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Combining field monitoring and aerial imagery to evaluate the role of gully erosion in a Mediterranean catchment (Tunisia)

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ABSTRACT

The objective of this study was to address the role of gully erosion on sediment delivery at the catchment scale by assessing the contribution of gullies to the total sediment yield at the outlet of the Kamech (Cape Bon, Tunisia), which is a small cultivated catchment in the Mediterranean environment. The methodology was based on the long-term analysis of the evolution of gully volume, and the total volume of sediment that reached the catchment outlet. The evolution of gully volume was assessed by field surveys and image analysis. The total volume of sediment was calculated using intensive field monitoring of the runoff and erosion in the reservoir at the catchment outlet. The contribution of gullies to the total flux of sediment that reached the catchment outlet was estimated to be less than 30%. This means that siltation of the reservoir was mainly due to erosion processes other than gully erosion, i.e., topsoil erosion processes such as rill and interrill erosion in cropland areas. This result was consistent with a previous independent estimation of the apportionment of gully and topsoil erosion sources conducted at the same site using the fingerprinting approach. Therefore, the study confirms that, even in a heavily eroded agricultural catchment area with a dense network of gullies, gully erosion nevertheless accounted for less than 30% of the total erosion balance. The results also showed that the cumulated gully length has decreased in the last fifty years, thus revealing the declining role of gullies. However, the decrease in gully activity could not be linked to an isolated factor. Complementary observations, such as the appearance of vegetation in the permanent gullies and the decrease in the percentage of active gullies, showed that the degree of hydro-sedimentary connectivity in the Kamech catchment has probably entered a decreasing phase. We also analysed the potential use of historical aerial images for studying gully erosion. We found that these images were useful for calculating accurate ortho-photography but failed to provide a DEM with the precision required to measure the historical volume of gullies.

1. Introduction

Soil erosion has been recognised as one of the main environmental problems found worldwide, particularly in areas that have climatic variability, loose soil cover, non-favourable topographic characteristics and inappropriate farming and soil management practices (Borrelli et al., 2017; Cantón et al., 2011; Chartin et al., 2011; Fox and Bryan, 2000; García-Ruiz, 2010; Lesschen et al., 2008; Ochoa et al., 2016). These conditions are prominent in the Mediterranean region, which is characterised by high sediment yields (Vanmaercke et al., 2011, 2012; Woodward, 1995) that generate rapid siltation of the numerous artificial reservoirs that have been built during previous decades to mitigate water scarcity (Ben Mammou and Louati, 2007; Hentati et al., 2010; Lahlou, 2000).

In the Mediterranean environment, many studies have highlighted the importance of gully erosion as the dominant source of sediment (Poesen et al., 1996, 2003; Roose et al., 2000) and the major factor responsible for reservoir siltation (De Vente et al., 2006, 2008; Verstraeten et al., 2003). However, measuring the contributions of individual erosion processes at the catchment scale and over a multi-

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annual period is difficult to achieve (Porto et al., 2014). Existing estimations are often provided for a limited area (typically a few hectares) or a limited number of erosive events. As a result, there is a lack of knowledge on the contribution of gully erosion to sediment fluxes at the catchment scale over mid- to long-term temporal scales.

In a recent study, Ben Slimane et al. (2013) used fingerprinting techniques to quantify the respective contributions of gully erosion and surface erosion to the sediment deposited during a 17 year period into a small reservoir located downstream of a 2.63-km^2 catchment in northern Tunisia. The authors used a mixing model based on the fact that top soil, which is the sediment source for surface erosion, was rich in ^{137}Cs and Total Organic Carbon (TOC), while the deeper layers, which are the sediment sources for gully erosion, were poor in ^{137}Cs and TOC. The result of their study was unexpected; specifically their results showed that the contribution of gullies to total sediment yield was only 20% even though the catchment had a very well-developed gully network, and it was well connected to the reservoir (Inoubli et al., 2017). Because of the strong consensus on the importance of gully erosion in the Mediterranean region, and because the specificity of the study area made it a good candidate for observing the dominance of gully erosion over other erosion processes, this result questioned the validity of the use of the fingerprinting approach. Fingerprinting is indeed an indirect method that may eventually lead to large uncertainties because of the many challenges the fingerprinting techniques has still to face (Smith et al., 2015). Thus; an independent study that would confirm is needed, and this is the main objective of the study presented in this article. If the result was confirmed, it would further the discussion on the importance of gully erosion in the Mediterranean region. Furthermore, since the fingerprinting technique has already been applied at the regional scale in an additional study (Ben Slimane et al., 2016), a confirmation of this methodology would also strengthen the conclusions reported at the regional scale.

A straightforward approach would use 3D data: when DEMs of comparable resolution and precision are available for two dates, the difference between the two provides the mean erosion rate over that time. This approach has been successfully used by Marzolff and Poesen (2009) and later by Kaiser et al. (2014) and Frankl et al. (2015), among many others. When analysing a few gully sections, Castillo et al. (2012) regarded this approach as superior to the other alternatives in terms of cost, accuracy and effectiveness. However, in regard to applying this approach to large areas over long periods of time, numerous limitations have been reported. First, the 3D mapping of previous gully conditions relies on conventional historical aerial images, which were not designed to meet the requirements of modern SfM-MVS algorithms. These limitations will be discussed in a dedicated section of this paper. Briefly, historical images may yield a DEM that is good enough to produce an orthophotograph from which the gully location could be accurately digitised; however, the precision would be insufficient to directly calculate the historical volume of these gullies. The alternative to the straightforward DEM subtraction approach is to combine the planimetric information contained in the images with additional field data. Indeed, conventional images taken from airplanes and satellites have been widely used to map the occurrence of erosion features (Desprats et al., 2013), to discriminate between eroded and sedimentation areas (Bergsma, 1974; Jones and Keech, 1966; Vrieling, 2006; Vrieling et al., 2008), and to assess the rate of planimetric gully changes (Buskard and Kostaschuk, 1995; Frankl et al., 2013; Parkner et al., 2007). The conversion of the gully change from planimetric to volumetric can be done afterwards. For example, Bouchnak et al. (2009) evaluated the evolution of gully length in 8 micro-catchments from a diachronic analysis of conventional historical aerial photographs; the volumetric estimation was conducted in a second step, after the "gully volume–gully length" curves (one on gentle slope and one on steep slope) were established by field monitoring surveys of the morphology of 58 gullies. This example confirms that conventional historical aerial photographs are very valuable in regard to mapping historical gully erosion, and it may be possible to assess the volumetric evolution of gullies over several decades at the catchment scale if the required additional data are available to convert planimetric changes to volumetric changes.

In this context, the objective of this study was to assess the long-term contribution of gully erosion in the Kamech catchment at its outlet. This was done by combining the planimetric changes measured using conventional historical aerial images with the adequate field observations that made it possible to convert planimetric changes into volumes. The methodology was divided into three steps: 1) diachronic analysis of gully extension over the last 50 years; 2) conversion of planimetric changes into volumes; and 3) evaluation of the ratio of the gully volume erosion to the total volume of sediment that reached the outlet of the Kamech using the result from step 2 and intensive field monitoring of runoff and erosion at the catchment outlet over a 17 year period.

The main novelty of the paper lies in the opportunity offered by the Kamech catchment; specially, this catchment enables a consistent comparison between the direct approach, which provided an annual estimate of the volume eroded by gullies (in m^3 year^{-1}), and the fingerprinting approach, which provided the apportionment of erosion sources contributions between gullies and surface erosion (in %). Indeed, the long-term runoff and sediment monitoring conducted at the catchment outlet made it possible to evaluate the annual volume of sediment that reached the catchment outlet (in m^3 year^{-1}), and consequently the ratio of gully erosion to total erosion was derived and directly compared with the fingerprinting result. Moreover, a better understanding of the long-term gully dynamics inside the catchment could be useful to help explain the level of gully contribution to total erosion and to help with the proposal of more focused soil conservations strategies. This research also provided methodological elements for a catchment with an insufficient ^{137}Cs activity rate, preventing its use as a tracer for discriminating among sediment sources.

2. Materials and methods

2.1. The Kamech catchment

The Kamech catchment (2.63 km^2, Fig. 1) is located within the agricultural region of Northern Cape Bon, Tunisia (36.88° N, 10.88° E). This catchment is part of the *OMERE* long-term environmental research observatory (http://www.umr-lisah.fr/omere). A small reservoir with an initial storage capacity of 140,000 m^3 was built at the catchment outlet in 1994. The drainage network has intermittent flow discharge. The climate is between semi-arid and sub humid. The study area has a dry season that spans from April to September, a mean annual rainfall of 650 mm and a mean annual temperature of 14 °C. The mean annual evapotranspiration was estimated at 1100 mm based on daily data collected from an evaporation pan and using a pan coefficient of 0.8. The substrate formed from Miocene marine sediments, and it is mainly composed of alternations of slightly calcareous laminated mudstone and thin hard sandstone layers. The latter are visible on the right bank in the form of outcrop strips that are oriented southwest-northeast (Fig. 1). The elevation of the catchment varies from 90 m near the reservoir to 190 m to the northeast (Fig. 2a). The average slope gradient in the catchment is approximately 10–12%; furthermore it is quite uniform on the right bank, while the sandstone layers structure the landform on the left bank. The soils were directly developed both over and from the Miocene deposits. According to the FAO classification (WRB, 2015), the main soil types within the catchment (Fig. 2c) include Calcil or Chromic Vertisols (52.5%), Clayic Calcisols (22%), Vertic Regosols (17%), Leptosols (5%) and Colluvic Cambisols (3.5%). Most of the catchment area features soils with clay content ranging from 30 to 70% and significant active shrinking-swelling processes (Inoubli et al., 2016). Annually ploughed croplands occupy 70% of the total area of the Kamech catchment and are mainly located on slopes with gradients less than 15% (Jenhaoui et al., 2008). Cereals (e.g., wheat, barley, and oats)