

Please cite this article as:

Vanmaercke, M., Panagos, P., Vanwalleghem, T., Hayas, A., Foerster, S., Borrelli, P., ... & Poesen, J. (2021). Measuring, modelling and managing gully erosion at large scales: A state of the art. *Earth-Science Reviews*, 218, 103637.

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

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62 **Abstract**

63 Soil erosion is generally recognized as the dominant process of land degradation. The formation and
64 expansion of gullies is often a highly significant process of soil erosion. However, our ability to assess
65 and simulate gully erosion and its impacts remains very limited. This is especially so at regional to
66 continental scales. As a result, gullying is often overlooked in policies and land and catchment
67 management strategies. Nevertheless, significant progress has been made over the past decades. Based
68 on a review of >590 scientific articles and policy documents, we provide a state-of-the-art on our
69 ability to monitor, model and manage gully erosion at regional to continental scales. In this review we
70 discuss the relevance and need of assessing gully erosion at regional to continental scales (section 1);
71 current methods to monitor gully erosion as well as pitfalls and opportunities to apply them at larger
72 scales (section 2); field-based gully erosion research conducted in Europe and European Russia
73 (section 3); model approaches to simulate gully erosion and its contribution to catchment sediment
74 yields at large scales (section 4); data products that can be used for such simulations (section 5); and
75 currently existing policy tools and needs to address the problem of gully erosion (section 6). Section 7
76 formulates a series of recommendations for further research and policy development, based on this
77 review. While several of these sections have a strong focus on Europe, most of our findings and
78 recommendations are of global significance.

79

80 **Keywords:** gully erosion, gully initiation, gully expansion, sediment yield, measuring, modelling,
81 prediction, regional, continental, Europe, spatial data, policy

82

83 **1. Introduction**

84 *1.1 The relevance of gully erosion*

85 Soil erosion is globally recognized as the most dominant process of land degradation (e.g.
86 Montanarella et al. 2016; Pennock, 2019). Most efforts to understand and quantify soil erosion by
87 water have focussed on sheet and rill erosion (e.g. Renard et al., 1997; Montgomery, 2007; Maetens et
88 al., 2012a; de Vente et al., 2013; Borrelli et al., 2017a). Nonetheless, numerous studies have
89 highlighted the fact that also gully erosion is a key concern in many regions worldwide (Poesen et al.,
90 2003; Valentin et al., 2005; Vanmaercke et al., 2011; García-Ruiz et al., 2017; Sidle et al., 2019).
91 Overall, gully erosion is the formation and subsequent expansion of erosional channels in the soil as a
92 result of concentrated water flow (Poesen et al., 2003). Gully dimensions can vary over several orders
93 of magnitudes (e.g. Vanmaercke et al. 2016; Dube et al. 2020). However, conventionally a gully is
94 distinguished from a rill based on a critical cross-sectional area of at least one square foot, i.e. the size
95 of a channel that can no longer be erased via normal tillage operations (Poesen et al., 2003). An upper
96 limit for gully dimensions has not been clearly defined yet.

97 Gullies are often associated with a wide range of on-site and off-site impacts. On-site impacts include
98 the direct loss of land, trees and crops as well as reduced trafficability. These limit opportunities for
99 agriculture and other land uses (e.g. Poesen et al., 2003; Valentin et al., 2005). Gullies can also cause
100 significant damage to roads, buildings and other infrastructure. In severe cases, such destructions may
101 claim significant numbers of casualties (e.g. Guerra et al., 2007; Makanzu Imwangana et al., 2015). In
102 many regions, gully erosion contributes to significant soil losses and reduced soil quality (Poesen et
103 al., 1996; 2003; Ionita, 2006; Haregeweyn et al., 2008; Xu et al., 2016; Hayas et al., 2017a),
104 threatening the long-term sustainability of food production and other ecosystem services (e.g.
105 Montgomery, 2007). Gullies can also significantly alter surface and subsurface hillslope hydrology.
106 For example, their presence can lead to a more efficient water evacuation and, in some cases, lower
107 water tables. In dry environments, this can result in significantly lower crop yields in areas bordering
108 gullies (e.g. Frankl et al., 2016; Poesen, 2018) and reduced biomass production rates over larger
109 spatial scales (e.g. Avni, 2005), contributing to desertification. In addition, gullies can initiate or
110 aggravate other erosion processes, including soil piping (Bernatak-Jakiel & Poesen, 2018) and
111 landsliding (e.g. Ionita et al., 2015a). As a result of such impacts, gully erosion can also become a
112 significant driver of land use changes (e.g. Bakker et al., 2005; Valentin et al., 2005; Zgłobicki et al.
113 2015a). In extreme cases, gully erosion can even transform productive land into badland areas
114 (Cánovas et al., 2017; Torri et al., 2018a).

115 Potential off-site impacts of gully erosion include changes in catchment hydrology, such as lower river
116 baseflows and higher peak runoff discharges (e.g. Martineli Costa et al., 2007). Given their often high
117 erosion rates, gullies can also be a major sediment source. Where they occur, gullies can easily

118 account for 20-80% of the average catchment sediment yield (e.g. [Poesen et al., 1996; 2003;](#)
119 [Vanmaercke et al., 2012](#)). Furthermore, gullies can indirectly contribute to sediment loads by
120 increasing the runoff and sediment connectivity between upland areas, valley bottoms and river
121 networks or lakes ([Poesen et al., 2003](#)). These higher sediment loads and increased connectivity can
122 result in a plethora of problems, including (muddy) floods (e.g. [Verstraeten & Poesen, 1999](#)), reservoir
123 capacity losses due to sediment deposition (e.g. [Haregeweyn et al., 2006](#)), channel aggradation (e.g.
124 [Benda et al., 2003](#)) and reduced water quality (e.g. [Owens et al., 2005](#)). As such, gully erosion is a
125 great concern in many regions worldwide ([Valentin et al., 2005; Poesen, 2018](#)). It is a key process of
126 land degradation and desertification ([Vanmaercke et al., 2011a](#)), posing a significant threat to various
127 ecosystems and ecosystem services (e.g. [Kroon et al., 2012; 2016](#)).

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

138 Nevertheless, it is worth noting that gullies can sometimes also create interesting opportunities and
139 positive outcomes. When well managed, they can become productive and biodiverse hotspots that play
140 a key role as ecological corridors ([Romero-Díaz et al., 2019](#)). Likewise, gully channels can become
141 significant sediment traps and fill-up over time, especially when they are well vegetated (e.g.
142 [Vanwallegem et al., 2005c; Lanckriet al., 2015; Molina et al., 2009](#)). Furthermore, they can be of
143 significant geo-archeological value, providing important insight into (pre-)historic land use and human
144 occupation (e.g. [Dotterweich et al., 2003; 2012; Vanwallegem et al., 2003; Torri et al., 2018a;](#)
145 [Maerker et al., 2019](#)). As such, they are generally seen by the scientific community as a key landform
146 to understand the environmental change and soil erosion risks and they can play an important role in
147 raising general awareness about these issues (e.g. [Poesen et al. 2003; Frankl et al., 2011; Zgłobicki et](#)
148 [al., 2015b; 2019](#)). Given their great visibility they can also help in raising awareness on erosion
149 problems (e.g. [Bielders et al., 2003; Zegeye et al., 2010](#)). Because of their often great esthetical value
150 or spectacular nature, several gullied areas and badlands even have large potential as geoheritage sites
151 ([Zgłobicki et al., 2018](#)).

152

153 ***1.2. The challenge of assessing gully erosion at regional to continental scales***

154 Developing appropriate gully erosion prevention and remediation strategies requires a thorough
155 understanding of its dynamics and controlling factors. Gully erosion has already received a lot of
156 research attention over the past century (Castillo & Gomez, 2016). This led to valuable insights on the
157 formation and expansion of gullies, their contribution to sediment loads and their potential
158 remediation. This research also demonstrated the sensitivity of gully erosion to land use/land cover
159 (e.g. Prosser & Slade, 1994; Poesen et al., 2003; Torri and Poesen, 2014) and rainfall intensity (e.g.
160 Vanmaercke et al., 2016; Hayas et al., 2017b). Globally ongoing land use/land cover changes that have
161 a significant effect on sheet and rill erosion (Borrelli et al., 2017a) therefore probably also strongly
162 impact gully erosion rates. Likewise, climate change and in particular increases in rainfall intensities
163 (e.g. Polade et al., 2014) are likely to further intensify gully erosion rates (e.g. Nearing et al., 2004; Li
164 & Fang, 2016; Vanmaercke et al., 2016; Panagos et al., 2017). In order to address these challenges,
165 there is a need for tools and models that can quantify the current rates and impacts of gully erosion and
166 assess the effect of potential climate and land use change scenarios (e.g. Poesen, 2018; Pennock,
167 2019). However, our ability to simulate gully erosion and its impacts remains currently limited (Jetten
168 et al., 2003; Merrit et al., 2003; Poesen et al., 2011; Vanmaercke et al., 2016; Bennett & Wells, 2019;
169 Sidle et al. 2019), particularly at regional to continental scales (e.g. de Vente et al., 2013; Poesen,
170 2018). Insights at these scales are essential for the development of adequate and targeted land and
171 catchment management strategies.

172 These difficulties to simulate and quantify gully erosion at regional to continental scales arise from
173 several causes. First, there is a wide variety of gully types and sizes (Figure 1). Examples include
174 ephemeral gullies in cropland (e.g. Valcarcel et al., 2003), (pre-)historic gullies under forest (e.g.
175 Dotterweich et al., 2003; Vanwalleghem et al., 2003), permanent gullies in rangeland (e.g. Gomez-
176 Gutiérrez et al., 2009a), valley bottom gullies in alluvial planes (e.g. Amare et al., 2019), bank gullies
177 (i.e. gullies forming in earth banks such as river banks, agricultural terraces, lynchets or sunken lane
178 banks; e.g. Vandekerckhove et al., 2000; Poesen et al., 2003), large gullies in urban environments (e.g.
179 Guerra et al. 2007; Makanzu Imwangana et al., 2015), sunken lanes (or road gullies; e.g. De Geeter et
180 al., 2020) and gullies in badland areas (e.g. Nadal-Romero et al., 2015). Furthermore, the formation
181 and expansion of gullies typically involve a range of subprocesses, including the initial incision of a
182 flow channel by concentrated runoff and the formation of a gully headcut (e.g. Oostwoud Wijdenes et
183 al., 1999), gully headcut retreat (Vanmaercke et al., 2016), gully widening and deepening (e.g. Hayas
184 et al., 2019), mass movements (e.g. Zegeye et al., 2020), fluting (Poesen et al., 2002), piping or tunnel
185 erosion (Bernatak-Jakiel and Poesen, 2018), sediment transport and sediment deposition (e.g.
186 Vanwalleghem et al., 2005c). The relative importance of these subprocesses depends on the type of
187 gully, its environmental conditions, but also on the age of the gully (e.g. Oostwoud Wijdenes et al.,
188 1999; Sidorchuk et al., 2001; Poesen et al., 2006; Sidorchuk, 2006; Frankl et al. 2021). In addition, and

189 as a result of these complexities, gully erosion is also characterized by an important degree of
190 stochasticity (e.g. [Montgomery & Dietrich, 1994](#); [Prosser & Abernethy, 1996](#)). While significant
191 advancements have been made over the past decades, our understanding of these processes, their
192 interactions and their numerous potential controlling factors remains limited ([Poesen et al., 2011](#); [de](#)
193 [Vente et al., 2013](#); [Vanmaercke et al., 2016](#)).

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



214
 215 **Figure 1:** Illustration of different gully types across the world. (a) Ephemeral gully formed in a bare potato field with ridges
 216 and furrows (Neuville en Condroz, Belgium, May 2018; Photo: J. Poesen). (b) Historic gully under forest (Neigembos,
 217 Belgium, August 2013; Photo: M. Vanmaercke). (c) Permanent gully under rangeland (Burdekin catchment, Queensland,
 218 Australia, July 2019; Photo: M. Vanmaercke). (d) Permanent gully under grassland (Guder, Ethiopia, August 2017; Photo:
 219 M. Vanmaercke). (e) Permanent gully in a valley bottom (Moldova Province, Romania, May 2011; Photo: J. Poesen). (f)
 220 Bank gully formed in a sunken lane bank (Landen, Belgium, April 2019; Photo: J. Poesen). (g) Urban mega-gully that
 221 destroyed multiple houses (Kinshasa, D.R. Congo, November 2019; Photo: M. Vanmaercke). (h) Gullies formed in a badland
 222 area (near Quazvin, Iran, October 2014; Photo: M. Vanmaercke).

224 *1.3. Scope and overview of this review*

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

234 **Section 2** reviews remote-sensing and field approaches to measure and monitor gully properties and
235 their dynamics. We discuss the limitations and potential of these methods with a focus on their
236 application over larger areas. **Section 3** provides an overview of past field-based gully-erosion
237 research in Europe and European Russia. This to provide an overview of available data and
238 observations that may be useful for further model development, but also to identify current research
239 focuses and knowledge gaps. In **section 4**, we discuss modelling approaches used to simulate various
240 relevant aspects of gully erosion (gully occurrence, gully expansion and the contribution of gullies to
241 catchment sediment yields). Also here, our focus lies on the applicability of these approaches at
242 regional to continental scales. **Section 5** complements this objective by providing an overview of
243 currently available GIS datasets that may be used as input for such models. We concentrate on datasets
244 that are available for Europe or have a global coverage. **Section 6** discusses to what extent
245 environmental management policies and frameworks already account for the challenges posed by
246 gully erosion (with a focus on Europe). **Section 7** synthesizes our key findings into a list of key
247 recommendations with respect to the monitoring, modelling and managing of gully erosion at larger
248 scales.

249

250 **2. Assessing gully erosion through monitoring**

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

257

258 **2.1. Assessing the presence or absence of gullies**

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

275 Creating detailed inventories of gully presence at high resolution can be very labour-intensive (e.g.
276 one person-month for a 3,000 km² area at a 100m pixel resolution; Darr and Pringle, 2017). Zhao et al.
277 (2016) employed an alternative approach to estimate gully densities. Rather than systematically
278 mapping entire areas, they assessed for a large number of random points whether or not the point was
279 located inside a gully. The fraction of points located within a gully thus provides an estimate of the
280 areal gully density. Such crude but fast proxy can be used for meaningful empirical analyses, e.g. to
281 explore correlations between gully densities and catchment sediment yields (Zhao et al., 2016).
282 Overall, complete assessments or random sampling procedures provide the advantage that mapping
283 efforts are unbiased. In contrast, many existing gully occurrence studies focus on gully-prone areas
284 and are therefore often unrepresentative at regional to continental scales.

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

294

295 *2.2. Assessing gully properties*

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

309 However, such inventories also come with limitations. Digitizing gullies from aerial photos or remote
310 sensing products often involves significant uncertainties. For example, [Maugnard et al. \(2014\)](#) showed
311 that mapping features of ephemeral gullies remains to a large extent subjective. Furthermore, their
312 construction is generally very labour-intensive, resulting in important trade-offs between the size of
313 the study area, the level of detail and the labour investment required (e.g. [Mararakanye & Le Roux,
314 2012](#); [Golosov et al., 2018](#)). Key elements in this are the image resolution and/or the mapping altitude
315 (i.e. the difference between the altitude of the camera and the surface elevation) used but also whether
316 gullies are mapped as linear features or polygons. (Semi-)automatic detection procedures offer
317 promising perspectives here. They are typically based on high-resolution multi-spectral images (e.g.
318 [Shruthi et al., 2011](#)) and/or high-resolution digital elevation models (e.g. [Thommeret et al., 2010](#);
319 [Shabibi et al., 2019](#); [Walker et al., 2020](#)). Such imagery has become increasingly available at regional
320 to continental scales. Nonetheless, most of the current applications remain limited to relatively small
321 scales. The potential of these techniques needs to be further explored. Another promising option may
322 be to optimize sampling protocols to manually inventorize gullies. This can be done, by stratifying
323 areas in terms of ancillary information such as slope, land use or soil type (e.g. [Minasny and
324 McBratney, 2006](#)) or by using a (semi-)random sampling procedure of smaller sites to be mapped (e.g.
325 [Vanmaercke et al., 2020](#)).

326 Also the widths, cross-sectional areas and, by extent, the total gully volumes are often of interest.
327 Gully top-widths can typically be derived from aerial or satellite imagery (e.g. [Nachtergaele et al.,
328 2002a](#); [Hayas et al., 2017a](#)). However, gully floor-widths are typically hard to measure from such

329 imagery (Giménez et al., 2009). The top-widths may be significantly larger than the gully floor-
330 widths, especially for older gullies or gullies formed in soils with little cohesion (e.g. Hayas et al.,
331 2019). Nonetheless, gully floor-width and hydraulic radius are often of greater geomorphic relevance
332 as they relate more directly to the maximum runoff discharges passing through the gully (e.g.
333 Nachtergaele et al., 2002a; Vanwallegem et al., 2005b).

334 Also gully cross-sectional areas are difficult to quantify based on aerial photos or high resolution
335 satellite images. Nonetheless, they are a key prerequisite to estimate the volumes of gully systems
336 (Casalí et al., 2015; Castillo et al., 2019). Therefore they are often obtained through field
337 measurements (e.g. Nachtergaele et al., 2001a;b). An uncertainty assessment by Castillo et al. (2012)
338 showed that errors on individually measured cross-sections are overall relatively limited (3-15%).
339 Extrapolating these cross-sectional areas to estimate gully volumes typically generates larger
340 uncertainties. These depend on the gully length, its sinuosity and in particular the number of cross-
341 sections surveyed. Quantifying gully volumes with an acceptable degree of uncertainty (10-20%)
342 typically requires ten or more cross-sections per gully (Castillo et al., 2012). This can pose challenges
343 when aiming to quantify gully erosion volumes over larger areas. Fortunately, gully cross-sectional
344 areas are typically strongly correlated to their top-width (e.g. Frankl et al., 2013; Vanmaercke et al.,
345 2016), which can be assessed via remote sensing. It is often feasible to develop robust empirical
346 relationships between gully top-width and cross-sectional areas, based on a relatively limited amount
347 of field surveys. These relationships can then be used to estimate gully volumes with acceptable
348 uncertainties (e.g. Fiorucci et al., 2015; Hayas et al. 2017a). One concern with this approach is that the
349 cross-sectional shapes evolve over time, e.g. from a rectangular to a more trapezoidal shape (e.g.
350 Vanwallegem et al. 2005b; Hayas et al., 2019). Hence, applying such a (time-specific) relationship to
351 assess gully volumes over longer time periods may induce further uncertainties and biases.

352 The challenge to estimate gully volumes from 2D imagery is partly rendered obsolete by new
353 techniques. Airborne LIDAR instruments, for example, allow mapping the morphology and volume of
354 gully systems (e.g. James et al., 2007; Eustace et al., 2009; Perroy et al., 2010; Goodwin et al., 2017).
355 The method, albeit expensive (Castillo et al., 2012), is relatively fast and typically allows to construct
356 digital terrain models of gully systems with an accuracy of some centimeters to decimeters. Recently
357 developed Structure from Motion (SfM) techniques offer a promising and cheaper alternative, with
358 accuracies and precisions that are similar to LIDAR or in some cases even superior (e.g. Castillo et al.,
359 2012; Gómez-Gutiérrez et al., 2014; Clapuyt et al., 2016; Koci et al., 2017). The photographic surveys
360 required to construct a SfM-based digital terrain model can be conducted either from the ground or
361 through drone flights. They can be made with standard photo cameras, while freely available software
362 exists to process the photos into a 3D model (e.g. Koci et al., 2017). Nonetheless, vegetation cover can
363 form a significant constraint for assessing gully properties via SfM. Also, as with LIDAR, data
364 acquisition typically is labour-intensive and the computer resources required to construct such a 3D

365 model currently remain considerable. Hence, most studies applying LIDAR or SfM to characterize
366 gully systems cover only limited areas (e.g. [Eustace et al., 2009](#); [Perroy et al., 2010](#); [Castillo et al.,](#)
367 [2012](#); [Kropacek et al. 2016](#); [Koci et al., 2017](#)). Increases in computational power and more efficient
368 algorithms may make it feasible to apply these techniques at regional to continental scales in the near
369 future ([Bennett and Wells, 2019](#)).

370 Apart from assessing gully dimensions, assessing whether gullies are stable or actively expanding is
371 often of great relevance. While historic expansion of gullies is best assessed through repeated surveys
372 (cf. [section 2.3](#)), this is not always possible. Furthermore, to target mitigation efforts, it is often
373 required to identify the gullies that are currently active (e.g. [Whitford et al., 2010](#)). Some
374 morphological characteristics can indicate whether a gully is likely active ([Oostwoud Wijdenes et al.,](#)
375 [1999](#)). For example, (recently) active gully heads typically have sharp edges, a plunge pool, tension
376 cracks, recently deposited sediments and flow marks. Stabilized gullies typically have smoother or
377 rounded edges and vegetation re-growth on the gully head wall and at its foot ([Oostwoud Wijdenes et](#)
378 [al., 2000](#)). However, such distinctions are not always detectable on aerial/satellite imagery. Several
379 studies therefore assessed gully stability based on the vegetation cover inside the gully (e.g.
380 [Vanwallegem et al., 2005c](#); [Makanzu Imwangana et al., 2015](#); [Golosov et al., 2018](#)). While such
381 morphological or vegetation criteria can provide strong indications, it is important to note that they are
382 not a guarantee for gully stability. Extreme weather events or significant land cover changes may
383 reactivate gullies that have been stable for many years ([Vandekerckhove et al., 2001b](#)).

384 Likewise, classifying gullies into types (e.g. permanent, ephemeral, bank gully, valley-bottom and
385 valley-side gully) is generally useful, as this may help understanding the causing mechanisms,
386 potential erosion rates and optimal remediation strategies (e.g. [Amare et al., 2019](#); [Bartley et al.,](#)
387 [2020](#)). Such classifications can be based on the dimensions, the landscape position and/or the land use
388 type in which the gully occurs. However, while there is some agreement on different types of gullies
389 (cf. [section 3](#)), no universal gully classification scheme currently exists. This limits the comparability
390 of gully inventories and, by extent, gully erosion assessments at regional to continental scales. The
391 development of systematic gully typologies, similar to those developed for landslides (e.g. [Cruden and](#)
392 [Varnes, 1996](#)), may help address this issue.

393

394 **2.3. Assessing gully dynamics**

395 Various studies have assessed gully erosion rates through repeated field surveys or by determining the
396 age of gullies through the analyses of tree roots, terrestrial photography, interviews, optical dating,
397 sediment fingerprinting or other techniques (e.g. [Vandekerckhove et al., 2001a; 2003; Martinez-](#)
398 [Casasnovas et al., 2004; Ionita, 2006; Nyssen et al., 2006; Marzloff et al., 2011; Frankl et al., 2012;](#)
399 [Portenga et al., 2017; Bernatek-Jakiel & Wrońska-Wałach, 2018](#)). While such research can provide

400 key insights, they typically require intensive fieldwork and are therefore generally limited to specific
401 gullies or small study areas. Efforts to understand gully erosion dynamics over larger areas therefore
402 mainly rely on applying the techniques discussed above over different periods (e.g. Nachtergaele et al.,
403 2002b, Vandekerckhove et al., 2003; Vanwallegem et al., 2005c; Marzloff and Poesen, 2009; Frankl
404 et al., 2011; Yibeltal et al., 2019).

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

416 Apart from climatic variability, over- or underestimations strongly depend on the timing of the
417 imagery. Permanent gullies often show the highest headcut retreat rates shortly after their formation,
418 but then tend to stabilize over time (e.g. Nachtergaele et al., 2002b; Vanwallegem et al., 2005;
419 Sidorchuk, 2006; Whitford et al., 2010; Vanmaercke et al., 2016; Makanzu Imwangana et al., 2015;
420 Rysin, 1998). When gullies are already present on the first image of a series, this poses large
421 challenges in reconstructing the long-term average erosion rate (Vanmaercke et al., 2016).
422 Furthermore, gullies can expand through widening and deepening (e.g. Martinez-Casasnovas et al.,
423 2004; Marzloff and Poesen, 2009). Research suggests that these processes become relatively more
424 important in the later stages of gully development (e.g. Sidorchuk, 1999; Sidorchuk et al., 2003;
425 Sidorchuk, 2006; Hayas et al., 2017a). Nonetheless, few studies have focused on these processes. As a
426 result, they remain poorly quantified and understood (Whitford et al., 2010; Hayas et al., 2019).

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

436 In conclusion, assessing reliable gully erosion rates at regional to continental scales remains difficult,
437 especially at high temporal resolutions. Methodological challenges in both the detection (cf. [section](#)
438 [2.1](#)) and characterization (cf. [section 2.2](#)) of gullies may induce significant uncertainties. New remote
439 sensing products and (semi-)automatic detection procedures offer promising perspectives here.
440 Nevertheless, especially the large temporal variability that characterizes gully erosion remains a major
441 source of uncertainty. Accurately quantifying gully erosion rates therefore requires frequent imagery
442 over sufficiently long time periods (e.g. decades). Historic (aerial) photographs can be crucial assets in
443 this (e.g. [Nachtergaele and Poesen, 1999](#); [Frankl et al. 2011](#); [Golosov et al., 2018](#)). Nonetheless, such
444 photographs are rarely available over large areas, are often difficult to access for scientists and their
445 processing often remains very labour-intensive (e.g. [Guyassa et al., 2018](#)).

446

447 **3. Measurements on gully erosion in Europe: an overview**

448 As discussed above, field-based research is important for defining the locations, morphological
449 characteristics, erosion processes, dynamics and controlling factors of gullies. To gain insights into the
450 geographic distribution of field-based gully related research in Europe and European Russia, we
451 conducted a detailed literature review. This review concentrated on research results published in peer-
452 reviewed journals or in conference proceedings. Studies published in internal reports, MSc. or PhD.
453 theses, or newspaper articles (i.e. grey literature) were not considered. As some research teams
454 produced a large number of peer-reviewed papers about gullies in particular study areas, only the most
455 relevant papers, considered to be representative for the study area, were selected. In total over [224](#)
456 research papers have been selected ([Table 1](#)). [Figure 2](#) shows the spatial distribution of areas where
457 permanent, ephemeral or bank gullies as well as gullies in badlands have been studied. Although a
458 large number of papers report on various aspects of badlands, we only considered studies focusing on
459 gully erosion in badlands.

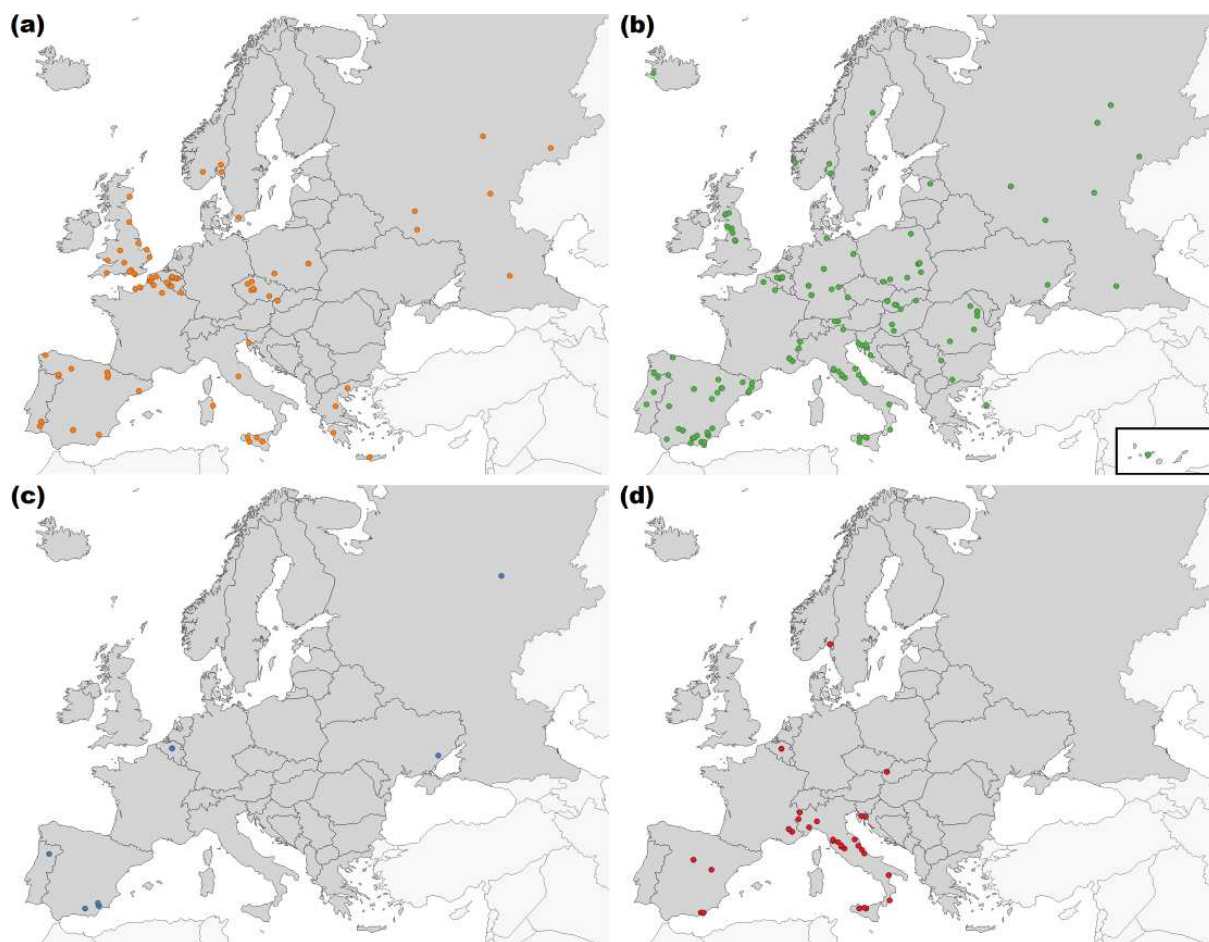
460 Overall, gully erosion mainly received significant field-based research attention in some particular
461 countries, i.e. Belgium, Germany, Italy, Spain, Romania and the UK. Most studies investigated
462 permanent gullies in forests or rangelands (including badlands; [Figure 2a, Figure 2d](#)). Relatively
463 fewer studies report on ephemeral gullies, which are typically observed after erosive periods in
464 cropland. As ephemeral gullies are filled in by tillage or land leveling operations shortly after their
465 formation, these gullies are also more difficult to study. Although quite common in rural areas with a
466 rolling or steep topography, bank gullies forming at river banks, agricultural terraces, lynchets or
467 sunken lane banks ([Poesen et al., 2003](#)) have also received less attention ([Figure 2c](#)).

Table 1: Overview of gully erosion research in Europe and European Russia.

Country	Ephemeral Gullies	Permanent Gullies	Bank Gullies	Gullies in Badlands
Austria	N.A.	Sass et al. (2012)	N.A.	N.A.
Belgium	Govers & Poesen (1988); Vandaele & Poesen (1995); Poesen et al. (1996); Vandaele & Poesen (1996); Vandaele & Poesen (1997); Desmet et al. (1999); Nachtergaele & Poesen (1999); Takken et al. (1999); Steegen et al. (2000); Gyssels et al. (2002); Gyssels & Poesen (2003); Vanwallegghem et al. (2005a); Evrard et al. (2007); Knapen & Poesen (2010); Maignard et al. (2014a); Maignard et al. (2014b)	Arnould-De Bontridder & Paulis (1966); De Ploey (1977); Langohr & Sanders (1985); Gullentops (1992); Poesen et al. (2003); Vanwallegghem et al. (2003); Vanwallegghem et al. (2005a); Vanwallegghem et al. (2005b); Vanwallegghem et al. (2005c); Vanwallegghem et al. (2006); Schotmans et al. (2015)	Poesen (1989); Poesen et al. (1996); Poesen et al. (2003); Frankl et al. (2015)	Gullentops (1992); Vanwallegghem et al. (2003); Vanwallegghem et al. (2006)
Bulgaria	N.A.	Malinov & Ilieva (2017)	N.A.	N.A.
Croatia	N.A.	Faivre et al. (2011); Gulam et al. (2018); Domazetović et al. (2019); Domlija et al. (2019)	N.A.	Gulam et al. (2018); Domlija et al. (2019)
Czech Republic	Báčová & Krása (2016); Dumbrovsky et al. (2019)	Tichavský et al. (2018)	N.A.	N.A.
France	Auzet et al. (1993); Cerdan et al. (2002); Souchère et al. (2003); Frankl et al. (2018); Patault et al. (2019)	De Foucault et al. (1997); Mathys et al. (2003); Rey (2003); Rey (2009); Erktan & Rey (2013); Rey & Burylo (2014); Taborelli et al. (2016)	N.A.	Mathys et al. (2003); Rey (2009); Erktan & Rey (2013); Rey & Burylo (2014)
Germany	N.A.	Bork & Rohdenburg (1979); Bork (1985); Bauer (1993); Semmel (1995); Bork et al. (1998); Dotterweich (2003); Dotterweich et al. (2003); Heine & Niller (2003); Schmidtchen & Bork (2003); Dreibrodt (2005); Stolz & Grunert (2006); Beyer (2008); Dotterweich (2008); Moldenhauer et al. (2010); Stolz (2011); Dotterweich et al. (2015)	N.A.	N.A.
Greece	Karydas & Panagos (2020)	Vandekerckhove et al. (2000)	N.A.	N.A.
Hungary	N.A.	Gabris et al. (2003); Jakab et al. (2011); Kertész & Gergely (2011); Kertész & Křeček (2019)	N.A.	N.A.
Iceland	N.A.	Hartmann et al. (2003)	N.A.	N.A.
Italy	Capra & Scicolone (2002); Poesen et al. (2003); Zucca et al. (2006); Conoscenti et al. (2013); Conoscenti et al. (2014); Fiorucci et al. (2015); Conoscenti et al. (2018); Conoscenti & Rotigliano (2020)	Battaglia et al. (2003); Strunk (2003); Clarke & Rendell (2006); Ciccacci et al. (2009); Buccolini & Coco (2010); Clarke & Rendell (2010); Battaglia et al. (2011); Cappadonia et al. (2011); Buccolini et al. (2013); Conoscenti et al. (2013); Pulice et al. (2013); Torri et al. (2013); Vergari et al. (2013a); Caraballo-Arias et al. (2014); Caraballo-Arias et al. (2015); Cocco et al. (2015); Bianchini et al. (2016); Bollati et al. (2019)	N.A.	Battaglia et al. (2003); Clarke & Rendell (2006); Ciccacci et al. (2009); Buccolini & Coco (2010); Clarke & Rendell (2010); Battaglia et al. (2011); Cappadonia et al. (2011); Buccolini et al. (2013); Pulice et al. (2013); Torri et al. (2013); Vergari et al. (2013b); Caraballo-Arias et al. (2014); Caraballo-Arias et al. (2015); Cocco et al. (2015); Bianchini et al. (2016); Bollati et al. (2019); Bosino et al. (2019); Maerker et al., 2020

Latvia	N.A.	Zglobicki et al. (2019)	N.A.	N.A.
Norway	Øygarden (2003)	Sønstegeard & Mangerud (1977); Erikstad (1992); Bogen et al. (1994)	N.A.	Erikstad (1992)
Poland	Maruszczyk & Trembacowski (1956); Teisseyre (1992); Janicki & Zglobicki (1998); Janicki (2014)	Schmitt et al. (2006); Smolska (2007); Malik (2008); Rodzik et al. (2009); Schmidt & Heinrich (2011); Zglobicki & Baran-Zglobicka (2011); Dotterweich et al. (2012); Gawrysiak & Harasimiuk (2012); Superson et al. (2014); Zglobicki et al. (2014); Kociuba et al. (2015); Zglobicki et al. (2015a); Zglobicki et al. (2015b); Bernatek-Jakiel & Wronska-Walach (2018)	N.A.	N.A.
Portugal	Poesen et al. (1996); de Figueiredo & Fonseca (1997); Vandaele et al. (1997); Vandekerckhove et al. (1998); Vandekerckhove et al. (2000); Nachtergaele et al. (2001a); Poesen et al. (2003)	de Figueiredo & Fonseca (1997); Vieira et al. (2014); Bergonse & Reis (2016); Martins et al. (2017); Martins et al. (2020)	Fernandes et al. (2017)	N.A.
Romania	N.A.	Motoc (1983); Motoc (1984); Ichim et al. (1990); Radoane et al. (1995); Ionita (2003); Ionita (2006); Mircea (2011); Niacsu & Ionita (2011); Boengiu et al. (2012); Ionita et al. (2015); Radoane & Radoane (2017); Nicu (2018)	N.A.	N.A.
Russia (European)	Litvin et al. (2003); Belyaev et al. (2005b); Belyaev et al. (2008); Platoncheva et al. (2020)	Bolysov (1987); Dedkov et al. (1990); Bolysov & Tarzaeva (1996); Rysin (1998); Litvin et al. (2003); Zorina (2003); Belyaev et al. (2004); Belyaev et al. (2005a); Yermolaev (2014); Vanmaercke et al. (2016); Rysin et al. (2017a); Rysin et al. (2017b); Gafurov et al. (2018); Golosov et al. (2018); Medvedeva et al. (2018); Rysin et al. (2018); Sharifullin et al. (2020)	Rysin (1998)	N.A.
Serbia	N.A.	Ristić et al. (2012)	N.A.	N.A.
Slovakia	Stankoviansky (2005); Stankoviansky & Ondrčka (2011)	Bučko & Mazúrova (1958); Stankoviansky (2003a); Stankoviansky (2003b); Papčo (2011); Stankoviansky (2003c); Dotterweich et al. (2013); Silhan et al. (2016); Mitusov et al. (2017); Nosko et al. (2019)	N.A.	Stankoviansky (2003a); Stankoviansky (2003b); Stankoviansky (2003c)
Slovenia	Zorn (2009a)	Zorn (2009b)	N.A.	N.A.

Spain	Vandekerckhove et al. (1998); Casali et al. (1999); Martínez-Casasnovas et al. (2002); Valcarcel et al. (2003); De Santisteban et al. 2006; Hayas et al. (2017a); Hayas et al. (2017b); Ollobarren Del Barrio et al. (2018); Hayas et al. (2019)	Donker & Damen (1984); Faulkner (1995); Poesen et al. (1996); Oostwoud Wijdenes et al. (1999); Nogueras et al. (2000); Oostwoud Wijdenes et al. (2000); Vandekerckhove et al. (2000); Canton et al. (2001); Vandekerckhove et al. (2001a); Vandekerckhove et al. (2001b); Martínez-Casasnovas et al. (2003); Ries & Marzloff (2003); Vandekerckhove et al. (2003); De Luna Armenteros et al. (2004); Faulkner et al. (2007); Lesschen et al. (2007); Menendez-Duarte et al. (2007); Gomez-Gutierrez et al. (2009a); Dóniz et al. (2011); Lucia et al. (2011); Marzloff et al. (2011); Campo-Bescos et al. (2013); Martín-Moreno et al. (2014); Stöcker et al. (2015); Caraballo-Arias et al. (2016); Ballesteros Cánovas et al. (2017); Hayas et al. (2017a); Hayas et al. (2017b); Selkimäki & González-Olabarria (2017); Castillo et al. (2018); Hayas et al. (2019)	Oostwoud Wijdenes et al. (2000); Vandekerckhove et al. (2000); Vandekerckhove et al. (2001a); Vandekerckhove et al. (2001b); Vandekerckhove et al. (2003)	Nogueras et al. (2000); Faulkner et al. (2007); Lucia et al. (2011); Martín-Moreno et al. (2014); Ballesteros Cánovas et al. (2017)
Sweden	Alström & Åkerman (1992)	Nordström (1984)	N.A.	N.A.
Ukraine	N.A.	Tsvetkova et al. (2015)	Tsvetkova et al. (2015)	N.A.
United Kingdom	Morris (1942); Howe (1955); Evans & Nortcliff (1978); Reed (1979); Boardman (1983); Boardman (1988); Watson & Evans (1991); Boardman et al. (1996); Boardman (2001); Clark & Vetere Arellano (2004); Watson & Evans (2007); Boardman et al. (2009); Boardman (2012); Boardman (2013); Boardman et al. (2020); Evans (2013)	Chiverrell et al. (2007); Rothwell et al. (2007); Evans & Lindsay (2010); Clay et al. (2012)	N.A.	N.A.



470
 471 **Figure 2:** Overview of study areas in Europe and European Russia where field-based gully erosion research was conducted,
 472 sub-divided according to the investigated gully-type: **(a)** ephemeral gullies, **(b)** permanent gullies (inset shows the Canary
 473 Islands), **(c)** bank gullies, **(d)** gullies in badlands. References per country and gully type are listed in **Table 1**. Countries
 474 shaded in dark grey indicate the study area considered for this review.

475
 476 Most studies focused on a single gully channel or on a limited number of selected gullies in a
 477 particular study area. However, a few studies provide gully inventories for extensive areas (> 10 000
 478 km²) or even entire countries (**Figure 3**). More specifically, such studies exist for Slovakia (Bučko &
 479 Mazúrová, 1958), Poland (Józefaciuk & Józefaciuk, 1983), SE-Poland (Gawrysiak & Harasimiuk,
 480 2012), East Romania (Radoane et al., 1995), Northern France (De Foucault et al., 1997), the Middle
 481 Volga region (Russian Federation; Golosov et al., 2018) and Hungary (Kertész & Krecek, 2019).
 482 These inventories are largely based on aerial imagery interpretation. They are often already relatively
 483 old and focused on larger, permanent gullies. Therefore it is generally difficult to assess their accuracy
 484 and completeness. Nonetheless, such inventories may be indispensable for calibrating and validating
 485 gully occurrence models at larger scales (cf. section 4.1).

486 It is beyond our scope to provide an in-depth review of all aspects of gully erosion that received
 487 research attention. Such thematic explorations have been conducted elsewhere (e.g. Poesen et al.,
 488 2003; Castillo & Gomez, 2016). Nonetheless, several major themes of gully erosion research in
 489 Europe could be identified. These include:

- 490 ▪ Developing and testing gully measuring and monitoring techniques, such as high-altitude aerial
491 photograph analysis (e.g. Nachtergaele & Poesen, 1999; Martinez-Casasnovas et al., 2002),
492 analysis of high-resolution aerial photos taken by drones (e.g. Marzolf & Poesen, 2009; Stöcker
493 et al., 2015), 3D-terrestrial image-based modelling (e.g. Frankl et al., 2015) and
494 dendrogeomorphology (Vandekerckhove et al., 2001a; Malik 2008; Tichavsky et al., 2018).
- 495 ▪ Dating of (pre-)historic gullies (e.g. Sonstegaard and Mangerud, 1977; Bork, 1985; Dotterweich et
496 al., 2003; 2012; 2013, Schmitt et al., 2006, Vanwallegem et al., 2006) and investigating the
497 environmental conditions that lead to their initiation and development (e.g. Bork, 1985; Faulkner,
498 1995; Dotterweich et al., 2003; Gabris et al., 2003; Nogueras et al., 2000; Stankoviansky, 2003a;
499 2003b; 2003c; Vanwallegem et al., 2005b; Martin Moreno et al., 2014; Ionita et al., 2015b;
500 Ballesteros et al., 2017).
- 501 ▪ Investigating factors controlling the initiation and development of contemporary gullies, including
502 soil profile characteristics (e.g. Vanwallegem et al., 2005b), plant roots (e.g. Gyssels & Poesen,
503 2003), topography and topographic thresholds (e.g. Vandekerckhove et al., 1998; Souchère et al.,
504 2003; Hayas et al. 2017a; 2017b; Torri et al., 2018b), snowmelt runoff (e.g. Oygarden, 2003;
505 Ionita, 2006; Rodzik et al., 2009; Rysin et al., 2017a,b; Golosov et al., 2018), rainfall conditions
506 (Hayas et al. 2017a; 2017b) and the role of piping (Bernatek-Jakiel & Wronska-Walachn, 2018).
- 507 ▪ Exploring the conditions leading to the infilling of gullies (e.g. Erikstad, 1992; Vanwallegem et
508 al., 2005c).
- 509 ▪ Evaluating the effectiveness of gully erosion control techniques, including geomembranes (e.g.
510 Poesen, 1989), check dams (e.g. Castillo et al., 2007), grassed waterways (e.g. Evrard et al., 2008)
511 and bioengineering structures (e.g. Rey & Burylo, 2014).
- 512 ▪ Quantifying the contribution of gully erosion to catchment sediment yields (e.g. Bogen et al.,
513 1994; Poesen et al., 1996; 2003).

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

- 516 1) Most studies are clustered in specific study areas, while many other areas remain poorly or not
517 investigated (cf. **Figure 2**). While these patterns may be partly caused by the absence of gullies,
518 many regions probably remain under-researched.
- 519 2) Only few studies investigated gully occurrence on regional or country-wide scales (cf. **Figure 3**).
- 520 3) Relatively few studies monitored the evolution of gullies over extensive time periods (e.g. > 20
521 years). Given their potentially large temporal variability (e.g. Rysin, 1998; Nachtergaele et al.,
522 1999; Martinez-Casasnovas et al., 2004; Vanmaercke et al., 2016; Hayas et al., 2017a; Rysin et al,

523 2017a,b; Rysin et al., 2018), this is critical to understand the long-term evolution and erosion rates
524 of gully systems.

525 4) Relatively few studies have focused on testing or developing models that simulate spatial patterns
526 of gully erosion. This is particularly the case for larger areas.

527 5) Evaluating the long-term effectiveness and efficiency of gully erosion control measures has
528 received little attention, both at the scale of gully channels and catchments (Poesen et al., 2003;
529 Bartley et al., 2020). Linked to that, our understanding of the conditions controlling the infilling of
530 gullies is limited (Poesen et al. 2003).

531



532 **Figure 3:** Regions and countries in Europe for which systematic gully inventories have been made. The mapped gully types,
533 level of detail and completeness of these inventories may vary. 1: N-France (De Foucault et al., 1997), 2: Poland (Józefaciuk
534 & Józefaciuk, 1983), 3: SE-Poland (Gawrysiak & Harasimiuk, 2012), 4: Slovakia (Bučko & Mazúrová, 1958), 5: Hungary
535 (Kertész & Krecek, 2019), 6: E-Romania (Radoane et al., 1995), 7: the Middle Volga region (Russian Federation; Golosov et
536 al., 2018). Countries shaded in dark grey indicate the study area considered for this review.

538

539 **4. Assessing gully erosion using models**

540 Predicting gully erosion rates and its impact on sediment loads encompasses several challenges. These
541 include predicting: (i) where and why gullies occur, (ii) when and how these gullies expand, and (iii)
542 to what extent these gullies contribute to catchment sediment yields. Numerous gully erosion models
543 have been developed. However, no single model presently exists that addresses these three

544 components. Furthermore, most modelling efforts have concentrated on individual gullies or local
545 scales. Here we review and discuss different modelling strategies to simulate these different aspects of
546 gully erosion. It is outside our scope to provide a comprehensive overview of all gully erosion models.
547 Instead, we discuss which modelling strategies potentially can be applied at regional to continental
548 scales, which future advancements may be expected and which research needs currently exist.

549

550 *4.1. Predicting gully occurrence and density*

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

555 In general, process-based approaches rely on the principle that gully initiation is a threshold-dependent
556 phenomenon. Gully heads typically initiate where the shear stress of concentrated runoff exceeds the
557 resisting forces, which mainly depends on local soil and vegetation conditions ([Istanbulluoglu et al.,](#)
558 [2003](#); [Knapen et al., 2007](#); [Knapen and Poesen, 2010](#)). The most common approach to characterize
559 these conditions is the topographic threshold concept. It builds upon the observation that gullies in a
560 landscape typically form at locations where the upslope area (A) and local slope steepness (s) exceed a
561 certain threshold (e.g. [Begin and Schumm, 1979](#); [Montgomery & Dietrich, 1994](#)). Given that A
562 provides a proxy of the potential flow discharge and s influences flow velocity, topographic thresholds
563 directly relate to the critical flow shear stress principle. They are commonly expressed in the form:

$$564 \quad s = kA^b \text{ (Eq. 1)}$$

565 where k and b are empirically fitted constants that depend on the environmental setting ([Begin and](#)
566 [Schumm 1979](#); [Montgomery & Dietrich, 1994](#); [Torri & Poesen, 2014](#)). Such thresholds often allow
567 fairly good identification of the positions of gully initiation within a study area and by extent their
568 density (e.g. [Desmet et al., 1999](#)). However, their highly site-specific nature makes them unsuitable for
569 applications at regional or continental scales. A meta-analysis by [Torri and Poesen \(2014\)](#) of 63 s - A
570 relations for various areas worldwide indicated a very large variability in k - and b -values (cf. [Eq. 1](#)).
571 Under the assumption that b -values are relatively constant, variations in k -values seem mainly
572 attributable to differences in land cover. Nonetheless, generalizing these empirical constants remains
573 difficult as also other environmental factors will play a role. For example, a main limitation of
574 topographic thresholds is that they typically reflect the “integrated” result of different gully initiation
575 episodes over time. Exact gully head initiation thresholds vary with rainfall intensity (e.g. [Torri and](#)
576 [Poesen 2014](#); [Hayas et al., 2017b](#)) and more specifically with the resulting peak flow discharge. Also
577 spatial patterns of vegetation and soil characteristics within the contributing area can play a large role
578 (e.g. [Rossi et al., 2015a](#)). Likewise, the upslope area can be modified by land management practices

579 that are not resolved by DEMs, such as tillage furrows (Souchère et al. 2003), drainage ditches and
580 stone bunds, all of which can affect the k -value (Monsieurs et al., 2015). Furthermore, gullies are not
581 necessarily the sole result of (Hortonian) runoff. They can also form and expand as a result of
582 saturation soil conditions and overland flow (e.g. Nachtergaele et al. 2001a; Tebebu et al., 2010;
583 Amare et al., 2019).

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

600 To account for factors other than topography (e.g. climate, land use/land cover, soil type) and their
601 potential interactions, several process-oriented model approaches have been proposed. Overall, they
602 aim to replace or complement the upslope contributing area (A) in Eq. 1 with better proxies of flow
603 discharge, and by extent the flow shear stress, that can occur at a potential gully location. This could
604 allow for more accurate and generalizable simulations of where and when gullies may form. Several
605 approaches are based on the Curve Number (CN) method, a simple empirical model that allows
606 estimating runoff based on rainfall, antecedent moisture, soil and land use conditions (e.g. Ponce &
607 Hawkins, 1996). In principle, such approach allows making gully initiation conditions dynamic
608 through time (e.g. Poesen and Torri 2014; Torri et al., 2018b). Likewise, combining a pixel-based CN
609 approach with flow-routing algorithms makes it possible to account for the effect of spatial patterns of
610 topography, soil conditions and land cover (Rossi et al., 2015a). An attractive element of the CN
611 approach is that its simple nature enables its application at regional to global scales (e.g. Hong et al.,
612 2007). Nonetheless, this also involves uncertainties and the risk of over-extrapolation as the CN
613 approach remains an empirical model that was developed and tested for a relatively limited set of
614 environmental conditions. Furthermore, such approach does not yet account for all relevant

615 mechanisms and possible interactions with other erosion processes. For example, also the amount of
616 sediments transported by the runoff from upslope areas will determine whether incision or aggradation
617 will take place (e.g. [Poesen et al., 2003](#)).

618 Also several landscape evolution models are to some extent capable of simulating gully initiation,
619 using a process-based approach (e.g. [Tucker et al., 2001](#); [Kirkby et al., 2003](#); [Willgoose, 2005, 2018](#);
620 [Harmon et al., 2019](#)). These typically define the threshold in terms of equilibrium between local
621 sediment load or entrainment and sediment transport capacity; often conceptualized in terms of shear
622 stress or stream power per unit flow width. Nevertheless, some empiricism remains. This mainly
623 relates to the definition of critical flow shear stress and the long-term effects of temporal variations in
624 environmental conditions.

625 Overall, process-oriented approaches offer significant promise to predict gully initiation as they aim to
626 account for the actual driving processes in a conceptually transparent way. This can make them highly
627 suitable for the evaluation of gully erosion risks in the context of climate or land use changes (e.g.
628 [Hancock et al., 2000](#); [Sidorchuk et al., 2001](#); [Sidorchuk et al., 2003](#); [Rossi et al., 2015a](#)). Furthermore,
629 these models may generally allow for a more straightforward and correct coupling between gully
630 initiation and expansion (cf. [section 4.2](#)). Several process-oriented gully erosion models already
631 account for both components, and perform acceptably over study sites with reasonably uniform
632 properties (e.g. [Willgoose, 2005](#); [Hancock et al., 2015](#)). Nonetheless, the application of most of these
633 models remains limited to theoretical considerations or small study areas (e.g. [Rossi et al., 2015a](#)). In
634 many cases, these models also remain poorly validated ([Poesen et al., 2011](#)). A major reason for this is
635 the relatively large data requirements (e.g. [Kirkby et al., 2003](#); [de Vente et al., 2013](#)). This includes
636 detailed information on the controlling factors, but also observations on gully initiation (e.g. knowing
637 which gully head was initiated and when exactly for a sufficiently long observation period). For the
638 former, the availability of new GIS data layers and products opens promising perspectives (cf. [section](#)
639 [5](#)). Nonetheless, the latter remains a critical point for applications at regional to continental scales (cf.
640 [sections 2 & 3](#)). As with most geomorphic models, also error propagation is a critical concern.
641 Accurate process descriptions of gully initiation typically require more input data. Errors and
642 uncertainties on these input data can easily become more important than errors and uncertainties
643 resulting from an inaccurate process description (e.g. [Van Rompaey et al., 2002](#)).

644 Empirical approaches to simulate gully occurrence and densities can offer a major advantage in this
645 regard: they typically result in more robust predictions and are often less demanding in terms of data
646 requirements (e.g. [de Vente et al., 2013](#)). Overall, a wide range of empirical approaches exist. To some
647 extent, they can be classified in bivariate methods, multivariate methods, and machine learning
648 approaches. An (non-exhaustive) overview of example studies is given in [Table 2](#). Most of these
649 procedures aim to predict the presence or absence of a gully on a given location. Their successful
650 application results in a gully erosion susceptibility map (GESM), from which proxies of gully density

651 can be derived. However, some approaches try to directly predict the gully density within a catchment
652 (Zhao et al., 2016) or pixel (Kheir et al., 2007; Vanmaercke et al., 2020).

653 Bivariate statistical approaches (e.g. Conforti et al., 2011; Conoscenti et al., 2013) can be robust but
654 reduce gully prediction to only one causal factor, typically leading to imprecise predictions. Except in
655 simple situations or very data-poor regions, these approaches are therefore generally inferior to the
656 other methods. Multivariate methods (e.g. Akgün and Türk, 2011; Lucà et al., 2011) analyse gully
657 occurrence as a function of different causal factors and to some extent allow determining the relative
658 contribution of each factor. Logistic regression (e.g. Vanwallegem et al., 2008; Conoscenti et al.,
659 2014; Dewitte et al., 2015) is the most commonly used multivariate approach. Its computational
660 simplicity and ability to deal with both continuous and categorical explanatory variables are important
661 advantages. However, its ability to fully disentangle the potentially non-linear role of different factors
662 and their interactions remains limited. In this regard, machine learning methods offer great potential
663 and have been increasingly used over recent years (Table 2). Especially techniques like random
664 forests (e.g. Gayen et al., 2019; Rahmati et al., 2017; Hosseinalizadeh et al., 2019) can, at least in
665 principle, better account for the fact that the role of explanatory variables may vary between different
666 subpopulations of gullies and over different scales. They can also be used to spatially assess
667 uncertainties on model outputs, thus guiding interpretation and targeting further data collection (e.g.
668 Kuhnert et al., 2010; Vanmaercke et al., 2020).

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

682 Models aiming to predict gully initiation and densities at regional to continental scales in the context
683 of future climate or land use changes should therefore seek to strike a balance between a relevant and
684 conceptually sound process description and feasible calculation and input requirements. Several
685 studies already apply a hybrid approach between empirical and process-based gully occurrence
686 prediction. For example, Dewitte et al. (2015) implemented a two-step procedure. First, potentially

687 gully-prone areas were delineated based on the slope-area threshold concept. Next, logistic regression
688 was used for a more detailed prediction of gully locations within those areas. Recent conceptual
689 advancements that replace the slope-area threshold concept with more detailed description of expected
690 runoff discharges (e.g. based on the CN-model approach; see above), also offer promising perspectives
691 in this regard.

692 **Table 2:** Examples of empirical gully occurrence and gully density models

Method	Sub method ^a	Authors	Scale (km ²)	location
Bivariate statistical	Conditional analysis	Conoscenti et al., 2013	250	Italy
	Index of entropy	Zabihi et al., 2018; Arabameri et al., 2018b	15.44 - 416	Iran
	Information value	Lucà et al., 2011; Conforti et al., 2011; Al-Abadi and Al-Ali, 2018	26,74 - 30	Iran, Italy
	EBF	Al-Abadi and Al-Ali, 2018	26,74	Iran
	Frequency ratio	Al-Abadi and Al-Ali, 2018; Rahmati et al., 2016; Zabihi et al., 2018; Arabameri et al., 2018b	15,44 – 2.595	Iran
	Weights of evidence	Rahmati et al., 2016; Arabameri et al., 2018b; Zabihi et al., 2018	15,44 – 2.595	Iran
Multivariate statistical	Logistic regression	Akgün and Türk, 2011; Lucà et al., 2011; Conoscenti et al., 2014; Maerker et al., 2020	9,5 - 424	Italy, Turkey
Machine learning	AHP	Arabameri et al., 2018b	416	Iran
	ANN	Pourghasemi et al., 2017	2595	Iran
	BRT	Maerker et al., 2011, 2020; Angileri et al., 2016; Rahmati et al., 2017; Arabameri et al., 2018a	245 - 848	Iran
	CRT	Kheir et al., 2007; Geissen et al., 2007; Gomez-Gutiérrez et al., 2009b; Märker et al., 2011	26,4 - 3500	Spain, Turkey, Mexico, Italy
	FDA	Gayen et al., 2019	709	India
	MARS	Gomez-Gutiérrez et al., 2009b; Gomez-Gutiérrez et al., 2009c; Gómez-Gutiérrez et al., 2015; Arabameri et al., 2018a; Gayen et al., 2019; ; Conoscenti et al., 2018; Conoscenti et al., 2020	9,5 - 848	India, Spain, Iran, Italy
	Maximum entropy	Zakerinejad & Maerker 2014; Pourghasemi et al., 2017; Maerker et al., 2020	2595	Iran, Italy
	Random forest	Kuhnert et al., 2010; Rahmati et al., 2017; Arabameri et al., 2018a; Gayen et al., 2019; Bui et al., subm.; Vanmaercke et al., 2020	245 - 848	India, Iran, Australia, Horn of Africa
SVM	Rahmati et al., 2017; Pourghasemi et al., 2017; Gayen et al., 2019;	245 – 2.595	India, Iran	

693 ^a EBF: Evidence belief function; AHP: Analytical hierarchy process; ANN: Artificial neural network; BRT: Boosted
694 regression tree; CRT: Classification and regression tree; FDA: Flexible discriminant analysis; MARS: Multivariate
695 adaptative regression spline; SVM: Support vector machine

696

697 **4.2. Predicting gully expansion**

698 Total gully erosion rates over an area not only depend on the occurrence of gullies (cf. [section 4.1](#)), but
699 also on their expansion rates. Actively eroding gullies generally produce sediment through headcut
700 retreat and channel widening/deepening (e.g. [Martinez-Casanovas et al., 2004](#); [Marzloff & Poesen,](#)
701 [2009](#); [Vanmaercke et al., 2016](#); [Hayas et al. 2017a](#)). In some contexts, piping can also contribute
702 significantly to gully expansion (e.g. [Valentin et al., 2005](#); [Bernatek-Jakiel and Poesen, 2018](#)).

703 **Table 3** shows a (non-exhaustive) overview of models that have been developed to predict gully
704 expansion. Gully headcut retreat is generally the best-studied expansion process and several process-
705 oriented models have been developed to simulate this. Examples include CHILD for permanent gullies
706 ([Flores-Cervantes et al., 2006](#)) or the module TIEGEM within AnnAGNPS for ephemeral gullies
707 ([Gordon et al., 2007](#)). Both are based on a model simulating the hydraulics at the gully head by [Alonso](#)
708 [et al. \(2002\)](#). While field validation of its predecessor, EGEM ([Woodward et al., 1999](#)), revealed
709 important flaws, TIEGEM tends to show better model performances. Nonetheless, testing currently
710 remains limited. Also evaluations of CHILD showed that it is capable of reproducing observed retreat
711 rates relatively well, at least in some contexts (e.g. [Campo-Bescós et al., 2013](#)). However, its
712 application requires several parameters that generally need to be obtained in the field (including the
713 height of the headcut, the shape of the plunge pool and soil erodibility). This greatly limits its use at
714 larger scales. This problem is not specific to the CHILD model, but affects most process-based gully
715 headcut retreat models (e.g. [Poesen et al., 2011](#)). Another important limitation are the often high data
716 requirements needed to accurately predict peak runoff discharges and flow velocities at the gully head.
717 This is a common challenge for ungauged basins ([Blöschl, 2006](#)). More simplified approaches that
718 predict headcut retreat based on (hydrological) model routines that require fewer and feasible
719 parameters therefore show greater promise at larger scales but require further development and field
720 validation (e.g. [Dabney et al., 2015](#); [Allen et al., 2018](#)).

721 As with gully occurrence (cf. [section 4.1](#)), empirical models based on statistical correlations between
722 observed headcut rates and environmental variables may offer an alternative (**Table 3**). Several studies
723 proposed empirical equations predicting gully headcut retreat rates for specific study sites (e.g.
724 [Vandekerckhove et al., 2003](#); [Marzloff et al., 2011](#); [Poesen et al., 2011](#); [Frankl et al., 2012](#); [Li et al.,](#)
725 [2015](#)). These models differ strongly in terms of incorporated factors. However, a meta-analysis of
726 >700 measured volumetric headcut retreat rates worldwide showed that the upslope contributing area
727 (A) of the gully headcut and the rainfall intensity (expressed as the rainy day normal, i.e. the average
728 annual rainfall depth divided by the average number of rainy days) are key factors ([Vanmaercke et al.,](#)

729 2016). Combined, these two variables explained nearly 70% of the observed global variation in
730 headcut retreat rates. As such, this opens promising perspectives to predict gully headcut retreat at
731 regional to continental scales. Nonetheless, several important challenges remain. For example,
732 applying this model to local or regional contexts can result in significant uncertainties. More accurate
733 predictions will likely require the incorporation of land use and other controlling factors (Vanmaercke
734 et al., 2016). Furthermore, its application requires knowing A and, by extent, the position of each
735 headcut. Therefore, successfully predicting gully erosion rates at regional to continental scales will
736 likely need the coupling of a headcut retreat model component to a module that simulates where these
737 headcuts occur. Hybrid approaches that combine a simple hydrological model with empirical
738 components are promising in this regard (cf. section 4.1).

739 Relatively fewer studies focussed on gully widening and deepening. Nonetheless, also they can
740 contribute significantly to gully expansion (e.g. Martinez-Casasnovas and Poesen 2004; Hayas et al.,
741 2017a). Some process-oriented models for gully-widening and deepening have been proposed (e.g.
742 Sidorchuk 1999, Sidorchuk et al. 2003; Table 3). However, as with gully initiation (cf. section 4.1)
743 and headcut retreat, their application at regional or continental scales is severely impeded by high data
744 requirements. For example, Istanbuluoglu et al. (2005) present a model to predict gully widening by
745 slab failures, but this requires knowing the slab geometry beforehand. Nevertheless, more simplified
746 approaches applicable at larger scales are likely possible. For example, Crouch (1987) indicated the
747 potential of gully sidewall to assess relative differences in erosion rates. Martinez-Casasnovas et al.
748 (2004) successfully used logistic regression to predict gully wall failures in the Penedes region
749 (Spain). Likewise, based on the analyses of gully widening rates in SW Spain, Hayas et al. (2019)
750 developed a simple empirical model that relates gully widening to the upslope contributing area (A)
751 and daily rainfall depth thresholds. This model shows strong similarities with the above-discussed
752 global empirical model for gully headcut retreat rates (Vanmaercke et al., 2016). This suggests that
753 developing relatively simple, integrated models of gully expansion should be possible. However, more
754 research on the factors controlling gully widening and deepening across contrasting environments, as
755 well as their associated time scales, is needed (e.g. Graf, 1977).

756 Also piping may contribute significantly to gully initiation and expansion, but no model currently
757 exists that can predict the location and rate of this process, nor its contribution to gully erosion
758 (Bernatek-Jakiel and Poesen, 2018). Furthermore, there is a large need for tools and models that can
759 evaluate and predict how gully expansion rates will evolve in response to gully remediation and, by
760 extent, assess the optimal spacing and dimensioning of such measures. This topic has received
761 relatively little research attention (Bartley et al., 2020; Frankl et al., 2021). For example, some studies
762 provide conceptual (e.g. Castillo et al., 2014b) or empirical (e.g. Pederson et al., 2006) strategies to
763 determine the spacing of check dams. However, their applicability at regional to continental scales
764 largely remains to be developed.

765

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

Type	Model name	References	Gully type ^a	Process modelled ^b	Main input parameters ^c	Field observations ^d
Process-Oriented	DIMGUL, STABGUL	Sidorchuk (1999); Sidorchuk et al. (2003)	PG	GHL, GW, GD	Ac, S, Q, K	Russia (n=1), Australia (n=1), Swaziland (n=1)
	EGEM	Nachtergaele et al. (2001a,b); Capra et al. (2005); Tekwa et al. (2015)	EG	GHL ^f	Aa, Ac, Pe, K, D	Belgium (n=116); Spain & Portugal (n=86); Italy (n=92); Nigeria (n=12)
	AnnAGNPS-TIEGEM ^e	Gordon et al. (2007)	EG	GHL ^f	Ac, M, Q, K, D	US (n=4)
	CHILD ^e	Flores-Cervantes et al. (2006); Campo-Bescós et al. (2013)	PG	GHL	Ac, M, Q, K, D	no; Spain (n=1)
	CHILD	Istanbulluoglu et al. (2005)	PG	GW	Aa, Ac, Pe, M, K, D	no
	-	Rengers and Tucker (2014)	PG	GHL	Aa, Ac, Pe, M, K, D	no
	LANDPLANER	Rossi (2014); Rossi et al. (2015a); Rossi et al. (2015b)	PG	GH, GA	Aa, Ac, S, Pe, Q, M	Italy
	EphGEE	Vieira et al. (2015); Dabney et al. (2015)	EG	GHL	Q, K	US (n=NA)
SWAT-DEG	Allen et al. (2018)	EG	GHL ^f	Ac, Q, K, D	US (n=3)	
Empirical	regression	Vanmaercke et al. (2016)	PG, EG	GHV	Aa, Pa	global (n=724)
	regression	Li et al. (2015)	PG	GA	Aa, Ac, S	China (n=30)
	regression	Frankl et al. (2012)	PG	GHV	Aa	Ethiopia (n=18)
	regression	Marzolf et al. (2011)	PG	GHV	Aa, Pe	Spain (n=9)
	regression	Vandekerckhove et al. (2001, 2003)	PG	GHV	Aa	Spain (n=46, n = 12)
	regression	Burkard and Kostaschuk (1997)	PG	GA	Aa	Canada (n=44)
	regression	Radoane et al. (1995)	PG	GHL	Aa, Ac, Gl	Romania
	regression	Stocking (1980, 1981)	PG	GHV	Aa, D	US (n=66)
	regression	US SCS (1966)	PG	GHL	Aa, Pe	US (n=210)
	regression	Seginer (1966)	PG	GHL	Aa	Israel
regression	Thompson (1964)	PG	GHL	Aa, S, Pe, K	US	

^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.

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

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

797 Other studies have attempted to directly account for gully erosion by incorporating spatially explicit
798 estimates of gully-prone areas in combination with other factors describing erosion and sediment
799 transfers (e.g. de Vente et al., 2008; Haregeweyn et al., 2017). Identifying gully-prone areas is
800 typically based on the slope-area threshold concept (cf. section 4.1; Eq. 1), while their contribution to
801 SY is either based on an empirical estimate of typical gully erosion rates (Haregeweyn et al., 2017) or
802 through model calibration with observed SY (de Vente et al., 2008). Apart from being spatially
803 explicit, this may also avoid the problem of reproducibility mentioned above. Nonetheless, these
804 approaches remain relatively rudimentary and scarcely applied. Wilkinson et al. (2009; 2014)

805 developed a more elaborate strategy where detailed maps of existing gullies underpin estimates of the
806 contribution of gully erosion to the sediment budget, based on the volumetric expansion rates of
807 gullies over time. This approach incorporates ancillary information on the relative development stage
808 of the gully networks and the fraction of soil textures likely to contribute to suspended sediment loads.
809 However, the requirement for gully mapping limits easy applications at larger scales. One of the most
810 complete models to date that allows accounting for the effect of gully erosion on SY is AnnGNPS
811 (Momm et al., 2012). It can identify gully mouth locations semi-automatically with the APET tool.
812 This could allow calculating the spatial contribution of gully erosion to SY and evaluating the effect of
813 gully conservation measures at catchment scale. Nevertheless, its applicability over larger areas
814 remains currently unknown.

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

831

832 **5. Model input data at the continental scale**

833 Modelling gully erosion not only requires observations on gully occurrence and dynamics (cf. sections
834 2 and 3). It also requires input data on the environmental factors controlling gully erosion, more
835 specifically the (i) topography, (ii) vegetation cover, (iii) land cover, use and management, (iv) soils
836 and lithology and (v) climate and weather conditions. The availability and quality of input data
837 condition the type of model that can be used (cf. section 4). Input data for small study areas can be
838 acquired with field-based methods. Gully erosion modelling at regional to continental scale generally
839 needs to rely on Earth Observation (EO) data. The spatial resolutions, revisiting times and level of

840 detail of such EO data have significantly increased over the past decades (e.g. [Belward and Skoien,](#)
841 [2015](#)). Continental to global EO-derived datasets are also made increasingly publically available.
842 Furthermore, an increasing number of cloud-based data processing platforms are developed in order to
843 deal with the associated increasing demands for data storage and processing power. These include the
844 Copernicus Data and Information Access Services (DIAS) launched by the European Commission in
845 2018 and the Google Earth Engine platform.

846 While datasets at the national level often provide higher resolutions and levels of detail, continental to
847 global datasets have the great advantage of providing harmonized information. The use of national
848 datasets for regional to global scale modelling is often hampered by their fragmentary availability,
849 varying data acquisition and treatment methods and possibly limited data access (e.g. [Höfle &](#)
850 [Rutzinger, 2011](#); [Lohani et al., 2018](#)). Such lack of harmonization can introduce additional important
851 uncertainties.

852 Hence, this review section aims to provide an overview of currently available harmonized (and ideally
853 free) datasets that can be used for gully erosion modelling at regional to continental scales. We focus
854 on data products that are available at a European or global scale. Based on our understanding of the
855 factors controlling gully erosion and expansion, we discuss datasets describing the (1) topography, (2)
856 vegetation cover, (3) land cover, use and management, (4) soil properties and lithology, and (5)
857 climate. The datasets presented and discussed below were selected based on their relevance, up-to-
858 datedness, accuracy, length of observation periods and frequency of updates. It is expected that with
859 the increasing availability of EO data, additional datasets will become available in the near future.

860

861 **5.1. Topography**

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

869 Among the first near-global DEM datasets derived from spaceborne observations were the SRTM-C
870 DEM (first released in 2003; [Rabus et al., 2003](#)), the ASTER GDEM (released 2009) and the
871 improved ASTER GDEM2 (released 2011; [Tachikawa et al. 2011](#)) and ASTER GDEM3 (released
872 2019). While SRTM-C and the more recent TanDEM-X DEM ([Krieger et al., 2007](#)) are based on
873 interferometric Synthetic Aperture Radar (SAR) image analysis, ASTER GDEMs and the ALOS
874 DEMs ([Tadono et al., 2014](#); [Takaku et al., 2014](#)) are derived from stereoscopic analysis of optical

875 satellite images. All these global DEMs can be considered as Digital Surface Models (DSMs), i.e. the
876 elevation values reflect the Earth's surface including objects such as vegetation and buildings.
877 Furthermore, most of these global DEMs are based on observations collected over longer time periods.
878 Only the SRTM data collection was conducted over only eleven days (in February 2000) and thus
879 reflects the surface elevation at a fairly specific moment (Rabus et al., 2003).

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

892 Despite their lower spatial resolution and accuracies as compared to airborne LiDAR DEMs, these
893 global satellite-derived DEMs (**Table 4**) remain the only consistent, harmonized datasets at regional to
894 continental scales in almost all regions of the world. Among them, the TanDEM-X and the ALOS
895 World 3D (AW3D5) are the best available products. However, their high cost and the computing
896 resources required to use them may pose limitations to continental or global modelling efforts.

Table 4: Overview of global and European Digital Elevation Models and their key characteristics

Dataset/ product	Spatial extent	Satellite data acquisition period	Satellite sensor, type of DEM generation	Pixel spacing	Source	Data download	Reference
SRTM-C	global (60°N to 56°S)	11-22 February 2000	SRTM, single-pass C-band interferometry	30 m	NASA, public	https://earthexplorer.usgs.gov/	Rabus et al. (2003)
ASTER GDEM	global (83°N to 83°S)	2000 to 2010	ASTER, stereo-correlation of optical images	30 m	METI and NASA, public	https://asterweb.jpl.nasa.gov/gdem.asp	Tachikawa et al. (2011)
ALOS World 3D (AW3D5 and AW3D30)	global (82°N to 82°S, void-filled within 60°N to 60°S)	2006 to 2011	ALOS PRISM, stereo-correlation of optical images	5 m and 30 m	JAXA, 5 m product commercial, 30 m product public	AW3D30 (login required): http://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm	Tadono et al. (2014); Takaku et al. (2014)
EU-DEM	Europe	2000 to 2010	Hybrid product based on SRTM and ASTER GDEM data	25 m	European Environment Agency (EEA) under the framework of the Copernicus programme, public	https://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem	Gonzalez (2015)
TanDEM-X DEM	global (pole-to-pole)	2010 to 2015	TanDEM-X, bistatic X-band interferometric SAR	12 m and 30 m	12 m commercial product available from Airbus Defence and Space as WorldDEM™; 12/30 m products available by research agreement from DLR	http://www.intelligence-airbusds.com/elevation-models/#worldem ; products available by research agreement from DLR: https://tandemx-science.dlr.de/	Krieger et al. (2007)

898 5.2. Vegetation cover

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

905 Various indices exist to map patterns of vegetation cover from satellite imagery and several publically
906 available, ready-to-use, datasets exist ([Table 5](#)). The most commonly used proxy for vegetation cover
907 is the Normalized Difference Vegetation Index (NDVI). Various studies successfully used NDVI as a
908 predictor for gully densities (e.g. [Zhao et al., 2016](#); [Vanmaercke et al., 2020](#)). Nonetheless, also other
909 indices may be useful for gully erosion modelling, e.g. the Soil-Adjusted Vegetation Index (SAVI)
910 and the Modified SAVI. [Bennari et al. \(1995\)](#) and [Barati et al. \(2011\)](#) provide reviews of these
911 different indices. While such indices provide proxies for plant biomass and productivity, biophysical
912 variables like the leaf area index (LAI), the fraction of absorbed photosynthetically active radiation
913 (FAPAR) and the fraction of green vegetation cover (Fcover or FVC) provide more physically-based
914 descriptions of the vegetation cover. The latter is particularly relevant in the context of soil erosion
915 susceptibility ([Panagos et al., 2015](#); [Borrelli et al., 2017b](#)). It corresponds to the fraction of green
916 vegetation, covering the ground as seen from the nadir direction. Similarly, Vegetation Continuous
917 Fields (VCF) provides estimates of vegetation cover as the percentage of tree cover, percentage of
918 non-tree vegetation, and percentage of non-vegetated area (e.g. [Sexton et al., 2013](#)). An important
919 limitation of these EO-derived indices is that they only relate to the above-ground vegetation.
920 Currently, information on below-ground biomass can only be indirectly estimated (e.g. based on
921 above-ground vegetation characteristics, in-situ data and expert knowledge). Nevertheless, important
922 progress has recently been made in this regard. For example, based on empirical modelling, [Fan et al.](#)
923 [\(2017\)](#) provide estimates of maximum rooting depth at a global scale.

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

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

Dataset/ product	Spatial extent	Sensor	Satellite data acquisition period	Spatial resolution	Temporal resolution	Source	Data download	Reference
Fcover Copernicus Land Monitoring	global, 75°N to 60°S	Proba V, SPOT- VGT/ PROBA V	01/2014 to present, 1999 to present	300 m, 1 km	10 days composite	ESA, public	http://land.copernicus.eu/global/products/fcover	Smets et al. (2017); Smets et al. (2018)
MODV1 FCover	global	MODIS	2000-2016	1 km	monthly composite	ISPRA, public	Available upon request from the author	Filipponi et al. (2018)
MOD44B Vegetation Continuous Fields	global	MODIS	2000 to present	250 m	annual composite	NASA, public	https://lpdaac.usgs.gov/products/mod44bv006/	Dimiceli et al. (2015)
MOD13Q1 NDVI	global	MODIS	2000 to present	250 m	16-day composite	NASA, public	https://lpdaac.usgs.gov/products/mod13q1v006/	Didan (2015)
Copernicus Land Monitoring NDVI	global	PROBA-V, SPOT- VGT/PROBA-V	02/2016 to present, 04/1998 to present	300 m, 1 km	10 days composite	ESA, public	http://land.copernicus.eu/global/products/ndvi	Smets et al. (2016); Smets et al. (2018)
GEE NDVI	global	Landsat	1984 to present	30 m	8-day composite, 32-day composite, annual composite	USGS/ Google Earth Engine, public	https://earthengine.google.com/datasets/	Gorelick et al. (2017)
WELD NDVI	global	Landsat	1984-2001	30 m	monthly composite, annual composite	USGS/ WELD, public	https://lpdaac.usgs.gov/products/gweldmov031/ https://lpdaac.usgs.gov/products/gweldyrv031/	Roy et al. (2010)

935 *5.3. Land cover, use and management*

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

947 Several studies (e.g. [Tsendbazar et al., 2015](#); [Grekousis et al., 2015](#)) provide comprehensive
948 comparisons of available regional to global LULC datasets regarding their spatial and temporal
949 resolution, accuracy and thematic coverage. Overall, the opening of the Landsat satellite image archive
950 in 2008 and the launch of the Sentinel-2 satellites at 10 to 20 m spatial resolution in 2015 and 2017 lay
951 the foundations for a new generation of high resolution global land cover products. The GlobeLand30
952 dataset was the first open-access global land cover map at 30 m spatial resolution ([Chen et al., 2017](#)).
953 It comprises ten types of land cover for the years 2000 and 2010, extracted from more than 20,000
954 Landsat and HJ-1 satellite images.

955 **Table 6** lists a selection of global and European LULC datasets. Similar to **Table 5**, datasets in this
956 selection are freely available, based on sufficiently long observation periods, relatively recent and/or
957 regularly updated. Overall accuracies of these products vary between 64 and 80% ([Grekousis et al.,](#)
958 [2015](#)). Of this selection, CORINE Land Cover provides the longest temporal coverage (1990, 2000,
959 2006, 2012, 2018) and highest classification detail (44 land cover classes) at pan-European scale
960 ([Büttner et al., 2014](#)). The S2GLC product based on the analysis of Sentinel-2 imagery currently
961 provides the finest spatial detail at pan-European scale with a pixel size of 10 m. It distinguishes 13
962 land cover classes with an overall accuracy of 83% ([Lewiński et al., 2019](#)).

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

969 Yet detailed information on land management practices and the implementation of gully control or
970 other soil and water conservation measures remains largely lacking at (sub)continental scales. We
971 believe this is a highly important research gap. It not only impedes the accurate prediction of gully
972 erosion, but also the evaluation of prevention and mitigation measures at larger scales. Nonetheless,
973 for Europe, several datasets were developed over recent years that can help assessing these aspects.
974 Examples include the Copernicus Pan-European dataset on Small Woody Features ([EEA, 2015](#)) and
975 the EU-wide assessments of the Crop Management factor of the Universal Soil Loss Equation ([EU](#)
976 [JRC, 2015](#)). Also estimates of the effect of support practices (i.e. the P-factor in the Universal Soil
977 Loss Equation) have become available at the EU level, based on extensive field surveys (e.g. [Panagos](#)
978 [et al., 2015e](#)). However, these estimates remain subject to important uncertainties and relate to sheet
979 and rill erosion rather than to gully erosion.

Table 6: Selection of global and European Land Use/Land Cover datasets

Dataset/ product name	Spatial coverage	Temporal coverage	Sensor	Spatial resolution	Classification scheme / no of classes	Source	Data download	Reference/ report
MODIS Land Cover Type/ MCD12Q1	global	2001-2018 (annual)	MODIS	500 m	IGBP scheme, 17 classes	NASA, public	https://lpdaac.usgs.gov/products/mcd12c1v006/	Friedl et al. (2010)
GlobCover GlobCover2005 GlobCover2009	global	2004 - 2006 2009	MERIS	300 m	FAO LCCS 22 classes	ESA, public	http://due.esrin.esa.int/page_globcover.php	Bicheron et al. (2008); Bontemps et al. (2011)
GlobeLand30 2000 2010	global	2000 2010	Landsat, HJ- 1	30 m	10 classes	UN/ National Geomatics Centre of China (NGCC), public	http://www.globallandcover.com	Chen et al. (2015); Chen et al. (2017)
FROM-GLC	global	2010, 2015	Landsat	30 m	9 classes	Tsinghua University, public	http://data.ess.tsinghua.edu.cn/	Gong et al. (2013)
CCI-LC 2000 2005 2010	global	1998-2002 2003-2007 2008-2012	MERIS, SPOT VGT	300 m	FAO LCCS 22 classes	ESA, public	http://maps.elie.ucl.ac.be/CCI/viewer/index.php	ESA (2017)
CORINE Land Cover (CLC) CLC1990 CLC2000 CLC2006 CLC2012 CLC2018	Europe	1986-1998 1999-2001 2005-2007 2011-2012 2017-2018	Landsat, SPOT, IRS, Rapid Eye, Sentinel-2	100 m and 250 m (rasterized vector product, minim um mapping unit/width 25 ha/ 100 m)	44 classes	European Environment Agency (EEA), public	https://land.copernicus.eu/pan-european/corine-land-cover	Büttner et al. (2014)
Land cover 100m	global	2015	PROBA-V	100 m	FAO LCCS 22 classes	ESA, public	https://land.copernicus.eu/global/products/lc	Buchhorn et al. (2019)
S2GLC	Europe	2017	Sentinel-2	10 m	13 classes	ESA, public	http://s2glc.cbk.waw.pl/	Lewiński et al. (2019)

981 *5.4. Soil properties and lithology*

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

991 Nonetheless, there are several soil properties that are known to potentially influence gully erosion and
992 are therefore worthwhile considering. Most of these can affect both the erodibility and hydrological
993 functioning of soils. The most relevant properties are likely soil texture characteristics (e.g. percentage
994 of sand, silt and clay), soil organic carbon content, the content and cover of coarse fragments (e.g.
995 [Poesen et al. 1999](#); [Torri et al., 1997](#); [Rieke-Zapp et al. 2007](#); [Panagos et al., 2014](#); [Borrelli et al.,](#)
996 [subm.](#)). Also the water holding capacity, soil depth, bulk density and underlying lithology (or parent
997 material) can play an important role in determining the occurrence and dimensions of gullies (e.g.
998 [Kheir et al., 2008](#); [Hopp & McDonnell, 2009](#)). Likewise, the presence of faults and joints can
999 influence gully occurrence, as they are often associated with higher degrees of weathering. Finally,
1000 gully occurrence and dynamics can be affected by the presence of specific soil horizons, dispersivity
1001 (e.g. sodic properties), susceptibility to soil piping, etc. (e.g. [Rienks et al., 2000](#); [Nachtergaele &](#)
1002 [Poesen, 2002](#); [Bernatek-Jakiel & Poesen, 2018](#); [Bernatek-Jakiel & Wrońska-Wałach, 2018](#)). Many of
1003 these properties remain difficult to assess in detail at (sub)continental scales. Nevertheless, qualitative
1004 soil maps can be very helpful when aiming to account for such context-specific aspects.

1005 **Table 7** provides an overview of relevant databases at European and global scales. The European Soil
1006 Database provides 73 attributes at 1:1 million scale or as a raster format with a 1 km resolution
1007 ([Panagos et al., 2012](#)). The dataset is mostly qualitative and mainly based on national soil data and
1008 maps from the period 1960-1990. Potentially relevant attributes include: the dominant and secondary
1009 parent material, depth to bedrock, soil structure, soil crusting and water holding capacity. Furthermore,
1010 the European Commission amended the LUCAS (Land Use/Cover) surveys of 2009/2012, 2015 and
1011 2018 by including a topsoil survey to collect around 20,000 soil samples from all EU countries
1012 ([Orgiazzi et al., 2018](#)). The resulting LUCAS topsoil database includes measured data for soil physical
1013 and chemical properties. Based on a geostatistical processing of these data, a number of soil property
1014 spatial datasets were developed at a 500m resolution. These include soil texture (sand, silt, clay),
1015 coarse fragment content and available water capacity ([Ballabio et al., 2016](#)). Also datasets on chemical
1016 properties (pH, CEC, P, N, K) were also made available at 500m resolution for the EU ([Ballabio et al.,](#)

1017 [2019](#)). Likewise, building on the LUCAS database, the EU Joint Research Centre (JRC) developed
1018 high resolution soil erodibility datasets ([Borrelli et al., 2014](#); [Panagos et al., 2014](#)). The latter are based
1019 on physical soil properties, taking into account the impact of stone cover. Other suitable sources for
1020 pan-European studies may be the 1:5 million Geological Map of Europe, which includes various
1021 lithological and geological attributes ([Asch, 2005](#)), or the Geo-LiM geo-lithological map for Central
1022 Europe ([Donnini et al., 2019](#)).

1023 At global scale, the most comprehensive soil property datasets are the Harmonised World Soil
1024 Database v 1.2 ([FAO, 2012](#)) and SoilGrids ([Hengl et al., 2017](#)). The first provides a 30 arc-second
1025 raster database with over 15,000 different soil mapping units. SoilGrids is a collection of soil
1026 properties and classes. It is based on an automated soil mapping procedure using global soil profile
1027 data and various (EO) covariates. A ten-fold cross-validation of SoilGrids at 250m resolution indicated
1028 that the automated algorithms explain 61% of the overall variation. However, this performance varies
1029 strongly depending on the property considered (e.g. 56% for coarse fragments, 83% for pH; [Hengl et
1030 al., 2017](#)). With respect to underlying lithology, the GLiM (Global Lithology Map) by [Hartmann &
1031 Moosdorf \(2012\)](#) is currently one of the most detailed globally consistent products.

Table 7: Selection of global and European soil and geological/lithological datasets

Dataset/ product name	Spatial extent	Data acquisition period	Spatial resolution	Source	Data download	Reference
Harmonized world soil database v1.2	global, continental, regional	1971-2012	30 arc seconds	FAO/ UNESCO, public	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/	FAO (2012)
LUCAS 2009 Topsoil physical properties for Europe	Europe	2009	500m	European Commission/ JRC, public	https://esdac.jrc.ec.europa.eu/content/topsoil-physical-properties-europe-based-lucas-topsoil-data	Ballabio et al. (2016)
LUCAS 2009 Chemical properties	Europe	2009	500m	European Commission/ JRC, public	https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data	Ballabio et al. (2019)
SoilGrids	global	2013-2017	250-1000m	ISRIC, public	https://soilgrids.org/#/?layer=ORCDRC_M_sl2_250m&vector=1	Ribeiro et al. (2015); Hegl et al. (2017)
European Soil Database	Europe (and Eurasia)	1960-1990	1km	European Commission/ JRC, public	https://esdac.jrc.ec.europa.eu/content/european-soil-database-v2-raster-library-1kmx1km	Panagos et al. (2012)
Soil erodibility dataset	Europe	2014	500m	European Commission/ JRC, public	https://esdac.jrc.ec.europa.eu/content/soil-erodibility-k-factor-high-resolution-dataset-europe	Panagos et al. (2014)
1: 5 million Geological Map of Europe (IGME 5000)	Europe and adjacent areas	1990-2000	1: 5million	BGR, national geological surveys, public	https://www.bgr.bund.de/EN/Themen/Sammlungen-Grundlagen/GG_geol_Info/Karten/International/Europa/IGME5000/IGME_Project/IGME_Projectinfo.html	Asch (2005)
Geo-lithological map for Central Europe (Geo-LiM)	Central Europe	1990-2010	1:1 million	CNR IRPI, public	https://zenodo.org/record/3530257	Donnini et al. (2020)
Global Lithology Map	global	unknown	1: 3750 000 (average)	University of Hamburg, (partly) public	https://doi.pangaea.de/10.1594/PANGAEA.788537	Hartmann & Moosdorf (2012)

1034 **5.5. Climate and weather conditions**

1035 Climate and weather conditions, and especially rainfall, are key drivers of gully erosion (cf. [section 4](#)).
1036 Rainfall can have short (i.e. triggering) and long term (i.e. conditioning) effects. On the short term,
1037 rainfall intensities and amounts are generally key parameters, as they will determine the runoff volume
1038 and hence shear stress exerted by the water. Numerous studies have demonstrated significant
1039 correlations between rainfall intensity and gully head initiation (e.g. [Hayas et al., 2017b](#)), headcut
1040 retreat (e.g. [Vanmaercke et al., 2016](#)) and gully widening (e.g. [Hayas et al., 2019](#)). Conversely,
1041 characterizing the effect of rainfall over long periods is more complicate. For example, rainfall
1042 controls the soil moisture, which may further condition the runoff response but also the soil resistance
1043 against erosion (e.g. [Capra et al., 2009](#)). Furthermore, climate over longer timescales can have
1044 significant indirect effects, e.g. through its influence on vegetation development and soil mechanical
1045 properties (e.g. [Dunne et al., 1991](#); [Sanchis et al., 2008](#); [Fan et al., 2017](#)). Complex relations exist
1046 among these different effects, making it difficult to define rainfall-related variables that accurately
1047 account for all relevant mechanisms. In some contexts, also snowmelt may be a key driver of gully
1048 erosion (e.g. [Ionita, 2006](#); [Golosov et al., 2018](#)). While snowmelt runoff can already be modelled and
1049 monitored to some extent, its effects on gully erosion remain relatively understudied, especially at
1050 (sub)continental scales (e.g. [Maltsev & Yermolaev, 2019](#)).

1051 Hence, the type and spatio-temporal resolution of precipitation data required will vary depending on
1052 the study region, but also in function of the purpose. Modelling exercises at short time scales (e.g.
1053 daily, event-based) require data of similar temporal resolutions. When aiming to understand mean
1054 tendencies and spatial variations, coarser data are already useful. For example, long-term average
1055 proxies like the rainy day normal can already serve as a useful predictor for average trends (e.g.
1056 [Vanmaercke et al., 2016](#); [Hayas et al., 2017b](#)).

1057 **Table 8** provides a selection of available global and European rainfall datasets, building on an earlier
1058 overview presented by [Sun et al. \(2018\)](#). These gridded datasets are based on a variety of methods.
1059 Several are derived from rain gauge data, using different regionalization methods (e.g. [Rudolf et al.,](#)
1060 [2009](#); [Schamm et al., 2014](#)). The accuracy of such datasets can be expected to depend on the gauge
1061 network density which may be limited, especially in Global South countries (e.g. [Schneider et al.,](#)
1062 [2014](#)). Despite their generally shorter time series, RADAR-derived products can provide an important
1063 alternative (e.g. [Ashouri et al., 2015](#)). RADAR-based rainfall observation networks are implemented
1064 in many countries. They measure rainfall rates, based on the analysis of the echoes generated by the
1065 interaction between active microwave signals and rain drops ([Sauvageot, 1994](#); [Wexler & Atlas,](#)
1066 [1963](#)). RADAR rainfall estimates are indirect and represent measures of rainfall far from the surface,
1067 which may be a limitation. However, their high spatio-temporal level of detail (e.g. estimates every 10
1068 minutes at a 5×5 km resolution) allows measuring local, short and intense rainfall events. Overall, data
1069 from regional RADAR networks (and in particular historical RADAR data series) remain scarcely

1070 accessible and underused. Other gridded rainfall products are derived from satellite observations. In
1071 general, they are based on algorithms that combine passive microwave and infrared measurements
1072 from geostationary and low earth orbit satellites. Despite their often limited spatio-temporal
1073 resolutions, their main advantages are their global coverage and their easy accessibility. Hence, they
1074 offer great potential for gully erosion modelling at larger scales, especially in countries where other
1075 rainfall data are scarce. Nonetheless, also these satellite products generally rely to some extent on
1076 gauging station observations and can be subject to uncertainties (e.g. [Monsieur et al., 2018](#)). Finally,
1077 several datasets have been produced through reanalysis, in which meteorological modelling results are
1078 combined with rainfall observations ([Gelaro et al., 2017](#)). These products have diverse spatial and
1079 temporal resolutions that cover extended periods (**Table 8**).

1080 At European scale, another relevant proxy worth mentioning is the rainfall erosivity dataset, which
1081 was produced with 30-minutes precipitation data from 1675 stations in the EU ([Panagos et al., 2015](#)).
1082 While this proxy was originally developed for simulating sheet and rill erosion rates, it may also be
1083 useful for gully erosion modelling.

1084

Table 8: Selection of global and European rainfall datasets (based on Sun et al., 2018).

Dataset/product	Spatial coverage	Spatial resolution	Temporal resolution	Period	Sensor and type of retrieval	Source	Data download	Reference
E-OBS	Europe	0.55°/0.50°/0.22° rotated/0.44° rot	Daily	1950-present	Gridded rain gauge	ECA&D	https://www.ecad.eu/download/ensembles/download.php#datafiles	Haylock et al. (2008); Cornes et al. (2018)
CRU	Global land	0.5° × 0.5°	Monthly	1901–2016	Gridded rain gauge	CRU of the University of East Anglia	http://www.cru.uea.ac.uk/data	Harris et al. (2014); New et al. (2000)
GHCN-M	Global land	5° × 5°	Monthly	1900-present	Gridded rain gauge	National Climatic Data Center	https://www.ncdc.noaa.gov/ghcnm/v2.php	Peterson & Vose (1997)
GPCC-monthly	Global land	0.25° × 0.25°, 0.5° × 0.5°, 1.0° × 1.0°, 2.5° × 2.5°	Monthly	1891–2016	Gridded rain gauge	Global Precipitation Climatology Centre	https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-monthly_v2018_doi_download.html	Schneider et al. (2014)
GPCC-daily	Global land	1.0° × 1.0°	Daily	1982–2013	Gridded rain gauge	Global Precipitation Climatology Centre	https://opendata.dwd.de/climate_environment/GPCC/html/fulldata-daily_v2018_doi_download.html	Schamm et al. (2014)
PREC/L	Global land	0.5° × 0.5°, 1.0° × 1.0°, 2.5° × 2.5°	Monthly	1948–2020	Gridded rain gauge	NCEP/NOAA	https://www.esrl.noaa.gov/psd/data/gridded/data.precl.html	Chen et al. (2002)
UDEL	Global land	0.5° × 0.5°	Monthly	1900–2017	Gridded rain gauge	University of Delaware	https://www.esrl.noaa.gov/psd/data/gridded/data.UDeL_AirT_Precip.html	Willmott & Matsuura (1995)
CPC	Global land	0.5° × 0.5°	Daily	1979–present	Gridded rain gauge	CPC	https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.globalprecip.html	Xie et al. (2010)
GPCP	Global	2.5°	Monthly	1979–present	Satellite + rain gauge	NOAA/OAR/ESRL PSD	https://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html	Adler et al. (2003)
GPCP 1dd	Global	1.0°	Daily	1996–present	Satellite + rain gauge	NASA	https://rda.ucar.edu/datasets/ds728.3/	Huffman & Bolvin (2013)
GPCP_PEN_v2.2	Global	2.5°	Pentad	1979–present	Satellite + rain gauge	NASA	https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00933	Xie et al. (2003; 2011)
CMAP	Global	2.5°	Monthly, Pentad	1979–2016, 1979–present	Satellite + rain gauge	NCEP–NCAR	https://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html	Xie et al. (2003); Xie & Arkin (1997)
TRMM 3B43	Global (50°S–50°N)	0.25°	3 h/Daily	1998–present	Satellite	NASA	https://pmm.nasa.gov/data-access/downloads/trmm	Huffman et al. (2007)
GSMaP	Global (60°S–60°N)	0.1°	1 h/daily	2000–2014	Satellite	JAXA	http://sharaku.eorc.jaxa.jp/GSMaP_crest/	Ushio et al. (2009)
PERSIANN-CCS	Global (60°S–60°N)	0.04°	30 min/3, 6	2003–present	Satellite	Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California	http://chrdata.eng.uci.edu/	Sorooshian et al. (2000); Nguyen et al. (2019)

PERSIANN-CDR	Global (60°S–60°N)	0.25°	Daily/monthly/yearly	1983–present	Satellite + rain gauge	Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California	http://chrdata.eng.uci.edu/	Ashouri et al. (2015); Nguyen et al. (2019)
CMORPH	Global (60°S–60°N)	0.25°	30 min/3 h/daily	2002–2017	Satellite	Climate Prediction Center	https://climatedataguide.ucar.edu/climate-data/cmorph-cpc-morphing-technique-high-resolution-precipitation-60s-60n	Joyce et al. (2004)
GPM	Global (60°S–60°N)	0.1°	30 min/3 h/daily	2000–present	Satellite	NASA	https://pmm.nasa.gov/data-access/downloads/gpm	Hou et al. (2008); Hou et al. (2014); Huffman et al. (2015)
MSWEP	Global	0.1°/0.5°	3 h/daily	1979–present	Satellite + rain gauge	Princeton University	http://www.gloh2o.org/	Beck et al. (2017)
NCEP1	Global	2.5° × 2.5°	Monthly/Daily/6 hourly	1948–present	Reanalysis	NCEP/NCAR	https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html	Kalnay et al. (1996)
NCEP2	Global	2.5° × 2.5°	Monthly/6 hourly	1979–present	Reanalysis	NCEP/NCAR	https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.surface.html	Kanamitsu et al. (2002)
ERA 40	Global	2.5° × 2.5°/1.125° × 1.125°	Monthly/6 hourly	1957–2002	Reanalysis	ECMWF	http://apps.ecmwf.int/datasets/data/era40-daily/levtype=sfc/	Uppala et al. (2005)
ERA Interim	Global	1.5° × 1.5°/0.75° × 0.75°	Monthly/6 hourly	1979–present	Reanalysis	ECMWF	http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/	Dee et al. (2011)
20CRv2	Global	2.0° × 2.0°	Daily/6 hourly	1851–2014	Reanalysis	NOAA	https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2c.pressure.html	Compo et al. (2011)
JRA-55	Global	60 km	Monthly/3 hourly/6 hourly	1958–present	Reanalysis	Japanese Meteorological Agency	http://jra.kishou.go.jp/JRA-55/index_en.html	Ebita et al. (2011)
MERRA	Global	0.5° × 0.67°	Daily	1979–present	Reanalysis	NASA	https://gmao.gsfc.nasa.gov/reanalysis/MERRA/	Rienecker et al. (2011)
MERRA Land	Global	0.5° × 0.67°	Monthly/Daily/1 hourly	1980–present	Reanalysis	NASA	https://gmao.gsfc.nasa.gov/reanalysis/MERRA-Land/	Reichle et al. (2011)
MERRA2	Global	0.5° × 0.67°	Daily	1980–present	Reanalysis	NASA	https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/	Gelaro et al. (2017)
CFSR 38	Global	38 km	hourly	1979–2011	Reanalysis	NOAA	https://www.ngdc.noaa.gov/metaview/page?xml=NOAA/NESDIS/NCDC/Geportal/iso/xml/C00765.xml&view=getDataView&header=none	Saha et al. (2010)
MSG CPP	Europe	3 × 3 km	15 minutes	2005–2011	Satellite	Koninklijk Nederlands Meteorologisch Instituut (KNMI)	http://msgcpp.knmi.nl/mediawiki/index.php/MSG_Cloud_Physical_Properties_%28CPP%29	Roebeling et al. (2009)

1087 **6. Policies relevant to gully erosion: frameworks and current needs**

1088 At the global level, the issue of soil erosion receives significant attention (e.g. [Montanarella et al.,](#)
1089 [2016](#)). For example, the United Nations Convention to Combat Desertification ([UNCCD, 2018](#)) and
1090 the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES;
1091 [Scholes et al., 2018](#)) both stress the importance of human-induced soil erosion as a key driver of land
1092 degradation and expresses concerns about the potential impacts of climate change on soil erosion rates.
1093 Also several of the UN Sustainable Development Goals (SDGs) clearly identify soil resources as being
1094 of crucial importance. More specifically, Goal 1 (No Poverty), Goal 2 (Zero Hunger), Goal 3 (Good
1095 Health and Well-being), Goal 6 (Clean Water and Sanitation), Goal 13 (Climate Action) and Goal 15
1096 (Life on Land) strongly link to the need to preserve soil resources in order to achieve these goals by
1097 2030 ([Keesstra et al., 2016](#); [Bouma, 2019](#); [Panagos & Katsoyiannis, 2019](#); [Albaladejo et al., 2021](#)).
1098 The Food Agriculture Organization has published Guidelines for Sustainable Soil Management ([FAO,](#)
1099 [2016](#)), aiming to support countries in implementing actions for soil protection.

1100 The European Union is a front-runner in attaining the SDGs and has committed to play an active role
1101 towards their realization. With respect to SDG 15 'Life on Land', the EU identifies 3 sub-themes:
1102 ecosystem status, biodiversity and land degradation ([Panagos & Katsoyiannis, 2019](#)). One of the
1103 indicators used to assess progress with respect to land degradation is soil erosion by water ([Panagos et](#)
1104 [al., 2015a; 2015b](#)). Overall, soil protection is not subject to a single, coherent legislation within the
1105 EU. Although a Soil Thematic Strategy ([COM 2006.231](#)) was proposed, the Commission withdrew
1106 this proposal to develop a Soil Framework Directive in 2014. Nevertheless, there is a strong
1107 commitment of the EU and its member states to conserve soil resources and several measures exist
1108 across different policies.

1109 In the EU agricultural sector, the main active policy instrument to promote agro-environmental
1110 friendly agriculture is the Cross Compliance mechanism, which was introduced in the Common
1111 Agricultural Policy (CAP) in 2003. In 2009, the standards of Good Agricultural and Environmental
1112 Conditions (GAEC) were introduced in the CAP legislation framework ([Common Agricultural Policy](#)
1113 [\(CAP\), 73/2009](#)). One of the requirements in the GAEC is to limit soil loss by water erosion and to
1114 maintain soil organic carbon ([Borrelli et al., 2016](#)). For this, the GAEC standards include a set of
1115 practices, such as reduced tillage, crop residues management, cover crops, maintaining terraces, grass
1116 margins next to watercourses, contour farming and crop rotation. While most of these practices may
1117 have a beneficial effect on preventing gully erosion, the GAEC makes no explicit reference to the
1118 mitigation of existing permanent gullies, nor to the management of ephemeral gullies. Nonetheless,
1119 specific measures can be taken by individual member states to tackle (gully) erosion, using funds from
1120 the European Agricultural Fund for Rural Development (EAFRD), under the Council Regulation EU
1121 1305/2013. For example, in the Spanish region of Andalusia, gully control measures were subsidized

1122 under this programme in 2009-2010. However, despite some initial successes, this programme was
1123 discontinued because of a shift in regional priorities. In Flanders (Belgium) municipalities can request
1124 subsidies for developing local erosion control plans and implementing small-scale erosion control
1125 measures like check dams or sediment control basins.

1126 Also the new legislative proposal of the European Commission for the post-2020 Common
1127 Agricultural Policy ([CAP 2021-27](#), [COM\(2018\) 392](#)) includes measures for soil conservation (e.g.
1128 cover crops) and maintaining soil organic carbon. Post-2020, soil protection will gain more
1129 importance through Eco-schemes as an integral part of the new Green Architecture design. In fact,
1130 effective soil management is one of the nine key objectives of the new CAP. While the post-2020 CAP
1131 is still being defined and will likely only come into force in 2023, it is clear that Member States will
1132 have greater flexibility in deciding on policy measures through the CAP national strategic plans. This
1133 may create opportunities to target gully erosion more specifically and to tailor the implementation of
1134 measures to particular farming contexts. However, apart from agriculture, also land use changes such
1135 as reforestation can have significant impacts on gully erosion. Presently, the European Union does not
1136 have a common forestry policy making it still primarily a national matter. Nonetheless, the CAP is the
1137 main funding source for forestry, with conversions of agricultural land to forest being supported by
1138 Rural Development funds.

1139 In the area of European water policy, the Water Framework Directive ([WFD](#), [Directive 2000/60/EC](#))
1140 and the [Nitrate Directive \(91/676/EEC\)](#) set environmental targets that promote soil conservation
1141 actions. Under the WFD, EU Member States need to establish Programmes of Measures (PoMs) to
1142 achieve good ecological and chemical statuses of water bodies. Diffuse pollution from soil erosion in
1143 cropland is identified as a key pressure on water quality in many River Basin Management Plans
1144 across the EU (e.g. [Heininger et al., 2015](#)), thus erosion control measures should be adopted in PoMs
1145 to curb agricultural impacts on water bodies. Similarly, the Nitrate Directive requires implementation
1146 of good agricultural practices in nitrate vulnerable zones to reduce runoff, erosion, and nitrate losses.
1147 However, the WFD and the Nitrate Directive do not mention soil (or gully) erosion and its control
1148 explicitly.

1149 Recently, the European Commission introduced the European Green Deal ([EU COM\(2019\) 640](#)) with
1150 the ambition to make EU the first climate-neutral continent by 2050. The EU Green Deal sets
1151 ambitious targets such as protecting 30% of the EU's land area, bringing back at least 10% of the
1152 agricultural area under high-diversity landscape features and plant more than three billion trees by
1153 2030 ([Montanarella and Panagos, 2021](#)). Although those targets have not yet been translated in
1154 specific policy measures, it is clear that implementing the EU Green Deal will contribute to
1155 sustainable soil management, introducing more soil conservation measures, reducing land degradation
1156 and mitigating soil losses due to erosion.

1157 In practice, a wide range of gully control practices exists and have been implemented in numerous
1158 areas (e.g. [Evrard et al. 2008](#); [Castillo & Gomez, 2016](#); **Figure 4**). The overall effectiveness of such
1159 measures has been recently reviewed (e.g. [Bartley et al., 2020](#); [Frankl et al., 2020](#)). The most common
1160 conservation practices include increasing the soil erosion resistance in concentrated flow zones,
1161 protecting the headcut, diverting overland flows away from gullies as well as creating terraces, grassed
1162 waterways, check dams and water and sediment control basins ([Casali et al., 1999](#); [Poesen et al. 2003](#),
1163 [Valentin et al., 2005](#)). Also in the EU, such measures have been implemented. Nevertheless, measures
1164 that directly address gully erosion are not yet compulsory in EU policies. Also soil conservation
1165 measures such as reduced tillage are applied at a more limited scale in the EU (4% no till and 22%
1166 reduced tillage; [EU Agricultural census, 2010](#); [Panagos et al., 2015b](#)) as compared to for example the
1167 USA (35% no till and 27% reduced tillage; [Census of Agriculture, 2012](#)). In terms of land
1168 management, this makes European arable land potentially more vulnerable to ephemeral gully erosion.
1169 Overall, soil erosion is clearly considered an important agro-environmental indicator to assess the
1170 effectiveness of EU policies such as the Common Agricultural Policy (e.g. [Gobin et al., 2004](#); [Zalidis
1171 et al., 2004](#)). However, the CAP-induced soil conservation practices consider only sheet and rill
1172 erosion and do not account for gully erosion ([Panagos et al., 2015a; 2015b](#)).

1173 The situation in the EU contrasts, with other regions. For example in the United States, gully control
1174 measures are more widespread. Measures to reduce gully erosion have been implemented as early as
1175 the 1930s in the USA, including those by the Civilian Conservation Corps ([USDA, 2007](#)). The
1176 development of handbooks on the formation and control of gullies by national agencies greatly
1177 contributed to this (e.g. [USDA, 2007](#)). Grade stabilization structures such as drop pipes were the most
1178 common conservation practice to control gully erosion ([Wilson et al., 2008](#)), but also extensive
1179 reforestation and reservoir construction programmes were implemented (e.g. [Rhemtulla et al., 2009](#);
1180 [Abbasi et al., 2019](#)). In China, The Grain for Green programme strongly mitigated gully erosion in the
1181 Loess Plateau by implementing slope conservation measures and check-dams on a massive scale
1182 ([Xiang-zhou et al., 2004](#); [Sun et al., 2019](#)). In some areas, the restoration of vegetation on hillslopes
1183 through the Grain for Green programme reduced gully erosion rates with up to 90% ([Wang et al.,
1184 2016](#)). Also in Australia, there are several large government-funded programmes focused on gully
1185 remediation ([Wilkinson et al., 2019](#)). They aim to reduce sediment and particulate nutrient loads that
1186 form, in combination with climate change, an important threat to the Great Barrier Reef ([MacNeil et
1187 al., 2019](#)). A variety of gully remediation approaches are currently tested in catchments draining to the
1188 Great Barrier Reef, ranging from low-cost erosion control structures to larger scale landscape
1189 remediation ([Koci et al., 2021](#)). Also Ethiopia has implemented several large-scale soil and water
1190 conservation programmes that included measures specifically targetting gully erosion (e.g.
1191 [Haregeweyn et al., 2015](#)).

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Figure 4: Examples of commonly applied gully control measures. **(a)** Cropland in Litichovice, Czech Republic with rill and ephemeral gully erosion (photo: J. Krása). **(b)** The same cropland area, treated with grassed waterways (foreground) and grass buffer strips to control sediment production and transfer by ephemeral gully erosion (photo: J. Krása). **(c)** Grass buffer strip installed at a parcel border to reduce the transfer of sediments originating in an ephemeral gully (Huldenberg, Belgium) (photo: J. Poesen). **(d)** Control of ephemeral gully erosion in the concentrated flow zone with a life vegetation barrier forming a hedgerow (Wisques, France) (photo: J. Poesen). **(e)** Control of ephemeral gully erosion in the concentrated flow zone with a dam made of straw bales (Huldenberg, Belgium) (photo: J. Poesen). **(f)** Control of a permanent gully erosion with a gabion check dam in the concentrated flow zone (Andalucia, Spain) (photo: J. Poesen). **(g)** Control of a permanent gully erosion in the concentrated flow zone with a wood/concrete check dam (Wisques, France) (photo: J. Poesen). **(h)** Revegetation of a permanent gully channel (Adi Shuhu, Ethiopia) (photo: J. Poesen).

1205 In summary, the large number of policy initiatives at the European level (i.e. the Soil Thematic
1206 Strategy, the Common Agricultural Policy, the Water Framework Directive, and EU Green Deal) as
1207 well as global initiatives (Sustainable Development Goals, FAO guidelines, IPBES, UNCCD) show
1208 that soil erosion is widely recognized as a problem. Nonetheless, relatively limited attention is given to
1209 gully erosion. This likely results from insufficient awareness and understanding of this process.
1210 Developing adequate policies to deal with gully erosion requires reliable, spatially explicit indicators
1211 on where this problem occurs. Furthermore, it requires tools and data to assess the effectiveness and
1212 efficiency of soil conservation measures. This is especially pertinent since gully erosion generally
1213 requires interventions that are more drastic and expensive than for sheet and rill erosion (e.g. [Valentin
1214 et al., 2005; Bartley et al., 2021](#)).

1215 Holistically addressing the problem of soil erosion and land degradation requires models that can
1216 simulate and assess all relevant erosion processes, as well as their impacts on catchment sediment
1217 budgets (e.g. [Borrelli et al., 2018; Poesen, 2018](#)). While detailed models and maps at the European and
1218 global level exist to assess sheet and rill erosion (e.g. [Borrelli et al., 2017a](#)) this is clearly not the case
1219 for gully erosion (cf. [sections 3 and 4](#)). Our current inability to quantify gully erosion and its impacts
1220 should not imply that this process should remain neglected in policies. Building on the already
1221 extensive scientific knowledge gained in several regions worldwide (e.g. [USDA, 2007; Sabir et al.,
1222 2020](#)), EU and national/regional agro-environmental policies should aim to address, prevent and
1223 mitigate gully erosion and its impacts. It deserves mentioning that the EU already makes important
1224 efforts in this regard, including through initiatives like the ‘Land Use/Cover Area frame statistical
1225 Survey Soil’ (LUCAS; e.g. [Blum et al., 2004; Panagos et al., 2015b; Borrelli et al., 2017b; Orgiazzi et
1226 al. 2018](#)) which aims at monitoring soil health in the EU. In the LUCAS 2018 campaign, a soil erosion
1227 module was introduced where different processes of soil erosion (including gully erosion) were
1228 assessed for more than 20,000 visited points across the EU ([Borrelli et al., subm.](#)).

1229

1230 **7. Conclusions and recommendations**

1231 Gully erosion is an important land degradation process, leading to major on- and off-site impacts (cf.
1232 [section 1](#)). Climate change and land use/land cover changes may aggravate these impacts in many
1233 regions. Adequately addressing land degradation in a context of global change therefore requires
1234 strategies and policies that specifically account for gully erosion. However, the development of these
1235 is strongly hampered by our inability to accurately quantify and simulate gully erosion in relation to its
1236 driving factors, especially at larger (i.e. regional to global) scales. More specifically, we need tools and
1237 models that are capable of:

- 1238 (i) identifying gully erosion hotspots;
- 1239 (ii) quantifying gully erosion rates at different spatio-temporal scales;

- 1240 (iii) assessing the impacts of gullies, including their (direct and indirect) contribution to catchment
1241 sediment yields; and
- 1242 (iv) simulating the effects of land use/land cover changes, climate change, land management and
1243 conservation measures on gully erosion and its impacts.

1244 While the development of such tools and models poses an important challenge, significant progress
1245 has been made over recent decades. Based on a review of over 590 scientific publications and policy
1246 documents, this article presents a state-of-the-art on monitoring, modelling and managing gully
1247 erosion at larger scales. Here we list our key conclusions and recommendations regarding these three
1248 aspects.

1249

1250 ***7.1 Gully monitoring***

1251 Monitoring the occurrence and dynamics of gully systems remains essential for better understanding
1252 and constraining rates and controlling factors of gully erosion. Especially datasets on the initiation and
1253 evolution of gully systems over large areas are a prerequisite for the development of models that can
1254 simulate this process at larger scales. Such datasets currently remain scarce. New remote sensing
1255 products can greatly help in addressing this gap. Nevertheless, monitoring gully erosion at larger
1256 scales remains highly labour-intensive and/or requires significant concessions in accuracy,
1257 completeness and level of detail (cf. [section 2](#)). Also the limited length of the observation periods and
1258 the coarse temporal resolution often form important constraints.

1259 We make the following recommendations with respect to gully monitoring via remote sensing:

- 1260 (i) Further research is needed to develop approaches that allow assessing the occurrence,
1261 properties and evolution of gully systems at larger spatial scales in efficient and accurate
1262 ways. Promising avenues for this are strategies that rely on monitoring gullies in large sets of
1263 small yet representative case study areas and the (semi-)automatic detection and
1264 characterization of gullies.
- 1265 (ii) More studies are needed that provide data on the dynamics of gully erosion at high temporal
1266 resolutions across different environmental settings. This is particularly relevant for ephemeral
1267 gullies which may be formed and erased again over short time spans, potentially leading to
1268 significant underestimations of their erosion rates. Repeated analyses of frequent imagery,
1269 preferably taken shortly after every significant runoff event is likely the best way to address
1270 this need. The increasing availability of EO products at high spatio-temporal and spectral
1271 resolutions opens promising perspectives here.
- 1272 (iii) Better insight and data are needed on the long-term evolution of gully systems. Gullies often
1273 form and expand over short time periods and then remain stable for many years. In some
1274 environments they may even be filled in again. Likewise, apparently stable gullies may be

1275 reactivated as a result of extreme climatic events or land cover/use/management changes.
1276 Nonetheless, most of the available data on gully erosion rates cover relatively short time
1277 periods (i.e. a few years) and are not necessarily representative for long-term average erosion
1278 rates. Systematically assessing the evolution of both active and seemingly stable gullies over
1279 decadal timescales will help addressing this need. Historical (aerial) photos and early satellite
1280 imagery can be an important asset for this.

1281 (iv) Methodological advancements are required that allow better quantifying the uncertainties
1282 associated with gully monitoring. Assessed gully dimensions and dynamics are often subject
1283 to considerable uncertainties as a result of mapping errors, observation biases, the large
1284 temporal variability of gully erosion and conversion errors (e.g. when deriving gully volumes
1285 from gully lengths or areas). We recommend more research that allows quantifying these
1286 different sources of uncertainty, as well as their combined effects on the total uncertainty.
1287 Linked to that, we recommend developing procedures that allow better comparisons of
1288 collected data. Classifying gullies according to a consistent typology across different studies
1289 will be an important element in this.

1290 Apart from remote sensing, also field-based research in well-targeted areas will remain essential to
1291 understand gully erosion. Our overview for Europe (section 3) may serve as a starting point for future
1292 studies aiming to develop gully erosion models at regional to continental scales. However, it also
1293 uncovered shortcomings and gaps. For example, most studies focused on permanent gullies, while
1294 bank gullies and ephemeral gullies received considerably less attention. Nonetheless, their associated
1295 impacts can be very high. Other pertinent research needs include:

- 1296 (i) studies that monitor gully densities and gully expansion rates systematically over larger areas;
- 1297 (ii) studies that monitor gully dynamics (i.e. initiation, headcut retreat, but also gully widening,
1298 deepening and infilling) and related subprocesses (e.g. piping, mass movement) at decadal
1299 timescales, preferably at high temporal resolutions;
- 1300 (iii) studies that evaluate the performance of different gully modelling strategies based on detailed
1301 field observations; and
- 1302 (iv) studies that assess the effectiveness of different gully erosion control measures over
1303 sufficiently long time periods.

1304

1305 **7.2. Gully modelling**

1306 There is an important need for models and tools that can simulate and predict gully erosion at regional
1307 to global scales. Various viable model approaches and concepts have already been proposed, but need
1308 to be further developed, upscaled and tested so that they can be applied at larger scales (cf. section 4).
1309 A major challenge is finding a good balance between an accurate process representation and feasible

1310 data requirements. The recent and ongoing development of new environmental data products at
1311 (sub)continental to global scales opens promising perspectives in this regard (cf. [section 5](#)).

1312 More specifically, process-oriented model approaches can yield relevant insights into the factors and
1313 mechanisms driving gully erosion, as well as their interactions. As such, they can be important tools
1314 for scenario analyses. However, their generally high data requirements make it difficult to apply them,
1315 especially at larger scales. Empirical modelling strategies, and in particular machine-learning
1316 approaches, offer great potential. However, their overall 'black box' nature can impede clear insights
1317 into the actual drivers of gully erosion. Different modelling strategies will therefore need to be
1318 developed and combined.

1319 We make the following recommendations with respect to modelling gully erosion and its impacts:

- 1320 (i) Better insights are needed on the factors controlling gully erosion at larger scales and how the
1321 role of these factors can be translated into meaningful variables and proxies that can be
1322 derived from GIS/EO data. This is especially so for the effects of climate and weather
1323 conditions, vegetation cover, land use/management, soil and lithological properties.
- 1324 (ii) While numerous modelling strategies have already been proposed, more work is required to
1325 scale up these approaches from case studies to larger regions. This is the case for process-
1326 oriented strategies (e.g. relying on a spatially explicit hydrological model) as well as for
1327 empirical (e.g. machine learning) approaches. Much of this work will revolve around finding
1328 optimal trade-offs between model accuracy and feasible data and calculation requirements.
- 1329 (iii) The potential to couple and combine different approaches needs to be further explored and
1330 developed. Most efforts so far have focussed on simulating either gully initiation, density or
1331 expansion (mainly through headcut retreat), while little research has been conducted on how
1332 to integrate these different aspects into models that predict total gully erosion rates. Such
1333 integration will also need accounting for potential interactions between these different
1334 components of gully erosion and their controlling factors as well as with potential interactions
1335 with other erosion processes (e.g. sheet and rill erosion).
- 1336 (iv) Additional research is necessary on accounting for the effects of land use and land
1337 management practices, and in particular soil and water conservation measures, on gully
1338 erosion and its impacts at larger scales. This will require further developing large-scale
1339 datasets indicating the presence of specific erosion control measures but also modelling
1340 frameworks that allow quantifying their effectiveness and efficiency.
- 1341 (v) There is a large need for tools and model frameworks that allow better assessing and
1342 quantifying the diverse on- and off-site impacts of gully erosion, both at short and longer
1343 timescales. This includes the effects of gully erosion on hillslope hydrology, crop yields,
1344 biomass production and other ecosystem services of soils, but also downstream impacts (e.g.
1345 assessing the contribution of gullies to river sediment load and catchment hydrology). This

1346 will likely require coupling gully erosion models to available models, but also developing new
1347 model components (e.g. accounting for the impacts of gullies on sediment connectivity).
1348 (vi) On a more general level, the potential of models to simulate gully erosion and its impacts for
1349 scenario analyses needs to be further developed and tested. A key element in this will be the
1350 thorough validation of these models, using reliable observations over a large range of
1351 environmental conditions.

1352

1353 **7.3. Gully management**

1354 Overall, there is a significant and growing international interest to tackle the challenges of soil erosion
1355 and land degradation in the context of global change (cf. [section 6](#)). In Europe, numerous frameworks
1356 and policies help addressing the problem of soil erosion. However, very few of them explicitly
1357 account for (or even mention) gully erosion. More specific guidelines and recommendations to deal
1358 with this process are required. To a large extent, the absence of gully erosion in current policies is
1359 mainly due to our inability to accurately assess and quantify this process and its impacts. This hampers
1360 effective communication between scientists and policy makers on setting realistic targets and
1361 solutions. Nevertheless, our current state of knowledge does already allow accounting more explicitly
1362 for gully erosion.

1363 We believe the following elements can aid in a better management of gully erosion at larger scales:

- 1364 (i) Scientific initiatives that help to better quantify and understand gully erosion, allowing for
1365 more targeted policies, need to be further supported. Especially initiatives that help identifying
1366 (potentially) problematic areas and assessing the effectiveness, costs and benefits of
1367 prevention and control measures are needed in this regard.
- 1368 (ii) Lessons learned from other policy implementations (e.g. with respect to sheet and rill erosion)
1369 as well as from regions where gully control measures are already implemented should be
1370 integrated in policies dealing with gully erosion.
- 1371 (iii) Given that the formation, expansion rates and impacts of gullies strongly vary between
1372 regions, (future) policy instruments should accommodate for this diversity of contexts.

1373

1374 **Acknowledgements**

1375 We thank the Joint Research Centre (JRC), European Commission for organizing the workshop on
1376 gully erosion (March 2018) that led to the idea of this paper. Most of this article has been written
1377 during the COVID-19 lockdown. We therefore dedicate this paper to the many victims of this

1378 pandemic, as well as to the numerous health workers, scientists and policy makers that try to keep it at
1379 bay.

1380

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