Invited Review

Measuring, modelling and managing gully erosion at large scales: A state of the art

Matthias Vanmaercke a,b,* , Panos Panagos c, Tom Vanwalleghem d, Antonio Hayas e, Saskia Foerster f, Pasquale Borrelli g,h, Mauro Rossi i, Dino Torri j, Javier Casali j, Lorenzo Borselli k, Olga Vigiak c, Michael Maerker k, Nigussie Haregeweyn m, Sofie De Geeter a,b, Wojciech Zgjobicki b, Charles Bielders s, Artemi Cerda p, Christian Conoscenti q, Tomáš de Figueiredo r, Bob Evans s, Valentin Golosov l,i, Ion Ionita v, Christos Karydas w, Adam Kertész x,y, Josef Krása s, Caroline Le Bouteiller a,g, Maria Radoane a,b, Ratko Ristić n, Svetla Rousseva a,d, Milos Stankoviansky ae, Janes Stolte af, Christian Stolz ag, Rebecca Bartley ah, Scott Wilkinson a, Ben Jarihani aj,ak, Jean Poesen b,n

a University of Liège, Department of Geography (U.R. SPHERES), Clos Mercator 3, 4000 Liège, Belgium
b KU Leuven, Department of Earth and Environmental Sciences, Celestijnenlaan 200E, 3001 Heverlee, Belgium
c University of Plovdiv, Department of Geography, 1407 Plovdiv, Bulgaria
d University of Cergy Pontoise, Department of Earth and Environmental Sciences, Erap 1, 95000 Cergy-Pontoise, France
e University of Cantabria, Department of Geography, Av. de los Castros s/n, 39005 Santander, Spain
f University of Liège, Department of Geography (U.R. SPHERES), Clos Mercator 3, 4000 Liège, Belgium
g University of Rome Tor Vergata, Department of Earth and Environmental Sciences, Via della Ricerca Scientifica 1, 00133 Rome, Italy
h Palacký University in Olomouc, Department of Geography, Palackého námestí 1, 771 46 Olomouc, Czech Republic
i University of Silesia in Katowice, Faculty of Geography, Pod Pekinem 4, 40-011 Katowice, Poland
j University of Ljubljana, Faculty of Architecture and Geodesy, Jadranska 8, 1000 Ljubljana, Slovenia
k Università degli Studi di Firenze, Department of Earth and Environmental Sciences, Via E. Fermi, 1, 50121 Florence, Italy
l University of Turin, Department of Earth Sciences, Via G. Canal 6, 10125 Turin, Italy
m Vrije Universiteit Brussel, Department of Earth and Environmental Science, Pleinlaan 2, 1050 Brussels, Belgium
n Vrije Universiteit Brussel, Department of Earth and Environmental Science, Pleinlaan 2, 1050 Brussels, Belgium

* Corresponding author at: KU Leuven, Department of Earth and Environmental Sciences, Division of Geography and Tourism, Celestijnenlaan 200E, 3001 Heverlee, Belgium.

https://doi.org/10.1016/j.earscirev.2021.103637

Available online 20 April 2021
0012-8252/© 2021 Elsevier B.V. All rights reserved.
1. Introduction

1.1. The relevance of gully erosion

Soil erosion is globally recognized as the most dominant process of land degradation (e.g. Montanarella et al., 2016; Pennock, 2019). Most efforts to understand and quantify soil erosion by water have focussed on sheet and rill erosion (e.g. Renard, 1997; Montgomery, 2007; Maetens et al., 2012a; de Vente et al., 2013; Borrelli et al., 2017a). Nonetheless, numerous studies have highlighted the fact that also gully erosion is a key concern in many regions worldwide (Poesen et al., 2003; Valentín et al., 2005; Vanmaercke et al., 2011; García-Ruiz et al., 2017; Sidle et al., 2019). Overall, gully erosion is the formation and subsequent expansion of erosional channels in the soil as a result of concentrated water flow (Poesen et al., 2003). Gully dimensions can vary over several orders of magnitudes (e.g. Vanmaercke et al., 2016; Dube et al., 2020). However, conventionally a gully is distinguished from a rill based on a critical cross-sectional area of at least one square foot, i.e. the size of a channel that can no longer be erased via normal tillage operations (Poesen et al., 2003). An upper limit for gully dimensions has not been clearly defined yet.

Gullies are often associated with a wide range of on-site and off-site impacts. On-site impacts include the direct loss of land, trees and crops as well as reduced trafficability. These limit opportunities for agriculture and other land uses (e.g. Poesen et al., 2003; Valentín et al., 2005). Gullies can also cause significant damage to roads, buildings and other infrastructure. In severe cases, such destructions may claim significant numbers of casualties (e.g. Guerra et al., 2007; Makanzu Imwangana et al., 2015). In many regions, gully erosion contributes to significant soil losses and reduced soil quality (Poesen et al., 1996, 2003; Ionita, 2006; Haregeweyn et al., 2008; Xu et al., 2016; Hayas et al., 2017a), threatening the long-term sustainability of food production and other ecosystem services (e.g. Montgomery, 2007). Gullies can also significantly alter surface and subsurface hillslope hydrology. For example, their presence can lead to a more efficient water evacuation and, in some cases, lower water tables. In dry environments, this can result in a significant reduction of water availability and impact on vegetation composition. In glacial environments, gullies can also become significant conduits for meltwater runoff and contribute to debris flows (e.g. Ionita et al., 2015a).

As a result of such impacts, gully erosion can also become a significant driver of land use changes (e.g. Bakker et al., 2005; Valentín et al., 2005; Zgliczynski et al., 2015a). In extreme cases, gully erosion can even transform productive land into badland areas (Canovas et al., 2017; Torri et al., 2018a).

Potential off-site impacts of gully erosion include changes in catchment hydrology, such as lower river baseflows and higher peak runoff discharges (e.g. Martinelli Costa and Bacellar, 2007). Given their often high erosion rates, gullies can also be a major sediment source. Where they occur, gullies can easily account for 20–80% of the average catchment sediment yield (e.g. Poesen et al., 1996, 2003; Vanmaercke et al., 2012). Furthermore, gullies can indirectly contribute to sediment loads by increasing the runoff and sediment connectivity between upland areas, valley bottoms and river networks or lakes (Poesen et al., 2003). These higher sediment loads and increased connectivity can result in a plethora of problems, including (muddy) floods (e.g. Verstraeten and Poesen, 1999), reservoir capacity losses due to sediment deposition (e.g. Haregeweyn et al., 2006), channel aggradation (e.g. Benda et al., 2003) and reduced water quality (e.g. Owens et al., 2005). As such, gully erosion is a great concern in many regions worldwide (Valentín et al., 2005; Poesen, 2018). It is a key process of land degradation and desertification (Vanmaercke et al., 2011), posing a significant threat to various ecosystems and ecosystem services (e.g. Kroon et al., 2012, 2016).

Given these impacts and concerns, land use and catchment management strategies are needed that allow the prevention and mitigation of gully erosion and its impacts (e.g. Poesen et al., 2003; Poesen, 2018). Nevertheless, controlling gully erosion is often complex and costly and typically requires a catchment-wide approach (Golosov and Belyaev, 2013). Conventional erosion control measures aimed at reducing sheet and rill erosion on hillslopes are often insufficient and specific interventions, such as the installation of check dams or revegetation within the gully channel, are often required. Successfully implementing such measures is usually very challenging, due to their risk of failure, their need for maintenance, feedback mechanisms like the ‘clear water’ effect, but also their often high associated costs (e.g. Stokes et al., 2014; Frankl et al., 2016; Ayel et al., 2018; Lucas-Borja et al., 2018; Rey et al., 2019; Bartley et al., 2020; Frankl et al., 2021).

Nevertheless, it is worth noting that gullies can sometimes also create interesting opportunities and positive outcomes. When well managed, they can become productive and biodiverse hotspots that play a key role as ecological corridors (Romero-Díaz et al., 2019). Likewise, gully channels can become significant sediment traps and fill-up over time, especially when they are well vegetated (e.g. Vanwalleghem et al., 2005c; Lanckriet et al., 2015; Molina et al., 2009). Furthermore, they can be of significant geo-archeological value, providing important insight into (pre-)historic land use and human occupation (e.g.}
Developing appropriate gully erosion prevention and remediation strategies requires a thorough understanding of its dynamics and controlling factors. Gully erosion has already received a lot of research attention over the past century (Castillo and Gómez, 2016). This led to valuable insights on the formation and expansion of gullies, their contribution to sediment loads and their potential remediation. This research also demonstrated the sensitivity of gully erosion to land use/land cover (e.g. Prosser and Slade, 1994; Poesen et al., 2003; Torri and Poesen, 2014) and rainfall intensity (e.g. Vanmaercke et al., 2016; Hayes et al., 2017b). Globally ongoing land use/land cover changes that have a significant effect on sheet and rill erosion (Borrelli et al., 2017a) therefore probably also strongly impact gully erosion rates. Likewise, climate change and in particular increases in rainfall intensities (e.g. Polade et al., 2014) are likely to further intensify gully erosion rates (e.g. Nearing et al., 2004; Li and Fang, 2016; Vanmaercke et al., 2016; Panagos et al., 2017). In order to address these challenges, there is a need for tools and models that can quantify the current rates and impacts of gully erosion and assess the effect of potential climate and land use change scenarios (e.g. Poesen, 2018; Pennock, 2019). However, our ability to simulate gully erosion and its impacts remains currently limited (Jetten et al., 2003; Merritt et al., 2003; Poesen et al., 2011; Vanmaercke et al., 2016; Bennett and Wells, 2019; Sidle et al., 2019), particularly at regional to continental scales (e.g. de Vente et al., 2013; Poesen, 2018).

Insights at these scales are essential for the development of adequate and targeted land and catchment management strategies.

These difficulties to simulate and quantify gully erosion at regional to continental scales arise from several causes. First, there is a wide variety of gully types and sizes (Fig. 1). Examples include ephemeral gullies in cropland (e.g. Valcárcel et al., 2003), (pre-)historic gullies under forest (e.g. Dotterweich et al., 2003; Vanvalleghem et al., 2003), permanent gullies in rangeland (e.g. Gomez-Gutiérrez et al., 2009a), valley bottom gullies in alluvial planes (e.g. Amare et al., 2019), bank gullies (i.e. gullies forming in earth banks such as river banks, agricultural terraces, lynchnets or sunken lane banks; e.g. Vanekerchhove et al., 2000a; Poesen et al., 2003), large gullies in urban environments (e.g. Guerra et al., 2007; Makanzu Imwangana et al., 2015), sunken lanes (or road gullies; e.g. De Geeter et al., 2020) and gullies in badland areas (e.g. Nadal-Romero et al., 2015). Furthermore, the formation and expansion of gullies typically involve a range of subprocesses, including the initial incision of a flow channel by concentrated runoff and the formation of a gully headcut (e.g. Oostwoud Wijdenes et al., 1999), gully headcut retreat (Vanmaercke et al., 2016), gully widening and deepening (e.g. Hayas et al., 2019), mass movements (e.g. Zegeye et al., 2020), fluting (Poesen et al., 2002), piping or tunnel erosion (Bernatak-Jakiel and Poesen, 2018), sediment transport and sediment deposition (e.g. Vanvalleghem et al., 2005c). The relative importance of these subprocesses depends on the type of gully, its environmental conditions, but also on the age of the gully (e.g. Oostwoud Wijdenes et al., 1999; Sidorchuk et al., 2001; Poesen et al., 2006; Sidorchuk, 2006; Frankl et al., 2021). In addition, and as a result of these complexities, gully erosion is also characterized by an important degree of stochasticity (e.g. Montgomery and Dietrich, 1994; Prosser and Abernethy, 1996). While significant advancements have been made over the past decades, our understanding of these processes, their interactions and their numerous potential controlling factors remains limited (Poesen et al., 2011; de Vente et al., 2013; Vanmaercke et al., 2016).

From the aforementioned points it also becomes clear that the simulation of gully erosion at larger scales requires significant amounts of data. These include input data on relevant environmental controlling factors (i.e. topography, soil characteristics, climate/weather conditions and land use/cover/management) but also observations on gully occurrence, dimensions and erosion rates to calibrate and validate models. Although several studies have attempted to model gully erosion at local scales, applying these models over larger areas is mostly impossible due to data constraints (e.g. Poesen et al., 2011; de Vente et al., 2013; Poesen, 2018). Furthermore, the environmental factors that need to be considered can vary depending on the study area and gully type. For example, valley bottom gullies are often linked to the presence of dispersive soils or specific conditions in subsurface hydrology (Imeson and Kwaad, 1980; Brooks et al., 2009; Amare et al., 2019). In other areas, seismic/tectonic activity seems to exert an important control on gully erosion (e.g. Cox et al., 2010; Marden et al., 2018). Also farming practices like tillage or parcellation patterns can play a key role in the formation of gullies (Poesen et al., 1996; Gordon et al., 2008; Zglobski and Baran-Zglobska, 2011). This large variation of controlling factors, subprocesses and their interactions further hampers the development and application of (process-based) gully erosion models at regional to continental scales. Finally, given its threshold-dependent nature, gully erosion is typically a highly erratic process, characterized by a very large temporal variability (e.g. Vandekerckhove et al., 2001b; Vanmaercke et al., 2016; Hayes et al., 2017b). Hence, identifying and constraining the key factors controlling gully erosion requires data on gully dynamics, land use, land management and weather conditions that are sufficiently detailed over long periods.

1.3. Scope and overview of this review

The previous subsections reveal that there is an important need for tools and models that allow quantifying and predicting gully erosion at regional (e.g. >10,000 km²), continental and even global scales. Presently, no approaches can do this. However, important advancements have been made in this regard. These include a better understanding of gully erosion processes, novel model approaches and mapping techniques and the development of new high-resolution datasets. The objective of this review is to provide a state of the art of our ability to monitor, model and manage gully erosion at regional to continental scales. From this we aim to identify key research and policy gaps, but also opportunities and pathways to address this problem. The main focus area of this paper is Europe. However, the scope and relevance of this paper extend to other continents as well.

Section 2 reviews remote-sensing and field approaches to measure and monitor gully properties and their dynamics. We discuss the limitations and potential of these methods with a focus on their application over larger areas. Section 3 provides an overview of past field-based gully-erosion research in Europe and European Russia. This to provide an overview of available data and observations that may be useful for further model development, but also to identify current research focuses and knowledge gaps. In Section 4, we discuss modelling approaches used to simulate various relevant aspects of gully erosion (gully occurrence, gully expansion and the contribution of gullies to catchment sediment yields). Also here, our focus lies on the applicability of these approaches at regional to continental scales. Section 5 complements this objective by providing an overview of currently available GIS datasets that may be used as input for such models. We concentrate on datasets that are available for Europe or have a global coverage. Section 6 discusses to what extent environmental management policies and frameworks already account for the challenges posed by gully erosion (with a
Fig. 1. Illustration of different gully types across the world. (a) Ephemeral gully formed in a bare potato field with ridges and furrows (Neuville en Condroz, Belgium, May 2018; Photo: J. Poesen). (b) Historic gully under forest (Neigembo, Belgium, August 2013; Photo: M. Vanmaercke). (c) Permanent gully under rangeland (Burdekin catchment, Queensland, Australia, July 2019; Photo: M. Vanmaercke). (d) Permanent gully under grassland (Guder, Ethiopia, August 2017; Photo: M. Vanmaercke). (e) Permanent gully in a valley bottom (Moldova Province, Romania, May 2011; Photo: J. Poesen). (f) Bank gully formed in a sunken lane bank (Landen, Belgium, April 2019; Photo: J. Poesen). (g) Urban mega-gully that destroyed multiple houses (Kinshasa, D.R. Congo, November 2019; Photo: M. Vanmaercke). (h) Gullies formed in a badland area (near Quazvin, Iran, October 2014; Photo: M. Vanmaercke).
focus on Europe). Section 7 synthesizes our key findings into a list of key recommendations with respect to the monitoring, modelling and managing of gully erosion at larger scales.

2. Assessing gully erosion through monitoring

Observations on the occurrence of gullies, their dimensions and their dynamics are essential to quantify gully erosion rates, to identify the factors that control them and to develop and evaluate predictive models (cf. Section 4). In addition, such measurements are indispensable to assess the effectiveness of gully control measures (e.g. Frankl et al., 2013, 2021; Bartley et al., 2020). Here we review and discuss different methods to monitor the presence gullies (cf. Section 2.1), their properties (cf. Section 2.2) and their dynamics (cf. Section 2.3), in particular at regional to continental scales.

2.1. Assessing the presence or absence of gullies

Especially at larger scales, time and labour constraints often limit the accuracy and level of detail of gully inventories. Nonetheless, inventories that simply record the 'presence' or 'absence' of gullies rather than their precise outlines can already greatly help in identifying problem areas and guiding policy decisions. Such approach has been followed in various regions, including Portugal (Vandaele et al., 1997), Belgium (Nachtergaele and Poesen, 1999), Ethiopia (Frankl et al., 2011), the USA (e.g. Bernard et al., 2010), Spain (e.g. Selkimäki and González-Olabarria, 2017), the European Union (Orgiazzi et al., 2018) and Australia (e.g. Hughes and Prosser, 2012; Darr and Pringle, 2017). This presence or absence can be assessed based on field surveys, aerial/satellite photo interpretation and/or remote sensing analyses. For the latter, the presence of vegetation or snow can hamper successful detection (e.g. Marzolf and Poesen, 2009). Likewise, given that gullies can disappear or fill in over time, such inventories can be strongly time-dependent. This is especially a concern for ephemeral gullies, which are often filled in by ploughing shortly after the rain event that triggered them. Assessments based on infrequent surveys can thus severely underestimate the occurrence of ephemeral gullies (e.g. Nachtergaele and Poesen, 1999), and lead to high levels of error (Kuhnert et al., 2010). Furthermore, such inventories strongly depend on the size of the spatial units in which the presence or absence of gullies is recorded (e.g. parcels, catchments, grids of fixed dimensions).

Creating detailed inventories of gully presence at high resolution can be very labour-intensive (e.g. one person-month for a 3000 km² area at a 100 m pixel resolution; Darr and Pringle, 2017). Zhao et al. (2016) employed an alternative approach to estimate gully densities. Rather than systematically mapping entire areas, they assessed for a large number of random points whether or not the point was located inside a gully. The fraction of points located within a gully thus provides an estimate of the areal gully density. Such crude but fast proxy can be used for meaningful empirical analyses, e.g. to explore correlations between gully densities and catchment sediment yields (Zhao et al., 2016). Overall, complete assessments or random sampling procedures provide the advantage that mapping efforts are unbiased. In contrast, many existing gully occurrence studies focus on gully-prone areas and are therefore often unrepresentative at regional to continental scales.

A specific type of gully presence/absence inventories are maps that indicate the position of individual gully heads (e.g. Vandekerckhove et al., 1998, 2000b; Torri and Poesen, 2014; Hayas et al., 2017b). Since gully initiation and expansion are strongly controlled by local topographic and environmental conditions, such inventories are very useful for modelling purposes (cf. Section 4). However, since their construction is often labour-intensive, they typically remain limited to local study areas (Torri and Poesen, 2014). Nevertheless, the growing availability of high-resolution remote sensing imagery and digital elevation models (cf. Section 5) in combination with the development of (semi-)automatic gully detection procedures will likely increase the availability of such inventories at regional to continental scales.

2.2. Assessing gully properties

For some regions, more detailed inventories of gullies and their characteristics are available over large areas. An overview of such inventories for Europe is given in Section 3. Examples outside Europe include parts of Queensland (Australia; e.g. Brooks et al., 2009) and South Africa (e.g. Mararakanye and Le Roux, 2012). Most of these inventories represent gullies as either linear features (e.g. Rysin et al., 2017a; Rysin et al., 2017b) or as polygons (e.g. Saxton et al., 2012; Shellberg et al., 2016). They are mostly constructed by manually mapping gully extent from (historical) monoscopic/stereoscopic aerial photographs (e.g. Knight et al., 2007). More recent examples made use of high resolution DEMs and/or high resolution remote sensing images in combination with classification procedures that are increasingly automated, accurate and computationally efficient (e.g. Thommeret et al., 2010; Castillo et al., 2014a; Shruthi et al., 2014; Fiorucci et al., 2015; Shahabi et al., 2019; Walker et al., 2020). Evidently, such gully inventories allow for more detailed analyses. Characteristics like gully-head locations (cf. Section 2.1) may be extracted from them relatively easily (e.g. Hayas et al., 2017b). They also allow more precise assessments of the areal and/or linear gully density.

However, such inventories also come with limitations. Digitizing gullies from aerial photos or remote sensing products often involves significant uncertainties. For example, Maugnard et al. (2014a) showed that mapping features of ephemeral gullies remains to a large extent subjective. Furthermore, their construction is generally very labour-intensive, resulting in important trade-offs between the size of the study area, the level of detail and the labour investment required (e.g. Mararakanye and Le Roux, 2012; Golosov et al., 2018). Key elements in this are the image resolution and/or the mapping altitude (i.e. the difference between the altitude of the camera and the surface elevation) used but also whether gullies are mapped as linear features or polygons. (Semi-)automatic detection procedures offer promising perspectives here. They are typically based on high-resolution multi-spectral images (e.g. Shruthi et al., 2011) and/or high-resolution digital elevation models (e.g. Thommeret et al., 2010; Shahabi et al., 2019; Walker et al., 2020). Such imagery has become increasingly available at regional to continental scales. Nonetheless, most of the current applications remain limited to relatively small scales. The potential of these techniques needs to be further explored. Another promising option may be to optimize sampling protocols to manually inventorize gullies. This can be done, by stratifying areas in terms of ancillary information such as slope, land use or soil type (e.g. Minasny and McBratney, 2006) or by using a (semi-)random sampling procedure of smaller sites to be mapped (e.g. Vanmaercke et al., 2020).

Also the widths, cross-sectional areas and, by extent, the total gully volumes are often of interest. Gully top-widths can typically be derived from aerial or satellite imagery (e.g. Nachtergaele et al., 2002a; Hayas et al., 2017a). However, gully floor-widths are typically hard to measure from such imagery (Giménez et al., 2009). The top-widths may be significantly larger than the gully floor-widths, especially for older gullies or gullies formed in soils with little cohesion (e.g. Hayas et al., 2019). Nonetheless, gully floor-width and hydraulic radius are often of greater geomorphic relevance as they relate more directly to the maximum runoff discharges passing through the gully (e.g. Nachtergaele et al., 2002a; Vanwallegheem et al., 2005b).

Also gully cross-sectional areas are difficult to quantify based on aerial photos or high resolution satellite images. Nonetheless, there are a key prerequisite to estimate the volumes of gully systems (Casal et al., 2015; Castillo et al., 2019). Therefore they are often obtained through field measurements (e.g. Nachtergaele et al., 2001a, 2001b). An uncertainty assessment by Castillo et al. (2012) showed that errors on individually measured cross-sections are generally relatively limited (3–15%). Extrapolating these cross-sectional areas to estimate gully
volumes typically generates larger uncertainties. These depend on the gully length, its sinuosity and in particular the number of cross-sections surveyed. Quantifying gully volumes with an acceptable degree of uncertainty (10–20%) typically requires ten or more cross-sections per gully (Castillo et al., 2012). This can pose challenges when aiming to quantify gully erosion volumes over larger areas. Fortunately, gully cross-sectional areas are typically strongly correlated to their top-width (e.g. Frankl et al., 2013; Vanmaercke et al., 2016), which can be assessed via remote sensing. It is often feasible to develop robust empirical relationships between gully top-width and cross-sectional areas, based on a relatively limited amount of field surveys. These relationships can then be used to estimate gully volumes with acceptable uncertainties (e.g. Fiorucci et al., 2015; Hayas et al., 2017a). One concern with this approach is that the cross-sectional shapes evolve over time, e.g. from a rectangular to a more trapezoidal shape (e.g. Vanwalleghem et al., 2005b; Hayas et al., 2019). Hence, applying such a (time-specific) relationship to assess gully volumes over longer time periods may induce further uncertainties and biases.

The challenge to estimate gully volumes from 2D imagery is partly rendered obsolete by new techniques. Airborne LIDAR instruments, for example, allow mapping the morphology and volume of gully systems (e.g. James et al., 2007; Eustace et al., 2009; Perroy et al., 2010; Goodwin et al., 2017). The method, albeit expensive (Castillo et al., 2012), is relatively fast and typically allows to construct digital terrain models of gully systems with an accuracy of some centimeters to decimeters. Recently developed Structure from Motion (SfM) techniques offer a promising and cheaper alternative, with accuracies and precisions that are similar to LIDAR or in some cases even superior (e.g. Castillo et al., 2012; Gómez-Gutiérrez et al., 2014; Clapuyt et al., 2016; Koci et al., 2017). The photographic surveys required to construct a SfM-based digital terrain model can be conducted either from the ground or through drone flights. They can be made with standard photo cameras, while freely available software exists to process the photos into a 3D model (e.g. Koci et al., 2017). Nonetheless, vegetation cover can form a significant constraint for assessing gully properties via SfM. Also, as with LIDAR, data acquisition typically is labour-intensive and the computer resources required to construct such a 3D model currently remain considerable. Hence, most studies applying LIDAR or SfM to characterize gully systems cover only limited areas (e.g. Eustace et al., 2009; Perroy et al., 2010; Castillo et al., 2012; Kropacek et al., 2016; Koci et al., 2017). Increases in computational power and more efficient algorithms may make it feasible to apply these techniques at regional to continental scales in the near future (Bennett and Wells, 2019).

Apart from assessing gully dimensions, assessing whether gullies are stable or actively expanding is often of great relevance. While historic expansion of gullies is best assessed through repeated surveys (cf. Section 2.3), this is not always possible. Furthermore, to target mitigation efforts, it is often required to identify the gullies that are currently active (e.g. Whitford et al., 2010). Some morphological characteristics can indicate whether a gully is likely active (Oostwoud Wijdenes et al., 1999). For example, (recently) active gully heads typically have sharp edges, a plunge pool, tension cracks, recently deposited sediments and flow marks. Stabilized gullies typically have smoother or rounded edges and vegetation re-growth on the gully head wall and at its foot (Oostwoud Wijdenes et al., 2000). However, such distinctions are not always detectable on aerial/satellite imagery. Several studies therefore assessed gully stability based on the vegetation cover inside the gully (e.g. Vanwalleghem et al., 2005b; Makanzu Imwangana et al., 2015; Golosov et al., 2018). While such morphological or vegetation criteria can provide strong indications, it is important to note that they are not a guarantee for gully stability. Extreme weather events or significant land cover changes may reactivate gullies that have been stable for many years (Vandekerckhove et al., 2001b).

Likewise, classifying gullies into types (e.g. permanent, ephemeral, bank gully, valley-bottom and valley-side gully) is generally useful, as this may help understanding the causing mechanisms, potential erosion rates and optimal remediation strategies (e.g. Amare et al., 2019; Bartley et al., 2020). Such classifications can be based on the dimensions, the landscape position and/or the land use type in which the gully occurs. However, while there is some agreement on different types of gullies (cf. Section 3), no universal gully classification scheme currently exists. This limits the comparability of gully inventories and, by extent, gully erosion assessments at regional to continental scales. The development of systematic gully typologies, similar to those developed for landslides (e.g. Cruden and Varnes, 1996), may help address this issue.

2.3. Assessing gully dynamics

Various studies have assessed gully erosion rates through repeated field surveys or by determining the age of gullies through the analyses of tree roots, terrestrial photography, interviews, optical dating, sediment fingerprinting or other techniques (e.g. Vandekerckhove et al., 2001a, 2003; Martínez-Casasnovas et al., 2004; Ionita, 2006; Nyssen et al., 2006; Marzolf et al., 2011; Frankl et al., 2012; Portenga et al., 2017; Bernatek-Jakiel and Wrońska-Walach, 2018). While such research can provide key insights, they typically require intensive fieldwork and are therefore generally limited to specific gullies or small study areas. Efforts to understand gully erosion dynamics over larger areas therefore mainly rely on applying the techniques discussed above over different periods (e.g. Nachtergaele et al., 2002b; Vandekerckhove et al., 2003; Vanwalleghem et al., 2005a; Marzolf and Poesen, 2009; Frankl et al., 2011; Yibeltal et al., 2019).

Such analyses based on available imagery typically face important limitations. A first one is the length of the observation period. Given its threshold-dependent nature, gully erosion is often a highly erratic process (e.g. Vandekerckhove et al., 2001b; Martínez-Casasnovas et al., 2004). For example, Hayas et al. (2017a) showed average gully erosion rates may vary up to a factor 60 over short (< 5 years) observation periods. A global review of observed gully headcut retreat rates indicated similar ranges of variability (Vanmaercke et al., 2016). Hence, average gully erosion rates derived from short observation periods are often subject to very important uncertainties. While these uncertainties generally remain poorly quantified, they may easily dwarf the uncertainties related to assessing gully properties (cf. Section 2.2). These uncertainties are often asymmetric: gully erosion rates derived from short periods are more likely to underestimate the long-term average, but may in some cases result in severe overestimations (Vandekerckhove et al., 2003; Hayas et al., 2017a; Vanmaercke et al., 2016).

Apart from climatic variability, over- or underestimations strongly depend on the timing of the imagery. Permanent gullies often show the highest headcut retreat rates shortly after their formation, but then tend to stabilize over time (e.g. Nachtergaele et al., 2002b; Vanwalleghem et al., 2005a; Sidorchuk, 2006; Whitford et al., 2010; Vanmaercke et al., 2016; Makanzu Imwangana et al., 2015; Rysin, 1998). When gullies are already present on the first image of a series, this poses large challenges in reconstructing the long-term average erosion rate (Vanmaercke et al., 2016). Furthermore, gullies can expand through widening and deepening (e.g. Martínez-Casasnovas et al., 2004; Marzolf and Poesen, 2009). Research suggests that these processes become relatively more important in the later stages of gully development (e.g. Sidorchuk, 1999; Sidorchuk et al., 2003; Sidorchuk, 2006; Hayas et al., 2017a). Nonetheless, few studies have focused on these processes. As a result, they remain poorly quantified and understood (Whitford et al., 2010; Hayas et al., 2019).

Finally, also the timing and frequency of the imagery greatly affects the reliability. Long periods between images make it difficult to accurately assess the initiation of gullies and may lead to biases. This is especially a concern for ephemeral gullies in arable land. As many ephemeral gullies are ploughed away shortly after their formation, assessing their erosion rate based on infrequent imagery can strongly underestimate the actual rate (Nachtergaele and Poesen, 1999). Ideally, imagery should be acquired shortly after every significant rainstorm.
event. However, that is rarely possible and especially hard for large areas. The rise of satellite imagery products with high spatial, temporal and spectral resolutions in combination with (semi-)automatic detection procedures (e.g. Shruhti et al., 2014) may help address this gap.

In conclusion, assessing reliable gully erosion rates at regional to continental scales remains difficult, especially at high temporal resolutions. Methodological challenges in both the detection (cf. Section 2.1) and characterization (cf. Section 2.2) of gullies may induce significant uncertainties. New remote sensing products and (semi-)automatic detection procedures offer promising perspectives here. Nevertheless, especially the large temporal variability that characterizes gully erosion remains a major source of uncertainty. Accurately quantifying gully erosion rates therefore requires frequent imagery over sufficiently long time periods (e.g. decades). Historic (aerial) photographs can be crucial assets in this (e.g. Nachtergaele and Poesen, 1999; Frankl et al., 2011; Golosov et al., 2018). Nonetheless, such photographs are rarely available over large areas, are often difficult to access for scientists and their processing often remains very labour-intensive (e.g. Guyassa et al., 2018).

3. Measurements on gully erosion in Europe: an overview

As discussed above, field-based research is important for defining the locations, morphological characteristics, erosion processes, dynamics and controlling factors of gullies. To gain insights into the geographic distribution of field-based gully related research in Europe and European Russia, we conducted a detailed literature review. This review concentrated on research results published in peer-reviewed journals or in conference proceedings. Studies published in internal reports, MSc. or PhD. theses, or newspaper articles (i.e. grey literature) were not considered. As some research teams produced a large number of peer-reviewed papers about gullies in particular study areas, only the most relevant papers, considered to be representative for the study area, were selected. In total over 224 research papers have been selected (Table 1).

Fig. 2 shows the spatial distribution of areas where permanent, ephemeral or bank gullies as well as gullies in badlands have been studied. Although a large number of papers report on various aspects of badlands, we only considered studies focusing on gully erosion in badlands.

Overall, gully erosion mainly received significant field-based research attention in some particular countries, i.e. Belgium, Germany, Italy, Spain, Romania and the UK. Most studies investigated permanent gullies in forests or rangelands (including badlands; Fig. 2a, d). Relatively fewer studies report on ephemeral gullies, which are typically observed after erosive periods in cropland. As ephemeral gullies are filled in by tillage or land leveling operations shortly after their formation, these gullies are also more difficult to study. Although quite common in rural areas with a rolling or steep topography, bank gullies forming at river banks, agricultural terraces, lynchets or sunken lane banks (Poesen et al., 2003) have also received less attention (Fig. 2c). In conclusion, assessing reliable gully erosion rates at regional to continental scales remains difficult, especially at high temporal resolutions. Methodological challenges in both the detection (cf. Section 2.1) and characterization (cf. Section 2.2) of gullies may induce significant uncertainties. New remote sensing products and (semi-)automatic detection procedures offer promising perspectives here. Nevertheless, especially the large temporal variability that characterizes gully erosion remains a major source of uncertainty. Accurately quantifying gully erosion rates therefore requires frequent imagery over sufficiently long time periods (e.g. decades). Historic (aerial) photographs can be crucial assets in this (e.g. Nachtergaele and Poesen, 1999; Frankl et al., 2011; Golosov et al., 2018). Nonetheless, such photographs are rarely available over large areas, are often difficult to access for scientists and their processing often remains very labour-intensive (e.g. Guyassa et al., 2018).

This review also revealed some important research gaps with respect to understanding and quantifying gully erosion at regional to continental scales:

1) Most studies are clustered in specific study areas, while many other areas remain poorly or not investigated (cf. Fig. 2). While these patterns may be partly caused by the absence of gullies, many regions probably remain under-researched.
2) Only few studies investigated gully occurrence on regional or country-wide scales (cf. Fig. 3).
3) Relatively few studies monitored the evolution of gullies over extensive time periods (e.g. > 20 years). Given their potentially large temporal variability (e.g. Rysin, 1998; Nachtergaele and Poesen, 1999; Martinez-Casasnovas et al., 2004; Vanmaercke et al., 2016; Hayas et al., 2017a; Rysin et al., 2017b; Golosov et al., 2018), rainfall conditions (Hayas et al., 2017a, 2017b) and the role of piping (Bernetek-Jakiel and Wronska-Walach, 2018).
4) Evaluating the effectiveness of gully erosion control techniques, including geomembranes (e.g. Poesen, 1989), check dams (e.g. Castillo et al., 2007), grassed waterways (e.g. Evrard et al., 2008) and bioengineering structures (e.g. Rey and Burylo, 2014).
5) Quantifying the contribution of gully erosion to catchment sediment yields (e.g. Bogen et al., 1994; Poesen et al., 1996, 2003).

Developing and testing gully measuring and monitoring techniques, such as high-altitude aerial photograph analysis (e.g. Nachtergaele and Poesen, 1999; Martinez-Casasnovas et al., 2002), analysis of high-resolution aerial photos taken by drones (e.g. Marzolf and Poesen, 2009; Stocker et al., 2015), 3D-terrestrial image-based modelling (e.g. Frankl et al., 2015) and dendrogeomorphology (Vandekerckhove et al., 2001a; Malik, 2008; Tichavsky et al., 2018).

Dating of (pre-)historic gullies (e.g. Sonsteegaard and Mangerud, 1977; Bork, 1985; Dotterweich et al., 2003, 2012, 2013; Schmitt et al., 2006; Vanwalleghem et al., 2006) and investigating the environmental conditions that lead to their initiation and development (e.g. Bork, 1985; Faulkner, 1995; Dotterweich et al., 2003; Gábris et al., 2003; Nogueras et al., 2000; Stankoviantsky, 2003a, 2003b, 2003c; Vanwalleghem et al., 2005b; Martin-Moreno et al., 2014; Ionita et al., 2015b; Balisteros Canovas et al., 2017).

Investigating factors controlling the initiation and development of contemporary gullies, including soil profile characteristics (e.g. Vanwalleghem et al., 2005b), plant roots (e.g. Gysels and Poesen, 2003), topography and topographic thresholds (e.g. Vandekerckhove et al., 1998; Souchere et al., 2003; Hayas et al., 2017a, 2017b; Torri et al., 2018b), snowmelt runoff (e.g. Øygarden, 2003; Ionita, 2006; Rodzik et al., 2009; Rysin et al., 2017a; Rysin et al., 2017b; Golosov et al., 2018), rainfall conditions (Hayas et al., 2017a, 2017b) and the role of piping (Bernatek-Jakiel and Wronska-Walach, 2018).

Evaluating the effectiveness of gully erosion control techniques, including geomembranes (e.g. Poesen, 1989), check dams (e.g. Castillo et al., 2007), grassed waterways (e.g. Evrard et al., 2008) and bioengineering structures (e.g. Rey and Burylo, 2014).

Quantifying the contribution of gully erosion to catchment sediment yields (e.g. Bogen et al., 1994; Poesen et al., 1996, 2003).

This review also revealed some important research gaps with respect to understanding and quantifying gully erosion at regional to continental scales:

1) Most studies are clustered in specific study areas, while many other areas remain poorly or not investigated (cf. Fig. 2). While these patterns may be partly caused by the absence of gullies, many regions probably remain under-researched.
2) Only few studies investigated gully occurrence on regional or country-wide scales (cf. Fig. 3).
3) Relatively few studies monitored the evolution of gullies over extensive time periods (e.g. > 20 years). Given their potentially large temporal variability (e.g. Rysin, 1998; Nachtergaele and Poesen, 1999; Martinez-Casasnovas et al., 2004; Vanmaercke et al., 2016; Hayas et al., 2017a; Rysin et al., 2017b; Rysin et al., 2017c; Golosov et al., 2018), rainfall conditions (Hayas et al., 2017a, 2017b) and the role of piping (Bernetek-Jakiel and Wronska-Walach, 2018).
4) Evaluating the effectiveness of gully erosion control techniques, including geomembranes (e.g. Poesen, 1989), check dams (e.g. Castillo et al., 2007), grassed waterways (e.g. Evrard et al., 2008) and bioengineering structures (e.g. Rey and Burylo, 2014).
5) Quantifying the contribution of gully erosion to catchment sediment yields (e.g. Bogen et al., 1994; Poesen et al., 1996, 2003).
<table>
<thead>
<tr>
<th>Country</th>
<th>Ephemeral Gullies</th>
<th>Permanent Gullies</th>
<th>Bank Gullies</th>
<th>Gullies in Badlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>N.A.</td>
<td>Sass et al. (2012)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Belgium</td>
<td>N.A.</td>
<td>Arnould-De Bontridder and Paulis (1966); De Ploey (1977); Langohr and Sanders (1985); Gullentops (1992); Poens et al. (2003); Vanwalleghem et al. (2003); Vanwalleghem et al. (2005a); Vanwalleghem et al. (2005b); Vanwalleghem et al. (2005c); Vanwalleghem et al. (2006); Schotmans et al. (2015)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>N.A.</td>
<td>Malinov and Ilieva (2017)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Croatia</td>
<td>N.A.</td>
<td>Fairve et al. (2011); Gulam et al. (2018); Domazetović et al. (1999); Domlija et al. (2019); Domazetović et al. (2019); Dumbrovsky et al. (2019); Tichavský et al. (2018); Battaglia et al. (2003); Clarke and Rendell (2009); Erktan and Rey (2013); Rey and Burylo (2014)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>N.A.</td>
<td>De Foucault et al. (1997); Mathys et al. (2003); Rey (2003); Rey (2009); Erktan and Rey (2013); Rey and Burylo (2014); Mathys et al. (2003); Rey (2009); Vanwalleghem et al. (2005c); Vanwalleghem et al. (2006); Moldenhauer et al. (2015); Stolz et al. (2016); Dotterweich et al. (2015)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>France</td>
<td>N.A.</td>
<td>Bork et al. (1998); Dotterweich et al. (2003); Dumbrovsky et al. (2019); Heine and Niller (2003); Schotmans et al. (2015); Schmitt and Heinrich (2011); Zglobicki et al. (2014); Belyaev et al. (2008); Rysin et al. (2019); Maerker et al. (2020)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Germany</td>
<td>N.A.</td>
<td>Bork and Rodenberg (1979); Bork (1985); Bork et al. (1998); Dotterweich et al. (2003); Dotterweich et al. (2003); Heine and Niller (2003); Schimdtchen und Bork (2003); Dreibrodt (2005); Stolz and Grunert (2006); Beyer (2008); Dotterweich (2008); Dotterweich et al. (2015)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Greece</td>
<td>N.A.</td>
<td>Gábris et al. (2003); Jakab et al. (2011); Kertész and Gergely (2011); Kertész and Kreek (2019)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Hungary</td>
<td>N.A.</td>
<td>Hartmann et al. (2003); Battaglia et al. (2003); Strunk (2003); Clarke and Rendell (2006); Cicciacci et al. (2009); Buccolini and Coco (2010); Clarke and Rendell (2010); Battaglia et al. (2011); Cappadonia et al. (2011); Buccolini and Coco (2013); Conoscenti et al. (2013); Pulice et al. (2013); Torri et al. (2013); Vergari et al. (2013); Carallo-Arias et al. (2013); Cocco et al. (2015); Bianchini et al. (2016); Bolletti et al. (2019)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Iceland</td>
<td>N.A.</td>
<td>Capra and Scicolone (2002); Poens et al. (2003); Zucca et al. (2006); Conoscenti et al. (2013); Conoscenti et al. (2014); Fiorucci et al. (2015); Conoscenti et al. (2018); Conoscenti and Rotiglano (2020)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Italy</td>
<td>N.A.</td>
<td>Battaglia et al. (2003); Battaglia et al. (2003); Strunk (2003); Clarke and Rendell (2006); Cicciacci et al. (2009); Buccolini and Coco (2010); Clarke and Rendell (2010); Battaglia et al. (2011); Cappadonia et al. (2011); Buccolini and Coco (2013); Conoscenti et al. (2013); Pulice et al. (2013); Torri et al. (2013); Vergari et al. (2013); Carallo-Arias et al. (2013); Cocco et al. (2015); Bianchini et al. (2016); Bolletti et al. (2019)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Latvia</td>
<td>N.A.</td>
<td>Zglobicki et al. (2019)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Norway</td>
<td>N.A.</td>
<td>Snærgaard and Mangerud (1977); Erikkstad (1992); Bogen et al. (1994); Schmitt et al. (2006); Smolka (2007); Malik (2008); Rodzik et al. (2009); Schmidt and Heinrich (2011); Zglobicki and Baran-Zglobicki (2011); Dotterweich et al. (2012); Gwaryskiak and Harazmiski (2012); Superson et al. (2014); Zglobicki et al. (2014); Kociuba et al. (2015); Zglobicki et al. (2015a); Zglobicki et al. (2015b); Bernatek-Jakiel and Wrońska-Walach (2018)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Poland</td>
<td>N.A.</td>
<td>Uygarden (2003)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Portugal</td>
<td>N.A.</td>
<td>Poens et al. (1996); de Figueiredo and Fonseca (1997); Vandaele et al. (1997); Vandekerkhove et al. (1998); Vandekerkhove et al. (2000); Sassen et al. (2012)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Romania</td>
<td>N.A.</td>
<td>Motoc (1980); Motoc (1984); Ichim et al. (1990); Radoane et al. (1995); Ionita (2003); Ionita (2006); Mircă (2011); Nisacu and Ionita (2011); Boengiu et al. (2012); Ionita et al. (2015); Radoane and Radoane (2017); Nicu (2018)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Russia (European)</td>
<td>N.A.</td>
<td>Litvin et al. (2000); Belyaev et al. (2005b); Belyaev et al. (2008); Platoncheva et al. (2020); Bolshyov (1987); Dedkov et al. (1990); Bolshyov and Tarzaeva (1996); Rysin (1998); Litvin et al. (2003); Zorina (2003); Belyaev et al. (2004); Belyaev et al. (2005a); Yermolaev et al. (2014); Vanmaercke et al. (2016); Rysin et al. (2018); Vanmaercke et al. (2019); Erktan and Rey (2013); Rey and Burylo (2014)</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

(continued on next page)
Predicting gully erosion rates and its impact on sediment loads encompasses several challenges. These include predicting: (i) where and why gullies occur, (ii) when and how these gullies expand, and (iii) to what extent these gullies contribute to catchment sediment yields. Numerous gully erosion models have been developed. However, no single model presently exists that addresses these three components. Furthermore, most modelling efforts have concentrated on individual gullies or local scales. Here we review and discuss different modelling strategies to simulate these different aspects of gully erosion. It is outside our scope to provide a comprehensive overview of all gully erosion models. Instead, we discuss which modelling strategies potentially can be applied at regional to continental scales, which future advancements may be expected and which research needs currently exist.

### 4.1. Predicting gully occurrence and density

Several modelling approaches exist to predict the occurrence of gullies in a landscape (e.g., Poens et al., 2011). Overall, these can be characterized based on whether they aim to predict the initiation of gullies from process-based principles or whether they aim to predict their occurrence in a purely empirical or statistical way. Most of these involve a combination of both strategies.

In general, process-based approaches rely on the principle that gully initiation is a threshold-dependent phenomenon. Gully heads typically initiate where the shear stress of concentrated runoff exceeds the resisting forces, which mainly depends on local soil and vegetation conditions (Istanbulluoglu et al., 2003; Knapen et al., 2007; Knapen and Dietrich, 2004). Such thresholds often allow generalizing these empirical constants remains difficult as also other environmental factors will play a role. For example, a main limitation of the assumption that $b$-values are relatively constant, variations in $k$-values (cf. Eq. (1)) Under the assumption that $b$-values are relatively constant, variations in $k$-values seem mainly attributable to differences in land cover. Nonetheless, generalizing these empirical constants remains difficult as also other environmental factors will play a role. For example, a main limitation of topographic thresholds is that they typically reflect the “integrated” result of different gully initiation episodes over time. Exact gully head initiation thresholds vary with rainfall intensity (e.g. Torri and Poens, 2014) and more specifically with the resulting peak flow discharge. Also spatial patterns of vegetation and soil characteristics within the contributing area can play a large role (e.g. Rossi et al., 2015a). Likewise, the upslope area can be modified by land management practices that are not resolved by DEMs, such as tillage furrows (Soucche et al., 2003), drainage ditches and stone bunds, all of which can affect the k-value (Monsieurs et al., 2015). Furthermore, gullies are not

$$s = kA^b$$  

(1)

where $k$ and $b$ are empirically fitted constants that depend on the environmental setting (Begin and Schumm, 1979; Montgomery and Dietrich, 1994; Torri and Poens, 2014). Such thresholds often allow fairly good identification of the positions of gully initiation within a study area and by extent their density (e.g. Desmet et al., 1999). However, their highly site-specific nature makes them unsuitable for applications at regional or continental scales. A meta-analysis by Torri and Poens (2014) of 63 $s$-$A$ relations for various areas worldwide indicated a very large variability in $k$- and $b$-values (cf. Eq. (1)). Under the assumption that $b$-values are relatively constant, variations in $k$-values seem mainly attributable to differences in land cover. Nonetheless, generalizing these empirical constants remains difficult as also other environmental factors will play a role. For example, a main limitation of topographic thresholds is that they typically reflect the “integrated” result of different gully initiation episodes over time. Exact gully head initiation thresholds vary with rainfall intensity (e.g. Torri and Poens, 2014; Hayas et al., 2017b) and more specifically with the resulting peak flow discharge. Also spatial patterns of vegetation and soil characteristics within the contributing area can play a large role (e.g. Rossi et al., 2015a). Likewise, the upslope area can be modified by land management practices that are not resolved by DEMs, such as tillage furrows (Soucche et al., 2003), drainage ditches and stone bunds, all of which can affect the k-value (Monsieurs et al., 2015). Furthermore, gullies are not

\[ s = kA^b \]  

(1)
necessarily the sole result of (Hortonian) runoff. They can also form and expand as a result of saturation soil conditions and overland flow (e.g. Nachtergaele et al., 2001a; Tebebu et al., 2010; Amare et al., 2019).

Alternative topographic indices have therefore been proposed to better reflect landscape positions where gullies may initiate. For example, Moore et al. (1988) proposed an index that accounts for saturation overland flow. Istanbulluoglu et al. (2008) incorporated a probabilistic approach in order to account for uncertainties associated with these kinds of topographic relations. The AnnAGNPS model uses the Compound Topographic Index (CTI) to determine the location of potential ephemeral gullies (Taguas et al., 2012; Momm et al., 2012, 2013). This index is also based on contributing area and slope steepness, but aims to better reflect the potential effect of soil wetness conditions on gully initiation (Momm et al., 2015). Daggupati et al. (2013) compared models based on four different topographic indices, i.e. CTI, slope-area (SA), topographic wetness index (TWI), and slope area power (SAP). Results showed that a SA-based approach predicted ephemeral gully occurrence better than the other models tested. Nevertheless, they also showed that CTI has potential for predicting gully headcut location and total gully length. Conoscenti and Rotigliano (2020) also tested CTI, SA, TWI and modified versions of the latter two (named MSpI and MTWI) which incorporate an index to reflect flow convergence/divergence. MSpI outperformed the other topographic indices, revealing that a convergence index may help in detecting hollows where gullies are more likely to form. However, local calibration is required (Daggupati et al., 2013). This currently limits regional applications.

To account for factors other than topography (e.g. climate, land use/land cover, soil type) and their potential interactions, several process-oriented model approaches have been proposed. Overall, they aim to replace or complement the upslope contributing area (A) in Eq. (1) with better proxies of flow discharge, and by extent the flow shear stress, that can occur at a potential gully location. This could allow for more accurate and generalizable simulations of where and when gullies may form. Several approaches are based on the Curve Number (CN) method, a simple empirical model that allows estimating runoff based on rainfall, antecedent moisture, soil and land use conditions (e.g. Ponce and Hawkins, 1996). In principle, such approach allows making gully initiation conditions dynamic through time (e.g. Torri and Poesen, 2014; Torri et al., 2018b). Likewise, combining a pixel-based CN approach with flow-routing algorithms makes it possible to account for the effect of spatial patterns of topography, soil conditions and land cover (Rossi et al., 2015a). An attractive element of the CN approach is that its simple nature enables its application at regional to global scales (e.g. Hong et al., 2007). Nonetheless, this also involves uncertainties and the risk of over-extrapolation as the CN approach remains an empirical model that was developed and tested for a relatively limited set of environmental conditions. Furthermore, such approach does not yet account for all relevant mechanisms and possible interactions with other erosion.

---

**Fig. 2.** Overview of study areas in Europe and European Russia where field-based gully erosion research was conducted, sub-divided according to the investigated gully-type: (a) ephemeral gullies, (b) permanent gullies (inset shows the Canary Islands), (c) bank gullies, (d) gullies in badlands. References per country and gully type are listed in Table 1. Countries shaded in dark grey indicate the study area considered for this review.
processes. For example, also the amount of sediments transported by the runoff from upslope areas will determine whether incision or aggradation will take place (e.g. Poesen et al., 2003). Also several landscape evolution models are to some extent capable of simulating gully initiation, using a process-based approach (e.g. Tucker et al., 2001; Kirkby et al., 2003; Willgoose, 2005, 2018; Harmon et al., 2019). These typically define the threshold in terms of equilibrium between local sediment load or entrainment and sediment transport capacity; often conceptualized in terms of shear stress or stream power per unit flow width. Nevertheless, some empiricism remains. This mainly relates to the definition of critical flow shear stress and the long-term effects of temporal variations in environmental conditions. Overall, process-oriented approaches offer significant promise to predict gully initiation as they aim to account for the actual driving processes in a conceptually transparent way. This can make them highly suitable for the evaluation of gully erosion risks in the context of climate or land use changes (e.g. Hancock et al., 2000; Sidorchuk et al., 2001; Sidorchuk et al., 2003; Rossi et al., 2015a). Furthermore, these models may generally allow for a more straightforward and correct coupling between gully initiation and expansion (cf. Section 4.2). Several process-oriented gully erosion models already account for both components, and perform acceptably over study sites with reasonably uniform properties (e.g. Willgoose, 2005; Hancock et al., 2000; Sidorchuk et al., 2001; Sidorchuk et al., 2003; Rossi et al., 2015a). In many cases, these models also remain poorly validated (Poesen et al., 2011). A major reason for this is the relatively large data requirements (e.g. Kirkby et al., 2003; de Vente et al., 2013). This includes detailed information on the controlling factors, but also observations on gully initiation (e.g. knowing which gully head was initiated and when exactly for a sufficiently long observation period). For the former, the availability of new GIS data layers and products opens promising perspectives (cf. Section 5). Nonetheless, the latter remains a critical point for applications at regional to continental scales (cf. Sections 2 & 3). As with most geomorphic models, also error propagation is a critical concern. Accurate process descriptions of gully initiation typically require more input data. Errors and uncertainties on these input data can easily become more important than errors and uncertainties resulting from an inaccurate process description (e.g. Van Rompaey et al., 2002). Empirical approaches to simulate gully occurrence and densities can offer a major advantage in this regard: they typically result in more robust predictions and are often less demanding in terms of data requirements (e.g. de Vente et al., 2013). Overall, a wide range of empirical approaches exist. To some extent, they can be classified in bivariate methods, multivariate methods, and machine learning approaches. An (non-exhaustive) overview of example studies is given in Table 2. Most of these procedures aim to predict the presence or absence of a gully on a given location. Their successful application results in a gully erosion susceptibility map (GESM), from which proxies of gully density can be derived. However, some approaches try to directly predict the gully density within a catchment (Zhao et al., 2016) or pixel (Kheir et al., 2007; Vannmaercke et al., 2020).

Bivariate statistical approaches (e.g. Conforti et al., 2011; Conoscenti et al., 2013) can be robust but reduce gully prediction to only one causal factor, typically leading to imprecise predictions. Except in simple situations or very data-poor regions, these approaches are therefore generally inferior to the other methods. Multivariate methods (e.g. Akşın and Türk, 2011; Lucà et al., 2011) analyse gully occurrence as a function of different causal factors and to some extent allow determining the relative contribution of each factor. Logistic regression (e.g.

Fig. 3. Regions and countries in Europe for which systematic gully inventories have been made. The mapped gully types, level of detail and completeness of these inventories may vary. 1: N-France (De Foucault et al., 1997), 2: Poland (Józefaciuk and Józefaciuk, 1983), 3: SE-Poland (Gawrysiak and Harasimiuk, 2012), 4: Slovakia (Bučko and Mazišová, 1958), 5: Hungary (Kertész and Krecz, 2019), 6: E-Romania (Radoane et al., 1995), 7: the Middle Volga region (Russian Federation; Golosov et al., 2018). Countries shaded in dark grey indicate the study area considered for this review.
Vanvalleghem et al., 2008; Conoscenti et al., 2014; Dewitte et al., 2015) is the most commonly used multivariate approach. Its computational simplicity and ability to deal with both continuous and categorical explanatory variables are important advantages. However, its ability to fully disentangle the potentially non-linear role of different factors and their interactions remains limited. In this regard, machine learning methods offer great potential and have been increasingly used over recent years (Table 2). Especially techniques like random forests (e.g. Gayen et al., 2019; Gomez-Gutiérrez et al., 2009a; Gomez-Gutiérrez et al., 2009b; Gomez-Gutiérrez et al., 2009c; Gomez-Gutiérrez et al., 2015) can, at least in principle, better account for the fact that the role of explanatory variables may vary between different subpopulations of gullies and over different scales. They can also be used to spatially assess uncertainties on model outputs, thus guiding interpretation and targeting further data collection (e.g. Kühnert et al., 2010; Vanmaercke et al., 2020).

Given their typically smaller data requirements as compared to process-oriented models, empirical approaches could be suitable to predict gully occurrence at regional to continental scales (e.g. Hughes and Prosser, 2012; de Vente et al., 2013). However, most empirical modelling studies focus on relatively small study areas (Table 2). Jurchescu and Grecu (2015) compared gully prediction performances with regression trees at different spatial scales. They report that predictions at the regional scale are affected by larger uncertainties as compared to predictions for smaller areas. A main limitation lies in the need for gully inventories at regional to continental scales in order to calibrate and validate such models. As discussed in Sections 2 and 3, such inventories remain scarce as they are labour-intensive to compile. Another important constraint of such empirical models is that they generally remain ‘black box’ approaches. While they can provide some insight into the dominant factors controlling gully occurrence, the underlying mechanisms and interactions are generally less clear (e.g. Zhao et al., 2016). This may limit the potential of such empirical approaches for scenario analyses, especially in the case of machine learning techniques.

Models aiming to predict gully initiation and densities at regional to continental scales in the context of future climate or land use changes should therefore seek to strike a balance between a relevant and conceptually sound process description and feasible calculation and input requirements. Several studies already apply a hybrid approach between empirical and process-based gully occurrence prediction. For example, Dewitte et al. (2015) implemented a two-step procedure. First, potentially gully-prone areas were delineated based on the slope-area threshold concept. Next, logistic regression was used for a more detailed prediction of gully locations within those areas. Recent conceptual advancements that replace the slope-area threshold concept with more detailed description of expected runoff discharges (e.g. based on the CN-model approach; see above), also offer promising perspectives in this regard.

### 4.2. Predicting gully expansion

Total gully erosion rates over an area not only depend on the occurrence of gullies (cf. Section 4.1), but also on their expansion rates. Actively eroding gullies generally produce sediment through headcut retreat and channel widening/deepening (e.g. Martínez-Casasnovas et al., 2004; Marzolf and Poesen, 2005; Vanmaercke et al., 2016; Hayas et al., 2017a). In some contexts, piping can also contribute significantly to gully expansion (e.g. Valentín et al., 2005; Bernatek-Jakiel and Poesen, 2018).

Table 3 shows a (non-exhaustive) overview of models that have been developed to predict gully expansion. Gully headcut retreat is generally the best-studied expansion process and several process-oriented models have been developed to simulate this. Examples include CHILD for permanent gullies (Flores-Cervantes et al., 2006) or the module TIEGEM within AnnAGNPS for ephemeral gullies (Gordon et al., 2007). Both are based on a model simulating the hydraulics at the gully head by Alonso et al. (2002). While field validation of its predecessor, EGEM (Woodward, 1999), revealed important flaws, TIEGEM tends to show better model performances. Nonetheless, testing currently remains limited. Also evaluations of CHILD showed that it is capable of reproducing observed retreat rates relatively well, at least in some contexts (e.g. Campo-Bescós et al., 2013). However, its application requires several parameters that generally need to be obtained in the field (including the height of the headcut, the shape of the plunge pool and soil erodibility). This greatly limits its use at larger scales. This problem is not specific to the CHILD model, but affects most process-based gully headcut retreat.

---

**Table 2** Examples of empirical gully occurrence and gully density models.

<table>
<thead>
<tr>
<th>Method</th>
<th>Sub method</th>
<th>Authors</th>
<th>Scale (km²)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bivariate statistical</td>
<td>Conditional analysis</td>
<td>Conoscenti et al., 2013</td>
<td>250</td>
<td>Italy</td>
</tr>
<tr>
<td></td>
<td>Index of entropy</td>
<td>Zabih et al., 2018; Arabameri et al., 2018b</td>
<td>15.4-416</td>
<td>Iran</td>
</tr>
<tr>
<td></td>
<td>Information value</td>
<td>Luca et al., 2011; Conforti et al., 2011; Al-Abadi and Al-Ali, 2018</td>
<td>26.7-40</td>
<td>Iran, Italy</td>
</tr>
<tr>
<td></td>
<td>EBF</td>
<td>Al-Abadi and Al-Ali, 2018</td>
<td>26.74</td>
<td>Iran</td>
</tr>
<tr>
<td></td>
<td>Frequency ratio</td>
<td>Al-Abadi and Al-Ali, 2018; Rahmati et al., 2016; Zabih et al., 2018; Arabameri et al., 2018b</td>
<td>15.4-2.595</td>
<td>Iran</td>
</tr>
<tr>
<td></td>
<td>Weights of evidence</td>
<td>Rahmati et al., 2016; Arabameri et al., 2018b; Zabih et al., 2018</td>
<td>15.4-2.595</td>
<td>Iran</td>
</tr>
<tr>
<td>Multivariate statistical</td>
<td>Logistic regression</td>
<td>Akgün and Türk, 2011; Luca et al., 2011; Conoscenti et al., 2014; Maerker et al., 2020</td>
<td>9.5-424</td>
<td>Italy, Turkey</td>
</tr>
<tr>
<td>Machine learning</td>
<td>AHP</td>
<td>Arabameri et al., 2018b</td>
<td>416</td>
<td>Iran</td>
</tr>
<tr>
<td></td>
<td>ANN</td>
<td>Pourghasemi et al., 2017</td>
<td>2595</td>
<td>Iran</td>
</tr>
<tr>
<td></td>
<td>BRT</td>
<td>Maerker et al., 2011, 2012; Angileri et al., 2016; Rahmati et al., 2017; Arabameri et al., 2018a</td>
<td>245-848</td>
<td>Iran</td>
</tr>
<tr>
<td></td>
<td>CRT</td>
<td>Rheir et al., 2007; Geissen et al., 2007; Gomez-Gutiérrez et al., 2009b; Maerker et al., 2011</td>
<td>26.4-3500</td>
<td>Spain, Turkey, Mexico, Italy</td>
</tr>
<tr>
<td></td>
<td>FDA</td>
<td>Gayen et al., 2019</td>
<td>709</td>
<td>India</td>
</tr>
<tr>
<td></td>
<td>MARS</td>
<td>Gomez-Gutiérrez et al., 2009b; Gomez-Gutiérrez et al., 2009c; Gomez-Gutiérrez et al., 2015; Arabameri et al., 2018a; Gayen et al., 2019; Conoscenti et al., 2018; Conoscenti and Rotigliano, 2020</td>
<td>9.5-848</td>
<td>India, Spain, Iran, Italy</td>
</tr>
<tr>
<td></td>
<td>Maximum entropy</td>
<td>Zakirinejad and Maerker, 2014; Pourghasemi et al., 2017; Maerker et al., 2020</td>
<td>2595</td>
<td>Iran, Italy</td>
</tr>
<tr>
<td></td>
<td>Random forest</td>
<td>Kühnert et al., 2010; Rahmati et al., 2017; Arabameri et al., 2018c; Gayen et al., 2019; Vanmaercke et al., 2020</td>
<td>245-848</td>
<td>India, Iran, Australia, Horn of Africa</td>
</tr>
<tr>
<td></td>
<td>SVM</td>
<td>Rahmati et al., 2017; Pourghasemi et al., 2017; Gayen et al., 2019c;</td>
<td>245-2.595</td>
<td>India, Iran</td>
</tr>
</tbody>
</table>

*EBF: Evidence belief function; AHP: Analytical hierarchy process; ANN: Artificial neural network; BRT: Boosted regression tree; CRT: Classification and regression tree; FDA: Flexible discriminant analysis; MARS: Multivariate adaptive regression spline; SVM: Support vector machine.*
models (e.g. Poesen et al., 2011). Another important limitation are the often high data requirements needed to accurately predict peak runoff discharges and flow velocities at the gully head. This is a common challenge for ungauged basins (Bloschl, 2006). More simplified approaches to predict headcut retreat based on (hydrological) model routines that require fewer and feasible parameters therefore show greater promise at larger scales but require further development and field validation (e.g. Dabney et al., 2015; Allen et al., 2018).

As with gully occurrence (cf. Section 4.1), empirical models based on statistical correlations between observed headcut rates and environmental variables may offer an alternative (Table 3). Several studies proposed empirical equations predicting gully headcut retreat rates for specific study sites (e.g. Vandekerckhove et al., 2003; Marzolf et al., 2011; Poesen et al., 2011; Frankl et al., 2012; Li et al., 2015). These models differ strongly in terms of incorporated factors. However, a meta-analysis of >700 measured volumetric headcut retreat rates worldwide showed that the upslope contributing area (A) of the gully headcut and the rainfall intensity (expressed as the rainy day normal, i.e. the average annual rainfall depth divided by the average number of rainy days) are key factors (Vannaercke et al., 2016). Combined, these two variables explained nearly 70% of the observed global variation in headcut retreat rates. As such, this opens promising perspectives to predict gully headcut retreat at regional to continental scales. Nevertheless, several important challenges remain. For example, applying this model to local or regional contexts can result in significant uncertainties. More accurate predictions will likely require the incorporation of land use and other controlling factors (Vannaercke et al., 2016). Furthermore, its application requires knowing A and, by extent, the position of each headcut. Therefore, successfully predicting gully erosion rates at regional to continental scales will likely need the coupling of a headcut retreat model component to a module that simulates where these headcuts occur. Hybrid approaches that combine a simple hydrological model with empirical components are promising in this regard (cf. Section 4.1).

Relatively fewer studies focussed on gully widening and deepening. Nonetheless, also they can contribute significantly to gully expansion (e.g. Martinez-Casasnoves et al., 2004; Hayas et al., 2017a). Some process-oriented models for gully-widening and deepening have been proposed (e.g. Sidorchuk, 1999; Sidorchuk et al., 2003; Table 3). However, as with gully initiation (cf. Section 4.1) and headcut retreat, their application at regional or continental scales is severely impeded by high data requirements. For example, Istanbulluoglu et al. (2005) present a model to predict gully widening by slab failures, but this requires knowing the slab geometry beforehand. Nevertheless, more simplified approaches applicable at larger scales are likely possible. For example, Crouch (1987) indicated the potential of gully sidewall to assess relative differences in erosion rates. Martinez-Casasnoves et al. (2004) successfully used logistic regression to predict gully wall failures in the Penedes region (Spain). Likewise, based on the analyses of gully widening rates in SW Spain, Hayas et al. (2019) developed a simple empirical model that relates gully widening to the upslope contributing area (A) and daily rainfall depth thresholds. This model shows strong similarities with the above-discussed global empirical model for gully headcut retreat rates (Vannaercke et al., 2016). This suggests that developing relatively simple, integrated models of gully expansion should be possible. However, more research on the factors controlling gully widening and deepening across contrasting environments, as well as their associated time scales, is needed (e.g. Graf, 1977).

Table 3
Overview of process-oriented and empirical gully expansion models.

<table>
<thead>
<tr>
<th>Type</th>
<th>Model name</th>
<th>References</th>
<th>Gully type</th>
<th>Process modelled</th>
<th>Main input parameters</th>
<th>Field observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process-Oriented</td>
<td>DIMGUL, STABGUL</td>
<td>Sidorchuk (1999); Sidorchuk et al. (2003)</td>
<td>PG</td>
<td>GHL, GW, GD</td>
<td>Ac, S, Q, K</td>
<td>Russia (n = 1), Australia (n = 1), Swaziland (n = 1)</td>
</tr>
<tr>
<td>EGEM</td>
<td>Nachtergaele et al. (2001a, 2001b); Capra et al. (2005); Tekwa et al. (2015)</td>
<td>EG</td>
<td>GHL</td>
<td>Aa, Ac, Pe, K, D</td>
<td>Belgium (n = 116); Spain &amp; Portugal (n = 86); Italy (n = 92); Nigeria (n = 12)</td>
<td></td>
</tr>
<tr>
<td>AnoAGNPS-TIEGEM</td>
<td>Gordon et al. (2007)</td>
<td>EG</td>
<td>GHL</td>
<td>Ac, M, Q, K, D</td>
<td>US (n = 4)</td>
<td></td>
</tr>
<tr>
<td>CHILD</td>
<td>Flores-Cervantes et al. (2000); Campana-Bescos et al. (2013)</td>
<td>PG</td>
<td>GHL</td>
<td>Ac, M, Q, K, D</td>
<td>no; Spain (n = 1)</td>
<td></td>
</tr>
<tr>
<td>CHILD</td>
<td>Istanbulluoglu et al. (2005)</td>
<td>PG</td>
<td>GW</td>
<td>Aa, Ac, Pe, M, K, D</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>LANDPLANER</td>
<td>Rossi (2014); Rossi et al. (2015a); Rossi et al. (2015b)</td>
<td>PG</td>
<td>GHL, GA</td>
<td>Aa, Ac, S, Pe, Q, M</td>
<td>Italy</td>
<td></td>
</tr>
<tr>
<td>EphGEE</td>
<td>Vieira et al. (2015); Dabney et al. (2015)</td>
<td>EG</td>
<td>GHL</td>
<td>Q, K</td>
<td>US (n = NA)</td>
<td></td>
</tr>
<tr>
<td>SWAT-DEG</td>
<td>Allen et al. (2018)</td>
<td>EG</td>
<td>GHL</td>
<td>Ac, Q, K, D</td>
<td>US (n = 3)</td>
<td></td>
</tr>
<tr>
<td>Empirical</td>
<td>regression</td>
<td>Vannaercke et al. (2016)</td>
<td>PG, EG</td>
<td>GHL</td>
<td>Aa, Pa</td>
<td>global (n = 724)</td>
</tr>
<tr>
<td>regression</td>
<td>Li et al. (2015)</td>
<td>PG</td>
<td>GA</td>
<td>Aa, Ac, S</td>
<td>China (n = 30)</td>
<td></td>
</tr>
<tr>
<td>regression</td>
<td>Frankl et al. (2012)</td>
<td>PG</td>
<td>GHV</td>
<td>Aa</td>
<td>Ethiopia (n = 18)</td>
<td></td>
</tr>
<tr>
<td>regression</td>
<td>Marzolf et al. (2011)</td>
<td>PG</td>
<td>GHV</td>
<td>Aa, Pe</td>
<td>Spain (n = 9)</td>
<td></td>
</tr>
<tr>
<td>regression</td>
<td>Vandekerckhove et al. (2001a), Vandekerckhove et al., 2003</td>
<td>PG</td>
<td>GHV</td>
<td>Aa</td>
<td>Spain (n = 46, n = 12)</td>
<td></td>
</tr>
<tr>
<td>regression</td>
<td>Burkard and Kostanchuk (1997)</td>
<td>PG</td>
<td>GA</td>
<td>Aa</td>
<td>Canada (n = 44)</td>
<td></td>
</tr>
<tr>
<td>regression</td>
<td>Radosne et al. (1995)</td>
<td>PG</td>
<td>GHL</td>
<td>Aa, Ac, Gl</td>
<td>Romania</td>
<td></td>
</tr>
<tr>
<td>regression</td>
<td>US Soil Conservation Service (1966)</td>
<td>PG</td>
<td>GHL</td>
<td>Aa, Pe</td>
<td>US (n = 210)</td>
<td></td>
</tr>
<tr>
<td>regression</td>
<td>Seginer (1966)</td>
<td>PG</td>
<td>GHL</td>
<td>Aa</td>
<td>Israel</td>
<td></td>
</tr>
<tr>
<td>regression</td>
<td>Thompson (1964)</td>
<td>PG</td>
<td>GHL</td>
<td>Aa, S, Pe, K</td>
<td>US</td>
<td></td>
</tr>
</tbody>
</table>

\( a \) PG: permanent gully, EG: ephemeral gully.

\( b \) GHL: linear gully headcut retreat, GHV: volumetric gully headcut retreat, GW, gully widening, GD: gully deepening, GA = gully area.

\( c \) Aa: catchment area, Ac: catchment characteristics (slope, length, CN, etc.), S: local slope at gully head, Pa: average rainfall data, Pe: event rainfall data, M: gully headcut morphology, Q: flow discharge, K: soil data (e.g. critical shear stress, soil cohesion, ...), D: (maximum) gully depth, Gl: gully length.

\( d \) For process-oriented models n refers to the gully validation years (i.e. number of gullies times the period over which they were evaluated); for empirical models n refers to the number of data points used for establishing the regression equation.

\( e \) Based on Alonso et al. (2002) hydraulic “plunge-pool” model.

\( f \) The model simulates gully headcut retreat, however gully widening and deepening are estimated through empirical formula based on flow discharge.
4.3. Predicting the contribution of gullies to catchment sediment yield

Several studies already attempted to account for the contribution of gully erosion to catchment sediment yields (SY) via an empirical approach. These studies mostly rely on directly correlating observed SY to proxies of average gully densities (e.g. Zhao et al., 2016) or, alternatively, a semi-quantitative score describing the overall presence of gullies in the catchment in combination with other factors (e.g. de Vente et al., 2013). These approaches generally result in good model performances, while their relatively low data requirements make it feasible to apply them at larger scale. However, they also come with limitations. First, these are spatially lumped models that do not account for spatial patterns of gully densities. Second, they often depend on expert-based judgments of the presence and importance of gullies (e.g. de Vente et al., 2005, 2006) and therefore may not always be perfectly reproducible and objective. Third, factors controlling gully formation typically also control other erosion processes and sediment yields (e.g. steeper topography, erodible soils, limited vegetation cover; Syvitski and Milliman, 2007; Pelletier, 2012; Vanmaercke et al., 2014). Hence, it is often hard to tell to what extent observed correlations between proxies of gully density and SY are indeed attributable to the gullies or to inter-correlations with other factors. On the other hand, factors known to drive gully erosion (e.g. rainfall intensity; Vanmaercke et al., 2016; Hayas et al., 2017b) are not always incorporated in these models because they did not reveal a statistically significant correlation (e.g. de Vente et al., 2005; Zhao et al., 2016). These limitations make such empirical approaches often unsuitable for land or climate change scenario analyses or for developing detailed catchment management strategies (de Vente et al., 2013). Nevertheless, such models may be useful for predicting SY at regional to continental scales.

To address these shortcomings, several studies aimed to model the contribution of gully erosion in a more spatially explicit and process-oriented way. Some studies have adapted sediment yield models like SWAT or WATEM-SEDEM. They generally predict SY by estimating sheet and rill erosion rates and then accounting for sediment deposition between the hillslopes and river system (e.g. Van Rompaey et al., 2001; Vigiak et al., 2017). By changing some of the model assumptions or parameters, these models may partially account for gully erosion (e.g. Verstraeten et al., 2007; Easton et al., 2010). Nonetheless, such approaches remain difficult to parameterize and validate and are conceptually problematic, especially in the case of permanent gullies (e.g. de Vente et al., 2013).

Other studies have attempted to directly account for gully erosion by incorporating spatially explicit estimates of gully-prone areas in combination with other factors describing erosion and sediment transfers (e.g. de Vente et al., 2008; Hargreweyn et al., 2017). Identifying gully-prone areas is typically based on the slope-area threshold concept (cf. Section 4.1, Eq. (1)), while their contribution to SY is either based on an empirical estimate of typical gully erosion rates (Hargreweyn et al., 2017) or through model calibration with observed SY (de Vente et al., 2008). Apart from being spatially explicit, this may also avoid the problem of reproducibility mentioned above. Nonetheless, these approaches remain relatively rudimentary and scarcely applied. Wilkinson et al. (2009, 2014) developed a more elaborate strategy where detailed maps of existing gullies underpin estimates of the contribution of gully erosion to the sediment budget, based on the volumetric expansion rates of gullies over time. This approach incorporates ancillary information on the relative development stage of the gully networks and the fraction of soil textures likely to contribute to suspended sediment loads. However, the requirement for gully mapping lists easy applications at larger scales. One of the most complete models to date that allows accounting for the effect of gully erosion on SY is AnnGNPS (Momm et al., 2012). It can identify gully mouth locations semi-automatically with the APET tool. This could allow calculating the spatial contribution of gully erosion to SY and evaluating the effect of gully conservation measures at catchment scale. Nevertheless, its applicability over larger areas remains currently unknown.

An additional challenge lies in the fact that gullies not only directly influence SY by contributing sediments, but also indirectly by altering the runoff and sediment connectivity between hillslopes and river systems (e.g. Poensen et al., 2003; Martinelli Costa and Bacellar, 2007; de Vente et al., 2009). They can significantly increase sediment connectivity (e.g. Ionita et al., 2015a) but also temporarily store sediments (e.g. Taylor et al., 2018). Especially vegetated gullies can function as significant runoff and sediment traps (e.g. Zierholf et al., 2001; Rey et al., 2007; Molina et al., 2009). The same holds for check dams built in gullies (e.g. Castillo et al., 2007; Frankl et al., 2013; Guyassa et al., 2017). In addition, high gully densities may lead to more direct rainfall-runoff responses (e.g. Martinelli Costa and Bacellar, 2007) and therefore potentially higher floodplain deposition rates, as riverbank overtopping may occur more frequently. While different modelling approaches for sediment connectivity already exist (e.g. Borselli et al., 2008; Vigiak et al., 2012), their suitability to deal with sediment transfers by gullies remains largely untested. Their application would also require information on the spatial extent of gully networks as well as on their vegetation cover and the presence of check dams or similar measures. As such, assessing both the direct and indirect contribution of gullies to SY at large scales remains very difficult, in particular because the necessary data (e.g. inventories of gullies and gully control measures) remain mostly unavailable.

5. Model input data at the continental scale

Modelling gully erosion not only requires observations on gully occurrence and dynamics (cf. Sections 2 and 3). It also requires input data on the environmental factors controlling gully erosion, more specifically the (i) topography, (ii) vegetation cover, (iii) land cover, use and management, (iv) soils and lithology and (v) climate and weather conditions. The availability and quality of input data condition the type of model that can be used (cf. Section 4). Input data for small study areas can be acquired with field-based methods. Gully erosion modelling at regional to continental scale generally needs to rely on Earth Observation (EO) data. The spatial resolutions, revisiting times and level of detail of such EO data have significantly increased over the past decades (e.g. Belward and Skoien, 2015). Continental to global EO-derived datasets are also made increasingly publically available. Furthermore, an increasing number of cloud-based data processing platforms are developed in order to deal with the associated increasing demands for data storage and processing power. These include the Copernicus Data and Information Access Services (DIAS) launched by the European Commission in 2016 and the Google Earth Engine platform.

While datasets at the national level often provide higher resolutions and levels of detail, continental to global datasets have the great advantage of providing harmonized information. The use of national datasets for regional to global scale modelling is often hampered by their fragmentary availability, varying data acquisition and treatment methods and possibly limited data access (e.g. Höele and Rutzinger, 2011; Lobani et al., 2018). Such lack of harmonization can introduce additional important uncertainties.
Hence, this review section aims to provide an overview of currently available harmonized (and ideally free) datasets that can be used for gully erosion modelling at regional to continental scales. We focus on data products that are available at a European or global scale. Based on our understanding of the factors controlling gully erosion and expansion, we discuss datasets describing the (1) topography, (2) vegetation cover, (3) land cover, use and management, (4) soil properties and lithology, and (5) climate. The datasets presented and discussed below were selected based on their relevance, up-to-datedness, accuracy, length of observation periods and frequency of updates. It is expected that with the increasing availability of EO data, additional datasets will become available in the near future.

5.1. Topography

Topographic variables play a key role in the prediction of both gully initiation and expansion. The most relevant factors are the local slope steepness and the topographic area draining to a specific point in the landscape (cf. Sections 4.1, 4.2). Such information can be derived from digital elevation models (DEMs). Remotely-sensed DEMs for areas of limited spatial extent have been obtained from stereoscopic aerial image analysis or airborne LiDAR for decades. Numerous countries nowadays produce national DEMs based on airborne LiDAR surveys down to sub-meter pixel size (e.g. Lahani et al., 2018). Here we focus on DEMs having a (nearly) global or European coverage (Table 4).

Among the first near-global DEM datasets derived from spaceborne observations were the SRTM-C DEM (first released in 2003; Rabus et al., 2003), the ASTER GDEM (released 2009) and the improved ASTER GDEM2 (released 2011; Tachikawa et al., 2011) and ASTER GDEM3 (released 2019). While SRTM-C and the more recent TanDEM-X DEM (Krieger et al., 2007) are based on interferometric Synthetic Aperture Radar (SAR) image analysis, ASTER GDEMs and the ALOS DEMs (Tadono et al., 2014; Takaku et al., 2014) are derived from stereoscopic analysis of optical satellite images. All these global DEMs can be considered as Digital Surface Models (DSMs), i.e. the elevation values reflect the Earth’s surface including objects such as vegetation and buildings. Furthermore, most of these global DEMs are based on observations collected over longer time periods. Only the SRTM data collection was conducted over only eleven days (in February 2000) and thus reflects the surface elevation at a fairly specific moment (Rabus et al., 2003).

As the data source documentation and various comparison studies indicate (see e.g. review by Alganci et al., 2018), the vertical accuracies of these DEMs strongly depend on the terrain characteristics. Among the publically available global DEMs with finer spatial-resolution (<30 m grid spacing), Purinton and Bookhagen (2017) found that SRTM-C, ALOS World 3D and TanDEM-X provide the highest vertical accuracies (below 3.5 m). This estimate was based on a large number of GPS reference measurements across a wide range of terrain types and elevations. Apart from freely available datasets, some commercial global DEMs have also been recently released (e.g. TanDEM-X, ALOS World 3D; Table 4). These generally have higher spatial resolutions. Based on the same GPS reference dataset, vertical accuracies of both datasets were assessed to be below 2 m (Purinton and Bookhagen, 2017). Several authors have also assessed the suitability of these global DEMs for geomorphological and hydrological analyses in different landscapes (see e.g. Purinton and Bookhagen, 2017; Boulton and Stokes, 2018; Mondal et al., 2017).

Despite their lower spatial resolution and accuracies as compared to airborne LiDAR DEMS, these global satellite-derived DEMs (Table 4) remain the only consistent, harmonized datasets at regional to continental scales in almost all regions of the world. Among them, the TanDEM-X and the ALOS World 3D (AW3DS) are the best available products. However, their high cost and the computing resources required to use them may pose limitations to continental or global modelling efforts.

5.2. Vegetation cover

Also vegetation is generally considered as a key controlling factor of gully erosion and its impacts on SY (cf. Section 4). Overall, a negative relation between vegetation cover and gully density/erosion can be expected as (i) plant material at the surface can slow down flow velocities and reduce runoff shear stresses; (ii) below-ground biomass (in particular plant roots) can increase the soil cohesion; and (iii) vegetation can affect the soil structure and soil hydrological balance, leading to lower runoff production rates (e.g. Gyselis and Poesen, 2003; Knapen et al., 2007; Vannoppen et al., 2015).

Various indices exist to map patterns of vegetation cover from satellite imagery and several publically available, ready-to-use, datasets exist (Table 5). The most commonly used proxy for vegetation cover is the Normalized Difference Vegetation Index (NDVI). Various studies successfully used NDVI as a predictor for gully densities (e.g. Zhao et al., 2016; Vannaeereke et al., 2020). Nonetheless, also other indices may be useful for gully erosion modelling, e.g. the Soil-Adjusted Vegetation Index (SAVI) and the Modified SAVI. Bannari et al. (1995) and Barati et al. (2011) provide reviews of these different indices. While such indices provide proxies for plant biomass and productivity, biophysical variables like the leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (FPAR) and the fraction of green vegetation cover (Fcover or FVC) provide more physically-based descriptions of the vegetation cover. The latter is particularly relevant in the context of soil erosion susceptibility (Panagos et al., 2015a; Borrelli et al., 2017b). It corresponds to the fraction of green vegetation, covering the ground as seen from the nadir direction. Similarly, Vegetation Continuous Fields (VCF) provides estimates of vegetation cover as the percentage of tree cover, percentage of non-tree vegetation, and percentage of non-vegetated area (e.g. Sexton et al., 2013). An important limitation of these EO-derived indices is that they only relate to the above-ground vegetation. Currently, information on below-ground biomass can only be indirectly estimated (e.g. based on above-ground vegetation characteristics, in-situ data and expert knowledge). Nevertheless, important progress has recently been made in this regard. For example, based on empirical modelling, Fan et al. (2017) provide estimates of maximum rooting depth at a global scale.

Table 5 lists a selection of publically available global NDVI and FCover datasets. They were selected because they are free, have a high spatial resolution (1 km or finer), are based on a sufficiently long observation period (at least several years) and can be considered representative for the current vegetation cover (i.e. their observation period includes recent years). Several of these datasets are regularly updated. Most of these selected datasets are derived from the analysis of MODIS, Proba-V, Spot Vegetation, and Landsat satellite imagery. They provide temporal coverages ranging from 8-day composites to annual composites. However, some of these series (especially monthly and sub-monthly Landsat composites) contain gaps due to cloud or snow cover. Datasets based on Landsat imagery currently provide the highest spatial detail, with 30 m grid spacing for continental to global products.

5.3. Land cover, use and management

While vegetation cover refers to the quantity of above-ground biomass (see Section 5.2), land use and land cover (LULC) datasets classify the land surface in categories describing how the land is used. Many of the currently existing modelling tools (e.g. CN-based approaches, cf. Section 4) rely on LULC classes, rather than indices of vegetation cover. As such, LULC dataset can be an important asset for gully erosion modelling. Furthermore land cover, use and management encompass several other relevant elements that are not necessarily reflected by vegetation indexes. Examples include the shapes and sizes of parcels, parcel boundary characteristics, cropping cycles and tillage practices (e.g. Poesen et al., 2003; Valentin et al., 2005; Piccarreta et al., 2012). Also soil conservation measures often have a significant impact.
on runoff and sediment production (e.g. Maetens et al., 2012a, 2012b). The effects of erosion-preventing or reducing measures on gully erosion rates and sediment production can be large (for detailed reviews, see Bartley et al., 2020 and Frankl et al., 2021).

Several studies (e.g. Tsendbazar et al., 2015; Grekousis et al., 2015) provide comprehensive comparisons of available regional to global LULC datasets regarding their spatial and temporal resolution, accuracy and thematic coverage. Overall, the opening of the Landsat satellite image archive in 2008 and the launch of the Sentinel-2 satellites at 10 to 20 m spatial resolution in 2015 and 2017 lay the foundations for a new generation of high resolution global land cover products. The Globe-Land30 dataset was the first open-access global land cover map at 30 m spatial resolution (Chen et al., 2017). It comprises ten types of land cover for the years 2000 and 2010, extracted from more than 20,000 Landsat and LIDAR satellite images.

Similar to Table 5, datasets in this selection are freely available, based on sufficiently long observation periods, relatively recent and/or regularly updated. Overall accuracies of these products vary between 64 and 80% (Grekousis et al., 2015). Of this selection, CORINE Land Cover provides the longest temporal coverage (1990, 2000, 2006, 2012, 2018) and highest classification detail (44 land cover classes) at pan-European scale (Büttner et al., 2014). The S2GLC product based on the analysis of Sentinel-2 imagery currently provides the finest spatial detail at pan-

### Table 4
Overview of global and European digital elevation models and their key characteristics.

<table>
<thead>
<tr>
<th>Dataset/Prefix</th>
<th>Spatial extent</th>
<th>Satellite data acquisition period</th>
<th>Spatial resolution</th>
<th>Source</th>
<th>Data download</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TanDEM-X DEM</td>
<td>global (pole-to-pole)</td>
<td>2010 to 2015</td>
<td>12 m and 30 m</td>
<td>12 m commercial product available from Airbus Defence and Science as WorldDEM®; 12/30 m products available by research agreement from DLR: <a href="https://tandemx-science.dlr.de/">https://tandemx-science.dlr.de/</a></td>
<td></td>
<td>Krieger et al. (2007)</td>
</tr>
</tbody>
</table>

### Table 5
Selection of global vegetation cover datasets (focusing on NDVI and FCover).

<table>
<thead>
<tr>
<th>Dataset/Prefix</th>
<th>Spatial extent</th>
<th>Sensor</th>
<th>Satellite data acquisition period</th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
<th>Source</th>
<th>Data download</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fcover Copernicus</td>
<td>global, 75°N to 60°S</td>
<td>Proba V, SPOT-VGT/PROBA V</td>
<td>01/2014 to present, 1999 to present</td>
<td>300 m, 1 km</td>
<td>10 days composite</td>
<td>ESA, public</td>
<td><a href="http://land.copernicus.eu/global/products/fcover">http://land.copernicus.eu/global/products/fcover</a></td>
<td>Smets et al. (2017a, 2018)</td>
</tr>
<tr>
<td>MODV1 FCover</td>
<td>global</td>
<td>MODIS</td>
<td>2000–2016</td>
<td>1 km</td>
<td>monthly composite</td>
<td>ISPRA, public</td>
<td>Available upon request from the author</td>
<td>Filipponi et al. (2018)</td>
</tr>
<tr>
<td>Continuous Fields</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copernicus Land</td>
<td>global</td>
<td>PROBA-V, SPOT-VGT/PROBA-V</td>
<td>02/2016 to present, 04/1998 to present</td>
<td>300 m, 1 km</td>
<td>10 days composite</td>
<td>ESA, public</td>
<td><a href="http://land.copernicus.eu/global/products/ndvi">http://land.copernicus.eu/global/products/ndvi</a></td>
<td>Smets et al. (2016a, 2018)</td>
</tr>
<tr>
<td>Monitoring NDVI</td>
<td>global</td>
<td>PROBA-V, SPOT-VGT/PROBA-V</td>
<td>1984 to present</td>
<td>30 m</td>
<td>8-day composite, 32-day composite, annual composite monthly composite, annual composite</td>
<td>USGS/Google Earth Engine, public</td>
<td><a href="https://earthengine.google.com/datasets/">https://earthengine.google.com/datasets/</a></td>
<td>Gorelick et al. (2017)</td>
</tr>
</tbody>
</table>
European scale with a pixel size of 10 m. It distinguishes 13 land cover classes with an overall accuracy of 83% (Lewinski et al., 2019).

At global scale, the land cover product recently released by the Copernicus Global Land Service currently overview provides the highest level of detail. Besides a discrete classification with 22 land cover classes, this product contains fraction cover layers for ten base land cover classes (Buchhorn et al., 2019). It is worth mentioning, that the generation of a global land cover product by the ESA WorldCover initiative is in progress, aiming at a 10 m global land cover map with a minimum of 10 land cover classes and a minimum overall accuracy of 75% (to be released in 2021).

Yet detailed information on land management practices and the implementation of gully control or other soil and water conservation measures remains largely lacking at (sub)continental scales. We believe this is a highly important research gap. It not only impedes the accurate prediction of gully erosion, but also the evaluation of prevention and mitigation measures at larger scales. Nonetheless, for Europe, several datasets were developed over recent years that can help assessing these aspects. Examples include the Copernicus Pan-European dataset on Small Woody Features (EEA, 2015) and the EU-wide assessments of the Crop Management factor of the Universal Soil Loss equation (EU JRC, 2015; Panagos et al., 2015c). Also estimates of the effect of support Crop Management factor of the Universal Soil Loss equation (EU JRC, 2015; Panagos et al., 2015e). However, these estimates remain subject to important uncertainties and relate to sheet and rill erosion rather than to gully erosion.

5.4. Soil properties and lithology

The formation and expansion of gullies is commonly influenced by particular soil characteristics and behaviour. However, the role of soil properties in explaining patterns of gully erosion remains relatively poorly understood (e.g. Torri and Poesen, 2014; Vanmaercke et al., 2016, 2020). One reason for this is that soil properties affect both the hydrological functioning of soils but also their erosion resistance during concentrated flow shear stresses (e.g. Knapen et al., 2007; cf. Section 4). These effects may counteract each other in ways that currently remain hard to quantify. For example, clayey soils often have high runoff coefficients but can also be very cohesive. Furthermore, accurately quantifying soil properties is generally labour-intensive and therefore remains a big challenge at larger scales. This also impedes our understanding of their influence on gully erosion.

Nonetheless, there are several soil properties that are known to potentially influence gully erosion and are therefore worthwhile considering. Most of these can affect both the erodibility and hydrological functioning of soils. The most relevant properties are likely soil texture characteristics (e.g. percentage of sand, silt and clay), soil organic carbon content, the content and cover of coarse fragments (e.g. Poesen et al., 1999; Torri et al., 1997; Rieke-Zapp et al., 2007; Panagos et al., 2014; Borrelli et al., submitted). Also the water holding capacity, soil depth, bulk density and underlying lithology (or parent material) can play an important role in determining the occurrence and dimensions of gullies (e.g. Kheir et al., 2008; Hopp and McDonnell, 2009). Likewise, the presence of faults and joints can influence gully occurrence, as they are often associated with higher degrees of weathering. Finally, gully occurrence and dynamics can be affected by the presence of specific soil horizons, dispersivity (e.g. sodic properties), susceptibility to soil piping, etc. (e.g. Riensk et al., 2000; Nachtergaele and Poesen, 2002; Bernatcek-Jakiel and Poesen, 2018; Bernatcek-Jakiel and Wrońska-Walcza, 2018). Many of these properties remain difficult to assess in detail (at sub-)continental scales. Nevertheless, qualitative soil maps can be very helpful when aiming to account for such context-specific aspects.

Table 7 provides an overview of relevant databases at European and global scales. The European Soil Database provides 73 attributes at 1:1 million scale or as a raster format with a 1 km resolution (Panagos et al., 2012). The dataset is mostly qualitative and mainly based on national soil data and maps from the period 1960–1990. Potentially relevant attributes include: the dominant and secondary parent material, depth
drivers of gully erosion (cf. Section 4). Rainfall can have short (i.e. triggering) and long term (i.e. conditioning) effects. On the short term, rainfall intensities and amounts are generally key parameters, as they will determine the runoff volume and hence shear stress exerted by the water. Numerous studies have demonstrated significant correlations between rainfall intensity and gully head initiation (e.g. Hayas et al., 2017b), headcut retreat (e.g. Vanmaercke et al., 2016) and gully widening (e.g. Hayas et al., 2019). Conversely, characterizing the effect of rainfall over long periods is more complicated. For example, rainfall controls the soil moisture, which may further condition the runoff response but also the soil resistance against erosion (e.g. Capra et al., 2009). Furthermore, climate over longer timescales can have significant indirect effects, e.g. through its influence on vegetation development and soil mechanical properties (e.g. Donnini et al., 1991; Sanchis et al., 2008; Fan et al., 2017). Complex relations exist among these different effects, making it difficult to define rainfall-related variables that accurately account for all relevant mechanisms. In some contexts, also snowmelt may be a key driver of gully erosion (e.g. Ionita, 2006; Golosov et al., 2018). While snowmelt runoff can already be modelled and monitored to some extent, its effects on gully erosion remain relatively understudied, especially at (sub)continental scales (e.g. Maltsev and Yermolaev, 2019).

Hence, the type and spatio-temporal resolution of precipitation data required will vary depending on the study region, but also in function of the purpose. Modelling exercises at short time scales (e.g. daily, event-based) require data of similar temporal resolutions. When aiming to understand mean tendencies and spatial variations, coarser data are already useful. For example, long-term average proxies like the rainy day normal can already serve as a useful predictor for average trends (e.g. Vanmaercke et al., 2016; Hayas et al., 2017b).

Table 8 provides a selection of available global and European rainfall datasets, building on an earlier overview presented by Sun et al. (2018). These gridded datasets are based on a variety of methods. Several are derived from rain gauge data, using different regionalization methods (e.g. Rudolf et al., 2009; Schamm et al., 2014). The accuracy of such datasets can be expected to depend on the gauge network density which

### 5.5. Climate and weather conditions

Climate and weather conditions, and especially rainfall, are key

<table>
<thead>
<tr>
<th>Dataset/product name</th>
<th>Spatial extent</th>
<th>Data acquisition period</th>
<th>Spatial resolution</th>
<th>Source</th>
<th>Data download</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUCAS 2009 Topsoil physical properties for Europe</td>
<td>Europe</td>
<td>2009</td>
<td>500 m</td>
<td>European Commission/JRC, public</td>
<td><a href="https://esdac.jrc.ec.europa.eu/content/topsoil-physical-properties-europe-based-topsoil-data">https://esdac.jrc.ec.europa.eu/content/topsoil-physical-properties-europe-based-topsoil-data</a></td>
</tr>
<tr>
<td>LUCAS 2009 Chemical properties</td>
<td>Europe</td>
<td>2009</td>
<td>500 m</td>
<td>European Commission/JRC, public</td>
<td><a href="https://esdac.jrc.europa.eu/content/chemical-properties-european-scale-based-lucass-topsoil-data">https://esdac.jrc.europa.eu/content/chemical-properties-european-scale-based-lucass-topsoil-data</a></td>
</tr>
<tr>
<td>European Soil Database</td>
<td>Europe (and Eurasia)</td>
<td>1960–1990</td>
<td>1 km</td>
<td>European Commission/JRC, public</td>
<td><a href="https://esdac.jrc.europa.eu/content/european-soil-database-v2-raster-library-1km1km">https://esdac.jrc.europa.eu/content/european-soil-database-v2-raster-library-1km1km</a></td>
</tr>
<tr>
<td>Soil erodibility dataset</td>
<td>Europe</td>
<td>2014</td>
<td>500 m</td>
<td>European Commission/JRC, public</td>
<td><a href="https://esdac.jrc.europa.eu/content/soil-erodibility-k-factor-high-resolution-dataset-europe">https://esdac.jrc.europa.eu/content/soil-erodibility-k-factor-high-resolution-dataset-europe</a></td>
</tr>
<tr>
<td>Geo-lithological map for Central Europe (Geo-LiM)</td>
<td>Central Europe</td>
<td>1990–2010</td>
<td>1:1 million</td>
<td>CNR IRPI, public</td>
<td><a href="https://zemozo.org/record/3530257">https://zemozo.org/record/3530257</a></td>
</tr>
<tr>
<td>Global Lithology Map</td>
<td>global</td>
<td>unknown</td>
<td>1: 3750 000 (average)</td>
<td>University of Hamburg, (partly) public</td>
<td><a href="https://doi.pangaea.de/10.1594/PANGAEA.788537">https://doi.pangaea.de/10.1594/PANGAEA.788537</a></td>
</tr>
</tbody>
</table>

M. Vanmaercke et al.  Earth-Science Reviews 218 (2021) 103637
may be limited, especially in Global South countries (e.g. Schneider et al., 2014). Despite their generally shorter time series, RADAR-derived products can provide an important alternative (e.g. Ashouri et al., 2015). RADAR-based rainfall observation networks are implemented in many countries. They measure rainfall rates, based on the analysis of the echoes generated by the interaction between active microwave signals and rain drops (Sauvageot, 1994; Wexler and Atlas, 1963). RADAR rainfall estimates are indirect and represent measures of rainfall far from the surface, which may be a limitation. However, their high spatio-temporal level of detail (e.g. estimates every 10 min at a 5 × 5 km resolution) allows measuring local, short and intense rainfall events. Overall, data from regional RADAR networks (and in particular historical RADAR data series) remain scarcely accessible and underused. Other gridded rainfall products are derived from satellite observations. In general, they are based on algorithms that combine passive microwave and infrared measurements from geostationary and low earth orbit satellites. Despite their often limited spatio-temporal resolutions, their main advantages are their global coverage and their easy accessibility. Hence, they offer great potential for gully erosion modelling at larger scales, especially in countries where other rainfall data are scarce. Nonetheless, also these satellite products generally rely to some extent on gauging station observations and can be subject to uncertainties (e.g. Monsieurs et al., 2018). Finally, several datasets have been produced through reanalysis, in which meteorological modelling results are combined with rainfall observations (Gelaro et al., 2017). These products have diverse spatial and temporal resolutions that cover extended periods (Table 8).

At European scale, another relevant proxy worth mentioning is the rainfall erosivity dataset, which was produced with 30-min precipitation data from 1675 stations in the EU (Panagos et al., 2015d). While this proxy was originally developed for simulating sheet and rill erosion rates, it may also be useful for gully erosion modelling.

6. Policies relevant to gully erosion: frameworks and current needs

At the global level, the issue of soil erosion receives significant attention (e.g. Montanarella et al., 2016). For example, the United Nations Convention to Combat Desertification (UNCCD, 2018) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; Scholes et al., 2018) both stress the importance of human-induced soil erosion as a key driver of land degradation and expresses concerns about the potential impacts of climate change on soil erosion rates. Also several of the UN Sustainable Development Goals (SDGs) clearly identify soil resources as being of crucial importance. More specifically, Goal 1 (No Poverty), Goal 2 (Zero Hunger), Goal 3 (Good Health and Well-being), Goal 6 (Clean Water and Sanitation), Goal 13 (Climate Action) and Goal 15 (Life on Land) strongly link to the need to preserve soil resources in order to achieve these goals by 2030 (Keesstra et al., 2016; Bouma, 2019; Panagos and Katsoyiannis, 2019; Albaladejo et al., 2021). The Food Agriculture Organization has published Guidelines for Sustainable Soil Management (FAO, 2016), aiming to support countries in implementing actions for soil protection. The European Union is a front-runner in attaining the SDGs and has committed to play an active role towards their realization. With respect to SDG 15 ‘Life on Land’, the EU identifies 3 sub-themes: ecosystem status, biodiversity and land degradation (Panagos and Katsoyiannis, 2019). One of the indicators used to assess progress with respect to land degradation is soil erosion by water (Panagos et al., 2015a, 2015b). Overall, soil protection is not subject to a single, coherent legislation within the EU. Although a Soil (Thematic Strategy (COM 2006, 2010) was proposed, the Commission withdrew this proposal to develop a Soil Framework Directive in 2014. Nevertheless, there is a strong commitment of the EU and its member states to conserve soil resources and several measures exist across different policies. In the EU agricultural sector, the main active policy instrument to promote agro-environmental friendly agriculture is the Cross Compliance mechanism, which was introduced in the Common Agricultural Policy (CAP) in 2003. In 2009, the standards of Good Agricultural and Environmental Conditions (GAEC) were introduced in the CAP legislation framework (Common Agricultural Policy (CAP), 73/2009, 2020). One of the requirements in the GAEC is to limit soil loss by water erosion and to maintain soil organic carbon (Borreli et al., 2016). For this, the GAEC standards include a set of practices, such as reduced tillage, crop residues management, cover crops, maintaining terraces, grass margins next to watercourses, contour farming and crop rotation. While most of these practices may have a beneficial effect on preventing gully erosion, the GAEC makes no explicit reference to the mitigation of existing permanent gullies, nor to the management of ephemeral gullies. Nonetheless, specific measures can be taken by individual member states to tackle (gully) erosion, using funds from the European Agricultural Fund for Rural Development (EAFRD), under the Council Regulation EU 1305/2013. For example, in the Spanish region of Andalucia, gully control measures were subsidized under this programme in 2009–2010. However, despite some initial successes, this programme was discontinued because of a shift in regional priorities. In Flanders (Belgium) municipalities can request subsidies for developing local erosion control plans and implementing small-scale erosion control measures like check dams or sediment control basins.

Also the new legislative proposal of the European Commission for the post-2020 Common Agricultural Policy (CAP) 2021–27, COM (2018) 392 (2018) includes measures for soil conservation (e.g. cover crops) and maintaining soil organic carbon. Post-2020, soil protection will gain more importance through Eco-schemes as an integral part of the new Green Architecture design. In fact, effective soil management is one of the nine key objectives of the new CAP. While the post-2020 CAP is still being defined and will likely only come into force in 2023, it is clear that Member States will have greater flexibility in deciding on policy measures through the CAP national strategic plans. This may create opportunities to target gully erosion more specifically and to tailor the implementation of measures to particular farming contexts. However, apart from agriculture, also land use changes such as reforestation can have significant impacts on gully erosion. Presently, the European Union does not have a common forestry policy making it still primarily a national matter. Nonetheless, the CAP is the main funding source for forestry, with conversions of agricultural land to forest being supported by Rural Development funds.

In the area of European water policy, the Water Framework Directive (WFD, Directive 2000/60/EC, 2020) and the Nitrate Directive (91/676/EEC, 1991 set environmental targets that promote soil conservation actions. Under the WFD, EU Member States need to establish Programmes of Measures (PoMs) to achieve good ecological and chemical statuses of water bodies. Diffuse pollution from soil erosion in cropland is identified as a key pressure on water quality in many River Basin Management Plans across the EU (e.g. Heiminger et al., 2015). Thus erosion control measures should be adopted in PoMs to curb agricultural impacts on water bodies. Similarly, the Nitrate Directive requires implementation of good agricultural practices in nitrate vulnerable zones to reduce runoff, erosion, and nitrate losses. However, the WFD and the Nitrate Directive do not mention soil (or gully) erosion and its control explicitly.

Recently, the European Commission introduced the European Green Deal EU COM(2019) 640 (2019) with the ambition to make EU the first climate neutral continent by 2050. The EU Green Deal proposes numerous targets such as protecting 30% of the EU’s land area, bringing back at least 10% of the agricultural area under high-diversity landscape features and plant more than three billion trees by 2030 (Montanarella and Panagos, 2021). Although these targets have not yet been translated in specific policy measures, it is clear that implementing the EU Green Deal will contribute to sustainable soil management, introducing more soil conservation measures, reducing land degradation and mitigating soil losses due to erosion.
Table 8
Selection of global and European rainfall datasets (based on Sun et al., 2018).

<table>
<thead>
<tr>
<th>Dataset/product</th>
<th>Spatial coverage</th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
<th>Period</th>
<th>Sensor and type of retrieval</th>
<th>Source</th>
<th>Data download</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-OBS</td>
<td>Europe</td>
<td>0.55°/0.50°/0.22° rotated/0.44° rotated</td>
<td>Daily</td>
<td>1950-present</td>
<td>Gridded rain gauge</td>
<td>ECAD</td>
<td><a href="https://www.ecac.eu/download/ensembles/download.php">https://www.ecac.eu/download/ensembles/download.php</a></td>
<td>Haylock et al. (2008); Cornes et al. (2018)</td>
</tr>
<tr>
<td>CRU</td>
<td>Global land</td>
<td>0.5° × 0.5°</td>
<td>Monthly</td>
<td>1901–2016</td>
<td>Gridded rain gauge</td>
<td>CRU</td>
<td><a href="http://www.cru.uea.ac.uk/data">http://www.cru.uea.ac.uk/data</a></td>
<td>Harris et al. (2014); New et al. (2000)</td>
</tr>
<tr>
<td>GPCC-monthly</td>
<td>Global land</td>
<td>0.25° × 0.25°, 0.5° × 0.5°, 1.0° × 1.0°, 2.5° × 2.5° × 1.0°</td>
<td>Monthly</td>
<td>1891–2016</td>
<td>Gridded rain gauge</td>
<td>Global Precipitation Climatology Centre</td>
<td><a href="https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-monthly_v2018_doi_download.html">https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-monthly_v2018_doi_download.html</a></td>
<td>Schneider et al. (2014)</td>
</tr>
<tr>
<td>GPCC-daily</td>
<td>Global land</td>
<td>0.5° × 0.5°</td>
<td>Daily</td>
<td>1982–2013</td>
<td>Gridded rain gauge</td>
<td>Global Precipitation Climatology Centre</td>
<td><a href="https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-dail">https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-dail</a> y_v2018_doi_download.html</td>
<td>Schamm et al. (2014)</td>
</tr>
<tr>
<td>PREC/L</td>
<td>Global land</td>
<td>0.5° × 0.5°, 1.0° × 1.0°</td>
<td>Monthly</td>
<td>1948–2020</td>
<td>Gridded rain gauge</td>
<td>NCEP/NOAA</td>
<td><a href="https://www.esrl.noaa.gov/psd/data/gridded/data.precl.html">https://www.esrl.noaa.gov/psd/data/gridded/data.precl.html</a></td>
<td>Chen et al. (2002)</td>
</tr>
<tr>
<td>CPC</td>
<td>Global land</td>
<td>0.5° × 0.5°</td>
<td>Daily</td>
<td>1979–present</td>
<td>Gridded rain gauge</td>
<td>CPC</td>
<td><a href="https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.globalprecip.html">https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.globalprecip.html</a></td>
<td>Xie et al. (2010); Adler et al. (2003)</td>
</tr>
<tr>
<td>GSMaP</td>
<td>Global</td>
<td>0.1°</td>
<td>1 h/daily</td>
<td>2000–2014</td>
<td>Satellite</td>
<td>JAXA</td>
<td><a href="https://sharaku.eorc.jaxa.jp/GSMaP_cr">https://sharaku.eorc.jaxa.jp/GSMaP_cr</a> est/</td>
<td>Soroshashan et al. (2000); Nguyen et al. (2019)</td>
</tr>
<tr>
<td>PERSIANN-CCS</td>
<td>Global</td>
<td>0.04°</td>
<td>30 min/3, 6</td>
<td>2003–present</td>
<td>Satellite</td>
<td>Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California</td>
<td><a href="http://chrsdata.eng.uci.edu/">http://chrsdata.eng.uci.edu/</a></td>
<td>Soroshashan et al. (2000); Nguyen et al. (2019)</td>
</tr>
<tr>
<td>CMORPH</td>
<td>Global</td>
<td>0.25°</td>
<td>30 min/3 h/daily</td>
<td>2002–2017</td>
<td>Satellite</td>
<td>Climate Prediction Center</td>
<td><a href="https://climatedataguide.ucar.edu/climate-data/cmorph-cpc-morphing-technique-high-resolution-precipitation-60s-60n">https://climatedataguide.ucar.edu/climate-data/cmorph-cpc-morphing-technique-high-resolution-precipitation-60s-60n</a></td>
<td>Joyce et al. (2004)</td>
</tr>
<tr>
<td>GPM</td>
<td>Global</td>
<td>0.1°</td>
<td>30 min/3 h/daily</td>
<td>2000–present</td>
<td>Satellite</td>
<td>NASA</td>
<td><a href="https://pmn.nasa.gov/data-access/downloads/gpm">https://pmn.nasa.gov/data-access/downloads/gpm</a></td>
<td>Hou et al. (2008); Hou et al. (2014); Huffman et al. (2015); Beck et al. (2017)</td>
</tr>
<tr>
<td>MSWEP</td>
<td>Global</td>
<td>0.1°/0.5°</td>
<td>3 h/daily</td>
<td>1979–present</td>
<td>Satellite + rain gauge</td>
<td>Princeton University</td>
<td><a href="http://www.glob2o.org/">http://www.glob2o.org/</a></td>
<td>Kalnay et al. (1996)</td>
</tr>
<tr>
<td>NCEP1</td>
<td>Global</td>
<td>2.5° × 2.5°</td>
<td>Monthly/Daily/6 hourly</td>
<td>1948–present</td>
<td>Reanalysis</td>
<td>NCEP/NCAR</td>
<td><a href="https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html">https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html</a></td>
<td>Schneider et al. (2014)</td>
</tr>
<tr>
<td>NCEP2</td>
<td>Global</td>
<td>2.5° × 2.5°</td>
<td>1979–present</td>
<td>Reanalysis</td>
<td>NCEP/NCAR</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In practice, a wide range of gully control practices exists and have been implemented in numerous areas (e.g. Evrard et al., 2008; Castillo and Gómez, 2016; Fig. 4). The overall effectiveness of such measures has been recently reviewed (e.g. Bartley et al., 2020; Frankl et al., 2021). The most common conservation practices include increasing the soil erosion resistance in concentrated flow zones, protecting the headcut, diverting overland flows away from gullies as well as creating terraces, grassed waterways, check dams and water and sediment control basins (Casali et al., 1999; Poesen et al., 2003; Valentin et al., 2005). Also in the EU, such measures have been implemented. Nevertheless, measures that directly address gully erosion are not yet compulsory in EU policies. Also soil conservation measures such as reduced tillage are applied at a more limited scale in the EU (4% no till and 22% reduced tillage; EU Agriculture Census, 2011; Panagos et al., 2015b) as compared to for example the USA (35% no till and 27% reduced tillage; Census of Agriculture, 2012). In terms of land management, this makes European arable land potentially more vulnerable to ephemeral gully erosion. Overall, soil erosion is clearly considered an important agro-environmental indicator to assess the effectiveness of EU policies such as the Common Agricultural Policy (e.g. Gobin et al., 2004; Zalidis et al., 2004). However, the CAP-induced soil conservation practices consider only sheet and rill erosion and do not account for gully erosion (Panagos et al., 2015a, 2015b).

The situation in the EU contrasts, with other regions. For example in the United States, gully control measures are more widespread. Measures to reduce gully erosion have been implemented as early as the 1930s in the USA, including those by the Civilian Conservation Corps (USDA, 2007). The development of handbooks on the formation and control of gullies by national agencies greatly contributed to this (e.g. USDA, 2007). Grade stabilization structures such as drop pipes were the most common conservation practice to control gully erosion (Wilson et al., 2008), but also extensive reforestation and reservoir construction programmes were implemented (e.g. Rhemtulla et al., 2009; Abbasi et al., 2019). In China, The Grain for Green programme strongly mitigated gully erosion in the Loess Plateau by implementing slope conservation measures and check-dams on a massive scale (Xiang-zhou et al., 2004; Sun et al., 2019). In some areas, the restoration of vegetation on hillslopes through the Grain for Green programme reduced gully erosion rates with up to 90% (Wang et al., 2016). Also in Australia, there are several large government-funded programmes focused on gully remediation (Wilkinson et al., 2019). They aim to reduce sediment and particulate nutrient loads that form, in combination with climate change, an important threat to the Great Barrier Reef (MacNeill et al., 2019). A variety of gully remediation approaches are currently tested in catchments draining to the Great Barrier Reef, ranging from low-cost erosion control structures to larger scale landscape remediation (Koci et al., 2021). Also Ethiopia has implemented several large-scale soil and water conservation programmes that included measures specifically targeting gully erosion (e.g. Haregeweyn et al., 2015). In summary, the large number of policy initiatives at the European level (i.e. the Soil Thematic Strategy, the Common Agricultural Policy, the Water Framework Directive, and EU Green Deal) as well as global initiatives (Sustainable Development Goals, FAO guidelines, IPBES, UNCCD) show that soil erosion is widely recognized as a problem. Nonetheless, relatively limited attention is given to gully erosion. This likely results from insufficient awareness and understanding of this process. Developing adequate policies to deal with gully erosion requires reliable, spatially explicit indicators on where this problem occurs. Furthermore, it requires tools and data to assess the effectiveness and efficiency of soil conservation measures. This is especially pertinent since gully erosion generally requires interventions that are more drastic and expensive than for sheet and rill erosion (e.g. Valentini et al., 2005; Bartley et al., 2020).

Table 8 (continued)

<table>
<thead>
<tr>
<th>Dataset/ Source</th>
<th>Spatial coverage</th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
<th>Period</th>
<th>Sensor and type of retrieval</th>
<th>Source</th>
<th>Data download</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA Interim</td>
<td>Global</td>
<td>1.5° × 0.75°</td>
<td>Monthly/ 6 hourly</td>
<td>1979–present</td>
<td>Reanalysis</td>
<td>ECMWF</td>
<td><a href="http://apps.ecmwf.int/datasets/data/era40-daily/levtype=sfc/">http://apps.ecmwf.int/datasets/data/era40-daily/levtype=sfc/</a></td>
<td>Upda et al. (2005)</td>
</tr>
<tr>
<td>MERRA</td>
<td>Global</td>
<td>0.5° × 0.67°</td>
<td>Daily</td>
<td>1979–present</td>
<td>Reanalysis</td>
<td>NASA</td>
<td><a href="https://gmao.gsfc.nasa.gov/reanalysis/MERRA/">https://gmao.gsfc.nasa.gov/reanalysis/MERRA/</a></td>
<td>Rienecker et al. (2011)</td>
</tr>
<tr>
<td>MERRA Land</td>
<td>Global</td>
<td>0.5° × 0.67°</td>
<td>Monthly/ Daily/ 1 hourly</td>
<td>1980–present</td>
<td>Reanalysis</td>
<td>NASA</td>
<td><a href="https://gmao.gsfc.nasa.gov/reanalysis/MERRA-Land/">https://gmao.gsfc.nasa.gov/reanalysis/MERRA-Land/</a></td>
<td>Reichle et al. (2011)</td>
</tr>
</tbody>
</table>
While detailed models and maps at the European and global level exist to assess sheet and rill erosion (e.g. Borrelli et al., 2017a) this is clearly not the case for gully erosion (cf. Sections 3 and 4). Our current inability to quantify gully erosion and its impacts should not imply that this process should remain neglected in policies. Building on the already extensive scientific knowledge gained in several regions worldwide (e.g. USDA, 2007; Sabir et al., 2020), EU and national/regional agro-environmental policies should aim to address, prevent and mitigate gully erosion and its impacts. It deserves mentioning that the EU already makes important efforts in this regard, including through initiatives like the ‘Land Use/Cover Area frame statistical Survey Soil’ (LUCAS; e.g. Blum et al., 2004; Panagos et al., 2015b; Borrelli et al., 2017b; Orgiazzi et al., 2018) which aims at monitoring soil health in the EU. In the LUCAS 2018 campaign, a soil erosion module was introduced where different processes of soil erosion (including gully erosion) were assessed for more than 20,000 visited points across the EU (Borrelli et al., submitted).

7. Conclusions and recommendations

Gully erosion is an important land degradation process, leading to major on- and off-site impacts (cf. Section 1). Climate change and land use/land cover changes may aggravate these impacts in many regions. Adequately addressing land degradation in a context of global change therefore requires strategies and policies that specifically account for gully erosion. However, the development of these is strongly hampered by our inability to accurately quantify and simulate gully erosion in relation to its driving factors, especially at larger (i.e. regional to global) scales. More specifically, we need tools and models that are capable of:

(i) identifying gully erosion hotspots;
(ii) quantifying gully erosion rates at different spatio-temporal scales;
(iii) assessing the impacts of gullies, including their (direct and indirect) contribution to catchment sediment yields; and
(iv) simulating the effects of land use/land cover changes, climate change, land management and conservation measures on gully erosion and its impacts.

While the development of such tools and models poses an important challenge, significant progress has been made over recent decades. Based on a review of over 590 scientific publications and policy documents, this article presents a state-of-the-art on monitoring, modelling and managing gully erosion at larger scales. Here we list our key conclusions and recommendations regarding these three aspects.

7.1. Gully monitoring

Monitoring the occurrence and dynamics of gully systems remains essential for better understanding and constraining rates and controlling factors of gully erosion. Especially datasets on the initiation and evolution of gully systems over large areas are a prerequisite for the development of models that can simulate this process at larger scales. Such datasets currently remain scarce. New remote sensing products can greatly help in addressing this gap. Nevertheless, monitoring gully erosion at larger scales remains highly labour-intensive and/or requires significant concessions in accuracy, completeness and level of detail (cf. Section 2). Also the limited length of the observation periods and the coarse temporal resolution often form important constraints.

We make the following recommendations with respect to gully monitoring via remote sensing:

(i) Further research is needed to develop approaches that allow assessing the occurrence, properties and evolution of gully systems at larger spatial scales in efficient and accurate ways. Promising avenues for this are strategies that rely on monitoring gullies in large sets of small yet representative case study areas and the (semi-)automatic detection and characterization of gullies.
(ii) More studies are needed that provide data on the dynamics of gully erosion at high temporal resolutions across different environmental settings. This is particularly relevant for ephemeral gullies which may be formed and erased again over short time spans, potentially leading to significant underestimations of their erosion rates. Repeated analyses of frequent imagery, preferably taken shortly after every significant runoff event is likely the best way to address this need. The increasing availability of EO products at high spatio-temporal and spectral resolutions opens promising perspectives here.
(iii) Better insight and data are needed on the long-term evolution of gully systems. Gullies often form and expand over short time periods and then remain stable for many years. In some environments they may even be filled in again. Likewise, apparently stable gullies may be reactivated as a result of extreme climatic events or land cover/use/management changes. Nonetheless, most of the available data on gully erosion rates cover relatively short time periods (i.e. a few years) and are not necessarily representative for long-term average erosion rates. Systematically assessing the evolution of both active and seemingly stable gullies over decadal timescales will help addressing this need. Historical (aerial) photos and early satellite imagery can be an important asset for this.
(iv) Methodological advancements are required that allow better quantifying the uncertainties associated with gully monitoring. Assessed gully dimensions and dynamics are often subject to considerable uncertainties as a result of mapping errors, observation biases, the large temporal variability of gully erosion and conversion errors (e.g. when deriving gully volumes from gully lengths or areas). We recommend more research that allows quantifying these different sources of uncertainty, as well as their combined effects on the total uncertainty. Linked to that, we recommend developing procedures that allow better comparisons of collected data. Classifying gullies according to a consistent typology across different studies will be an important element in this.

Apart from remote sensing, also field-based research in well-targeted areas will remain essential to understand gully erosion. Our overview for Europe (Section 3) may serve as a starting point for future studies aiming to develop gully erosion models at regional to continental scales. However, it also uncovered shortcomings and gaps. For example, most studies focused on permanent gullies, while bank gullies and ephemeral gullies received considerably less attention. Nonetheless, their associated impacts can be very high. Other pertinent research needs include:
(i) studies that monitor gully densities and gully expansion rates systematically over larger areas;
(ii) studies that monitor gully dynamics (i.e. initiation, headcut retreat, but also gully widening, deepening and infilling) and related subprocesses (e.g. piping, mass movement) at decadal timescales, preferably at high temporal resolutions;
(iii) studies that evaluate the performance of different gully modelling strategies based on detailed field observations; and
(iv) studies that assess the effectiveness of different gully erosion control measures over sufficiently long time periods.

7.2. Gully modelling

There is an important need for models and tools that can simulate and predict gully erosion at regional to global scales. Various viable model approaches and concepts have already been proposed, but need to be further developed, upscaled and tested so that they can be applied at larger scales (cf. Section 4). A major challenge is finding a good balance between an accurate process representation and feasible data requirements. The recent and ongoing development of new environmental data products at (sub)continental to global scales opens promising perspectives in this regard (cf. Section 5).

More specifically, process-oriented model approaches can yield relevant insights into the factors and mechanisms driving gully erosion, as well as their interactions. As such, they can be important tools for scenario analyses. However, their generally high data requirements make it difficult to apply them, especially at larger scales. Empirical modelling strategies, and in particular machine-learning approaches, offer great potential. However, their overall ‘black box’ nature can impede clear insights into the actual drivers of gully erosion. Different modelling strategies will therefore need to be developed and combined.

We make the following recommendations with respect to modelling gully erosion and its impacts:

(i) Better insights are needed on the factors controlling gully erosion at larger scales and how the role of these factors can be translated into meaningful variables and proxies that can be derived from GIS/EO data. This is especially so for the effects of climate and weather conditions, vegetation cover, land use/management, soil and lithological properties.
(ii) While numerous modelling strategies have already been proposed, more work is required to scale up these approaches from case studies to larger regions. This is the case for process-oriented strategies (e.g. relying on a spatially explicit hydrological model) as well as for empirical (e.g. machine learning) approaches. Much of this work will revolve around finding optimal trade-offs between model accuracy and feasible data and calculation requirements.
(iii) The potential to couple and combine different approaches needs to be further explored and developed. Most efforts so far have focused on simulating either gully initiation, density or expansion (mainly through headcut retreat), while little research has been conducted on how to integrate these different aspects into models that predict total gully erosion rates. Such integration will also need accounting for potential interactions between these different components of gully erosion and their controlling factors as well as with potential interactions with other erosion processes (e.g. sheet and rill erosion).
(iv) Additional research is necessary on accounting for the effects of land use and land management practices, and in particular soil and water conservation measures, on gully erosion and its impacts at larger scales. This will require further developing large-scale datasets indicating the presence of specific erosion control measures but also modelling frameworks that allow quantifying their effectiveness and efficiency.

(v) There is a large need for tools and model frameworks that allow better assessing and quantifying the diverse on- and off-site impacts of gully erosion, both at short and longer timescales. This includes the effects of gully erosion on hillslope hydrology, crop yields, biomass production and other ecosystem services of soils, but also downstream impacts (e.g. assessing the contribution of gullies to river sediment load and catchment hydrology). This will likely require coupling gully erosion models to available models, but also developing new model components (e.g. accounting for the impacts of gullies on sediment connectivity).
(vi) On a more general level, the potential of models to simulate gully erosion and its impacts for scenario analyses needs to be further developed and tested. A key element in this will be the thorough validation of these models, using reliable observations over a large range of environmental conditions.

7.3. Gully management

Overall, there is a significant and growing international interest to tackle the challenges of soil erosion and land degradation in the context of global change (cf. Section 6). In Europe, numerous frameworks and policies help addressing the problem of soil erosion. However, very few of them explicitly account for (or even mention) gully erosion. More specific guidelines and recommendations to deal with this process are required. To a large extent, the absence of gully erosion in current policies is mainly due to our inability to accurately assess and quantify this process and its impacts. This hampers effective communication between scientists and policy makers on setting realistic targets and solutions. Nevertheless, our current state of knowledge does already allow accounting more explicitly for gully erosion.

We believe the following elements can aid in a better management of gully erosion at larger scales:

(i) Scientific initiatives that help to better quantify and understand gully erosion, allowing for more targeted policies, need to be further supported. Especially initiatives that help identifying (potentially) problematic areas and assessing the effectiveness, costs and benefits of prevention and control measures are needed in this regard.
(ii) Lessons learned from other policy implementations (e.g. with respect to sheet and rill erosion) as well as from regions where gully control measures are already implemented should be integrated in policies dealing with gully erosion.
(iii) Given that the formation, expansion rates and impacts of gullies strongly vary between regions, (future) policy instruments should accommodate for this diversity of contexts.

Declaration of Competing Interest

None.

Acknowledgements

We thank the Joint Research Centre (JRC), European Commission for organizing the workshop on gully erosion (March 2018) that led to the idea of this paper. Most of this article has been written during the COVID-19 lockdown. We therefore dedicate this paper to the many victims of this pandemic, as well as to the numerous health workers, scientists and policy makers that try to keep it at bay.

References


