UNIVERSIDAD DE CÓRDOBA

Análisis y modelización de la contribución de la erosión por cárcavas a la producción de sedimentos en la cuenca del Guadalquivir

Analysis and modelling of gully erosion contribution to sediment production in the Guadalquivir River basin

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TÍTULO DE LA TESIS: ANÁLISIS Y MODELIZACIÓN DE LA CONTRIBUCIÓN DE LA EROSIÓN POR CÁRCAVAS A LA PRODUCCIÓN DE SEDIMENTOS EN LA CUENCA DEL GUADALQUIVIR

DOCTORANDO/A: Antonio Hayas López

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

El Dr. Tom Vanwalleghem, Profesor Titular de la Universidad de Córdoba, y el Dr. Adolfo Peña Acevedo, Profesor Titular de la Universidad de Córdoba, como directores de la tesis doctoral con título: "Análisis y modelización de la contribución de la erosión por cárcavas a la producción de sedimentos en la cuenca del Guadalquivir.", realizada por D. Antonio Hayas López,

INFORMA que:

Los principales objetivos de esta tesis han sido la caracterización de la dinámica de la erosión por cárcavas en una zona representativa de la Campiña del Guadalquivir, la caracterización de los umbrales topográficos para la iniciación de cárcavas y la cuantificación del proceso de ensanchamiento de las mismas.
Los resultados de la tesis son de interés para la gestión del agua y del medio ambiente en la cuenca del Guadalquivir, y por extrapolación a otras zonas mediterráneas que sufren el problema de la erosión por cárcavas.
El doctorando ha realizado un excelente trabajo, cumpliendo con satisfacción todos los objetivos propuestos en su plan de formación. De esta forma, ha desarrollado ampliamente una capacidad de comunicación y docente. Durante su doctorado, el doctorando ha evolucionado rápidamente y ha demostrado su capacidad para poder trabajar en grupo y de forma individual.
De la tesis doctoral derivan las siguientes publicaciones:

1. Hayas, A., Vanwalleghem, T., Laguna, A., Peña, A., Giráldez, J.V., 2017. Reconstructing long-term gully dynamics in Mediterranean agricultural areas. Hydrol. Earth Syst. Sci. 21, 235-249, doi:10.5194/hess-235-2017

2. Hayas, A., Poesen, J., Vanwalleghem, T., 2017. Rainfall and Vegetation Effects on Temporal Variation of Topographic Thresholds for Gully Initiation in Mediterranean Cropland and Olive Groves. Land degradation and development 28: 2540–2552. doi: 10.1002/ldr.2805

3. Hayas, A., Peña, A., Vanwalleghem, T., Accepted. Predicting gully width and widening rates from upstream contribution area and rainfall: a case study in SW Spain. Geomorphology.

Aportaciones en congresos

Vanwalleghem T., Hayas A., Román A., Hervas C., Laguna A., Peña A., Giráldez JV., 2014. Evaluating long-term gully dynamics by data fusion from field measurements, photogrammetry and modelling. Geophysical Research Abstracts Vol. 16, EGU2014-15366, EGU General Assembly 2014, 27 April – 2 May, Vienna Austria.

Hayas, A., Vanwalleghem, T., Giráldez, J.V., Laguna, A., Peña, A., 2015. Quantifying gully erosion contribution from morphodynamic analysis of historical aerial photographs in a large catchment SW Spain. Geophysical Research Abstracts Vol. 17, EGU2015-798, 2015, EGU General Assembly 2015, 12-17 April, Vienna, Austria.

Hayas, A., Vanwalleghem, T., Poesen, J., 2016. Evaluating time dynamics of topographic threshold relations for gully initiation. Geophysical Research Abstracts Vol. 18, EGU2016-16185, 2016, EGU General Assembly 2016, 17-22 April, Vienna, Austria.

Hayas, A., Vanwalleghem, T., Giráldez, J.V., Laguna, A., Guzmán, G., Peña, A., 2015. Análisis de la dinámica de la erosión en cárcavas mediante fotointerpretación y modelos hidrológicos. IV Jornadas de Ingeniería del Agua, La precipitación y los procesos erosivos. 21- 22 Octubre 2015, Cordoba. Spain

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 15 de mayo de 2019

Firma del/de los director/es

Fdo. Tom Vanwalleghem Fdo.: Adolfo Peña Acevedo

A mi familia.

A los compañeros de viaje.

A las amistades del camino.

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No quiero dejar pasar esta oportunidad para agradecer profundamente su colaboración a todos aquellos que han participado en la realización de este trabajo. Empezando por el Profesor Tom Vanwalleghem, sin cuya inestimable guía, entusiasmo, dedicación y ayuda esta tesis no hubiese sido posible. Al Profesor Adolfo Peña por su apoyo, sus observaciones y consejos, gracias a los cuales, los artículos que han sido fruto de esta tesis han mejorado notablemente. Al Profesor Juan Vicente Giráldez por poner a disposición de esta tesis su conocimiento y experiencia. A la Profesora Ana Laguna por todas las gestiones necesarias, sus observaciones y la exhaustividad con la que contribuyó a las revisiones. Y por último, pero no por ello menos importante, al Profesor Jean Poesen por haberme acogido de la mejor manera y, haber hecho de mi estancia en la KU Leuven una experiencia de lo más enriquecedora y fructífera. También por las magníficas discusiones mantenidas, siempre ilustradas por su larga experiencia en los procesos erosivos y por un abundante reguero de anécdotas.

RESUMEN

La erosión por cárcavas es un proceso de degradación del suelo que afecta gravemente a muchas regiones. Estos procesos causan importantes impactos tanto *in-situ* como *ex-situ*. A diferencia de lo que ocurre con otros procesos de erosión, como son la erosión laminar y la erosión por regueros, para la erosión por cárcavas no hay desarrollados en la actualidad modelos ampliamente aceptados. Sin embargo, distintos autores han demostrado que la contribución de las cárcavas a la producción total de sedimentos puede superar con creces la del resto de procesos en determinadas regiones, como ocurre por ejemplo en la cuenca del Mediterráneo.

En esta tesis se ha analizado una cuenca de la Campiña representativa de las zonas más afectadas por la erosión por cárcavas en la Cuenca del Río Guadalquivir. Mediante técnicas de fotointerpretación de imágenes aéreas, se analizó la dinámica de la red de cárcavas en un periodo de 57 años. Para ello se utilizó una secuencia de 10 ortofotos del periodo comprendido entre 1956 y 2013, con el apoyo de datos de campo. Por último, se avanzó en la modelización de las cabeceras de las cárcavas y del ensanchamiento de las mismas a través de relaciones con el área de contribución, y con índices de precipitación.

Los resultados obtenidos mostraron que las tasas de erosión durante el periodo de estudio fueron muy variables, siendo de 39 t ha^{-1} $año^{-1}$ el valor medio para el conjunto del periodo y 591 t ha^{-1} $año^{-1}$ el máximo obtenido. Por otro lado, se demostró que los umbrales topográficos para la formación de cabeceras pueden variar notablemente a lo largo del tiempo en un mismo área. Por último, se determinó que existe una correlación significativa entre la tasa de ensanchamiento de las cárcavas y el área de contribución aguas arriba. Tanto los umbrales topográficos como las tasas de ensanchamiento pudieron correlacionarse con índices de precipitación. Mientras que, los distintos usos del suelo presentes en la zona de estudio, resultaron poco relevantes para la modelización de los crecimientos en cabecera y en anchura.

ABSTRACT

Gully erosion is widely recognised as an important soil degradation process in many regions, causing important on-site (e.g. soil losses, environmental degradation, crop losses...) and off-site effects (e.g. muddy floods, water pollution, reservoir siltation...). In contrast to other erosion processes, as for instance sheet and rill erosion, where models have been successfully developed and tested extensively over the world, no widely accepted model exists for gully erosion. The reasons for this are the varied and complex subprocesses involved in gully erosion, the factors that control it and, its dependence on the spatial and temporal scale of study. Notwithstanding the above, gully erosion has been proved to be the major erosion process contributing to the total sediment yield in various regions, especially in the Mediterranean Region. This is particularly the case of the Guadalquivir River Basin, where the lithology added to the topography and the climate condition make of it a gully prone area. At present, very little information is available on gully processes and dynamics in this area.

In this thesis, a complex gully network with a contributing area of 20 km^2 was selected as a representative case of the gully prone agricultural landscape of the Campiña of the Guadalquivir River Basin, which land use consists mainly of herbaceous crops and olive groves on Vertisols developed over soft parent material (marls and calcareous sandstone). The dynamics of the gully network was study over a period of 57 years by a combination of photointerpretation techniques in a GIS, field surveys and probabilistic approaches. Gully network evolution was derived from a dataset of 10 aerial orthophotos from the period 1956 to 2013. Field data and a Monte Carlo approach were then applied to estimate gully erosion rates dynamics over the study period. Modelling of gully erosion was then assessed by means of the study of the topographic thresholds for gully head initiation and by means of the gully widening rates dynamics.

The results showed that gully erosion rate in the study area was 39 ton/ha/year on average, with peaks up to 591 ton/ha/year. However, these gully erosion rates were highly variable over the study period, and therefore the estimation through average values should be taking with caution. The variability on the gully erosion rates obtained highlights the importance of appropriately selecting the time scale on which gully erosion processes are assessed. For the first time, an important temporal variability in the topographic thresholds (TT) values for a given study area was demonstrated. In addition, this TT variability could be correlated to rainfall regime through various rainfall indexes, as for instance the Rainy Day Normal (RDN). A significant correlation between the gully widening rates and the runoff contributing area were found. Variability in gully widening rates were related to a rainfall index expressing the number of days exceeding a threshold rainfall depth of 13 mm. Land use present in the study area (herbaceous crops and olive groves) showed no significant effects on the TT and the widening rates.

Table of contents

Chapter 1

General Introduction and Objectives

1. General introduction and Objectives

Soil and gully erosion

Soil erosion is a geomorphological process that occurs naturally all over the world at different rates. However, whenever that soil erosion rates exceed soil formation rates it results in soil degradation. This degradation process is well known to have been accelerated due to human intervention in the landscape (Vanwalleghem, 2017). On the one hand, land use changes have been long recognized as a key factor in the increment of soil loss rates in different environments. On the other hand, land management itself, mainly through intensification, has resulted in a further increase of soil loss rates under different crop types (Vanwalleghem *et al.*, 2017).

Soil erosion by water accounts for more than 50% of the total human-induced soil degradation according to the estimations made by Oldeman *et al.* (1991). Soil erosion by water consist in the detachment and transportation of soil materials by erosive rainfalls and runoff (Foster and Meyer, 1972). It is considered as a major process of soil degradation worldwide with potentially significant environmental and economic impacts both *in-situ* (loss of ecosystem services of soils threatening long-term sustainability of agricultural production, environmental degradation, increasing poverty…) and *ex-situ* (muddy floods, surface water pollution, reservoir siltation...). Forms of soil erosion by water include sheet, rill, ephemeral gully, classical gully and streambank erosion. Each succeeding type is associated with the progressive concentration of runoff water into channels as it moves downslope.

Definition of soil erosion terms

A significant barrier to gully erosion studies is the confusing nomenclature employed to define a gully and its geomorphic position within a landscape (Bennett and Wells, 2019).

Among the reasons of this confusion are the different uses and perceptions of the terms gully, ephemeral, classical and permanent gully that agricultural and geomorphic communities employ. In a recent review, Castillo and Gómez (2016) summarized the different criteria that are most frequently used to define gullies: a) morphological and topographical criteria: relatively deep-walled, poorly vegetated incisions in the landscape with a catchment area of 10 km^2 or less in Eustace *et al.* (2011); b) hydrological criteria: water courses that are subjected to ephemeral flash floods during rainstorms (e.g. Morgan, 2005); c) allowance of agricultural practices: stream channels whose width and depth do not allow normal tillage (SSSA, 2015); and d) instability: recently formed incision within a valley where no well-defined channel previously existed, in Bettis and Thompson (1985).

Hereafter, on behalf of the proper interpretation of the terms used in the text, the next definitions will apply throughout this work:

- Sheet or interrill erosion: is the removal of a relatively uniform thin layer of soil from the land surface by rainfall and largely unchanneled surface runoff (sheet flow) (Soil Science Society of America, 2008).
- Rill erosion: is an erosion process on sloping fields in which numerous and randomly occurring small channels of only several centimetres in depth are formed; occurs mainly on recently cultivated soils (Soil Science Society of America, 2008). Usually do not re-occur in the same place.
- Gully: erosional channel caused by intermittent concentrated water flow usually during and immediately after a heavy rainfall event (Soil Science Society of America, 2008) (Figure 1-1).
- Ephemeral gully: small channels eroded by concentrated flow that can be easily filled by normal tillage, only to reform again in the same location by additional runoff events (Soil Science Society of America, 2008). Once removed by tillage, will reform in the same location by subsequent runoff events.
- Classical or permanent gully: erosional channel typically deep enough (>0.5 m) to interfere with normal tillage operations (Foster, 1996; Poesen *et al.*, 2003).

- Bank gully: gully developed wherever concentrated runoff crosses an earth bank (e.g. river bank, terrace bank, sunken lane bank, lynchet or quarry bank) (Poesen *et al.*, 2006).

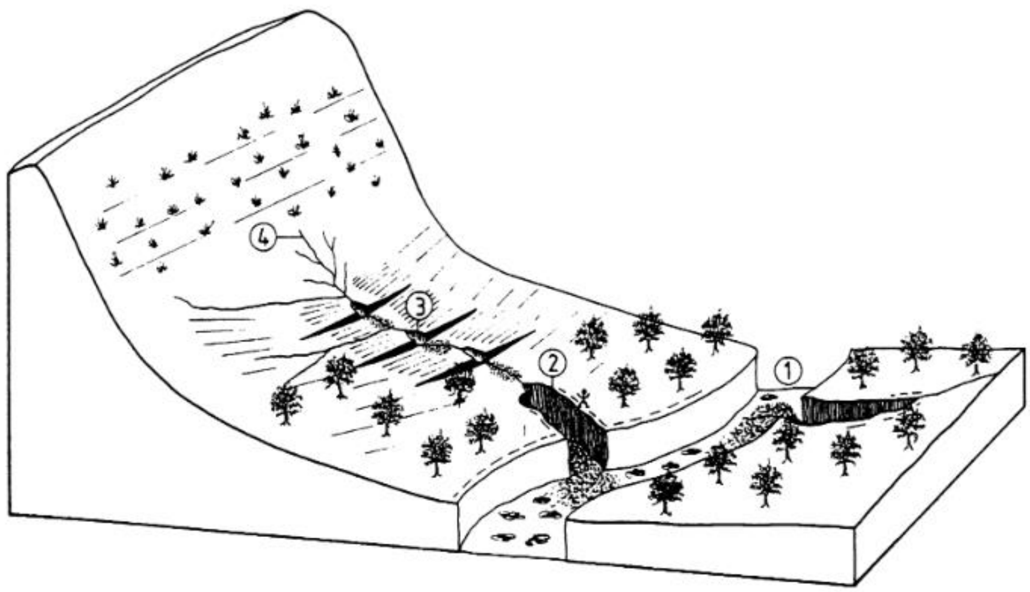

Figure 1-1. Mean gully forms in a Mediterranean landscape. 1) River channel; 2) Bank gully in a river; 3) Bank gully in a terrace; 4) Classical gullies (from Poesen et al., 2003).

GULLY RELEVANCE AND MODELLING DIFFICULTIES

Gully erosion remains a global driver of soil and landscape degradation. While gullies may not be present in all hillslopes, when they do occur, gullies tend to be the dominant contributor to soil loss and sediment production (Poesen *et al.*, 2003; Wu *et al.*, 2018). Soil losses attributed to ephemeral gully erosion can range from 10 to 97% of total soil losses (Bennett *et al.*, 2000; Poesen *et al.*, 2003; Capra, 2013). Rates of soil loss due to permanent gullies significantly exceed losses by sheet and rill erosion observed in agricultural areas, which can be the leading cause of landscape degradation worldwide (Castillo and Gómez, 2016; Ayele *et al.*, 2018).

Based on the scientific production over the last century, gully erosion research could be considered at a stage of maturity (Castillo and Gómez, 2016). These authors found that gully erosion research presented at least 10% of the total soil erosion research. In the last few decades soil scientists, geomorphologists and environmentalists, as wells as farmers and policy-makers have paid increasingly more attention to gully erosion. This has in turn resulted in an increase of the production of gully literature in gully erosion processes, modelling and remediation.

Despite all of these huge efforts, we still do not have a complete understanding of gully erosion processes. In contrast with other water erosion forms, as for instance sheet and rill erosion, for whom prediction models having successfully developed and tested (e.g. RUSLE, Renard *et al.*, 2011), no reliable methods exist for predicting the rate of ephemeral gully or classical gully erosion. While estimations have been made of soil loss by sheet and rill erosion at regional (Panagos *et al.*, 2015) and global scales (Borrelli *et al.*, 2017), there is still no quantification available of gully erosion at broad, regional or national scales.

The absence of reliable models widely suitable for gully erosion has been attributed to various reasons. On one hand, the long-recognised complexity of the erosional processes involved in gully erosion (e.g. piping, headcut retreat, mass wasting, slab failure, temporal and space dependency, etc). On the other hand, several authors have pointed out the need for:

- Establishing appropriate and standardized monitoring techniques enabling the study of gully development with higher precision (Poesen *et al.*, 2003).
- Misleading nomenclature employed to define gullies (Bennett and Wells, 2019).
- Need for additional data (Vanmaercke *et al.*, 2016). Longer data series with consistent survey frequency (Castillo and Gómez, 2016).

GULLY EROSION PROCESSES

Gully initiation and development is generally the result of multiple episodes of channel erosion. At the first stage of initiation, it is a condition that surface or subsurface runoff concentrates in small depressions that would then coalesce to form an initial channel. Afterwards, is necessary that the concentrated flow intensity exceeds the soil resistance to detach and transport topsoil material, creating near-vertical scarps that would be the initial headwalls. Eventually, the headwalls are undermined by concentrated scouring, caused by the dissipation of kinetic flow energy of the dropping water at the base, until the channel section reaches or exceeds the square foot criterion.

Several processes have been identified and described related to the gully channel expansion once the channel is formed (Bull and Kirkby, 1997; Collison, 2001; Poesen *et al.*, 2002; Istanbulluoglu *et al.*, 2005; Kirkby and Bracken, 2009). These processes take place alone or in diverse combinations where each of them plays different roles. The most cited processes in the gully development includes: piping, headcut migration, undercutting by plunge pool erosion, tension cracking, mass failure, fluting and channel bifurcation.

- Piping consists in the removal of subsurface soils by subsurface flow in soil pipes to a free or escape exit (Masannat, 1980). Pipes formation and development are controlled by the interaction among climate conditions, soil/regolith characteristics and local hydraulic conditions (Bull and Kirkby, 2002).
- The dissipation of kinetic of flow energy of the flowing water at the drop causes excessive erosion and results in headcut (nearly-vertical drop in channel-bed elevation) upstream migration, which deepens and tends to widen the channel.
- Undercutting by plunge pool erosion is consequence of falling water at the base of vertical 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 (Poesen *et al.*, 2002).
- Tension crack development causes slab failures (Bradford and Piest, 1977). Gully head and gully wall collapse are a composite and cyclical process resulting from downslope creep, tension crack development, crack saturation by overland flow, head or wall collapse followed by debris erosion which facilitates the next failure (Collison, 1996, 2001).
- Mass failure of homogeneous, cohesive gully banks can take place either as continuous failure over long period or as catastrophic shear failure of the bank

(Alonso and Combs, 1990). The later 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) or an increase in the stress due to saturation or human activities (Poesen *et al.*, 2002).

- Fluting at headwalls and on gully banks is mainly caused by differential erosion between ridges and depressions. The resultant flutes are vertically elongated grooves, generally tapering toward the top that furrows into the gully wall. Fluting can result in pronounced gully wall retreat.
- Gully channel bifurcation is a process of lateral budding that extends the gully head or along a gully channel (Bull and Kirkby, 1997). It is considered the most frequent mode of gully branching.

GULLY CONTROLLING FACTORS

Gullying has been defined as a threshold-dependent process controlled by a wide range of factors (Poesen *et al.*, 2003; Valentin *et al.*, 2005). Vanmaercke *et al.* (2016) distinguished between factors reflecting the erosive forces in the gullying (e.g. upstream area draining to the gully, shape of the drainage area, weather and climate conditions, land cover and soil characteristics, and topography) and factors reflecting the resisting forces (e.g. mainly vegetation and soil properties). The first are related, in one way or another, with the generation of runoff and flow intensity, whereas the latter ones are related with the cohesion of the eroding material. Vegetation cover reduces the gully erosion rates by increasing the cohesion of the soil (e.g. Stokes *et al.*, 2007; De Baets *et al.*, 2008) and by increasing the hydraulic roughness, therefore reducing the flow velocity. Soil properties, in this case, mainly refer to soil cohesion, which in turns depends on various parameters including soil texture, organic matter content and chemical properties that prevent or promote dispersion of soil aggregates (e.g. Sanchis *et al.*, 2008).

Likewise, for its part, the most widely studied gully thresholds around the world are the topographic and rainfall thresholds (Capra, 2013). Topographic thresholds are based on the dependency relationship between the kinetic energy of the concentrated flow with the runoff and slope. Considering that the drainage area can be used as a surrogate for runoff volume, a critical drainage area (A) is necessary for a given slope (S) to produce sufficient runoff to concentrate and initiate gulling. Thresholds lines for gully development by hydraulic erosion are usually expressed by a power-type equation (Begin and Schumm, 1979; Vandaele *et al.*, 1996): $S = a \cdot A^{-b}$ with a and b coefficients depending on the environmental characteristics. In the absence of detailed process-based models for gully erosion, this simplified threshold relation has been widely applied in different environments (Torri and Poesen, 2014).

On the other hand, rainfall height and intensity are widely used as rainfall thresholds as they are direct correlated with the flow shear stress. Threshold rains from 14.5 to 22 mm have been described for ephemeral gully formation on cropland over loamy or clay soils in various study areas (Poesen *et al.*, 2003). However, information on threshold rains are usually restricted to small areas and examined over short time periods. In addition to the rainfall height and intensity, rainfall erosivity indices have been used to show the influence of rainfall in erosion processes, as for instance the rainfall erosivity (R-factor) proposed by Wischmeier and Smith (1978) for sheet and rill erosion.

SOIL LOSS RATES BY GULLY EROSION AND SCALE DEPENDENCIES

The spatial scale

It is well demonstrated that when scaling up area-specific soil loss rates, the latter do not remain constant but vary in a strongly non-linear way with the size of the area considered. Area-specific soil loss rates may suddenly increase one order of magnitude once a critical area (corresponding to the topographic threshold value need for gully development) has been exceeded (Poesen *et al.*, 1996; Osterkamp and Toy, 1997; Poesen *et al.*, 2003; Marzolff *et al.*, 2011). Osterkamp and Toy (1997) clearly illustrate the importance of spatial scale when it comes to the assessment of the contribution of soil loss rate by gully to sediment yield, showing that once the study areas considered exceed a critical value ranging between 1 and 10 ha (Figure 1-2), gully erosion becomes very important and even becomes the dominant sediment producing process. This was conceptualized by de Vente and Poesen (2005) and they link these processes to river catchments, where generally a negative relation between area-specific sediment yield and catchment area is observed.

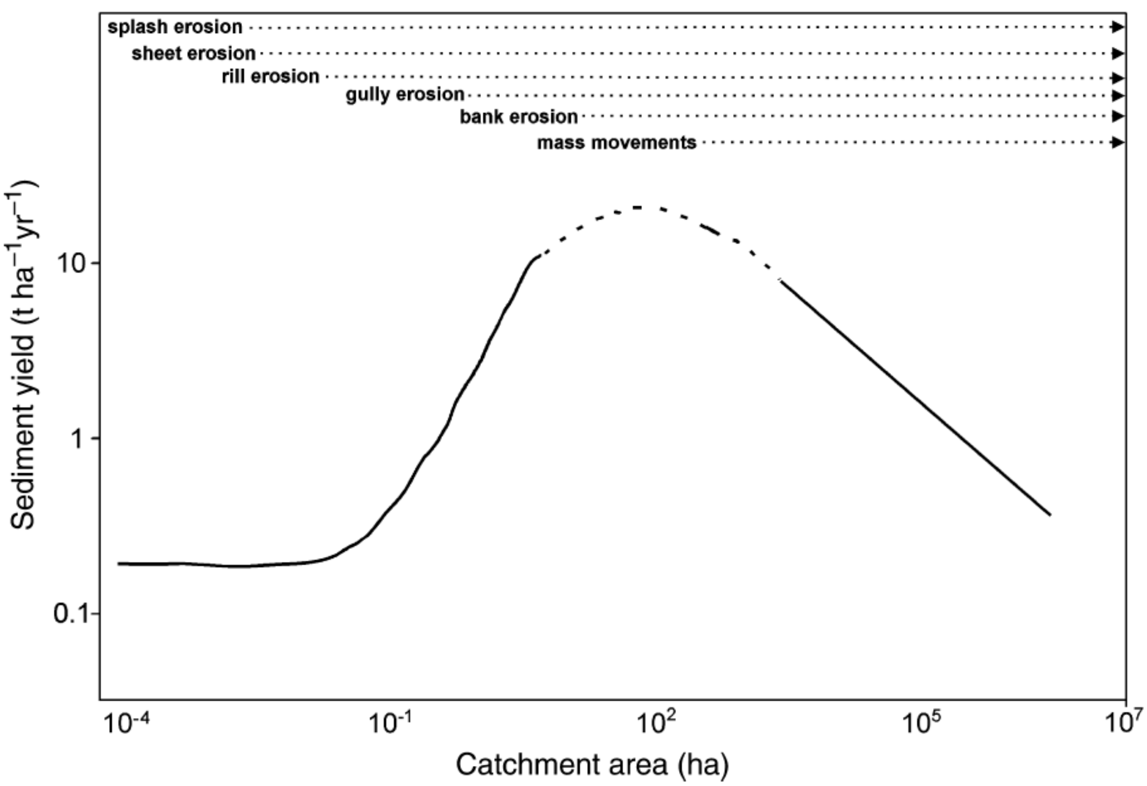

Figure 1-2. Relationship between catchment area and area-specific sediment yield (SSY) for Spain. Dominant erosion processes for each spatial scale is indicated as well (From de Vente and Poesen, 2005).

The temporal scale

Gullies may be subjected to rapid cycles of alternating incision and infilling, and material eroded at the gully edges may be deposited within the gully, not even leaving the system during the same observation period (Vanwalleghem *et al.*, 2005; Marzolff and Poesen, 2009). Also, as seen above, gullying involves a wide range of subprocesses related to water erosion and mass movements, such as headcut retreat, piping, fluting, tension-crack development and mass wasting, and it is the complex interaction of these subprocess on varying time scales which complicates reliable measurements as well as forecasting by gully erosion models. Marzolff *et al.* (2011) investigated how medium-term gully development data differ from short-term data at nine selected retreating bank gullies located in Spain. They confirmed that short-term data are not representative of longer-term gully development, and indicated that short-term data is better correlated with rare rainfall events, sudden land use changes, management operations and human activity.

GULLY EROSION IN THE CAMPIÑA OF GUADALQUIVIR

The Mediterranean area (Spain, Morocco, Tunisia, Italy, Iran and Israel) accounts for many of the gully research documented (Castillo and Gómez, 2016) until present. This is particularly the case of the south of Spain, where gullies are prominent features in the landscape, and a large number of studies resulting from a long tradition of research in soil erosion (e.g. Bennett, 1960; Garcia-Ruiz *et al.*, 1991; Oostwoud Wijdenes *et al.*, 2000; Verstraeten *et al.*, 2003; Marzolff *et al.*, 2011) have shown that gully erosion plays an important role on the Iberian Peninsula. The semi-arid climate prevailing in Spanish agricultural regions, the high soil erodibility and a long history of land use and land use changes are among the key factors controlling soil erosion processes in Spain (Thornes, 1976; Poesen and Hooke, 1997; Marzolff *et al.*, 2011).

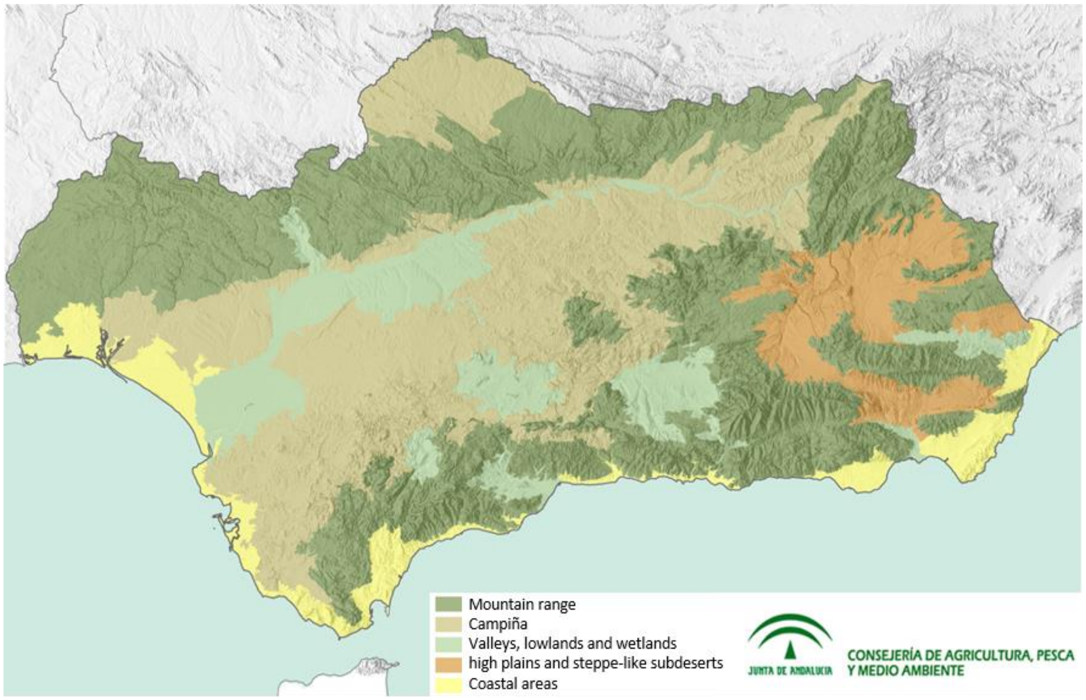

Figure 1-3. Main landscape unit in Andalusia including the domain of the Campiña (source: Junta de Andalucía, 2012).

Gully erosion has been repeatedly recognized as a serious threat for agricultural soils in the Guadalquivir River basin by scientists and government administrators (Vanwalleghem *et al.*, 2011; Taguas *et al.*, 2015b; Inventario Nacional de Erosión de Suelos, 2001). In particular, the domain of the Campiña (Figure 1-3) has been identified as an area particularly prone to gully erosion due to the erodibility of its soils, its land use, its climate and its topography. The so-called "Campiña" landscape is the area of rolling hills comprised mainly between the Sierra Morena to the north and the Baetic Mountains to the south. It is comprised of a deep post-alpine depression filled with Tertiary and Quaternary sediments, making up deep soils in which large gullies can form. Among the land uses prevailing in the area the most susceptible to gully erosion are those covered by herbaceous crops and by olive groves, which suppose 18.5% and 16.2% respectively in Andalusia. This is evidenced by various researches made focused on gully erosion on these two land use classes (Gomez *et al.*, 2009; Castillo *et al.*, 2013; Taguas *et al.*, 2015a, 2015b). Governmental programmes aimed to the prevention and control of soil degradation are mostly focussed on sheet and rill erosion, as there is very little information on gully erosion. Only one specific government programme was directed towards gully erosion control in 2010 (BOJA nº 216 de 2010) , but this was discontinued due to lack of financing. Recently, other initiatives have arisen as for instance an Operative group was established to study the phenomenon and a FEDER founded project (INNOLIVAR) are tackling with the gully erosion control with the support of the Environmental Ministry and the Olive Producers Commitment.

MONITORING OF GULLY DYNAMICS AT MEDIUM-TERM TIME SCALES

As mentioned above, temporal scale is a key issue in the understanding of the relevance of gully erosion in soil erosion processes. However, different reasons have motivated that only a few study sites have been subject to detailed monitoring for a period long enough in order to understand the involved complexity and variability. In this context, aerial photograph collections generated from the second half of the twentieth century in several parts of the world suppose an excellent opportunity to face this problem. Some studies exist that have proved the utility of historical aerial photographs as a source of information for medium-term gully monitoring in different parts of the world (e.g. Martınez-Casasnovas, 2003; Saxton *et al.*, 2012; Frankl *et al.*, 2012, 2013). At present, no such study has been done for the Guadalquivir basin.

RESEARCH OBJECTIVES AND THESIS STRUCTURE

As a result of the foregoing, it can be deduced that an urgent need exists to improve our knowledge of gully processes and gully dynamics in the Campiña of Guadalquivir River. This is particularly the case for the olive groves since there has been a significant shift to this land use type in the last century in this region (more than 178.000 ha from 1956 to 2015 in Andalusia). At the same time, the degree of the technical development of the photointerpretation of aerial orthophotos by means of their integration in a GIS, convert them into an excellent tool to address medium-term gully dynamics. Therefore, the main objective of the present work is to analyse and model gully erosion in the Guadalquivir River Basin, by means of a case study of a representative area prone to gully erosion in the Campiña of Guadalquivir. This will be achieved through a medium-term study of the dynamics of complex gully network and its relationship with the land use and the rainfalls recorded. More specifically, the objectives of this work are:

1. Quantify the erosion and infilling dynamics of a gully network in a typical agricultural area of southwestern Spain from historical air photos between 1956 and 2013.
2. Quantify the temporal variation of topographic thresholds for gully initiation in Mediterranean croplands reflecting the variability of rainfall, land use and vegetation cover.
3. To design a simple method to predict gully width and its increase over time as a function of upstream contributing area, rainfall and land use.

The structure of this PhD thesis is detailed below in Figure 1-4, and the following chapter address each of these three specific objectives consecutively.

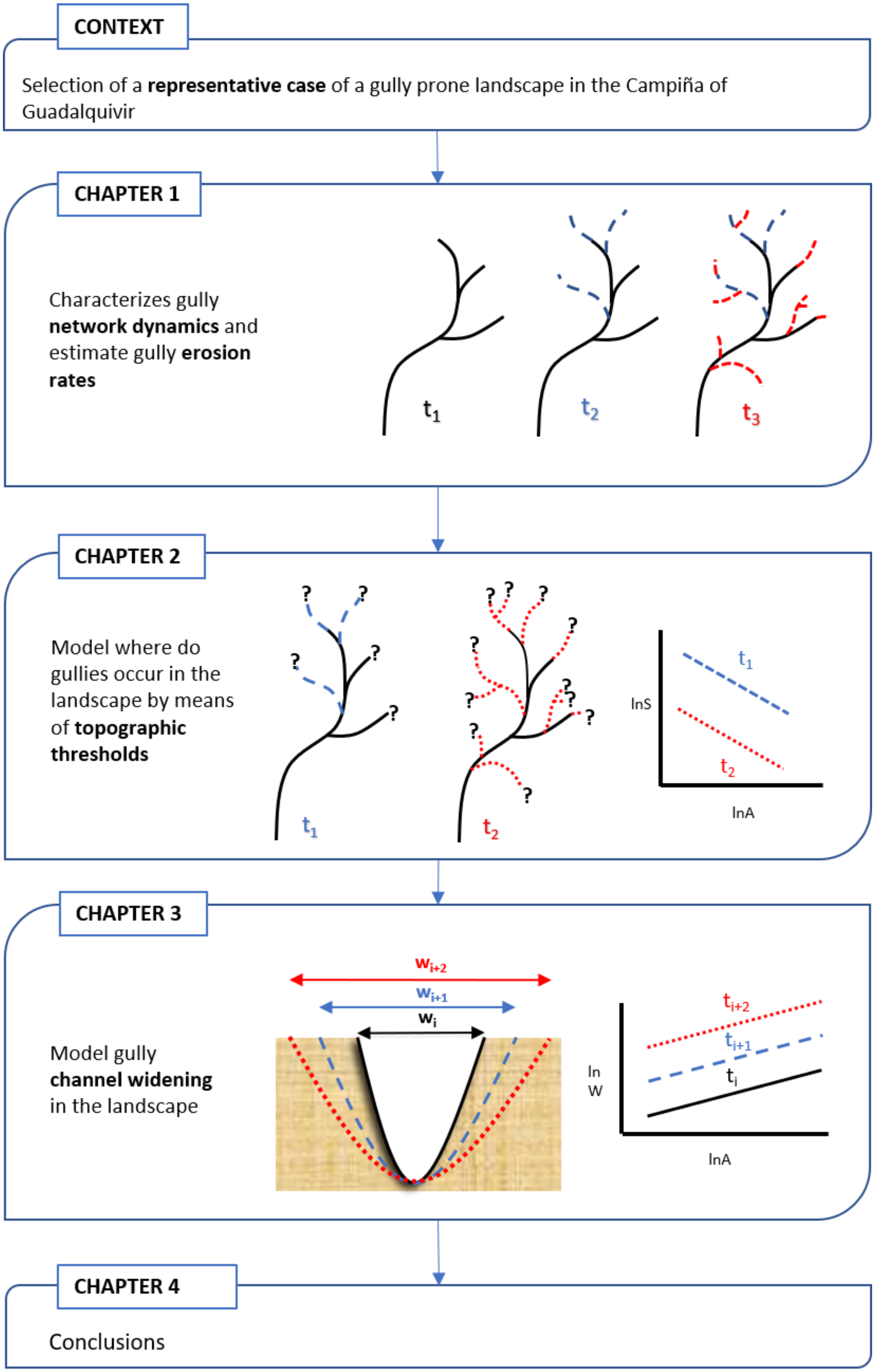

Figure 1-4. Structure of the thesis.

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Chapter 2

Reconstructing long-term gully dynamics in Mediterranean agricultural areas

2. RECONSTRUCTING LONG-TERM GULLY DYNAMICS IN MEDITERRANEAN AGRICULTURAL AREAS

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ABSTRACT

Gully erosion is an important erosive process in Mediterranean basins. However, the long-term dynamics of gully networks and the variations in sediment production in gullies are not well known. Available studies are often conducted only over a few years, while many gully networks form, grow, and change in response to environmental and land use or management changes over a long period. In order to clarify the effect of these changes, it is important to analyze the evolution of the gully network with a high temporal resolution. This study aims at analyzing gully morphodynamics over a long time scale (1956-2013) in a large Mediterranean area in order to quantify gully erosion processes and their contribution to overall sediment dynamics.

A gully network of 20 km^2 located in SW Spain, has been analysed using a sequence of 10 aerial photographs in the period 1956-2013. The extension of the gully network both increased and decreased in the study period. Gully drainage density varied between 1.93 km km^{-2} in 1956, a minimum of 1.37 km km^{-2} in 1980, and a maximum of 5.40 km km^{-2} in 2013. The main controlling factor of gully activity appeared to be rainfall. Land use changes were found to have only a secondary effect. A new Monte Carlo-based approach was proposed to reconstruct gully erosion rates from orthophotos. Gully erosion rates were found to be relatively stable between 1956 and 2009, with a mean value of 11.2 t $ha^{-1} yr^{-1}$. In the period 2009-2011, characterized by severe winter rainfalls, this value increased significantly to 591 t $ha^{-1} yr^{-1}$. These results show that gully erosion rates are highly variable and that a simple interpolation between the starting and ending date greatly underestimate gully contribution during certain years, such as, for example, between 2009 and 2011. This illustrates the importance of the methodology applied using a high temporal resolution of orthophotos.

Key words: gully initiation; drainage area; slope gradient; land use; herbaceous crops; olive groves

INTRODUCTION

Understanding gully erosion dynamics under changing land use and climate conditions is essential for soil and water conservation. Erosion is one of the most significant threats to soils and sustainable agriculture worldwide (Amundson *et al.*, 2015). To satisfy long-term food production and food safety, soil erosion rates should be drastically reduced to the level of soil formation rates. Additionally, sediment dispersion induces environmental pollution, with severe downstream problems for infrastructure. Soil erosion is a major factor in the anthropogenic perturbation of the global carbon cycle (Regnier *et al.*, 2013). Given its importance, much research effort has gone into characterizing and modelling erosion rates in order to identify key problem areas and propose management solutions. Recently, a European-wide effort was conducted to improve the quantification of water erosion either with RUSLE (Panagos *et al.*, 2015), or with similar models (Quinton *et al.*, 2010; Van Oost *et al.*, 2007). Nevertheless, such models represent a minor part of the water erosion processes by not considering the contribution of gullies. Poesen *et al.* (2002) concluded that gully erosion could be the source of up to 83% of sediment yield in Mediterranean areas. Recent efforts to measure gullies in detail confirm these numbers. For instance Castillo (2012) estimated the range of gully erosion rates in a set of cultivated catchments in Cordoba as being 37 to 250 t $ha^{-1} yr^{-1}$.

Most erosion models for gully erosion focus on modelling headcut growth. Examples are REGEM and its adaptation TIEGEM, both used in the model Annualized AGricultural Non-Point Source (AnnAGNPS; Gordon *et al.*, 2007; Taguas *et al.*, 2012), CHILD (Flores-Cervantes *et al.*, 2006; Campo-Bescós *et al.*, 2013) or the headcut growth model by Rengers and Tucker (2014). Kirkby and Bracken (2009) presented an areal gully growth model that showed how the ratio of channel versus sidewall processes is a key determinant in its evolution. In contrast, Dabney *et al.* (2015) modeled gully erosion rates by shear stress by inserting a new Ephemeral Gully Erosion Estimator (EphGEE), included in a new version of RUSLE2, in a small agricultural watershed in Iowa. More mathematically based models seek general laws controlling areal gully growth and ramification (*e.g.* Devauchelle *et al.*

2012). In general however, there is an important lack in suitable field data for understanding and modelling long-term gully evolution.

Different methodologies, apart from traditional field measurements with total station, laser profilemeters and poles (Castillo *et al.*, 2012), have been proposed and successfully applied to estimate gully volumes. For instance, at the individual gully scale, 3D reconstruction from high resolution aerial photography and digital photogrammetry has been widely applied (e.g. Marzolff and Poesen, 2009). Recently, terrestrial imagery modelling and Structure from Motion - Multi View Stereo (SfM - MVS) procedures have been used to determine gully volumes (Gómez-Gutiérrez *et al.* 2014; Frankl *et al.*, 2015 and Castillo *et al.*, 2015). Terrestrial LiDAR has been applied to measure rills or gullies at both laboratory and plot scale (Vinci *et al.*,2016; Momm *et al.*, 2011, 2012). Nevertheless, at the catchment scale, the number of studies is limited. At this scale, most studies focus on the areal extension of gully networks, using aerial photos or other remotely sensed imagery. Few studies report gully volumes due to the inherent difficulties of determining depths for the whole gully network. Nachtergaele and Poesen (1999) determined gully length from aerial photos and, by using additional field measurements, they established a mean cross section to calculate volumes of small ephemeral gullies in the Belgian loess belt. Martínez-Casasnovas (2000) mapped and quantified the erosion produced in gully systems of big dimensions by processing multitemporal orthophotograms and DEMs in a GIS for a 25 km^2 catchment located in NE Spain. Frankl *et al.* (2011) used sequential photographs to link long-term gully and river dynamics to environmental change in Northern Ethiopia. More recently, Peter *et al.* (2014) used UAVs and photogrammetric analysis to quantify gully erosion, albeit at a local scale in the Souss Basin (Morocco).

Due to the recent nature of most of these field studies on gully erosion, their temporal coverage is limited to a few years at best. More recent studies usually focus on one specific moment in time, where the gully system is visited and measured once or during a couple of years. This implies that no dynamic behaviour of the gully system can be described adequately and that it is difficult to single out the controlling processes. Growth of gully systems in the Belgian loess belt was shown by Vanwalleghem *et al.* (2005) to be a highly non-linear process, with a rapid initial growth followed by a stabilization phase. Under different climates, where rainfall is less uniform and much more concentrated, such non-linear gully dynamics can be expected to be accentuated. It could therefore happen that a single measurement of a gully volume that has been growing for several decades does not offer a good estimate of yearly growth rates. Gully growth can be expected to be much greater during specific years compared to the long-term mean. Any model efforts will therefore need experimental data collected with a high temporal resolution.

Over such longer time scales, exceeding several decades, few experimental data are available. Over time scales of up to several centuries, different studies indicate that gully erosion is not a new process. In Northern and Central Europe, gullies have been dated between Early Bronze Age and Late Medieval times (Vanwalleghem *et al.*, 2006). In the Western Mediterranean, with a long history of land use, such historical studies are rare however (Dotterweich, 2013). Over the medium term, of several decades, available studies point to an important dynamic of ephemeral gullies, with erosion phases and infilling ones. These can be due to normal tillage operations for small, ephemeral gullies; deliberately done by farmers in case of larger gullies; or during land use change phases, in which farmers erase such topographic features by tillage, as has been supported by field evidence. Gordon *et al.* (2008) showed by simulations using the REGEM model that those erosion and infilling cycles could produce up to double the amount of sediment as when gullies were left to erode naturally. Each infilling phase prepares sediment for the next important storm event. Field data for this time scale are rare and generally come from the analysis of historical aerial photos. Frankl *et al.* (2013) quantified the evolution of a permanent gully network in Ethiopia using long-term historical aerial photos over the period 1963-2010 for an area of 123 km^2. After an initial stability phase, they identified a peak erosion period in 1994, after which the system stabilized again. These results stress the importance of frequent temporal observations. Saxton *et al.* (2012) analysed multitemporal aerial photographs between 1951 and 2006 to derive historical gully erosion rates in terms of surface growth per year in three catchments in south-east Queensland in Australia. They associated the gully initiation to post-European settlement land use practice and above average rainfall and runoff. Also, Shellberg *et al.* (2016) observed an increase in the gully erosion by the changes in the land use produced by post-European settlement in the Mitchell River fluvial megafan (Queensland, Australia). This relationship between pioneers and gully erosion was previously suggested by Leopold

(1924) in the US. Other methods have been tested, such as using local farmer knowledge on gully morphology (Nyssen *et al.*, 2006; Tebebu *et al.*, 2010) or multi-temporal oblique photography of gully cross sections (Frankl *et al.*, 2011), but the uncertainty in the results is generally too great to allow a quantitative analysis of controlling climate or land use factors.

The objective of this study wass, then, to quantify the erosion and infilling dynamics of a gully network in a typical agricultural area of SW Spain, from historical air photos between 1956 and 2013. A new method is presented that not only allows one to determine the evolution of gully length, but also, by using Monte Carlo analysis to generate gully width and depth, to calculate the volume of gully erosion and infilling and to constrain uncertainty. Moreover, the controls in terms of land use and rainfall variability are analysed and the importance of these results for the regional sediment budget assessed.

MATERIALS AND METHODS

Study site

The study area is located between 37.74 and 37.81 N, 4.36 and 4.43 W, in the West Campiña of the Guadalquivir basin in the SW Spain (Figure 2-1) and comprises an area of 20.6 km^2. The studied gully network drains towards a series of small ephemeral rivers (Arroyo de Garuñana, Arroyo del Cuadrado, Arroyo del Pozo Muerto, Arroyo de las Monjas, and Arroyo del Barranco), which all drain to the Guadajoz, a tributary of the Guadalquivir river. Although the limits between rills, gullies and larger ephemeral river channels are subject to discussion in the scientific community, this ephemeral river network was not included in the analysis, as it is indicated on the topographical maps and assumed to be stable. The observed gullies can be considered to be mostly permanent (Figure 2-2), although some ephemeral ones are included as long as they have a width equal to or higher than the resolution of the orthophotos that were used, ranging between 0.5 and 1.0 m (Table 2-1).

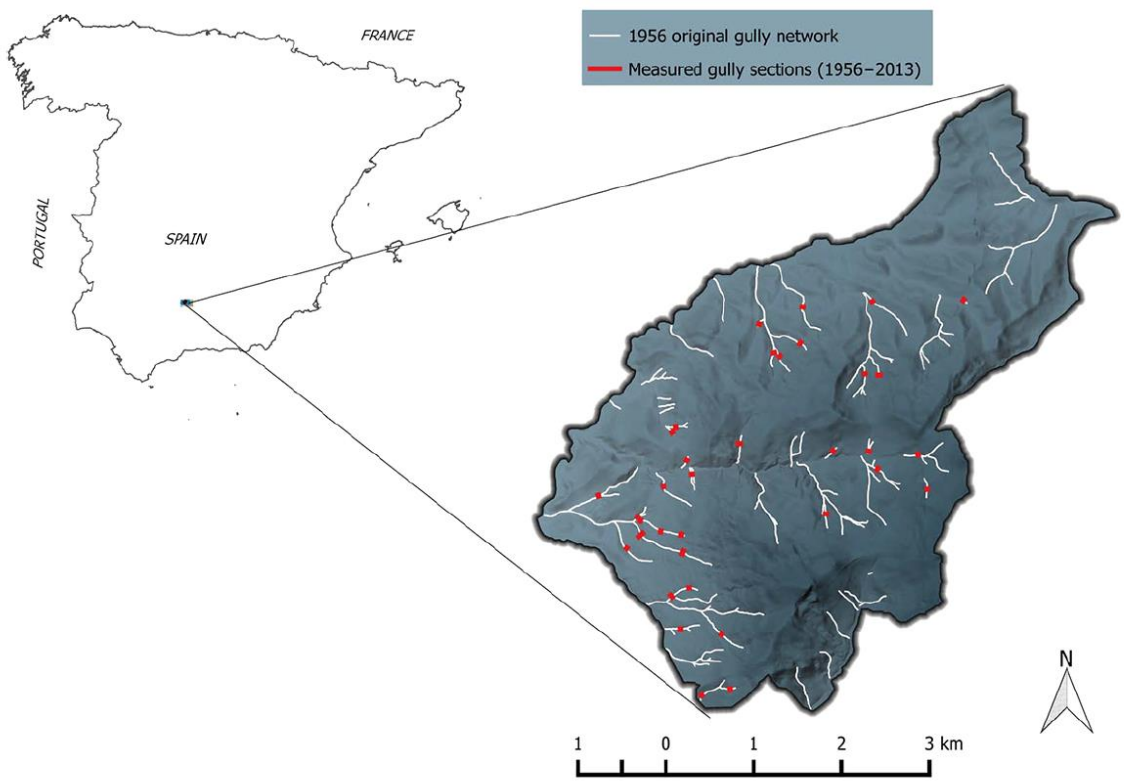

Figure 2-1.Site location with details of the original gully network and measured gully sections.

Table 2-1. Orthophoto dataset properties.

Capture year	1956	1980	1984	1999	2001	2005	2007	2009	2011	2013
Resolution, m	1.0	0.5	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5
Colour	b/w	b/w	b/w	b/w	b/w	col.	col.	col.	col.	col.

b/w: black and white; col.: colour; all restitution scales are 1 : 10 000, except 1980 with scale 1 : 5000.

Gentle hills prevail in the study area except for the south and the center east where steeper ones exist (up to 32%). Altitudes range from 233 to 558 m high and mean slopes are 13%. The soils in the area are dominated by Vertisols, formed mainly in marls and calcareous sandstones deposited during the Miopliocene.

Currently the dominating land uses are olive orchards and herbaceous crops covering almost the whole area, except some 5% of the surface area occupied by grassland. Mean annual precipitation varies between 500 and 600 mm (Córdoba Airport station and Baena RIA station). The distribution of the precipitation shows a marked dry season between June and September, while the main wet period occurs from October to May.

Figure 2-2. Typical gullies in olive orchards (left) and in herbaceous crops (right) in the study zone.

Rainfall characterization

Characterization of the rainfall regime was performed from daily rainfall collected in the periods 1956-2013 at Castro del Río weather station (37.69 N, 4.47 W), belonging to the Spanish National Meteorological Agency (AEMET). Isolated data gaps of between 1970 and 1971 were filled from the data recorded at Cañete de las Torres weather station (37.83 N, 4.36 W, Phytosanitary Warnings Network of Andalusia, RAIF) and Córdoba Airport weather station (37.84 N 4.84 W, AEMET). Anomalies in annual rainfall were evaluated by means of normalization, through average and standard deviation of annual rainfall for a 57 years period (1956-2013), following Martínez-Casasnovas *et al.* (2003). Values falling outside the interval R_{mean} (average rainfall) $\pm$ sd (standard deviation), which correspond to the normalized values >1 and <-1, were considered as anomalies.

The frequency distribution of daily rainfall above a threshold value of 13 mm was analysed, considering this as the minimum rainfall that produces erosive effects as proposed by Wischmeier and Smith (1978) and Renard *et al.* (1997). In addition, the frequency distribution of records above the average daily rainfall event plus the standard deviation were analysed as well, assuming that these events represent the extreme rainfall events within the study period.

Photointerpretation process

Analysis of gully evolution and land use change was conducted by photointerpretation based on a dataset of aerial orthophotos of different years from 1956 to 2013. Performance characteristics of the orthophotos dataset are summarized in Table 2-1. Orthophoto dataset properties.. The working scale in the photointerpretation processes was established at 1:5000 for the whole dataset.

Land use

Land use in the study area for 2001, 2005, 2009, 2011, and 2013 was derived from the respective orthophotos while for the rest of the years (1956, 1980, 1984, 1999, 2003, and 2007) existing Maps of the Land Use and Vegetation Cover of Andalusia (Red de Información Ambiental de Andalucía, REDIAM) were employed. Different land uses present in the area were simplified to three classes as shown in Table 2-2.

Table 2-2. Correspondences of the simplified land use classes adopted in this study with the Map of the Land Use and Vegetation Cover of Andalusia (MUCVA, REDIAM).

MUCVA classes	Simplified classes
Herbaceous crops with scattered trees Non-irrigated herbaceous crops Irrigated herbaceous crops	Herbaceous crops
Non-irrigated tree crops: olive orchards	Olive orchards
Pasture Dense scrubland Streams and natural watercourses Agricultural buildings and farms	Other land use

Gully network length

Gully length was obtained by digitizing the extension of the network for each available year (Figure 2-3), distinguishing between newly incised and infilling stretches. Gully network was decomposed in m_y segments, where subscript y indicates the year. Each segment comprises the length between consecutive junctions (Figure 2-4). Due to changes in the drainage network during the study period, the number of segments ranged between 108 in 1980 and 940 in 2013.

Figure 2-3. Example of orthophotos showing gully incision between 2009 and 2013 from and old (top) into a new plantation (bottom).

The total length of the drainage network for a given year, L_y, was calculated as the sum of the lengths of individual segments, $l_{y,i}$

$$L_y = \sum_{i=1}^{m_y} l_{y,i} \qquad \textit{Equation 2-1}$$

with m_y equal to the total number of individual segments of the gully network for each digitalized year.

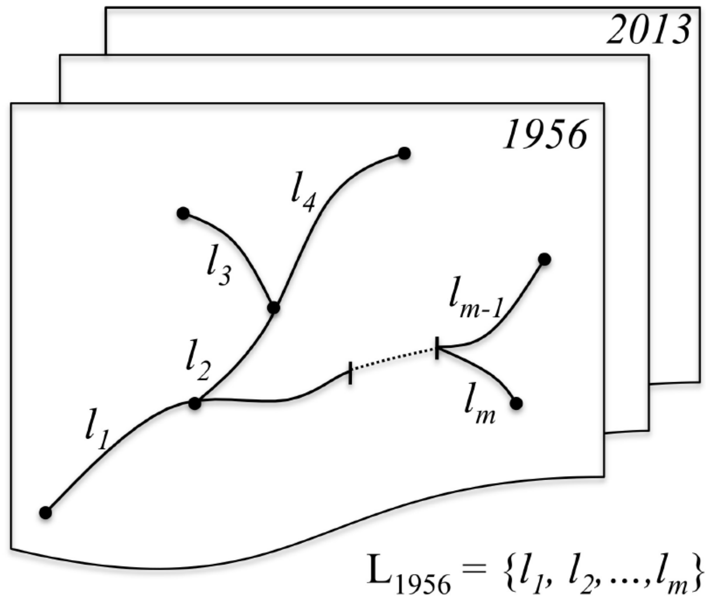

Figure 2-4. Illustration of the decomposition of the gully network into individual segments for the Monte Carlo-based simulation process.

Gully network width

In order to measure gully width representatively 35 stretches were selected from the earliest digitalized gully network of 1956 (Figure 2-1), covering a wide range of widths. Gully width was measured at the same locations on later orthophotos, allowing the evaluation of the widening process during the complete study period.

Field campaign

During 2013 and 2014, several field campaigns were conducted to measure current gully widths and depths with measuring tape and a clinometer (Suunto PM-5/360 PC). Gully top width and depth were measured at 27 representative sections that were located as close as possible to the 35 sections used in the photointerpretation. These representative sections covered the entire range of width and depth variability, including different landscape positions, from upstream close to the divide to the junction with the stream network, and both in gullies on herbaceous crops and under olive trees. This method of combining photointerpretation with field measurements of gully morphology is similar to Nachtergaele and Poesen (1999).

Monte Carlo-based simulations

Although gully length for the different years between 1956 and 2013 could be determined directly from observations using the available air photographs, determination of the gully volume was not so straightforward. As we used freely available orthophotos, it was only possible to measure the size of the gullies in two dimensions and no measure of depth was readily available. Also observations of gully width for each year were limited to the representative sections measured on the orthophotos of that particular year, and therefore included a term of uncertainty as the real population mean remained unknown.

Estimation of overall gully network volume for each year, $\bar{V}_y$, was therefore tackled by conducting a Monte Carlo simulation in which a volume and an associated uncertainty were calculated for every single gully segment, $l_{y,i}$, described in section "Gully network length" (Figure 2-4).

For each year, y, a set of $n = 1000$ estimated cross area sections, $S_{y,i} = \{s_{y,i,j}, j = 1, \ldots, n\}$ for every single segment, $l_{y,i}$, were generated as shown in Figure 2-5, which required the generation of sets of width and depth values for each year. Each generated section is calculated as

$$\mathrm{s_{y,i,j}} = \mathrm{kw_{y,i,j}d_{y,i,j}} \qquad \textit{Equation 2-2}$$

where k is a shape factor, and $w_{y,i,j}$, and $d_{y,i,j}$, the simulated gully width and depth respectively. Field observations suggested that a triangular section is a reasonable approximation of most gully sections, so a shape factor $k = 0.5$ was adopted in order to compute the simulated sections.

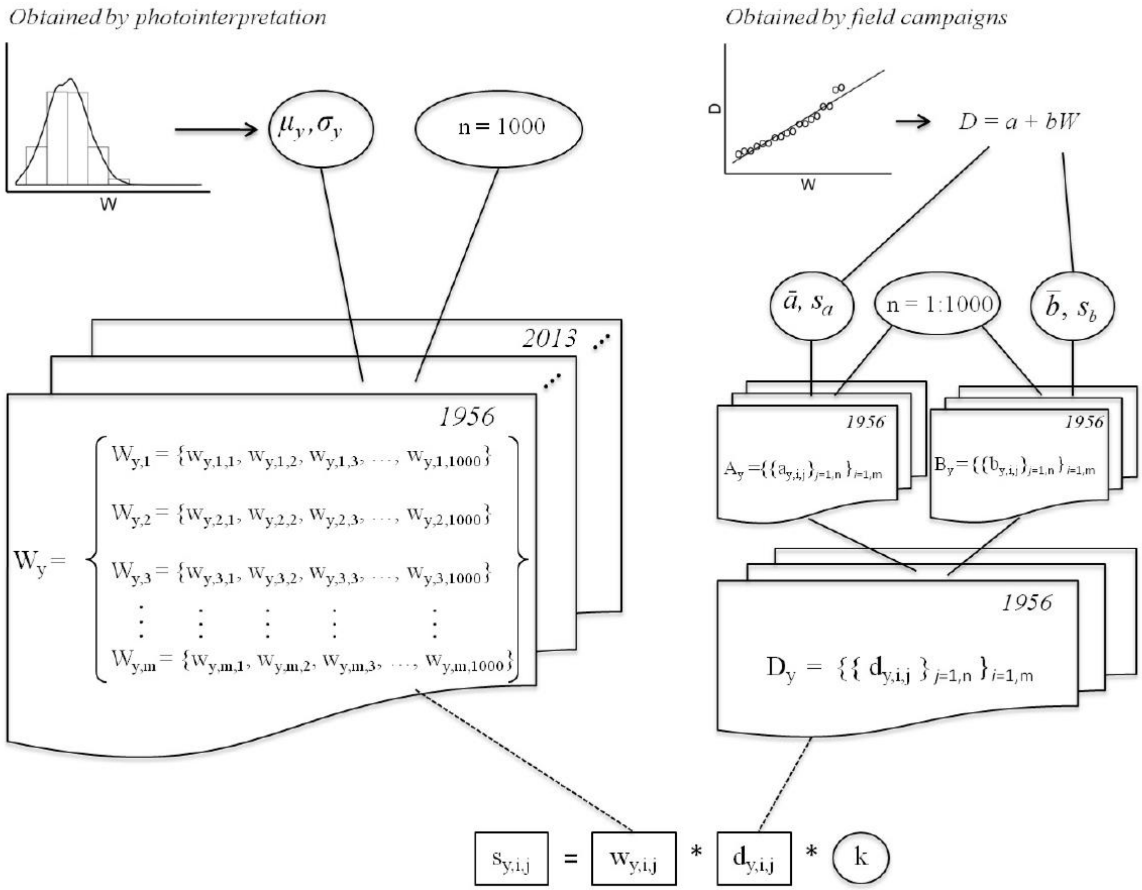

Figure 2-5. Conceptual scheme of the Monte Carlo simulation processes conducted to generate gully widths ($w_{y,i,j}$: single simulated width for a given segment and year, $W_{y,i}$: set of 1000 simulated widths for a given segment and year) and depths ($d_{y,i,j}$: single simulated depth for a given segment and year, $D_{y,i}$: set of 1000 simulated depths for a given segment and year) and calculate the cross section ($S_{y,i}$) for each gully segment and year. k is a shape factor for the gully cross section, m is the number of gully segment, n is the number of simulations, and a and b are fitted linear regression coefficients of the depth-width relation, with respective means ($\bar{a}$,$\bar{b}$) and standard deviations (s_a, s_b).

To generate a representative measure of gully width, first of all, the gully width distribution measured for each year by photointerpretation at the representative sections was fitted to different probability distribution functions (normal or Gaussian, gamma, lognormal, exponential and Weibull) using the maximum likelihood method. Next, goodness of fit was evaluated for these different distributions by means of the Kolmogorov-Smirnov statistics. Finally, the best overall fitting theoretical probability distribution was selected to obtain the necessary parameters (μ_y, σ_y) to generate n random simulations of representative gully widths for any particular year.

The estimation of gully depth for each year was based on the field data gathered in 2013-14. In order to estimate depth for previous years, firstly a width-depth relationship was estimated by linear regression analysis from the collected field data. Such a relationship could only be established for the present-day situation. Uncertainty on this linear width-depth relation was then taken into account by computing the estimated intercept, slope and their respective standard deviations (a, b, s_a, s_b). Assuming a normal distribution, a set of one thousand slope and intercept pairs were simulated. Depths for unique segments $(D_{y,i})$ were then derived from simulated widths and slope-intercept pairs.

Finally, a set of n simulated volumes $V_{y,i} = \{v_{y,i,j}, j = 1, \ldots, n\}$ was calculated for each year and segment multiplying individual measured lengths by the simulated sections (Figure 2-5).

$$v_{y,i,j} = s_{y,i,j} l_{y,i} \qquad \textit{Equation 2-3}$$

A set of n different simulated volumes of the complete gully network for a particular year V_y was eventually calculated as the sum of volumes of single segments $v_{y,i,j}$

$$V_y = \{v_{y,i,j}, j = 1, \ldots, n\} \qquad \textit{Equation 2-4}$$

and

$$v_{y,j} = \sum_{i=1}^{m_y} v_{y,i,j} \qquad \textit{Equation 2-5}$$

Finally average volume of the total gully network for a given year, $\bar{V}_y$, was computed as

$$\bar{V}_y = \frac{1}{n} \sum_{j=1}^{n} v_{y,j} \qquad \textit{Equation 2-6}$$

Erosion rates were then obtained from the difference between pairs of simulated volumes on consecutive dates divided by the duration of the period.

RESULTS

Rainfall characteristics during the study period

The annual rainfall depths in the analysed period ranged between 180 mm in the hydrological years 2004/2005 and 973 mm in 2009/2010, with an average value of 546 mm (Table 2-3). Figure 2-6 shows standardized annual rainfall between 1956 and 2013 and the anomalies of annual rainfall. Annual rainfalls over the 0.75 percentile (656 mm) were recorded on 15 occasions of which 10 surpassed the average annual rainfall plus the standard deviation (748 mm). Among the lapses between aerial orthophotos dataset, the period 1984-1999 and 2009-2011 concentrated the highest number of positive extreme annual rainfall events. In 1984-1999 eight out of fifteen records were over the 0.75 percentile, and 6 of them were considered to be anomalies since they were higher than the average annual rainfall plus the standard deviation. In the period 2009-2011, in both years, larger amounts of annual rainfall than the standard deviation were recorded and can thus be considered anomalous severe rainy period.

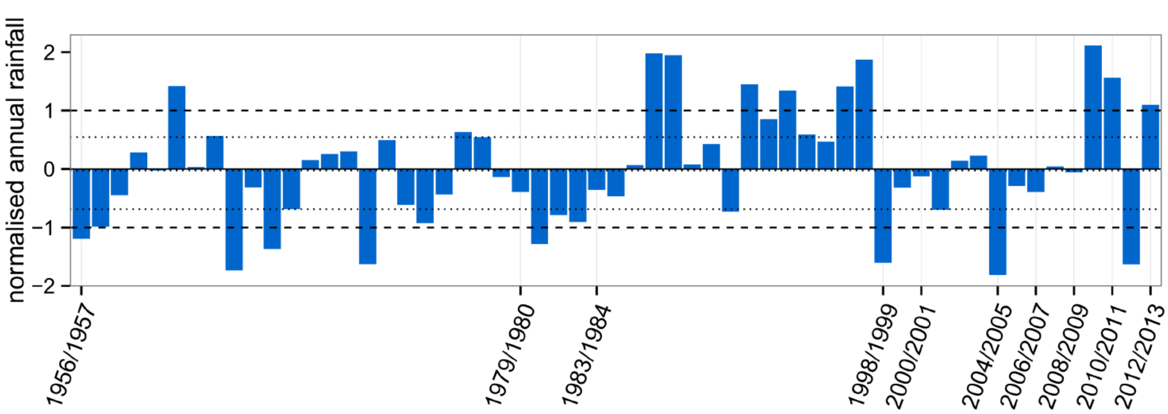

Figure 2-6. Standardized annual rainfall in the period 1956-2013.

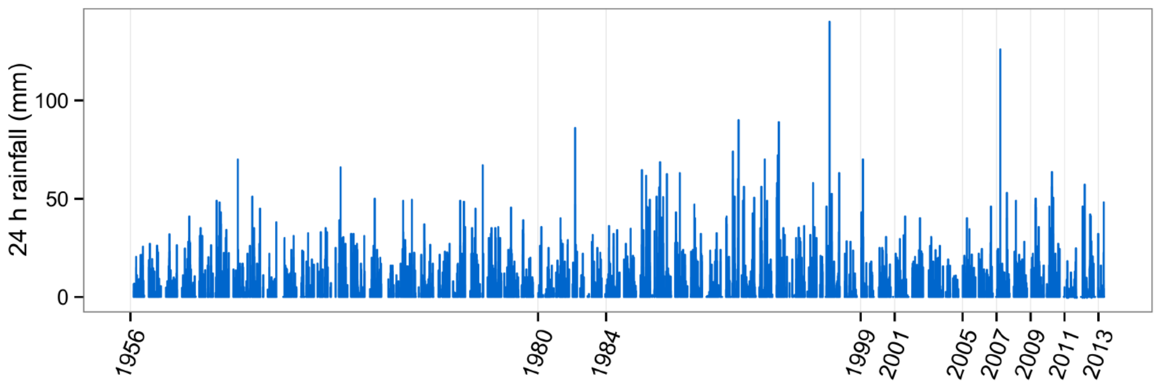

Figure 2-7. Daily rainfall recorded in the period 1956-2013.

Figure 2-7 shows the distribution of the 3698 daily rainfall events recorded during the study period. Daily rainfall events (R_{24}) higher than 13 mm accounted for 21.7% of the total recorded. Among the different periods the highest proportion of R_{24} >13 mm was recorded in 2009-2011 (27.5 events per year, Table 2-3) whereas the average proportion was 13.9 R_{24} events>13 mm per year. Rain depths higher than the average value (8.4 mm) plus the standard deviation (10.8 mm) were considered extraordinary events, which were concentrated in a higher proportion in the periods 1984-1999 (10.5 records per year) and 2009-2011 (13 records per year) (Table 2-3). Maximum daily rainfalls were recorded in the hydrological years 1997/1998 (140 mm) and 2007/2008 (126 mm), with an average value of 48.68 mm for the entire period.

Table 2-3. Land use, rainfall indicators and gully growth. f_h and f_o: fractions of surface dedicated to herbaceous and olive crops, in the first year of each period. nle: number of 24 hours rainfall events per year higher than 13 mm, nleo: number of 24 hours ra infall events per year over the average 24 hours rainfall plus the standard deviation, R_{max}: highest daily rain depth registered within the period, MAR: Mean annual rainfall in the period. ΔL: total, and ΔL/Δt, partial increase in gully length, and GH: gully headcut growth, averaged over the area.

		Land use		Rainfall				Gully growth		
Period	Δt yr	f_h	f_o	nle	nleo	R_{max} mm	MAR mm	ΔL km	$\Delta L/\Delta t$ km yr^{-1}	GH m ha^{-1} yr^{-1}
1956		.85	.13							
1956–1980	24	.74	.25	12.9	6.8	70.0	494	−7.37	−0.31	−0.15
1980–1984	4	.74	.25	9.5	5.0	86.0	377	10.58	2.65	1.25
1984–1999	15	.52	.48	17.1	10.5	140.0	677	29.67	1.98	0.94
1999–2001	2	.50	.50	11.0	5.0	70.0	501	−3.06	−1.53	−0.72
2001–2005	4	.49	.50	11.8	4.5	41.0	438	−3.49	−0.87	−0.41
2005–2007	2	.41	.59	13.0	5.5	46.0	477	1.36	0.68	0.32
2007–2009	2	.39	.61	11.5	5.5	126.0	545	−5.48	−2.74	−1.30
2009–2011	2	.38	.61	27.5	13.0	68.5	917	48.77	24.39	11.54
2011–2013	2	.36	.63	12.5	6.0	57.2	492	2.36	1.18	0.56

Land use change

Land use experienced a progressive conversion from herbaceous crops to olive orchards as shown in Figure 8. In the study period, olive orchards grew from 13% to 63% of the total catchment area at the same as time herbaceous crops decreased from 85% to 35% of the total catchment area. The main land use change occurred between 1984 and 1999, when the olive orchards went from occupying 25% to 48% of the total catchment area. The highest rates of change however were observed in the period 2005-2007 with a more than 4% rate of annual land use change from herbaceous crop to olive orchards.

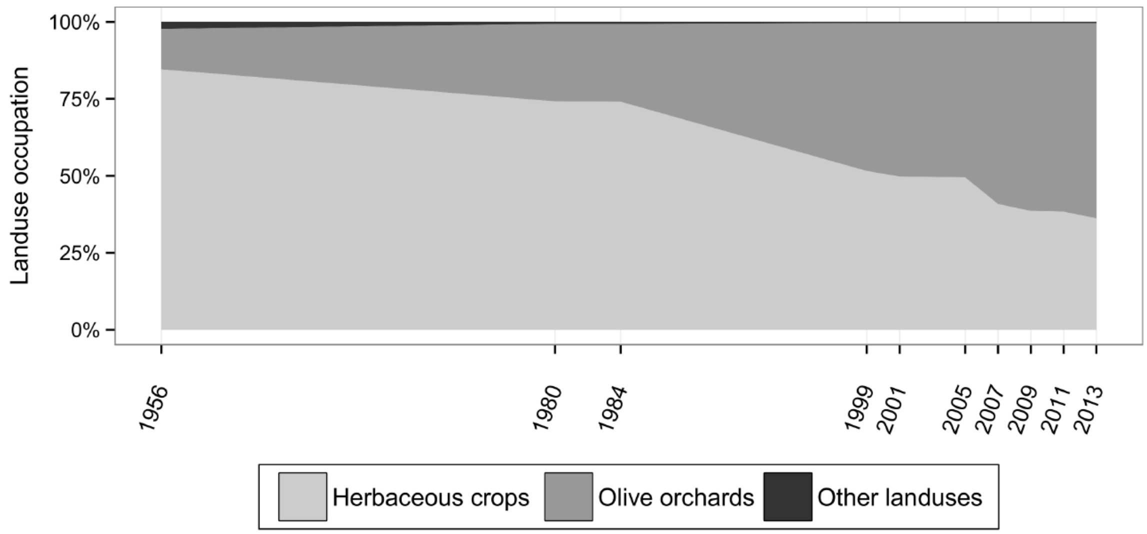

Figure 2-8. Land use changes in the period 1956-2013.

Gully network length dynamics

Figure 2-9 shows the evolution of the gully network derived by photo-interpretation between 1956 and 2013, with drainage density included. From 1956 to 2013 the gully network increased not only in length but in number of branches as well. Further analysis on the length and area ratio showed that the drainage density had grown from 17.2 m ha $^{-1}$ to 53.3 m ha $^{-1}$. There seeems to be a greater increase in the south compared to the north, which suggests a more stable condition in the latter. In most of the analysed period, the variations in drainage density were small. However, there were two significant periods when the increase was very high and that account for the main increases in the overall value. From 1984 to 1999 and 2009 to 2011 there was an increment of 14.6 m ha $^{-1}$ and 23.6 m ha $^{-1}$, respectively, which accounted for 84% of the total drainage density growth. When comparing these gully length dynamics to controlling factors of land use and rainfall, it can be seen in Table 2-3 that this rapid growth could be related to extreme rainfall events that occurred in 1997 and anomalous rainy periods in 2009-2011. In contrast, in some periods, such as for instance in 1956-1980, 1999-2001, 2001-2005 and 2007-2009 the gully network underwent several decreases in the drainage density, although in no case was this decrease more than 4 m ha $^{-1}$, and can therefore be considered modest. These decreases may be directly related to farming operations, in which farmers fill in the upstream gully stretches that are limited in depth and can be considered to be ephemeral gullies.

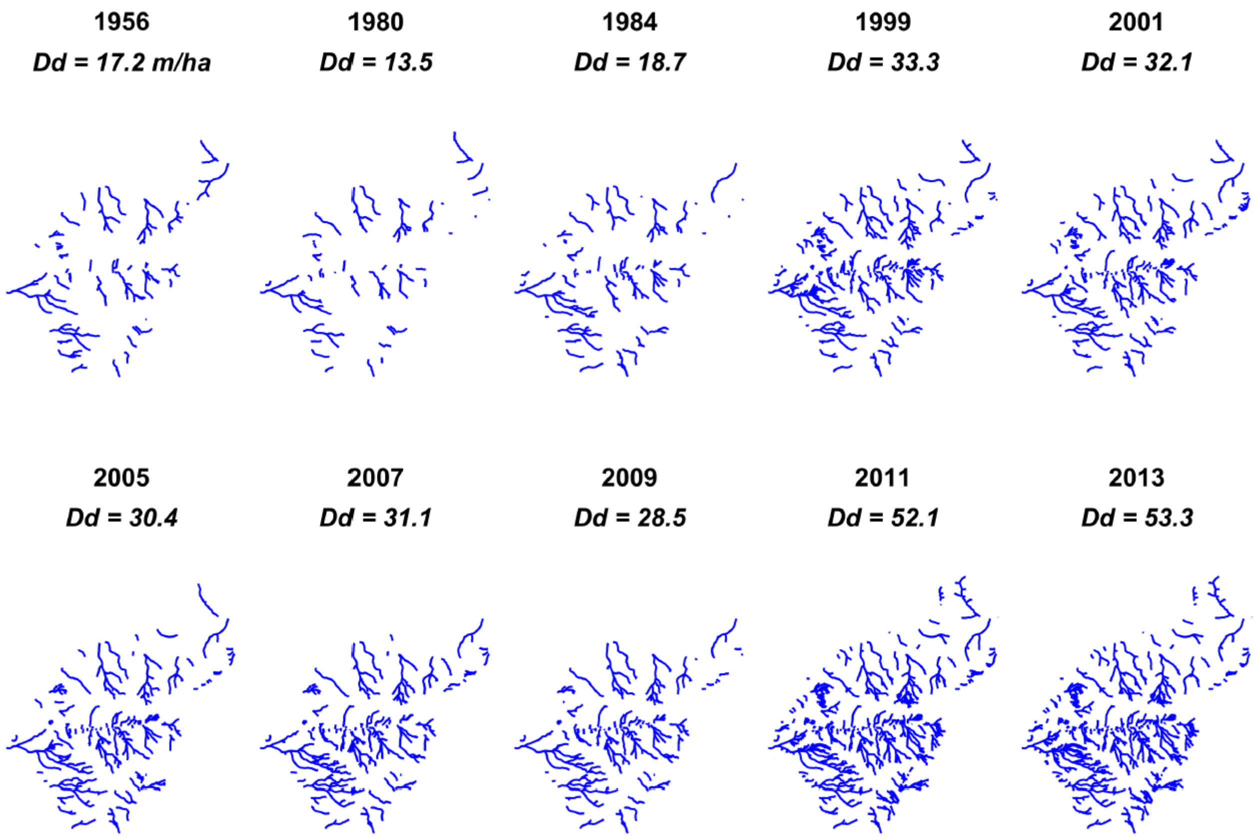

Figure 2-9. Gully network evolution and drainage density (D_d), in m ha^{-1}, at each period.

Figure 2-10 shows the frequency distribution of headcut growth and infilling of individual gullies for the different periods between 1956-2013. Some of the observation periods exhibit a balance between infilling and growing reaches, which leads to a very minor overall change of the total gully network length. During a few distinct intervals however, 1984-1999 and 2009-2011, this balance shifts drastically and results in a fast increase of the gully network's total length, as can be seen in *Figure 2-11*. This can partly be explained by the fact that, in these two periods infillings are almost negligible (Figure 2-10 and *Figure 2-11*). However, in *Figure 2-11*, the growth of the gully at the end of those periods (1999 and 2011) is much greater (31 km and 49 km) than those from the other end periods (13 km as the highest value), which clearly shows that gully growth was the dominant process controlling gully dynamics in those periods.

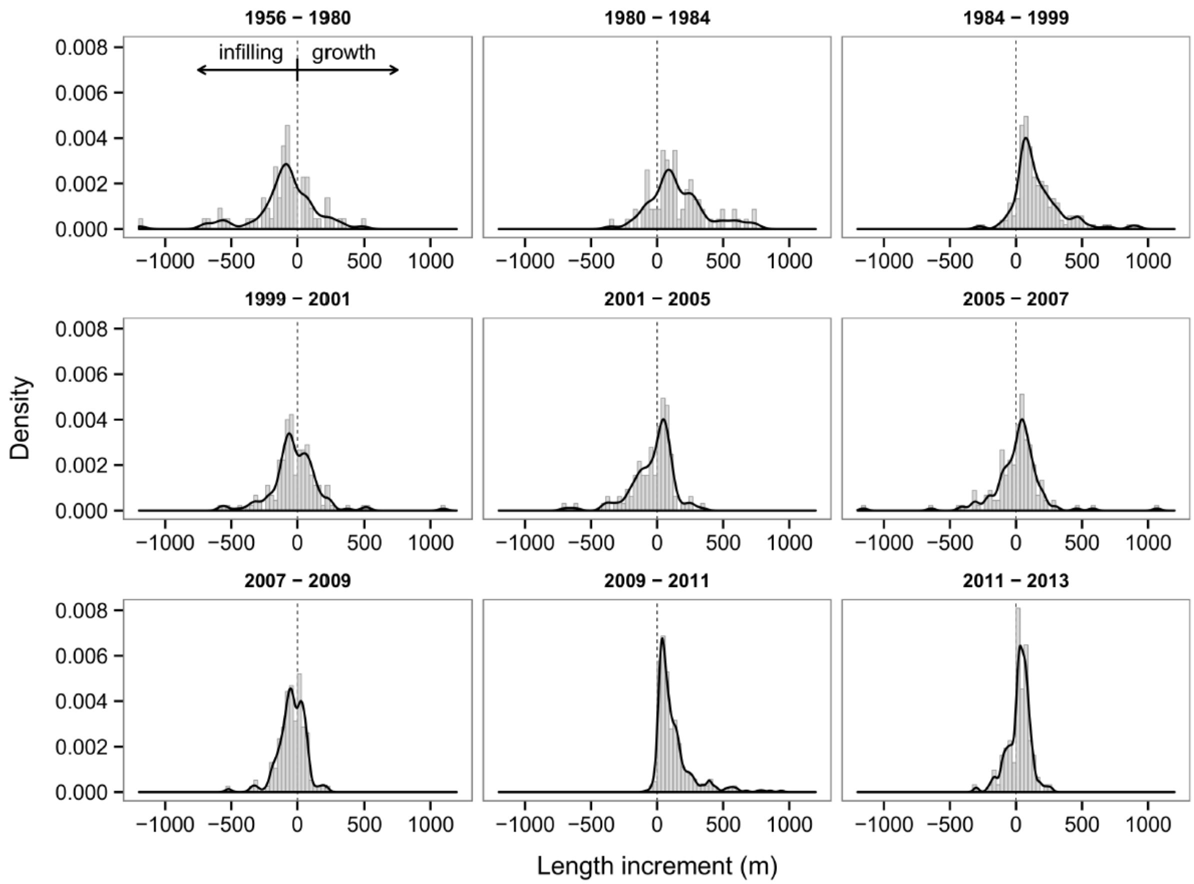

Figure 2-10. Gully headcut growth or decrease in the different periods between 1956 and 2013.

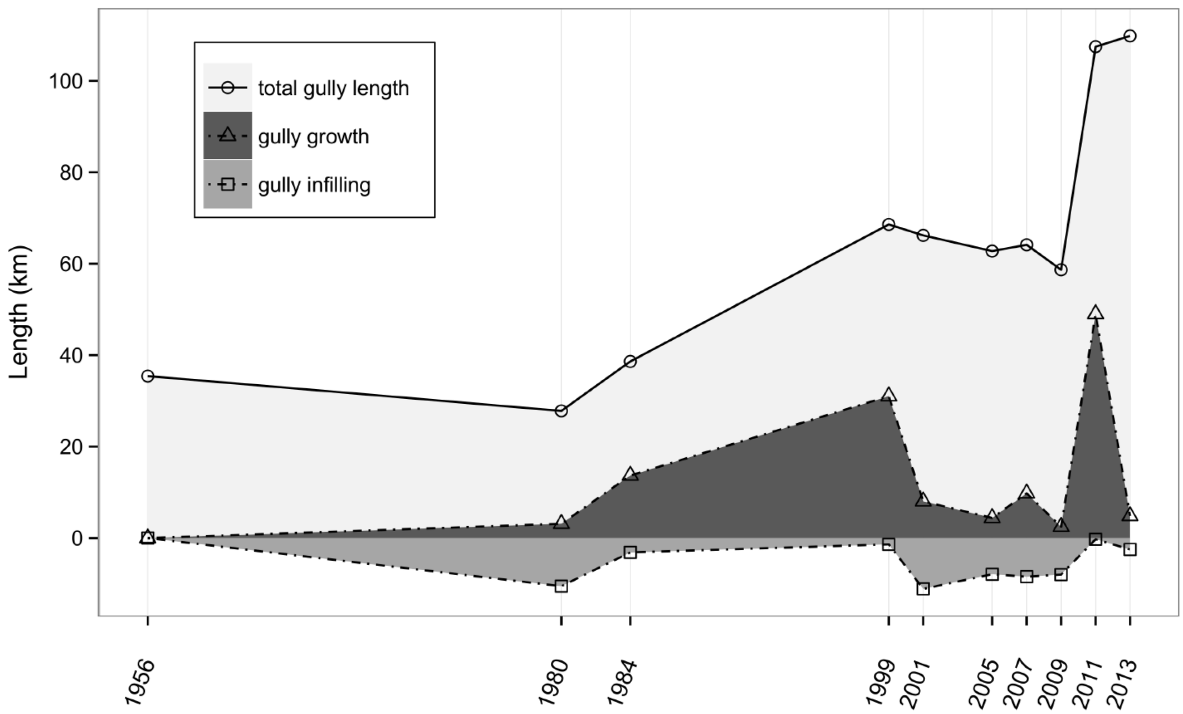

Figure 2-11. Gully length dynamics in the period 1956-2013.

Figure 2-11 shows how the total length of the gully network tripled from 35.4 km in 1956 to 109.8 km in 2013. Main enlargement periods were registered in 1980-1984 (10.6 km), 1984-1999 (29.9 km) and 2009-2011 (48.8 km). In contrast, during some other periods, like, for instance, in 1956-1980, 1999-2001, 2001-2005 and 2007-2009, the balance between infilling and growing stretches resulted in a net reduction of the total gully network length. Infilling gully stretches identified during photointerpretation, could be classified into two different types: those made during regular tilling operations at the end of the summer, usually in the order of several tens of meters and those resulting from land levelling during land use change phases, which may reach some hundreds of meters.

Extraordinary annual rainfalls as well as individual extreme precipitation events seem to be the main factors that can be linked to gully retreat (Table 2-3). Land use does not seem to be the dominant factor controlling these observed peaks in gully length increase. However, we cannot exclude that land use change could have contributed to the rainfall extremes inducing high peak discharges, because, since 1956, a shift from cereal crops to olive orchards occurred in half of the study area, and was especially intensive from 1984 onward. Young olive trees with limited root systems and small canopies leave an important soil surface bare and give little protection to overland flow or gully headcut advance. However, further analysis should be made in order to confirm this hypothesis.

Gully network width dynamics

Top width at the representative cross sections, as derived from the orthophotos dataset, experienced continuous widening over time (Figure 2-12). While at the beginning of the study period (1956), the maximum top width was close to 12.0 m, this value progressively increased over subsequent years, until reaching a maximum value of 59.0 m in 2013. The average value increased smoothly from 4.5 m wide in 1956 to 8.0 m in 2005, whereas the rate of increase for the period 2005-2013 clearly got steeper, resulting in final average width of 13.1 m in 2013. Although widening could be expected at every time step, average widths derived from the cross sections in 2007 (7.7 m) actually experienced a narrowing with respect to those measured in 2005 (8.0 m). Since this period (2005-2007) underwent the highest rate of land use change in the series, this reduction in cross section could be explained by the reopening of gullies that had previously been removed by land leveling during a land use shift to olive orchards.

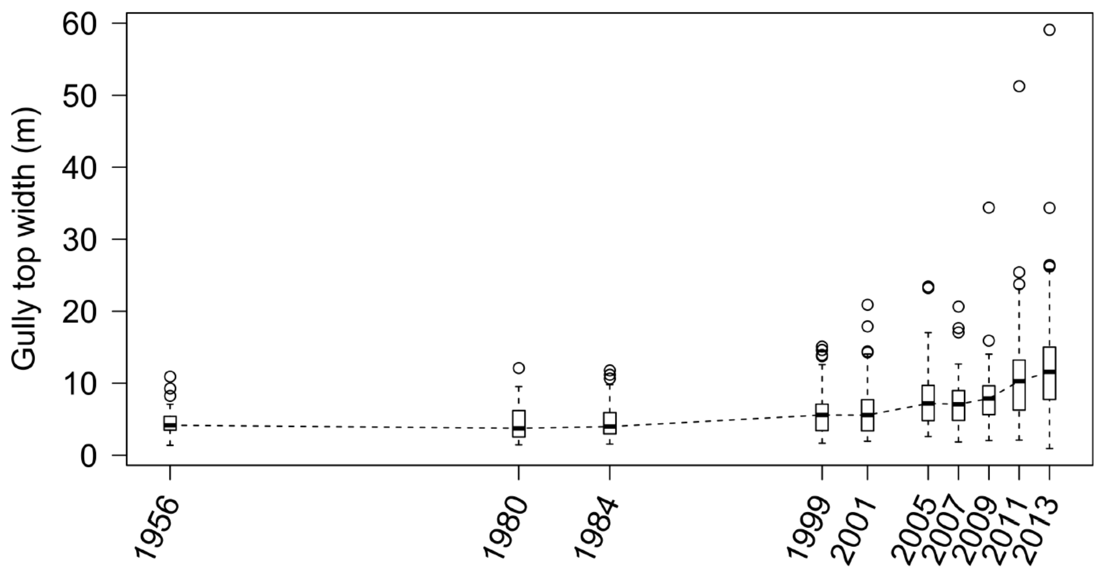

Figure 2-12. Gully top widths dynamics in the period 1956-2013 derived by measuring by photointerpretation. The dashed line indicates the mean, box and whiskers indicate the 25-50% and 5-95% quantile ranges, respectively.

Table 2-4 summarizes p-values obtained by means of the Kolmogorov-Smirnov statistic, which was used to evaluate the suitability of different theoretical probability distributions for fitting the observed top widths. The lognormal distribution showed itself to be the most suitable for almost all the years, with the highest p-value of 0.98, in 1980 and 1999 and lowest p-value of 0.64 for 2011, although it was still the best fit for all the distributions tested. These fitted probability distributions were then used to simulate 1000 random widths for each year and single segment composing the gully network.

Table 2-4. Kolmogorov-Smirnov tests (p-values) obtained by fitting observed gully widths during different years.

Pdf	1956	1980	1984	1999	2001	2005	2007	2009	2011	2013
Normal	0.18	0.24	0.25	0.19	0.21	0.33	0.21	0.12	0.03	0.07
Gamma	0.66	0.77	0.55	0.81	0.74	0.96	0.77	0.67	0.43	0.71
Lognormal	0.71	0.98	0.69	0.98	0.97	0.94	0.90	0.92	0.64	0.76
Weibull	0.36	0.60	0.60	0.48	0.66	0.65	0.42	0.47	0.21	0.48

Pdf: probability distribution function.

Width and Depth relationship

In order to compute the volume of the gully network, depths at the different stretches were derived from the Monte Carlo simulated widths using a width-depth relation resulting from field work, shown in Figure 2-13. A coefficient of determination $R^2 = 0.83$ was obtained from a logarithm-based fitting, with slope, intercept and their standard deviation, respectively, 1.73 ± 0.16 and 0.55 ± 0.32. Normal deviates based on those coefficients were used to generate 1000 width and depth pairs.

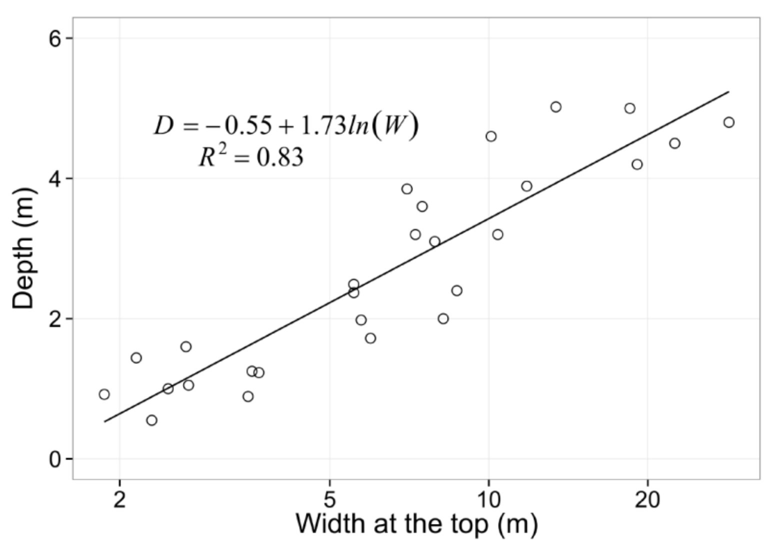

Figure 2-13. Width-depth relationship derived from field measurements.

Gully volume dynamics

Figure 2-14 presents the final volume evolution, as calculated by means of the Monte Carlo simulation. Gully stretches with a single, observed length were multiplied by the generated width and depth pairs, resulting in 1000 simulated gully network volumes for each stretch and for each period. Average volume in addition to minimum and maximum volumes were then obtained from the set of simulations, showing the growth of the gully in terms of mean eroded volume, as well as a measure of uncertainty, by means of the 5-95% confidence interval of these inferences, shown in grey. Gully network volume grew from 0.18 hm^3 in 1956 to 3.24 hm^3 in 2013. These results show how the original value of the total gully volume has increased 17 times. Main periods of rapid volume growth occurred at the end of the study period, between 2009 and 2013, when the gully volume increased from 0.82 hm^3 until its final value of 3.24 hm^3. Moreover, the period 2009-2011 alone accounts for nearly 52% of the observed growth. Infilling phases were also reflected in the volume evolution curve shown in Figure 2-14, such as for instance at the end of the period 1956-1980, when the gully volume decreased until it reached its minimum value (0.15 hm^3), and in 2007 which shows a 0.015 hm^3 decrease from the average volume in 2005 (0.81 hm^3).

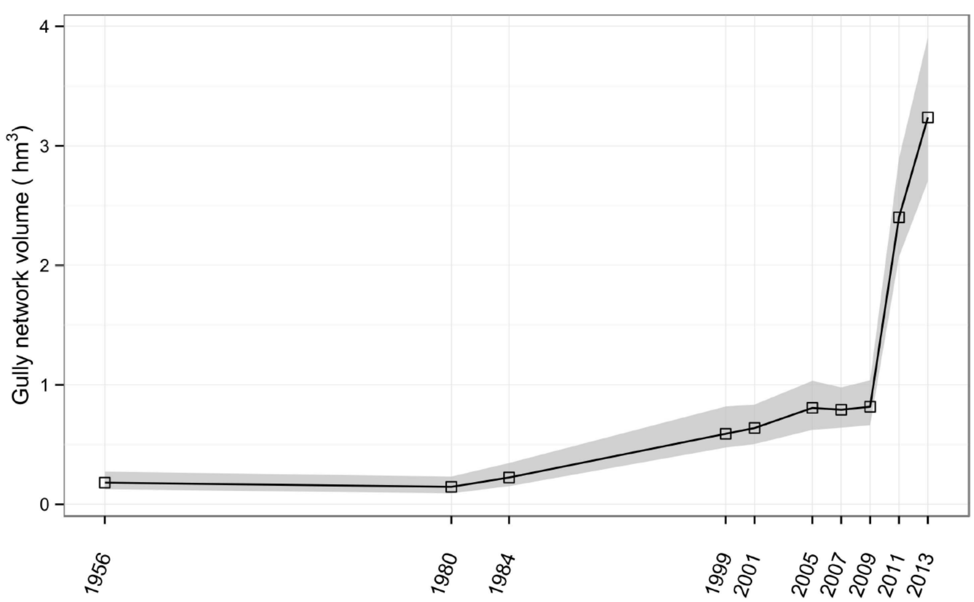

Figure 2-14. Gully network volume dynamics in the period 1956-2013 and uncertainty interval (grey).

Gully erosion rate dynamics

Dynamics of gully erosion rate are shown in Figure 2-15. Maximum erosion rate was reached in the period 2009-2011 when 591 t ha $^{-1}$yr $^{-1}$ were lost according to the Monte Carlo results. Minimum erosion rate (-5.21 t ha $^{-1}$yr $^{-1}$) was recorded in the period 2005-2007. Negative values here reflect the decrease of the gully network volume, and it should therefore be considered as an infilling not an erosion rate. Average erosion rate for the whole study period was 39.7 t ha $^{-1}$yr $^{-1}$.

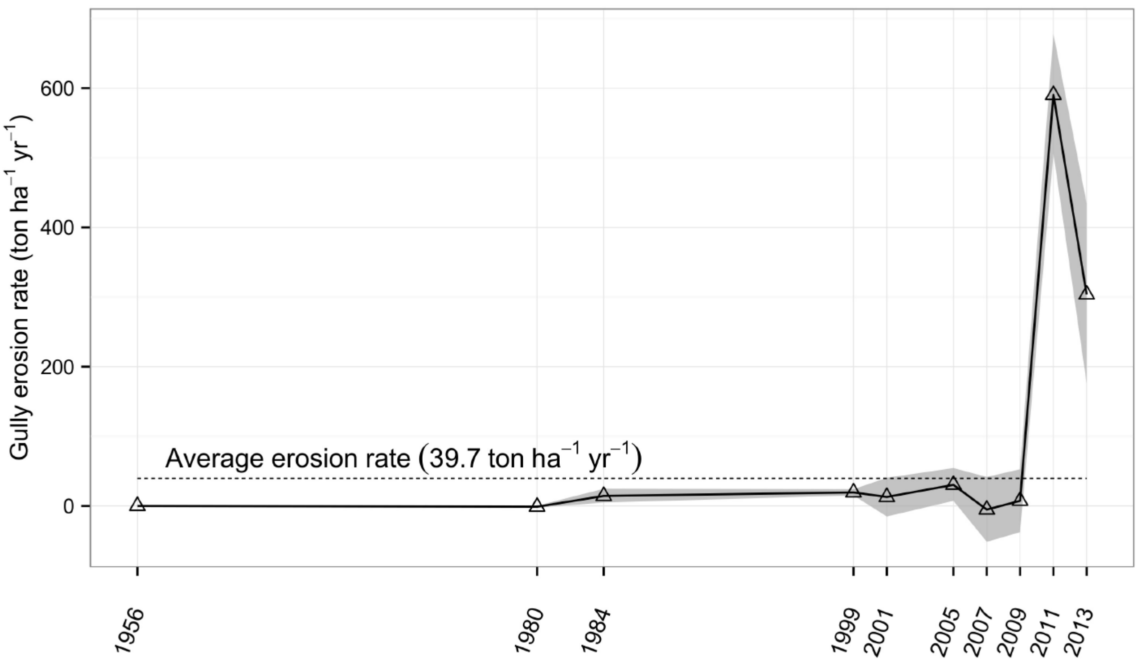

Figure 2-15. Gully erosion rate in t ha^{-1} yr^{-1} calculated by Monte Carlo simulation method, and average erosion rate in the period 1956-2013. The grey area represents the 90% uncertainty level.

DISCUSSION

The average gully erosion rate of 39.7 t ha $^{-1}$yr $^{-1}$ for the total catchment area obtained in this study, by means of photo-interpretation techniques combined with stochastic methods, is of the same order of magnitude as those found in the literature in Mediterranean basins. Oostwoud Wijdenes *et al.* (2000) reported erosion rates of 1.2 t ha $^{-1}$yr $^{-1}$ in bank gullies developing into highly erodible sedimentary deposits in the southeast of Spain, derived by aerial photo analysis over a 38 year period. The highest gully erosion rate of 331 t ha $^{-1}$yr $^{-1}$ referring to its catchment was found by Martínez-Casasnovas *et al.* (2003) in large gullies in the NE Spain, from high resolution DEMs and GIS analysis in a 36 year period. Compared to other erosion processes, the gully erosion rates measured here almost double the average erosion rates for sheet and rill erosion reported for olive orchards in the Mediterranean (23.2 t ha $^{-1}$yr $^{-1}$) by Gómez *et al.* (2008). Olive orchards are one of the most important crops in the Mediterranean and are generally considered to be highly affected by sheet and rill erosion. This clearly stresses the importance of adequately considering gully erosion processes when modelling soil losses from water erosion.

Most importantly, the results show a wide variability in gully erosion rates, ranging between -5.21 and 591 t ha $^{-1}$yr $^{-1}$. This includes periods dominated by infilling and rapid growth, underlining the importance of measuring erosion rates at the finest temporal resolution possible in order to prevent under- and/or overestimations in sediment production. Such variability is in part explained by the inherent irregularity of the local rainfall regime, which appears to be the main controlling factor for gully erosion at this site. However, land use change has played an important role, intensifying in some cases and masking in other cases gully erosion rates. For instance, in the initial period between 1956 and 1980, the erosion rate gave a negative value. However, given the length of this period and since there were some particular years (*i.e.* 1961-1962) with extreme rainfall, it is likely that positive gully growth occurred during this period, that was later masked by infilling. This shows that longer periods, such as 1956-1980 and 1984-1999, were subject to a greater uncertainty with respect to the post-1999 period, when a higher temporal resolution was available. Infilling phases could be expected to be followed by those with higher erosion rates. Gordon *et al.* (2008) obtained the latter from periodically infilled gullies compared to gullies left undisturbed. However, our results do not show that trend. For example, land use change and infilling between 2005 and 2007 was followed by only a moderate gully erosion phase in the 2007-2009 period.

Moreover, the data presented here clearly show that, in Mediterranean areas (Köppen climate type Csa), the gully growth dynamics are different, for instance, to those in Temperate Oceanic west-European areas (Köppen type Cfb). A review of different studies on gully growth over time by Poesen *et al.* (2006) indicated a rapid initial growth, followed by a stable phase with slow growth for "mature" gullies. Data for this study was from the Temperate Oceanic (Cfb) Loess belt or from lab experiments under constant discharge conditions. In our case, with a high variability in natural rainfall, even after several decades, intense growth phases were observed. This observation is not unique since, in another environment Shellberg *et al.* (2016) have detected an almost continuous increasing trend in the gullies of the Mitchell River in Queensland. As stated before, these could mainly be attributed to an increase of the gully's cross sections, and less to a gully headcut retreat. Therefore, models such as CHILD or REGEM, which have been applied with success to gully modelling, but focus mainly on headcut activities, would probably not yield good results in this case.

From a wider geomorphological perspective, other phenomena such as lowering of the base level and incision of the river bed could be suggested as being a cause of the progressive increase in the erosion rate. During the Quaternary, the main Guadalquivir River was at an incision stage due to its base level fall. However, this incision has been slow, as demonstrated by Uribelarrea and Benito (2008), who found evidence of only a 1.2 m incision over the last 500 years. In any case, since the 1950-60s, when many dams were constructed, the Guadalquivir has been a highly regulated river. Such dams are known to have a downstream incision effect due to removal of sediment load and an upstream aggradation effect. With respect to our study area, there are no upstream but only downstream dams. Therefore, it is surmised that the influence of the incision stage has been artificially limited in this catchment since the 1950s and that the observed changes in the gully network can be fully attributed to upstream changes in the rainfall or land use regimes.

Gully erosion rates computed between the start and the end of the study period would incur in gross underestimation. Erosion rates between 1956 and 2009 were under the average (39.7 t ha $^{-1}$yr $^{-1}$), while the last period (2009-2013) accounted for around 52% of the gully volume growth, reaching a peak value of 591 t ha $^{-1}$ yr $^{-1}$ in the period 2009/2011. Nevertheless, these observations are in accordance with other studies in the Mediterranean. Gully erosion rates after some extreme rainfall events in the Mediterranean basin has been reported to occasionally reach 207 t ha $^{-1}$ (Martínez-Casasnovas *et al.*, 2002). In a review of the western Mediterranean basin, González-Hidalgo *et al.* (2007) found that, on average, the three largest daily events per year accounted for more than 50% of the total sediment exported from the basin. Nevertheless Woman and Miller (1960) observed the relevance of relative frequent events of moderate magnitude. Gioia *et al.* (2008) stressed the importance of different runoff thresholds to explain flood occurrence in the Mediterranean areas. Ordinary flows are produced when rainfall rate exceeds the infiltration rate of the soil in a small area, a typical case of Hortonian runoff generation, or Hortonian threshold, while what Gioia *et al.* (2008) denominated outlier events, occurred when the water of almost continuous rain spells surpassed the storage capacity of the soil in a large area of the catchments, or Dunnean threshold. The so-called time compression of Mediterranean climate with respect to soil erosion is therefore very high, as is demonstrated by the data from this study. Our data seem to indicate that land use did not play a dominant role, although we cannot exclude that land use changes to olives and soil management have lowered the land's resilience towards gully incision.

The Monte Carlo stochastic modelling performed allows one to verify that while gully length dynamics (*Figure 2-11*) could explain some of the rapid increases in the volume and erosion rate computed, widening processes (Figure 2-12) determine the shape of volume curve (Figure 2-14) pointing to the importance of that parameter in the computed volume as opposed, in this particular case, to that suggested by other authors, who, for other areas and climates that the leading controlling parameter is gully length (Nachtergaele and Poesen, 1999). This observation will lead to future field work and modelling efforts, which should not only consider gully headcut advance, but also the mechanisms of gully sidewall collapse and erosion. Possibly a very important factor here, in order to control gully growth, is the possible effect of roots on stabilizing the gully walls (De Baets *et al.*, 2008).

The main advantage of the new method described here, is that by means of Monte Carlo simulation, an estimation of the uncertainty associated with the measurement of gully erosion volume is generated. This is especially relevant when suitable knowledge of erosion dynamics is required, and management systems need to be evaluated or compared. Although more field measurements of gully sections would be advantageous in order to reduce uncertainty, time and money spent on ground truthing would increase accordingly. However, the high p-values of 0.64-0.98 obtained here for the fit between the theoretical probability distribution function and the experimental data suggests satisfactory results can be obtained, even with a limited field sample. Moreover, also Istanbulluoglu *et al.* (2002) successfully used a Monte Carlo approach to estimate gully incision locations using a similar amount of field data.

CONCLUSIONS

A new method was presented to evaluate gully growth over decadal time scales, combining airphotos interpretation with a stochastic approach through Monte Carlo modeling for the channel section parameters. This method constitutes a reliable procedure to determine gully network dynamics over time. Uncertainty ranges obtained in the simulation provide an unprecedented view on the gully network dynamics useful from a management perspective. While highly variable, the observed erosion rates were in accordance with previous studies in Mediterranean basins. The fluctuations in erosion rates were mainly attributed to the variability in rainfall regime variations, likely to have been exacerbated by land use changes, although further research of runoff, gully headcut retreat rates and sidewall dynamics should be made at this last point.

Simple interpolation between the start and end date would highly underestimate gully contribution during certain years, as it could be verified when comparing the average erosion rate (39.7 t $ha^{-1}yr^{-1}$) with sporadic erosion rates at the end of the study period at to a maximum of 591 t $ha^{-1}yr^{-1}$. Gully erosion is confirmed to be an important sediment generation process in Mediterranean basins. Average erosion rates from gullies in the study period almost double their values for similar locations and conditions obtained for rill and sheet erosion.

Further studies with more field data are needed to improve the estimations of the contribution of the different land uses to gully growth. Implementation of physically-based models of gully retreat rates and sidewall collapse as well as more field measurements and interviews with local farmers on soil management practice could contribute to a better understanding of the of the elongation processes, and predict gully erosion under different scenarios, including the effect of added root cohesion to sidewall stability or gully headcut protection.

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Chapter 3

Rainfall and vegetation effects on temporal variation of topographic thresholds for gully initiation in mediterranean cropland and olive groves

3. RAINFALL AND VEGETATION EFFECTS ON TEMPORAL VARIATION OF TOPOGRAPHIC THRESHOLDS FOR GULLY INITIATION IN MEDITERRANEAN CROPLAND AND OLIVE GROVES

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ABSTRACT

Topographical threshold conditions (s >= k a^{-b}), expressed by local slope (s) and drainage area (a), have been widely used to predict gully incision locations. However, little attention has gone to the variation of the thresholds over time. Rainfall variability and changing land use or vegetation cover can potentially lead to important shifts in established thresholds. In this study, we determine topographic thresholds for gullies forming under olive groves and herbaceous crops between 1956 and 2013 in a catchment in Southern Spain. For 10 different time periods, we then analysed the impact of rainfall, land use and vegetation cover on the variation of these thresholds. The results show similar topographic thresholds for olive groves and herbaceous crops. However, important variations were found over time. Rainfall indexes, in particular Rainy Day Normal, were generally best correlated. Finally, although overall no effect of land use was obtained, the results did show a significant effect of vegetation cover, but mainly in those years where rainfall was low. This seems to indicate that during years with high rainfall, topographic thresholds are primarily controlled by rainfall, while vegetation cover seems to exert a secondary control.

Keywords: Gully initiation, drainage area, slope gradient, land use, herbaceous crops, orchards.

INTRODUCTION

Gully erosion has been widely recognised as a major threat leading to soil degradation, damages in infrastructures and alterations on the hydrological functioning of the catchments (Valentin *et al.*, 2005). Furthermore, gully erosion represents the dominant soil erosion process in many Mediterranean and arid environments (Poesen *et al.*, 2002, 2003; Frankl *et al.*, 2013; Dewitte *et al.*, 2015) which are often more sensitive to the negative impacts from erosion. In order to prevent the undesired effects of gullies, there is a need to develop a standardised system for evaluating site susceptibility to gully erosion and anticipate the places where new gullies might initiate (Torri & Poesen, 2014; Dewitte *et al.*, 2015) . In this way, soil management and soil conservation measures can be adapted at those sites in a targeted manner. Also, for modelling sediment production by gullies, most models need to be informed about the location of gully heads. Predicting gully head development susceptibility has been addressed from different approaches. Initially gully erosion was modelled as a threshold process by Patton & Schumm (1975) and Begin & Schumm (1979) as a function of the flow shear stress exerted by the concentrated overland flow and a critical value that should be exceeded to erode a gully channel. Montgomery & Dietrich (1994) developed this initial approach and simplified it through the expression:

$$s >= k \quad a^{-b} \qquad \textit{Equation 3-1}$$

where *s* represents the slope gradient of the soil surface near the gully head, *a* is the area of the catchment draining towards the gully head per unit of contour length. The coefficient *b* depends on the overland flow type. Theoretical values of 0.5-0.857 have been proposed for laminar and turbulent flow respectively (Montgomery & Dietrich, 1994). Torri & Poesen (2014) observed lower values under field conditions. These authors, explored two theoretical ways of predicting the value of *b*, one related to flow shear stress considerations and the other based on the stream power per unit of volume, and finally proposed a value of around 0.4. The coefficient *k* reflects gully erosion resistance and depends on local climate, soil type and land use. Higher *k* values correspond to higher resistance to gully erosion incision or less erosive rainfall. Hereafter, this general approach has proven successful in a wide range of environments and land use classes all over the world (Patton & Schumm, 1975;

Montgomery & Dietrich, 1994; Vandaele *et al.*, 1996; Vandekerckhove *et al.*, 1998, 2000; Gómez-Gutiérrez *et al.*, 2009; Imaizumi *et al.*, 2010).

Apart from the local slope *s* and the contributing area per unit of contour length *a*, other approaches have incorporated additional terrain variables to predict and map gully head susceptibility. Kheir *et al.* (2007) used a tree-based regression model, where different terrain variables were significant, for predicting gully erosion susceptibility in Lebanon. Logistic regression models have also been widely used either in combination with topographic threshold indicators or with other terrain attributes. Vanwalleghem *et al.* (2008) applied logistic regression, corrected for rare events, adding soil types and anthropogenic indicators to predict the location of historic gullies in Belgium. Conoscenti *et al.* (2014) tested GIS-based logistic regression model based on the potential influence on erosion processes of 27 environmental attributes that describe the variability of lithology, land use, topography and road position. Dewitte *et al.* (2015) used a combined two-step method, first limiting gully-prone areas by means of topographic thresholds, then boosted with logistic regression to identify gully initiation points in data-poor regions. Moreover gully erosion proneness has been evaluated through other different topographical attributes such as the curvature, the erosive power of the flowing water, the topographic wetness index (De Santisteban *et al.*, 2005; Gómez-Gutiérrez *et al.*, 2015) and a modified compound topographic index (Momm *et al.*, 2013).

From the approaches described above the Topographic Threshold (TT; $s >= k \quad a^{-b}$ *Equation 3-1*) remains as the most discussed and data-rich index (Torri & Poesen, 2014), partly by its simplicity and partly by its physical background as it reflects a critical overland flow shear stress to initiate a gully head. Because of this wide adoption, the TT approach could be considered the standard method for predicting gully head locations. In Mediterranean environments TT research mainly focused on cropland (Vandekerckhove *et al.*, 2000; Nachtergaele *et al.*, 2001a), rangeland (Vandekerckhove *et al.*, 2000), almond groves (Vandekerckhove *et al.*, 1998, 2000; Nachtergaele *et al.*, 2001a) and dehesa or pastures (Gómez-Gutiérrez *et al.*, 2009). However, there is still no information on TT for olive groves, even though they cover ca. 10 million ha in the Mediterranean Basin alone (FAOSTAT, 2012) that are considered to be one of the hotspots for soil erosion (Gómez *et al.*, 2008).

More importantly, little attention has been paid to the dynamics of the TT and the role of the rainfall variability and changing vegetation cover. Montgomery & Dietrich (1994) showed how the physical basis of the TT implies that it uses both area and slope as proxies for runoff discharge and critical shear stress. However, runoff production might change significantly as a function of rain event and infiltration characteristics of the soil surface. Infiltration rates may easily change by one order of magnitude depending on soil management and cover (Gómez *et al.*, 2009). In addition, under traditional tillage, soil infiltration characteristics change throughout the growing season due to surface sealing or soil compaction (Edwards & Larson, 1969; Assouline & Mualem, 1997). Therefore, the timing of the erosive rain event causing gullying will control the runoff rate generated. The same is true for the critical flow shear stress that might vary with changes in ground cover (Knapen *et al.*, 2007; De Baets *et al.*, 2007). Istanbulluoglu *et al.* (2002) tried to incorporate this variability into the deterministic TT approach by a stochastic model representation of different input variables. Goméz-Gutiérrez *et al.*, (2009) demonstrated that for a given region TT may change due to land use changes. Rossi *et al.* (2015) discussed how the probabilistic nature of the rainfall intensity-duration-frequency in combination with land use may affect TT for gully head development. However, to our knowledge, no field data about the changes of TT for a given land use over time have been reported. A model that uses a single, deterministic TT for an area implicitly assumes no changes in the runoff-generating characteristics or in the critical flow shear stress for gully initiation. This may yield good predictions for a limited area and over short time periods. Over long periods however, especially if soil management changes, this TT model will lead to either an over- or underprediction of critical drainage areas which affect gully head locations. Rain characteristics can also be expected to differ from year to year. Especially in the Mediterranean climate, year-to-year rainfall variability is large. However, past studies on TT often rely on a single field campaign that -at a specific moment in time- either measure ephemeral gullies formed during one particular year or rain event or else permanent gullies that integrate the effects of rainfall over a longer period (years to decades). In the first case, TT coefficients derived from a short-term study will be conditioned by the characteristics of the rainfall during that particular year or rain event and will therefore not describe TT as well in the past or for future events. In the second case, the location of the gully head will be the cumulative result of many rain events, probably with periods of faster and slower growth that average out specific conditions of gully incision.

Thus, this paper aims to quantify the temporal variation of TT in Mediterranean croplands reflecting the variability of rainfall, land use and vegetation cover. More specifically, the objectives are: (1) to determine TT for olive groves and herbaceous crops, (2) to investigate the dynamics of TT for different periods and (3) to link the TT dynamics to rainfall characteristics and vegetation cover.

MATERIALS AND METHODS

Study zone

The study area covers 20.6 km^2 located in the Western Campiña of the Guadalquivir basin in SW Spain (Figure 3-1). This area was selected because it is representative of agricultural landscapes, which are much affected by gully erosion. Gently sloping hills prevail in the study area, with altitudes ranging from 233 to 558 m a.s.l. The parent material is made up of marls, with a clay content between 40-60 %, and calcareous sandstones, mainly made up of $CaCO_3$ (30-85 %). Vertisols are the dominant soil type in this area. Most soils have a clayey texture and a subangular or prismatic structure, typically with a shallow Ap horizon (0.05 to 0.10 m) and an AC horizon up to 0.50m depth. Clay content is ca. 60-70% in the first meter, with 20-25 % silt and a low sand content, the latter increasing with depth. Mean gully density in the study area has increased from 17.2 m ha^{-1} to 53.3 m ha^{-1} between 1956 and 2013. Hayas *et al.* (2016) attributed this mainly to highly erosive rainfall events in 2009 - 2011, possibly aggravated by important land use changes.

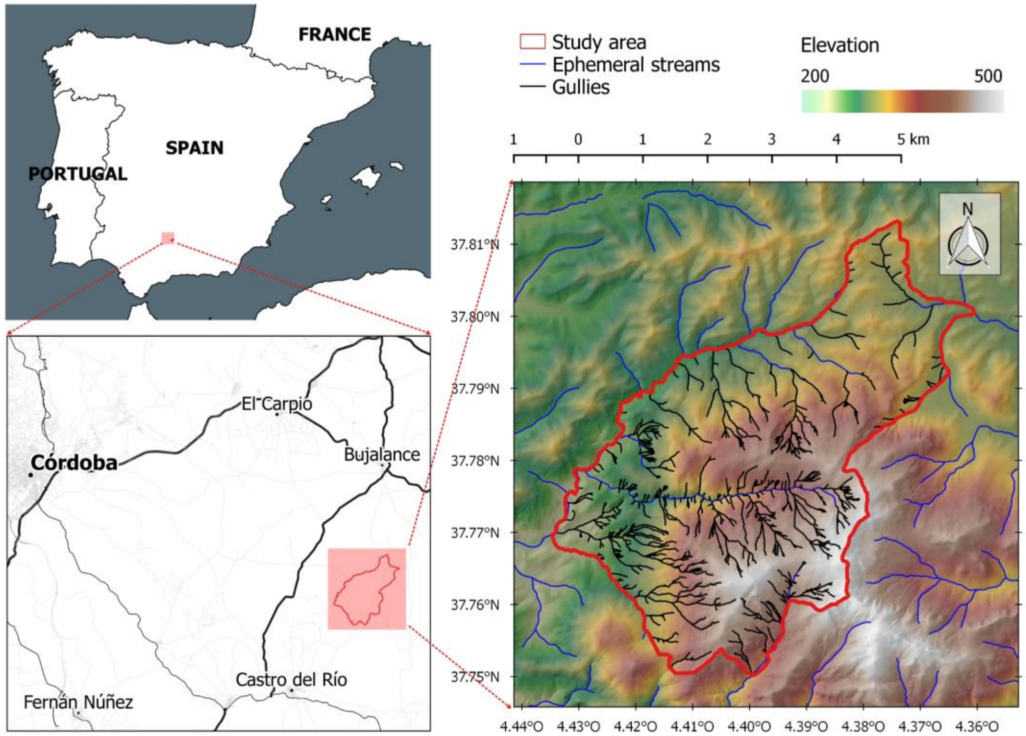

Figure 3-1. Location of the study area with the gully network and ephemeral streams in SW Spain.

The main land use classes in the study area are olive orchards and herbaceous crops. During the study period the fraction of land covered by olive orchards and herbaceous crops changed respectively from 13 - 85 % in 1956 to 63 - 36 % in 2013. The main management practice in olive orchards is conventional tillage to control weed growth, which involves three annual ploughing operations. Wheat - sunflower rotation is the common practice in herbaceous cropland, which generally involves 3-4 tillage operations.

Mean annual precipitation is ca. 550 mm, and shows a marked dry season between June and September while the main wet period occurs from October to May. Further description on the study zone can be found in Hayas *et al.* (2016).

Determination of TT and analysed scenarios

The position of the gully heads was derived from gully networks previously digitised from an orthophoto dataset representing ten individual years: i.e. photos were taken in 1956, 1980, 1984, 1999, 2001, 2005, 2007, 2009, 2011 and 2013. This implies that the position of the gully head corresponds to the year of each particular orthophoto, and that its position is a consequence of the flow incision processes during the period between this particular year and the year the preceding orthophoto was taken. Orthophotos were usually taken in the same month (September). The resolution of the photos limits the width of the gully channels that can be identified to 0.5 - 1 m. More details about the photointerpretation process can be found in Hayas *et al.* (2016).

Since the study area has been subject to changes in crop and soil management and in some cases even to changes in land use, an infilling of some gully channels (by land levelling) could be detected by comparing two consecutive orthophotos. In order to compute TT, only active gullies, where channel growth with respect to the previous orthophoto year was observed, were included in the analysis, hereby excluding stabilised, inactive and artificially infilled or levelled gully heads.

Soil surface slope and cumulative drainage area were extracted from a 5 meter resolution DEM in QGIS. Drainage area was calculated by means of the D-infinity algorithm through the module TauDEM (Tarboton, 1997). This algorithm calculates the runoff contributing area per unit of contour length "a", that was converted to the area "A" (ha) of the catchment draining towards the gully head, to compute the topographic thresholds as follows:

$$s >= kA^{-b} \qquad \textit{Equation 3-2}$$

Since both variables *s* and *A* should be considered independent, s - A relations were determined by means of orthogonal regression, computed in R (R Stats Package). Finally, *k* coefficients were obtained from lowering the previous regression line to the lowest point in a s-A scatter plot, but maintaining the original slope or *b* coefficient, so that all datapoints fall above this threshold line.

Three scenarios were analysed for the *b* coefficient.

(i) The first results from the statistical fit of s-A pairs and allows *b* and *k* to vary freely.

Torri & Poesen (2014) suggested that *b* can be represented by a constant value to simplify $s >= kA^{-b}$ *Equation 3-2*. Therefore, two additional scenarios were analysed with a fixed *b* coefficient:

(ii) A coefficient *b* equal to 0.38 was fixed based on field results by different authors (Nachtergaele *et al.* 2001; Torri & Poesen, 2014).

(iii) Finally, a fixed coefficient *b* equal to 0.5 was also evaluated based on theoretical considerations by Montgomery & Dietrich (1994).

Fixing *b* coefficients allows to isolate the effects of land use and rainfall on the *k* coefficient. By assuming a constant *b* value, one obtains a simpler model that only reflects changes in *k*, representing the resistance to gullying. The constant *b* value implies that one assumes the same overland flow type throughout the study period and study area, and this can be justified from theoretical considerations, as shown by Torri and Poesen (2014) and Rossi *et al.* (2015).

TT and land use

Land use was obtained from maps of the Land Use and Vegetation Cover of Andalusia (REDIAM) for the years 1956, 1980, 1984, 1999, 2003 and 2007, and was derived from the respective orthophotos for the remaining years (2001, 2005, 2009, 2011 and 2013). Three main land use classes were analysed, corresponding to herbaceous crops, olive saplings and olive trees. Herbaceous crops and olive groves were extracted from the land use maps. Olive orchards present in the first map of 1956 were considered mature during the entire analysis. Parcels in which a land use conversion from herbaceous crops to olive groves was observed were considered olive saplings during the next 10 years following the year in which the change was detected. Typical gullies in the three different land use types analysed are shown in Figure 3-2.

Figure 3-2. Illustration of gully types observed in herbaceous cropland and in olive groves of the study area. (a) Headcut at the boundary between an ephemeral gully and a permanent gully in herbaceous cropland; (b) permanent gully after land levelling in an olive saplings parcel; (c) permanent gully in a mature olive grove.

TT and rainfall

The relationship between topographic thresholds and precipitation was studied through 6 different rainfall indexes at 3 different temporal scales. The following rainfall indexes calculated for three periods were used: a) the maximum daily rainfall (mm/day), b) the mean annual rainfall (mm/yr), c) the number of days with a daily rainfall above 13 mm (# days) as this value is considered as the minimum rainfall that produces erosive effects as proposed by Wischmeier & Smith (1978), d) the number of days with a daily rainfall 20 mm (# days) because such rainfall corresponds to a critical rainfall depth needed for gully head development in cropland on clay soils (Poesen *et al.* 2003), e) cumulative rainfall depth for the days with precipitation above 20 mm (mm) and f) rainy day normal (RDN, mm/day; Vanmaercke *et al.* 2016) calculated by dividing total annual rainfall by the number of rainy days during a given year.

The three periods considered include: a) the previous hydrological year which runs from the October 1st to September 30th of the year in which the orthophoto was taken, b) the two previous hydrological years and c) the period between the two dates that orthophotos were made, which varies between 2 and 24 years (i.e. 1956-1980; 1980-1984; 1984-1999; 1999-2001; 2001-2005; 2005-2007; 2007-2009; 2009-2011; 2011-2013).

Rainfall indexes were computed from daily rainfall collected in the period 1956 – 2013 at Castro del Rio meteorological station (37.69º N, 4.47º W), located at 10 km from the study area, belonging to the Spanish State Meteorological Agency (AEMET).

TT and vegetation cover

Vegetation cover was estimated from the aerial orthophotos in order to evaluate their effects on the TT in ENVI 5.2 software. Panchromatic orthophotos (1956, 1980, 1984, 1999 and 2001) were classified into two classes (bare soil and vegetation) based on thresholds values determined by photointerpretation. Colour orthophotos (2005, 2007, 2009, 2011 and

2013) were classified using a supervised classification approach with a maximum likelihood classifier according to two classes (i.e. bare soil and vegetation). Next, the fraction of vegetation cover was extracted for each single parcel characterized by a homogeneous land use composing the landscape mosaic. This vegetation cover fraction was then assigned to the gully heads with a contributing area falling within that land use parcel. For those cases where several gully heads occurred within the same parcel, the k coefficients ($s >= kA^{-b}$

Equation 3-2) for the individual gully heads were averaged. Although orthophotos only provide information at a specific moment (typically during summer) they are still useful to derive a proxy of the vegetation cover preceding the rainy season (October to March). There is of course an important within-season variability associated with the growth and killing of the cover crop, which has been studied by other authors using close-range photography (Taguas *et al.*, 2015) or dedicated aerial photography campaigns (Peña-Barragán *et al.*, 2004). The absence of any other detailed temporal and spatial sources of information makes aerial orthophotos a valuable alternative to derive vegetation cover (Kadmon & Harari - Kremer, 1999), especially at the regional scale. Nevertheless, incorporating the detailed dynamics of cover crops extends beyond the scope of this study and the results on the vegetation cover analysis presented here should thus be interpreted with caution due to the differences in the orthophoto features (B&W or colour images, spatial resolution, etc.) and to their limited temporal coverage.

RESULTS

TT and land use

Figure 3-3 shows the TT for gully head incision for the three land use classes analysed (olive trees, olive saplings and herbaceous crops) over the different years. In this figure, both coefficients *b* and *k* ($s >= kA^{-b}$ *Equation 3-2*) were allowed to vary (scenario 1). TT values of the coefficient *k* obtained varied considerably among the different years: between a minimum value of 0.02 and a maximum of 0.15. The minimum is the same for all land use classes, and was reached in 1999 for herbaceous crops and olive saplings, and in 2011 for olive trees. The maximum *k* value was reached in 2009 in herbaceous crops. Olives and olive saplings reached lower maximum *k* values, respectively of 0.08 (2005) and 0.06 (2007). Note that olive saplings are only present in half of the analysed years, as in the period 1956 - 1984 no olive saplings could be detected in the orthophotos and, in 2005 and 2009 all gully heads in olive sapling areas were stabilised or infilled. In the case of the threshold values of the coefficient *b*, the minimum and the maximum values varied between 0.03 in 2009 and 0.26 in 2011 for herbaceous crops, 0.01 in 1999 and 0.30 in 2007 for olive saplings and 0.02 in 1984 and 0.24 in 2011 for olive trees.

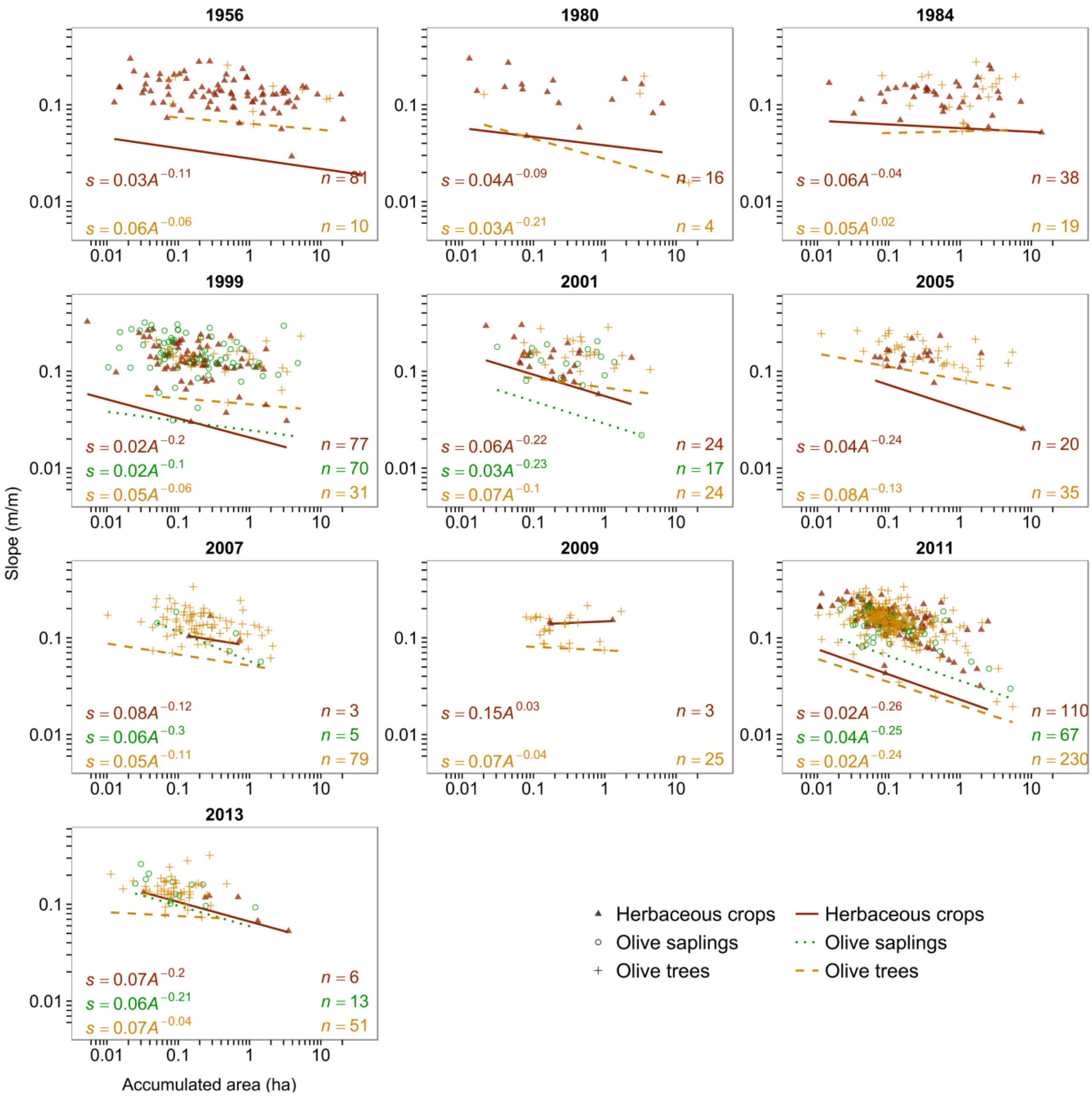

Figure 3-3. Topographic threshold relations for gully heads formed in different years, allowing coefficients b and k (s >= kA-b Equation 3-2*) to vary, and considering three land use classes (herbaceous crops, olive saplings and olive trees).*

From

Figure *3-3* it becomes clear that there is considerable variation and no consistent pattern as to which land use is most susceptible to gully incision. At the beginning of the studied period, in 1956, herbaceous crops are characterized by a smaller topographic threshold (k_{1956}=0.03), clearly below that of olives (k_{1956} = 0.06). However, in subsequent years the threshold lines are more similar to olive trees and they almost overlap (e.g. k_{2013} = 0.07 for both). When olive saplings first appear in the study area, in 1999 and 2001, they seem to have a lower TT (k_{1999} = 0.02 and k_{2001} = 0.03) than mature olive plantations (k_{1999} = 0.05 and k_{2001} = 0.07) although in 2007 and especially 2011 this tendency is reversed.

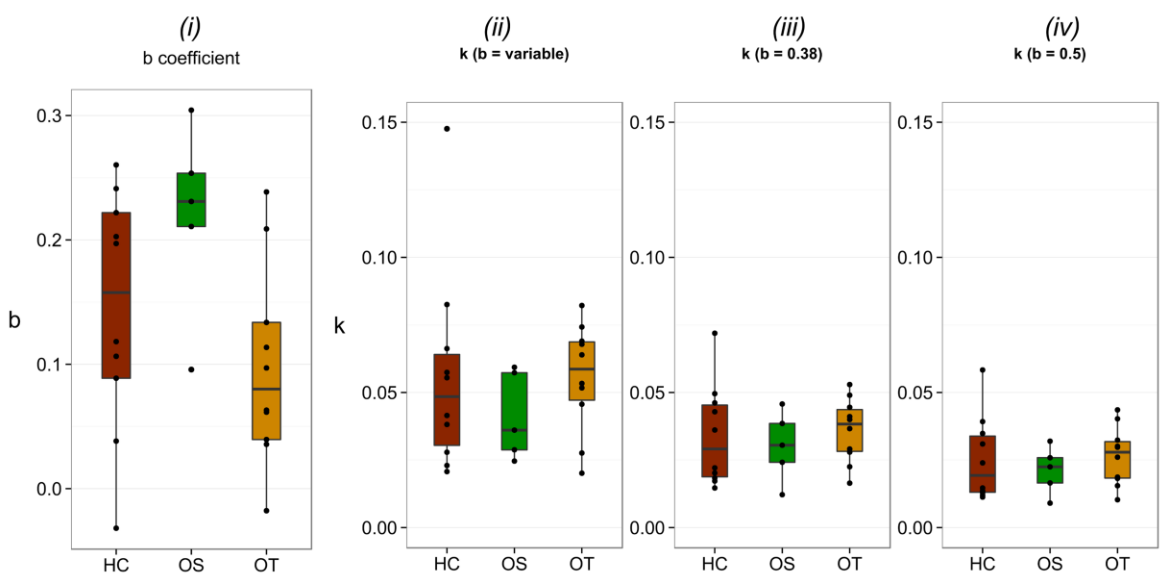

Figure 3-4. Plot box of coefficients b (i) and k (ii) (s >= kA-b
Equation 3-2*) for different b values (i.e. b = variable, b = 0·38 and b = 0·5) for the main land use classes (HC, herbaceous crops; OS, olive saplings; OT, olive trees).*

Also, a more systematic statistical analysis did not reveal any clear differences between land use classes. Figure 3-4 and Table 3-1 show the distribution and mean values of the coefficient *k* and *b* (*s* >= kA-b Equation 3-2) for the three land use classes and the three scenarios analysed: 1) *b* is left variable for different years (Figure 3-4 *i* and *ii*), 2) *b* is fixed at 0.38 (Figure 3-4 *iii*) and 3) *b* is fixed at 0.5 (Figure 3-4 *iv*). The latter two scenarios follow the procedure proposed by Torri & Poesen (2014). Herbaceous crops and olive trees present similar high variability for the *b* coefficient, while in olive saplings the variability of the coefficient *b* is lower. For the *k* coefficient under the three scenarios, herbaceous crops show the largest variability whereas olive saplings show less dispersion.

Table 3-1. Topographic threshold coefficient b (s >= kA-b Equation 3-2*) for gully heads that developed in the different land use classes of the study zone, and coefficient k (s >= kA-b* Equation 3-2*), calculated for different values of the coefficient b (variable, 0.38 and 0.5) for different land use classes. Mean, standard deviation, number of observations for the whole dataset period and p-value.*

Coefficient	Cases	Land use	Mean	SD	*n*	Tukey*	*p*-value**
b	(–)	Herbaceous crops	–0·14	0·10	10	*a* and *b*	$0·0539^{ns}$
		Olive saplings	–0·22	0·08	5	*a*	
		Olive trees	–0·10	0·08	10	*b*	
k	(*b* = variable)	Herbaceous crops	0·06	0·04	10	*a*	$0·59^{ns}$
		Olive saplings	0·04	0·02	5	*a*	
		Olive trees	0·06	0·02	10	*a*	
	(*b* = 0·38)	Herbaceous crops	0·03	0·02	10	*a*	$0·79^{ns}$
		Olive saplings	0·03	0·01	5	*a*	
		Olive trees	0·04	0·01	10	*a*	
	(*b* = 0·5)	Herbaceous crops	0·03	0·02	10	*a*	$0·75^{ns}$
		Olive saplings	0·02	0·01	5	*a*	
		Olive trees	0·03	0·01	10	*a*	

*Pairwise comparisons: land use classes sharing the same letter are not significantly different at α = 0·05.
**ANOVA *p*-value.
^{ns}Nonsignificant.

In the first case, where both *b* and *k* coefficients were left to vary freely (Figure 3-4 *i* and *ii*), mean *b* values ranged between 0.10 and 0.22 for olive trees and olive saplings respectively, but mean *k* values were similar and ranged between 0.04 and 0.06. The results of the ANOVA analysis (Table 3-1) show that there was no significant difference between the *b* values of these land use classes, except between olive saplings and olive groves. In terms of *k* value, mean *k* values were slightly lower in the two scenarios where *b* was fixed compared to the first scenario, respectively 0.03-0.04 (for *b* = 0.38) and k = 0.02 – 0.03 (for *b* = 0.5), but again, no significant land use effect was observed for any of the three scenarios.

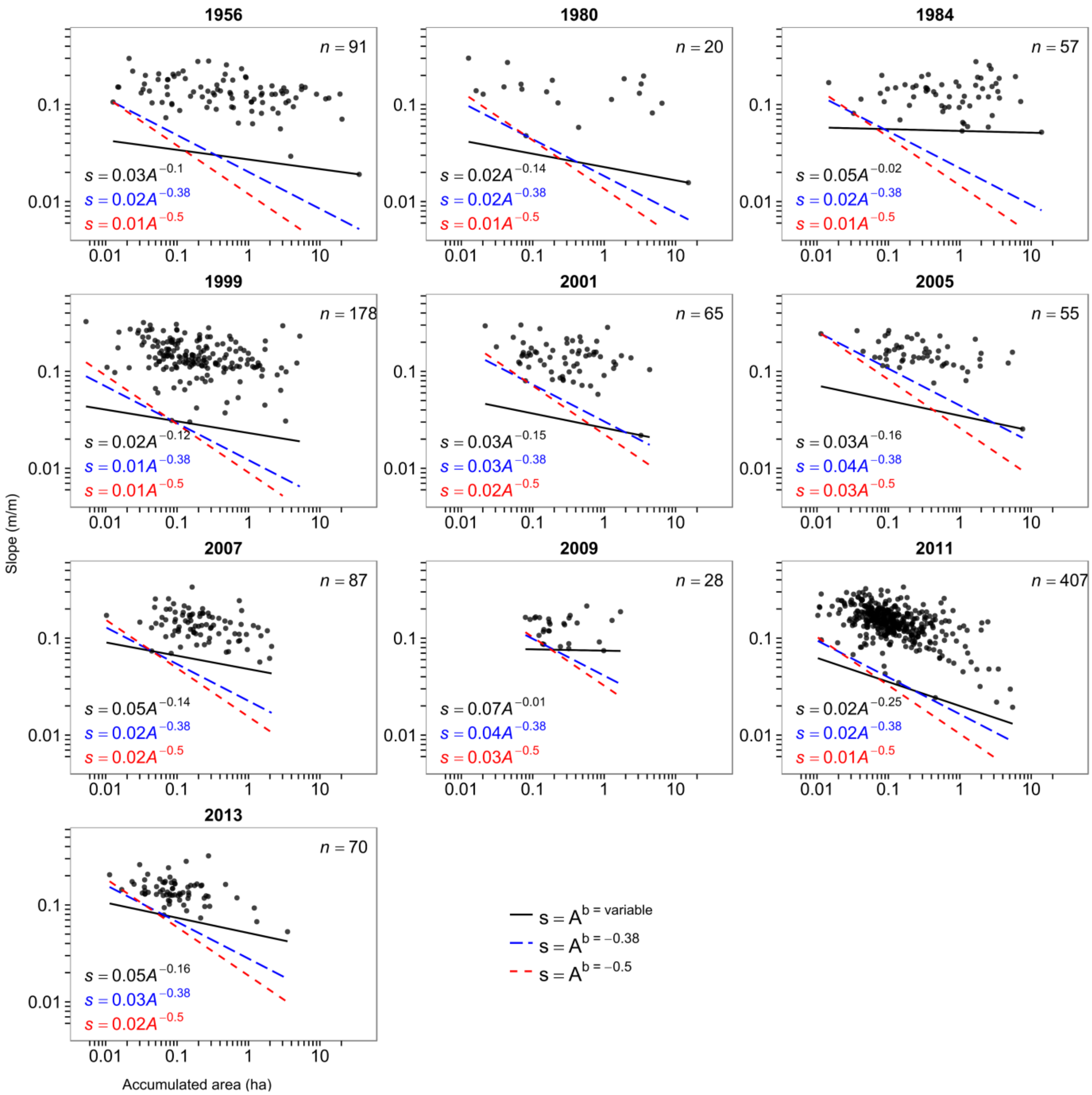

Figure 3-5. Topographic thresholds of gully heads for the different years, considering different values of the coefficient b (variable 0·38 and 0·5) and considering a single land use.

Given that b and k values were not significantly different for the different land use classes investigated, new TT were computed considering a single, uniform land use over the entire study area ("cropland"). These new, single-land use TT are shown in

Figure *3-5*. Again, the same three scenarios were considered for calculating the b coefficient and are shown in black, blue and red in

Figure *3-5*. In the case of the b coefficient left variable over time (scenario 1), its values ranged between 0.01 in 2009 and 0.25 in 2011 whereas the corresponding k values ranged between 0.02 (in 1980, 1999 and 2011) and 0.07 (in 2009). For the second scenario of b fixed at 0.38, k values ranged between 0.01 in 1999 and 0.04 in 2005 and 2009. For the third scenario with b fixed at 0.5, slightly lower k values were obtained, ranging from 0.01 between 1956 – 1999 and in 2011, to a maximum value of 0.03 in 2005 and 2009. From

Figure *3-5*, it can be observed that the position of the TT line varies considerably over time. Subsequent analysis therefore focussed on relating this variability to changes in rainfall and vegetation cover. As discussed in the introduction, both factors can be expected to have a direct influence on TT through changing runoff generation characteristics or by altering the critical flow shear stress to gully incision. Although in the previous analysis, no significant land use effect was observed, it is possible that absolute vegetation cover changes over time, even within different land use classes, and that those changes are more important than land use effects.

TT and rainfall

The relation between the gully erosion resistance coefficient *k* ($s >= k \quad a^{-b}$ *Equation 3-1* and $s >= kA^{-b}$ *Equation 3-2*) and rainfall indexes is shown in Figure 3-6 and Figure 3-7. Figure 3-6 shows the correlation of the three most significant rainfall indexes with the *k* value. Rainfall indexes generally explain a high proportion of the observed variation in the temporal variation of the coefficient *k*. The highest r^2-values were obtained for the RDN index computed for the two previous hydrological years when *b* was fixed at 0.38 ($r^2 = 0.77$) and at 0.5 ($r^2 = 0.73$). The RDN was the index that best explained the variation of the coefficient *k*. Only in the case of *b* coefficients left variable the other rain indexes showed a higher explanatory power. In those cases, both the number of days with more than 20 mm/24h and the number of days with more than 13 mm/24h, computed for the entire period between two orthophotos, were similar (r^2 = 0.39). Figure 3-7 explores in more detail the relationships found between the *k* coefficient and the RDN index computed for the two previous hydrological years when considering *b* equal to 0.38. In this case, a significant correlation (p – value = 0.002) was found when clustering all land use classes.

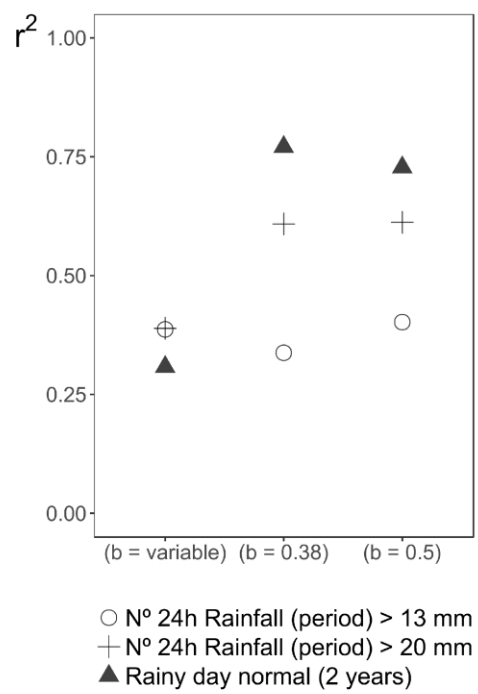

Figure 3-6. Coefficient of determination (r^2) between the gully erosion resistance coefficient k (s >= kA-b Equation 3-2*) considering a single land use and three rainfall indexes: #P_{daily} > 13 mm in the complete interperiod, #P_{daily} > 20 mm in the complete interperiod and the RDN computed for the two previous hydrological years.*

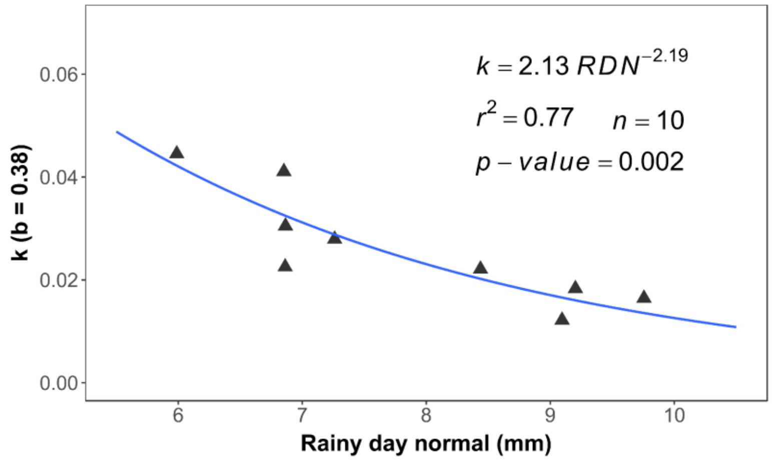

Figure 3-7. Gully erosion resistance coefficient k (s >= kA-b
Equation 3-2*) for a fixed coefficient b = 0·38 as a function of the rainy day normal (RDN) computed for the two preceding hydrological years and considering a single land use.*

TT and vegetation cover

The influence of vegetation cover on the temporal variation of the *k* coefficient is shown in Figure 3-8. The mean fraction of vegetation cover for the whole period was 0.14, with a standard deviation of 0.11. A significant positive exponential correlation was found between the vegetation cover and the mean value of the coefficient *k* for specific years: 1999, 2005, 2007 and 2013. For the remaining years, no significant correlation could be found. For the years where a significant relation could be observed, vegetation cover explains generally less of the variability in k coefficients than rainfall indexes, except for the years 2007 and 2013 where the model explains 46-71% of the observed variance.

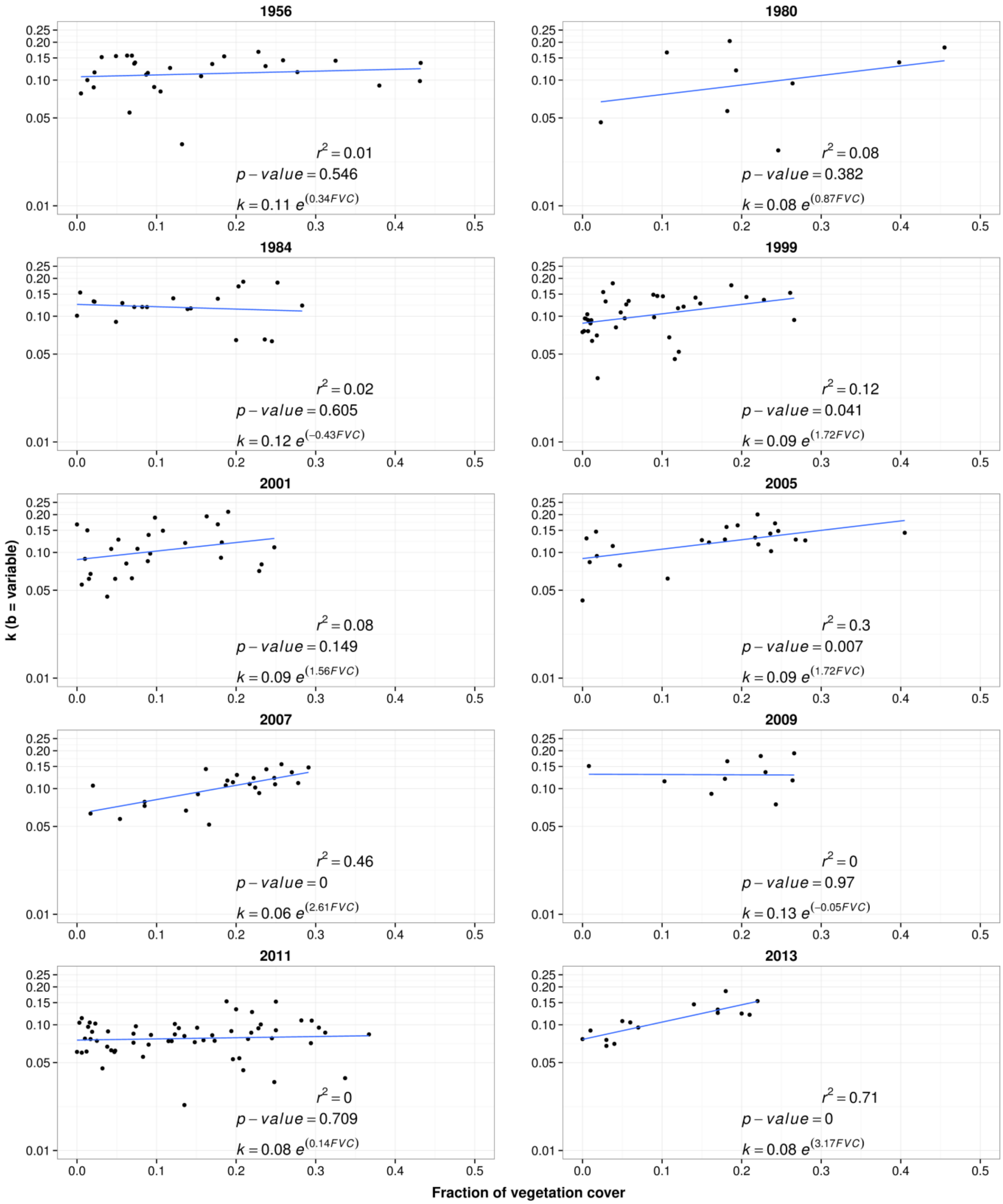

Figure 3-8. Annual gully erosion resistance coefficient k (s >= kA-b Equation 3-2*) as a function of vegetation cover (for the case of b = variable).*

DISCUSSION

This study calculated TT coefficients for gully incision during 10 different time frames and for three land use classes: herbaceous crops, olives and olive saplings. However, for none of the studied periods a significant effect of land use class on TT could be detected. This is in contrast to other water erosion processes, such as splash, sheet and rill erosion, where land use has a strong control on erosion rates (Cerdan *et al.*, 2010; Maetens *et al.*, 2012). The lack of differences in TT between the three land use classes present in the study zone, either in the *b* or in the *k* coefficients, can be attributed to two main reasons. Firstly, absolute vegetation cover as measured from the orthophotos is small, both in olive orchards and in herbaceous crops. Vegetation cover in olive orchards in the area is in most cases below 25 %. The average vegetation cover for both olive classes (saplings and mature trees) is 16% with a standard deviation value of 9% which is similar to that obtained for herbaceous crops (10 ± 14 %). Secondly, olive orchards and herbaceous crops present similar runoff behaviour. Based on empirical observations of runoff, Taguas *et al.* (2015) calculated the Runoff Curve Numbers (CN) for olive orchards catchments in Vertisols, in a location nearby the study area, to vary between 84 and 87. Likewise in herbaceous crops, CN values for different crop cover treatments and for the same soil group range between 80 and 88 (USDA-NRCS, 2004). Hence both land use classes present a similar high runoff potential and similar soil cover, leading to a similar flow shear stress for gully incision. It has to be noted that although there is generally no significant land use effect, this might be different for the extreme values. Figure 3-4 suggests that although the mean *k* and *b* values are similar, a probabilistic approach could give slightly different results due to a difference in the high values (Istanbulluoglu & Bras, 2006). Herbaceous crops are characterized by the highest *k* values in all three scenarios: from 0.15 to 0.06 in the case of *b* variable and *b* = 0.05 respectively.

Table 3-2. Comparison of b and k values (s >= kA-b Equation 3-2*) from this study with those reported for similar land use classes in Mediterranean Environments.*

Land use	Location	Source	b	k	k (b = 0·38)	k (b = 0·5)
Herbaceous crops	Castro del Rio (Spain)	This study	0·15 (−0·03–0·26)	0·06 (0·02–0·15)	0·03 (0·01–0·07)	0·03 (0·01–0·06)
Olive saplings	Castro del Rio (Spain)	This study	0·22 (0·1–0·3)	0·04 (0·02–0·06)	0·03 (0·01–0·05)	0·02 (0·01–0·03)
Olive trees	Castro del Rio (Spain)	This study	0·1 (−0·02–0·24)	0·06 (0·02–0·08)	0·04 (0·02–0·05)	0·03 (0·01–0·04)
All land use classes	Castro del Rio (Spain)	This study	0·13 (0·01–0·25)	0·04 (0·02–0·07)	0·03 (0·01–0·04)	0·02 (0·01–0·03)
Almond groves	Cerro Tonosa (Spain)	Vandekerckhove *et al.* (2000)	0·10	0·23	0·06	0·03
	Rambla Chortal (Spain)	Vandekerckhove *et al.* (1998, 2000)	0·14	0·15	0·05	0·06
	Guadalentín (Spain)	Nachtergaele *et al.* (2001a)	0·13	0·15	0·03	0·02
Cereal crops	Alentejo (Portugal)	Vandekerckhove *et al.* (2000)	na	na	0·04	0·03
	Alentejo (Portugal)	Nachtergaele *et al.* (2001b)	0·29	0·09	0·04	0·05
Rangeland	Cabo de Gata (VC < 0·15) (Spain)	Vandekerckhove *et al.* (2000)	0·27	0·1	0·05	0·04
	Cabo de Gata (VC > 0·15) (Spain)	Vandekerckhove *et al.* (2000)	0·27	0·1	0·06	0·05
Dehesa: treeless pastureland–savannah-like oak ranges	Parapapuños (Spain)	Gómez-Gutiérrez *et al.* (2009)	0·41	0·09	0·07	0·09

Fixing the value of the *b* coefficient allows to compare the results of standardised *k* coefficients with those obtained by other authors in a similar environment. Table 3-2 summarizes the TT coefficients *b* and *k* from this study and from other Mediterranean environments. Values of the standardised coefficient *k* found for herbaceous crops in this study are very similar to those reported by Torri & Poesen (2014) based on the studies of Vandekerckhove *et al.* (2000) and Nachtergaele *et al.* (2001) for cereal crops in South Portugal (see Table 3-2), although South Portugal's climate has some oceanic influence. So far there are no studies reporting TT for gully development in olive orchards. Therefore, the *k* coefficients found in this study could not be compared for this land use class. However, there are Mediterranean orchards with similar structure and cover that may be used to compare with the *k*-values obtained. For instance, Vandekerckhove *et al.* (1998, 2000) and Nachtergaele *et al.* (2001) reported values for the TT coefficients in almond groves in Southwest Spain. Coefficients in almond groves, later standardised by Torri & Poesen (2014), are similar to those obtained in this study for olive orchards (see Table 3-2). Gómez-Gutiérrez *et al.* (2009), reported *b* and *k* values for gully development in dehesas, which in spite of being a more naturalized agrosystem, present a similar canopy cover and values for the standardised *b* and *k* coefficients (Table 3-2). In conclusion, TT for gully development in olive groves observed in this study are not statistically different from the TT under herbaceous cropland. Possibly variations in planting patterns or the presence of terraces could affect the TT, but this could not be investigated in this study.

The method used here, based on interpretation of orthophotos, allows for a quick and reliable estimation of TT values for gully head development over large areas. As shown in Table 3-2, the results for cropland and orchards in Mediterranean environments found in this study are very similar to those reported in other studies. The difference is that previous studies are mostly based on detailed and often time-consuming field campaigns where gully heads are located in the field and local slope and contributing area are measured on the ground. The wide availability of detailed orthophotos for many regions in the globe, and of increasingly detailed DEMs contributes to enhance the use of this method. Many areas in the world also have LiDAR-based DEMs available, which allows for a more accurate estimation of slope and contributing area.

While no significant effect of different cropland types was found, this study did find an important variability of the TT for gully incision over time. This variability could be related to a variability of rainfall and absolute vegetation cover.

Of the different rainfall indexes analysed, three showed particularly successful in explaining the temporal variation of *k*. In general, the RDN index, and the number of rainfall events exceeding a threshold depth (i.e. 13 and 20 mm) during the entire period between two orthophoto dates are best correlated with the variation of the coefficient *k*. In all cases, the correlation with the *k* coefficient values is negative, as can be expected, which implies that higher rainfall index values lead to a decrease of the threshold for gully incision. The RDN index explains up to 77% of the variation in the *k* coefficient, in the case of considering a single land use class and fixing the *b* coefficient at 0.38. This is in line with recent findings by Vanmaercke *et al.* (2016) who reported that RDN is a suitable rain index for predicting gully headcut retreat rates at a global scale. Similar correlations between gully headcut retreat rates and daily precipitation have been previously reported by Frankl *et al.* (2012). Although, there are some differences depending on whether the analysis is limited to a single land use class or by considering all three land use classes together, and depending on the rainfall index used, in general rainfall characteristics perform well in explaining the variability of TT. Previous studies on the dynamics of gullies and its relation with precipitation have been mainly focussing on gully-head retreat rates (Rieke-Zapp & Nichols, 2011; Vanmaercke *et al.* 2016) and the gully erosion rates (Oostwoud Wijdenes *et al.*, 2000; Martínez-Casasnovas *et al.*, 2003; Hayas *et al.*, 2016). The linkage between the dynamics of the TT for gully head development for a given land use type and temporal variations in precipitation characteristics in this study is novel. TT for gully incision could also be linked to absolute vegetation cover. Vegetation cover shows in some years a significant, positive correlation with the *k* coefficient (for 1999, 2005, 2007 and 2013). This implies that during those years a higher vegetation cover leads to a lower susceptibility to gully incision. It is remarkable that particularly in those years with a relatively small rainfall depth recorded over the previous years. This seems to indicate that vegetation cover does play a role, but only a secondary one. A more relevant role of vegetation could be expected in other areas where a larger range of vegetation cover occurs. In our study, the range of rainfall variability is large while the range of vegetation cover is small. Therefore, in our study, the effect of rainfall appears to be dominant and explains a high proportion of the temporal variability of *k*-values. Only in years with a small rainfall depth, vegetation can make a difference in gully head development.

However, further statistical analysis of the relation between the slope of the *k* vegetation cover relation in Figure 3-8 and the different rainfall indexes did not allow to confirm this hypothesis. This could be partially explained by the different resolution of the oldest orthophotos, which made the computed vegetation cover for those years somewhat difficult to compare with those obtained in the last period (2005 - 2013). On the other hand, gully infilling and land levelling have resulted in a reduction of detectable gully initiation sites in some years (i.e. 1980 and 2009). Finally, this method does not allow to distinguish between cropland plots treated by different soil management and agricultural practices.

Further research should therefore be made to take this into account. Svoray & Markovitch (2009) for example found that including tillage direction and unpaved roads improved prediction of gully incision in orchards. Significantly higher runoff coefficients have been reported for conventional tillage as compared to cover crops in olives (e.g. Gómez *et al.*, 2009). Cover crops will also result in a higher root density and, consequently, higher critical flow shear stress (De Baets *et al.*, 2007). Changes in soil management can therefore be expected to result in significant changes of the TT for gully initiation. A more detailed study on the dynamics of vegetation cover over the growing season is needed. The publicly available orthophotos that were used in this study only offer a snapshot of the vegetation cover. As aerial photos are usually taken in summer (August-September), because of optimal meteorological conditions, this implies that this study detected only a minimum vegetation cover. It remains to be seen how a cover crop, grown in winter between the olive trees for example, could affect gully incision.

CONCLUSIONS

In this study of ephemeral and permanent gully development in a 20.6 km^2 catchment Topographic Threshold (TT) conditions for gully head development under olive orchards and herbaceous crops and their dynamics over a period of 57 years have been determined. The results indicate that the TT for gully initiation (s >= kA-b *Equation 3-2*) were similar for both cropland classes. Normalized *k* coefficients found for olive orchards are very similar to those for herbaceous crops in the study area and for those reported in other studies for similar orchards (almond groves) and cereal crops.

For the first time however, an important temporal variability in the TT values for a given study area was demonstrated. This variability was explained by rainfall effects and by vegetation cover, the latter being dominant. Such observation has important implications for using TT in future predictions of gully network development, especially under changing rainfall conditions or different soil and crop management practices. Rainfall erosivity indexes, such as the RDN computed for the two previous hydrological years and those expressing the number of precipitation events exceeding a threshold depth value (13 and 20 mm) successfully explain the decrease in *k* values. The results obtained in this study further suggest that the effect of vegetation cover on the TT is limited to those years with moderate precipitation. This indicates that during rainy years, vegetation cover below 25% could not prevent gully incision, although the limitations of the applied method require further investigation.

Another interesting conclusion is that when *b* values are allowed to vary freely, they do not converge necessarily to the theoretical values proposed. Rossi *et al.* (2015) suggested this could be due to a possible bias for larger contributing areas, although this could be excluded in our case. Gully catchment areas are relatively small, i.e. generally below 10 ha, with overland flow concentration times below 1 hour. Future studies should explore further the discrepancy between theoretical considerations and field data.

Finally, the methodology applied in this study, based on a combination of orthophotos and GIS analysis, provides important advantages compared to previous studies that are based on field surveys. This methodology allows saving time, surveying larger areas and also allows for a sequential analysis over decades. Nevertheless, its limitations are that it does not allow exploring the seasonal or interannual variability of gully thresholds if one does not have access to several orthophotos taken annually.

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Chapter 4

Predicting gully width and widening rates from upstream contribution area and rainfall: a case study in SW Spain

4. PREDICTING GULLY WIDTH AND WIDENING RATES FROM UPSTREAM CONTRIBUTION AREA AND RAINFALL: A CASE STUDY IN SW SPAIN

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ABSTRACT

Gully width (W) is usually characterized by a power relation with discharge. However, calculating runoff discharge in ungauged basins, where these gullies typically form, is inherently difficult and associated with large uncertainties. This paper examines a simplified approach to relate gully width directly to runoff contributing area (A) in a cultivated area in SW Spain. The effect of rainfall and land use on this W-A relation was also analysed. Gully width was measured in 46 sections by analysis of 10 historical orthophotos between 1956 and 2013, in a 21 km^2 catchment in S Spain. These were validated by field measurements in 2013.

Widening rates varied strongly over time, between ~0 and 2,19 m year^{-1}. No significant differences in gully widening rates were found between the two land uses present in the study zone (olive groves and herbaceous crops). The obtained data show a significant power relation of the form $W=\alpha A^{\beta}$ for all analysed time periods, except for 1980 when many gullies were filled in artificially due to a change of land use in the study area. The coefficient of the power relation (β) varied between 0.2 and 0.3. A good correlation was obtained between the number of days with daily rainfall above 13 mm and the increase of the α coefficient over time. The results of this study on gully width dynamics provide new insight to improve the estimation of gully volume, for example in combination with gully headcut retreat models, and including the effect of different climatic scenarios.

Keywords: gully erosion, width, catchment area, land use, rainfall index, Spain

INTRODUCTION

The expansion of gully networks takes place through a combination of different physical processes: incision, gully headcut migration and channel widening (Bingner *et al.*, 2015). Each of these processes can be dominant during specific phases of gully development. Most research effort has focused on the processes of gully headcut incision and migration. In a recent review by (Vanmaercke *et al.*, 2016), an average gully headcut retreat rate of 0.89 m yr^{-1} was established based on 70 study areas globally. In contrast, current understanding of gully widening processes and its contribution to sediment production in gullies is much more limited. Yet often, this process can be considered the dominant source of sediment. In mature gullies, where gully heads are stabilized or headcut retreat rates are low, sediment production is mainly due to widening or incision processes of the gully channels. Also, where incision processes are limited due to the presence of a hard, non-erodible layer, widening processes can be considered dominant processes of sediment production. Gully sidewall failures accounted for more than 80% of the total eroded sediment in gullies in the loess area of the Midwest United States (Simon and Rinaldi, 2000), and for over half the gully volume in New South Wales, Australia (Blong *et al.*, 1982). Hayas *et al.* (2017a) also found that widening processes have a relevant contribution to the total eroded volume in permanent gullies in Mediterranean orchards. They observed from historical aerial orthophotos for the period 1999-2009 that while total gully length decreased, the overall gully volume increased by 50%. This increase was caused completely by gully widening and deepening. Therefore, this paper explores a novel, simplified approach to relate gully width directly to runoff contributing area (*A*) in a cultivated area in SW Spain.

In previous studies, different approaches have been made to measure gully width evolution. At laboratory scale most experiments have been designed to investigate the impact of a non-erodible layer on gully widening (Gordon *et al.*, 2007; Wells *et al.*, 2013; Momm *et al.*, 2015; Qin *et al.*, 2018). Under field conditions, non-erodible layers often develop due to conventional tillage operations (Wells *et al.*, 2013) where the lower edge of the plow tends to compact the soil, resulting in a plow pan. Under these conditions, gully widening rates increase as incision reaches this plow pan (Qin *et al.*, 2018). Wells *et al.* (2013) established an empirical equation relating equilibrium gully width to slope and discharge, based on measured channel width from constant discharge experiments. An experiment by Qin *et al.* (2018) evaluated different form parameters in addition to gully width, such as the scour length of basal undercutting, failure arc length and tension crack length. They were able to decompose sediment delivery into concentrated flow erosion at the sidewall toe and gravity erosion due to sidewall collapse. Although such laboratory gully widening experiments have contributed significantly to the understanding and prediction of channel widening processes, they are subject to several limitations. Due to the inherent constraints of laboratory conditions, that limit the width and depth of the gullies that can be studied, these experiments simulate large rills or small ephemeral gullies at best. Under field conditions, where larger, permanent gullies develop, this less erodible soil layer is often found at larger depths, for example a bedrock layer. Deep gullies are more prone to the process of gully widening through the combined undercutting of gully sidewalls, either by concentrated flow erosion or by subsurface flow and piping, and subsequent gravitational gully sidewall failures. More field studies are needed to fully understand the complexity of these interacting processes.

At field scale, there is a general lack of detailed observations on gully widening. Existing algorithms have been developed mainly based on hydraulic theories, combined with field observations. Foster and Lane (1983) proposed a set of equations to describe channel adjustment from an initial shape to its equilibrium shape. These expressions were later simplified by Watson *et al.* (1986) by means of a non-linear regression analysis with computed gully width values and causative variables. Watson *et al.*'s (1986) analysis resulted in a predictive equation for gully width as a function of peak flow discharge, Manning's roughness coefficient, soil surface slope and critical flow shear stress. Thereafter, this theoretical framework by Foster and Lane (1983) and the subsequent developments by Watson *et al.* (1986), were implemented in multiple ephemeral gully erosion models, as for instance CREAMS (Knisel, 1980), WEPP (Ascough *et al.*, 1997), EGEE (Watson *et al.*, 1986), and EGEM (Woodward, 1999). These equations and models have two disadvantages however. On the one hand, the input parameters required are difficult to retrieve accurately over a broad area. On the other hand, these models have not been found successful enough in predicting ephemeral gully erosion processes, especially when tested in Mediterranean areas (Nachtergaele *et al.*, 2001; Capra *et al.*, 2005). Instead, Nachtergaele *et al.* (2002) proposed an alternative predictive equation. Following the empirical relations proposed by

Leopold and Maddock (1953) and Wolman (1955) for the hydraulic geometry of rivers, who expressed channel width (W) as a function of the flow discharge (Q) in the form of,

$$W = a \cdot Q^{b} \qquad \textit{Equation 4-1}$$

he reported an empirical channel width equation for ephemeral gullies for sealed croplands, were a and b coefficient resulted as follows (Nachtergaele *et al.*, 2002):

$$W = 2.51 \cdot Q^{0.412} \qquad \textit{Equation 4-2}$$

These equations are currently used in the most recent gully erosion models, implemented in AnnAGNPS (Bingner *et al.*, 2009). In principle, gully channel width refers here to bottom width. However, in most cohesive soils this relation can be expected to be valid as well for gully top width, as in such soils the gully walls can be expected to be relatively steep.

However, the calculation of representative peak flow discharge values could be complex and entails high uncertainty. Nachtergaele *et al.* (2002) for example used the rational method. Although this rational formula is still widely used in the absence of accurate input data, it oversimplifies the complex catchment hydrology and is well known to exhibit several limitations (Grimaldi and Petroselli, 2015). In any case, as the rational formula calculates peak discharge as a simple linear function of contributing area, one can wonder whether or not the latter variable would be enough to predict gully width. While AnnAGNPS allows more advanced discharge calculations, that partly solve this drawback, there is another limitation to using the Nachtergaele equation, as it defines gully widening from a deterministic approach, solely dependent on the maximum discharge occurring over the gully's lifespan, and independent of the initial gully channel width. Under that approach, once a big rainstorm passes and shapes a gully channel, this gully will not increase in width anymore in later rainstorms of smaller intensity. This is contrary to existing field observations (for example, Hayas *et al.*, 2017a).

Other efforts have focussed on specific processes involved in gully channel widening. Istanbulluoglu *et al.* (2005) explored gully widening by slab failures through a soil mechanics approach. They tested their theory successfully with field data from Colorado and implemented it in the CHILD landscape evolution model. However, its use is also complicated over larger areas as it requires detailed field information on bank height, tension crack and slab failure geometry. More recently, Salvador Sanchis *et al.* (2009) related gully width to gully channel junctions. They extend the validity of the *W-Q* relation in badlands and forest areas and develop a procedure to estimate the *W-Q* exponent and proportionality coefficient based on channel junctions. They report how the proportionality coefficient a is not constant but increases with increasing gully width, from approximately 0.35 to 0.60. However, the authors state that their approach is not sufficiently parameterized yet to be of practical use in predicting gully width evolution.

In order to obtain an approach that can easily be used to predict gully widths over large areas, and even historical time scales, and considering that prediction of runoff discharges in ungauged basins is highly uncertain, we hypothesize that a simpler approach is needed that relates width simply to contributing area. Typically, contributing flow area (*A*) has been used as proxy for flow discharge (*Q*). Based on the Leopold and Maddock (1953) relationship cited above (Equation 1), a direct relation between W and A could therefore be expected, that will be of the same power form. On that basis, Frankl *et al.* (2013) obtained a relationship between gully channel width and contributing flow area for shale and volcanic soils in Northern Ethiopia Highlands. In a review, Vanmaercke *et al.* (2016) established a significant relation between gully channel width and contributing flow area including sandy, silty and clayey soils obtained from more than 70 different studies worldwide.

This *W-A* relation can be expected to evolve over time as gullies grow. Also, the relation *A-Q* is influenced by the catchment's runoff response, that is controlled by land use and rainfall intensity. Therefore, it can be expected that land use and land cover changes, as well as temporal changes in the rainfall dynamics, influence this relation as well.

The general objective of this study is to design a simple method to predict gully width and its increase over time as a function of upstream contributing area, rainfall and land use.

The specific objectives are to:

(i) Develop an optimal method to derive gully width from aerial orthophotos.

(ii) Characterize gully width dynamics between 1956-2013 for the two different land use classes in our study area: cereal and olive.

(iii) Analyse the relation between gully width and upstream drainage area, and the influence of rainfall and land use (cereal vs olive) on this relation.

MATERIALS AND METHODS

Study zone

Gully sections were selected from a gully network of approx. 110 km located in the town council of Castro del Rio (Cordoba), in the Western Campiña of the Guadalquivir Basin (Spain) (Figure 4-1). The study area has been previously reported to experiment an expansion of the gully network from a drainage density of 17.2 m/ha in 1956 to 53.3 m/ha in 2013. Apart from the enlargement of the gully network, gully widening processes has also been detected over the last 60 years. Landscape in the study area is representative of the predominant agricultural landscape in the low valley of the Guadalquivir mainly dedicated to herbaceous crops and olive trees (Figure 4-2). It is located in the geographical unit of Campiña Baja. The conformed gully network drains to several tributaries of the Guadajoz river which in turn drain to the Guadalquivir river. Geomorphologically speaking, landforms are dominated by a succession of rounded hills (mean slopes 13%) and shallow valleys, only interrupted by occasional promontories made up of harder lithology. Steeper slopes (up to 34%) exceptionally appear in the south and central-east of the study zone. Altitude varies from 233 to 558 m a.s.l. Parent material is conformed of marls and calcareous sandstone deposited in the Neogene. Dominant soil type in the area are Vertisols mainly developed over marls and calcareous sandstones. Soils have a high clay content, typically higher than 60 % in the first metre, 20–25% silt and a low sand content, the latter increasing with depth. Soils generally present an Ap-horizon (0.05 to 0·10 m) and an AC-horizon up to 0.50 m depth.

The climate in the area is representative of the Hot-summer Mediterranean climate (Köppen type Csa). Mean annual temperature is 17 ºC and the mean annual rainfall is 573 mm (Castro del Rio station, Spanish State Meteorological Agency). Rainfalls are mainly concentrated between October and May, while the dry season extends from June to September.

Figure 4-1. Location of the study area within Spain and within the Guadajoz catchment.

Agriculture, mainly consisting of cereal crops, and livestock activities have been documented from the Neolithic to the Iberian period (Sáez *et al.*, 2015). A process of increasing degradation of the previous evergreen oak woodland took place during the Chalcolithic by increasing farming activities. This deforestation process would become even more evident during the Late Bronze and the Iberian period.

Recent land use changes were analysed by Hayas *et al.* (2017b). In the period between 1954 and 2013 the land use cover by olive groves has progressively increased from 13% to 63%, while cereal cropland has decreased from 85% to 36%. Herbaceous cropland usually consists of a wheat-sunflower rotation involving between 3 and 4 annual tillage operations. Weeds are controlled in olive groves by conventional tillage. Further description on soil characteristics, management practices and land use changes could be found in Hayas *et al.* (2017a) and Hayas *et al.* (2017b).

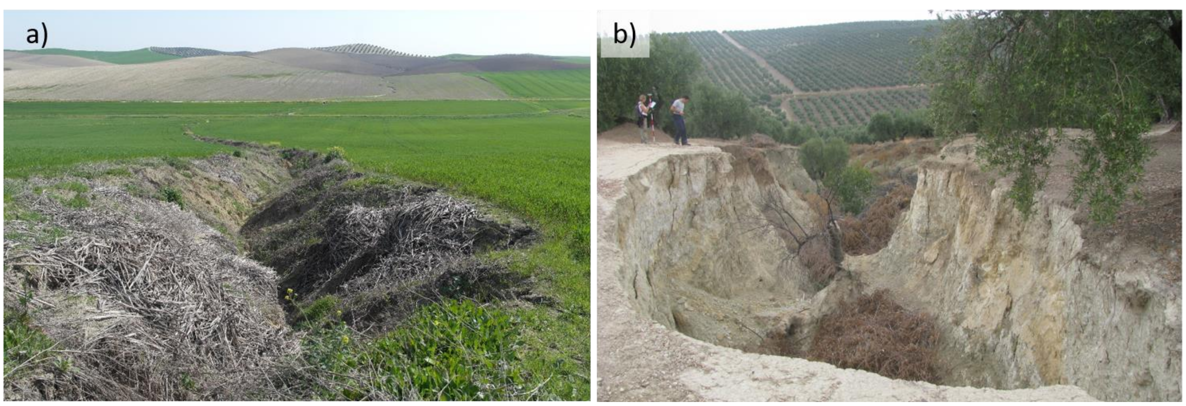

Figure 4-2. Representative gullies and landscape in the study area. A) gully in herbaceous crop partially filled in with harvest remains of sunflowers stems. B) large gully in an olive grove.

Measurement of gully width

Gully top widths were determined by photointerpretation based on a dataset of ten different aerial orthophotos taken in the years 1956, 1980, 1984, 1999, 2001, 2005, 2007, 2009, 2011 and 2013. Table 4-1 summarizes the main characteristic of the orthophotos used. Forty-nine different gully segments well distributed along the gully network were selected. As a selection criterion it was checked that these segments presented clearly recognizable gully borders in all the years of the orthophoto dataset. In practice, this was not always possible, as in some years gully channels were partially filled in by farmers. Therefore, the total number of gully width data points obtained was 460, slightly below the theoretical 490 data points (49 segments x 10 time periods). Gully top widths in the selected segments were measured by digitalizing the distance between the recognizable borders, perpendicular to the flow direction.

Table 4-1. Summary of aerial orthophotos dataset.

	1956	*1980*	*1984*	*1999*	*2001*	*2005*	*2007*	*2009*	*2011*	*2013*
Resolution (m)	*1.0*	*0.5*	*1.0*	*1.0*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*
Colour	*b/w*	*b/w*	*b/w*	*b/w*	*b/w*	*colour*	*colour*	*colour*	*colour*	*colour*
Scale of photographs	*1/32.000*	*1/18.000*	*1/30.000*	*1/40.000*	*1/40.000*	*1/30.000*	*1/30.000*	*1/30.000*	*1/30.000*	*1/30.000*

One potential problem that was identified in this phase is that as small irregularities in the gully width occur frequently over small distances, it is sometimes difficult to establish a location to measure gully width in a representative way, or it is not clear whether a single measurement of gully width is representative. In order to evaluate the optimal number of distance measurement replications required for obtaining a representative gully width, 20 segments were measured in detail in the orthophoto of 2013. In these, a total of 10 measures were made over a short distance along the gully segment. It was then evaluated how much increase in accuracy each of the additional measurement replications adds to the averaged obtained gully width.

This evaluation was performed by means of an adaptation of the Nash-Sutcliffe model efficiency coefficient, *NSE*, as described below:

$$NSE = 1 - \frac{\sum_{s=1}^{S}\left(w_m^s - w_o^s\right)^2}{\sum_{s=1}^{S}\left(w_o^s - \overline{w_o^S}\right)^2} \qquad \textit{Equation 4-3}$$

where w_o^s is assumed to be the observed width for each segment *s*. It is hypothesized that the average of all the ten measured widths equals the "real" or observed value of gully width in a segment *s*. $\overline{w_o^S}$ is then the average observed width over the twenty observed segments. w_m^s is the model width, computed as the mean width obtained from a limited number of observations. This model width is first calculated using a single observation. Next, two sections are used, and so forth until all 10 measurements are included. The latter gives an *NSE* =1.

The reliability of the photointerpreted width measures were also compared to field-measured width. In total, gully width was measured at twenty gully cross sections in 2013. These field measures were made in locations selected from among the forty sections measured by photointerpretation. Field measurement was done using a traditional tape meter.

Measurement of catchment area

Digital elevation model (DEM) with a pixel of 2 meters resolution in X and Y, and centimetric resolution in Z, was produced from LiDAR data obtained from the National Plan of Aerial Orthophotography (PNOA) with FUSION 3.8 and LasTools software, with a precision better than 0.2 m RMSE in Z. Then the contributed area at each section were computed by means of the D-Infinity Contributing Area algorithm of TAUDEM 5.0.6

(Tarboton, 1997) in QGIS 2.12 software.

Main statistical descriptors were calculated distinguishing between gully widths measured in olive groves and herbaceous crops to characterize widening processes in both land uses. Significant differences between widening processes in olive groves and herbaceous crops were then evaluated by means of an analysis of variance (ANOVA test).

Simple linear regression for log-transformed variables was performed to evaluate the relation between the gully top width (W) and the drainage area (A) of the form:

$$W = \alpha A^{\beta} \qquad \textit{Equation 4-4}$$

with β the power coefficient and α the proportionality constant. The β coefficient expresses the rate of increase of width with drainage area. Nachtergaele *et al.* (2002) suggested that β varies between rills, gullies and river according to: (i) differences in flow shear stress distribution over the wetted perimeter, (ii) the probability of reaching a more erosion-resistant layer and (iii) the average surface slope. On the other hand, the α coefficient expresses gully widening proneness due to local conditions (i.e. climate, soil type and land use).

In order to compare the effects of rainfall and land use on this relation, we fixed the β coefficient at 0.3. Normalizing the β value gives the advantage that variations in the proportionality constant α express the variation in external factors. A detailed explanation of the background of this normalization procedure and motivation for choosing this value of 0.3 is given in the results and discussion section.

Rainfall analysis

As explained earlier, the effect of rainfall on the W-A relation was evaluated by assessing the variability of the proportionality coefficient α, assuming the β coefficient to be constant. Daily rainfall for the period from 1956 to 2013, recorded at Castro del Rio meteorological station (37·69°N, 4·47°W), located at 10 km from the study area, belonging to the Spanish State Meteorological Agency, were used to compute the rainfall indexes. The rainfall indexes were computed for the two hydrological years previous to the end of each period (hydrological years run from 1 October to 30 September).

Five different rainfall indexes were computed, in order to explore the relationship between gully widening rates and rainfall: (i) the maximum daily rainfall (*MDR*, mm day-1), (ii) the mean annual rainfall (*MAR*, mm y^{-1}), (iii) the number of days with a daily rainfall above 13 mm ($\#P_{24} > 13\ mm$, # days) as this value is considered as the minimum rainfall that produces erosive effects as proposed by Wischmeier and Smith (1978), (iv) the number of days with a daily rainfall above 20 mm ($\#P_{24} > 20\ mm$, # days), following Poesen *et al.* (2003) who consider this the critical rainfall depth needed for gully head development in cropland on clay soils, and hypothesizing that gully widening processes respond in a similar way , (v) rainy day normal (*RDN*, mm day^{-1}; Vanmaercke *et al.*, 2016) calculated by dividing total annual rainfall by the number of rainy days during a given year.

RESULTS AND DISCUSSION

Determination of representative gully width from aerial orthophotos

Figure 4-3a shows a typical aerial orthophoto with four different gully segments (S1 to S4) where gully width was measured 10 times. Figure 4-3b shows the variation of the *NSE* ($NSE = 1 - \frac{\sum_{s=1}^{S}\left(w_m^s - w_o^s\right)^2}{\sum_{s=1}^{S}\left(w_o^s - \overline{w_o^S}\right)^2}$ *Equation 4-3*) as a function of the number of measurement replications. As expected, the *NSE* coefficient increases directly proportional to the number of replications used to obtain the mean width. The *NSE* coefficient ranged from 0.93 obtained for a unique measure, to 1 obtained for 10 replications of the gully width measure (per definition). Since the *NSE* obtained for a unique measure is quite close to the perfect match (*NSE* = 1) and given the significant increase in effort or time cost to repeat these measurements yielding only a very small marginal increase of the *NSE* coefficient, it was decided that a unique measure offers acceptable results. Hereafter, all results of gully width derived from orthophotos are based on a single measurement.

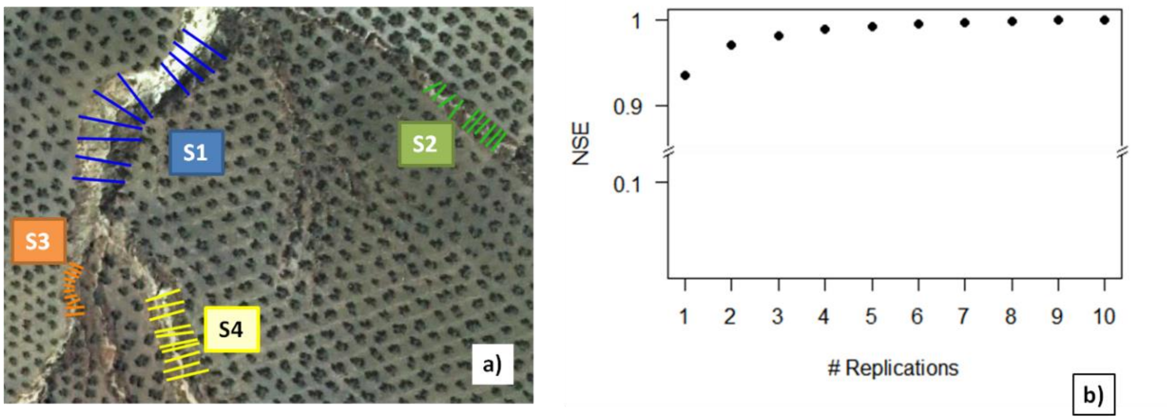

Figure 4-3. a) Orthophoto showing different segments (S1, S2, S3 and S4) and sections measured to test the optimal number or replication to get representative measures of gully segment width. b) Variation of the model efficiency (Nash-Sutcliffe Error) as a function of the number of replications (NSE=1 $- \frac{\sum_{s=1}^{S}\left(w_m^s - w_o^s\right)^2}{\sum_{s=1}^{S}\left(w_o^s - \overline{w_o^s}\right)^2}$ Equation 4-3*).*

Figure 4-4a and Figure 4-4b show a representative gully segment that experienced important widening between the years 2011 and 2013. Figure 4-4c shows a typical gully cross section as it was measured during the field campaign. Gully width measured from orthophotos in a GIS were validated against field measures. Figure 4-4d shows the correlation between gully width measured in the field and from orthophotos. It can be observed that a good correlation between both was obtained, with a root mean square error (*RMSE*) equal to 3.17 meters and a *Nash-Sutcliffe Error* (*NSE*) between the field measure and the orthophotos measures of 0.79 (Figure 4-4d). Taking into account that also field measurements, especially of the larger gullies, are associated with important errors, this result can be considered satisfactory.

Casalí *et al.* (2006) reviewed the accuracy of different methods for determining the volume of rills and ephemeral gullies. They suggested a 5 m spacing between gully cross section measurements in order to obtain errors below 10%. However, they study channels between 0.2 – 1.0 m, while the channels studied here are an order of magnitude larger. In addition, their study refers to errors on the entire cross section while our results only refer to gully width.

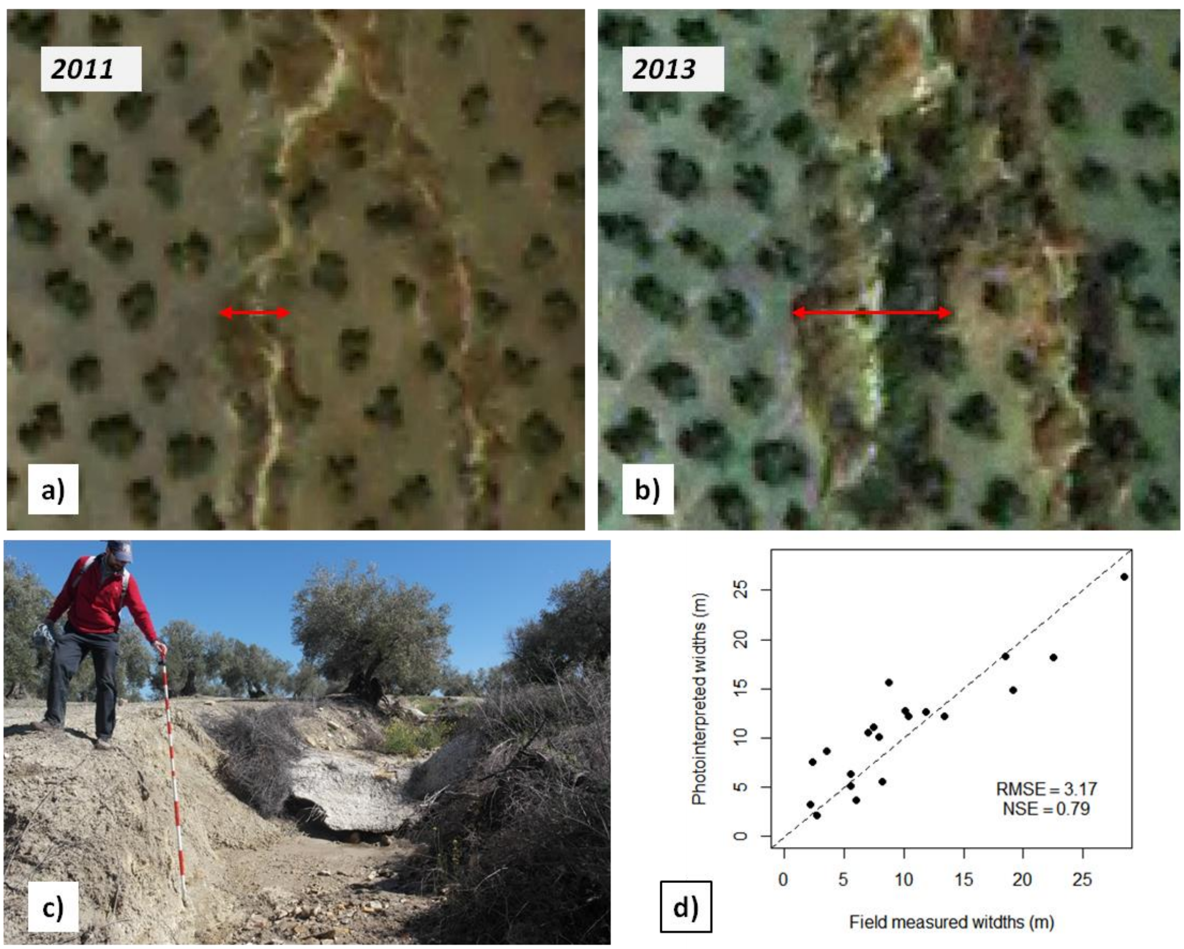

Figure 4-4. a) and b) orthophotos showing the widening of a gully between 2011 and 2013. c) gully section in the study zone. d) Relationship between photo-interpreted gully

widths and field measured widths.

Gully widening rates and land use

Aerial orthophotos were found to be suitable to obtain gully width measures at the selected sections. This is in accordance with the results of the analyses performed by García *et al.* (2011) who classified the orthophotos of the 1956 American flight and the 1984 National flight as "suitable" for the study and quantification of erosion in permanent gullies, while orthophotos of a higher quality from the Ministerial flight (1980), SIGPAC (1999 and 2001) and PNOA (2005, 2007, 2009, 2011 and 2013) were classified as "good" for the same purpose. It is important to notice that due to the different resolutions and characteristics of the orthophoto dataset, different photointerpretation precisions between the different years could be expected. However, since no data on field width measures were available previous to 2013, the accuracy of the photointerpretation for that period (1956 - 2011) could not be evaluated. Henceforth, measures for the years of less quality orthophotos (1956 and 1984) should be considered with caution.

Gullies widening rates were obtained in the study area for sections located both under herbaceous crops as under olive groves (Table 4-2). The mean widening rate for the period 1956 - 2013 was 0.44 $m \cdot yr^{-1}$ and 0.34 $m \cdot yr^{-1}$ for herbaceous crops and olive groves sections, respectively. However, a high variation of this widening rate was observed over time. The highest widening rates were obtained for the period 2009 - 2011 for both herbaceous crops (2.09 $m \cdot yr^{-1}$) and olive crops (1,99 $m \cdot yr^{-1}$), this is in agreement with an extraordinary humid period recorded. Results show anomalous narrowing rates for the period 2005 - 2007, due strong infilling effort by farmers. In the period 1956 - 1980, the widening rate for herbaceous crops sections were almost negligible (~ 0.00 $m \cdot yr^{-1}$). This period also marks the lowest widening rate for olive groves sections (0.02 $m \cdot yr^{-1}$).

Few studies have reported long term widening rates for permanent gullies. Most research on gully widening in croplands have often focused on ephemeral gullies developed due a particular rainfall event. From data reported by Thomas *et al.* (2004), although they do not report them directly, widening rates could be calculated. They report mean gully widening of nearly 0.30 $m \cdot yr^{-1}$ over 35 years in a valley-bottom gully with a contributing watershed of nearly 30 ha in Western Iowa. Thomas *et al.* (2004) focused on a gully in which the land use in the contributing area shifted from mixed cropping, including corn, oats, alfalfa and pasture, to no-till corn and soybean rotation during the study period. On average, the widening rates from Thomas *et al.* (2004) are similar to those obtained in the present study in olive groves and cereal crops. However, their study does not report more detailed data on inter-periods to confront the extreme values of the widening rates in the present study. Another study by Frankl *et al.* (2011) also allows to deduce average widening rates of 0.08 $m \cdot yr^{-1}$ over 34 years in gullies in Northern Ethiopia Highlands with 110 - 300 ha contributing watersheds. The widening rate obtained by Frankl *et al.* (2011) is significantly lower than the average widening rate obtained in this study (0.34 - 0.44 $m \cdot yr^{-1}$). This could be due the differences in the land use of the study areas covered in both works. While the Northern Ethiopia Highlands site analysed by Frankl *et al.* (2011) were covered by a mix of degraded Afromontane forests, shrubs, trees and cultivated land, as well as pastures, the present study is completely occupied by crop lands (cereal crops and olive groves), and is much more intensively plowed. Furthermore, Nyssen *et al.* (2004) indicate that since the 1980s there have been made huge efforts to tackle environmental degradation in the Ethiopian Highlands studied by Frankl *et al.* (2011), which could explain their low widening rates.

Next it was analysed whether land use exerts a significant control over widening rates. Analysis of variance (ANOVA) between widening rates in both land use classes showed no significant differences. The only exception is for the period 1984 - 1999 where distribution of widening rates between herbaceous crops and olive groves were slightly different (*p-value* equal to 0.03). The same was observed by Hayas *et al.* (2017b), who did not find any difference in topographic thresholds for gully initiation under cereal compared to olive groves. They attributed this to the similar runoff curve numbers of both land uses, yielding a similar runoff response. Henceforth no distinction between land use classes was made in the following analysis and the different gully sections were lumped into a single group to focus on the effects of contributing area and rainfall.

Table 4-2. Summary of gully widening rates in herbaceous crops and olive groves (mean, standard deviation – Sd- and number of elements considered) and p-values from Anova test.

	herbaceous crops			olive groves			
	Mean	Sd		Mean	Sd		ANOVA
Year	($m \cdot yr^{-1}$)	($m \cdot yr^{-1}$)	n	($m \cdot yr^{-1}$)	($m \cdot yr^{-1}$)	n	*p-value*
1956 - 1980	0,00	0,08	31	0,02	0,06	4	0,74
1980 - 1984	0,10	0,32	31	0,12	0,14	10	0,82
1984 - 1999	0,15	0,10	23	0,06	0,09	11	0,03
1999 - 2001	0,49	1,17	24	0,03	0,80	22	0,13
2001 - 2005	0,37	0,52	24	0,32	0,30	22	0,71
2005 - 2007	-0,17	1,37	21	-0,18	1,00	22	0,99
2007 - 2009	0,35	0,94	17	0,23	1,15	25	0,71
2009 - 2011	2,09	1,90	17	1,41	1,99	29	0,27
2011 - 2013	0,56	1,79	16	1,04	1,45	30	0,33

Gully widths and contributing area

The relationship between gully widths and contributing area is shown in Figure 4-5, separated for the different years analysed, and considering a single land use class. While the coefficient of determination, r^2, was in all cases lower than 0.3, significant correlations (*p-values*) were obtained for all the periods analysed, except for the year 1980. β coefficients varied between 0.16 in 1980 and 0.3 in 1999, with a mean value of 0.23 for the complete study period (1956 - 2013) and a standard deviation of 0.04. α coefficients reflected an increasing trend from 2.15 in 1956 to 6.11 in 2013, although occasional decreases occurred in 1984 ($\alpha = 2.53$) and 1999 ($\alpha = 2.45$). Such increase indicates the progressive growing of the gully sections over time. A positive relation between the α coefficient and gully width W was also observed by Salvador Sanchis *et al.* (2009). The β coefficients obtained here are similar with those reported from Frankl *et al.* (2013), who obtained β coefficients equal to 0.20 and 0.32 for shale and volcanic soils respectively, and equal to 0.24 when considering both soil types together with sandstone. In contrast, the α coefficients values reported for Frankl *et al.* (2013) were one order of magnitude lower ($\alpha \approx 0.3$). This difference could be due the distinct soil types and land uses. However, our results are in line with those obtained by Vanmaercke *et al.* (2016), who reported an α coefficient value equal to 3.47 and a β coefficient equal to 0.15, derived from a meta-analysis from 548 gully widths all over the world.

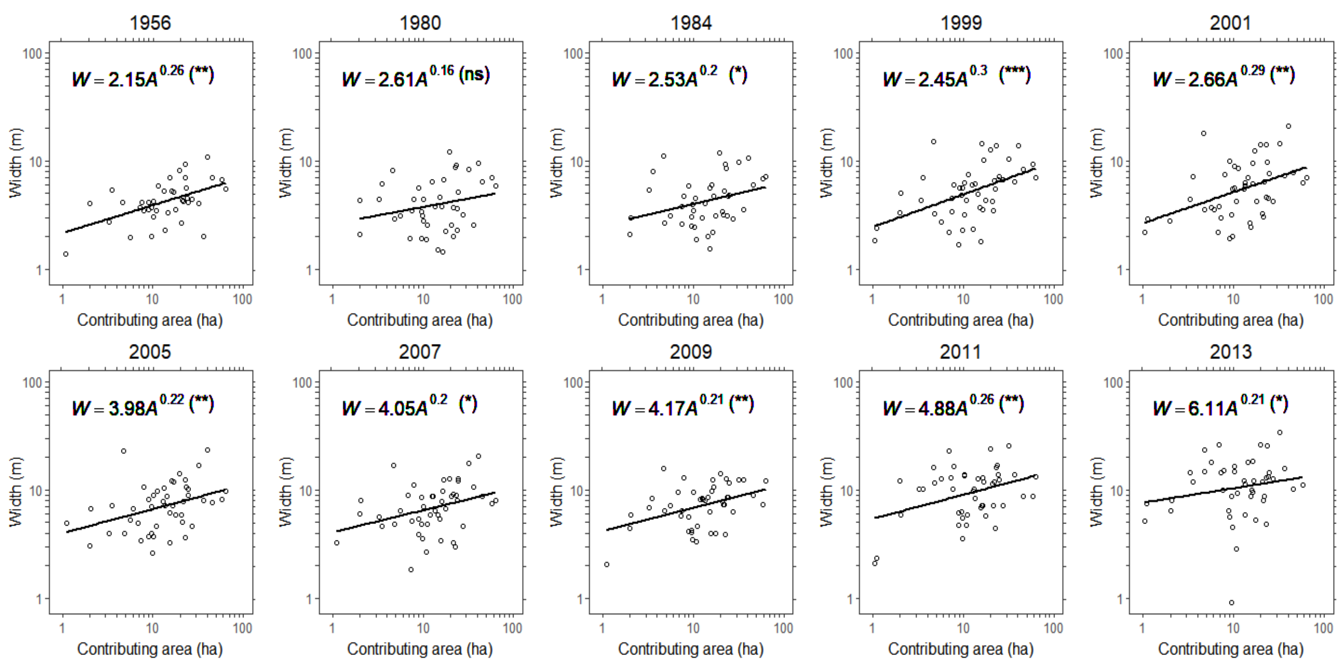

*Figure 4-5. Relationship between gully width and contributing area (A) in the different time periods, considering a single land use (i.e. no differences between gullies in herbaceous crops and those in olive groves). (*** p <0.001; ** p <0.01; * p<0.05; ns p>0.05)*

Gully widening rates and rainfall

Next, gully widening rates were related to the rainfall characteristics of the different analysed time periods. In order to do so, it was necessary to simplify the *W*-*A* relation. Following the same procedure used by Torri and Poesen (2014) to standardize topographic threshold relations for gully headcut formation, a constant value for the β coefficient was set. This allows to isolate the variation of the α coefficient and relate it to external variables, in this case, variations in rainfall regime. The decision about which β-value to adopt is somewhat arbitrary as there are no good reasons to select a particular value, as Torri and Poesen (2014) also indicate. In this case, the β coefficient was set equal to 0.3. This is the value for the year 1999, which was the year with the highest significance in the data (lowest p-value obtained). This value is close to the β value of 0.3-0.4 proposed by Nachtergaele *et al.* (2002) for rills and gullies respectively, with the caveat that his values relate width to discharge (*W*-*Q*) directly. However, it can be assumed that the exponents of the *W*-*Q* and *W*-*A* relations are similar. If one uses a simple method for peak discharge calculation such as the rational formula for example, *Q* can be directly replaced by *A* and therefore the same β coefficient applies. This does imply that additional variability in the *W*-*A* relation can be expected, as variables influencing in the rainfall-runoff generation are now implicit in this equation.

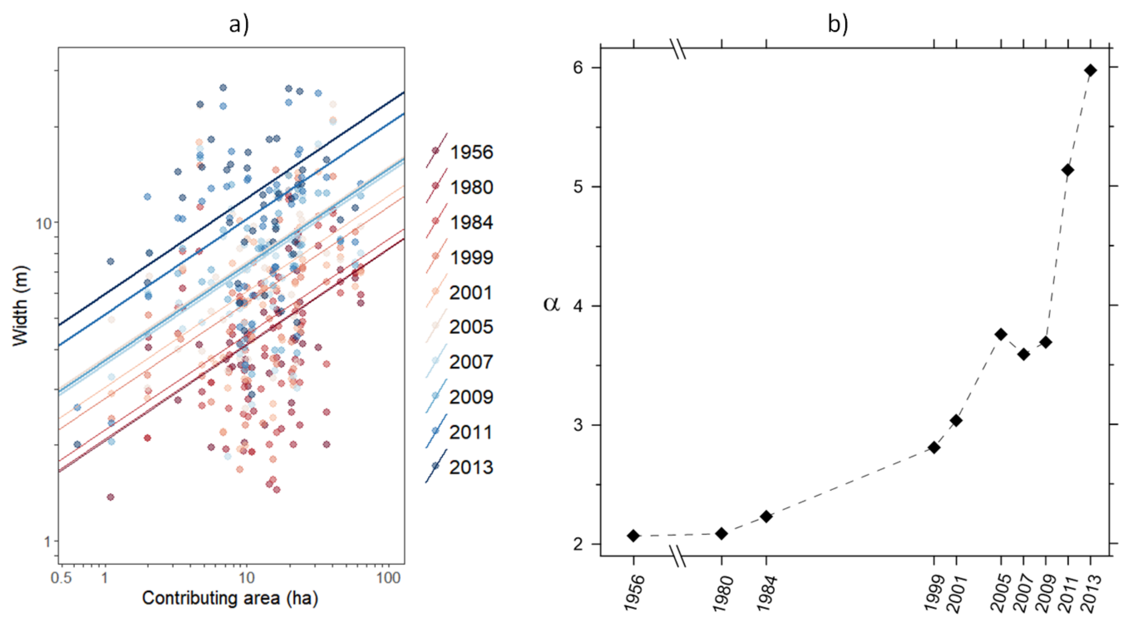

Figure 4-6. a) Evolution of the relation between width-catchment area (A) over time, using a fixed β coefficient = 0.3. b) Evolution of α coefficient over time.

The variation of the α coefficient over time is shown in Figure 4-6. Under the hypothesis of a fixed β coefficient equal to 0.3, α coefficient varied between 2.06 in 1956 and 5.98 in 2013, reflecting the increase in gully width over time. The α coefficient showed an increasing trend only interrupted in the year 2007. This increase is strongly non-linear with long periods of stability, followed by short periods of rapid increase. These results show that gully width increases in a non-linear way over time in the study zone. It can be expected that these variations respond to an external forcing, and rainfall exerts possibly the most important control.

In order to check the effect of rainfall, the increment in the α coefficient ($\Delta\alpha$) was related to different rainfall indexes. Table 4-3 summarizes the results of this correlation analysis. Note that one negative value of $\Delta\alpha$ (between 2005 and 2007) was excluded from the analysis as it corresponds to an artificial infilling phase. All explored indexes showed a positive correlation with α coefficient increment. Although, the goodness of the performances was significantly different among the five rainfall indexes explored.

Table 4-3. Coefficients of determination (r^2) and p-values from the relationship analyses between α coefficient increments and rainfall indexes.

Rainfall index	r^2	***p-value***
# days with rainfall > 13 mm ($\#_{P24 > 13}$; # days)	0.65	0.015
# days with rainfall > 20 mm ($\#_{P24 > 20}$; # days)	0.45	0.067
Maximum Daily Rainfall (MDR; mm day^{-1})	0.49	0.404
Mean Annual Rainfall (MAR; mm y^{-1})	0.52	0.044
Rainy Day Normal (RDN; mm day^{-1})	0.39	0.100

The rainfall indexes analysed could be grouped in three types: those which express the degree of wetness of the study period (i.e. Mean Annual Rainfall and Rainy Day Normal); those related with the frequency of erosive events in the period by means of a threshold value (i.e. # P_{24} > 13 mm; and # P_{24} > 20 mm); and finally those that express the erosive potential through the magnitude of an extraordinary rainfall event (i.e. Maximum Daily Rainfall). Within the first group, Mean Annual Rainfall was significant (*p-value* = 0.044) and showed a reasonably good performance (r^2 = 0.52), while the Rainy Day Normal yielded a non-significant correlation with the increment of α coefficient. The number of days with a daily rainfall above 13 mm was highly significant and was the better correlated index with the α increment (*p-value* = 0.015; r^2 = 0.65). In contrast, the number of days with a daily rainfall above 20 mm was not significant. This could be explained, under a threshold value hypothesis, by the fact that once the first threshold value of 13 mm is reached, slightly higher rainfall events do not make a significant different in the widening rate in this particular case. It is interesting to note that the maximum daily rainfall yielded a non-significant correlation with the α increment. This could imply that deterministic models in this environment would not work well (i.e. REGEM model) as these models relate gully width directly to peak discharge, while here maximum daily rainfall is not significant.

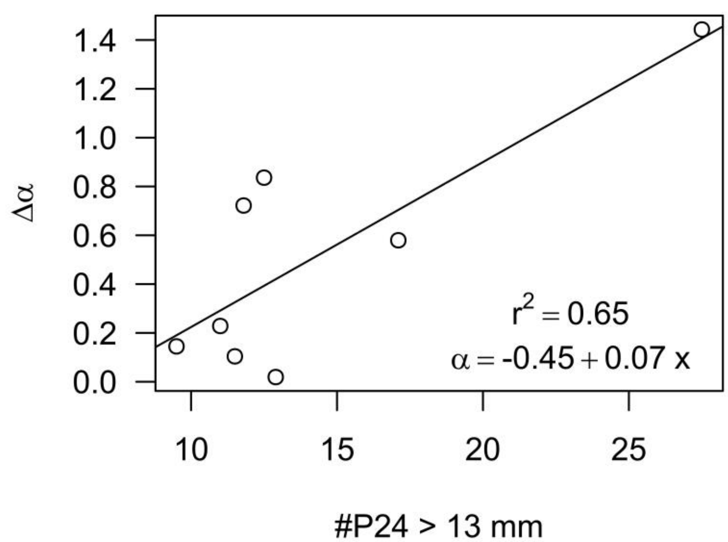

Figure 4-7. Relation between widening rate, expressed through the increase of the α coefficient, and rainfall index N13 (number of days with a daily rainfall above 13 mm) in a given time period.

The obtained relationship between rainfall indexes and α increments in this study could not be compared to other studies, as this is the first study of its kind as far as the authors are aware. In previous studies, gully widening was only studied under constant rainfall conditions. In laboratory experiments on gully widening, usually discharge is maintained constant and in field measurements width was measured on ephemeral gullies after a single rainfall event. Other processes involved in gully expansion have previously been related to rainfall indexes; as for instance the rainy day normal (*RDN*) and gully volumetric retreat rate (Vanmaercke *et al.*, 2016) or the gully headcut retreat rate (Hayas *et al.*, 2017b). In our study, *RDN* did not yield a significant relation with gully widening. This seems to indicate that different processes control gully widening as opposed to gully headcut retreat.

Gully widening is a complex process and is the result of the interaction of discharges flowing through the gully channel with collapse of the gully walls. Runoff flowing through the channel contributes to undercutting and oversteepening of the gully walls, leading to collapse. However, collapse is also controlled by saturation of the gully walls and the development of tension cracks and/or undercut hollows. Tension cracks in the sidewalls induce mass failures that also contribute to the gully widening (Bradford *et al.*, 1973; Bradford and Piest, 1977; Oostwoud Wijdenes and Bryan, 2001; Collison, 2001; Istanbulluoglu *et al.*, 2005). These tension cracks have been related by Oostwoud-Wijdenes and Bryan (2001) to the duration of the dry period between storms. Their observation is in line with widening of gullies observed in dry periods by Castillo *et al.* (2013) and the results of the present study, both in gullies on clayey soils in the South of Spain.

The reason why in this case the $\#P_{24} > 13mm$ index is a better predictor for gully widening than the *RDN*, may be related to the fact that a threshold flow is needed that begins to erode the gully base sidewalls before they collapse. The relative importance for the gully headcut retreat erosion of the gully wall collapses compare to other processes as the plunge pool erosion and the seepage erosion is lower than to the widening processes, where mass wasting of the sidewalls contributes significantly to the growth of the section width. In that case, the *RDN* could better represent the duration of the processes involved in the enlargement of the gully network. It should be noticed that, in addition to rainfall effects, other features could be playing a relevant role in the dynamics of the widening rates. For instance, changes in the hydrological capacity over time due the modification of the cross section (widening and deepening) could occur. While widening is the object of the model and therefore implicitly taken into account, deepening or incision could modify the local slope and consequently affect the shear stress exerted on the base of the walls. However, on a broader scale, lowering of the base level of the Gualdaquivir River and incision of the river bed as a major cause of the increased erosion rates has been previously discussed and dismissed in Hayas *et al.* (2017a). Incision rates in the Guadalquivir have been reported to be slow (1.2 m) over the last 500 years (Uribelarrea and Benito, 2008) and there is no dam upstream of the study area that could artificially influence the incision of the river bed. On the other hand, the increase of the gully network density as a hole over the time could potentially affect the widening dynamics. However, such processes are complex to capture with our simplified method, but could be studied by the application of a full hydrological model. In any case, understanding all the physical processes involved in gully widening reaches far beyond the scope of this study, but the results presented here do show that catchment area and simple rainfall indexes can be used to obtain a reasonably good estimate of gully width and widening trends over time in our study area. This yields a powerful and simple tool to estimate width in gully networks, if similar relations are confirmed in other areas. Future research in different environments will be needed to confirm this.

CONCLUSIONS

In this study, it was shown that gully width and widening rates could be determined as a simple function of runoff contributing area and rainfall regime. First, the feasibility of a methodology to derive gully width from orthophotos was tested. The proposed methodology, based on direct measures by photointerpretation in a GIS from orthophotos, has shown an acceptable accuracy (*NSE* = 0.79 for 2013) for images with a spatial resolution between 0.5 and 1 m. The evaluation of the optimal number of gully width measures through the adapted *NSE* coefficient ($NSE = 1 - \frac{\sum_{s=1}^{S}\left(w_m^s - w_o^s\right)^2}{\sum_{s=1}^{S}\left(w_o^s - \overline{w_o^S}\right)^2}$ *Equation 4-3*) revealed that a single measure provides a fairly good approximation to the real gully width (adapted *NSE* = 0.93). Despite the recent advances in gully width measurement through improved technologies (LiDAR, Sfm…), which provide unprecedented precision, the methodology presented in this study is useful at various levels. On the one hand, there is no other technology, apart from high resolution satellite imagery, that provides a worldwide cover, which makes it a powerful technique to explore gully widening at different environments and conditions. And on the other hand, the historical datasets available in much of the world offer an extraordinary opportunity to analyse gully widening over decadal time scales and its relationship with changing environmental conditions (rainfall, agricultural practices, land use changes…).

For the complete study period, 460 gully width measures were obtained, distributed along the 49 analysed segments. Land use in the study zone was found not to exert a significant control on gully widening. Gully widening rates in olive groves and herbaceous crops did not present significant differences in the period analysed. During the study period, widening rates varied considerably in the study zone. Widening rates ranged from an almost negligible value between 1956 and 1980, to 1.66 $m \cdot yr^{-1}$ (combining herbaceous crops and olive groves) between 2009 and 2011.

Leopold and Maddock's (1953) approach by means of an exponential relationship between the gully width and the contributing area resulted in a significant correlation, showing that it is possible to predict gully widths directly from catchment area. The β coefficient in the exponential relationship varied between 0.16 and 0.3 without a significant trend over the study period. On the other hand, the α coefficient increased from 2.16 in 1956 to 6.11 in 2013 (2.06 to 5.98 when $\beta = 0.3$), showing a growing trend over the same period. This approach has important implications as it considerably simplifies the estimation of the gully network widths. As this is a critical parameter to calculate gully erosion volumes, it can contribute to improve the estimation of gully erosion rates over large areas.

Gully widening rates could be related to rainfall. By means of a simple rainfall index (number of days with a daily rainfall above 13mm; $\#P_{24} > 13mm$) the increment of the gully widening rate was estimated (*p-value* = 0.015 and $r^2 = 0.65$). This could be potentially used to explore the effect on the gully width and the sediment contribution from gullies under different climate scenarios.

This paper significantly contributes to the understanding of the gully widening processes in permanent gullies in cropland. The simple model proposed here could be an alternative for more detailed process-based models in data-poor areas or to estimate the contribution of gully erosion over large areas. Although this method does not allow to assess gully widening due to single rainfall events, it offers a method to take into account the full expansion of the gully network. Where previous models have mainly focused on gully headcut retreat, this analysis clearly shows the importance of taking into account the dynamics of gully wall retreat and gully widening.

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5. CONCLUSIONS

Based on land use, topography and lithology, a representative landscape of the most gully erosion prone areas in the Guadalquivir River Basin was selected for a complete study on the gully dynamics over a period of 57 years. This study was undertaken by a combination of photointerpretation techniques in a GIS, field surveys and probabilistic approaches. The controlling factors of the dynamics of the gully network, the topographic thresholds for gully incision and the gully widening rates were analysed. Differences between the main land uses present in the area (herbaceous crops and olive groves) were evaluated, as well as the influence of land use changes and rainfall variability. The information presented in this thesis provides a better understanding of gully erosion processes in the Guadalquivir basin and a first assessment of the contribution of gully erosion to the total sediment yield in the Guadalquivir River Basin over the last decades. The results obtained in this work underscore the relevance of gully erosion (e.g. up to 591 t ha^{-1} yr^{-1} gully erosion rate in two years), as well as the significant contribution of gully widening in addition to gully headcut retreat on the sediment balance in this type of landscape.

In chapter 2, a combination of a stochastic approach, through Monte Carlo modelling, and the photointerpretation of aerial orthophotos was successfully applied to the evaluation of gully growth over the study period (1957 - 2013). This novel methodology presents the advantage of revealing the range of uncertainty on the estimations of the gully erosion rates. The results showed that the erosion rates were highly variable over the study period ranging between -5.21 t ha^{-1} yr^{-1} in a period dominated by artificial infilling between 2005 - 2007 (in fact, this is therefore an infilling rate and cannot be be considered an erosion rate) and 591 t ha^{-1} yr^{-1} in the period 2009 - 2011, and with a mean value of 39.7 t ha^{-1} yr^{-1}. This variability was mainly attributed to the fluctuations in the rainfall regime, although during specific periods, some of the variation was significantly impacted by land use change as well (e.g. in the period 2005 - 2007). The variability on the gully erosion rates obtained highlights the importance of appropriate selecting the time scale on which gully erosion processes are assessed. The results presented in this thesis clearly show that if gully erosion would have been determined only as an average between the start and end date of the study, this would highly underestimate gully erosion peaks during some years of the study period. Such sediment peaks can potentially cause important ecological problems downstream, lead to important pulses of sediment mobilization in the catchment and problems downstream such as reservoir silting.

In chapter 3, dynamics on topographic threshold (TT) conditions for gully headcut initiation were evaluated for herbaceous crops and olive groves. TT for gully initiation for both land uses were similar, and comparable with TT reported in previous studies for other orchards and cereal crops. For the first time, an important temporal variability in the TT values for a given study area was demonstrated. It was possible to link this temporal variability to rainfall and, in a minor extent, vegetation dynamics. Rainfall indexes such as the Rainy Day Normal (RDN) and those expressing the number of precipitation events exceeding a threshold depth value (13 and 20 mm) were successfully related with the variability in the TT. The effect of the vegetation cover provided by the crops in the study zone was found to be limited to the years with moderate precipitations.

In chapter 4, gully width and gully widening rates were shown to be potentially determined as a simple function of runoff contributing area and rainfall regime. Leopold and Maddock's (1953) approach by means of an exponential relationship between the gully width and the contributing area resulted in a significant correlation, showing that it is possible to predict gully widths directly from catchment area. This approach has important implications as it considerably simplifies the estimation of the gully network widths. Similar with the result obtained for TT for gully initiation, land use showed no significant effects on gully widening rates. However, the widening rates could be successfully related to a rainfall index expressing the number of days exceeding a threshold rainfall depth of 13 mm. This then has important implication for the study of the gully evolution under different climate scenarios. The results obtained in the study stress the importance of taking into account the dynamics of gully wall retreat and gully widening when estimating gully erosion.

As a result of this thesis, some research lines clearly emerge as a priority for further research effort. A first line of future research derives from two important developments. First of all, the extraordinary development of artificial intelligence (AI) technologies in recent years, especially in the field of image recognition, new algorithms could be developed to automatically extract gully features from aerial orthophotos and satellite images. Secondly, this remote sensing imagery is expected to experiment an important enhancement in terms of the temporal and spatial resolution of its delivered products. Emerging aerospace technologies, as for instance the High-Altitude Pseudo Satellites (HAPS) and its applications, could potentially provide us with high frequency (monthly periodicity) images with decimetre spatial resolution in a near future. This unprecedent spatial and temporal resolution, joined together with the beforementioned AI technologies, applied to gully cartography would result in the generation of massive data on gully features. Apart from the invaluable utility as a monitoring tool for gully evolution and as input for gully control strategies, this data would impact on the enhancement of the current gully erosion models. Another research line immediately arises, since gully depth would be difficult to observe from this sort of images, new researches on the deepening processes should be carried out to accurately estimate the gully erosion rates.

A second line of future research should focus on the lack of knowledge on the influence of alternative cycles of wet and dry periods in gully widening process. The results shown in chapter 4 of this thesis suggest that gully widening could even occur during dry periods. This is somewhat counterintuitive as most of the gully erosion models focus strongly on the driving force of water flow in the gully channel. Therefore, more research focusing on gully wall stability and failures is needed. Since some of the most gully prone areas are locate in semiarid environments, which are subject to marked droughts, this may be important to understand how gullies widen, and ultimately to estimate the total volume of gully erosion. New research should be done with emphasis on the inter-rainfall periods, for example by observing gully wall collapses. These knowledge gaps represent an excellent opportunity for new researches in this line.

Last but not least, given the magnitude and the widespread nature of gully erosion, a third line of research should focus on the control and stabilization of gullies. Compared to studies on quantifying, process description and modelling, relatively little has been done to this respect. In this regard, the effects and interactions between roots and gully erosion processes (e.g. de Baets, 2011) could be extremely useful to prevent and stabilise gully erosion. Additionally, new experiences and researches with the combination of check-dams and vegetation, as well as other contention structures, should be addressed to stabilize gullies.

ANEXOS

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Reconstructing long-term gully dynamics in Mediterranean agricultural areas

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Abstract. Gully erosion is an important erosive process in Mediterranean basins. However, the long-term dynamics of gully networks and the variations in sediment production in gullies are not well known. Available studies are often conducted only over a few years, while many gully networks form, grow, and change in response to environmental and land use or management changes over a long period. In order to clarify the effect of these changes, it is important to analyse the evolution of the gully network with a high temporal resolution. This study aims at analysing gully morphodynamics over a long timescale (1956–2013) in a large Mediterranean area in order to quantify gully erosion processes and their contribution to overall sediment dynamics.

A gully network of 20 km^2 located in southwestern Spain has been analysed using a sequence of 10 aerial photographs in the period 1956–2013. The extension of the gully network both increased and decreased in the study period. Gully drainage density varied between 1.93 $km\,km^{-2}$ in 1956, a minimum of 1.37 $km\,km^{-2}$ in 1980, and a maximum of 5.40 $km\,km^{-2}$ in 2013. The main controlling factor of gully activity appeared to be rainfall. Land use changes were found to have only a secondary effect. A new Monte Carlo-based approach was proposed to reconstruct gully erosion rates from orthophotos. Gully erosion rates were found to be relatively stable between 1956 and 2009, with a mean value of 11.2 $t\,ha^{-1}\,yr^{-1}$. In the period 2009–2011, characterized by severe winter rainfalls, this value increased significantly to 591 $t\,ha^{-1}\,yr^{-1}$. These results show that gully erosion rates are highly variable and that a simple interpolation between the starting and ending dates greatly underestimates gully contribution during certain years, such as, for example, between 2009 and 2011. This illustrates the importance of the methodology applied using a high temporal resolution of orthophotos.

1 Introduction

Understanding gully erosion dynamics under changing land use and climate conditions is essential for soil and water conservation. Erosion is one of the most significant threats to soils and sustainable agriculture worldwide (Amundson et al., 2015). To satisfy long-term food production and food safety, soil erosion rates should be drastically reduced to the level of soil formation rates. Additionally, sediment dispersion induces environmental pollution, with severe downstream problems for infrastructure. Soil erosion is a major factor in the anthropogenic perturbation of the global carbon cycle (Regnier et al., 2013). Given its importance, much research effort has gone into characterizing and modelling erosion rates in order to identify key problem areas and propose management solutions. Recently, a European-wide effort was conducted to improve the quantification of water erosion either with RUSLE (Panagos et al., 2015) or with similar models (Quinton et al., 2010; Van Oost et al., 2007). Nevertheless, such models represent a minor part of the water erosion processes by not considering the contribution of gullies. Poesen et al. (2002) concluded that gully erosion could be the source of up to 83 % of sediment yield in Mediterranean areas. Recent efforts to measure gullies in detail confirm these

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RAINFALL AND VEGETATION EFFECTS ON TEMPORAL VARIATION OF TOPOGRAPHIC THRESHOLDS FOR GULLY INITIATION IN MEDITERRANEAN CROPLAND AND OLIVE GROVES

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ABSTRACT

Topographical threshold conditions ($s \geq k\ a^{-b}$), expressed by local slope (s) and drainage area (a), have been widely used to predict gully incision locations. However, little attention has gone to the variation of the thresholds over time. Rainfall variability and changing land use or vegetation cover can potentially lead to important shifts in established thresholds. In this study, we determine topographic thresholds for gullies forming under olive groves and herbaceous crops between 1956 and 2013 in a catchment in Southern Spain. For ten different time periods, we then analysed the impact of rainfall, land use and vegetation cover on the variation of these thresholds. The results show similar topographic thresholds for olive groves and herbaceous crops. However, important variations were found over time. Rainfall indexes, in particular rainy day normal, were generally best correlated. Finally, although overall no effect of land use was obtained, the results did show a significant effect of vegetation cover, but mainly in those years where rainfall was low. This seems to indicate that during years with high rainfall, topographic thresholds are primarily controlled by rainfall, while vegetation cover seems to exert a secondary control.

KEY WORDS: gully initiation; drainage area; slope gradient; land use; herbaceous crops; olive groves

INTRODUCTION

Gully erosion has been widely recognised as a major threat leading to soil degradation, damages in infrastructures and alterations on the hydrological functioning of the catchments (Valentin *et al.*, 2005). Furthermore, gully erosion represents the dominant soil erosion process in many Mediterranean and arid environments (Poesen *et al.*, 2002, 2003; Frankl *et al.*, 2013; Dewitte *et al.*, 2015), which are often more sensitive to the negative impacts from erosion. In order to prevent the undesired effects of gullies, there is a need to develop a standardised system for evaluating site susceptibility to gully erosion and anticipate the places where new gullies might initiate (Torri & Poesen, 2014; Dewitte *et al.*, 2015). In this way, soil management and soil conservation measures can be adapted at those sites in a targeted manner. Also, for modelling sediment production by gullies, most models need to be informed about the location of gully heads. Predicting gully head development susceptibility has been addressed from different approaches. Initially, gully erosion was modelled as a threshold process by Patton & Schumm (1975) and Begin & Schumm (1979) as a function of the flow shear stress exerted by the concentrated overland flow and a critical value that should be exceeded to erode a gully channel. Montgomery & Dietrich (1994) developed this initial approach and simplified it through the expression:

$$s \geq k\ a^{-b} \qquad (1)$$

Where: *s* represents the slope gradient of the soil surface near the gully head and *a* is the area of the catchment draining towards the gully head per unit of contour length. The coefficient *b* depends on the overland flow type. Theoretical values of 0·5–0·857 have been proposed for laminar and turbulent flow respectively (Montgomery & Dietrich, 1994). Torri & Poesen (2014) observed lower values under field conditions. These authors explored two theoretical ways of predicting the value of *b*, one related to flow shear stress considerations and the other based on the stream power per unit of volume, and finally proposed a value of around 0·4. The coefficient *k* reflects gully erosion resistance and depends on local climate, soil type and land use. Higher *k* values correspond to higher resistance to gully erosion incision or less erosive rainfall. Hereafter, this general approach has proven successful in a wide range of environments and land use classes all over the world (Patton & Schumm, 1975; Montgomery & Dietrich, 1994; Vandaele *et al.*, 1996; Vandekerckhove *et al.*, 1998, 2000; Gómez-Gutiérrez *et al.*, 2009; Imaizumi *et al.*, 2010).

Apart from the local slope *s* and the contributing area per unit of contour length *a*, other approaches have incorporated additional terrain variables to predict and map gully head susceptibility. Kheir *et al.* (2007) used a tree-based regression model, where different terrain variables were

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