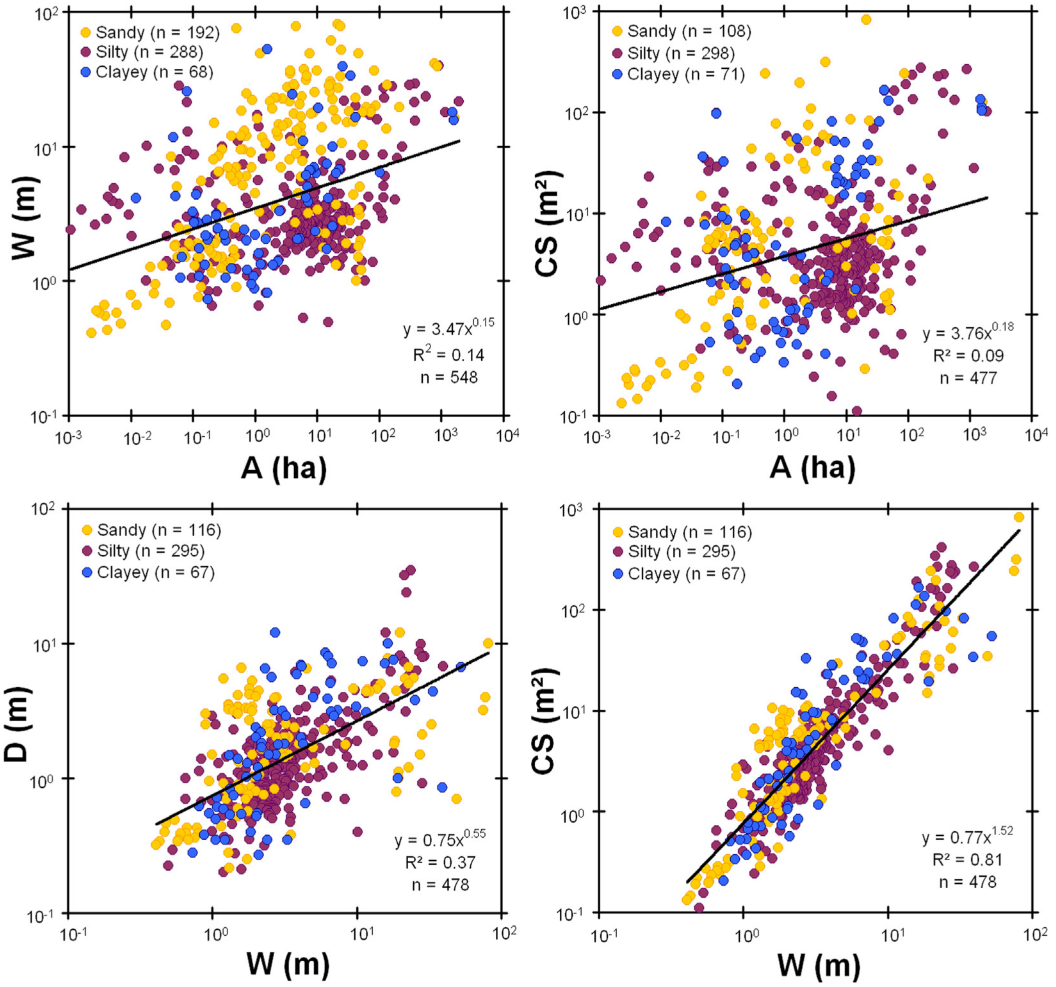

Fig. 5. Relationships between the average depth (D), width (W), cross-sectional area (CS) and contributing area (A) for all gullies where these properties were reported or could be calculated in a non-spurious way. Symbols are coloured based on the soil texture at the gully headcut, while the regressions are based on all observations. 'n' indicates the number of gullies.

on GHR rates. Firstly, CN values do not always account for spatial and temporal variation in land use and soil conditions. Rossi et al. (in press) recently demonstrated that catchments with the same CN-value may have a completely different runoff response, depending on the spatial configuration of soil and land use characteristics within the catchment. Likewise, the runoff response during a rainfall event will depend on weather conditions (e.g. antecedent moisture conditions) that could not be quantified with our estimated CN-values.

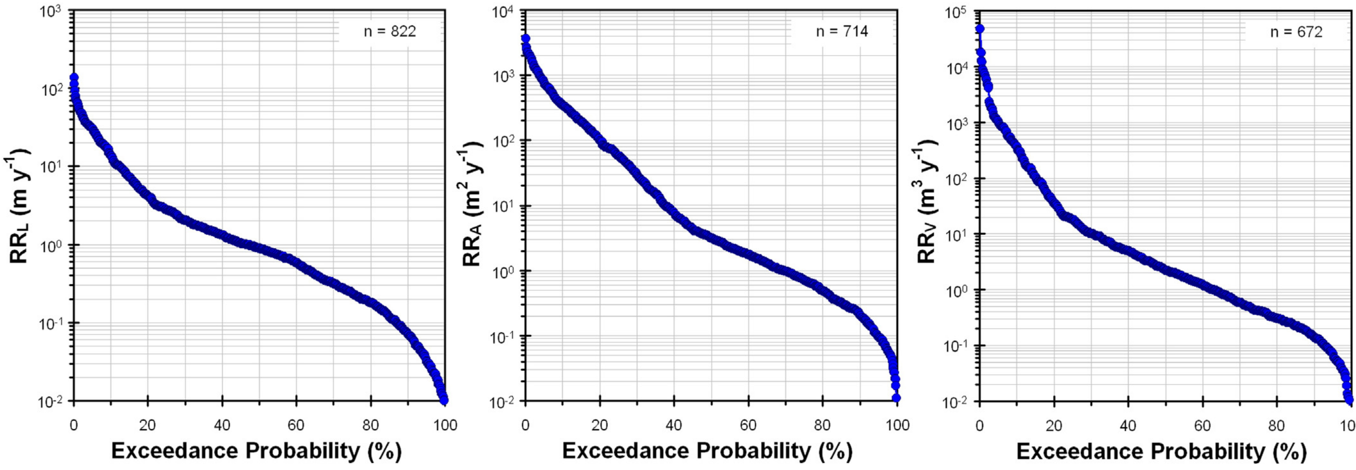

Fig. 6. Exceedance probabilities of average observed linear (RR_L), areal (RR_A) and volumetric (RR_V) gully headcut retreat rates. Each exceedance probability plot is based on all gully headcuts for which RR_L, RR_A or RR_V was reported or could be calculated using field and remote sensing data. 'n' indicates the number of gullies.

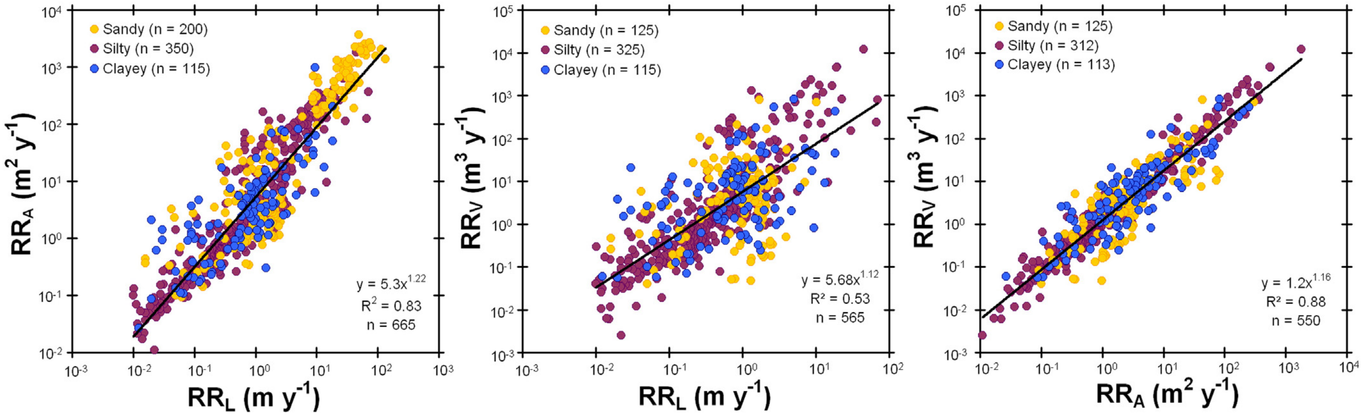

Fig. 7. Relationships between the average observed linear (RR_L), areal (RR_A) and volumetric retreat rates (RR_V), based on all gullies for which these retreat rates were reported or could be calculated in a non-spurious way. Symbols are coloured based on the soil texture of the gully headcut, while the regressions are based on all observations. 'n' indicates the number of gullies.

Secondly, the range of land cover conditions at the headcuts in our database, may be too small to induce significant differences in runoff response. As can be derived from Fig. 8c, most upstream catchments considered have a CN-value between 70 and 90 while only a very small fraction has a CN < 60. Torri and Poesen (2014) showed that gully initiation depends on a soil surface slope-area threshold that is strongly influenced by land use. No gully initiation, and hence no GHR, occurs below this threshold. Given that our database only considers actively retreating gully headcuts, it is therefore logical that most of our data points represent erosion-prone land cover conditions. This relates to a third potential reason explaining why no clear impact of land cover conditions on RR_V could be detected: whereas gully initiation is mainly caused by concentrated flow, the actual retreat of a gully headcut can occur through a wide range of processes (see Section 2.1). While land cover conditions in the upstream catchment can strongly influence runoff production and hence gully initiation (e.g. Torri and Poesen, 2014; Rossi et al., in press), this is not necessarily the case for the processes causing gully headcut retreat (e.g. tension crack development, soil toppling or fall; Vandekerckhove et al., 2001b). In other words: the fact that we observe no clear trends between CN values and RR_V (Fig. 8c) may also indicate that land use indeed only plays a limited role in explaining spatial variation in average GHR rates for actually eroding gullies at a global scale. As is the case with snowmelt, this would not imply that land use is an irrelevant factor for GHR, as it may certainly be an important factor explaining local and/or temporal variations in retreat rates.

Factors relating to the topography and degree of seismicity near the gully headcut (i.e. LR and PGA; Table 3) showed no meaningful correlation with RR_V (Table 4). This remained the case after correcting for RDN and/or A through a partial correlation analysis. Here also, this lack of correlation might be attributed to the large uncertainties associated with these factors. However, also few studies at a local scale have identified a significant topographic control on GHR rates (Table 1). Likewise, although it has been suggested that the occurrence/density of gullies may be controlled by seismicity (e.g. Cox et al., 2010), hitherto no studies have shown that also GHR rates are influenced by seismicity. Therefore, the lack of correlations between RR_V and topography or seismicity may also indicate that these factors are indeed only of limited importance for explaining spatial variation in GHR rates at a global scale.

5.3. Temporal variability in gully headcut retreat rates

We detected a slightly positive correlation between the duration of the measuring period (MP) and RR_V (Table 4; Fig. 8d). However, this correlation disappeared after controlling for upstream drainage area (A), which is also positively correlated to MP (Table 4). This suggests that the influence of MP on our average GHR rates is limited.

Nonetheless, gully headcut retreat rates are characterized by a very large temporal variability. Fig. 9 shows the running average of RR_L for all gullies in our database that were monitored on a yearly basis for at least 7 years, divided by the mean RR_L for the entire measuring period. Evidently, this ratio converges to one for each gully. However, for short measuring periods (<5 years), the average retreat rate can deviate more than one order of magnitude from its long-term average value. RR_L estimates based on only one year of observation can deviate more than 2 orders of magnitude from their long-term average value (measured over 7 to 17 years). Data with a similar temporal quality were

Table 3
List of considered factors that potentially explain the observed variance in volumetric gully headcut retreat rates (RR_V) of the 724 selected gullies.

Variable	Units	Description	Derived from	Resolution
MP	y	Measuring period over which the GHR rate was measured	Original source of the GHR data	N.A.
A	ha	Area of the catchment draining to the gully headcut	Original source of the GHR data	N.A.
LR	m	Local relief at the study site (i.e. the maximum height difference within a radius of 5 km)	ERSDAC (2009)	30″ × 30″
CN	N.A.	Estimated runoff Curve Number value, based on available descriptions of the land use and soil type in the catchment and following the procedure of Hawkins et al. (2009)	Original source of the GHR data	N.A.
T	°C	Average annual air temperature (1961–1990)	New et al. (2002)	10′ × 10′
P_a	mm $year^{-1}$	Average annual precipitation depth (1961–1990)	New et al. (2002)	10′ × 10′
P_m	mm $month^{-1}$	Average monthly precipitation depth in the wettest month (1961–1990)	New et al. (2002)	10′ × 10′
RDN	mm day^{-1}	Rainy day normal, i.e. the total mean annual precipitation depth, divided by the average number of rainy days per year (1961–1990)	New et al. (2002)	10′ × 10′
P_{day99}	mm day^{-1}	Daily rainfall depth with a cumulative probability of 99% (1983–2012)	Ashouri et al. (2015)	15′ × 15′
Snow	N.A.	Boolean variable indicating whether snowmelt is a potentially significant (1) or insignificant contributor to gully headcut expansion (based on expert judgement)	Original source of the GHR data	N.A.
PGA	m s^{-2}	Peak ground acceleration with an exceedance probability of 10% in 50 years.	Shedlock et al. (2000)	6′ × 6′

Resolution indicates the original spatial resolution of the data layer from which the parameter was derived. 'N.A.' indicates not applicable.

Table 4
Spearman's rank correlation coefficients between all considered factors (Table 3) and the observed volumetric gully headcut retreat rates (RR_V) for the 724 gully headcuts selected for detailed analyses.

	MP	A	LR	CN	T	P_a	P_m	RDN	P_{day99}	SNOW	PGA	RR_v
MP	**1**											
A	**0.32**	**1**										
LR	−0.09	**−0.32**	**1**									
CN	*0.05*	0.10	*−0.05*	**1**								
T	−0.14	**−0.36**	**0.45**	*0.00*	**1**							
P_a	*−0.07*	**0.21**	**−0.43**	0.11	0.10	**1**						
P_m	**−0.15**	0.09	−0.10	*0.05*	**0.41**	**0.73**	**1**					
RDN	*−0.06*	−0.11	**0.17**	**0.16**	**0.78**	**0.46**	**0.79**	**1**				
P_{day99}	*−0.02*	*−0.01*	**−0.29**	*0.00*	**0.31**	**0.73**	**0.64**	**0.47**	**1**			
SNOW	**0.32**	**0.56**	**−0.46**	*0.01*	**−0.83**	*0.03*	**−0.20**	**−0.61**	−0.10	**1**		
PGA	*0.00*	**−0.23**	**0.56**	*0.02*	**0.20**	**−0.67**	**−0.27**	*−0.01*	**−0.42**	**−0.24**	**1**	
RR_v	**0.18**	**0.34**	*0.03*	**0.14**	**0.45**	**0.39**	**0.60**	**0.67**	**0.38**	**−0.17**	−0.13	**1**

Values in italic are insignificant ($p > 0.05$). Values in normal font are significant ($p < 0.05$), while values in bold are highly significant ($p < 0.0001$).

not available for RR_V. However, given the overall larger range in retreat rates (Fig. 6), year-to-year deviations for volumetric retreat rates can be expected to be at least as large. This implies that average GHR rates can be subject to very large uncertainties when measuring periods are short. Similar results were also reported for soil loss rate measurements on runoff plots (Maetens et al., 2012b) and catchment sediment yields, where inter-annual variation can easily be the most dominant source of uncertainty on mean values estimated from short measuring periods (<5 years; Vanmaercke et al., 2012b).

Another striking observation about Fig. 9, is that for most gullies RR_L tends to decrease over time. For three of the four study areas, the median retreat rate of all gullies during the first year of observation was a factor 2 to 4 higher than the long-term average. Similar trends were reported in other studies as well (e.g. Graf, 1977; Rutherford

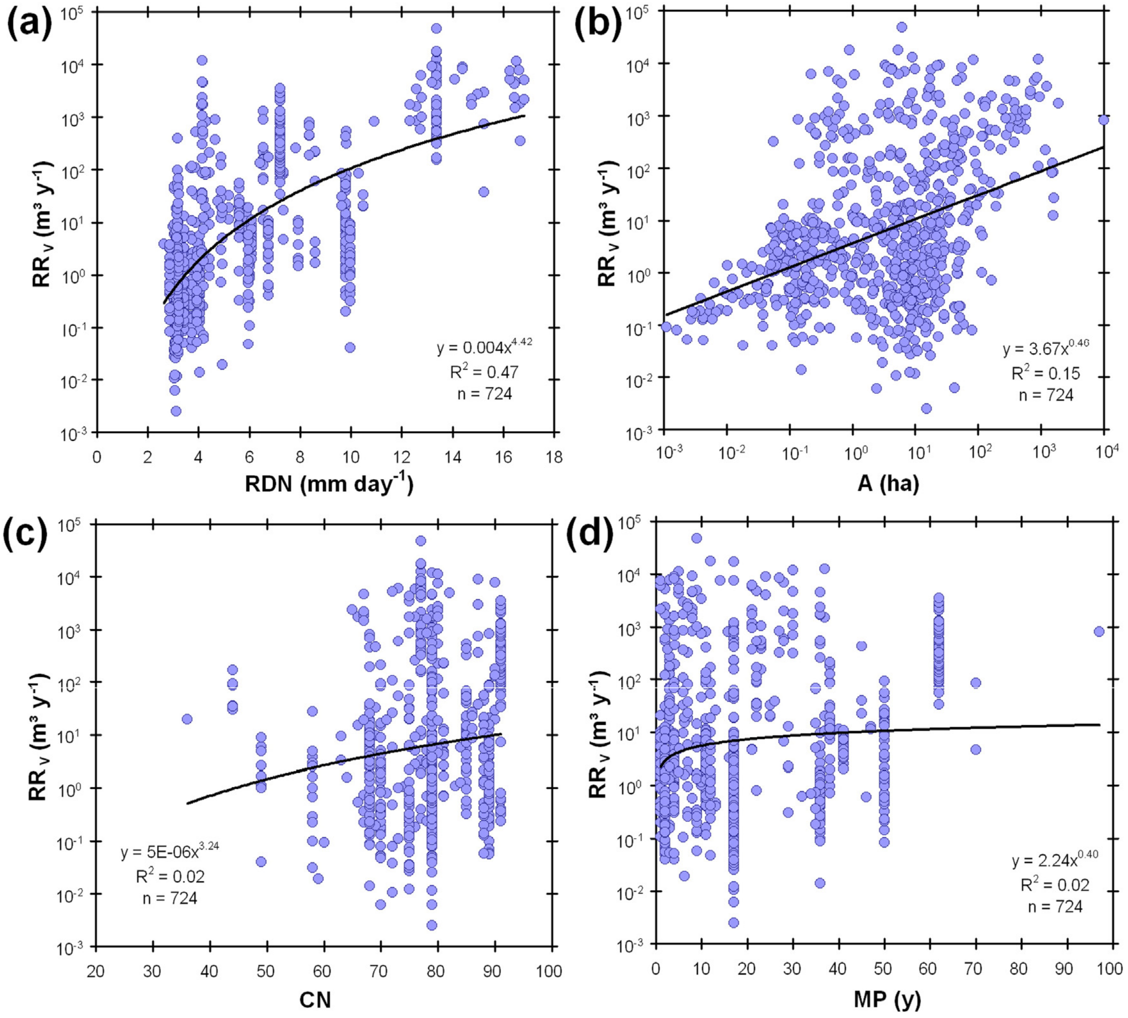

Fig. 8. Scatter plots showing the volumetric retreat rate (RR_V) of the gullies selected for detailed analyses (see text) and various potentially explaining factors (see Table 3). (a) Shows the correlation between RR_V and the rainy day normal (RDN). (b) Shows the correlation between RR_V and the area draining to the gully head (A). (c) Shows the correlation between RR_V and the estimated Curve Number (CN) of the catchment draining to the gully head. (d) Shows the correlation between RR_V and the corresponding length of the measuring period (MP). 'n' indicates the number of gullies.

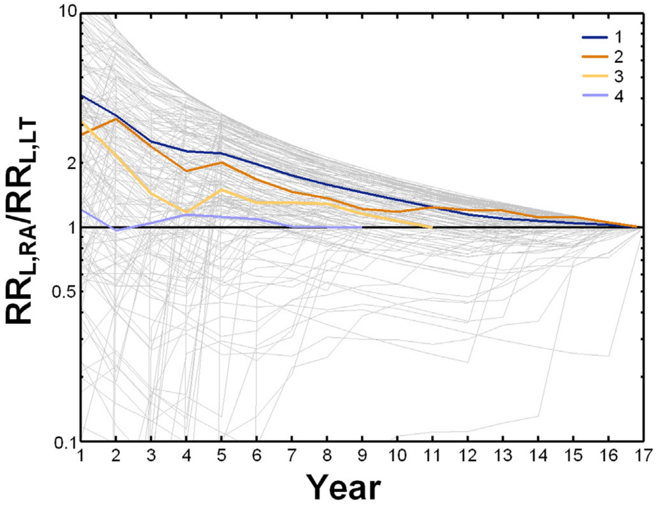

Fig. 9. Ratio of the running average of the linear gully headcut retreat rate, calculated over the number of years indicated on the x-axis ($RR_{L,RA}$) and the long-term average linear gully headcut retreat rate, calculated over the entire measuring period ($RR_{L,LT}$). Each thin grey line corresponds to one gully headcut for which the linear retreat rate was measured on an annual basis for 7 to 17 years (n = 178). Each thick line corresponds to the average ratio of all gullies monitored in the same study: (1) average of 141 gullies in the Udmurt region (Russia); (2) average of 6 gullies in the Netivot Area (Israel); (3) average of 3 gullies in the Negev Highlands (Israel); (4) average of 28 gullies in Tatarstan (Russia).

et al., 1997; Nachtergaele et al., 2002a; Vanwalleghem et al., 2005; Makanzu Imwangana et al., 2015). Surprisingly, this tendency is opposite to what is observed for time series of catchment sediment yield: shorter measuring periods tend to underestimate long-term sediment yields because they often do not capture disproportionately large events (Vanmaercke et al., 2012b). The decrease in RR_L may be attributable to several reasons. A first cause may be that, as gullies retreat, the area draining to the gully headcut becomes smaller. This may result in smaller runoff (peak) discharges and, hence, lower retreat rates. Nonetheless, this effect can most likely not explain the observed decreases in retreat rates on its own. While many studies have observed a positive power relationship between drainage area and GHR rate (see Table 1 for examples), the exponent of this relationship is almost always less than one and mostly around 0.5. This implies that upstream areas should decrease with a factor 4 to 16 in order to explain the observed median decrease in GHR (Fig. 9). Observed decreases in upstream areas due to GHR are typically much smaller and in the order of only a few percentages. Probably more important is the fact that gully headcuts often originate on relatively steep slopes, consistent with the concept of an area-slope threshold (e.g. Torri and Poesen, 2014). Once the headcut retreats, it can migrate towards less steep slopes (e.g. on a plateau). This (together with a decrease in A) could often result in a decrease in stream power and hence lower GHR rates (e.g. Nachtergaele et al., 2002b). Thirdly, gullies often get stabilized over time, either through human intervention (such as check dam construction or revegetation; e.g. Frankl et al., 2013) or by the development of natural vegetation, resulting in a smaller average GHR rates over longer time periods. Finally, it is possible that available measurements over shorter measuring periods are biased towards higher retreat rates. I.e. it is possible that some gullies in a given study area were selected for further monitoring because of their high retreat rate during the first year(s) of observations, while other (less actively retreating) gullies were not considered. Whereas temporal variations in GHR rates may be largely coincidence, such bias may help explain why for most gullies the initial GHR rate is generally slightly higher than the long-term average retreat rate (Fig. 9).

Nonetheless, it should be noted that the 178 time series of annual GHR rates used for Fig. 9 were derived from only 4 study sites, while for one of the study sites (i.e. Tatarstan; Yermolaev, 2014) no decreasing trend was observed. Other studies reported a positive trend between gully length (which can be expected to be strongly correlated to gully age) and retreat rate (e.g. Beer and Johnson, 1963; Radoane et al., 1995). As a result, the overall validity of the negative trends observed in Fig. 9 remains uncertain. Also for our entire dataset of volumetric retreat rates, we found no evidence that average RR_V values are negatively correlated to the measuring period, even after correcting for the effect of other factors (see Section 5.2.2; Fig. 8d). This may be due to the fact that, for many GHR rate observations in our dataset, the actual age of the gully is unknown and may exceed the measuring period by several years, decades or centuries. In addition, potential overestimations due to short measuring periods (with estimations in the order of a factor 2 to 5; see Makanzu Imwangana et al., 2015 and Fig. 9) are relatively small when compared to the large year-to-year variations in GHR rates (typically a factor 10 to 100; see Fig. 9) or with the very large spatial variation in average GHR rates at a global scale (i.e. 7 orders of magnitude; see Fig. 6).

5.4. Synthesis: a global gully headcut retreat model

Based on the results described in Sections 5.2 and 5.3, we constructed a first simple multiple regression model that simulates the average annual volumetric retreat rate of a gully headcut at the global scale. Following the results of our statistical analyses (Section 5.2), we included the rainy day normal (RDN) and upstream drainage area (A) as explanatory factors. Other variables related to land use, topography, soil characteristics, seismicity or other factors were not incorporated as they did not explain a significant part of the observed spatial variation in RR_V. To account for the fact that RR_V-values based on short measuring periods are subject to large uncertainties and potentially slightly overestimate the long-term average retreat rate (see Section 5.3), each observation was weighted according to the square root of the measuring period. This is consistent with the central limit theorem, and a technique that is commonly used for constructing erosion or sediment export models (e.g. Cerdan et al., 2010; Vanmaercke et al., 2011b, 2012b; de Vente et al., 2013). The model was fitted by conducting a weighted multiple linear regression on the log-transformed data points (n = 724) and then back-transforming the fitted equation. This resulted in the following model:

$$RR_V = 0.001 \times A^{0.52} \times RDN^{4.97} \tag{2}$$

With RR_V the simulated volumetric gully headcut retreat rate (in $m^3\ y^{-1}$), A the upstream drainage area (in ha) and RDN the rainy day normal (in mm day^{-1}; see Table 3). Despite the limited number of factors included, this model performs well and has a weighted coefficient of determination (R_w^2) of 0.68 (Fig. 10). This implies that A and RDN explain almost 70% of the observed global variation in average volumetric GHR rates after accounting for differences in measuring period. For 76% of the gullies, the simulated value deviates less than one order of magnitude from the observed value (while 96% of the simulated values deviate less than two orders of magnitude; Fig. 10). This indicates that, although uncertainties on individual RR_V estimates remain large, Eq. (2) can certainly be used to obtain first order assessments of average volumetric GHR rates.

In accordance with our results described in Section 5.2.2, analyses of the residues of our model revealed no other factors that could explain a significant part of the observed variance in RR_V. As shown in Fig. 11, the distributions of model residues are very similar for gullies formed in soils with a dominantly sandy, silty or clayey texture. Grouping the residues according to the dominant land use in the upstream catchment reveals some differences: after accounting for A and RDN, GHR rates tend to be slightly higher when the upstream catchment is dominated by urbanized area or rangeland and slightly lower when dominated by arable land or forest (Fig. 11). These results are consistent with the expected role of land use on runoff production and gully erosion

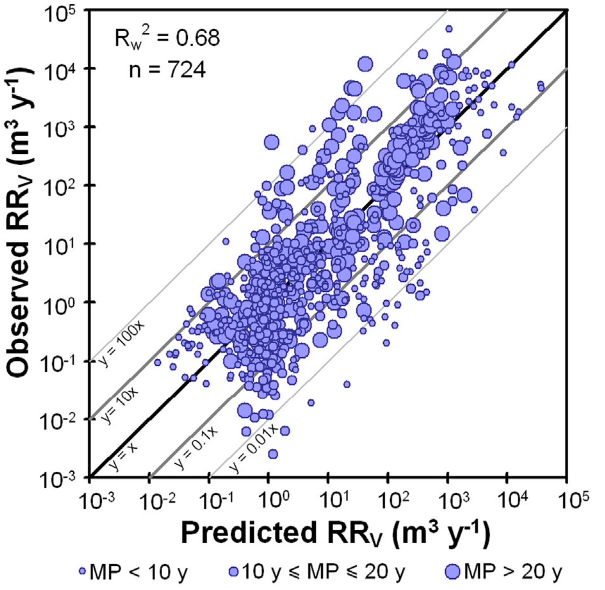

Fig. 10. The volumetric retreat rates (RR_V) predicted using Eq. (2) versus the corresponding observed RR_V for the 724 selected gullies. Symbols are sized according to the duration of the measuring period (MP). R^2_W indicates the coefficient of determination of the weighted regression, where the weight of each observation corresponds to the square root of the measuring period in years (see text). 'n' indicates the number of gullies.

(e.g. Hawkins et al., 2009; Torri and Poesen, 2014; Rossi et al., in press; Moeyersons et al., 2015) and suggest that our model can be further improved by adding a land use factor. Nonetheless, a stepwise regression analyses indicated that this was not the case. Neither the CN-value (Table 3), nor a simpler scoring factor corresponding to the observed median differences in residue distribution was selected as significant variables. This is likely explained by the fact that the observed differences in residues between dominant land use classes remain very limited when compared to the overall range of RR_V-values or model residues (i.e. typically within a factor 3; Fig. 11). Only for forested catchments, observed RR_V values are clearly smaller than their corresponding values predicted with Eq. (2). However, this comparison is based on only 14 data points. As discussed in Section 5.2.1, more detailed and accurate data on land use conditions might have revealed a significant effect of land use on GHR rates. Nonetheless, this effect would most likely remain only secondary compared to the role of drainage area (A) and rainfall intensity (RDN).

The exponent of A in our model (Eq. (2)) falls well within the range of previously reported power relationships between upstream area and GHR rate, indicating retreat rates are generally proportional to the square root of their catchment area (e.g. Seginer, 1966; Vandekerckhove et al., 2003; Nazari Samani et al., 2010; Rieke-Zapp and Nichols, 2011; Frankl et al., 2012; Grellier et al., 2012; Li et al., 2015). However, the large exponent of RDN clearly indicates that especially climatic variations exert a very strong control over spatial variations in GHR rates at global and continental scales. Our statistical analyses further support this finding (see Section 5.2.1). The large role of climate and weather conditions as a driver of GHR rates was already reported in some studies, but remained hitherto largely unquantified (e.g. Poesen et al., 2003; Moeyersons et al., 2015).

An important consequence of this finding is that gully erosion rates are also highly sensitive to climate change. For example, current global climate model projections forced by the Representative Concentration Pathway 8.5 (RCP 8.5) indicate that for the period 2060–2089, precipitation intensities during precipitating days (i.e. the RDN) will globally be 5 to 25% higher compared to the period 1960–1989 (Polade et al., 2014). Based on Eq. (2) and considering all other factors to remain equal, this would imply that volumetric GHR rates will.

increase with 27 to 300%. While the spatial variation in predicted RDN change is large, there are no significant land masses where RDN is expected to decrease (Polade et al., 2014). Moreover, many tropical and subtropical regions (e.g. Eastern Africa and India) are expected to experience a strong increase in RDN (Polade et al., 2014). Due to a combination of high rainfall intensities and the large pressure on land and vegetation, gully erosion already forms an important problem in many of these regions (e.g. Tekwa and Usman, 2010; Frankl et al., 2012; Makanzu Imwangana et al., 2015; Ranga et al., in press). Our results suggest that this challenge will significantly increase during the following decades.

6. Conclusions and scope for further research

6.1. Summary and conclusions

Controlling gully erosion is an important challenge in many environments worldwide. An important prerequisite in addressing this challenge is understanding the rates and factors controlling gully headcut retreat (GHR). As this reviews showed, dozens of studies over the past

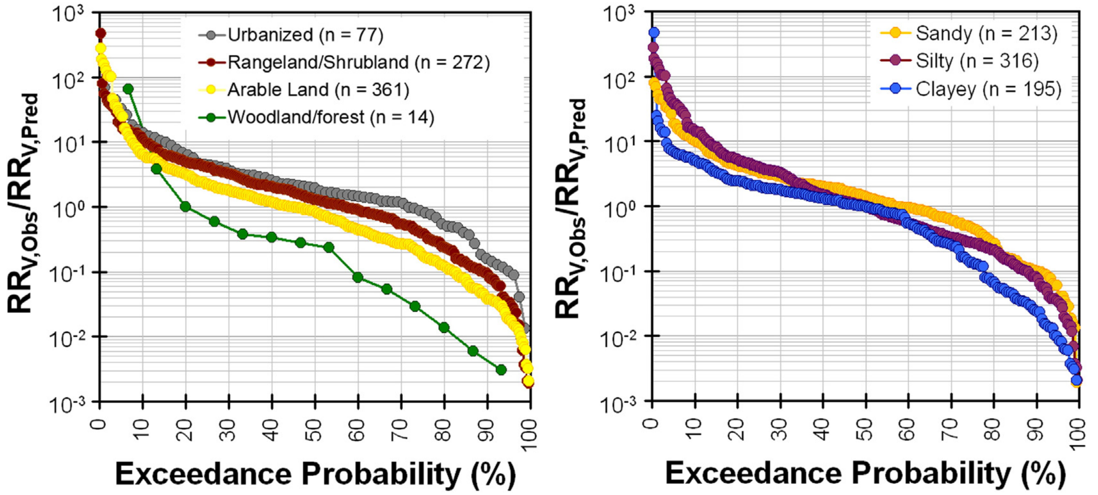

Fig. 11. Exceedance probability plots of the observed volumetric gully headcut retreat rate ($RR_{V,obs}$), divided by the volumetric gully headcut retreat rate predicted using Eq. (2) ($RR_{V,pred}$) for the 724 selected gullies (see text), subdivided according to the dominant land use in the area draining to the gully headcut (left) and according to the dominant soil texture at the gully headcut (right). 'n' indicates the number of gullies.

decades have quantified GHR rates for specific gullies and have aimed to identify the factors controlling these rates. However, almost all these studies focused on a specific study area and only identified differences in GHR rates at a local or a given regional scale. This review provided a first important step towards understanding the magnitude and controlling factors of GHR rates at global and continental scales by compiling all available measurements (Table 2) and conducting a meta-analysis on these data.

A first important conclusion is that GHR rates show a very large spatial variability at the global scale: linear, areal and volumetric retreat rates vary over respectively five, six and seven orders of magnitude (Fig. 6). Although for most gullies, only one average GHR rate was reported, available time series indicated that also the year-to-year variability in GHR rates can be very large: in a given year, the GHR rate can be zero but can also exceed the long-term average value by up to two orders of magnitude (Fig. 9). This large temporal variability implies that average GHR rates based on short (<5 years) measuring periods are subject to important (>100%) uncertainties, regardless of other factors that may influence the accuracy with which the GHR was determined.

Based on a subset of 724 gullies for which both the volumetric GHR rate and the upstream drainage area was known, we explored the factors controlling this large spatial variability. In accordance to most local GHR studies (Table 1), upstream drainage area explained a significant part of the observed variability (Fig. 8b). Nonetheless, climate clearly appears to be a much more relevant factor at a global scale. For example, the rainy day normal (RDN, i.e. the average rainfall depth on a rainy day) explained almost half of the observed variation in GHR rates (Fig. 8a).

An important implication of this is that GHR rates may be highly sensitive to climate change. Combining our analysis with available climate predictions indicates that (when all other factors remain equal) GHR rates will increase worldwide due to an increase in rainfall intensity. In some (sub)tropical areas, average GHR rates may even triple. This is a highly relevant issue, given the fact that gully erosion is already an important problem in many of these areas.

Building on our analysis, we developed a regression model that allows to simulate volumetric GHR rates, based on the upstream drainage area of the gully headcut and the rainy day normal (Eq. (2)). To account for the larger uncertainties associated with GHR rates based on short measuring periods each observation was weighted proportionally to its measuring period. Despite its simplicity, this model performs well: it explains almost 70% of the observed variability in volumetric GHR rates, while 76% of the simulations deviate less than an order of magnitude from their corresponding observed value (Fig. 10). Hence, this model allows to make a robust first order assessment of GHR rates.

Nonetheless, the variance that could not be explained by our model remains rather large. Part of this variance can be attributed to measuring errors and uncertainties, but a large proportion is most probably also due to other (local) factors that may control GHR rates (e.g. land use, soil characteristics, topography, snow melt and potentially seismicity). The role of these factors was explored with the available data. However, no statistical significant effects could be detected. This may be explained by the fact that these factors could only be quantified based on variables that provide only a crude representation of these factors. Hence, more accurate (spatially and temporally explicit) variables could potentially reveal other significant controls and improve our ability to simulate GHR rates. Nevertheless, the role of other factors in explaining GHR rates at global and continental scale will probably remain only secondary compared to the role of climate and drainage area.

6.2. Scope for further research

This review not only improved our understanding of the magnitude and controlling factors of gully headcut retreat rates. It also revealed some important research gaps. Here we highlight some topics for further research that could advance our understanding of gully erosion.

6.2.1. The need for additional data

This review compiled GHR rate measurements from 933 individual gully headcuts worldwide (Table 2). One can reasonably argue that this is enough and for several areas indeed a wealth of measurements are available. Nonetheless, additional data could certainly further improve our understanding (Fig. 1). For example, our analyses show that rainfall intensity (e.g. as expressed by RDN) has a tremendous influence on GHR rates (Fig. 8a). However, the currently available measurements only cover areas with a RDN < 18 mm day^{-1}, while in many subtropical (monsoon affected) regions the RDN values can easily exceed 20 mm day^{-1}. For many of these regions, the rainfall intensity is expected to increase strongly during the following decades. Nonetheless, based on the currently available data, it is unclear if the observed relationship between RDN and GHR rates is also valid in these regions with even higher rainfall intensities. In addition, most GHR rates available for regions with a high RDN were made in urbanized environments while only few observations exist for other land use types. We therefore believe that especially GHR rate measurements in regions with very high rainfall intensities can further contribute to a better understanding of gully erosion rates.

6.2.2. Understanding temporal variability of gully erosion rates

Available data showed that GHR rates can be subject to very large temporal variabilities. Nonetheless the overall range of this variability, its causes and its impacts on long-term average GHR rates remain poorly understood. For example, many of the available time-series data suggests that average GHR rates decrease as measuring periods increase. While there are several potential mechanisms that could explain such a decrease, it remains unclear to what extent such a decrease is due to coincidence (or measuring biases) or to negative feedbacks between GHR and its controlling factors (e.g. decreases in contributing area and slope gradients). Addressing this issue is highly relevant as it would indicate to what extent gully erosion rates vary as a function of time and, hence, how representative available GHR measurements are. Likewise, such insight is a vital step in better understanding how gullies can be stabilized over longer time periods. Currently, little is known about the long-term effectiveness of measures aimed at stabilizing gullies. Detailed time series analyses of gully erosion in combination with rainfall records and other environmental data series could provide important insights into this but are currently only scarcely available.

6.2.3. The role of land use and other factors

In our analyses, only upstream drainage area and rainfall-related factors significantly correlated to the measured GHR rates. Since these two factors alone already explained a dominant proportion of the observed variance, it is likely that the role of other factors (e.g. land use, soil characteristics, topography, snowmelt, seismicity) in explaining GHR rates at global and continental scale is relatively limited. However, several studies at local scales do indicate that such other factors are relevant at a local scale (e.g. Table 1) and it is likely that they account for a large part of the variance that could not be explained by our model (Eq. (2); Fig. 10). Our understanding would strongly benefit from research that aims at integrating the role of factors that control GHR rates at global and continental scales (e.g. climate) with factors that more likely play at local scales (e.g. land use patterns, soil characteristics) and explores its potential interactions. Especially strategies that try to integrate the role of different factors (land use, soil stoniness and other soil characteristics, catchment size and shape, rainfall patterns, runoff due to snowmelt in areas where this is relevant, etc.) by using spatially and temporally explicit runoff models appear promising here. Evidently, this will require more accurate (spatially and temporally explicit) data on potential controlling factors which were unavailable in the framework of this review.

6.2.4. From gully headcut retreat to gully erosion

Whereas this study focused on gully headcut retreat, the total soil loss by gully erosion in an area depends on other factors as well. These include: the frequency with which new gullies originate, the gully density, the number of gully headcuts and the rate of lateral gully expansion. Many of these factors and processes have been the subject of previous research. Quantifying total gully erosion rates for specific areas or estimating the contribution of gully erosion to catchment sediment yield will require an integration of these different aspects. For example, higher gully densities can be expected to result in higher erosion rates, but will also decrease the average area draining to each headcut. This in turn could result in lower erosion rates. This negative feedback also closely relates to the issue of temporal variations in gully erosion rates discussed above. Aiming at identifying and understanding the many interactions between the different processes and factors that control the total soil loss by gully erosion therefore offers a challenging but highly promising strategy for further research.

Acknowledgments

M. Vanmaercke and M. Demuzere acknowledge their postdoctoral research grant from the Research Foundation Flanders (FWO), Belgium. Part of the Russian data used in this study was financially supported by the Russian Science Foundation (Project no. 15-17-20006). Data collection in Ethiopia was partly supported by VLIR-UOS (Zala Daget Project). We thank two anonymous reviewers for their constructive comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2016.01.009.

References

Alonso, C.V., Combs, S.T., 1990. Streambank erosion due to bed degradation — a model concept. Trans. ASAE 33, 1239–1248.

Archibold, O.W., Levesque, L.M.J., De Boer, D.H., Aitken, A.E., Delanoy, L., 2003. Gully retreat in a semi-urban catchment in Saskatoon, Saskatchewan. Appl. Geogr. 23 (4), 261–279.

Ashouri, H., Hsu, K.-L., Sorooshian, S., Braithwaite, D.K., Knapp, K.R., Cecil, L.D., et al., 2015. PERSIANN-CDR: daily precipitation climate data record from multisatellite observations for hydrological and climate studies. Bull. Am. Meteorol. Soc. 96 (1), 69–83. http://dx.doi.org/10.1175/BAMS-D-13-00068.1.

Avni, Y., 2005. Gully incision as a key factor in desertification in an arid environment, the Negev highlands, Israel. Catena 63, 185–220.

Bazhenova, O.I., Lyubtsova, E.M., Ryzhov, Y.V., Makarov, S.A., 1997. Spatio-Temporal Analysis of the Dynamics of Erosion Processes in the South of Eastern Siberia. Siberian Enterprise RAS, Novosibirsk (208 pp.).

Beer, C.E., Johnson, H.P., 1963. Factors in gully growth in the deep loess area of western Iowa. Trans. Am. Soc. Agric. Eng. 6, 237–240.

Berg, P., Haerter, J.O., Thejll, P., Piani, C., Hagemann, S., Christensen, J.H., 2009. Seasonal characteristics of the relationship between daily precipitation intensity and surface temperature. J. Geophys. Res. 114, D18102. http://dx.doi.org/10.1029/2009JD012008.

Blong, R.J., 1985. Gully sidewall development in New South Wales, Australia. In: El-Swaify, S.A., Moldengauer, W.C. (Eds.), Soil erosion and conservation. Wiley, pp. 574–584.

Bolysov, S.I., 1982. Морфометрический признак стабильности или роста свежих эрозионных врезов (Morphometric indication of stability or increase of ravines). Некоторые геоморфологические процессы и их воздействие на ландшафты и их компоненты. (Some Geomorphological Processes and their Influence on Landscapes and their Components). MSNT, Moscow, pp. 14–17 (in Russian).

Bolysov, S.I., Borsuk, O.A., Evteev, A.O., 1985. Стационарные наблюдения за овражной эрозией в Подмосковье (Stationary observations of ravine erosion in the Moscow region). Факторы и процессы ландшафтообразования. (Factors and Processes of Landscapes Origin). MSNT, Moscow, pp. 59–63 (in Russian).

Bolysov, S.I., Tarzaeva, N.V., 1996. Метеорологический фактор в развитии регрессивной эрозии на юго-западе Подмосковья (Meteorological factor of regressive erosion dynamics in South-West part of Moscow region). Геоморфология (Geomorphologiya) 4, 97–103 (in Russian).

Brooks, A.P., Shellberg, J.G., Knight, J., Spencer, J., 2009. Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia. Earth Surf. Process. Landf. 34, 1951–1969.

Bruynseels, A., 2015. Ravijnerosie in tropische steden: Een verkennende studie via Google Earth (Gully Erosion in Tropical Cities: an Explorative Study Based on Google Earth). BSc Thesis University of Leuven, Department of Earth and Environmental Sciences, Leuven, Belgium, p. 61.

Burkard, M.B., Kostaschuk, R.A., 1995. Initiation and evolution of gullies along the shoreline of Lake Huron. Geomorphology 14, 211–219.

Burkard, M.B., Kostaschuk, R.A., 1997. Patterns and controls of gully growth along the shoreline of lake Huron. Earth Surf. Process. Landf. 22, 901–911.

Campo, M.A., Alvarez-Mozos, J., Casali, J., Giménez, R., 2007. Effect of topography on retreat rate of different gully headcuts in Bardenas Reales (Navarre, Spain). In: Casali, J., Giménez, R. (Eds.), Progress in Gully Erosion Research (Proceedings of the IVth International Symposium on Gully Erosion, Sept 17–19, 2007. Pamplona, Spain). Universidad Publica de Navarra, pp. 24–25.

Campo, M.A., Flores-Cervantes, J.H., Bras, R.L., Casali, J., 27 June – 1 July 2010. CHILD evaluation with a field data set. In: Proceedings of the 2nd Joint Federal Interagency Conference Vol. 27.

Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F., Raclot, D., Ionita, I., Rejman, J., Rousseva, S., Muxart, T., Roxo, M., Dostal, T., 2010. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. Geomorphology 122, 167–177.

Coelho Netto, A.L., Fernandes, N.F., Edegard De Deus, C., 1988. Gullying in the southeastern Brazilian Plateau, Bananal, SP. In: Bordas, M.P., Walling, D.E. (Eds.), Sediment Budgets (Proceedings of the 1988 Porto Alegre Symposium). IAHS Publ. 174, pp. 35–42.

Collison, A., 1996. Unsaturated strength and preferential flow as controls on gully head development. In: Anderson, M.G., Brooks, S.M. (Eds.), Advances in Hillslope Processes 2, pp. 753–769.

Cox, R., Zentner, D., Rakotondrazafy, A., Rasoazanamparany, C., 2010. Shakedown in Madagascar: occurence of lavakas (erosional gullies) associated with seismic activity. Geology 38, 179–182.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerdemaeker, J., Muys, B., 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. Plant Soil 305, 207–226.

De Luna Armenteros, E., Laguna Luna, A.M., Poesen, J., Cervera, J.V.G., 2004. Evoluciòn de un sistema de càrcavas activas en el sureste español (Evolution of an active gully system in southeastern Spain). Ing. Agua 11, 65–73.

Dedkov, A.P., Boiko, F.F., Mozzherin, V.I., Butacov, G.P., Dvinskich, A.P., Yermolaev, O.P., Lapteva, N.N., Tukaiev, R.M., Nazarov, N.N., Korotina, N.M., Rysin, I.I., 1990. Овражная эрозия на востоке Русской равнины (Gully Erosion in the East of the Russian Plain). Казань, Изд-во Казанского Университета [Kazan University, Kazan], p. 145 (In Russian).

de Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth Sci. Rev. 71, 95–125.

de Vente, J., Poesen, J., Verstraeten, G., Govers, G., Vanmaercke, M., Van Rompaey, A., Arabkhedri, M., Boix-Fayos, C., 2013. Predicting soil erosion and sediment yield at regional scales: where do we stand? Earth Sci. Rev. 127, 16–29.

Earth Remote Sensing Data Analysis Center (ERSDAC), 2009. ASTER GDEM. Available at: http://www.jspacesystems.or.jp/ersdac/GDEM/E/index.html (last accessed: 11 January 2016).

Ehiorobo, J.O., Izinyon, O.C., 2012. Monitoring gully formation and development for effective remediation and control. FIG Working Week 2012, TS09I – Engineering Surveying 5919.

El Maaoui, M.A., Felfou, M.S., Boussema, M.R., Snane, M.H., 2012. Sediment yield from irregularly shaped gullies located on the Fortuna lithologic formation in semi-arid area of Tunisia. Catena 93, 97–104.

Fisher, R.A., 1924. The distribution of the partial correlation coefficient. Metron 3 (3–4), 329–332.

Francisco, A.B., Nunes, J.O.R., 2009. Aplicação de metodologia de estaqueamento para estudo do processo de voçorocamento no município de rancharia-SP (Applying the pin method to study gully erosion processes in the Rancharia-SP municipality). Carderno Prudentino Geogr. 1, 183–189 (In Portuguese).

Frankl, A., Poesen, J., Deckers, J., Haile, M., Nyssen, J., 2012. Gully head retreat rates in the semi-arid highlands of Northern Ethiopia. Geomorphology 173-174, 185–195.

Frankl, A., Poesen, J., Scholiers, N., Jacob, M., Haile, M., Deckers, J., Nyssen, J., 2013. Factors controlling the morphology and volume (V)–length (L) relations of permanent gullies in the Northern Ethiopian highlands. Earth Surf. Process. Landf. 38, 1672–1684.

Ghimire, S.K., Higaki, D., Bhattarai, T., 2006. Gully erosion in the Siwalik Hills, Nepal: estimation of sediment production from active ephemeral gullies. Earth Surf. Process. Landf. 31, 155–165.

Godin, E., Fortier, D., 2012. Geomorphology of a thermo-erosion gully, Bylot Island, Nunavut, Canada. Can. J. Earth Sci. 49 (8), 979–986.

Grellier, S., Kemp, J., Janeau, J.L., Florsch, N., Ward, D., Barot, S., Podwojeske, P., Lorentz, S., Valentin, C., 2012. The indirect impact of encroaching trees on gully extension: a 64 year study in a sub-humid grassland of South Africa. Catena 98, 110–119.

Guerra, A.J.T., Bezerra, J.F.R., Fullen, M.A., Mendoça, J.K.S., Sathler, R., Lima, F.S., Mendes, S.P., Guerra, T.T., 2007. Urban gullies in Sao Luis city, Maranhao state, Brazil. In: Casali, J., Giménez, R. (Eds.), Progress in Gully Erosion Research. (IVth International Symposium on Gully Erosion, Sept 17–19, 2007. Pamplona, Spain). Universidad Publica de Navarra, pp. 58–59.

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5 (1), 3–17.

Guzzetti, F., Ardizzone, F., Cardinali, M., Rossi, M., Valigi, D., 2009. Landslide volumes and landslide mobilization rates in Umbria, Central Italy. Earth Planet. Sci. Lett. 279 (3), 222–229.

Gyssels, G., Poesen, J., Bochet, E., Li, Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. Prog. Phys. Geogr. 29 (2), 189–217.

Graf, W.L., 1977. The rate law in fluvial geomorphology. Am. J. Sci. 277, 178–191.

Haregeweyn, N., Poesen, J., Nyssen, J., Deckers, J., 2011. Assessment of Gully-head Erosion Rates and Controlling Factors for Gully Initiations in the Northern Ethiopian Highlands, Report of the Zala Daget Project.

Harvey, A., 1982. The role of piping in the development of badlands and gully systems in south-east Spain. In: Bryan, R., Yair, A. (Eds.), Badland Geomorphology and Piping. GeoBooks, Norwich, UK, pp. 317–335.

Hawkins, R.H., Ward, T.J., Woodward, D.E., et al., 2009. Curve Number Hydrology: State of the Practice. ASCE Publications, Reston, Virginia, USA (106 pp.).

Hu, G., Wu, Y., Liu, B., Yu, Z., You, Z., Zhang, Y., 2007. Short-term gully retreat rates over rolling hill areas in black soil of Northeast China. Catena 71, 321–329.

Hu, G., Wu, Y., Zhang, Y., You, Z., Yu, Z., 2009. The characteristics of gully erosion over rolling hilly black soil areas of Northeast China. J. Geogr. Sci. 19, 309–320.

Ionita, I., 2000. Formarea si evolutia ravenelor din Podisul Barladului (Formation and Development of the Gullies in the Barlad Plateau). Editura Corson, Iasi 973-8225-01-9.

Ionita, I., 2006. Gully development in the Moldavian Plateau of Romania. Catena 68, 133–140.

Ionita, I., Niacsu, L., Petrovici, G., Blebea-Apostu, A.M., 2015. Gully development in eastern Romania: a case study from Falciu Hills. Nat. Hazards 79 (Suppl. 1), 113–138.

Ionita, I., 2008. Sediment movement from small catchments within the Moldavian Plateau of Eastern Romania. In: Schmidt, J, Cochrane, T, Phillips, C, Elliot, S, Davies, T, Basher, L (Eds.), Sediment dynamics in changing environments, IAHS 325. IASH Press; Wallingford, United Kingdom, pp. 316–320 ISSN 0144-7815.

Ithshack M (1998) Annual gully head development of 6 gully heads in Hagadi watershed (Netivot area-North West Negev), Pers. comm. (27-12-1998)

Jakeman, A.J., Hornberger, G.M., 1993. How much complexity is warranted in a rainfall-runoff model? Water Resour. Res. 29 (8), 2637–2649.

Karimov, V., Sheshukov, A., Barnes, P., 2014. Impact of precipitation and runoff on ephemeral gully development in cultivated croplands. In: Jun Xu, Y., Allison, M., Bentley, S., Collins, A., Erskine, W., Golosov, V., Horowitz, A., Stone, M. (Eds.), Sediment Dynamics from the Summit to the Sea: Proceedings of ICCE2014, New Orleans, USA, December 2014. IAHS Publ 367, pp. 87–92.

Knapen, A., Poesen, J., Govers, G., Gyssels, G., Nachtergaele, J., 2007. Resistance of soils to concentrated flow erosion: a review. Earth Sci. Rev. 80, 75–109.

Knapen, A., Poesen, J., 2010. Soil erosion resistance effects on rill and gully initiation points and dimensions. Earth Surf. Process. Landf. 35, 217–228.

Kosov, B.F., 1970. Рост оврагов на территории СССР (Gully growth on the territory of the USSR). In: Makkaveev, N.I. (Ed.)Эрозия почв и русловые процессы. (Soil Erosion and Fluvial Processes) vol. 1. Moscow University Publ. House, pp. 61–78 (in Russian).

Larsen, I.J., Montgomery, D.R., Korup, O., 2010. Landslide erosion controlled by hillslope material. Nat. Geosci. 3 (4), 247–251.

Leopold, L.B., Emmett, W.W., Myrick, R.M., 1966. Channel and hillslope processes in a semi-arid area, New Mexico. U. S. Geol. Surv. Prof. Pap. 352-G, 192–243.

Lessa, L.G.F., De Lima, S.L., Zimback, C.R.L., 2007. Analise multitemporal das perdas de solo por vocorocas, da sub-bacia ribeirao das bicas - botucatu, atraves de geoprocessamento e sensoriamento remote (Multitemporal analysis of soil loss from gullies in Bicas Stream Watershed — Boutucatu/SP, through geoprocessings and remote sensing). Energy Agric. Botucatu 22, 61–74 (In Spannish).

Li, Y., Poesen, J., Liu, L.M., He, F.H., Zhang, Q.W., Li, R., 2007. Gully erosion in mountain area of SW-China, assessed using 137Cs and 210Pbex tracers and GPS survey. In: Casali, J., Giménez, R. (Eds.), Progress in Gully Erosion Research (IVth International Symposium on Gully Erosion, Sept 17–19, 2007. Pamplona, Spain). Universidad Publica de Navarra, pp. 70–71.

Li, Z., Zhang, Y., Zhu, Q., He, Y., Yao, W., 2015. Assessment of bank gully development and vegetation coverage on the Chinese Loess Plateau. Geomorphology 228, 462–469.

Loague, K.M., Freeze, R.A., 1985. A comparison of rainfall-runoff modeling techniques on small upland catchments. Water Resour. Res. 21 (2), 229–248.

Maetens, W., Vanmaercke, M., Poesen, J., Jankauskas, B., Jankauskiene, G., Ionita, I., 2012a. Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: a meta-analysis of plot data. Prog. Phys. Geogr. 36 (5), 599–653.

Maetens, W., Poesen, J., Vanmaercke, M., 2012b. How effective are soil conservation measures in reducing plot runoff and soil loss in Europe and the Mediterranean? Earth Sci. Rev. 115, 21–36.

Makanzu Imwangana, F., 2014. Etude de l'érosion ravinante à Kinshasa: Dynamisme Pluvio-Morphogénique et Développement d'un Outil de Prévision (Study on Gully Erosion in Kinshasa: Rainfall-formation Dynamics of and prevention strategies). PhD. Thesis Université de Kinshasa, Faculté des Sciences, Kinshasa, D.R. Congo, p. 208 (in French).

Makanzu Imwangana, F., Dewitte, O., Ntombi, M., Moeyersons, J., 2014. Topographic and road control of mega-gullies in Kinshasa (DR Congo). Geomorphology 217, 131–139.

Makanzu Imwangana, F., Vandecasteele, I., Trefois, P., Ozer, P., Moeyersons, J., 2015. The origin and control of mega-gullies in Kinshasa (DR Congo). Catena 125, 38–49.

Mao, Z., Saint-André, L., Genet, M., Mine, F.X., Jourdan, C., Rey, H., Courbaud, B., Stokes, A., 2012. Engineering ecological protection against landslides in diverse mountain forests: choosing cohesion models. Ecol. Eng. 45, 55–69.

Marc, O., Hovius, N., 2014. Amalgamation in landslide maps: effects and automatic detection. Nat. Hazards Earth Syst. Sci. Discuss. 2, 7651–7678.

Marzolff, I., Ries, J., 2007. Gully erosion monitoring in semi-arid landscapes. Z. Geomorphol. 51 (4), 405–425.

Marzolff, I., Ries, J.B., Poesen, J., 2011. Short-term versus medium-term monitoring for detecting gully-erosion variability in a Mediterranean environment. Earth Surf. Process. Landf. 36, 1604–1623.

Mehdipour, A., Soufi, M., Baniasadi, M., 2007. Gully development and topographic thresholds, case study: Kermand province, Southeast of I. R. Iran. In: Casali, J., Giménez, R. (Eds.), Progress in Gully Erosion Research (IVth International Symposium on Gully Erosion, Sept 17–19, 2007. Pamplona, Spain). Universidad Publica de Navarra, pp. 92–93.

Menéndez-Duarte, R., Marquínez, J., Fernández-Menéndez, S., Santos, R., 2007. Incised channels and gully erosion in Northern Iberian peninsula: controls and geomorphic setting. Catena 71, 267–278.

Moeyersons, J., Makanzu Imwangana, F., Dewitte, O., 2015. Site-and rainfall-specific runoff coefficients and mega-gully development in Kinshasa (DR Congo). Nat. Hazards 79, 203–233.

Nachtergaele, J., Poesen, J., Oostwoud, D.W., Vandekerckhove, L., 2002a. Medium-term evolution of a gully developed in a loess-derived soil. Geomorphology 46, 223–239.

Nachtergaele, J., Poesen, J., Sidorchuk, A., Torri, D., 2002b. Prediction of concentrated flow width in ephemeral gully channels. Hydrol. Process. 16 (10), 1935–1953.

Nazari Samani, A., Ahmadi, H., Mohammadi, A., Ghoddousi, J., Salajegheh, A., Boggs, G., Pishyar, R., 2010. Factors controlling gully advancement and models evaluation (Hableh Rood Basin, Iran). Water Resour. Manag. 24, 1532–1549.

New, M., Lister, D., Hulme, M., Makin, I., 2002. A high-resolution data set of surface climate over global land areas. Clim. Res. 21 (1), 1–25.

Niacsu, L., Ionita, I., 2011. Gully erosion in the Pereschiv catchment of Eastern Romania. Landf. Anal. 17, 135–137.

Nir, D., Klein, M., 1974. Gully erosion induced in land use in a semi-arid terrain (Nahal Shiqma, Israel). Z. Geomorphol. 21, 191–201.

Nyssen, J., Poesen, J., Veyret-Picot, M., Moeyersons, J., Haile, M., Deckers, J., Dewit, J., Naudts, K., Govers, G., 2006. Assessment of gully erosion rates through interviews and measurements: a case study from northern Ethiopia. Earth Surf. Process. Landf. 31, 167–185.

Nyssen, J., Clymans, W., Descheemaeker, K., Poesen, J., Vandecasteele, I., Vanmaercke, M., Haile, Mitiku, Haregeweyn, Nigussie, Moeyersons, J., Martens, K., Zenebe, A., Van Camp, M., Gebreyohannes, Tesfamichael, Deckers, J., Walraevens, K., 2010. Impact of soil and water conservation on catchment hydrological response — a case in northern Ethiopia. Hydrol. Process. 24, 1880–1895.

Olofin, E.A., 1990. The dynamics of gully head recession in a savanna environment. In: Walling, D.A., Yair, A., Berkowicz, S. (Eds.), Erosion, Transport and Deposition Processes (Proceedings of a Workshop held at Jerusalem, March–April 1987)IAHS Publ. 189. IAHS Press, Wallingford, pp. 135–144.

Oostwoud Wijdenes, D., Poesen, J., Vandekerckhove, L., Ghesquiere, M., 2000. Spatial distribution of gully head activity and sediment supply along an ephemeral channel in a Mediterranean environment. Catena 39 (3), 147–167.

Oostwoud, D.J., Bryan, R., 2001. Gully-head erosion processes on a semi-arid valley floor in Kenya: a case study into temporal variation and sediment budgeting. Earth Surf. Process. Landf. 26, 911–933.

Otsuki, Y., Saijo, K., Taniguchi, T., Nakamura, M., Sakaida, K., 2008. Gully erosion and its relating soil moisture condition in the Wuchuan County, Inner Mongolia, China. Report of the Grant-in-Aid for Scientific Research (B) "Geographical Research on Desertification in Inner Area of China" (Project Number: 17401003, Principal Investigator: Kiyotaka Sakaida) by the Japan Society for the Promotion of Science, pp. 9–17.

Otsuki, Y., Saijo, K., 2015. Geomorphic Processes Related to Desertification and Land Degradation in Inner Mongolia, China. Booklet of Multidiscipline Research Center, Sapporo Gakuin University 7, 76–84.

Poesen, J., 1992. Mechanisms of overland flow generation and sediment production on loamy and sandy soils with and without rock fragments. In: Parsons, A.J., Abrahams, A.D. (Eds.), Overland Flow Hydraulics and Erosion Mechanics. UCL Press, London, pp. 275–305.

Poesen, J., de Luna, E., Franca, A., Nachtergaele, J., Govers, G., 1999. Concentrated flow erosion rates as affected by rock fragment cover and initial soil moisture content. Catena 36, 315–329.

Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G., van Wesemael, B., 2002. Gully erosion in dryland environments. In: Bull, L.J., Kirkby, M.J. (Eds.), Dryland Rivers: Hydrology and Geomorphology of Semi-arid Channels. Wiley, Chichester, U.K. ISBN: 0-471-49123-3, pp. 229–262.

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena 91, 91–133.

Poesen, J., Torri, D., Vanwalleghem, T., 2011. Gully erosion: procedures to adopt when modelling soil erosion in landscapes affected by gullying. In: Morgan, R., Nearing, M. (Eds.), Handbook of Erosion Modelling. Blackwell Publishing Ltd., pp. 360–386.

Polade, S.D., Pierce, D.W., Cayan, D.R., Gershunov, A., Dettinger, M.D., 2014. The key role of dry days in changing regional climate and precipitation regimes. Sci. Rep. 4, 4364. http://dx.doi.org/10.1038/srep04364.

Radoane, M., Ichim, I., Radoane, N., 1995. Gully distribution and development in Moldavia, Romania. Catena 24, 127–146.

Ranga, V., Van Rompaey, A., Poesen, J., Mohapatra, S.N., Pani, P., 2015. Semi-automatic Delineation of Badlands Using Contrast in Vegetation Activity: A Case Study in the Lower Chambal Valley, 2015. India; Geocarto Int. 30 (8), 919–936.

Rieke-Zapp, D., Poesen, J., Nearing, M., 2007. Effects of rock fragments incorporated in the soil matrix on concentrated flow hydraulics and erosion. Earth Surf. Process. Landf. 32, 1063–1076.

Rieke-Zapp, D.H., Nichols, M.H., 2011. Headcut retreat in a semiarid watershed in the Southwestern United States since 1935. Catena 87, 1–10.

Rodzik, J., Furtak, T., Zglobicki, W., 2009. The impact of snowmelt and heavy rainfall runoff on erosion rates in a gully system, Lublin Upland, Poland. Earth Surf. Process. Landf. 34, 1938–1950.

Rossi, M., Torri, D., Santi, E., 2015. Bias in topographic thresholds for gully heads. Nat. Hazards 79 (Supplement 1), 51–69.

Rutherford, I.D., Prosser, I.P., Davis, J., 1997. Simple approaches to predicting rates and extent of gully development. In: Wang, S.S.Y., Langendoen, E.J., Shields, F.D. (Eds.), Management of Landscapes Disturbed by Channel Incision. Proc. International Conference, The University of Mississippi, Oxford, Mississippi, May 19–23, 1997. Publ. by The Center for Computational Hydroscience and Engineering, The Univsersity of Mississippi, pp. 1125–1130.

Rysin, I.I., 1998. О современном тренде овражной эрозии в Удмуртии (About recent trend of gully erosion in Udmurtiya). Геоморфология (Geomorphologiya) 3, 92–101 (in Russian).

Rysin, I.I., Grigoriev, I.I., 2007. About the results of gully erosion monitoring in the territory of Udmurt Republic. Proceedings of the tenth International Symposium on River Sedimentation (August 1–4, Moscow, Russia) volume 1. M.V. Lomonosov Moscow State University, Moscow, pp. 355–361.

Rysin, I.I., Grigoriev, I.I., 2009. Использование ГИС при изучении техногенных и сельскохозяйственных оврагов (GIS application in the research of technogenic and agricultural gullies in Udmurtia). Геоморфология (Geomorfologiya) 2, 69–75 (in Russian).

Rysin, I.I., Grigoriev, I.I., 2010. About the result of ravine erosion monitoring in the territory of the Udmurt Republic. Slope processes and matter movement (Proceedings of the 1st Italian — Russian Workshop on Water Erosion), Moscow, pp. 78–82.

Ryzhov, Y.V., 1995. Рост оврагов на юге Сибири (Growth of gullies in the Southern Siberia). География и природные ресурсы (Geogr. Nat. Resour.) 3, 101–110 (in Russian).

Ryzhov, Y.V., 1998. Овражная эрозия в межгорных котловинах Юго-Западного Прибайкалья (Gully erosion in intermountaine basins of the South-West Pribaikalye). Геоморфология (Geomorphologiya) 3, 68–73 (in Russian).

Sanchis, M.P., Torri, D., Borselli, L., Poesen, J., 2008. Climate effects on soil erodibility. Earth Surf. Process. Landf. 33, 1082–1097.

Schmidt, R., Heinrich, J., 2011. 200 years of land-use change and gully erosion — a case study from Małopolska, SE Poland. Landf. Anal. 17, 167–171.

Seginer, I., 1966. Gully development and sediment yield. J. Hydrol. 4, 236–253.

Shedlock, K., Giardini, D., Grünthal, G., Zhang, P., 2000. The GSHAP Global Seismic Hazard Map. Seismological Research Letters 71, 679–686.

Sidorchuk, A., Marker, M., Moretti, S., Rodolfi, G., 2003. Gully erosion modelling and landscape response in the Mbuluzi River catchment of Swaziland. Catena 50, 507–525.

Sobolev, S.S., 1948. Развитие эрозионных процессов на территории Европейской части СССР и борьба с ними (Development of the erosion processes on territory of European part of USSR and the struggle with them). Moscow, Izd-vo AN SSSR vol. 1 (in Russian).

Steel, R.G.D., Torrie, J.H., 1960. Principles and Procedures of Statistics. McGraw-Hill, New York (672 pp.).

Stocking, M.A., 1980. Examination of factors controlling gully growth. In: De Boodt, M., Gabriels, D. (Eds.), Assessment of Erosion. John Wiley & Sons, Chichester, pp. 505–520.

Stocking, M.A., 1981. Causes and prediction of the advance of gullies. Proceedings of the South-East Asian Regional Symposium on 'Problems of Soil Erosion and Sedimentation', Bangkok, Thailand, 27–29 January 1981, pp. 37–47.

Stokes, A., Spanos, I., Norris, J.E., Cammeraat, E. (Eds.), 2007. Eco- and Ground Bio-engineering: the Use of Vegetation to Improve Slope Stability. Springer, Dordrecht, The Netherlands (438 pp.).

Summerfield, M.A., 2014. Global Geomorphology. Routledge (560 pp.).

Syvitski, J.P.M., Milliman, J., 2007. Geology, Geography, and Humans Battle for Dominance over the Delivery of Fluvial Sediment to the Coastal Ocean. J. Geol. 115, 1–19.

Tekwa, J.I., Usman, B.H., 2010. Estimation of soil loss by gully erosion in Mubi, Adamawa State, Nigeria. FUTY J. Environ. 1, 35–43.

Thomas, J.T., Iverson, N.R., Burkart, M.R., Kramer, L.A., 2004. Long-term growth of a valley-bottom gully, western Iowa. Earth Surf. Process. Landf. 29, 995–1009.

Thompson, J.R., 1964. Quantitative effect of watershed variables on rate of gully-head advancement. Trans. Am. Soc. Agric. Eng. 7, 54–55.

Torri, D., Poesen, J., 2014. A review of topographic threshold conditions for gully head development in different environments. Earth Sci. Rev. 130, 73–85.

US Soil Conservation Service, 1966. Procedures for determining rates of land damage, land depreciation and volume of sediment produced by gully erosion. Technical Release 32. USDA, Washington, DC (18 pp.).

Valentin, C., Poesen, J., Li, Y., 2005. Gully erosion: impacts, factors and control. Catena 63, 132–153.

Van Mele, B., 2013. How Fast do Gully Headcuts Retreat MSc Thesis University of Leuven, Department of Earth and Environmental Sciences, Leuven, Belgium, p. 136.

Vandekerckhove, L., Muys, B., Poesen, J., De Weerdt, B., Coppe, N., 2001a. A method for dendrochronological assessment of medium-term gully erosion rates. Catena 45, 123–161.

Vandekerckhove, L., Poesen, J., Oostwoud Wijdenes, D., Gyssels, G., 2001b. Short-term bank gully retreat rates in Mediterranean environments. Catena 44, 133–161.

Vandekerckhove, L., Poesen, J., Govers, G., 2003. Medium-term gully headcut retreat rates in Southeast Spain determined from aerial photographs and ground measurements. Catena 50, 329–352.

Vanmaercke, M., Poesen, J., Verstraeten, G., Maetens, W., de Vente, J., 2011a. Sediment yield as a desertification risk indicator. Sci. Total Environ. 409, 1715–1725.

Vanmaercke, M., Poesen, J., Verstraeten, G., de Vente, J., Ocakoglu, F., 2011b. Sediment yield in Europe: spatial patterns and scale dependency. Geomorphology 130, 142–161.

Vanmaercke, M., Maetens, W., Poesen, J., Jankauskas, B., Jankauskiene, G., Verstraeten, G., de Vente, J., 2012a. A comparison of measured catchment sediment yields with measured and predicted hillslope erosion rates in Europe. J. Soils Sediments 12, 586–602.

Vanmaercke, M., Poesen, J., Radoane, M., Govers, G., Ocakoglu, F., Arabkhedri, M., 2012b. How long should we measure? An exploration of factors controlling the inter-annual variation of catchment sediment yield. J. Soils Sediments 12, 603–619.

Vanmaercke, M., Poesen, J., Govers, G., Verstraeten, G., 2015. Quantifying human impacts on catchment sediment yield: a continental approach. Glob. Planet. Chang. 130, 22–36.

Vannoppen, W., Vanmaercke, M., De Baets, S., Poesen, J., 2015. A review of the mechanical effects of plant roots on concentrated flow erosion rates. Earth Sci. Rev. 150, 666–678.

Vanwalleghem, T., Van Den Eeckhaut, M., Poesen, J., Deckers, J., Nachtergaele, J., Van Oost, K., Slenters, C., 2003. Characteristics and controlling factors of old gullies under forest in a temperate humid climate: a case study from the Meerdaal Forest (Central Belgium). Geomorphology 56 (1), 15–29.

Vanwalleghem, T., Bork, H.R., Poesen, J., Schmidtchen, G., Dotterweich, M., Nachtergaele, J., Bork, H., Deckers, J., Brüsch, B., Bungeneers, J., De Bie, M., 2005. Rapid development and infilling of a buried gully under cropland, Central Belgium. Catena 63, 221–243.

Viero, A.C., dos Reis Castro, N.M., Goldenfum, J.A., Risso, A., 2005. Natural and anthropogenic factors controlling gully erosion in the basaltic upland of southern Brazil. Int. J. Sediment Res. 20, 211–223.

Vines, T.H., Albert, A.Y., Andrew, R.L., Débarre, F., Bock, D.G., Franklin, M.T., Gilbert, K.J., Moore, J.S., Renaut, S., Rennison, D.J., 2014. The availability of research data declines rapidly with article age. Curr. Biol. 24, 94–97.

Vrieling, A., Rodrigues, S.C., Sterk, G., 2005. Evaluating erosion from space: a case study near Uberlândia. Soc. Nat. 1 (1), 683–696.

Wang, X., Zhong, X., Liu, S., Li, M.H., 2008. A non-linear technique based on fractal method for describing gully-head changes associated with land-use in an arid environment in China. Catena 72, 106–112.

Withlow, R., Firth, C., 1989. Gully form and development on Karoo sediments in central Zimbabwe: a preliminary survey. Zambezia 16, 1–28.

Wilson, R.C., Jayko, A.S., 1997. Preliminary maps showing rainfall thresholds for debris-flow activity, San Francisco Bay Region, California. US Geological Survey Open-file Report 97–745 F.

Wu, Y., Cheng, H., 2005. Monitoring of gully erosion on the Loess Plateau of China using a global positioning system. Catena 63, 154–166.

Wu, Y., Zheng, Q., Zhang, Y., Liu, B., Cheng, H., Wang, Y., 2008. Development of gullies and sediment production in the black soil region of northeastern China. Geomorphology 101, 683–691.

Yermolaev, O.P., 2014. Erosion processes of the forest and forest-steppe zones in the eastern part of the Russian Plain. World Appl. Sci. J. 29 (3), 453–459.

Zanchi, C., Torri, D., 1980. Evaluation of rainfall energy in central Italy. In: Boodt, M.D., Gabriels, D. (Eds.), Assessment of Erosion. J. Wiley and Sons, Chichester, United Kingdom, pp. 133–142.

Zorina, E.F., Kovalev, S.N., Nikolskaya, I.I., 1998. Подходы к типизации оврагов (Approaches to gully typization). Геоморфологияб (Geomorphologiya) 2, 75–80 (in Russian).