EROSION PROCESSES ON DIFFERENT RELIEF UNITS: THE RELATIONSHIP OF FORM AND PROCESS

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ABSTRACT. *Geomorphological relief units are related to certain processes and the history of their development. They are well defined by form and material. This study investigates erosion processes on different relief units. Rainfall simulations, rill experiments and monitoring by aerial photography were performed on dunes, glacis, Holocene fillings, talus material and Quaternary loam terraces in order to analyse the varying process intensities. Splash, interrill erosion and runoff generation were quantified by rainfall simulation experiments, rill erosion by rill experiments and gully growth by monitoring over several years. The test sites are situated in NE- and SE-Spain, S-Morocco and N-Burkina Faso. The results clearly show that the measured processes are very different from those supposed to be relevant for the formation of relief units. Dunes and Holocene fillings are highly erodible by splash and interrill erosion. In contrast, Quaternary loam terraces show a low susceptibility to erosion processes. We conclude that the relief units show very different dominances of erosion processes and process intensities. The differentiation is more significant with increasing scale and complexity of the erosion process: The extent of gully growth varies much more between the different units than those of splash and interrill erosion do.*

Procesos de erosión en diferentes unidades del relieve: la relación entre forma y proceso

RESUMEN. *Las unidades geomorfológicas están relacionadas con ciertos procesos y con la historia de su formación. Además, se definen por sus formas y materiales. En este estudio se investigan los procesos de erosión en diferentes unidades de relieve. Simulaciones de lluvia, experimentos en rigolas y seguimientos a través de fotografía aérea se llevaron a cabo en dunas, glacis, rellenos holocenos, taludes y terrazas franco-arcillosos de origen cuaternario, con el objeto de conocer la variación en la intensidad de los procesos. Para ello, se evaluaron el impacto de las gotas de lluvia, la generación de escorrentía, la erosión en inter-rigolas y rigolas durante varios años. Las áreas de estudio se situaron*

en el NE y SE de España, sur de Marruecos y norte de Burkina Faso. Los resultados muestras claramente que los procesos medidos son muy diferentes entre sí según la formación de las propias unidades de relieve. Las dunas y los rellenos holocenos en los valles son altamente susceptibles a la erosión por el impacto de las gotas de lluvia y la formación de regueros. Por el contrario, las terrazas sobre materiales franco-arcillosos muestran baja susceptibilidad a los procesos de erosión. Por lo tanto, se puede concluir que las distintas unidades de relieve muestran diferente dominancia e intensidad de procesos. Las diferencias son más significativas con el incremento de la escala y la complejidad del proceso erosivo: el crecimiento de las cárcavas varía mucho más entre diferentes unidades que los efectos del impacto de la gota de lluvia y la formación de rigolas.

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1. Introduction

Terrain segmentation by means of the earth's surface morphology is a growing field of research since GIS and remote sensing data offer the possibility of gathering widespread topographical information at different scales (e. g. Minár and Evans, 2008; Pirotti, 2013). Hence, digital terrain data have found entry into many studies on hydrology and geomorphology (e. g. Drăguţ *et al.*, 2009; Kawabata and Bandibas, 2009; Schwanghart and Scherler, 2014; Tarolli, 2014; Tarolli *et al.*, 2015; Tarolli and Dalla Fontana, 2009; Wirtz *et al.*, 2012a). The morphology of a landscape is the result of a process combination that has shaped the earth surface over a short or long period. Geomorphology is able to identify and classify a great variety of forms and their attributed processes. On the other hand, the topographical features of a landscape can be decisive for certain current processes.

The concept of hydrological response units (HRU), developed two decades ago by Flügel (1995), identifies and distinguishes different zones of differentiated hydrological behaviour. Among other characteristics of the study area it incorporates topographic information. In this concept, it was assumed that process variability within the delineated unit is lower than between different units. Following this concept, more recent approaches, have led to attempts of process types regionalisation (Hellebrand and van den Bos, 2008; Müller *et al.*, 2009; Scherrer *et al.*, 2007).

A similar concept was adapted to erosion processes: Märker (2002) and Sidorchuk *et al.* (2003) defined erosion response units (ERUs). Until today the ERU concept has only been applied for the identification of areas prone to gully development and their subsequent use in gully-growth models. Recent studies aim at relating topographic characteristics to current processes and their prediction (Anders *et al.,* 2009; Carr *et al.*, 2015; Meissner *et al*., 2016). If recent efforts for automatic identification of relief units from digital terrain models (Anders *et al*., 2011; Martins *et al*., 2016; Smith *et al*., 2011) are taken into account, it is clear that relief units offer great potential for quantifying the current processes that shape the earth surface.

For this it is necessary to understand and quantify erosion processes that can be observed on different relief units with similar characteristics (e. g. similar genesis, topography and substrate). With the present study we intend to verify the following hypotheses:

– Certain relief units characterized by different materials and relief clearly differ in their current erodibility. Thus, the intensity of different erosion processes depends on the genesis, the substrate and even the age of the relief unit.

– The identification of the relationship between relief units and current process depends on the particular process, but also on the study method employed.

2. Material and methods

2.1. Study areas

We distinguished five relief units (dunes, glacis, Holocene fillings, talus material and Quaternary loam terraces) at eight study sites in Burkina Faso, Morocco and Spain (Fig. 1).

Table 1 summarizes the most important parameters of the different studied relief units. Slope ranges between 1° and 15°, substrate varies between coarse material, sand, silt and clay. Regarding the age, the relief units cover the period between Plio-Pleistocene and today.

To research runoff generation and initial erosion processes, different types of measurements and experiments were carried out. In the following, the relief units and the methods applied are briefly described.

Table 1. Main characteristics of the different relief units.

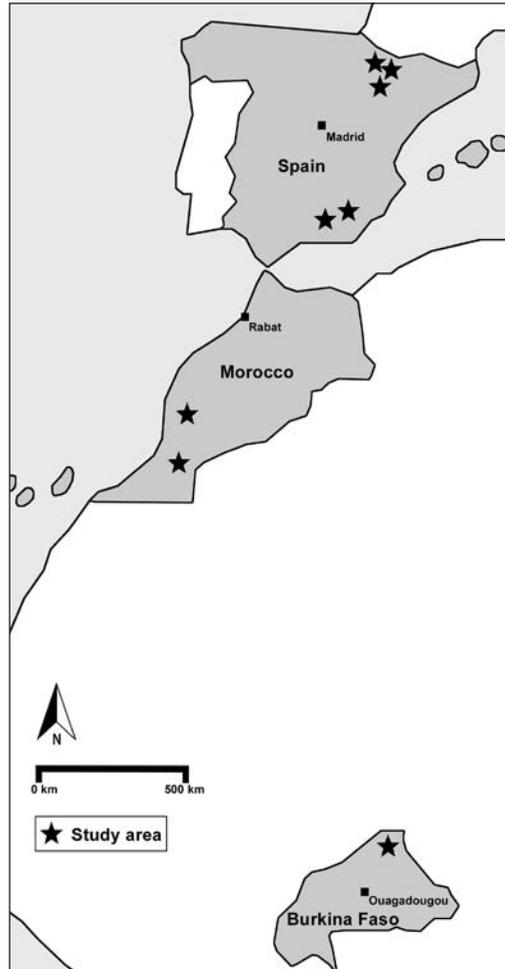| Relief unit	Location	Slope	Substrate	Age
Dune	Burkina Faso	3-8°	Sand	18-11000 BP
Glacis	Burkina Faso, Morocco, Spain	2-7°	Coarse material, silt, clay	Plio-Quaternary
Holocene filling	Spain	1-5°	Silt	Holocene
Talus material	Spain	8-15°	Coarse material	Holocene, recent
Quaternary terraces	Morocco	1-3°	Silt	Late Pleistocene/ Holocene

*Figure 1. Location of the study sites. Black lines show national boundaries
and coast lines, gray-shaded areas are national territories of Burkina Faso, Morocco and Spain,
squares are capitals and stars are study sites.*

2.1.1. Dunes

Currently remobilized Pleistocene dunes (Fig. 2a) occur in the north of Burkina Faso (province of Ouadalan). The dunes are composed of fine and medium sands accumulated in the late Pleistocene and transformed during the Holocene by intense pedogenetic processes. Without human impact, these dunes would be covered with dense grass vegetation. However, under current intense agricultural use with sorghum cultivation the surface tends to develop crusts due to intense erosion of the illuvial horizons. Even minor use – for example extensive grazing – leads to degradation processes with active sand movement. Thus small barchans, areas of deflation and slopes covered by recent sand accumulations are formed.
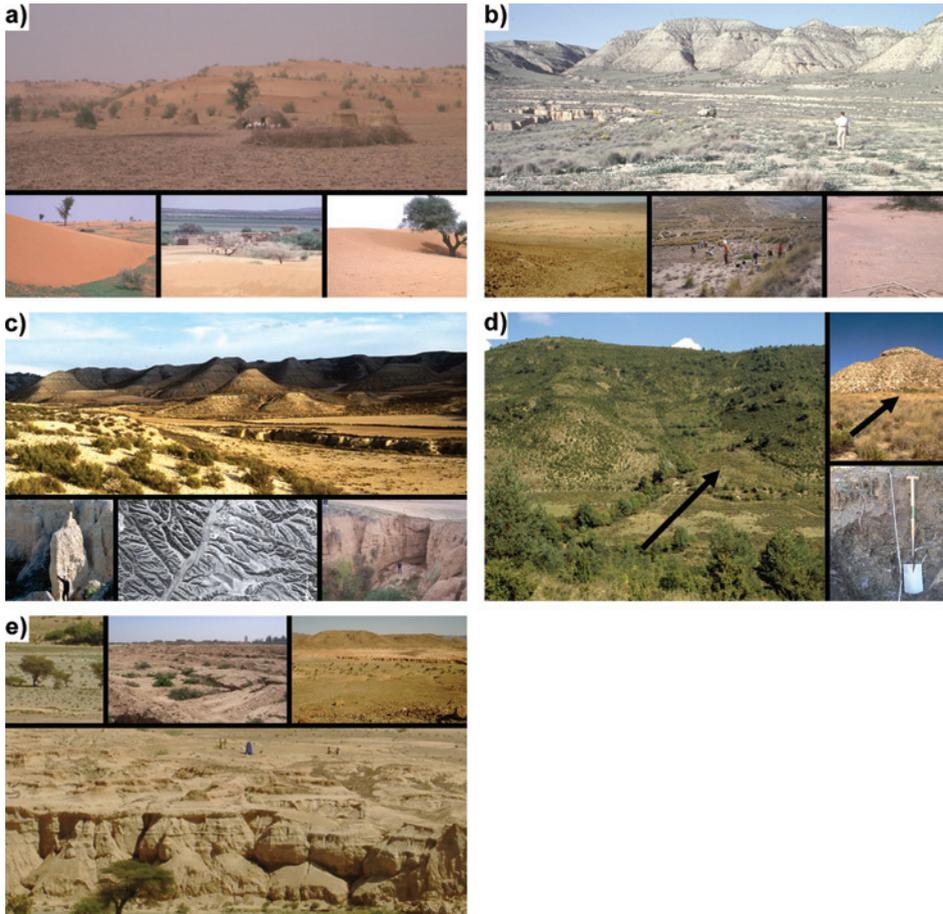
Figure 2. Photos of the five relief units listed in Table 1: a) dunes; b) glacis; c) Holocene fillings; d) talus material; e) Quaternary terraces.

2.1.2. Glacis

The glacis unit (Fig. 2b) is much more heterogeneous. Glacis are located at footslopes in the study sites of north-eastern and southern Spain. According to Spanish bibliography their origin is Plio-Quaternary (Peña Monné *et al.*, 1993). Depending on slope position they are characterized by erosion (*glacis d'érosion*) or accumulation (*glacis d'accumulation*). Additionally, silty pediments in South Morocco and clayey glacis in Burkina Faso were observed. This unit presents a great range concerning criterions related to climate and substrate.

2.1.3. Holocene filling

Holocene fillings (Fig. 2c) are located in the study areas of the Iberian Peninsula. These are slightly sloped valley bottoms filled with eroded material from the surrounding

slopes during periods of high erosive activity. The basis of these fillings has been dated to the Neolithic period (Andres *et al.,* 2002), but the main sedimentation occurred during the Bronze and Iron Ages as well as the Roman colonization.

The material ranges from large masses of gravel to thick layers of silt. The latter dominates the presented study areas. These flat-bottomed valleys are in many places incised by active gully systems. When they are not under agricultural use, they are grazed with different intensities and show an irregular vegetation cover.

2.1.4. Talus material

The foot slopes flanking the Holocene fillings (Fig. 2d) are covered by talus material. It consists of fine material with high stone and rock content and can be considered as a sediment originating from current erosion processes (e. g. slides, solifluction and water erosion). This relief unit was investigated in the central Ebro Basin and the central Pyrenees in north-eastern Spain. Talus material is generally covered by sparse to dense scrubland and is extensively grazed in this region.

2.1.5. Quaternary loam terraces

Quaternary loam terraces (Fig. 2e) are researched in the Souss Basin and the Drâa Basin in southern Morocco. In the latter, the terraces are the most common landforms on the southern slopes of the Anti-Atlas. They are connected, frequently without a change in slope, with the superior glacis. Nowadays, they are affected by the torrential regime descending from Atlas and Anti-Atlas.

These loam terraces are very similar to the Holocene fillings described above, but their age has not yet been determined. Pedologic findings indicate that their formation dates from the Pleistocene/Holocene transition. Due to dry climatic conditions they are bare of vegetation.

2.2. Quantification of erosion processes

2.2.1. Splash, interrill erosion and runoff generation

We performed 160 field rainfall simulations to investigate runoff generation and initial soil erosion by splash and interrill erosion on the different relief units.

The small portable rainfall simulator used in this study is described in detail by Iserloh *et al*. (2012) and is very common in Europe (e. g. Cerdà *et al*., 2016; Iserloh *et al*., 2013a, 2013b; Prosdocimi *et al*., 2017; Rodrigo Comino *et al*., 2016). A calibrated uniform and reproducible rainfall (intensity = 40 mm h^{-1}) is sprayed on a circular plot (d = 60 cm, A = 0.28 m^2) by a nozzle. The total runoff and eroded material produced during a 30-minute experiment is collected at 5-minute intervals. The amount of eroded material is weighted after filtering and drying at 105°C. Key data in this study are the runoff coefficient (RC), the amount of eroded material expressed in g m^{-2} and the suspended sediment load concentration (SSC) in g L^{-1}.

2.2.2. Rill erosion

The erosion caused by concentrated flows generates rills of small dimensions (< 1 m of width and depth) that are able to reach several tens of meters in length. The development of these rills may increase erosion rates to an order of magnitude higher than erosion caused by non-concentrated surface flows (Cerdan *et al.*, 2002; Merz and Bryan, 1993; Nouwakpo *et al.*, 2016b; Poesen, 1987; Wirtz *et al*., 2012a). Because of their highly erratic appearance and their easy destruction through soil management, erosion processes in rills are difficult to quantify (Casalí *et al*., 2006; Nouwakpo *et al*., 2016a; Wells *et al*., 2016).

To measure the effectiveness of linear erosion processes and for comparison with other measurements and experiments, rill experiments were developed and described in detail by Wirtz *et al*. (2010) and applied in several studies (Wirtz *et al*., 2013a, 2013b, 2012a, 2012b). As described in Wirtz *et al*. (2010), we discharged 72 liters of water with a flow rate of 9 L min^{-1} to a pre-existing rill. At three measuring points, water depth was recorded at different times of the experiment and sediment samples were collected. At the end of a defined distance from the starting point, runoff was continuously recorded. In addition, water velocity was recorded at the runoff front as well as through tracers at pre-defined moments. For rill characterization, slope was measured in segments of 1 m and detailed cross-sectional profiles were recorded at the sampling points. The eroded material was determined by filtration of the samples in laboratory. Similarly to the rainfall simulation experiment, the amount of eroded material was weighted after filtering and drying at 105°C. Key data for this study are the mean suspended sediment load concentration (SSC) in g L^{-1} and the runoff coefficient normalized in relation to the length of the gully (R-L). The factor R-L in L L^{-1} m is a specific runoff coefficient related to flow length and can be interpreted as inverse value of the infiltration in the rill. Thus it is an expression of the hydraulic activity.

Although rill erosion does occur, no data was available for the dunes in Burkina Faso because no rill experiments were performed.

2.2.3. Gully erosion

Gully erosion is difficult to quantify because of the size and complexity of the forms as well as the tempo-spatial variability of their development. Moreover, gully growth is the result of many different processes, such as headwall retreat, lateral collapses and incision. For the quantification of gully-erosion processes, detailed aerial photographic monitoring has proved to be the most efficient method (d'Oleire-Oltmanns *et al*., 2012; Eltner *et al*., 2016; Marzolff *et al*., 2011; Marzolff and Poesen, 2009; Marzolff and Ries, 2007; Ries and Marzolff, 2003; Stöcker *et al*., 2015; Wang *et al*., 2016). For this study we were able to use annual or semi-annual photographic series since 1995. Analogue and later digital photographs were taken from different camera carriers (hot-air blimps, kites and drones). After image rectification and photogrammetric evaluation, it was possible to document in detail the longitudinal and lateral growth of gullies, as well as incision and sedimentation in the system. In order to be able to make comparable measurements between different gully systems in

the study presented here, the quantification of the dynamics has been limited to their headcuts. Key data are maximum annual gully growth (R_{max}), the mean annual gully growth (R_{mean}) and the gully growth (Area loss).

3. Results

3.1. Splash, interrill erosion and runoff generation

The highest runoff coefficients were measured on dunes, with a median of 45%. However, these relief units also showed the highest variability (Fig. 3). On Holocene fillings, the median runoff was very similar (median RC = 41%) but much more homogeneous. Runoff generation was considerably less on glacis (30%), Quaternary loam terraces (29%) and talus material (23%).

Very similar to the runoff behavior but more homogeneous was the production of eroded material. The highest values were found on dunes (24 g m^{-2}), Holocene fillings (19 g m^{-2}) and Quaternary terraces (16 g m^{-2}). The measured sediment amounts were an order of magnitude lower on glacis and talus material (2.1 g m^{-2} and 1.4 g m^{-2}) and also showed a much lower variability.
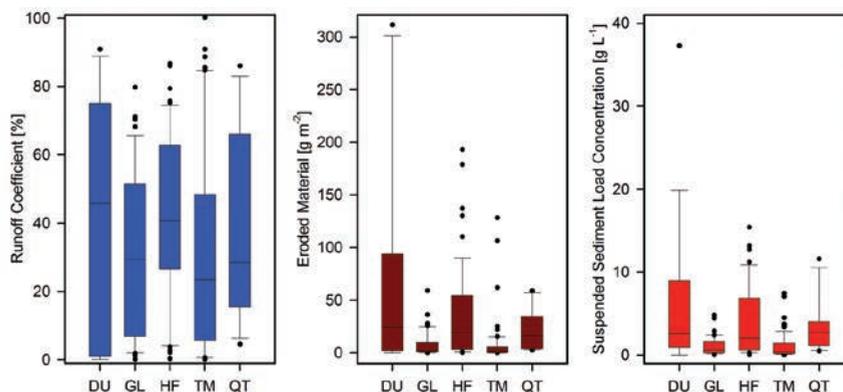

Figure 3. Runoff coefficient [%]; eroded material [g m-1] and suspended sediment load concentration [g L-1] in the rainfall simulation experiments. The lower and upper boundaries of each box represent the 25th and 75th percentiles, respectively, and the lower and upper error bars represent the 10th and 90th percentiles, respectively. Solid line represents the median value. DU = dunes; GL = glacis; HF = Holocene fillings; TM = talus material and QT = Quaternary terraces.

Suspended sediment load concentrations reached 2.7 g L^{-1} on Holocene fillings and 2.6 g L^{-1} on dunes and Quaternary terraces. On glacis and talus material lower concentrations of 1.6 g L^{-1} and 1.4 g L^{-1} were measured.

The data clearly show that in contrast to glacis and talus material, Holocene fillings, Quaternary terraces and dunes are highly susceptible to splash, interrill erosion and runoff generation (Table 2).

Table 2. Relief ranking based on mean, median and upper maximum values of runoff coefficient, eroded material and suspended sediment load concentration measured in the rainfall experiments.

Relief unit	Runoff Coefficient			Eroded Material			Suspended Sediment Load Concentration		
	Median	Mean	Upper max.	Median	Mean	Upper max.	Median	Mean	Upper max.
Dune	1	2	1	1	1	1	3	1	2
Glacis	3	5	4	4	5	4	4	5	5
Holocene filling	2	1	2	2	2	2	1	2	1
Talus material	5	4	5	5	4	5	5	4	4
Quaternary terraces	4	3	3	3	3	3	2	3	3

3.2. Rill erosion

The investigated rills are naturally developed, resulting in linear erosion forms that collect runoff from micro-watersheds of around 300 m^2. Taking into account the length of the rills (~20 m), the size of the observed surface exceeds one to two orders of magnitude the artificial plot size analyzed by the rainfall simulations.

The hydraulic activity of the rills studied in the glacis was very high with a median R-L factor of 5 L L^{-1} m (Fig. 4) and a broad scattering. This means that we can find areas within the rills with very low infiltration rates. Here we can assume that the clays of the *glacis d'accumulation*, or the bedrock in the *glacis d'érosion* inhibit the infiltration. Although much less variable, the Holocene fillings show a similar median R-L factor, clearly influenced by surface crusting. In contrast, talus material allowed more water infiltration during the experiments, but a high variability of hydraulic activity was shown as well. The values on Quaternary terraces in southern Morocco were extremely low and homogeneous.
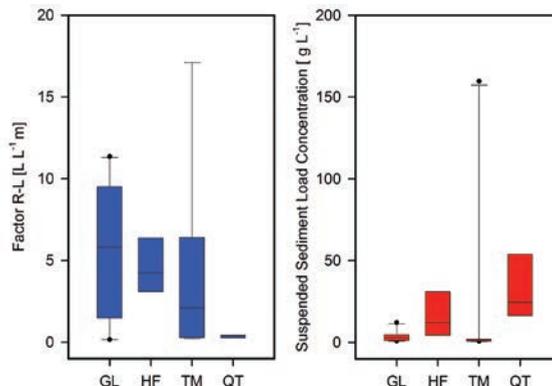

Figure 4. Factor R-L [L L-1 m] and measured suspended sediment load concentration [g L-1] in the rill experiments. Factor R-L is a specific runoff coefficient related to flow length as a value for hydraulic activity. Solid line represents the median value. The lower and upper boundaries of each box represent the 25th and 75th percentiles, respectively, and the lower and upper error bars represent the 10th and 90th percentiles, respectively. GL = glacis; HF = Holocene fillings; TM = talus material and QT = Quaternary terraces.

On all relief units, suspended sediment load concentrations in rill experiments were an order of magnitude higher than the concentrations measured in the rainfall simulations. On terraces and also on the Holocene fillings of the Iberian Peninsula, we found the highest concentrations, thus, they behaved reverse to what was described in relation to hydraulic activity (Table 3). Similar to the rainfall simulation results, very low erosion values were measured on glacis and talus material.

The high hydraulic activity observed on the glacis indicates that these were incised by the runoff concentrated in the rills. Low suspended sediment load concentrations were counteracted by high water amounts flowing through the system. However, as described above, erosion in the rills was minimal. This suggests that the glacis do not continue developing under the present conditions.

Table 3. Relief ranking based on mean, median and upper maximum values of the R-L factor and suspended sediment load concentration measured in the rill experiments. Factor R-L is a specific runoff coefficient related to flow length as a value for hydraulic activity.

Relief unit	Factor R-L			Suspended Sediment Load Concentration		
	Median	Mean	Upper max.	Median	Mean	Upper max.
Dune	-	-	-	-	-	-
Glacis	1	1	1	3	4	3
Holocene filling	2	2	3	2	3	2
Talus material	3	3	2	4	2	4
Quaternary terraces	4	4	4	1	1	1

High erosion rates can be expected in Holocene fillings, as these showed high runoff factors in conjunction with high sediment concentrations. The high susceptibility to erosion detected on the Quaternary terraces, based on the measured sediment concentrations, can only be considered as potential in this case, since in this unit low runoff was produced resulting in a low transport distance.

3.3. Gully erosion

Gullies were studied in areas up to about 150 ha. The gully growth rate is the result of complex interactions of different processes and factors within a catchment and in the substrate package in which the gullies incise. Therefore, the variability of gully development was very high and varied between 0.07 m and 10 m per year (Table 4). Gullies can be considered as the consequence of rill development, and record the highest growth rates on glacis (Table 5). Gullies on dunes also showed a high activity, while the development on Holocene fillings was lower. Furthermore, observed gullies on Quaternary terraces showed the lowest values. This high level of activity can be explained by the considerable differences in the hydraulic activity of the concentrated flows.

Table 4. Main characteristics of the monitored gullies.
Table modified from Marzolff and Ries (2007).

Gully site	Relief unit	Land use / land cover	Headcut type	Catchment size [ha]	Monitoring [years]	Headcut [m a⁻¹]
Northeast Spain						
Barranco de las Lenas	Holocene filling	abandoned fields/ sparse matorral	rilled-abrupt	21.00	11	0.07
Barranco Rojo	Holocene filling	cereal fields/ young fallow land	abrupt	1.20	4	0.50
Southeast Spain						
Salada 1	Holocene filling	almond plantation	abrupt	90.00	6	0.51
Salada 3	Holocene filling	young fallow land	abrupt	1.70	6	0.25
Salada 4	Holocene filling	cereal fields	abrupt	50.00	6	0.15
Luchena 1	Holocene filling	very sparse matorral	abrupt	0.30	4	0.13
Freila	Holocene filling	rangeland/ abandoned fields	abrupt	5.00	2	0.25
Casablanca	Holocene filling	rangeland	rilled-abrupt	0.70	2	0.17
South Morocco						
Foum eI Hassane	Quaternary terraces	loam terrace with stone pavement	rilled-abrupt	0.75	3	0
Icht	Quaternary terraces	loam terrace	abrupt	~150.00	3	0.31
Burkina Faso						
Gorom-Gorom	Glacis	grazed *Acacia*/ *raddiana*-savannah	abrupt	~100.00	2	9.85
Oursi	Dune	rangeland on dunes	abrupt	0.30	4	3.16

Table 5. Relief ranking based on gully-erosion rates. Ranked are the maximum annual gully growth (R_{max}), the mean annual gully growth (R_{mean}) and the gully growth (Area loss).

Relief unit	R_{max} [m a⁻¹]	R_{mean} [m a⁻¹]	Area loss [m a⁻¹]
Dune	2	2	2
Glacis	1	1	1
Holocene filling	3	3	3
Talus material	-	-	-
Quaternary terraces	4	4	4

4. Discussion

The results highlight that the different relief units showed differences in process dynamics, as a result of their very different landscape histories and different morphological and substrate characteristics.

On the one hand, it is obvious that certain forms of erosion, such as gullies, may be present or absent in certain morphological environments. Those gullies are the result of a process chain and structures linked to the current conditions of land use, climate etc. (Seeger *et al*., 2009; Torri and Poesen, 2014). But their current increase also shows that the history and genesis of certain relief units are decisive for the appearance of gullies. Gully growth intensity depends clearly on the relief unit. Thus, we can confirm the idea that leads to the formation of Erosion Response Units

Although many authors have noted their importance, the contribution of rills to total soil erosion has been intensely discussed for decades (e. g. Auzet *et al*., 1993; Cerdan *et al*., 2002; Nouwakpo *et al.*, 2016b). But their development, dynamics and generation processes are still not understood in their entirety and complexity (e. g. Govers *et al*., 2007; Wirtz *et al*., 2013b). Although often considered as precursor of gullies, rills showed a differentiated behavior on the different relief units: first, rills did not distinguish the relief units so clearly and, second, they also appeared in environments where gullies were not observed, such as the talus material. Within the gully systems, the intensity of erosion processes and sediment transport is very variable and gullies have also proved to be very difficult to quantify in the field (Castillo *et al*. 2012).

Our experiments allowed to identify differences in hydraulic and erosion dynamics between different relief units. In the case of the Quaternary terraces in southern Morocco, a clear difference between susceptibility to erosion and current erosion could be observed. Current erosion is greatly reduced on this unit because of the high infiltration rates. The units most affected by concentrated erosion were glacis and Holocene fillings.

Erosion rates and runoff produced by rainfall simulation experiments were highly variable within relief units. The detailed scale of this type of measurement makes it clear that some well-defined factors govern the generation of runoff and erosion (e. g. Arnáez *et al*., 2007; Cerdà *et al*., 1998; Le Bissonnais *et al*., 2005; Martínez-Murillo *et al*., 2013; Ries *et al*., 2014; Rodrigo Comino *et al.*, 2016). Despite the very small size of the experimental plots (0.28 m^2), it should be noted that rainfall simulation measurements give a very clear idea of process intensities in much larger scales. This confirms the results by Seeger (2007), indicating that the dependence of runoff generation and erosion intensity on individual soil surface characteristics is much more complex than those analyzed by other authors (e. g. Auzet *et al*., 2004; Le Bissonnais *et al*., 2005).

5. Conclusions

Our study provides the following conclusions: 1. Dunes and Holocene fillings are especially prone to splash, interrill erosion and surface runoff. 2. In contrast, glacis are currently incised by rills and gullies. 3. Quaternary loam terraces are the unit with the lowest geomorphodynamic activity.

We conclude that the relief units show very different dominance of erosion processes and process intensities. The differentiation is more significant with increasing scale and complexity of erosion processes: gully growth varies much more between the different units than splash and interrill erosion do. Our results show that a traditional geomorphological mapping including relief unit classification can provide useful information to quantify and understand current erosion processes.

Acknowledgements

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